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**Modeling and Validation of Sodium Plugging for Heat
Exchangers in Sodium-cooled Fast Reactor Systems**

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List of Acronyms

AC	Alternate Current	PE	Pulse Echo
ACPD	Alternate Current Potential Drop	RMS	Root Mean Square
ANL	Argonne National Laboratory	sCO ₂	Supercritical CO ₂
CFD	Computational Fluid Dynamics	SFR	Sodium Fast Reactor
CT	Computer Tomography	SPPL	Sodium Plugging Phenomena Loop
DC	Direct Current	SS	Stainless Steel
DCPD	Direct Current Potential Drop	SST	Shear Stress Transport
EM	Electromagnetic	T/C	Thermocouple
FEA	Finite Element Analysis	TD	Transducer
FM	Flowmeter	TOF	Time-of-flight
HX	Heat Exchanger	TT	Through Transmission
IHTS	Intermediate Heat Transport System	UTDR	Ultrasonic Time Domain Reflectometry
NDE	Non-destructive Evaluation	VCR	Variable Compression Ratio
PD	Potential Drop	WG	Waveguide

Executive Summary

The project “Modeling and Validation of Sodium Plugging for Heat Exchangers in Sodium-cooled Fast Reactor Systems” was conducted jointly by Westinghouse Electric Company (Westinghouse) and Argonne National Laboratory (ANL), over the period October 1, 2013- March 31, 2016. The project’s motivation was the need to provide designers of Sodium Fast Reactors (SFRs) with a validated, state-of-the-art computational tool for the prediction of sodium oxide (Na_2O) deposition in small-diameter sodium heat exchanger (HX) channels, such as those in the diffusion bonded HXs proposed for SFRs coupled with a supercritical CO_2 (sCO_2) Brayton cycle power conversion system. In SFRs, Na_2O deposition can potentially occur following accidental air ingress in the intermediate heat transport system (IHTS) sodium and simultaneous failure of the IHTS sodium cold trap. In this scenario, oxygen can travel through the IHTS loop and reach the coldest regions, represented by the cold end of the sodium channels of the HXs, where Na_2O precipitation may initiate and continue. In addition to deteriorating HX heat transfer and pressure drop performance, Na_2O deposition can lead to channel plugging especially when the size of the sodium channels is small, which is the case for diffusion bonded HXs whose sodium channel hydraulic diameter is generally below 5 mm. Sodium oxide melts at a high temperature well above the sodium melting temperature such that removal of a solid plug such as through dissolution by pure sodium could take a lengthy time.

The Sodium Plugging Phenomena Loop (SPPL) was developed at ANL, prior to this project, for investigating Na_2O deposition phenomena within sodium channels that are prototypical of the diffusion bonded HX channels envisioned for SFR- sCO_2 systems. In this project, a Computational Fluid Dynamic (CFD) model capable of simulating the thermal-hydraulics of the SPPL test section and provided with Na_2O deposition prediction capabilities, was developed. This state-of-the-art computational tool incorporates a first-principles Na_2O deposition model developed by ANL, and combines it with predictive capabilities for the spatial and temporal variation of temperature, velocity, dissolved oxygen concentration, and wall temperature under flowing sodium conditions. The CFD model was validated under no-deposition conditions using experimental data collected with the SPPL, demonstrating the model’s capability to predict the thermal-hydraulics of the SPPL test section within the measurement uncertainty characterizing the SPPL instrumentation. The model’s deposition prediction capability was not, however, validated as the SPPL could not be operated under plugging conditions during the project, resulting in the lack of deposition data with adequate pedigree for a CFD model validation.

Two novel diagnostic techniques to detect and characterize Na_2O deposits, i.e. Ultrasonic Time Domain Reflectometry (UTDR) and Potential Drop (PD) techniques, were developed to ultimately assist in the validation effort under plugging conditions, which can be performed once the SPPL becomes operational. This development effort consisted first in demonstrating, analytically and/or computationally, the capability of these techniques to diagnose Na_2O deposits inside of small channels (particularly the deposit’s thickness), and subsequently in the fabrication and testing of prototypical UTDR and PD instrumentation. The testing, performed on mockups of the SPPL test section, demonstrated the capability of these techniques to detect and characterize material discontinuities like those induced by sodium oxide deposition on stainless steel channel walls. Because of the mentioned impossibility to run the SPPL in a plugging mode, the developed

instrumentation could not be tested in-situ, i.e. at the SPPL while deposits are being formed inside of the SPPL test section.

Recommended future work includes a possible enhancement in the CFD modeling technique and installation of the developed UTDR and PD instrumentation on the test section, followed by plugging tests to be conducted with the SPPL. The installation of the UTDR and PD diagnostic instrumentation on the SPPL test section will allow collection of Na₂O deposition data after the onset of deposition to nearly complete channel plugging, which can ultimately be used for the validation of the CFD model.

This report is organized as follows:

- Chapter 1: Project overview and accomplishments
- Chapter 2: CFD analysis
- Chapter 3: Sodium Plugging Phenomena Loop operation
- Chapter 4: Ultrasonic Time Domain Reflectometry technique development
- Chapter 5: Potential Drop technique development
- Chapter 6: Project products
- Chapter 7: Conclusions and recommended future work
- Appendix A: Analyses in support of CFD modeling (e.g. sensitivity studies)
- Appendix B: Material properties used in CFD modeling
- Appendix C: Investigation on x-ray Computer Tomography as calibration tool for UTDR and PD techniques

1. Project overview and comparison of actual accomplishments with project goals

This chapter is organized as follows:

- Section 1.1: Project overview, which includes motivations, goals, a description of the Sodium Plugging Phenomena Loop (SPPL) facility and an introduction on the techniques for sodium oxide detection and characterization investigated throughout the project;
- Section 1.2: Accomplishments versus project goals.

1.1 Project overview

The project “Modeling and Validation of Sodium Plugging for Heat Exchangers in Sodium-cooled Fast Reactor Systems” was conducted jointly by Westinghouse Electric Company (Westinghouse) and Argonne National Laboratory (ANL), over the period, October 1, 2013- March 31, 2016.

1.1.1 Motivations

The project originated from the need to provide the designers of Sodium Fast Reactors (SFR) with a validated, state-of-the-art computational tool for the prediction of sodium oxide (Na_2O) deposition in small-diameter heat exchanger (HX) sodium channels, such as those in the diffusion bonded HXs proposed for SFRs coupled with a supercritical CO_2 Brayton cycle power conversion system. In SFRs, Na_2O deposition can potentially occur upon accidental air ingress in the intermediate heat transport system (IHTS) sodium and simultaneous failure of the IHTS sodium cold trap. In this scenario, oxygen can travel through the IHTS and reach the coldest regions, represented by the cold end of the sodium HX channels, where Na_2O precipitation can occur if the oxygen concentration is higher than the solubility limit at the local temperature. In addition to deteriorating HX heat transfer and pressure drop performance, Na_2O deposition can lead to channel plugging especially when the size of the sodium channels is small, which is the case for diffusion bonded HXs whose channel hydraulic diameter is generally below 5 mm. Sodium oxide melts at a high temperature well above the sodium melting temperature such that removal of a solid plug such as through dissolution by pure sodium could take a lengthy time.

1.1.2 Goals

The main goals envisioned for this project, which have been partially achieved as discussed in Section 1.2, are the following:

- GOAL 1: Identify/develop an analytical method to calculate the rate of Na_2O formation on the walls of reactor system components, and facilities in general, where hot flowing sodium experiences cooling.
- GOAL 2: Develop and test novel experimental techniques, i.e. Ultrasonic Time Domain Reflectometry and Potential Drop techniques (see Section 1.1.4), for detecting the presence and characterizing Na_2O deposits in small channel HXs, with particular interest for their thickness. The ultimate testing was to be performed at the Sodium Plugging Phenomena

Loop (SPPL) at ANL which, as described in Section 1.1.3 prototypically reproduces the operating conditions and the channel geometry of interest.

- GOAL 3: Implement the methodology from GOAL 1 in a Computational Fluid Dynamics (CFD) code, which will incorporate modeling for the deposition of Na_2O and for the spatial and temporal variation of temperature, velocity, dissolved oxygen concentration, and wall temperature under flowing sodium conditions.
- GOAL 4: Validate the CFD model from GOAL 3 against experimental data collected with the SPPL, with the support of the diagnostic techniques developed as part of GOAL 2.

Ultimately, the objective of a validated CFD tool with Na_2O deposition prediction capabilities is to enable SFR designers to:

- Predict the rate of deposition of Na_2O on sodium HX channel walls during scenarios, differing in severity, of air ingress and simultaneous failure of the cold-trap system. This will support quantification of the HX heat transfer and pressure drop performance degradation;
- Design HX sodium channels in such a way that the time required for complete plugging following a postulated failure of the sodium boundary is sufficiently long to allow detection¹.

1.1.3 Sodium Plugging Phenomena Loop description

The ANL Sodium Plugging Phenomena Loop (SPPL), schematically shown in Figure 1-1, was designed and built to obtain fundamental data on plugging induced by the precipitation of oxygen impurities in liquid sodium flowing through prototypical sodium-to- CO_2 heat exchanger channels under well-controlled experiment conditions. The SPPL utilizes the 30.7 inch (0.78 m) long stainless steel test section² shown in Figure 1-2, with rectangular cross section and containing, side-by-side, three 6 mm semicircular straight sodium channels that simulate sodium channels inside of a sodium-to- CO_2 Printed Circuit Heat Exchanger™ (Heatric Division of Meggitt (UK)).

¹ If detection occurs, the affected sodium loop can be shut down, drained and cleaned by dissolving the oxide deposits through forced convection of hot sodium. Dissolution with stagnant sodium, which would be needed if complete plugging occurred before detection, is less preferable if not impractical because of the significantly longer time needed.

² It should be noted that, in its original configuration, the SPPL had three parallel test sections containing 2mm, 4mm and 6mm semi-circular channels, respectively. The 2mm and 4mm test sections were later removed, and the 6mm test section placed in the center position, effectively becoming the only flow path since the paths to the other test sections were plugged shut at the connectors prior to the EM flow controllers. This can be schematically seen later, in Figure 1-5.

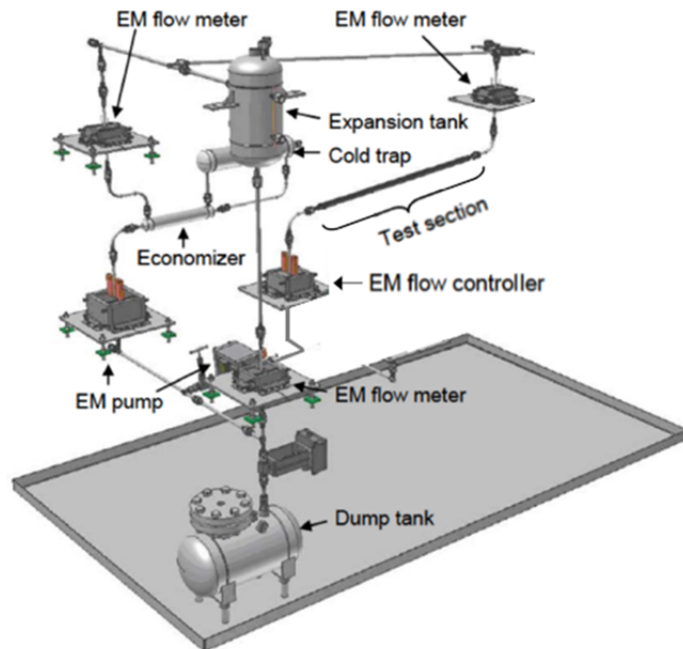


Figure 1-1: Sodium Plugging Phenomena Loop layout (modified from [1])

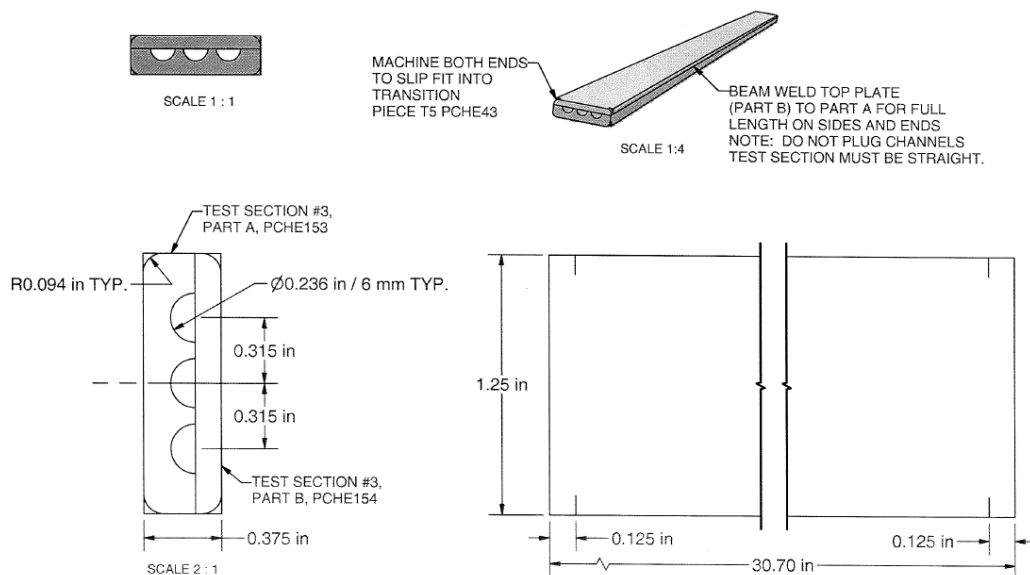


Figure 1-2: SPPL test section dimensions

The test section is provided with heaters and it is surrounded by a steel circular duct to also allow its cooling by forced convection of air. Figure 1-3 shows the test section, with the upper half of the duct removed. The sodium enters the test section from a single stainless steel tube and exits into a single stainless steel tube, as schematically represented in Figure 1-1; the test section is actually installed with a slight slope (5°) to facilitate drainage of sodium. As the sodium flows, the heating and cooling of the test section (and therefore of the sodium inside) are controlled using heaters and forced convection of air, respectively. By properly controlling heating and cooling, the facility's

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operator is able to hold the temperature at the location of plug formation unvarying during the plug formation. A variable-speed blower is used to generate the air flow inside the duct, with the same direction as sodium. As for the heaters, the test section length is divided into five equal-length heating zones, visible in Figure 1-3:

- the first three zones are provided with ceramic band (radiant) heaters (bottom left hand corner in Figure 1-3), which can be used to shape the sodium temperature profile along these zones as the sodium is cooled by the air;
- the last two zones are provided with platen contact heaters (right picture in Figure 1-3), which heat the test section and sodium to ensure that the minimum in the sodium temperature (and therefore the location of the deposit plug) is inside of the test section and not in the exit tubing downstream. Since the test section underneath the platen contact heaters is not affected by the cooling air, or at least not as much as the region with the ceramic band heaters, this minimum in sodium temperature generally occurs slightly upstream of the platen contact heater zone.

Thermocouples (T/Cs) are installed on the upper and lower surfaces of the test section, as shown in Figure 1-4. Some axial locations along the test section are monitored with one T/C, e.g. T/C #6, while others with two T/Cs, e.g. T/C #9 and 10, which measure the temperatures of the metal above two of the semicircular channels contained in the test section. The sodium is circulated in a closed circuit by an electromagnetic (EM) sodium pump, and its flow rate is measured with EM flowmeters. Flowmeter readings are in volts, and the conversion to mass (or volume) per unit of time is performed separately, using data obtained upon flowmeter calibration. A cold trap in a branch circuit is utilized as a reservoir to hold oxygen in the form of Na_2O and release it to achieve the desired dissolved oxygen concentration at the start of a plugging experiment. This is accomplished by heating the cold trap to the saturation temperature for the desired dissolved oxygen concentration, which exceeds that subsequently established at the desired plugging location along the length of the test section. Figure 1-5 shows the complete instrumentation installed on the SPPL.

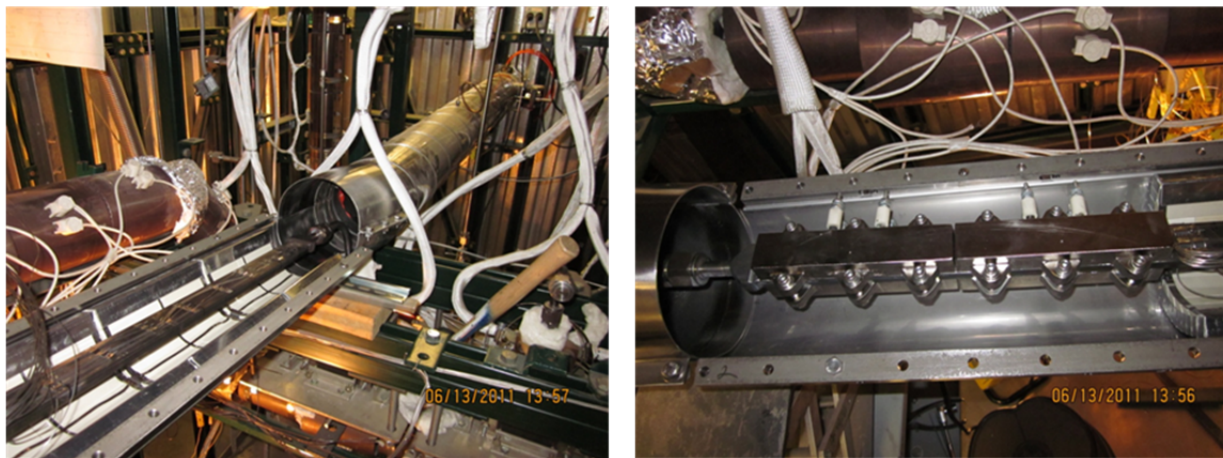


Figure 1-3: SPPL test section. Lower half of cooling air duct and first three heater zones with Ceramic Band Heaters (Left) and last two heater zones with Platen Contact Heaters (Right). Sodium and cooling air flow from back to front (in left figure) and from right to left (in right figure)

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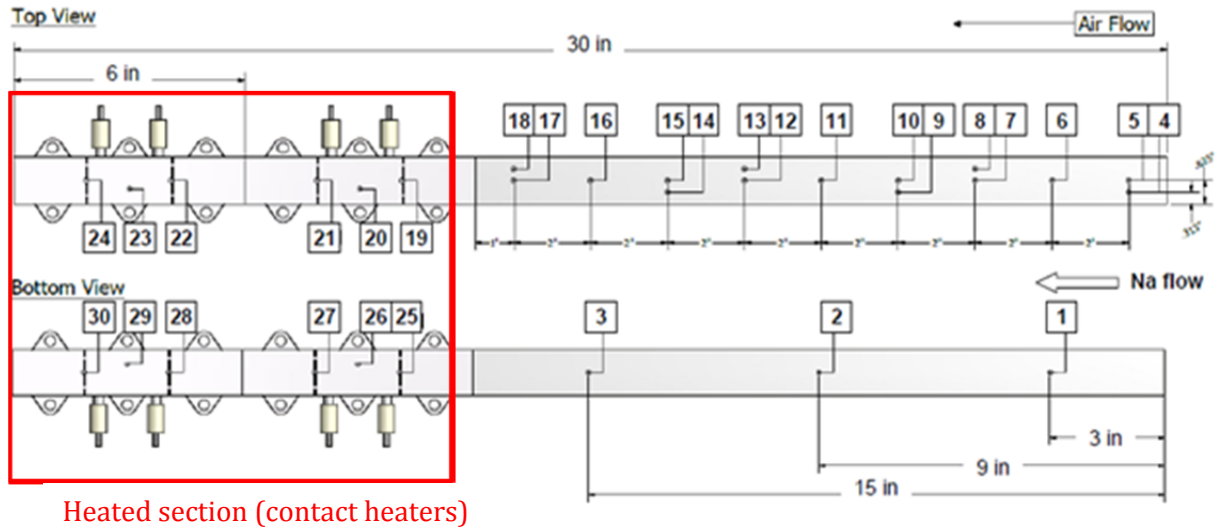


Figure 1-4: Locations of thermocouples on SPPL test section upper and lower surfaces (sodium and air flow from right to left)

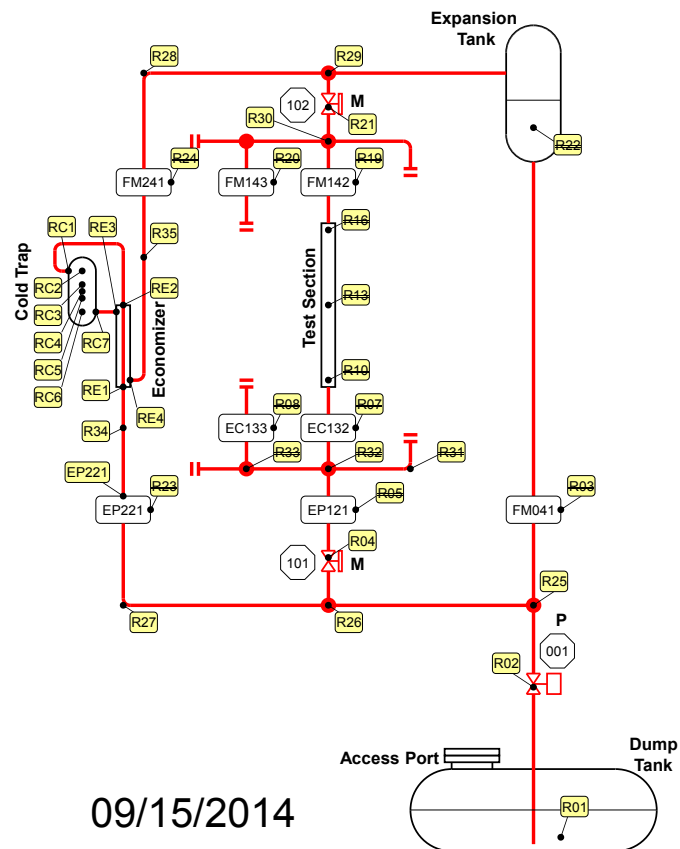


Figure 1-5: Location of thermocouples ("R"), flowmeters ("FM"), flow controllers ("EC") and electromagnetic pumps ("EM") along the loop (for a zoom-in on the test section see Figure 1-2 through Figure 1-4)

The correlations between the air blower speed (Hz) and the air velocity (m/s), and between the flowmeter readings (V) and the sodium flow rate (m^3/s), were obtained during a calibration campaign in 2008. The former is shown in Figure 1-6 and has been used in this project. The latter was affected by a large uncertainty, also due to some issues during calibration. Due to the key role that sodium flow rate plays in the deposition process, a re-calibration was performed during this project, as discussed in Section 2.3.

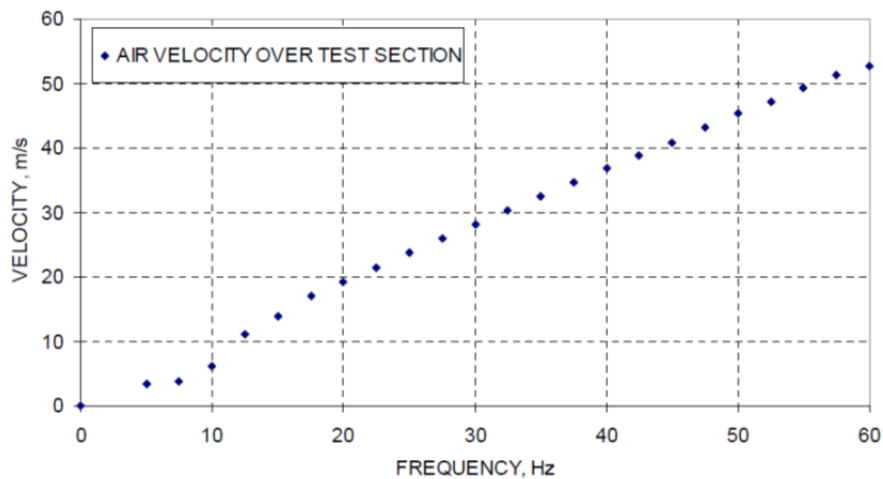


Figure 1-6. Calibration for the blower speed (variable frequency drive frequency) versus air velocity in the duct [2]

It should be noted that the SPPL was originally designed and assembled as a simple low-cost approach of quickly gaining some sodium plugging data. As such, it lacks a number of features that could have reduced the risk of difficulties encountered later. Operation with dirty sodium containing significant dissolved oxygen is risky and can be viewed as asking for trouble. The SPPL has to operate with dirty sodium during the conduct of plugging testing. The loop was originally designed with a small volume of circulating sodium. The volume was small enough that 1/2 -inch stainless steel tubing was installed for most piping runs. The small channel size of the tubing increases the risk of forming plugs inside of the tubing when circulating dirty sodium. At some locations, the tubing or other components are not heated as effectively as elsewhere potentially giving rise to local cold spots. A cold spot can be an unwanted location for sodium oxide precipitation and plugging when circulating dirty sodium.

1.1.4 Diagnostic techniques for deposit detection

The development of diagnostic techniques to characterize Na_2O deposits originated from the need to enhance the SPPL instrumentation capabilities in light of the fact that, without these techniques, the common practice at the SPPL facility was to use sodium flow rate measurements to “infer” the occurrence of deposition and assess its progression toward complete channel plugging. In addition, the intention to ultimately validate a CFD model with deposition prediction capabilities called for a more direct visualization technique of the deposits.

Two diagnostic techniques for detection and characterization of sodium oxide deposits have been investigated, although not ultimately tested at the SPPL:

- Ultrasonic time delay reflectometry (UTDR) technique, discussed in Chapter 4: this method is based on installing an ultrasonic transducer on the test section, such that ultrasonic waves can be transmitted into the thickness of the channel wall and into the deposit upon the channel wall. Reflection off of the inner surface of the deposit provides a means of determining the deposit thickness from the time delay for the wave to propagate through the deposit thickness and back.
- Potential drop (PD) technique, discussed in Chapter 5: this method measures the electrical resistance or impedance across a sodium channel between electrodes that provide point contact with the stainless steel test section. Pairs of opposing electrodes can be installed at various locations along a length of the channel. As the electrical resistivity of Na_2O is greater than that of sodium metal, the resistance should increase as a deposit grows thus providing a correlation between the variable measured (resistance) and deposit volume.

A third diagnostic technique, x-ray Computer Tomography, was also investigated, but mainly as a potential support for the calibration of the UTDR and PD techniques, as discussed in Appendix C.

1.2 Accomplishments versus project goals

The level of accomplishment achieved for each of the project's goals is discussed below.

- **GOAL 1:** Identify/develop an analytical method to calculate the rate of Na_2O formation on the walls of reactor system components, and facilities in general, where hot flowing sodium experiences cooling.

FULLY ACCOMPLISHED. The first principles deposition model developed by Sienicki ([3], [4]) was identified as the best suited for the objective sought, and supplemented with a complete suite of material property correlations. The latter included an equation specifically developed in this project for the computation of the temperature dependence of sodium oxide thermal conductivity, for which literature data are scarce.

- **GOAL 2:** Develop and test novel experimental techniques, i.e. Ultrasonic Time Domain Reflectometry (UTDR) and Potential Drop (PD) techniques, for detecting the presence and characterizing Na_2O deposits in small channel HXs, with particular interest for their thickness. The ultimate testing was to be performed at the Sodium Plugging Phenomena Loop (SPPL) at ANL which prototypically reproduces the operating conditions and the channel geometry of interest.

PARTIALLY ACCOMPLISHED (~80%). Prototypical UTDR and PD instrumentation was successfully developed, including fabrication and mockup testing, demonstrating both analytically and experimentally the capability of these techniques to detect and characterize materials discontinuities like those induced by sodium oxide deposition on stainless steel channel walls. Unanticipated issues with the SPPL did not allow such instrumentation to be run on the test section in a plugging mode, and as a consequence the developed instrumentation could not be tested in-situ, i.e. at the SPPL, while deposits are being formed inside the SPPL test section.

- **GOAL 3:** Implement the methodology from GOAL 1 in a Computational Fluid Dynamics (CFD) code, which will incorporate modeling for the deposition of Na_2O and for the spatial and temporal variation of temperature, velocity, dissolved oxygen concentration, and wall temperature under flowing sodium conditions.

FULLY ACCOMPLISHED. The sodium oxide deposition model identified as part of GOAL 1 was successfully implemented in CFD, together with a complete suite of material properties as well as a proper oxygen solubility correlation. The resulting CFD model is capable of modeling sodium oxide deposition, accounting for the spatial and temporal variation of temperature, velocity, dissolved oxygen concentration, and wall temperature under flowing sodium conditions. The kinetics of deposition, which determines the time-to-plugging, is modeled in a simplified way through a user-input acceleration factor. It should be noted that the purpose of this effort was not to model the deposition phenomenon at the dendritic structural level (where the full deposit details such as porous structure characteristics are needed), but to be able to use a commercial CFD software, without iterations with an external software or input, to model the deposition and estimate the time to plugging for a sodium HX, for an ultimate industry application. An enhancement in the CFD modeling technique is possible, and it is recommended as future work.

- **GOAL 4:** Validate the CFD model from GOAL 3 against experimental data collected with the SPPL, with the support of the diagnostic techniques developed as part of GOAL 2.

PARTIALLY ACCOMPLISHED (40%). The CFD model was developed, as part of GOAL 3, to predict the thermal-hydraulics of the SPPL test section and the sodium oxide deposition within it (if the local temperature and oxygen concentration are such to induce such deposition). The validation of the baseline model, i.e. without deposition capabilities, was successfully performed demonstrating the model's capability to predict the thermal-hydraulics of the test section within the measurement uncertainty characterizing the SPPL instrumentation. Instead, the validation of the ultimate model, i.e. the one with sodium oxide deposition prediction capabilities, was not performed because unanticipated issues with the SPPL did not allow plugging runs to be conducted, and thus data to be collected, by the end of the project's period of performance.

2. Sodium Plugging Phenomena Loop operation

This chapter is organized as follows:

- Section 2.1: SPPL unforeseen issues. This section briefly discusses some unforeseen issues that occurred with the SPPL, which had an impact on the project activities and deliverables;
- Section 2.2: SPPL operation: non-plugging runs. This section presents the data collected with the SPPL during non-plugging tests, which were used to validate the CFD model of the facility during steady-state and transient operation with no plugging;
- Section 2.3: Flow meter calibration. This section discusses the flow meter re-calibration performed in the attempt to improve sodium flow rate measurement accuracy;
- Section 2.4: SPPL operation: plugging runs. This section discusses the attempts made to conduct plugging tests;
- Section 2.5: Recommendations for future work on the SPPL.

2.1 SPPL unforeseen issues

Some unforeseen issues occurred at the SPPL in the first phase of the project, which resulted in some activities being delayed, ultimately preventing plugging tests to be performed by the end of the project. Initially, a leak occurred at a Variable Compression Ratio (VCR) fitting in the cold trap circuit at the economizer, which required repair and resulted in mandating the installation of about 100 thermocouples, at every VCR fitting, which became part of the Alkali Metal Early Warning System. The loop was then restarted on 11/13/2014, but only partial operation was achieved since sodium could circulate through the cold trap only, and not through the test section. The loop was repaired and the LabVIEW program upgraded to enable long-term sodium plugging testing (i.e., over weeks), resulting in the loop becoming fully operational on 6/22/2015, with the sodium now circulating through the test section. After several initial plugging attempts including a “freeze to plug” run, during which the coldest spot in the test section was cooled below the sodium melting point, it was concluded that the oxide inventory dissolved in the flowing sodium was too low, as no plugging had been observed despite the aggressive attempts to form a plug in the test section³. It was concluded that oxide had precipitated out from the sodium while it was previously cooled to a relatively low temperature inside of the loop sodium dump tank following earlier draining from the loop. A decision was then made to collect SPPL operational data before increasing the oxygen concentration, i.e. under no-plugging conditions, for use in the first phase of CFD validation as discussed in Section 2.2. The increase in oxygen concentration was planned for after the non-plugging tests, but a problem was encountered as discussed in Section 2.4.

³ The reason for the insufficient oxide inventory in the flowing sodium was believed to be the fact that some of the oxides had probably remained in the dump tank during the transfer from such a tank to the loop. This could have happened because the dump tank was not designed to perform this transfer at high temperatures (>~200°C), i.e. when oxide dissolution is favored over deposition, causing the relatively low temperature to probably induce some oxides to precipitate.

2.2 SPPL operation: non-plugging runs

2.2.1 Run description

Four no-plugging tests were conducted, differing in the sodium and air flow rates as shown in Table 2.1. In this table, “A” refers to a typical sodium coolant flow rate used for the SPPL test sections (~ 0.01 liters/sec [5]) and “B” refers to ~ 5 m/s blower air speed⁴.

Table 2.1. No-plugging test matrix

TEST	Sodium flow rate	Air flow rate
1	2A	B
2	2A	2B
3	A	B
4	A	0.5B

Each run started once an initial steady-state condition was established with zero blower speed (no air-cooling). The blower was then turned on and brought to the desired speed level, representing the start of the experiment. The run continued as the temperatures changed and until another steady-state condition was established with constant blower speed. The first phase of the run, i.e. when the temperatures are changing, represents the transient phase of the run, whereas the last part of the run (when the temperatures became steady) represents the steady-state phase. Collected data consisted of time stamps, flow meter readings, current to EM pumps and flow controllers, temperatures at various locations along the test section (see Figure 1-4) and the entire loop (see Figure 1-5).

2.2.2 Data collected

The temperatures measured along the test section during runs #1 to #4 are plotted as a function of time in Figure 2-1 through Figure 2-4.

⁴ The voltage and frequency readings associated with a sodium flow rate equal to “A” and an air flow rate equal to “B” are 0.75 mV and 6.1 Hz, respectively. The range of the blower speed was determined such that the temperature change in the test section was large enough for the experiments, but not too large to thermally shock the test section

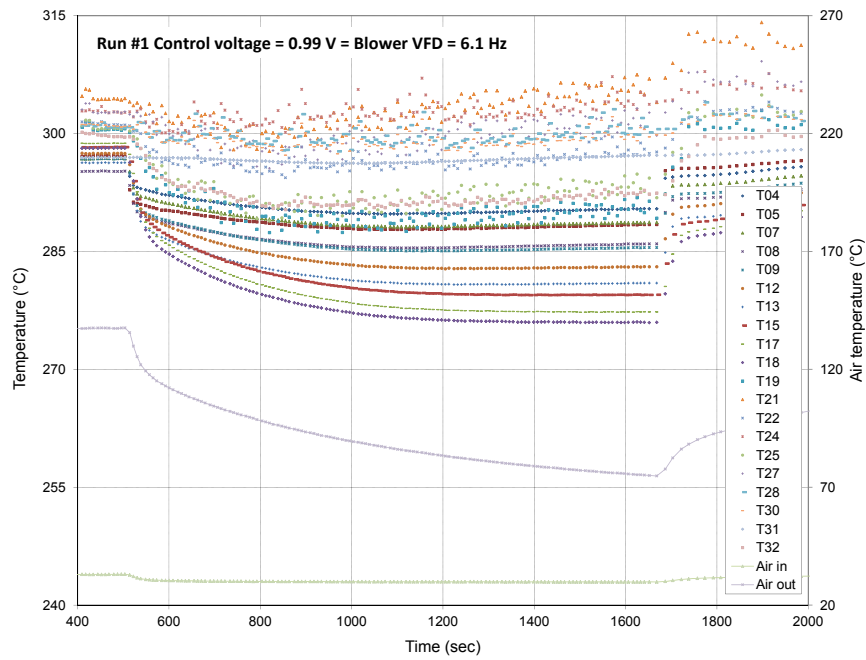


Figure 2-1: SPPL test section temperatures measured during Test #1

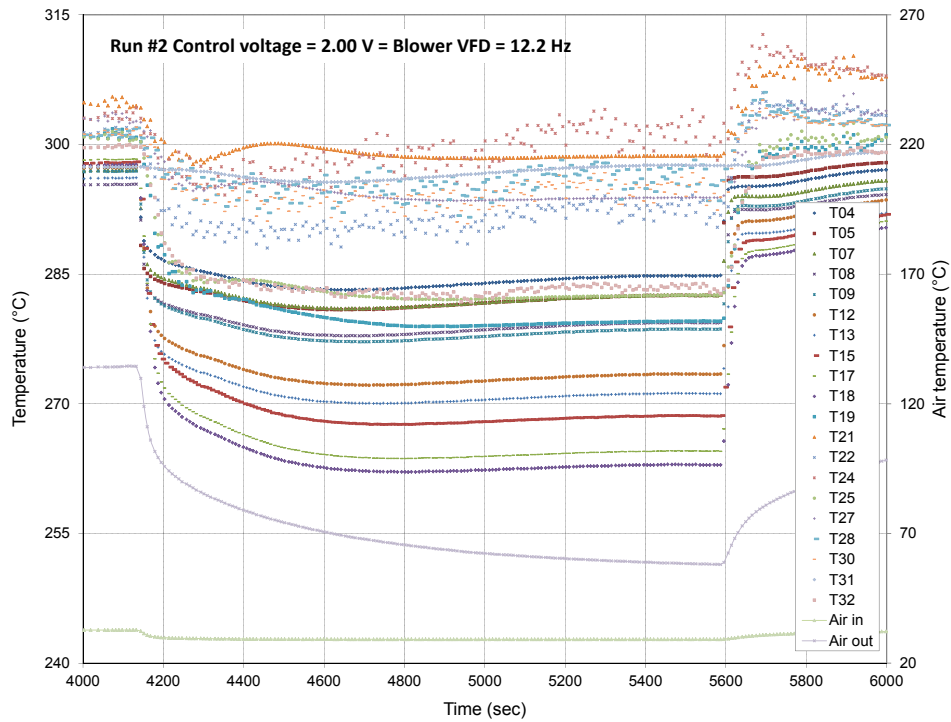


Figure 2-2: SPPL test section temperatures measured during Test #2

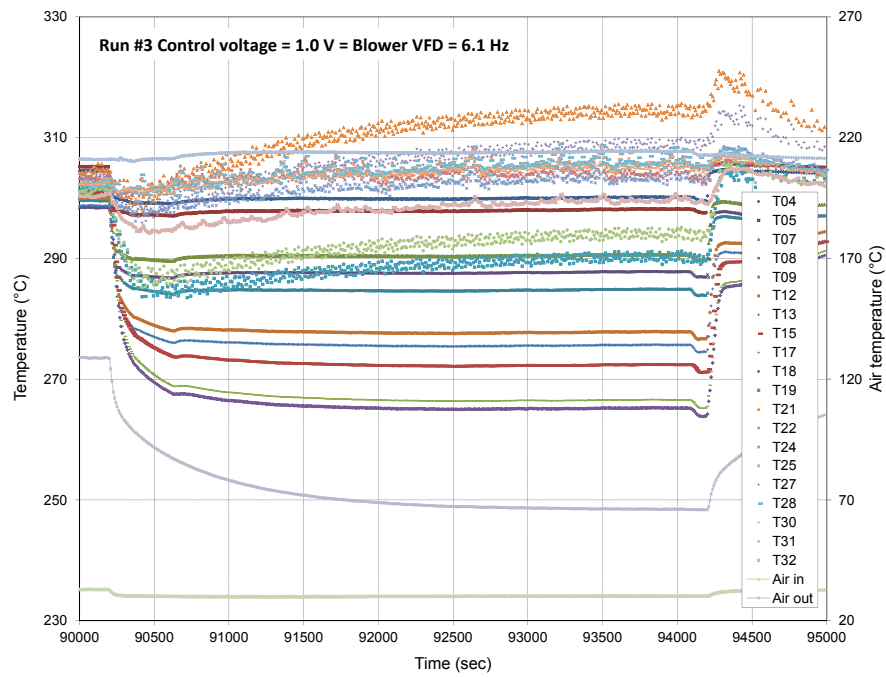


Figure 2-3. SPPL test section temperatures measured during Test #3

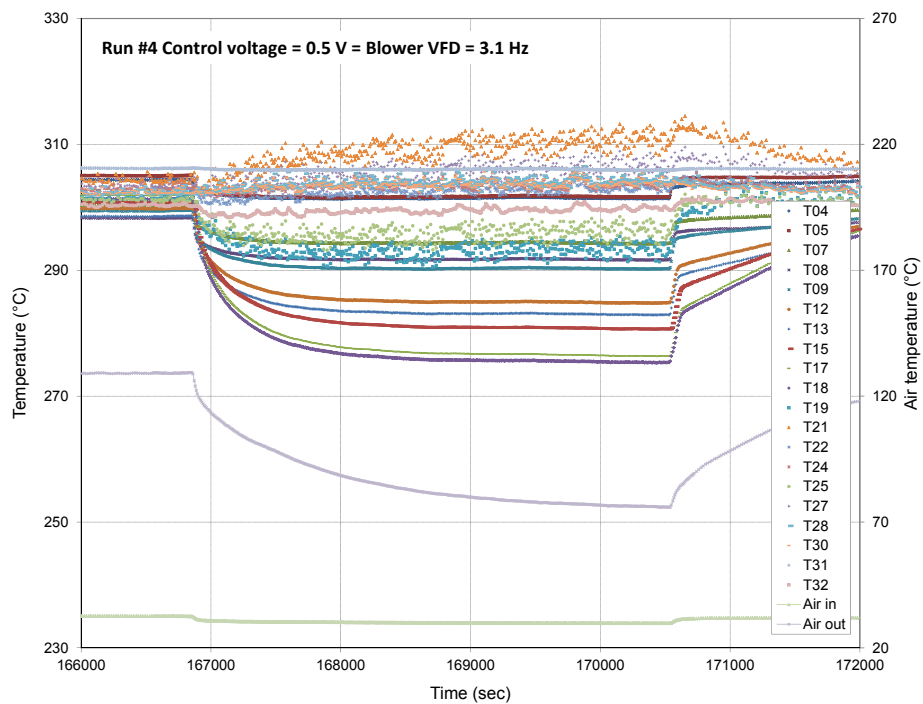


Figure 2-4. SPPL test section temperatures measured during Test #4

2.3 Flow meter calibration

In the SPPL, calibration of the main flow meter (FM041 in Figure 1-5) can be performed by either draining sodium from the expansion tank into the dump tank or by pushing it up from the dump tank, while recording the flow meter readings and monitoring the sodium level increase/decrease in either tank. Such monitoring is done through an electrical contact-type level probe, installed on the tank and provided with multiple pins which detect sodium level. The original calibration of the main flow meter, performed in August 2008 by monitoring level variation in the expansion tank, was not completely successful since the earlier probe previously employed had shorted out during the run and level data could not be collected. Later, by manually probing the sodium surface in the expansion tank with a metal rod, the amount of sodium that flowed out from the expansion tank through the flow meter had been estimated and a calibration factor obtained. The resulting calibration was acceptable for performing deposition phenomena identification, which was the original purpose of the SPPL facility, consisting of inducing sodium oxide deposition and of qualitatively, more than quantitatively, assessing the effect of key variables such as sodium flow rate and air cooling. However, because of the need in this project to collect accurate data for CFD model validation, a re-calibration was deemed necessary.

2.3.1 Calibration runs

Because of the lack of the available ports on the expansion tank, the re-calibration was performed with the probe for monitoring sodium level (Figure 2-5, right) installed in the dump tank, whose dimensions are also shown in Figure 2-5 (left). Figure 2-6 shows the relation between the distance between the bottom of the tank and the sodium level, and the volume of sodium (assuming the tank dimensions and without any effects of retained oxides), indicating the position of the contactor pins belonging to probe #2.

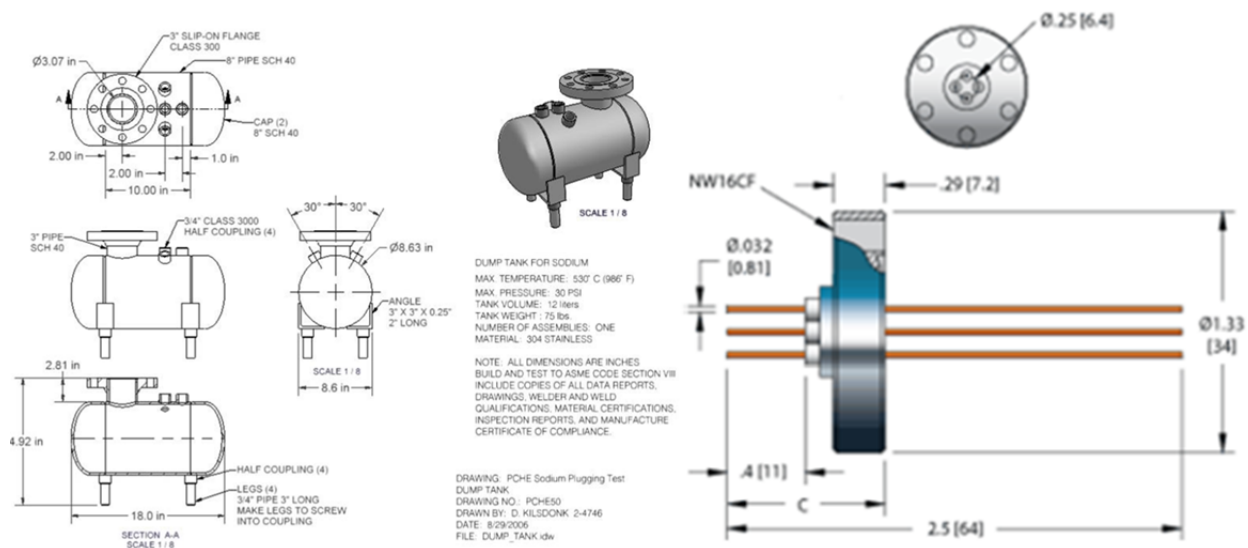


Figure 2-5. SPPL dump tank (left) and base of the electrical contact level probe (stainless steel pins were welded to extend the pins to the desired length)

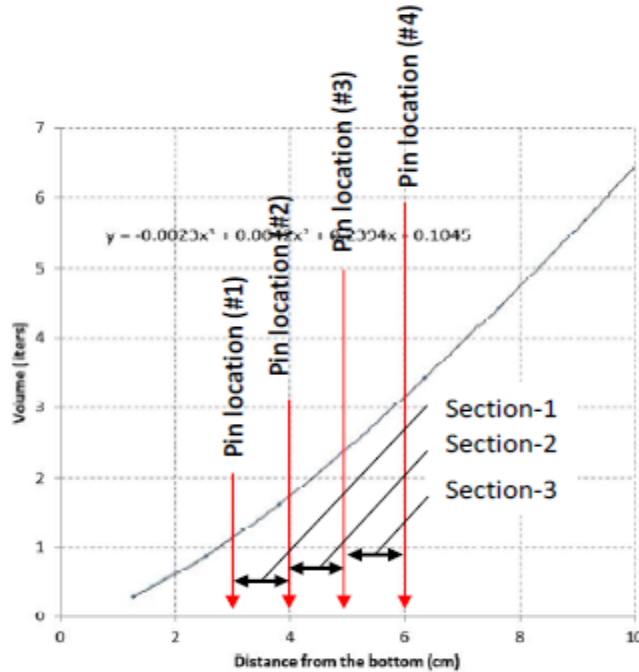


Figure 2-6. Relationship between the dump tank internal volume and the distance from the bottom of the tank (probe #2, 1 cm interval between contactor pins)

To maximize the sodium flow going from the expansion into the dump tank during the calibration, the valve located at the bottom of the test section (see Figure 2-7) was closed and later a freeze plug was induced downstream of the cold trap⁵. Calibration runs were performed both in the “flowing down” mode (sodium flows from the expansion to the dump tank) and in the “pushing up” mode (sodium flows from the dump tank to the expansion tank driven by cover gas pressure).

⁵ The need of the freeze plug was found during the initial calibration trial runs in the present calibration campaign.

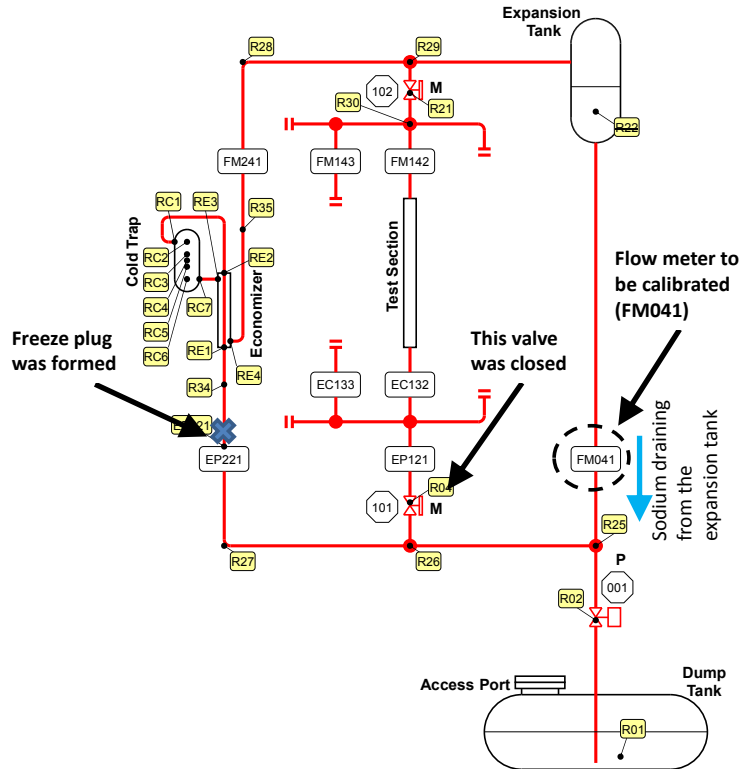


Figure 2-7. SPPL configuration during re-calibration of flow meter FM041

The loop was maintained at a constant temperature before each run. At the beginning of each run, the dump valve opened. As the run continued, the pressure difference between the expansion tank and the dump tank changed, reducing the flow rate. Because of the design of the argon cover gas delivery system, it was not possible to accurately provide controlled differential pressure between the tanks. When the available sodium ran out, the flow meter signal became zero, indicating the end of the run. A summary of the runs used for calibration is as follows⁶, with the corresponding measurements shown in Table 2.2:

- 09/28/2015: Calibrating FM041, test section valved off, probe #2 installed. Problem in creating good pressure differential.
 1. Flowing down
 2. Pushing up
- 10/01/2015: Calibrating FM041, test section valved off.
 1. Flowing down
 2. Pushing up
- 10/02/2015: Same as 10/01, longest pin shorted out.
 1. Flowing down
 2. Pushing up
- 10/06/2015: Same as 10/01, probe #2 cleaned and reinstalled.
 1. Flowing down

⁶ In all these runs the cold trap had the freeze plug shown in Figure 2-7.

2. Pushing up
3. Flowing down
4. Pushing up
5. Flowing down
6. Pushing up
7. Flowing down
8. Pushing up

2.3.2 Calibration data analysis

From the calibration runs, the 16 sets of data summarized in Table 2.2 were deemed acceptable for consideration⁷. The average calibration factor (coefficient to convert a voltage signal from the flow meter to actual sodium flow rate in m³/sec) was calculated to be 0.0102 m³/s-V. The distributions of the individual calibration factors as a function of flow meter signal strength (or flow rate) and sodium temperature are shown in Figure 2-8 and Figure 2-9, respectively. It can be seen that:

- a significant scatter, of about +/-25%, exists between the calibration factors obtained in the various measurements⁸;
- the average calibration factor is only about 5% lower than the value which can be calculated theoretically using the procedure detailed in Appendix 3 of [6], at the same temperature (0.0108 m³/s-V at 300 °C).

Table 2.2. Measurements used for obtaining flow meter calibration factor ("section" indicates the section between contactor pins used to determine the conversion coefficient, as shown in Figure 2-6)

date	run#	direction	Section	Coefficient (m ³ /s-V)	Average signal (V)	Average temp (°C)
"2015-09-28"	1	down	1	1.12E-02	3.86E-03	298.1
		up	1	1.07E-02	-6.81E-03	198.4
"2015-10-01"	1	down	3	9.49E-03	4.38E-04	282.3
		down	"1+2"	8.01E-03	3.70E-04	276.5
		down	"1+2+3"	8.45E-03	3.88E-04	278.1
	up	up	3	1.20E-02	-2.98E-03	242.0
		up	"3+2+1"	8.60E-03	-6.70E-04	235.2
		up	"2+1"	7.53E-03	-4.48E-04	233.3
"2015-10-02"	1	down	3	7.49E-03	4.62E-04	277.2
		up	3	9.55E-03	-7.74E-04	239.1
"2015-10-06"	2	down	1	1.21E-02	2.21E-04	245.5
		down	"2+3"	1.00E-02	3.92E-04	281.5
		up	"3+2"	9.95E-03	-3.98E-04	200.7
	up	up	1	1.49E-02	-2.52E-04	194.3
		3 down	"1+2"	1.19E-02	3.64E-04	276.4
		up	"2+1"	1.10E-02	-2.52E-04	232.9
Average				1.02E-02		

⁷ A set of data (reading from the flow meter) is reliable only when the section defined by 2 pins between which the data were recorded was repeatable in 2 successive measurements (flowing down and subsequent pushing up or pushing up and subsequent flowing down).

⁸ The measurement leading to a calibration factor of 0.0149 m³/s-V is considered an outlier and thereby not included in this scatter.

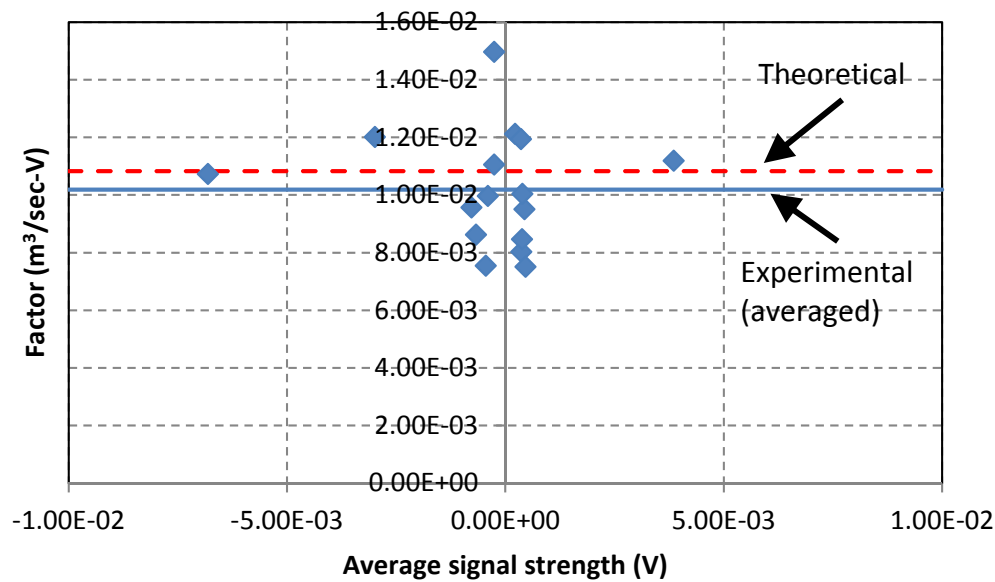


Figure 2-8. Calibration factor distribution as a function of signal strength

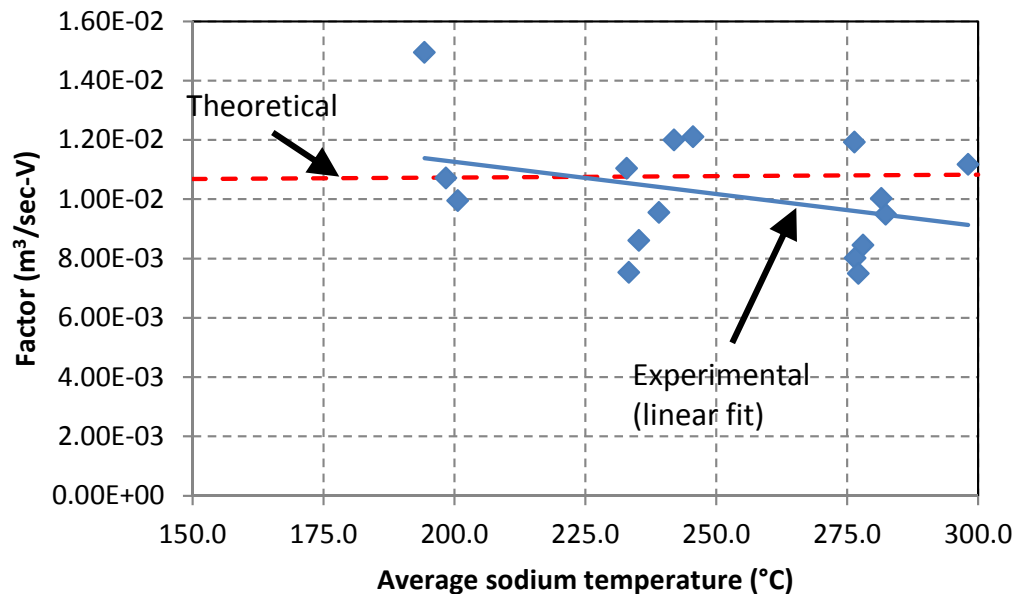


Figure 2-9. Calibration factor distribution as a function of sodium temperature

2.3.3 Conclusions and future work on flow meter calibration

The re-calibration work revealed that the electrical contact-type probe installed in the dump tank was less reliable than desired, resulting in a large data scatter. Possible reasons could be the following:

1. the extra volume of the tubing branching out between the flow meter and the dump tank (see Figure 2-7) added some uncertainty in the volume of the sodium that actually flowed

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through the flow meter during the “pushing up” runs, i.e. some of the sodium could have gone through this tubing instead of through the flow meter;

2. the presence of sodium films left behind on the pins and draining from the pins could have formed vertical bridges between the pins and the sodium pool surface such as the breaking of contact corresponds to breaking of a bridge rather than the surface falling below the pin;
3. oxides remaining inside of the dump tank alter the height versus volume relationship from the ideal assuming the absence of any solids inside of the dump tank;
4. the presence of impurities floating on top of the sodium surface in the dump tank could have prevented the pins to establish a reliable electrical contact with the sodium;
5. as sodium enters/leaves the dump tank in the flowing-down/pushing-up runs, waves might have been generated on the sodium surface, resulting in signals from the probe pin contactors representing “local” sodium levels different from the actual level averaged over the whole tank free surface;
6. the narrow spacing between pins due to the space limitation might have led to short-circuiting between the pins (e.g., due to sodium films on the pin surfaces).

To obtain more reliable calibration data, it is planned to install an electrical contact-type probe in the expansion tank as well, together with an ultrasonic-type surface detection probe. The former will not be subjected to the effect of item 1 above, and will allow simultaneous level measurements in the two tanks so that inconsistencies can be better identified and measurement scatter attenuated). The ultrasonic system will provide an important differentiation in the way calibration is performed, and will not be subjected to item 6 above.

2.4 SPPL operation: plugging runs

As mentioned in Section 2.1, from the unsuccessful attempts to induce plugging it was apparent that the loop did not contain enough oxides. Therefore, ~10 grams of sodium oxides were added, in the expansion tank, on 12/02/2015. The loop temperature including the expansion tank was immediately raised to re-establish the sodium circulation, but over the next few days the loop lost sodium circulation as if oxides had deposited throughout the loop tubing. In spite of an increase in pumping thrust to possibly remove deposits, the circulation ultimately stopped. It is thought that the oxide powder was added at too great a rate and too high a temperature such that it was possible for deposition to occur afterwards at relatively cooler locations.

In order to re-establish sodium circulation, the contaminated sodium was drained into the dump tank where the temperature was reduced to precipitate the oxides, and also resulting in sodium freezing. The sodium was then remelted and pushed up into the loop at a low temperature (120-150°C) in order to ensure that the sodium being transferred into the loop was cleaner than when it was drained. During this operation, multiple technical problems occurred (e.g. main EM pump malfunction, damaged downcomer tubing) which prevented restoring the loop condition in a timely manner to perform the plugging runs.

2.5 Recommendations for future work on the SPPL

The operation of the SPPL was not successful and recommendations for future work are provided to enhance its instrumentation accuracy and overall facility reliability:

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- Due to the key role played by sodium flow rate in deposition phenomena, it is strongly recommended to reduce the uncertainty with which this parameter is currently measured. While a reduction in uncertainty below the current +/-25% value is desirable for any future use of the SPPL, a significant reduction is deemed essential for applications involving code verification and validation. It is recommended to re-calibrate the flowmeters using both the technique used so far, i.e. electrical contact-type probes however installed in both the dump and the expansion tank, and a different technique such as ultrasonic detection of sodium level, in order to eliminate sources of uncertainty and inaccuracies which are specific to the electric contact-type probe method.
- The current loop configuration may not be particularly suited to conduct an aggressive (hence realistic) plugging run without possibly plugging other potential cold spots in the loop. This is a highly undesirable event due to the significant effort that is required to bring the facility back to operation. It is therefore recommended to take proper measures to make the facility less susceptible to unintended plugging and/or to carefully plan operations that could induce an unwanted plugging, such as significant temperature reductions and additions of sodium oxides. The experience gained in dealing with the unanticipated issues that occurred at the SPPL during this project will be very valuable for future uses of the SPPL as well as for the design of new sodium systems.

3. CFD analysis

This chapter is organized as follows:

- Section 3.2: No plugging CFD modeling and validation. This section discusses the CFD modeling of the SPPL test section and the validation of such modeling using the four no-plugging tests performed with the SPPL and discussed in Section 2.2.
- Section 3.3: Loop CFD run. This section builds upon the modeling technique developed in the previous section and extends the CFD domain beyond the test section, to include the loop piping immediately upstream and downstream of the test section to investigate entrance effects and possible flow non-uniformities between the three parallel semicircular channels.
- Section 3.4: Plugging modeling. This section discusses the analytical model implemented in CFD to reproduce sodium oxide deposition, and presents some results for a hypothetical deposition case.
- Section 3.5: CFD files location.
- Section 3.6: Conclusions, future work and suggestions.

It should be noted that validation of the CFD plugging model was not performed since the unanticipated issues occurred at the SPPL facility and discussed in Section 2.1 prevented plugging tests to be conducted and consequently plugging data to be generated.

3.1 Codes used

ANSYS CFX v14.5.7 (CFX) [7] was used for the Computational Fluid Dynamics (CFD) modeling work presented herein (including solver and pre/post processing). The computational meshes for sodium domains (including the three semi-circular channels, loop piping, and deposition domain) were generated using XYZ Scientific TrueGrid v2.3.2 [8]. The computational meshes for the stainless steel solid domains at the test section were generated using ANSYS ICEM v12.1 [9].

3.2 No plugging CFD modeling and validation

From the experimental standpoint, the focus of the project was the SPPL. Hence, the first step in CFD modeling was building a CFD model of the key component of the facility, i.e. the test section, capable to reproduce its thermo-hydraulic behavior. Validation of this model, using the experimental non-plugging data discussed in Section 2.2, was then performed to assess the model's accuracy.

3.2.1 SPPL no-plugging test description

The non-plugging tests conducted in support of CFD model validation have been described in Section 2.2, also showing the experimental data collected (Figure 2-1 through Figure 2-4). Only additional details deemed important for CFD modeling are presented here. Specifically, Figure 3-1 shows the test section, with the top half of blower air channel duct removed for visibility. The figure

(and the close-up) shows the contact heaters connected to the test section top and bottom surfaces, which heat the last 2/5th portion of the test section to prevent further cooling by the blown air and therefore possible solidification downstream. The location of all the T/Cs mounted on the test section was shown in Figure 1-4, which includes the T/Cs on the heated sections (in the red box) on the top and bottom surfaces of the test section (Top heater T/C numbers: 19, 20, 21, 22, 23, 24: Bottom heater T/C numbers: 25, 26, 27, 28, 29, 30 – not all T/C data were recorded in the tests). Figure 3-2 shows close-ups of the T/C connections on the test section. Note the wires along the test section surfaces, used to connect the T/Cs to the data acquisition system.

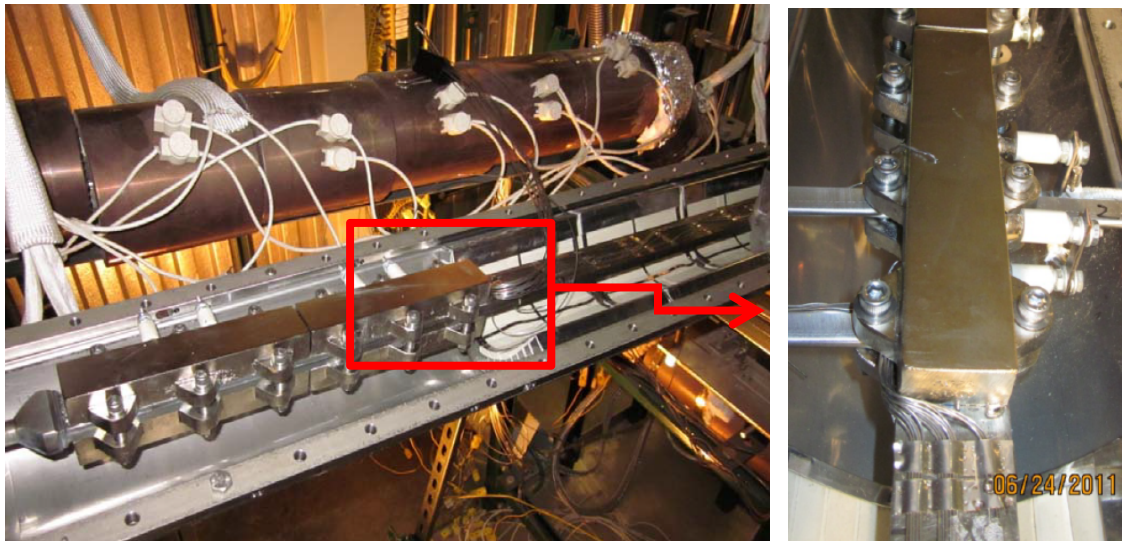


Figure 3-1. Test section view (top half of blower air channel removed for visibility)

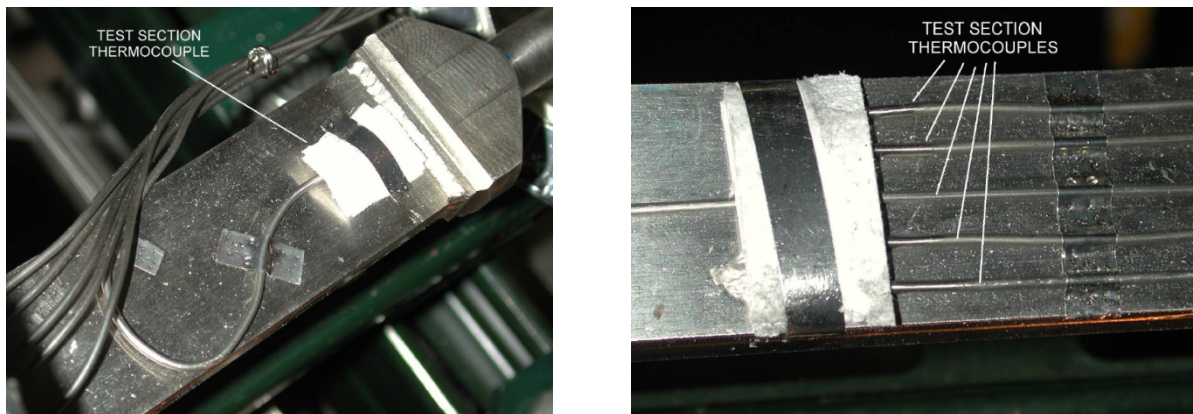


Figure 3-2. Close-up view of some of the thermocouple connections and wires on the test section surfaces

3.2.2 CFD modeling

The CFD model validation efforts commenced with an assessment of the available heat transfer correlations for liquid metals in pipes. In the literature, experimental data for low Prandtl number fluids, which include liquid metals, are scarce. In addition, some scatter exists between such experimental data, often due to differences in experimental conditions used to collect the data regarding surface wetting, possible gas-entrainment, oxidation, contamination, mixed convection

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effects and axial conduction at low Peclet numbers, as discussed in [10]. As a result, multiple correlations are available in the literature, and work was performed to identify the correlation most suited for this study. Details of these early validation studies are presented in Appendix A, Section A.1.

With the information gained through these early studies, the base no-plugging CFD model to be validated using the tests conducted at the SPPL was constructed. Within the calibration framework, the initial idea was to optimize the CFD model parameters to best match the experimental data for one of the four tests conducted with the SPPL and summarized in Table 2.1, and then apply this model to the other three tests for validation. Test #3 was selected as it was characterized by “nominal” values for sodium and air flow rates). However, due to some inconsistencies in some of the test data (as explained later), the comparisons between CFD results and experimental data from Test 1, 2 and 4 were also used to modify the CFD model parameters, resulting in an optimal fit for all test data.

3.2.2.1 Geometry/domain

The domain selected for the no-plugging CFD simulations is highlighted in the inset of Figure 3-3. The purpose of this selection, as opposed to using the full loop as the CFD domain, was to focus on an optimally-sized model to perform the large number of simulations to validate the CFD model that would allow the most efficient use of our computational resources without sacrificing accuracy. With the test section as the CFD domain, the inlet boundary conditions (velocity, temperature, turbulence quantities, etc.) were specified as uniform across the three 6mm semi-circular channels, as opposed to profiles that would naturally occur at the test section inlet if the full loop was modeled. But since the sodium flow rate through the channels was validated through a wide range, the velocity, turbulence quantities, etc. profiles entering the test section would differ/change significantly from case to case as well, and would prevent observing single variable effects. Thus, it was decided to rank the critical variables, in this case the inlet mean sodium flow rate topping the list, and then perform sensitivity studies on the inlet turbulence quantities to see the effects once a mean sodium flow rate was determined. Details on this sensitivity study are provided in Appendix A, Section A.4.2.

Another decision affecting the CFD domain selection was the choice of using a heat transfer coefficient on the bare test section surfaces instead of modeling the surrounding air channel that also included, in the first part of the test section, the radiant heaters attached to the duct walls (see left picture in Figure 1-3). This was done because of uncertainties on parameters affecting the heat transfer on the test section outer surfaces, and because of the need to avoid unnecessarily hiking the computational cell count to capture minute geometric features which were themselves uncertain. The following are examples of uncertainties affecting the heat transfer on the test section outer surfaces:

- “crude” T/C connections on the test section surfaces, including the connecting lines that are wired across (see Figure 3-2);
- test section surface effects (e.g. oxidation, dirt);
- some of the geometric details of the radiant heaters and connectors;
- blower air flow path upstream of test section (and thus the air flow profile);

- radiant heating non-uniformity through the length of the test section;

Additional details on the boundary conditions are described in Section 3.2.2.3.

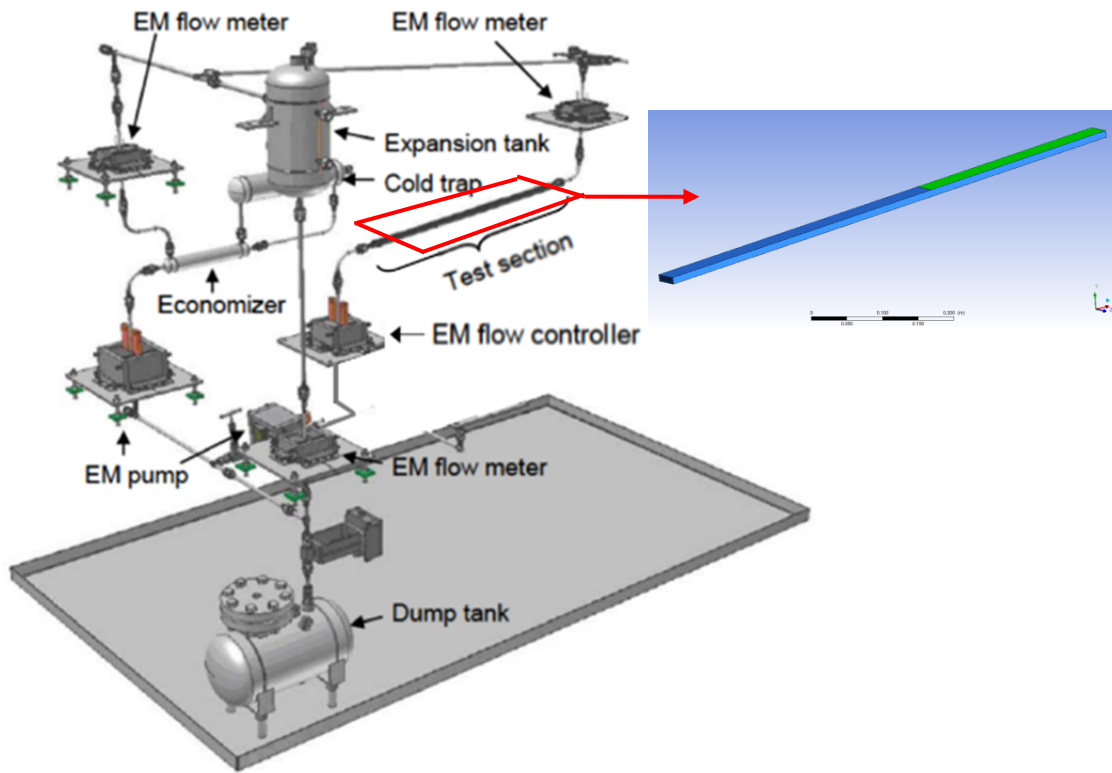


Figure 3-3. SPPL schematic (modified from [2]) and the CFD domain (shown in the red box and inset)

3.2.2.2 Computational mesh

The computational mesh for the stainless steel channel walls were generated using ANSYS ICEM v12.1 using hexahedral core - tetrahedral meshes (using a Delaunay algorithm to transition from hexahedral elements to tetrahedral elements approaching the surfaces with triangulated surface meshes). Figure 3-4 (top) presents the surface mesh density, and Figure 3-4 (bottom) presents the volume mesh density on a YZ cut plane in the domain. Similar to the domain selection, mesh density was adjusted to allow multiple solutions with the least number of cells for the large number of validation runs. Fluid domain mesh sensitivity study was conducted to verify the appropriateness of the mesh density (specifically the cell size jump between solid and fluid domains), as discussed in Appendix A, Section A.4.1.

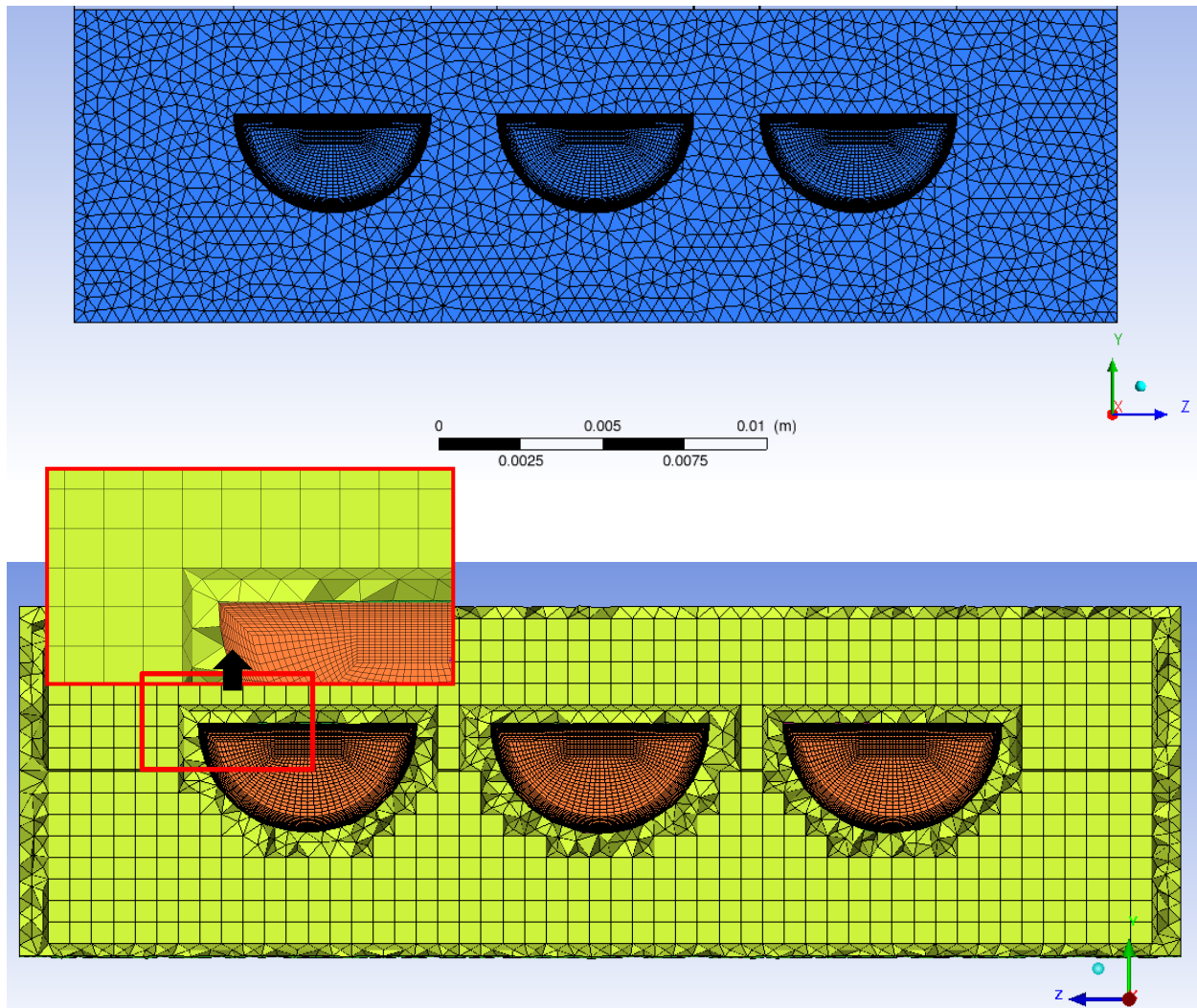


Figure 3-4. Surface mesh density (top) and volumetric mesh density (bottom) for SPPL test section.

The computational mesh for the three semi-circular sodium channels were generated using XYZ Scientific TrueGrid v2.3.2 [8] using fully hexahedral cells. The purpose was to generate very high quality meshes to capture the flow details (especially to be later used for the plugging CFD modeling, including recirculation regions, to be explained in later sections). The first layer thickness (0.02mm) and the number of prism layers (15) in the fluid channel were selected to be able to take full advantage of the SST (Shear Stress Transport) k- ω turbulence model. Figure 3-5 shows a close-up to one of the three identical semi-circular channel surface meshes. The mesh structure is the same throughout the axial length of the channel with 779.8 mm distance between the faces.

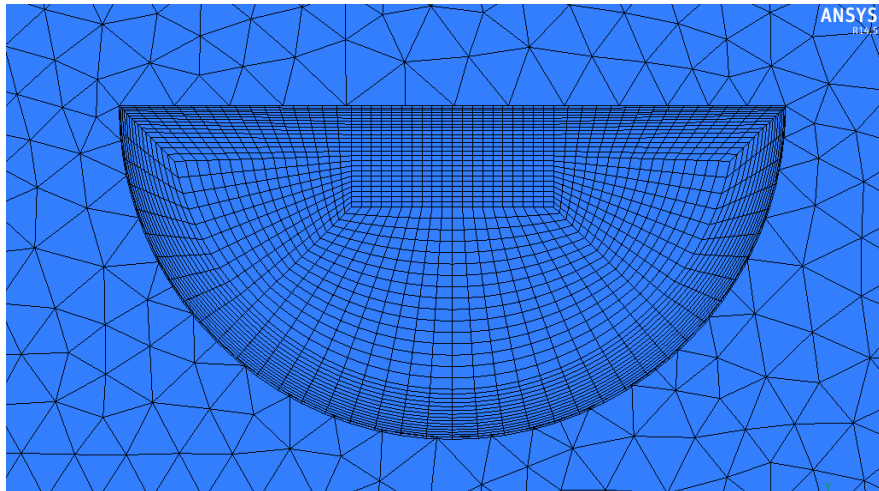


Figure 3-5. Mesh density on the end plate of the three identical semi-circular channels

Table 3.1 presents short reports of the computational mesh for the test section stainless steel walls, for one of the three identical semi-circular sodium channels, and also for the whole domain. Additional information on the meshes is presented in Appendix A, Section A.4.1.

Table 3.1. Computational mesh information

	# of nodes	# of elements	# of hexahedra elements	Maximum edge length ratio
Stainless steel test section walls	1,900,380	5,991,465	717,990	4.72
One of three identical semi-circular sodium channels	3,538,787	3,463,200	3,463,200	26.38 ^a
Total	12,516,741	16,381,065	11,107,590	26.38

^a Large stretches in the flow direction

3.2.2.3 Boundary conditions

Figure 3-6 presents the boundaries and the specifications for the CFD model. The green surface (along with the bottom surface not visible in figure), cover the final 2/5th length of the test section and represent the locations where the contact heaters are placed (see also Figure 3-1). These contact heaters, through a controller utilizing the information from the T/Cs attached between the heaters and the test section walls (T/Cs #19 through #30 in Figure 1-4), aim at keeping the local temperature at ~300°C in order to avoid any further cooling of sodium downstream of the radiant heater zone, thus preventing plugging in this zone and ensuring better control on the most likely plugging location, i.e. just upstream of the contact heaters. In the CFD model, these surfaces were specified as constant-temperature walls.

The selection of the CFD domain, focusing on the sodium channels and the stainless steel walls around them, was explained in the previous section. With this approach, items with very large uncertainties on heat transfer outside of the test section walls, such as crude T/C connections, T/C lines attached to the test section surfaces, etc. as described before, are all lumped under a heat transfer coefficient to be applied on “bare” test section surfaces - surfaces directly in contact with

blower air flow. This heat transfer coefficient is applied to the first 3/5th length of the test section top and bottom surfaces, and along the full length of the test section side surfaces (blue surfaces in Figure 3-6). Lumping all uncertainties allows performing the validation of the CFD model with fewer parameters.

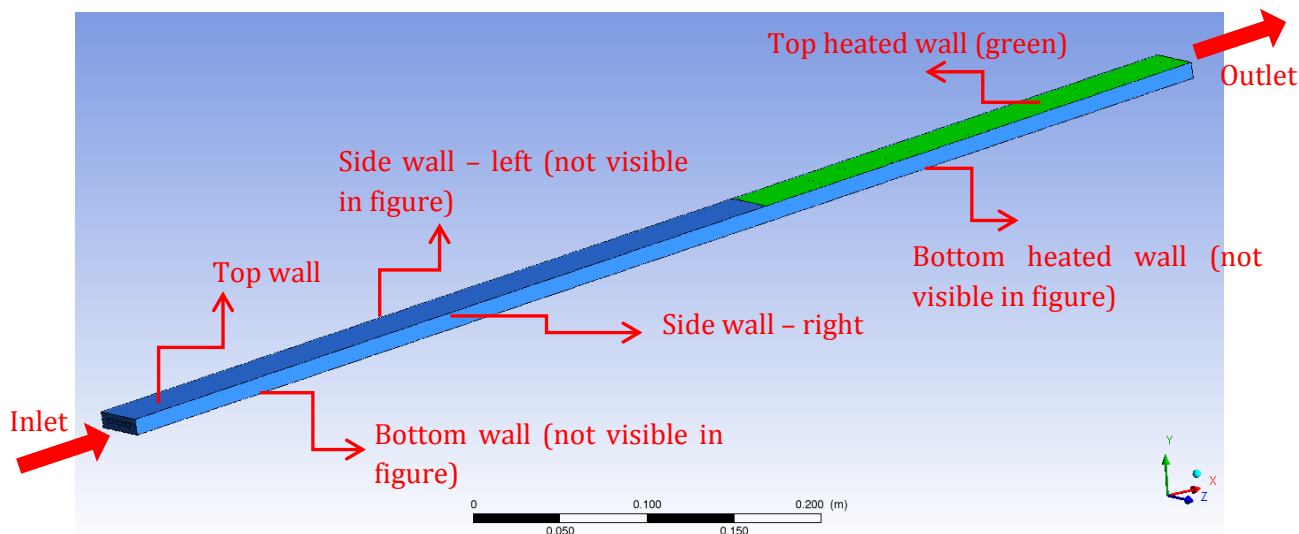


Figure 3-6. CFD domain boundaries and characteristics

Figure 3-7 presents a close-up of the CFD domain inlet. The outlet plane is similar and has three individual channel outlets, and an end wall for the stainless steel domain.

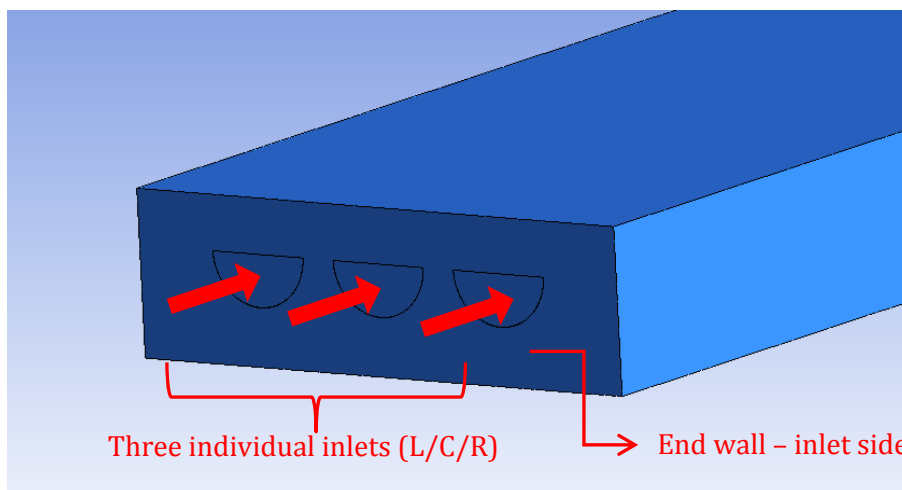


Figure 3-7. Close-up of CFD domain inlet

For each of the no-plugging tests (see Table 2.1 in Section 2.2), similar to the way the SPPL was run for the no-plugging tests, a steady-state initialization CFD run was conducted prior to the transient run to set the initial conditions through the domain. Thus, two sets of boundary conditions were fixed, as shown in Table 3.2, corresponding to the steady-state and the transient runs. Note that Table 3.2 presents the boundary conditions for one of the four no-plugging tests discussed in Section 2.2, i.e. Test 3, which is chosen as example for this discussion.

Table 3.2. Boundary conditions for no-plugging Test 3 steady-state initialization and transient*

Boundary	Steady state run (Initialization)	Transient run
Inlet (L/C/R)	$\dot{m}_C = 0.0012032 \text{ kg/s}$ $\dot{m}_{L/R} = 0.0011572 \text{ kg/s}$ (explained below)	$\dot{m}_C = 0.0012032 \text{ kg/s}$ $\dot{m}_{L/R} = 0.0011572 \text{ kg/s}$ (explained below)
Top wall (non-heated)	300 °C	HTC = 20 W/m ² K, T _{air} = 30.2 °C
Bottom wall (non-heated)	300 °C	HTC = 20 W/m ² K, T _{air} = 30.2 °C
Side walls	300 °C	HTC = 20 W/m ² K, T _{air} = 30.2 °C
Top heated wall	303 °C	303 °C
Bottom heated wall	303 °C	303 °C
Outlet (L/C/R)	Opening	Opening
End wall (inlet/outlet)	Adiabatic	Adiabatic

* L/C/R: Left/Center/Right channel

“General connection” interfaces were placed between the three semi-circular channels and the stainless steel solid walls.

Figure 3-8 presents the T/C readings through Test #3, as an example of the steady-state initialization transient portions of the test, whereas Figure 3-9, which is identical to Figure 1-4, is presented again to facilitate the understanding of the various temperature locations and profiles. The steady-state and transient portions of the test are discussed as follows:

- Steady-state initialization run (90,000 to 90,200 seconds): This is the time period when:
 - radiant and contact heaters are on
 - air blower is off
 - sodium is flowing at a set flow rate value at 300°C, with the goal to initialize the temperatures on the test section to 300°C (though slightly higher temperatures were observed in T/C readings between contact heaters and test section walls during the tests).

A steady state CFD run was conducted in order to simulate this period to initialize the domain temperatures, and also to fully develop the sodium flow in the channels. The temperature values for the boundary conditions were extracted from the test data by averaging T/C readings through the initialization time frame. Note that the boundary surfaces which had more than one T/C attached were not divided, but the average of the readings of the T/C's was applied to that surface. There are no T/C's attached to the side walls, so the average of the top and bottom surface temperatures were used for these.

- Transient run (90,200 to ~94,200 seconds): Once steady-state is reached during the test, the radiant heaters are turned off and the air blower is turned on to start cooling the test section, aiming at creating the coldest region in the test section immediately upstream of the contact heaters (near T/C #17, shown in Figure 3-9). To simulate this period, a transient CFD run was then started from steady-state results with the transient boundary conditions shown in Table 3.2 to capture the time varying temperatures across the domain. For the transient runs, a constant (in time and space) heat transfer coefficient (explained below in

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detail) and constant external air temperature (average of air inlet T/C readings) were specified to the bare surfaces of the test section as they were cooled down. Sensitivity studies, such as air temperature varying in time and location, were conducted to test this modeling approach.

Note that the boundary conditions for the contact heaters for steady-state and transient CFD runs were the average readings of all T/C's on the particular surface for the whole transient duration⁹.

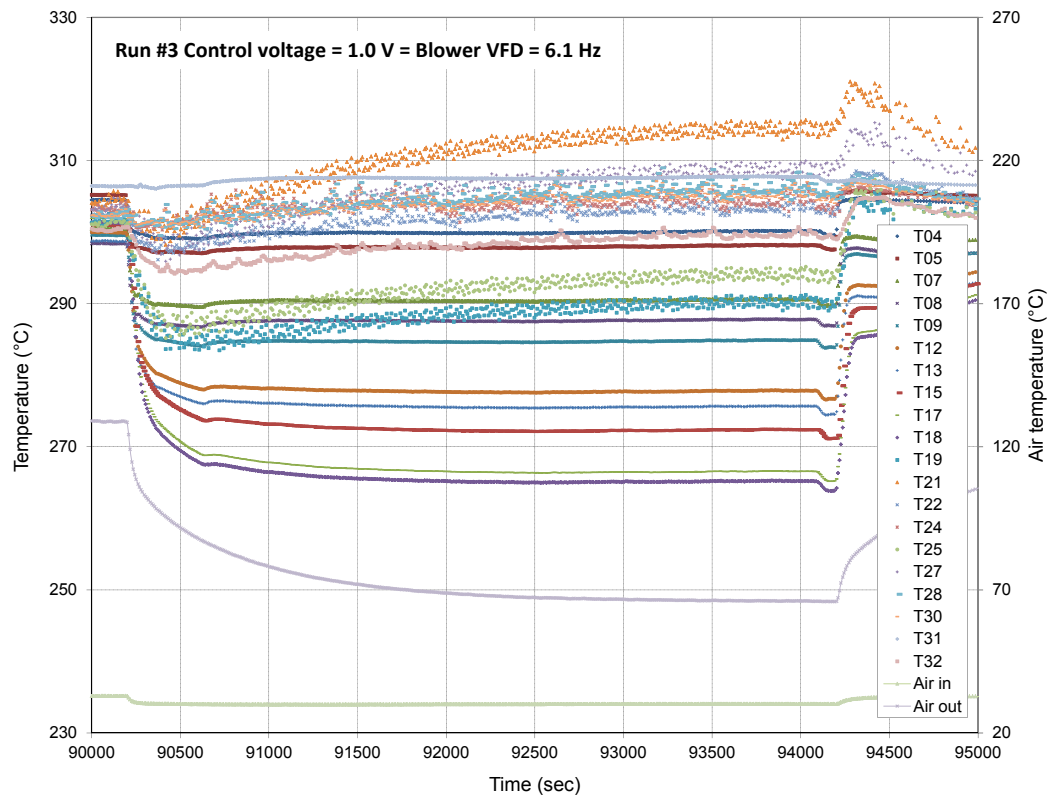


Figure 3-8. SPPL test section temperatures measured during Test #3. Same as Figure 2-3

⁹ The variance was considered small and sensitivity studies with +/- 1% specified temperature variation (see Appendix A, Section A.4.3) did not affect the results since the heaters are downstream of the region of interest.

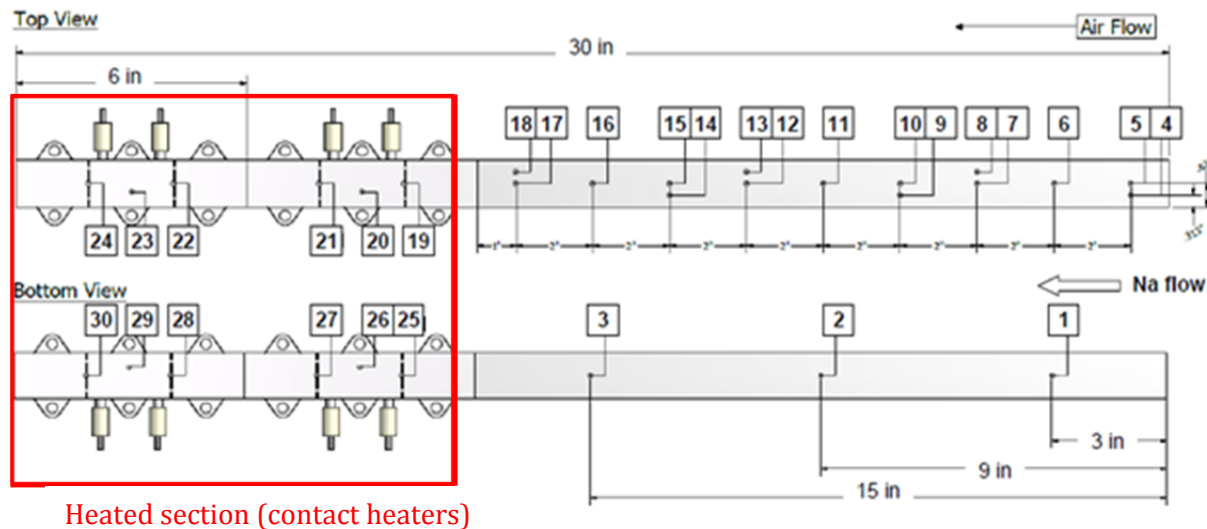


Figure 3-9: Locations of thermocouples on SPPL test section upper and lower surfaces (sodium and air flow from right to left). Same as Figure 1-4

As briefly mentioned in Section 3.2.2.1, the two parameters with the largest impact on the validations were decided to be the sodium flow rate flowing through the three 6mm semi-circular channels, and the heat transfer coefficient applied to the bare surfaces of the test section. Some important considerations on these parameters are presented below:

- **Sodium flow rate:** The main reason for not using sodium flow rate measurements directly as input to the CFD simulations was the large uncertainty in these measurements, both before the flow meter re-calibration (28%, [12]) and afterwards (+/-25%), as discussed in Section 2.3. An initial flow rate measurement of 0.01 L/s [5] was used as a starting point for the iterative validation process. In the end, it was observed that 40% of the measured flow rate proved the best match between test data and CFD simulations. The mass flow rates specified for Test #3 in Table 2.1 for the L/C/R sodium channel inlets are representative of this 40% adjustment factor. Note that the reason between the difference in L/R and C channel flow rates is that during exploratory full loop CFD runs with a range of sodium flow rates, it was observed that the center 6mm semi-circular channel had ~4% higher flow rate compared to the left and right channels, expected due to the fact that the center channel is aligned with the SPPL piping upstream of the test section.
- **Heat transfer coefficient:** As previously discussed, for the transient simulations, a heat transfer coefficient was specified for the bare surfaces of the test section, with an air temperature specified as average of test air inlet T/C readings (the minimal variance throughout test was in the order of 1°C). The value for the heat transfer coefficient on the surfaces was kept constant throughout the transient runs. For the validation runs, the first heat transfer coefficient value to start the iterative process was based on the air speed corresponding to the measured blower rotational speed for Test 3, i.e. 6.1 Hz (see Table 2.1), which corresponds to approximately 5 m/s (see Figure 1-6). The heat transfer coefficient CFD iterations were started with approximate values of 40 W/m²K that correspond to convective heat transfer of air flow at 5m/s over stainless steel.

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The air speed linearly changes with the blower frequency, and the heat transfer coefficient changes accordingly based on Reynolds number for turbulent flow over flat plate [11]:

$$h \sim Re^{0.8}$$

3.2.2.4 CFD modeling approach and settings

As discussed in Section 2.2, four no-plugging tests were conducted with the SPPL, resulting in the test matrix shown in Table 2.1. Within the validation framework, Test #3 T/C data were used to validate the CFD model against, and the validation was then tested on the remaining three tests. Several runs were conducted with different sodium flow rates and heat transfer coefficients in search for the combination that best matches T/C measurements for Test #3:

- Sodium flow rate was varied +/- 5% from the initial starting point provided from SPPL flow meters;
- Heat transfer coefficient was varied +/- 10 W/m²K based on the initial starting range of 10-100 W/m²K.

After the iterations simulating Test #3 were concluded, the following values for sodium flow rate and heat transfer coefficient were found to best match the temperature measurements for Test #3 shown in Figure 3-8:

- sodium flow rate = 40% of measured value for Test #3 = 0.0035175kg/s;
- heat transfer coefficient = 20 W/m²K for the blower frequency of 6.1Hz

These boundary conditions for Test #3 were then used to obtain the values for the same parameters for the remaining three tests, using the multipliers (0.5x, 1x, 2x) shown in Table 2.1 and the exponential dependence ($Re^{0.8}$) of the heat transfer coefficient from the air velocity. Results are shown in Table 3.3.

Table 3.3. No-plugging test matrix with sodium flow rate and heat transfer coefficient values resulting from validation of Test #3

TEST	Sodium flow rate			Air flow rate		
	Flow meter reading (mV)	Flow rate (kg/s)	Comment	Blower frequency reading (Hz)	Heat transfer coefficient (W/m ² K)	Comment
1	1.5	0.007035	Value below × 1.5/0.75	6.1	20	Same as for Test #3
2	1.5	0.007035		12.2	34.8	20 × (12.2/6.1) ^{0.8}
3	0.75	0.0035175	Value that best matches Test #3 T/C measurements	6.1	20	Value that best matches Test #3 T/C measurements
4	0.75	0.0035175	Same value as above	3.05	11.5	20 × (3.05/6.1) ^{0.8}

Other modeling choices made for the validation of the four no-plugging cases are as follows:

- The SST k- ω turbulence model with automatic wall function option was utilized¹⁰.
- A turbulence intensity equal to 1% was specified at the channel inlets.
- The turbulent flux closure for the heat transfer option was activated in the simulations with the eddy diffusivity option, and a Turbulent Prandtl number (Pr_t) specification of 4.12 based on sensitivity studies conducted. These sensitivity studies are presented in Appendix A, Section A.2, and are crucial to take into consideration in modeling of liquid metal flows simulations.
- Buoyancy was not modeled, and 1 atm pressure was specified.
- Double precision was used as this was observed to have an important effect.
- The advection scheme in addition to turbulence numerics were selected as high resolution.
- For the steady state initialization runs, auto time scale was used for both the solid and fluid domains. For the transient runs, a time step of 0.5 seconds was implemented, with 5 maximum inner coefficient loops.
- Temperature-dependent properties, summarized in Appendix B, were used for both sodium and stainless steel.

3.2.3 Results

This section presents the no-plugging CFD simulation results after the validation procedure was completed, and sodium flow rate and heat transfer coefficient on the test section outer surface were set, as previously shown in Table 3.3. Only the transient simulation results (which were started from the steady-state results) are presented. It should be noted that the focus of the no-plugging validation runs was the region near the expected coldest spot on the test section, which is in the proximity of T/C #17 right upstream of the contact heaters. Hence, the post processing will focus on this area, presenting detailed results for T/C #12, #15 and #17 (closest recorded T/C data to the expected plug location¹¹), whose location is shown in Figure 3-9.

In addition, the following monitoring points were created for the CFD model:

- Monitoring points for T/Cs: 1, 2, 3, 5, 6, 7, 10, 11, 12, 15, 16, 17.
- Four velocity (NPV_V1, V2, V3, V4) and four temperature (NPV_T1, T2, T3, T4) monitoring points along the center channel for sodium flow.

¹⁰ There are two main reasons for this choice:

- The Re numbers observed within the SPPL and in the test section channels can be in the laminar-to-turbulent transition, and the SST k- ω model is the most robust in handling these cases. k-epsilon tends to produce unrealistic results in laminar flow due to low/no turbulent kinetic energy. The SST k- ω model still adds some dissipation in the laminar flow, but comparing a small but similar channel flow test case with SST k- ω versus fully laminar selection, results were satisfactorily close (see Appendix A, Section A.3).
- The main focus of this validation is to eventually use the approach for plugging CFD modeling. In the plugging models, even if the inlet flow is laminar, the deposits formed in the channel cause turbulence and even recirculation regions in the wake of the deposit (see later in Section 3.4.2). The SST k- ω is the best model to handle these cases.

¹¹ T/C #16 data was not recorded during SPPL tests.

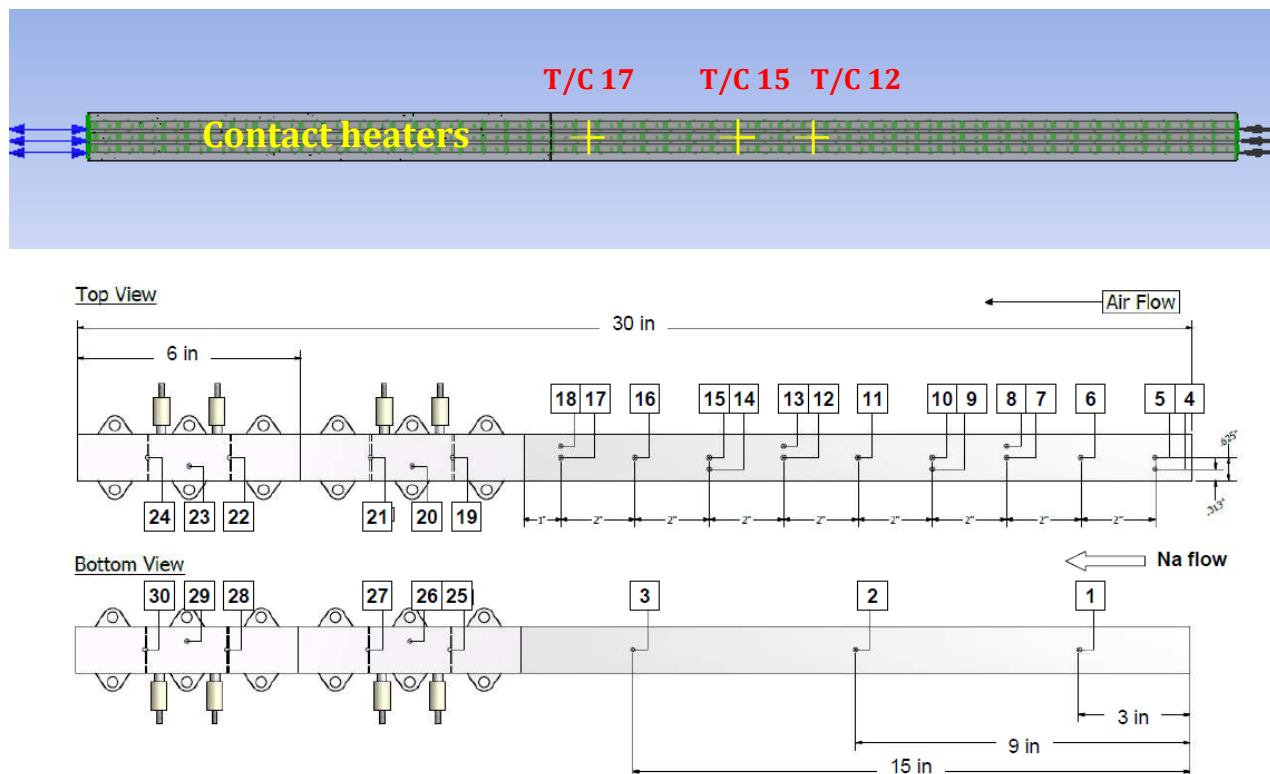


Figure 3-10: T/Cs selected to show results of no-plugging validation (top) and complete view of T/C locations (bottom)

CFD simulations of Tests 1, 2, 3 and 4 are presented below.

Figure 3-11 through Figure 3-14 compare the CFD simulation results with the experimental values for the temperatures associated with T/Cs 12, 15 and 17, for Tests 1, 2, 3 and 4, respectively. Figures (a) present the first 100 seconds focusing on the initial cooling period (which may play a critical role in deposit initiation), while Figures (b) zoom out showing the full transient until stabilization (different lengths for each run) to the final steady-state temperatures. Black lines represent experimental measurements, while red lines represent CFD simulation results. Different line patterns (solid, dashed, dotted) are used to distinguish between the three T/Cs. Note that the uncertainty in the SPPL T/C measurement, shown with arrows in the figures, is $\pm 3^\circ\text{C}$.

It can be seen that:

- during the first 20 seconds of the transients, i.e. when the cooling is faster, the CFD simulation results are within the measurement uncertainty bands, for all the tests.
- between 20 and 100 seconds, a good match (within measurement uncertainty bands) between CFD simulation results and experimental measurements characterize Test #1 (with the exception of T/C #17, off by about 7°C), whereas deviations can be seen for Test #2 (largest is for T/C #17, $\sim 20^\circ\text{C}$) and, although less significant, for Test #3 and Test #4 (largest is for T/C #17, $\sim 11^\circ\text{C}$)
- at the end of the transient, a good match (within measurement uncertainty bands) between CFD simulation results and experimental measurement characterize Test #1 (only T/C #15 is approximately 2°C outside of the band) and Test #4. For Test #2, CFD results are between

5-12°C outside of the measurement uncertainty bands. For Test #3, CFD results are 1-3°C outside of the measurement uncertainty bands.

- Test #2, for which the largest discrepancies exist between CFD simulation results and experimental measurements in the mid and end part of the transient, shows an increase in the measured temperatures starting after ~600 seconds for unexplained reasons, causing the discrepancies mentioned above.

As the results show, the validation process was an undertaking of finding the optimal settings for the sodium flow rate and the applied heat transfer coefficient to:

- Firstly, match the initial cooling rate which is very critical for the plugging CFD simulations for the initiation and growth of the sodium oxide deposit
- Secondly, match the stabilized temperatures at the end of the transients

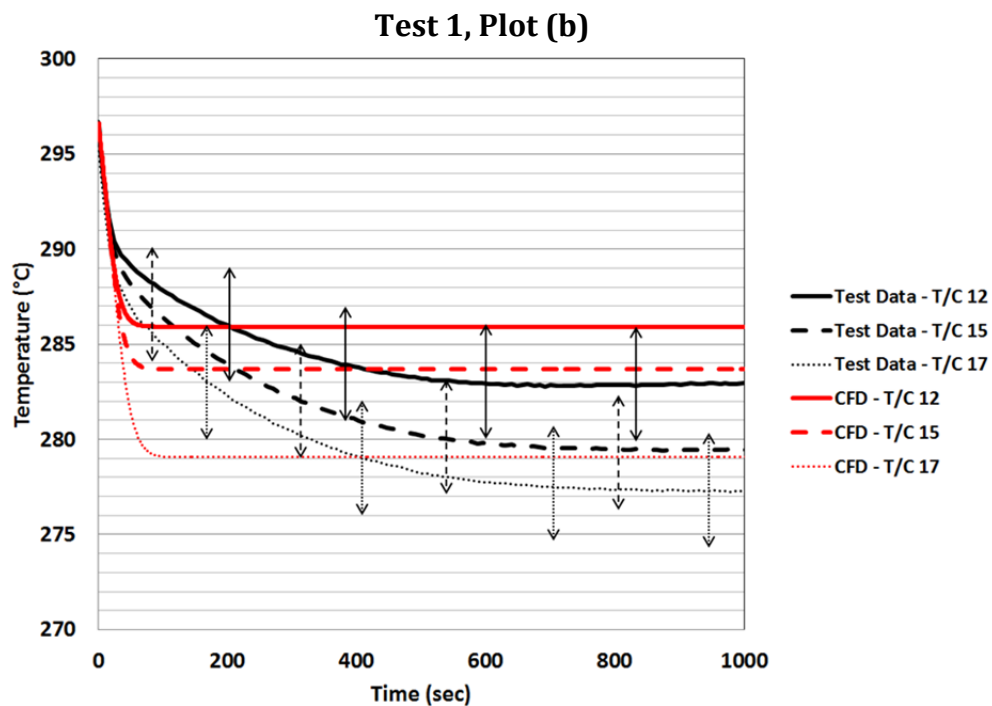
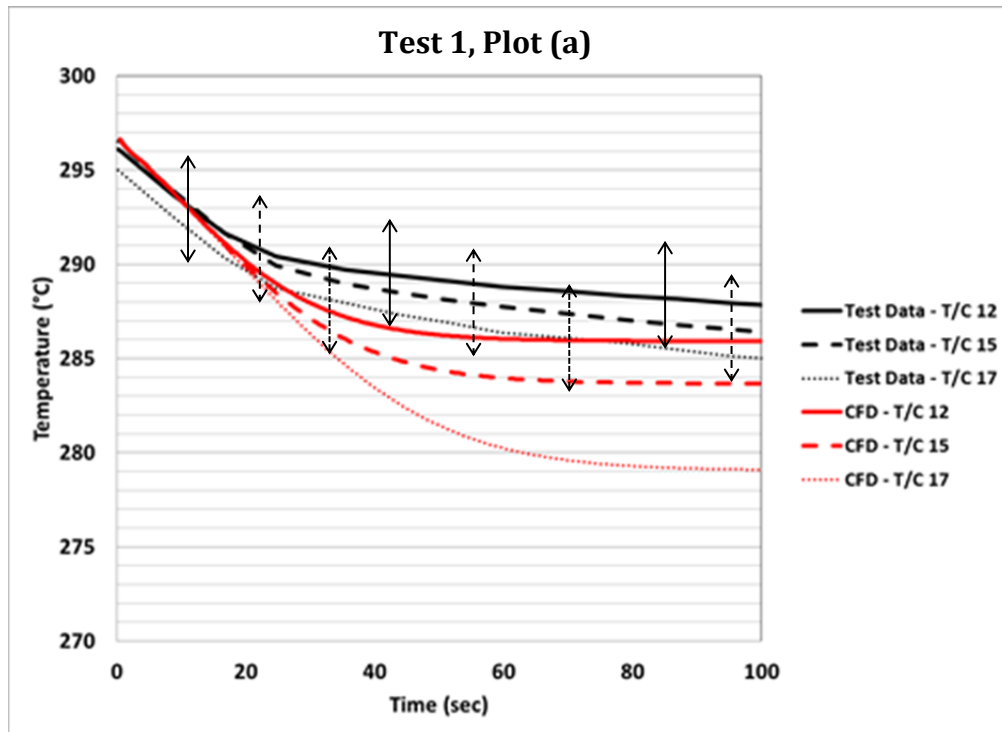


Figure 3-11: Comparison between CFD simulation and measured values, for temperatures in Test #1. Arrows indicate measurement uncertainty bands. First 100 s in Plot (a); whole transient in Plot (b)

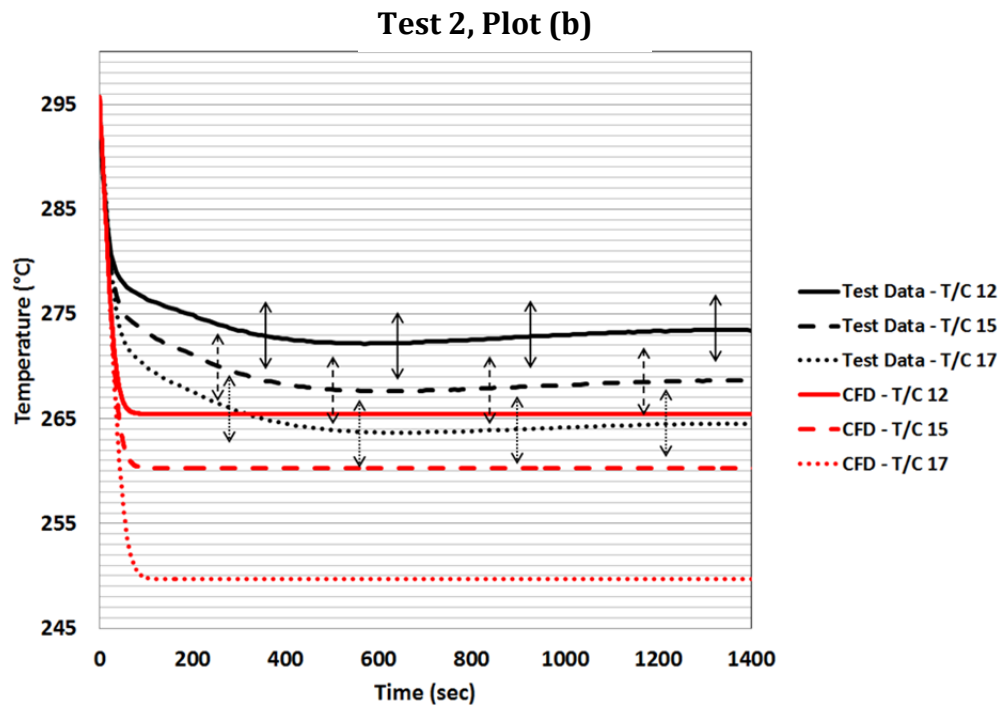
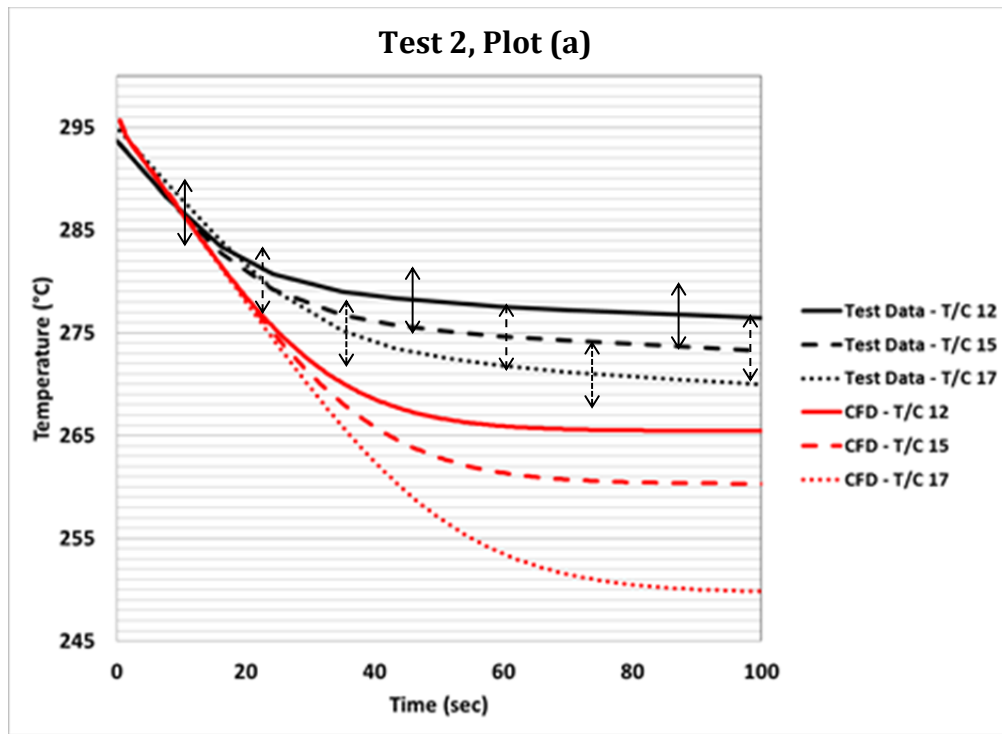


Figure 3-12: Comparison between CFD simulation and measured values, for temperatures in Test #2. Arrows indicate measurement uncertainty bands. First 100 s in Plot (a); whole transient in Plot (b)

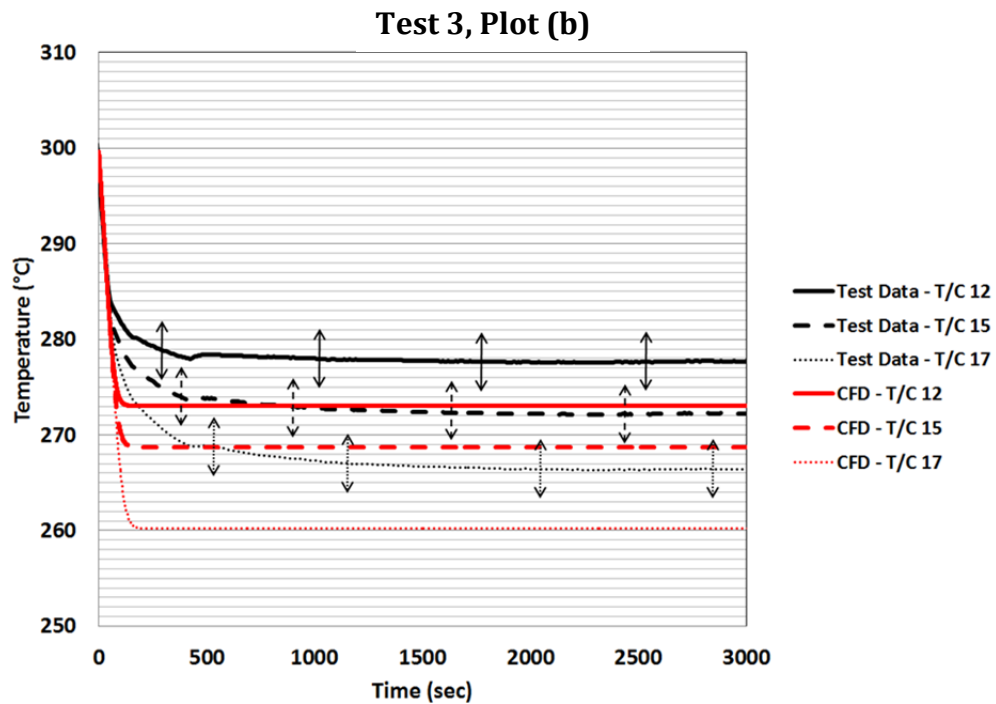
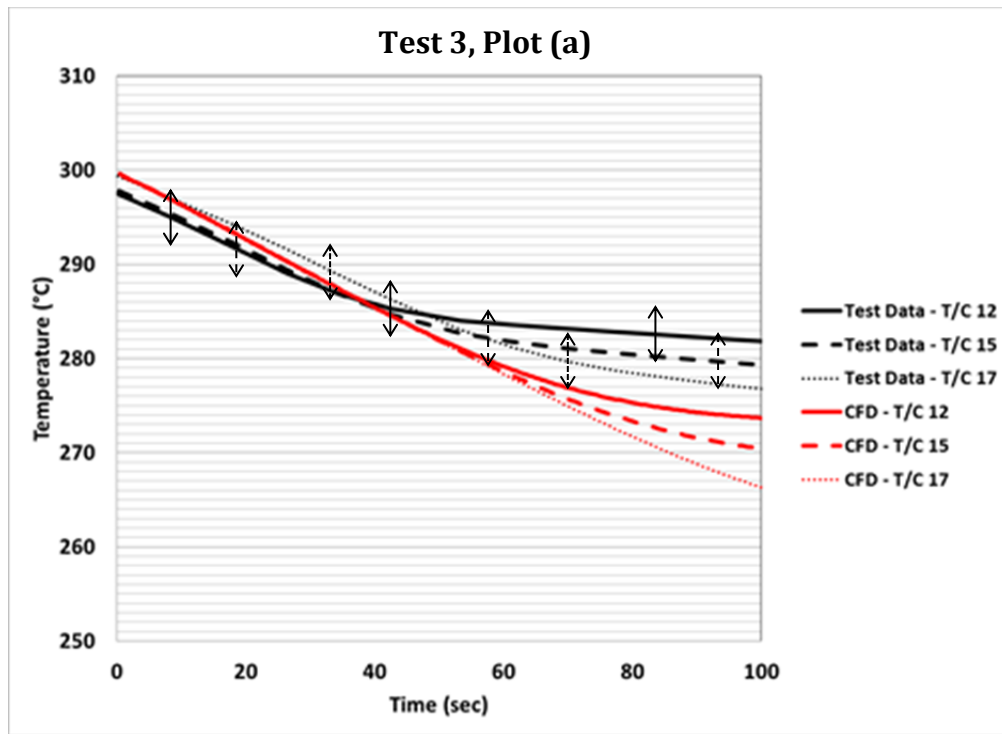


Figure 3-13: Comparison between CFD simulation and measured values, for temperatures in Test #3. Arrows indicate measurement uncertainty bands. First 100 s in Plot (a); whole transient in Plot (b)

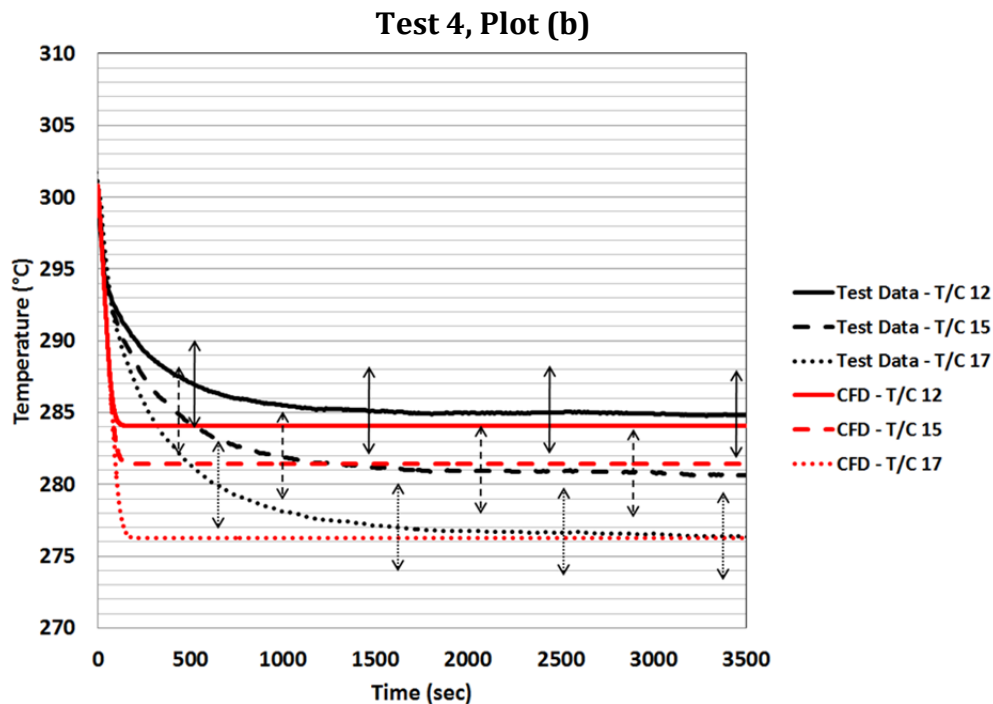
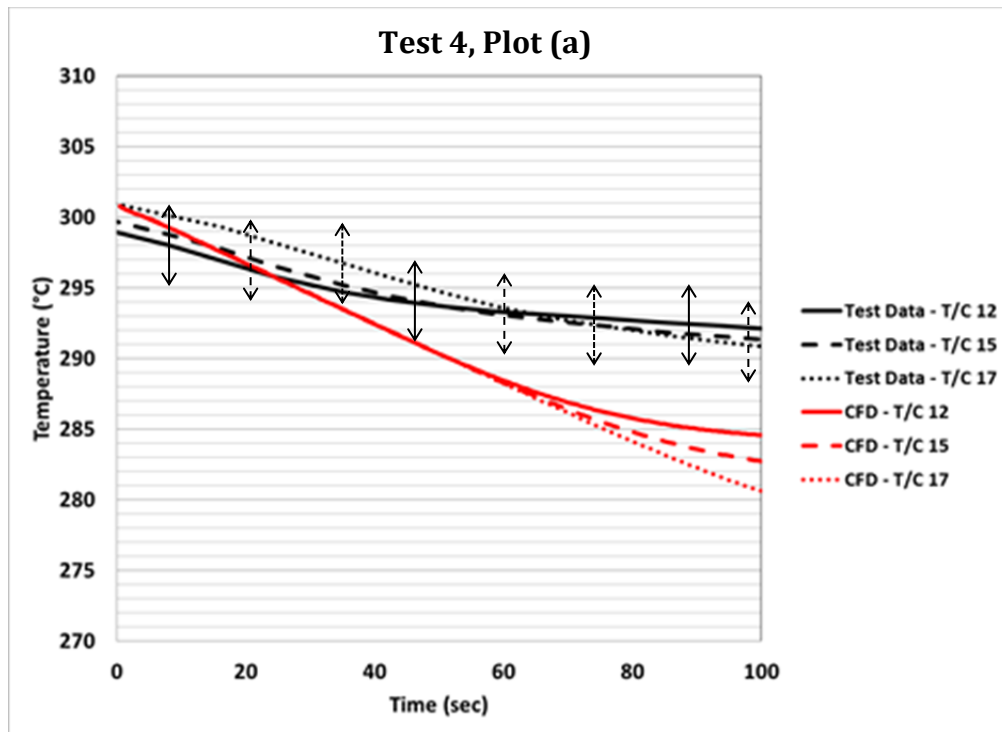


Figure 3-14: Comparison between CFD simulation and measured values, for temperatures in Test #4. Arrows indicate measurement uncertainty bands. First 100 s in Plot (a); whole transient in Plot (b)

Additional CFD results for the simulation of Test #3 are presented below. Figure 3-15 shows the temperature contours on post-processing cut planes at the axial locations corresponding to T/C 12,

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15 and 17. Figure 3-16 shows temperature contours for the test section outer surface, whereas Figure 3-17 shows temperature contours for the surface of the semi-circular channels, which interface with the solid body of the test section.

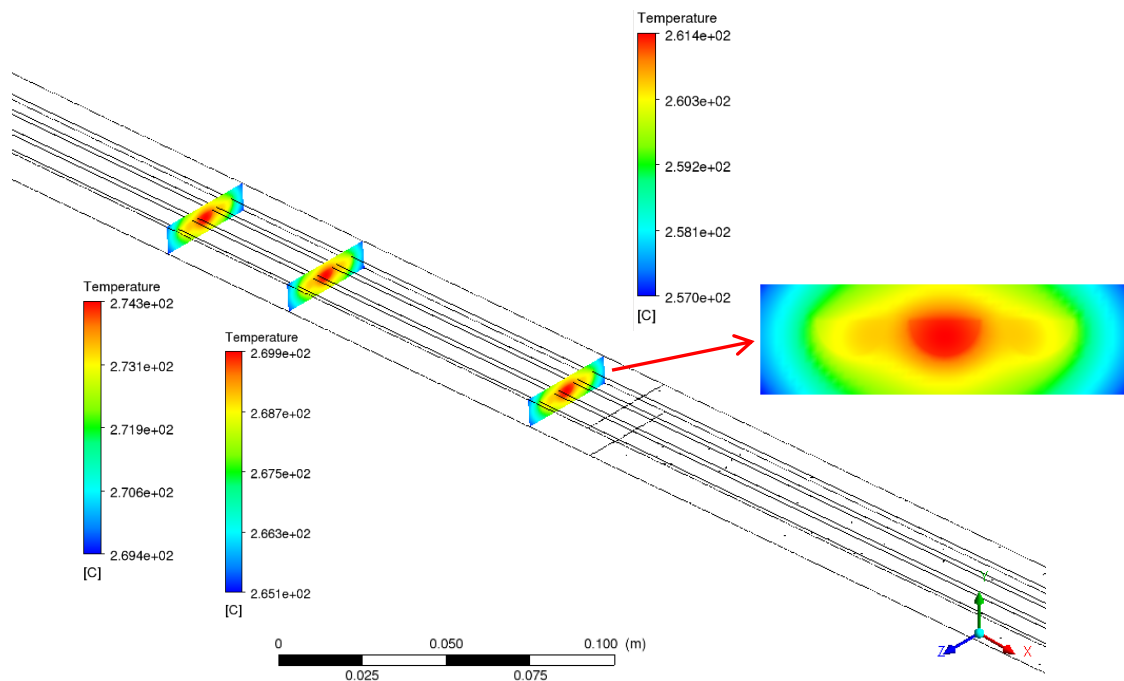


Figure 3-15: Temperature contours on cut planes at the same axial locations as T/C 12, 15 and 17

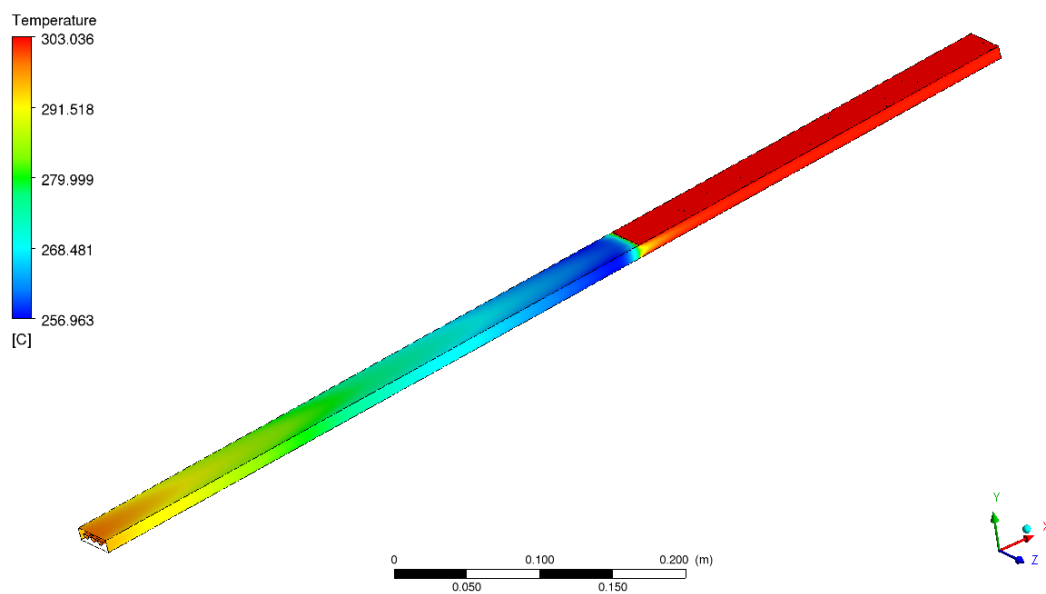


Figure 3-16: Stainless steel surface temperature contours

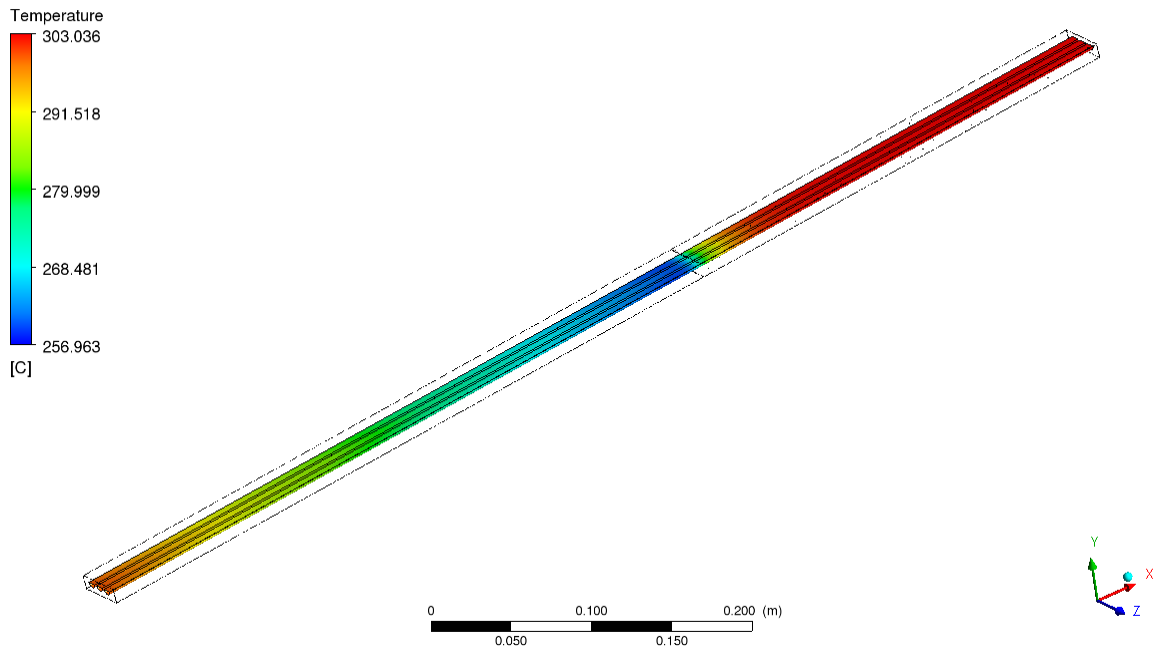


Figure 3-17: Semi-circular channel surface temperatures

3.3 Loop CFD run

This section presents the next step in the development path of the complete sodium oxide deposition CFD tool, detailing the no-plugging CFD model of the SPPL beyond the test section itself, and including portions of loop piping immediately upstream and downstream of the test section. This model, referred to as “loop model” even though it does not represent the whole loop, is envisioned to be combined with the plugging methodology presented in the next chapter to build the complete CFD tool.

The modeling approach is based on the calibration results presented in the previous chapter for sodium flow rate and heat transfer coefficient on the bare test section surfaces. In addition, the CFD model also incorporates the lessons learned through the Pr_t sensitivity study, which is presented in Appendix A, Section A.2.

Ultimately, the analysis in this section aims at providing a complete flow profile entering the test section, simulating Test #3 conditions presented in the previous chapter.

3.3.1 Domain/geometry

The current layout of the full SPPL is shown in Figure 3-18, with the domain selected for the “loop model” outlined in the red box. Note that the EM flow controller and meter were not modeled.

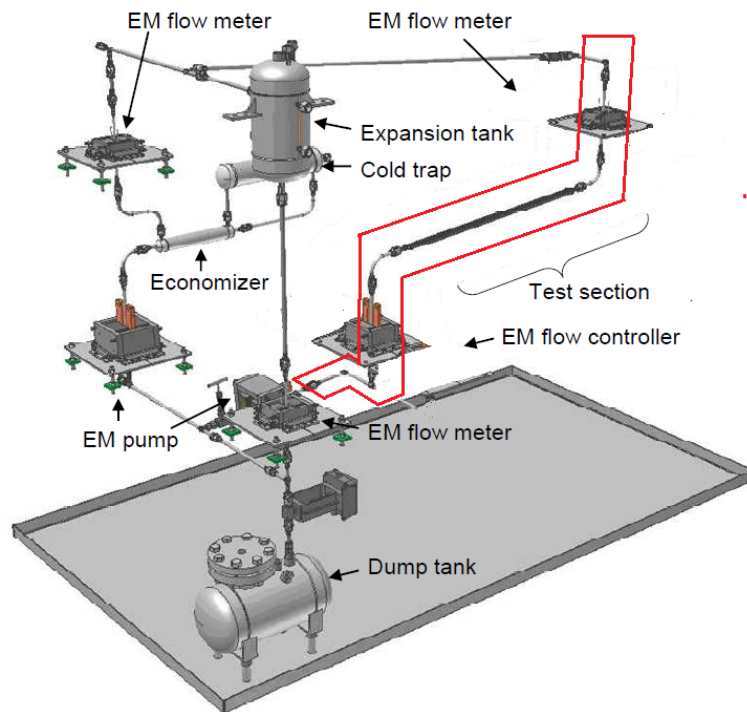


Figure 3-18: Current layout of SPPL layout, with the CFD domain shown within the red box (modified from [2])

Figure 3-19 presents the CFD model fluid (sodium) domain, with insets providing zoomed-in views of the inlet and outlet connector transition regions (“transition pieces”), in addition to the semi-circular channels of the test section. Within this CFD model, the liquid sodium was modeled, but the pipe thicknesses along the main loop lines, i.e. downstream and upstream of the test section, were not modeled (as they were kept at constant temperature during the tests). Similar to the CFD models used for calibrations in the previous chapter, the stainless steel test section walls covering the semi-circular channels were modeled (shown with the red outline). Further details regarding boundary conditions and model setup are provided in the next section.

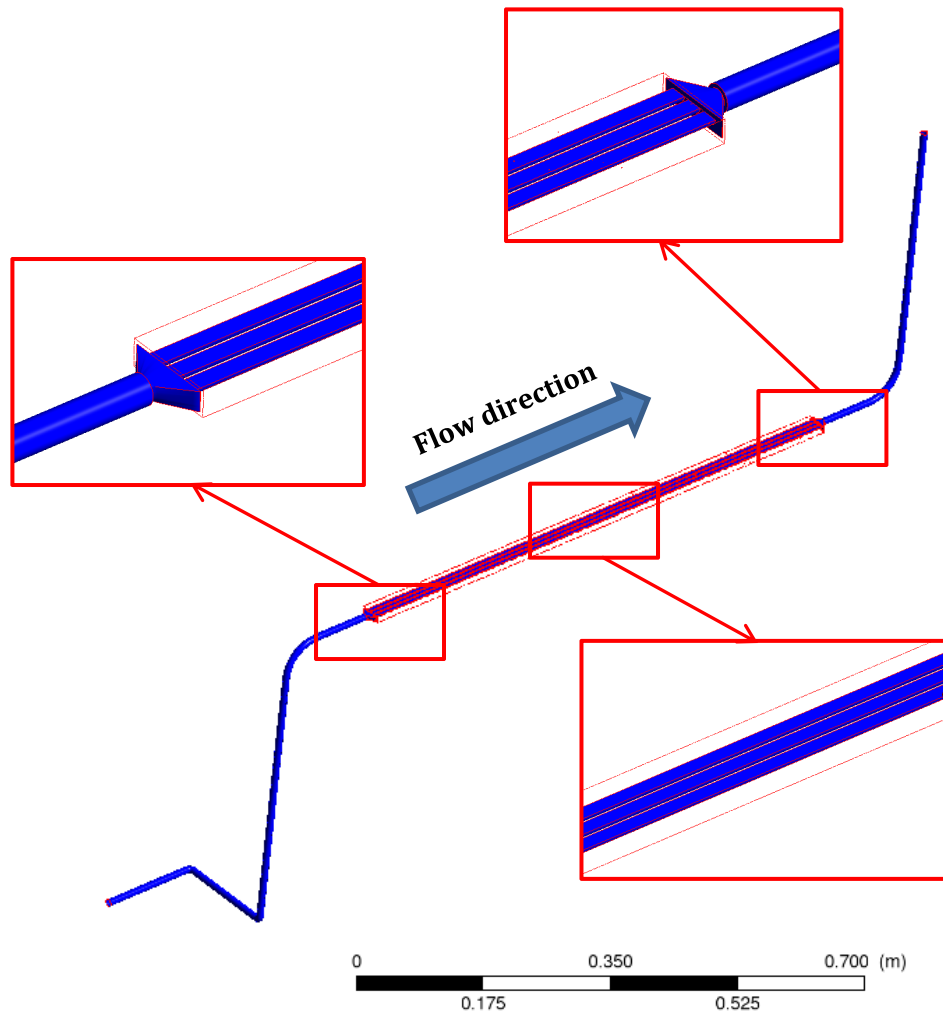


Figure 3-19: SPPL CFD fluid (sodium) domain, showing transition pieces (inlet: diverging); outlet (converging)

3.3.2 Computational mesh

The fluid (sodium) domain was meshed using TrueGrid and all blocks with hexahedral meshes were connected. There were no interfaces present within the fluid domain (different from the preliminary SPPL model used in the sensitivity studies). The stainless steel test section solid walls were meshed using ICEM-CFD with same settings as used in the no plugging calibration studies on the test section, with a combination of hexahedral cells at the core and tetrahedral/pyramid cells near the walls. Interfaces were placed between the solid and fluid domains through the test section length.

Total number of computational cells for the fluid domain was 9,144,212, and the solid domain contained a total of 5,991,465 cells, for a total model count of 15,135,677 cells. Detailed mesh information is provided in Appendix A, Section A.7.2.

Figure 3-20 presents a cut section perpendicular to the flow direction showing the mesh density.

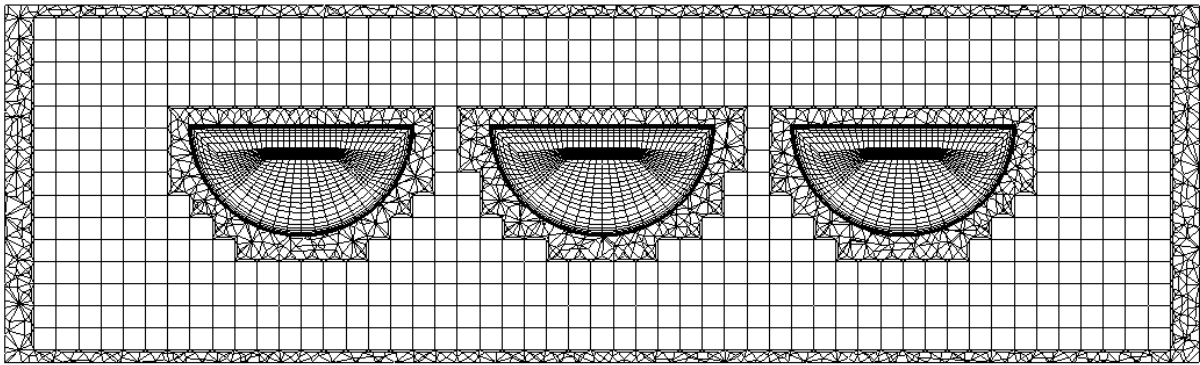


Figure 3-20: Cut plane perpendicular to flow direction showing mesh density

Figure 3-21 presents a horizontal cut section parallel to the flow direction at the middle elevation of the test section, showing the mesh density. Note the topology of the test section channel conformal meshes continuing through the main loop line without interfaces.

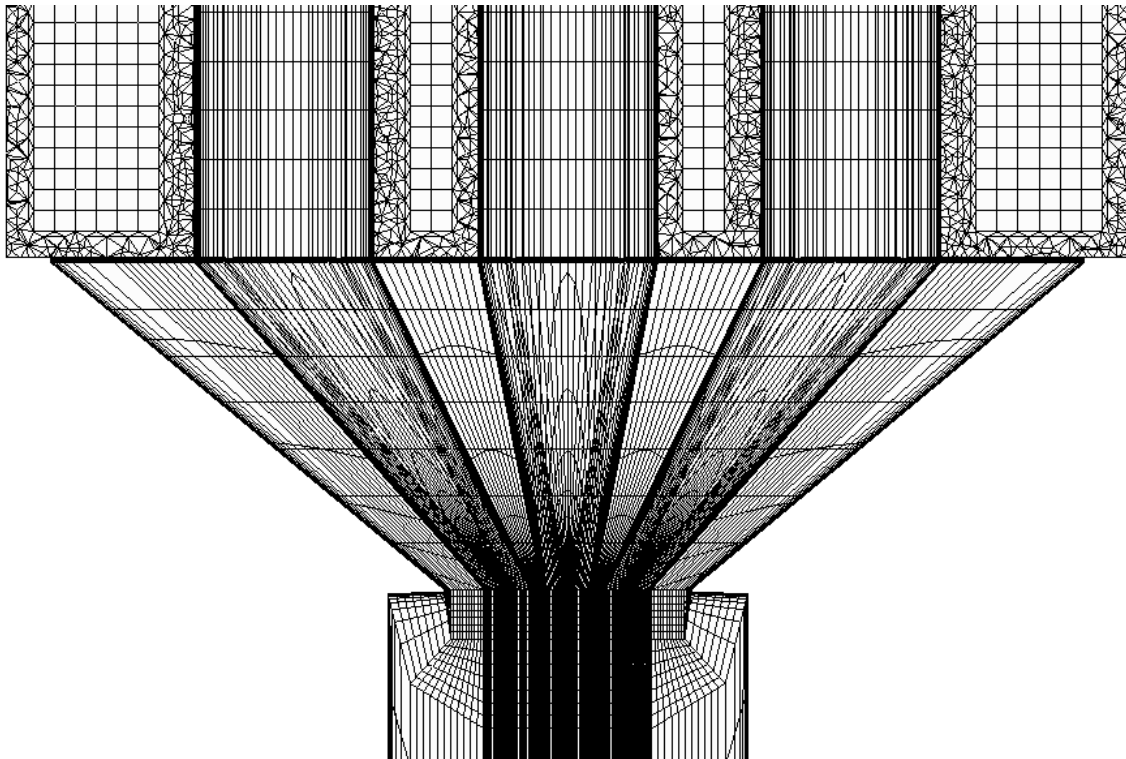


Figure 3-21: Horizontal cut plane parallel to the flow direction at the middle elevation of test channels

Figure 3-22 provides a vertical cut section parallel to the flow direction at the center of the test section, showing the mesh density. Again note the topology of the test section channel conformal meshes continuing through the main loop line without interfaces.

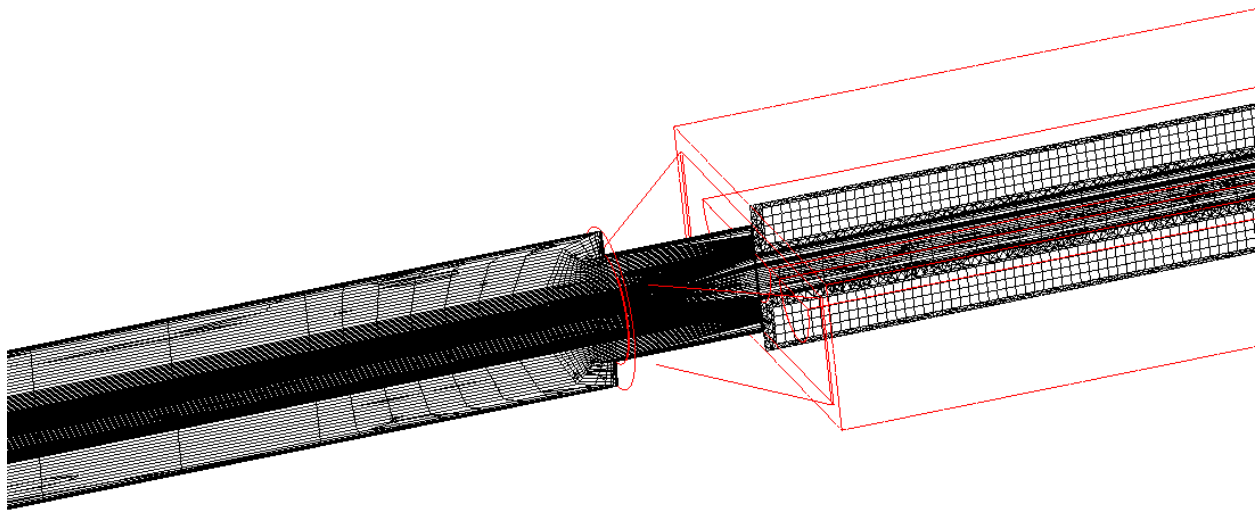


Figure 3-22: Vertical cut plane parallel to the flow direction at the center of the test section semi-circular channel showing mesh density

3.3.3 Boundary conditions and model setup

Boundary conditions (temperatures and heat transfer coefficient) on the test section portion for the loop CFD model are kept identical to the CFD model setup for Test #3 presented in Section 3.2.2 on calibration of the sodium flow rate and the heat transfer coefficient for the transient run settings. The inlet flow rate used was also the same as the sum of the three semi-circular channel inlet flow rates used for the Test #3 calibration model, at 0.0035176 kg/s, at 300°C, with 1% turbulence intensity. The loop main line pipe walls, including the inlet and outlet transition region walls, were set to adiabatic, as during SPPL tests these walls are kept at the same temperature as the inlet sodium flow temperature of 300°C.

The simulation was set up as steady-state, with automatic time scales for solid and fluid domains. Upwind advection scheme, and high resolution numerics for turbulence were utilized. Convergence criteria of 1.e-10 RMS, and 0.001 conservation targets were set. Double precision solver was used. Similar to the Test #3 calibration model, the SST k- ω turbulence model with automatic wall function option was utilized. The Pr_t value used was again 4.12. Temperature-dependent properties for sodium and stainless steel were used, same as for the modeling work discussed in Section 3.2. Different from the validation cases, due to large elevation changes, gravity was turned on in the loop model. Reference density and pressure were set to 879.31 kg/m³ and 1 atm, respectively.

3.3.4 Results

The simulation was run until convergence was deemed reached based on residuals, domain imbalances and monitor points. The details of the convergence information are provided in Appendix A, Section A.6.2.

Figure 3-23(a) presents the velocity magnitude contours on a vertical cut plane parallel to the flow direction, at the center of the test section, focusing at the inlet region of the test section. Note the increase in velocity entering the inlet transition piece, and through the center semi-circular

channel. Figure 3-23(b) presents the velocity magnitude contours on the same cut plane, focusing on the outlet of the test section. Again note the reduction in velocity of flow traveling through the outlet transition piece and through the main loop pipe.

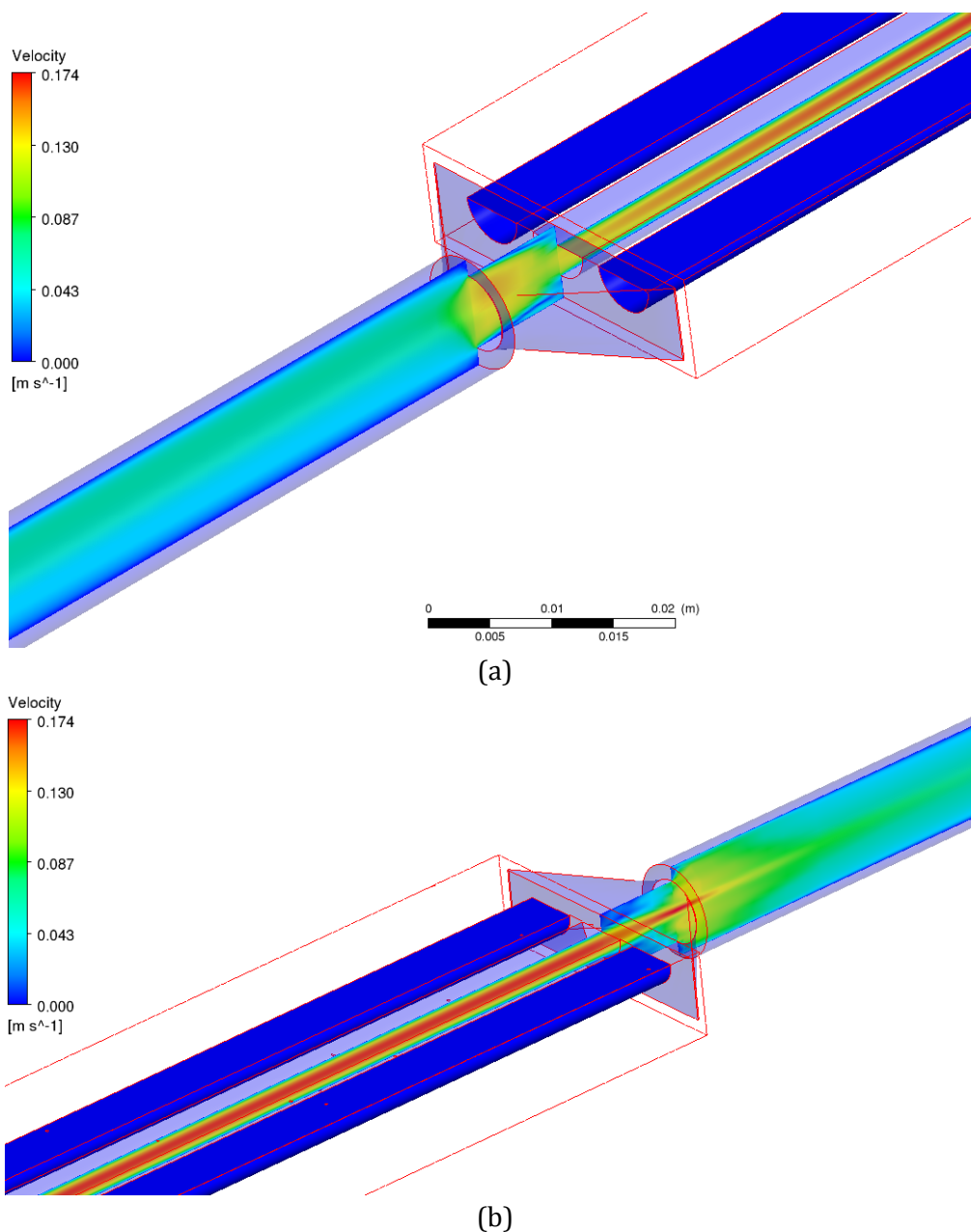


Figure 3-23: Velocity magnitude contours on a vertical cut plane parallel to the flow direction, at the center of the test section. Inlet (a) and outlet (b)

Figure 3-24(a) presents the 3D streamlines through the main SPPL pipe along the transition piece into the test section. The large turbulent structures at the transition piece region, especially at the corners are readily visible. Figure 3-24(b) presents a close-up view focusing on the inlet region of the test section. It is visible how the center semi-circular channel is lined up with the main loop flow and has less disturbances on the flow path at the entrance. Figure 3-24 (c) presents a close-up

view focusing on the outlet region of the test section. Note the large eddies due to the converging transition region and the three semi-circular channel flows joining through the main loop pipe, creating recirculation regions at the entrance of the outlet pipe.

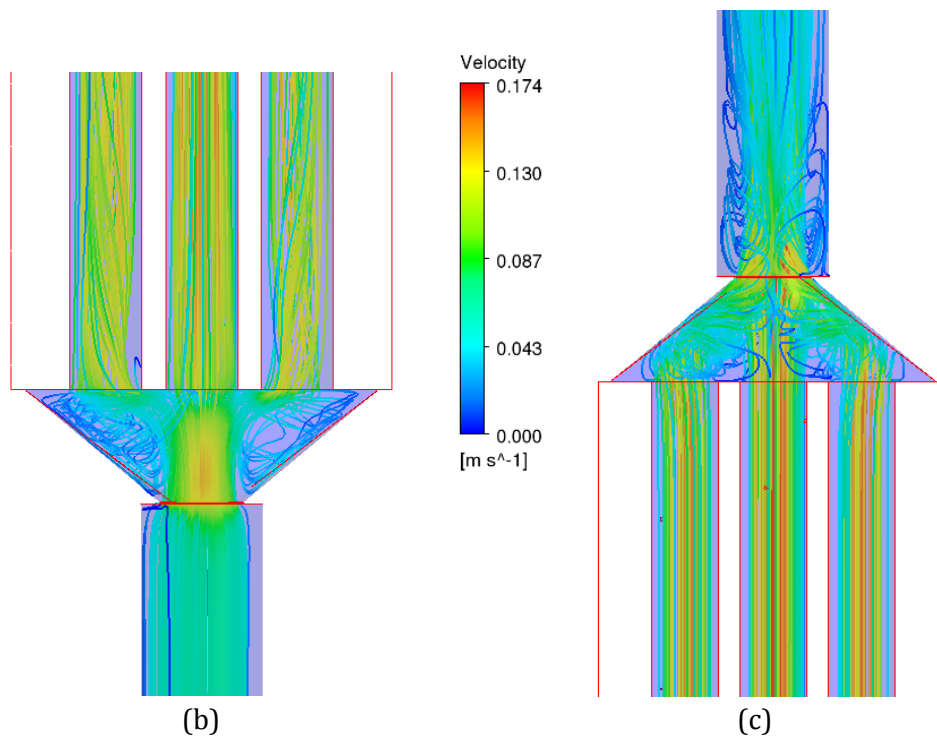
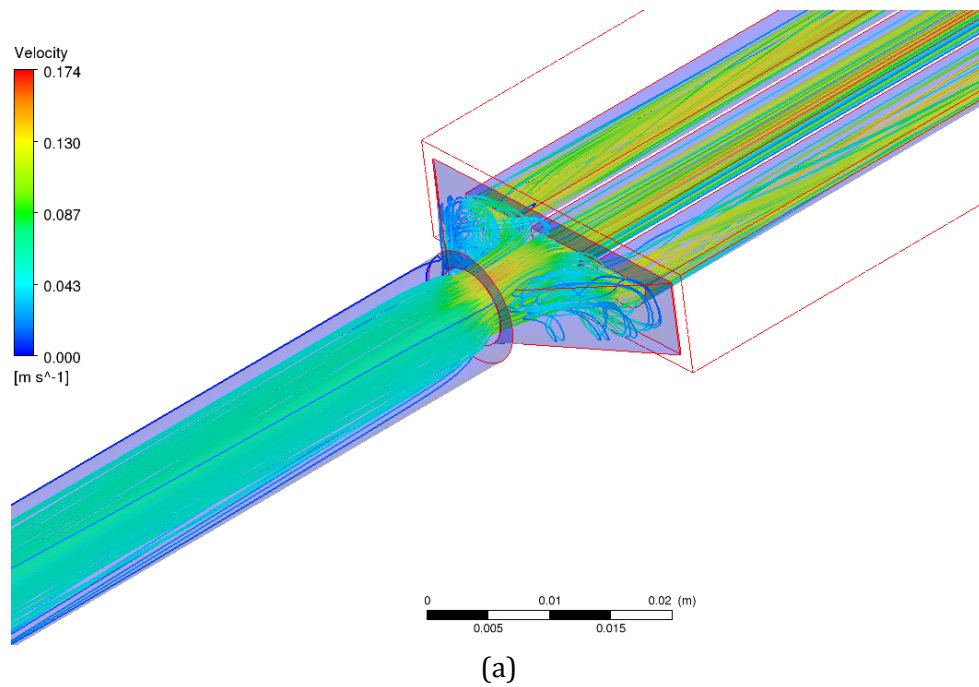


Figure 3-24: Streamlines through the inlet and outlet transitions regions to the test section

Figure 3-25 presents the inlet (a) and outlet (b) velocity magnitude contours on a horizontal cut plane through the center of the semi-circular channels. Similar to the streamline plots, the recirculation regions are visible.

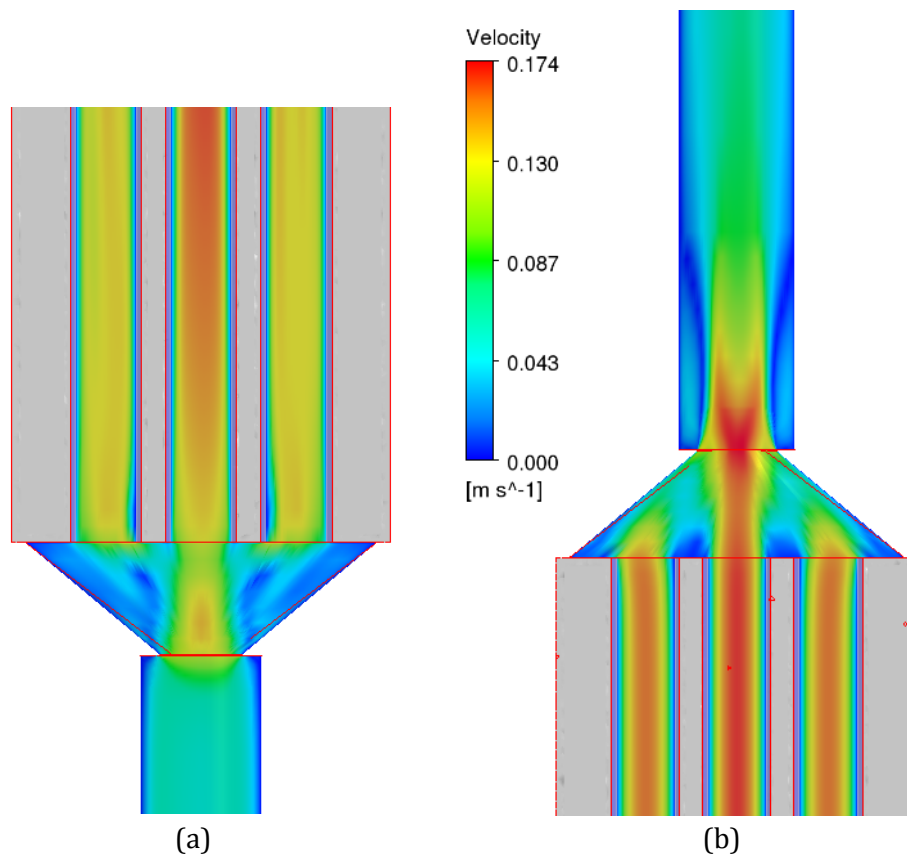


Figure 3-25: Velocity magnitude contours on a horizontal cut plane through the center of the test section

Figure 3-26 presents the streamlines originating from the inlet, providing information on the flow profiles through the bends of the main loop pipe.

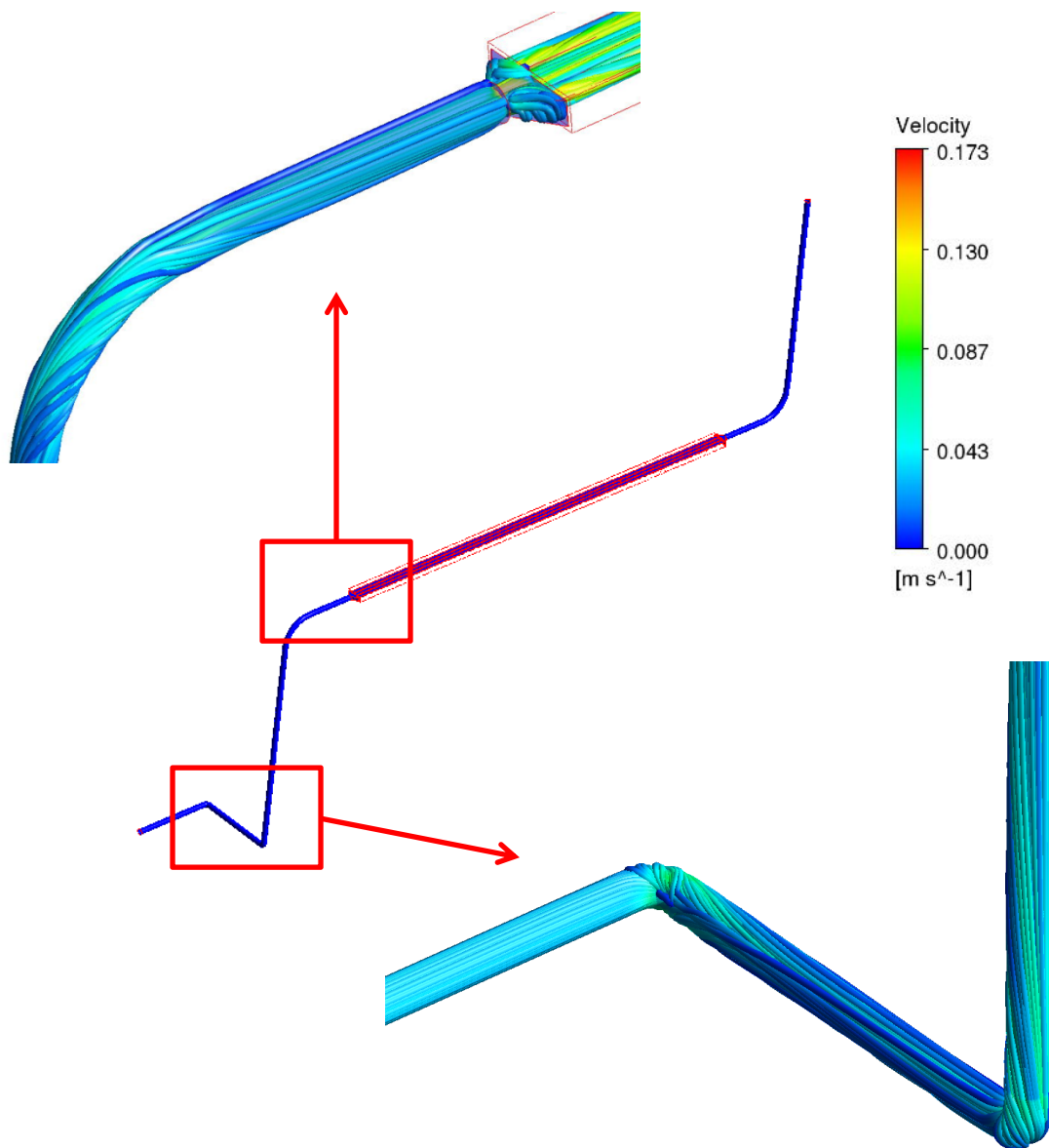


Figure 3-26: Streamlines through the main loop pipe

Figure 3-27 shows the velocity magnitude contour plot on a vertical cut plane perpendicular to the flow direction at T/C #17 location.

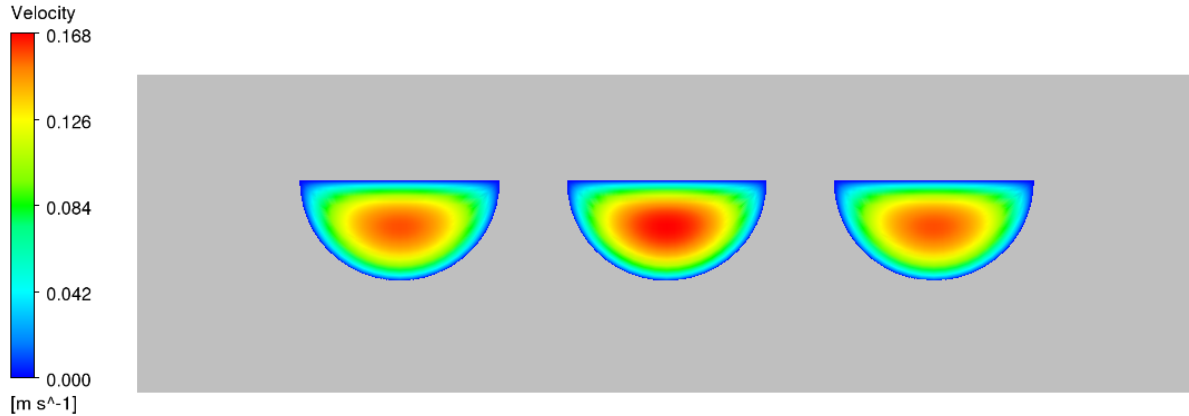
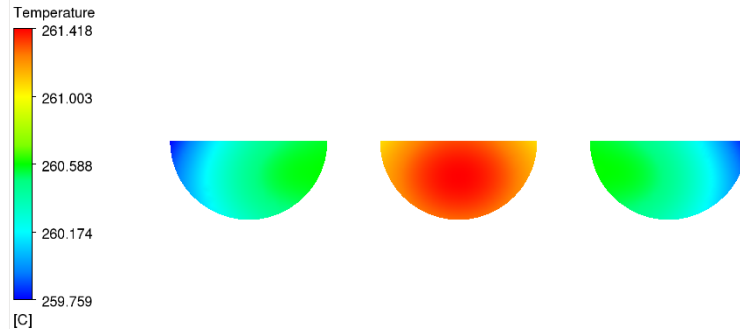


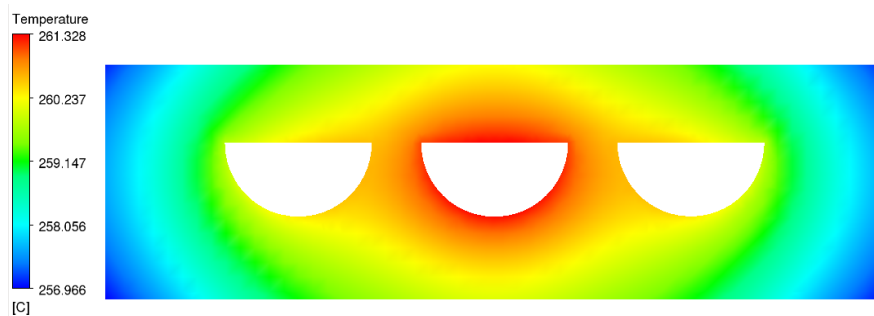
Figure 3-27: Velocity magnitude contour plot on a vertical cut plane perpendicular to the flow direction at T/C #17 location

Figure 3-28(a) presents the sodium temperature contour plot on a vertical cut plane perpendicular to the flow direction, again at the T/C #17 location. Note that although less than 2°C in difference, there is a temperature distribution observed within the channels, lowest temperatures at the top semi-circular corners. This information is important in future loop plugging modeling as the deposits are initiated at the colder regions.

Figure 3-28(b) presents the stainless steel temperatures on the same cut plane. Note the ~5 °C variation across, from the outer walls of the stainless steel channel to the boundaries with sodium semi-circular channels.



(a)



(b)

Figure 3-28: Temperature contour plots for sodium and stainless steel walls on a vertical cut plane perpendicular to the flow direction

Note that in the previous chapter explaining the calibration models, a 4% higher flow rate was assigned to the center semi-circular channel based on the preliminary loop model results (expected as the center channel aligns with the main flow path in the loop). The preliminary loop CFD model, presented in Appendix A, Section A.2 used for the Pr_t sensitivity study, was built before the SPPL was operated, and thus included boundary conditions that were expected to be applied during operation, but ended up being different. Within the updated loop CFD model presented herein, with the applicable boundary conditions, an 8% higher flow rate was observed through the center channel compared to the peripheral channels. Even though the flow distribution between the channels were now different, T/C #12, #15 and #17 readings from the updated CFD loop matched within 0.03% of the temperatures obtained in the previous chapter for the calibration model, showing the model's little sensitivity to the flow distribution as long as total flow through the test sections was the same.

3.4 Plugging modeling

This section summarizes the development of a sodium oxide (Na_2O) deposition CFD model. The end goal is to use the modeling criteria developed for the no-plugging CFD validations and the loop CFD simulations presented in the previous sections, coupled with the deposition modeling approach presented herein, to build the overall CFD prediction tool for Na_2O deposition in small-diameter channel heat exchangers.

When liquid sodium contains dissolved oxygen and it is cooled below the saturation temperature for oxygen solubility [4], Na_2O tends to nucleate and grow on the surfaces that are cooled, leading to formation of solid deposits. Modeling Na_2O deposition is a challenging task due to the many unknowns about the deposit morphology¹². Due to the reaction of sodium with oxygen in air, sodium loops cannot be exposed to air to examine deposits without altering their shape, structure and other details. There is extremely limited information in literature, and current efforts are ongoing by entities such as ANL to provide further insight. Thus, the approach presented herein is focused on the engineering application - on the overall plugging rate of the channel and the reduction of flow, which causes reductions in efficiency of heat exchangers. The purpose of this effort is not to model the phenomena at the dendritic structural level [13] where the full deposit details such as detailed porous characteristics are modeled, but to be able to use a commercial CFD software, without iterations with an external software or input, to model the deposit effects and provide predictions and estimates on the time to plugging for a heat exchanger, for industry applications. To be able to accommodate findings in the future regarding Na_2O deposition and growth details, the CFD modeling approach needs to be flexible to be able to adapt to new experimental findings, and have a well-defined structure for changes that may be necessary.

An important note here is that, as explained in prior sections, issues with the SPPL facility prevented ANL personnel to run plugging tests by the end of the project, and therefore to generate plugging data for CFD validation purposes. Hence, the approach presented herein has not been validated against experimental data. Necessary information regarding the modeling, including the challenges and suggested future improvements, are presented in detail for possible continuation of the validation project in the future once experimental plugging data become available.

¹² Note that numerous reference documents reviewed regarding liquid metal thermal-hydraulics, solidification, numerical modeling and implementation, etc. are not detailed herein, but a Bibliography is provided in Appendix A, Section A.9.

3.4.1 CFD modeling approach

3.4.1.1 *Brief overview of sodium oxide deposition analytical models*

Based on recent reported work in literature, two models were considered for the deposition modeling of Na_2O for this particular project: the first principles model by Sienicki ([3], [4]) and a mass-transfer kinetics model by Khatcheressian et al. [14]. The first principles model calculates a 1D linear growth of a two-phase deposit consisting of liquid sodium and solid sodium oxide volume fractions within a heat exchanger channel of a given shape. The growth of this deposit is a function of an overall mass transfer coefficient defined by local dimensionless heat or mass transfer numbers, the oxygen concentration gradient between the surface of the deposit (or the heat exchanger wall), the equilibrium oxygen concentration in the system, and the effective oxygen density in the deposit [3]. Localized Nusselt numbers can be used to describe the oxygen mass transfer process for either turbulent or laminar forced flow convection using the mass and heat transfer analogy [3]. After review it was concluded that this model provides a flexible mathematical approach for calculating deposit growth and is also advantageous since it had been compared against a plugging experiment at the SPPL under laminar flow, predicting the time of growth of a deposit within $\sim 25\%$ of a measured value [4].

The mass-transfer kinetics model presented in Reference [14] predicts instead the growth of sodium oxide and sodium hydride (NaH) deposits in larger scale cold traps that contain packing. In addition to mass-transfer considerations, this model also incorporates rate constants associated with both crystal nucleation and growth. The model provides the potential for a more fundamental description of the crystallization process; however kinetic parameters were not well defined for the heat exchanger channel conditions relevant to this project and values needed for the calculation of the kinetic parameters were also reported as proprietary [15]. For these reasons, modeling efforts presented herein are focusing on the use of the first principles model [3] with the CFD analysis, in addition to some aspects of the mass-transfer kinetics model.

3.4.1.2 *Modeling deposition in CFD*

In order to simulate the deposit formation using CFD, many different simulation approaches have been considered, including mesh deformation options. But in the end, particularly since full plugging of the channel may need to be modeled and that the modeling approach also needed to be able to handle dissolving of the deposit if channel was heated (unplugging process), the multi-component fluid structure of CFX was considered the optimum approach [7]. Within this structure, two materials co-exist throughout the domain – namely liquid sodium and Na_2O for the case herein, and depending on the temperature and oxygen concentration observed within the computational cell relative to the oxygen solubility in sodium at the said temperature, a combination of these materials are present (assuming local thermodynamic equilibrium within the cell control volume). This approach also aligns well with the observed solidification pattern of liquid metals as having solid, liquid and what's called a “mushy” region. Control volumes with a combination of sodium and Na_2O are considered, in simple terms, to simulate the mushy region (simple representation is in Figure 3-29).

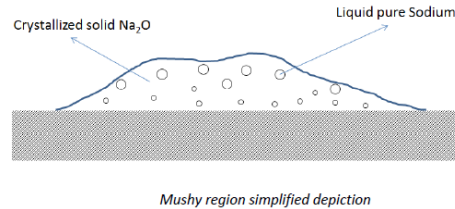


Figure 3-29: "Mushy" region simplified depiction

Within the multi-component approach to modeling solidification, in order to account for the loss of momentum due to the solidification process, appropriate momentum sinks were placed on each computational cell where deposit occurred, to be explained in detail later. Turbulence and energy sinks (due to the sodium and oxygen reaction to form Na_2O) were not added with the modeling herein, but will be a suggestion for future additions.

An important part of the deposit modeling is the accurate accounting of the deposit properties. But unlike for pure sodium, for Na_2O and for sodium- Na_2O mixtures, data on deposit structure and thermo-physical properties are scarce. In the case of Na_2O thermal conductivity, for example, it was necessary to develop a methodology to estimate this property, as discussed in Appendix B, Section B.3.

The CFD modeling of the deposition process was undertaken in two stages, increasing in complexity using, as parameters determining deposition, first temperature only (Section 3.4.1.2.1) and then both temperature and oxygen concentration (Section 3.4.1.2.2).

3.4.1.2.1 Description of sodium oxide deposition model as a function of temperature only

The first stage of deposition modeling assumed, as a starting simplification, that the oxide deposition is directly linked to the local temperature, instead of first determining the deposit mass flux due to temperature-dependent oxygen solubility and concentration (which will be discussed in the second stage of the modeling process). A simple relationship was assumed between liquid sodium volume fraction and temperature, based on a 150°C cooled wall set up in the original SPPL [2] in which liquid sodium volume fraction was set to 0 (indicating deposit only), and a linear rise to a value of 1 (indicating sodium only) at 160°C as an assumption. This means that between temperatures of 150°C and 160°C there is a mixture of sodium and Na_2O (can be representative of the 'mushy' region), and at any temperature at or above 160°C only liquid sodium exists. In order to account for the loss of momentum due to the solidification process, momentum sinks were placed on each cell with a mass fraction of sodium less than 0.8, an assumed value for the first stage analysis.

In order to test the modeling approach, a simplified 2D geometry representative of one of the 6mm diameter semi-circular test channels was built. A 6mm wide 2D domain (two computational cells thick), with an entrance section, a cooled section, and an exit section was built, as shown in Figure 3-30. The entrance section length was 240 mm ($L/D = 40$), and exit section length was 60 mm ($L/D = 10$), both lengths representative of the dimensions in the SPPL. Two lengths for the cooled section, i.e. 6 and 12mm, were used, as part of a sensitivity study discussed below.

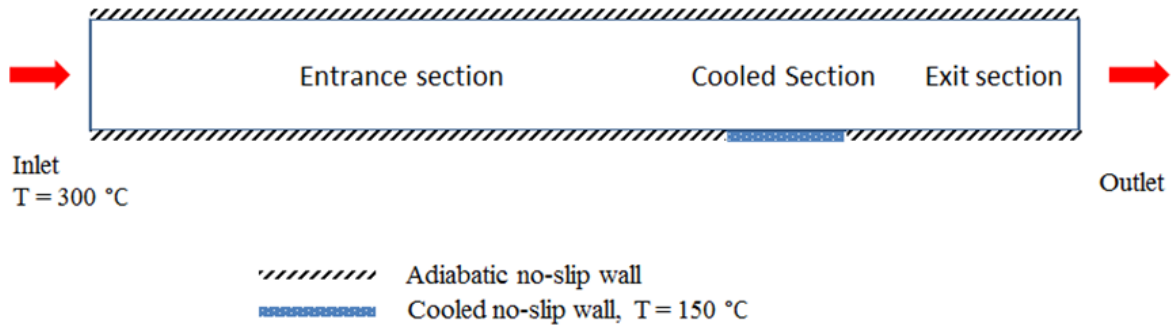


Figure 3-30: 2D CFD domain used to test modeling of deposition as a function of temperature only (not to scale)

This computational domain (fluid only) was meshed using TrueGrid) with hexahedral cells. The total number of cells for the 6mm cooled section model was 282,720, and it was 297,600 for the 12mm cooled section model. A cut plane showing mesh density near the lower wall is presented in Figure 3-31.

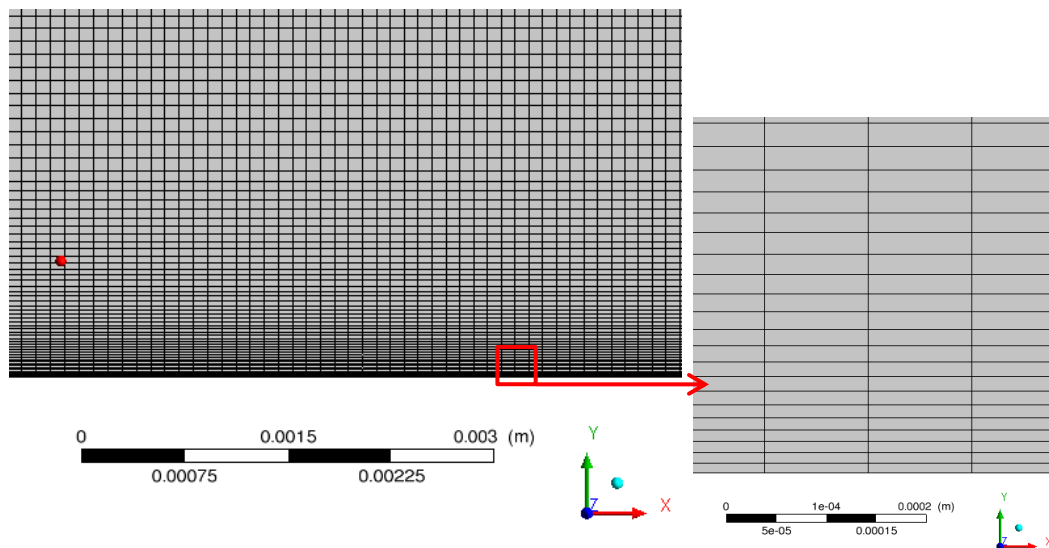


Figure 3-31: Cut plane showing mesh density on the lower wall (first layer thickness = 0.01mm)

A sensitivity study was conducted on some of the major parameters expected to affect deposit formation. These parameters are briefly discussed below and summarized in Table 3.4 which shows the complete test matrix considered in the work presented herein.

- Reynolds number: Re values inside the channels from approximately 100 to 1500, considered bounding values for the sensitivity herein, were tested.
- Deposit thermal conductivity: As mentioned in the previous section, no direct data for pure sodium oxide thermal conductivity is available in the literature, nor the composition/structure of the deposit is known. It is anticipated that the thermal conductivity of the deposit will have an important impact on deposit formation, and thus a sensitivity

analysis with two sets of deposit thermal conductivity values with respect to temperature were tested:

1. Deposit thermal conductivity is assumed to be equal to that of “pure” sodium oxide derived in Appendix B, Section B.3, i.e. without liquid sodium present within the deposit (k_{Na2O})
2. Considering the deposit solid fraction value of 0.18 from Sienicki [3], an ‘effective’ deposit thermal conductivity was calculated as a function of temperature ($k_{Effective}$)

$$\text{‘Effective’ deposit thermal conductivity } \left(\frac{W}{m \cdot K}\right) = k_{Na2O}(T) * (0.18) + k_{Sodium}(T) * 0.82$$

- Cooled section length: Two cooled section lengths of 6mm ($L/D = 1$) and 12mm ($L/D = 2$) were used.

Table 3.4: Test matrix used for sensitivity of first stage deposition model

Case	Re	Deposit thermal conductivity	Cooled section length (mm)
1	100	k_{Na2O}	6
2	1500	k_{Na2O}	6
3	100	$k_{effective}$	6
4	1500	$k_{effective}$	6
5	100	k_{Na2O}	12
6	1500	k_{Na2O}	12
7	100	$k_{effective}$	12
8	1500	$k_{effective}$	12

Uniform velocity profiles were prescribed for the inlet at values of 0.006468 m/s and 0.097027 m/s at 300°C, corresponding to Re values of 100 and 1500, respectively. The following modeling choices were made:

- SST $k-\omega$ turbulence model with automatic wall function was prescribed for both Re values, with a Pr_t of 4.12 (see Appendix A, Section A.2);
- Inlet turbulence intensity = 1%
- An “opening” boundary condition (available in CFX) was applied at the exit of the domain (which allows recirculation at the exit), with 0 psi gage pressure and 300 °C temperature¹³.
- Symmetry boundary conditions were applied at the two computational cells thick domain outer vertical sides.
- All walls were prescribed no-slip boundary conditions and all walls except the cooled wall were chosen to be adiabatic.

¹³ The authors determined this to be a critical decision over choosing an outlet boundary condition (which blocks the recirculation inflows during the calculation and only allows outflow) with respect to providing run stability. The choice for opening boundary condition provides all outlet velocities (no recirculation) at the end of the calculation when the run converges as there is no back flow 60 mm ($L/D = 10$) downstream of the cooled section for any of the cases presented herein, but it is important during the solution process.

For the first stage of modeling, all cases were run as steady-state with double precision to determine the final deposit profile. In addition to equation residuals, the domain imbalances were monitored for convergence as well as monitoring points for sodium mass fraction, temperature, and velocities placed throughout the domain. The time steps (pseudo time steps in CFX steady-state simulations, acting as under-relaxation factors) required for stable runs were determined to be very small (as low as in the order of 1.e-5 seconds) resulting in long run times until the final steady-state deposit shape was reached. Each case was run until total pseudo time had reached at least two full residence times.

Results of this sensitivity study are presented in Section 3.4.2.1.

3.4.1.2.2 Description of sodium oxide deposition model as a function of temperature and oxygen concentration

The conclusions from the first stage of modeling provided valuable insight into the selected modeling approach and the critical parameters. Thus, with this information, the assumption made in the first stage (the oxide deposit formation was directly linked to the local temperature), was updated to include the effects of the oxygen concentration within the control volume as well, and determining sodium and Na₂O fractions based on the relative oxygen solubility at the control volume temperature. In addition, unlike the first stage model which was run as steady-state, the second stage model was run as transient to observe temporal changes in the deposit.

There are many resources in literature regarding oxygen solubility in sodium, and some of the most widely used data sets are plotted in Figure 3-32 [16]¹⁴. The blue shaded box is the region of interest for the simulations presented in this section (from 150°C cooled wall temperature to the inlet and heated walls at 300°C). Per suggestions from the ANL team, the data set from Smith [17] was used for the oxygen solubility limit in sodium with a piecewise linear curve fit to the data points and implemented in the CFD model.

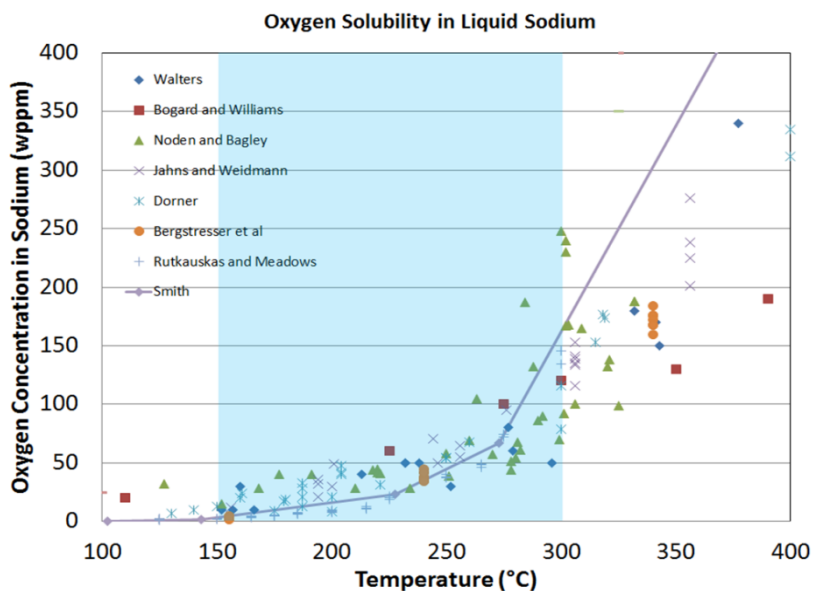


Figure 3-32: Oxygen solubility in liquid sodium according to various sources

¹⁴ Eichelberger provides an excellent resource collecting all historical oxygen solubility in liquid sodium data.

With this modeling approach, if the oxygen concentration within a control volume is higher than the solubility of oxygen in sodium at the computational cell temperature, the ‘extra’ oxygen is deposited; along with the sodium it bonds to form sodium oxide, within the control volume. This is the first major parameter (‘knob’) for the CFD model presented herein to be adjusted when the SPPL data becomes available, and it relates to the speed of deposition. This deposition was simulated in the model instantaneously, meaning all of the oxygen mass that was above the saturation limit at that temperature bonded with sodium to form sodium oxide and deposited completely, within that time step of the simulation. In reality, the process is expected to happen slower, and a correction factor to the amount of sodium oxide to be deposited as a function of time will need to be implemented when the experimental plugging data become available. [KNOBS #1 AND 2].

Note that all of the deposition mechanics discussed herein was implemented in CFX through the CFX Expression Language (CEL) through user defined expressions.

Within the CFD model, the oxygen concentration was defined as an additional variable in the simulation with a transport equation solved for it through the domain. The inlet oxygen concentration, as well as the inlet sodium flow rate, are modeled as constant in time. This was a simplifying assumption made to prove the concept, since during SPPL operation neither the inlet flow rate nor the oxygen concentration will actually be constant¹⁵. A kinematic diffusivity of 5e-5 m²/s was assumed for the results presented herein¹⁶. A sink was added to this transport equation to account for the solidified oxygen bonded with sodium, removed from the main flow. The proportionality constant for this sink is tied to the first ‘knob’ explained previously regarding the speed of sodium oxide deposition.

Once the sodium oxide mass within the control volume was determined, the fractions of sodium and sodium oxide within the cell can be calculated. Within the multi-component framework of CFX, the properties of the control volume are calculated based on their fractions within the cell.

Similar to modeling in the first stage, a momentum sink was added (equally in all three dimensions) to account for the solid sodium oxide formation within the cell. This time, the momentum sink uses the Carman-Kozeny formulation of flow through a packed bed [18], based on the control volume sodium fraction:

$$\text{Momentum sink} \sim \frac{1-(\text{Sodium Fraction})^2}{(\text{Sodium Fraction})^3}$$

The momentum sink can allow a low speed flow through the deposit, and can be considered simulating the possible mushy/porous structure of the deposit in a general way. This low speed flow through the deposit is especially important when the channel blockage, and thus the pressure drop across the deposit, is high. The momentum sink proportionality constant is another parameter to be calibrated when the SPPL data becomes available, and could be targeted by the diagnostic

¹⁵ In the SPPL, during deposition, the inlet sodium flow rate will decrease as the channel is plugged and the flow is diverted to other channels. At the same time, the inlet oxygen concentration will decrease since the total oxygen mass within the SPPL is constant and deposition will remove a portion of this from the main flow. Once extended to the whole SPPL, the CFD model can easily account for these variations by means of momentum balances for the fluid and mass conservation.

¹⁶ A sensitivity study with higher kinematic diffusivity was performed, and showed no effect on the results.

techniques discussed in Chapter 5 and 6. Information on the porosity and permeability of sodium oxide deposits for sodium is scarce and, as mentioned, plays a major role in the momentum sink proportionality constant particularly as the channel blockage is significant and deposit back pressure becomes high enough¹⁷.

Once the physics modeling was set up in CFX, the next step was to define the time integration process representing the accumulation of the deposit with the code and this is where the biggest challenge was faced using a commercial code in simulating the process. CFX currently does not have the capability to carry prior time step variable information to the current time step and thus the integration of the deposit volume over time was not available. Several paths were considered:

- Option 1: use junction box with Fortran routine, but this path was decided not to be followed due to the known challenges with Fortran routine implementations in parallel runs with CFX on multiple processors.
- Option 2: solve for an additional variable in CFX, representing the computational cell volumes, and solve for the diffusion equation for this additional variable through the domain with a very small diffusivity value. One would initialize the distribution of this additional variable in the domain with the original cell volumes, and then add a sink to account for the volume occupied by the deposit at each step of the solution based on the calculated sodium oxide mass fraction. This approach had some numerical issues including cyclic dependency, and needed more tweaking to operate but was abandoned once the option explained in the next step was deemed feasible.
- Option 3: this is the option that was most heavily pursued, and consisted of an unsupported CFX 'trick'/feature. Within this approach, an additional variable representing the accumulated deposit volume is created. We then solve an algebraic equation with this additional variable tied to an expression for accumulated deposit volume. The 'trick' here is to manually edit the additional variable properties by adding the below line (editing the additional variable in the command editor):

Update Loop = TRANS_LOOP

This command 'freezes' the update of the additional variable through the inner coefficient loops and basically delays it by one time step, and thus can be used within the CEL defined calculations as the 'old' value, allowing for integration of the deposit mass/volume.

Note that the additional variable needs to be initialized in a separate run, where the algebraic equation is specified as zero.

This approach works well for simple integrations, but due to the cyclic nature and cell-by-cell approach of the deposition modeling presented herein, and the fact that it's an unsupported feature, challenges were faced that were not resolved at the end of the project period. Thus, this approach was not implemented within the examples presented herein. But it was considered as the closest to success and is the suggested route for possible continuation of the efforts.

¹⁷ For stability purposes for the pressure-velocity coupling, a momentum source coefficient twice the value of the momentum sink was added. In addition, the momentum sink was included in the Rhie-Chow redistribution algorithm, and the momentum source coefficient was included in the Rhie-Chow coefficient.

Some further details regarding the implementation of the deposition modeling approaches in CFX are:

- The modeling approach presented herein takes a cell-by-cell approach and thus requires the need for the individual volume values for the deposition calculations. These values were extracted from CFX-Post as Volume of Finite Volumes, and read back into CFX-Pre as a comma separated variable (csv) file.
- Better stability was observed when the simulation was directly initiated as transient, and not started from a steady-state no-deposition solution due to the solidification routine implemented. The expert parameter in CFX under the I/O control tab was modified to activate transient initialization override.

The second stage CFD deposition modeling approach was tested using a similar 2D domain as the first stage described in the previous section, but the domain length has been shortened to a total of 126 mm ($L/D = 21$) with 60 mm ($L/D = 10$) for the entry region, 6 mm ($L/D = 1$) for the cooled section, and 60 mm ($L/D = 10$) for the exit region (Figure 3-33).

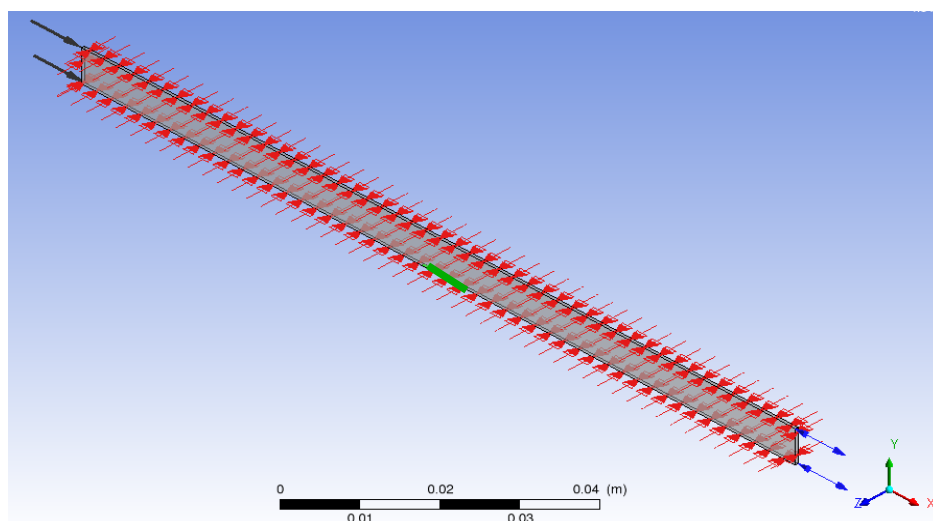


Figure 3-33: Simulation domain (green surface shows the cooled section, red arrows outline the symmetry planes)

The computational mesh for the fluid domain was generated using XYZ Scientific TrueGrid with all hexahedral cells for a total of 336,000 cells (mesh statistics provided in Appendix A, Section A.7.3). The inlet velocity was set at a constant value of 0.5 m/s at 300°C, with 1% turbulence intensity specified. Inlet oxygen concentration was set at a constant value of 40 ppm. Different from the model in the first stage, the top wall was set to 300 °C to avoid full plugging during the runs. All other boundary settings were the same as the first stage test model.

The simulation was run using double precision, with a time step of 1.e-3 seconds, with maximum number of coefficient loops of 10. The advection scheme was upwind (found to be better for stability compared to high resolution), turbulence scheme was first order backward Euler (not 2nd order, for better stability) and turbulence numeric was first order (the schemes are suggested to be switched to higher order in the future). Residual type was set to RMS with a target of 1.e-4, and a conservation target was set to 1.e-4.

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Note that as mentioned previously, the time integration of the deposit volume was not implemented within the example presented herein. This means that when the deposit volume was being calculated at each time step, instead of a reduced available control volume for the calculation of the deposit's mass fraction in such a volume, the full volume was made available for the calculations using the parts per million weight concentration. Thus the deposit mass fraction was larger than it should be (example as 10 ppm depositing in 1 m³ vs 10 m³ sodium). As it will be explained in the results section, this causes any control volume experiencing deposition to be filled completely with sodium oxide.

A large number of monitoring points were placed within the domain to check for the solution progress during the run.

3.4.2 Results of testing of CFD deposition models

The modeling approaches discussed in Section 3.4.1.2.1 (first stage modeling, with temperature as the only parameter affecting deposition) and in Section 3.4.1.2.2 (second stage modeling, with both temperature and oxygen concentration affecting deposition), have been tested using the domains and boundary conditions previously described, and results are presented next.

It is important to note that due to the non-standard modeling approaches implemented with the plugging simulations, run stability issues were faced with default CFX solver settings. Thus, various steps were taken before and during the solution process to stabilize the runs, which are not documented herein. An example issue was the Newton method convergence failure within the 100 iterations message for temperature to the specified 0.1 K tolerance, used default in CFX. This message related to C_p and needed adjustment of expert solver parameters.

3.4.2.1 Results of testing sodium oxide deposition model as a function of temperature only

Results are shown below starting with the effect of the test matrix parameters (see Table 3.4) on the sodium mass fraction for the eight cases, followed by a more detailed discussion on Case 5.

Figure 3-34 shows the sodium mass fraction contour plots on the center cut plane for Cases 1 through 4 (6 mm cooled section). It can be observed that:

- The Reynolds number has a strong effect on the deposit shape. This is an expected phenomenon since as the flow velocity over the cooled section (and any deposit) increases, the convective heat transfer is also enhanced, thus the opportunity of the deposit to grow is reduced by the sodium flow effectively heating the area around the cooled section.
- The thermal conductivity of the deposit also has an effect on the deposition, especially at low Re. The 'effective' deposit thermal conductivity, $k_{\text{Effective}}$, is approximately 12 times higher than the thermal conductivity for 'pure' sodium oxide, $k_{\text{Na}_2\text{O}}$, (derived as explained in Section 3.4.1.2.1) in the temperature range between 150°C and 300°C. With the increase in the thermal conductivity of the deposit, conduction through the deposit is enhanced, thus reducing the temperature of the flow around the cooled section more effectively, and thus growing the deposit deeper into the channel through solidification.

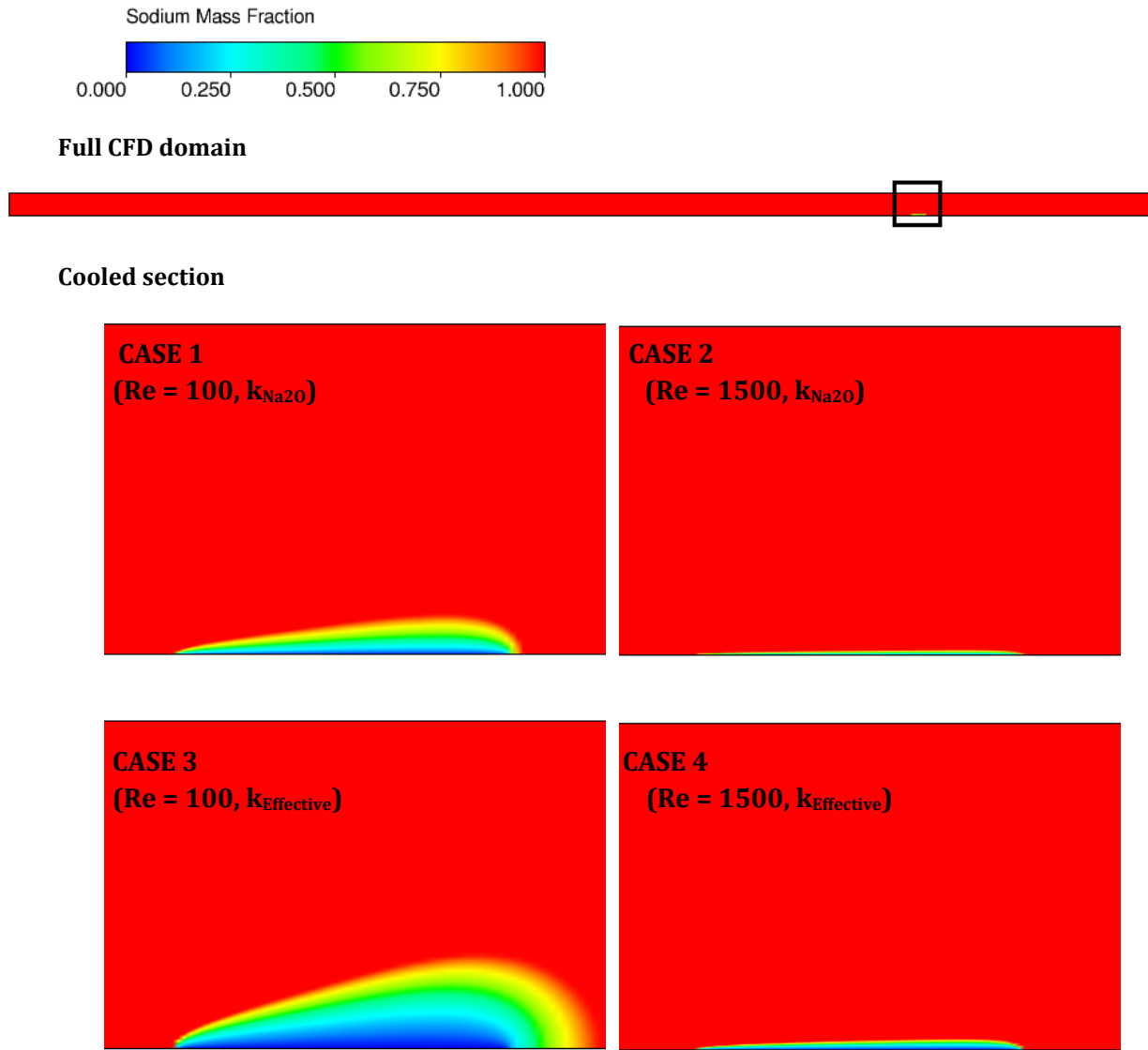


Figure 3-34: Sodium mass fraction contour plots for Cases 1 through 4 (cooled section length = 6 mm). Full domain (top) and zoomed in on the cooled section (bottom). Cooled section is marked with a black box in the full CFD domain

Figure 3-35 shows the sodium mass fraction contour plots on the center cut plane for Cases 5 through 8 (12 mm cooled section). The same observations can be made as for Cases 1 through 4 regarding the effect of Re and deposit thermal conductivity. In addition, comparing Cases 1 through 4 to Cases 5 through 8, one can observe that doubling the length of the cooled section has significantly expanded the deposit shape for the cases with lower Re numbers, as expected. In particular, for Case 7, noting that momentum sinks are implemented on any cell with sodium mass fraction of less than 0.8 as an assumption to test the modeling approach at the first stage, one can observe that the channel is completely blocked by the deposit formation and that there is no more flow through the channel. The heat transfer through the rest of the downstream channel is through pure conduction.

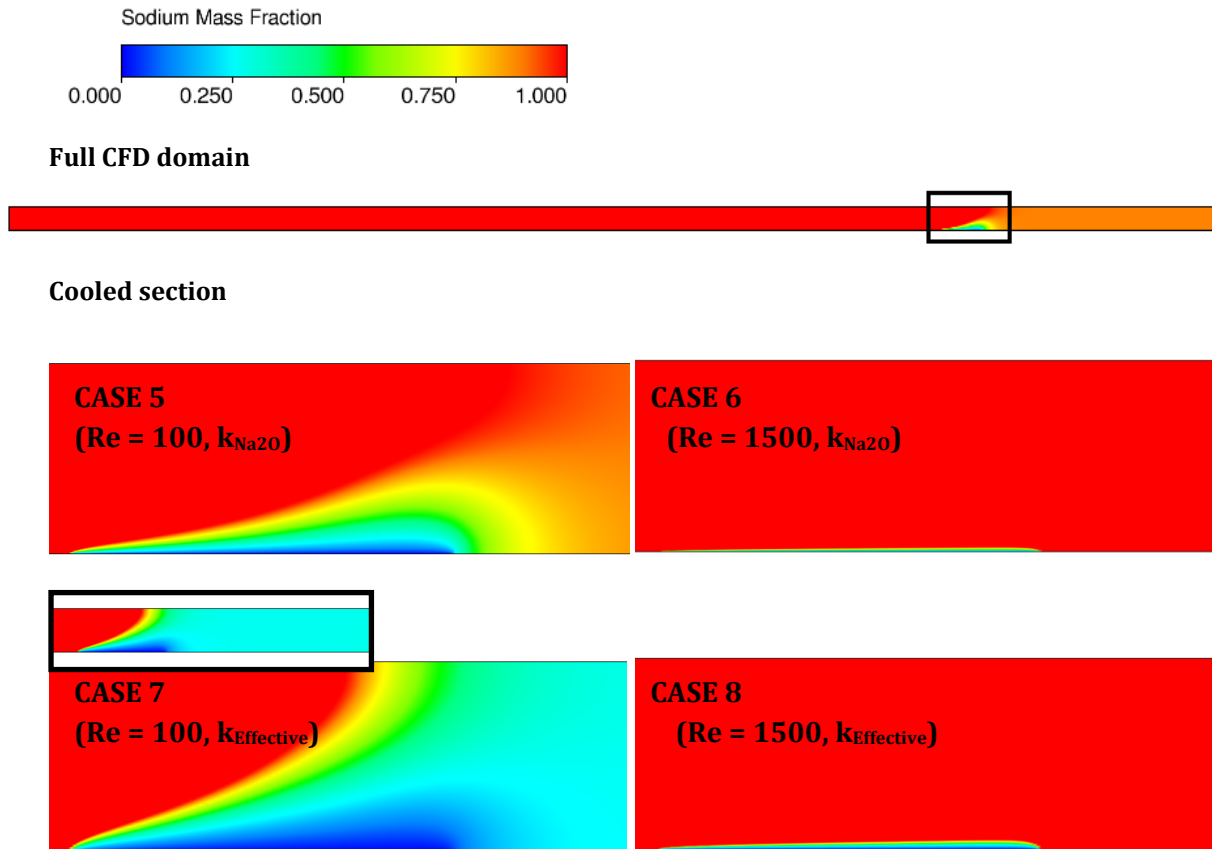


Figure 3-35: Sodium mass fraction contour plots for Cases 5 through 8 (cooled section length = 12 mm. Full domain (top) and zoomed in on the cooled section (bottom). Cooled section is marked with a black box on the full CFD domain (inset for Case 7 with blocked channel shows the sodium mass fraction values further downstream).

Figure 3-36 shows the temperature contour plot for Case 7 around the cooled section vicinity (similar to Figure 3-35, Case 7 inset). Note that a mixture of sodium and deposit is observed between 150 °C and 160 °C, and at any temperature higher than 160 °C, only sodium is observed.

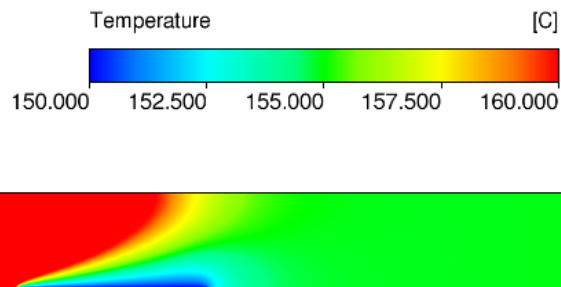


Figure 3-36: Temperature contour plot on vertical cut plane for Case 7 near the cooled section vicinity. Additional details are now presented for Case 5 as a representative scenario of deposition.

Figure 3-37 presents the temperature contour plot along the domain for Case 5. Due to the low flow rates and high thermal conductivity of sodium, sodium slightly upstream of the cooled surface is also cooled down through conduction.

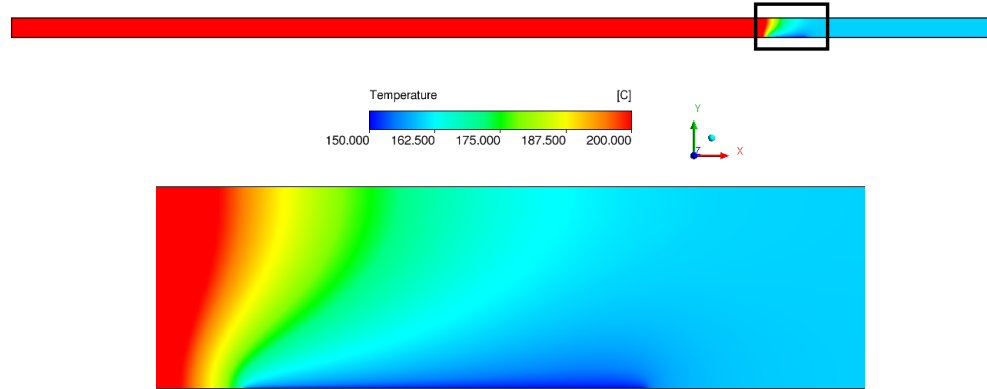


Figure 3-37: Temperature contour plot for Case 5, zoomed in on the cooled section

Figure 3-38 presents the velocity contour plots and streamlines for Case 5 and the change in the flow structure due to the deposit presence. As mentioned previously, although low Re numbers are reported in the channel, one can observe the recirculation region behind the deposit as depicted by the streamline plot in Figure 3-38 (b) (and thus the importance of using a turbulence model such as SST $k-\omega$ to be handle such transitions, as explained in Appendix A, Section A.3).

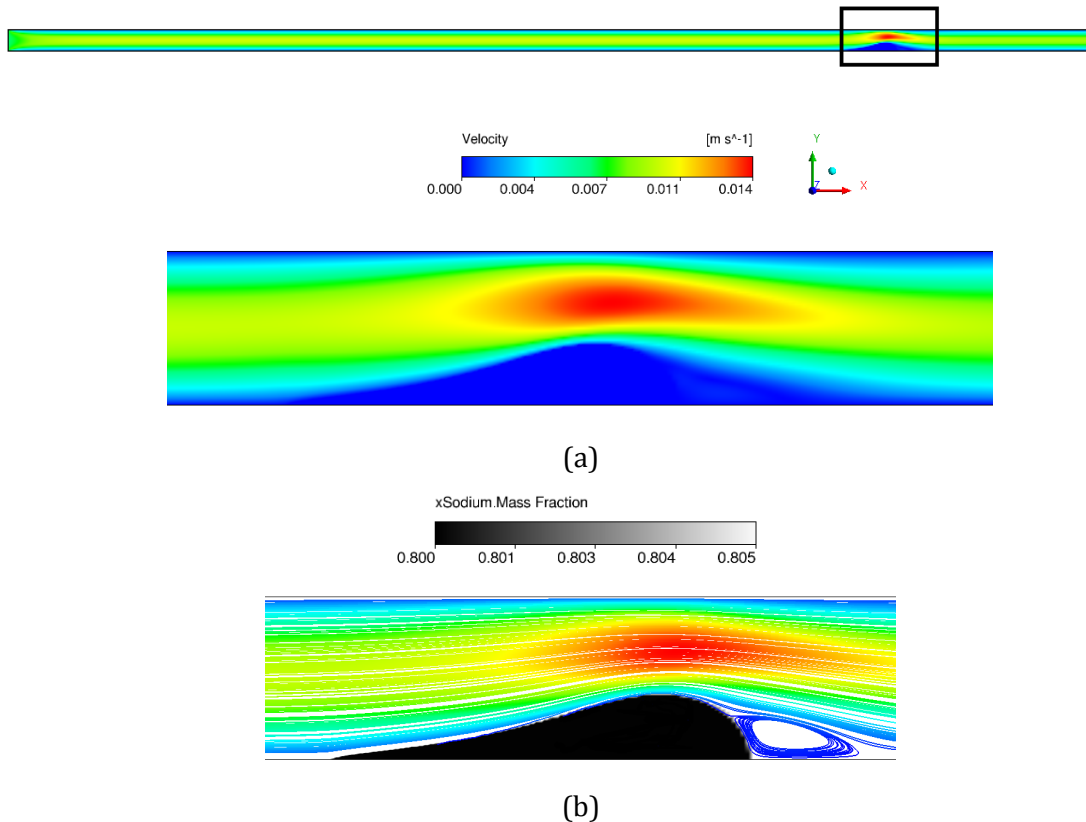


Figure 3-38: Velocity contour plots and streamlines for Case 5. Velocity magnitude contour plot around the cooled section (a), combined sodium mass fraction contour plot and streamline velocity plot around the deposit (b) showing the recirculation region behind the deposit (same velocity scale as in (a))

3.4.2.2 Results for sodium oxide deposition as a function of temperature and oxygen concentration

Results presented herein are generated at the end of transient simulation unless mentioned otherwise. Figure 3-39 presents the temperature contour plot on a vertical cut plane at the center of the domain. Note the checkerboard-type pattern visible in the inset of the figure. This numerical phenomenon is deemed to be present due to the sharp interface at the deposit / no deposit decision based on the oxygen concentration within the computational cell being above or below a discrete line (see Figure 3-32), which is coded into the model. As mentioned earlier, and until benchmarked against experimental data, the deposition is modeled to occur instantaneously. It is anticipated that the slowdown of the deposition will improve the 'checker boarding,' allowing for a smoother transition between deposit / no deposit decisions.

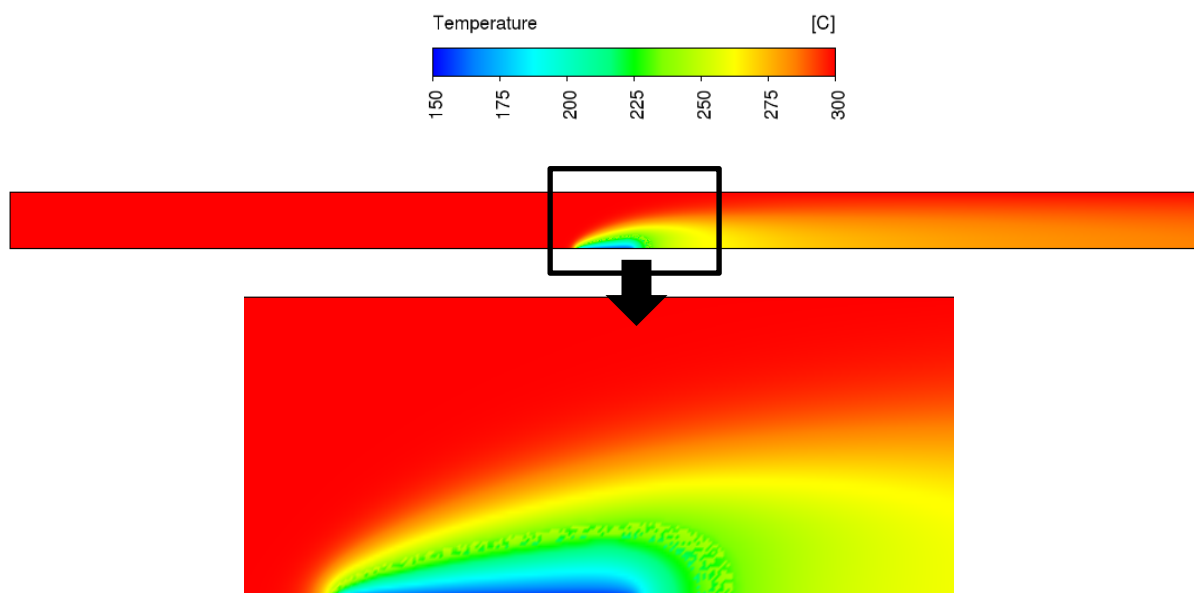


Figure 3-39: Temperature contour along the center vertical cut plane

Figure 3-40 presents the velocity magnitude contour plot on a vertical cut plane at the center of the domain. One can observe the converging-diverging structure of the flow, due to the formation of the deposit.

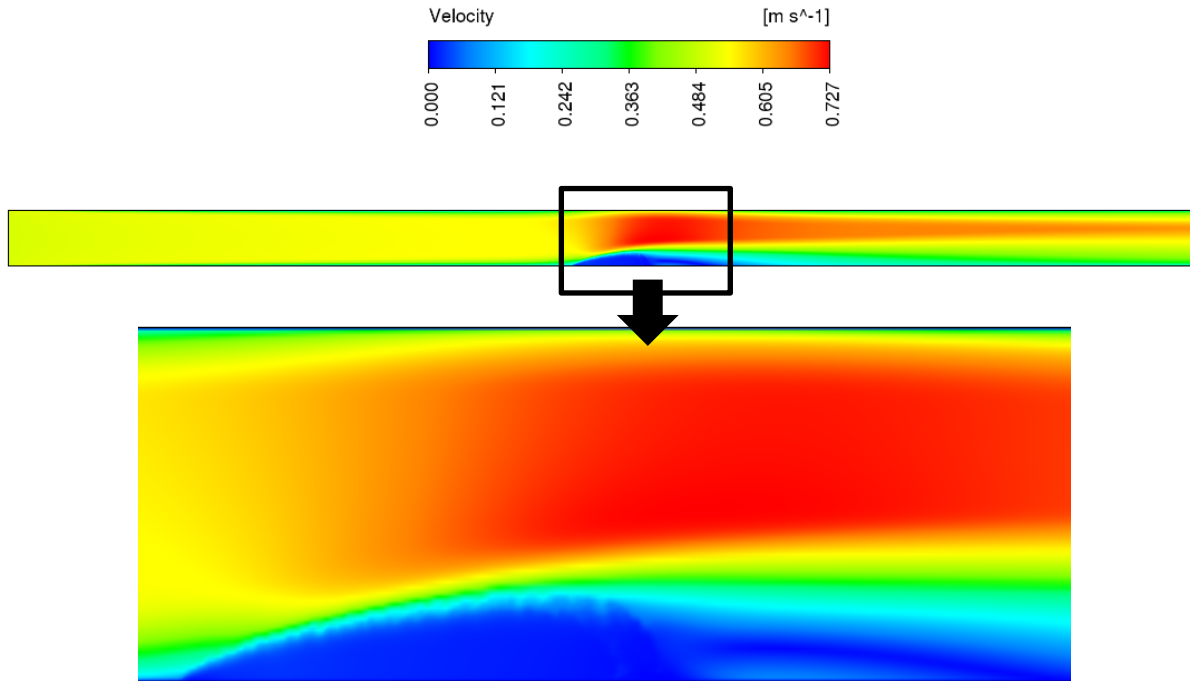


Figure 3-40: Velocity magnitude contour along the center vertical cut plane

Figure 3-41 presents the oxygen concentration (ppm) contour plot on a vertical cut plane at the center of the domain. The inlet concentration is specified as 40 ppm, but due to the deposit removing some of the oxygen, the concentrations downstream of the deposit are reduced as expected (due to the sinks within the computational cells).

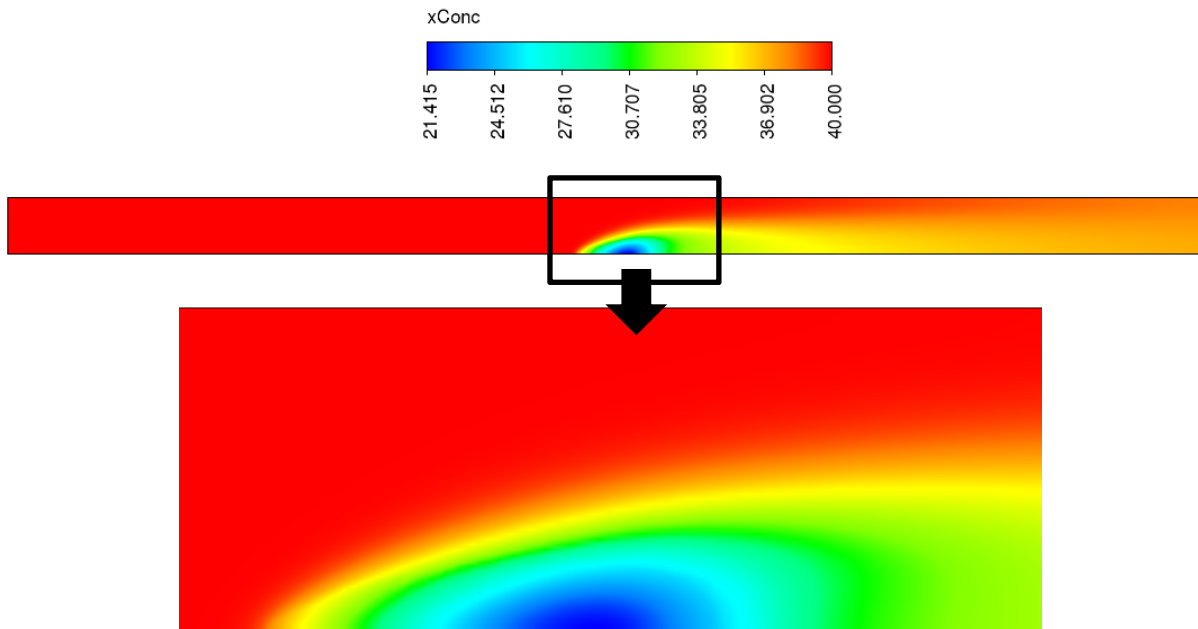


Figure 3-41: Oxygen concentration (ppm) contour along the center vertical cut plane

Figure 3-42 presents the sodium mass fraction contour plot on a vertical cut plane at the center of the domain. Note that, as explained before, the deposit regions show to be entirely filled with sodium oxide (and not with a mixture, especially at the deposit –flow boundaries) mainly due to the lack of integration of the deposit volume, which characterizes the preliminary model developed at this stage. Any cell that experiences deposition starts filling the control volume in an accelerated rate until the volume is completely occupied by sodium oxide. Again note the checker boarding structure as explained before consistent with the temperature profile (as they are tightly coupled). Also, the second insert of Figure 3-42 also provides the mesh density along the channel.

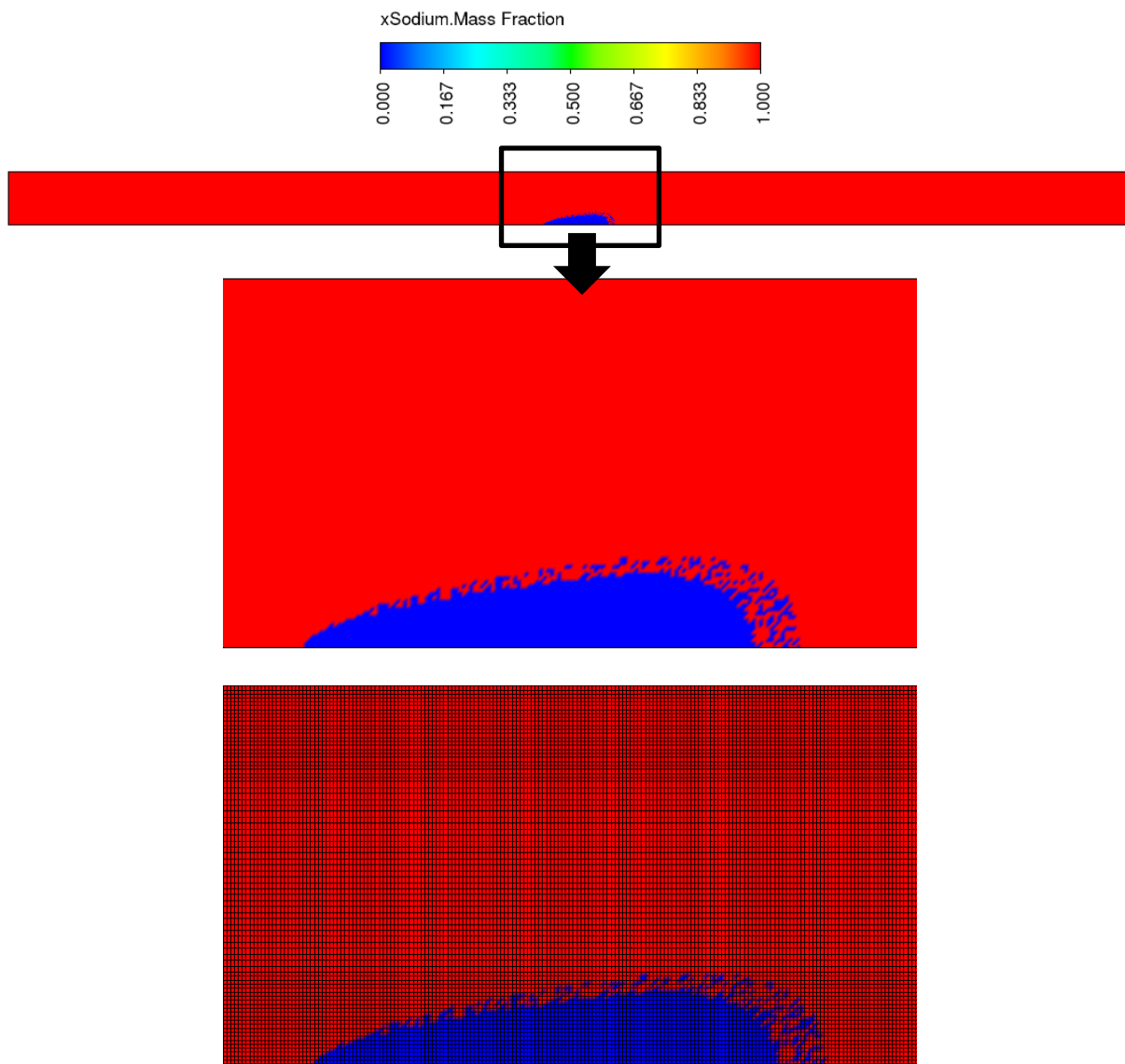


Figure 3-42: Sodium mass fraction contour and mesh density along the center vertical cut plane

Figure 3-43 presents the velocity magnitude streamlines along a vertical cut plane at the center of the domain. Note the very low speed flow through the deposit as well. Even though the deposit is

fully sodium oxide, the momentum sink does not completely stop the flow due to the proportionality coefficient (currently $1.e-10 \text{ m}^{-2}$) to be calibrated once experimental data is available. Also note the strong recirculation region observed in the deposit wake.

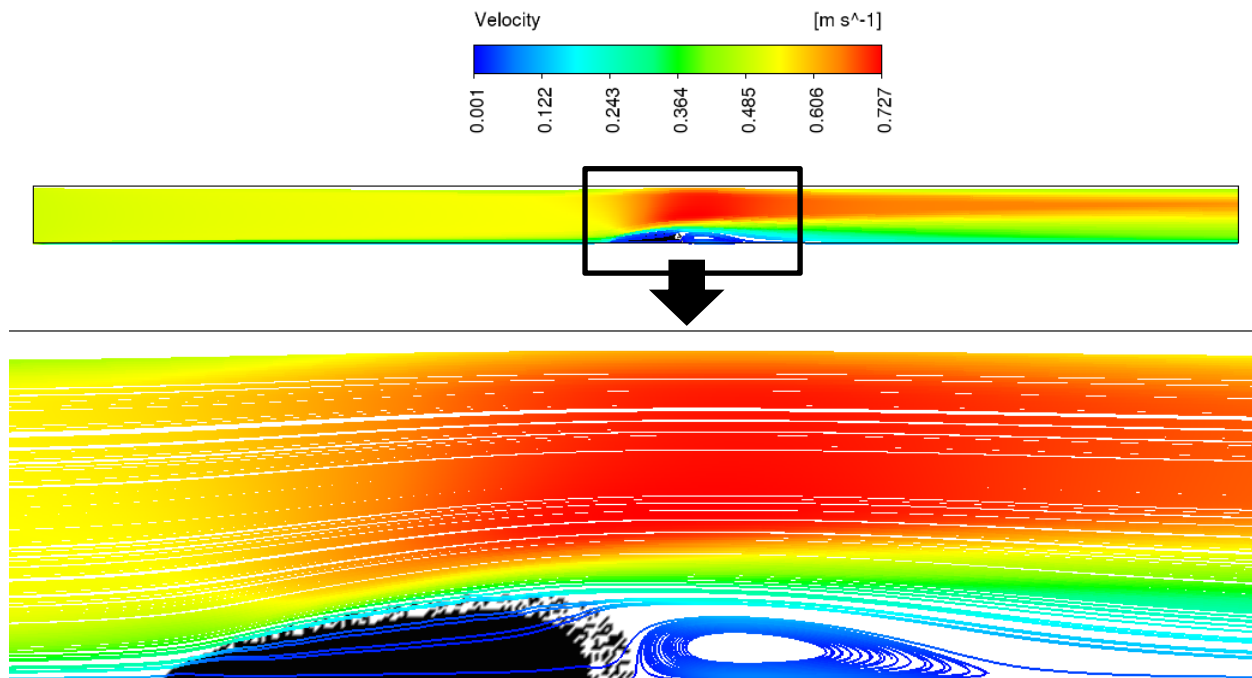


Figure 3-43: Velocity magnitude streamlines along the center vertical cut plane

Figure 3-44 presents the time evolution of the deposit shape through the transient. The results below are from a simulation conducted to test the sensitivity of the deposit evolution to time step size, and was conducted with $1.e-4$ seconds time step (compared to $1.e-3$ seconds used for the simulation presented prior). Same final deposit shapes were obtained comparing Figure 3-42 and Figure 3-44 at 1000 iterations. Note that the expected timeframes for complete plugging provided by ANL, based on previous plugging tests performed with a different SPPL configuration, are in the order of 12 to 18 hours. The below results with the current modeling adjustment factors ('knobs') provide a significantly shorter time frame for deposit formation, but these coefficients in the model can be adjusted for calibration to match experimental time frames.

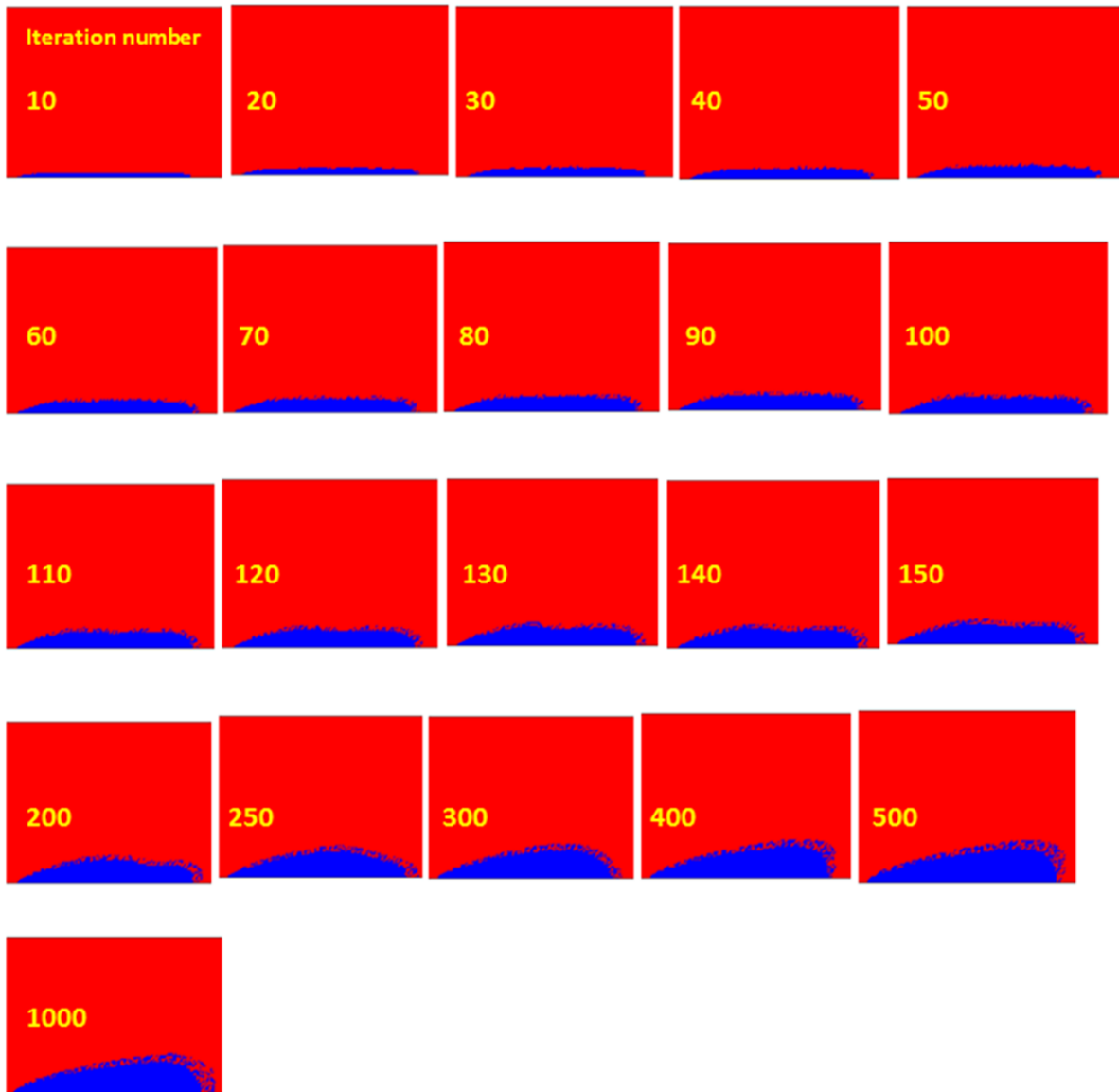


Figure 3-44: Deposition profile throughout a transient simulation (numbers represent iteration #)

A sample application of the deposition methodology to a 3D domain is presented in Appendix A, Section A.5

3.5 CFD files location

Table 3.5 lists representative files used in the CFD analysis discussed in this Chapter. Due to their size (from several hundred MB to GB), they cannot be archived in the Westinghouse Electric Company Electronic Document Management System, and are stored in the directory /data/tatie/RT-TR-16-14/ accessible with Linux operating system computers within Westinghouse.

Table 3.5: List of representative files used in CFD analysis

Directory/Subdirectory	File/Folder Name
/data/tatie/RT-TR-16-14/	
No_Plugging_Model/	NPV_Run3_SSinit_SFR_40perc_HTC_20_HeaterSens.cfx
	NPV_R3_SSinit_SFR40p_HTC20_HeaterSens.def
	NPV_R3_SSinit_SFR40p_HTC20_HeaterSens_001.out
	NPV_R3_SSinit_SFR40p_HTC20_HeaterSens_001.res
	NPV_Run3_TRwInit_SFR_40perc_HTC_20_HeaterSens.cfx
	NPV_R3_TRwInit_SFR40p_HTC20_HeaterSens.def
	NPV_R3_TRwInit_SFR40p_HTC20_HeaterSens_001.out
	NPV_R3_TRwInit_SFR40p_HTC20_HeaterSens_001.res
/2D_Plugging_Model/	2D_tr_v0_001/
	2D_tr_v0.cfx
	2D_tr_v0.def
	2D_tr_v0_001.out
	2D_tr_v0_001.res
	medium_refined_again.csv
/Loop_CFD_Model/	Full_Loop_40percSFR_v0.cfx
	FL_40percSFR_v0.def
	FL_40percSFR_v0_004.out
	FL_40percSFR_v0_004.res

3.6 Conclusions, future work and suggestions on CFD modeling

This chapter presented the work completed towards building a sodium oxide deposition CFD engineering tool for industry applications using a commercial code, capable of providing time to plugging information for designers and/or operators of small channel HXs. The approach was organized in two stages:

- 1) **No Plugging CFD Model Development and Validation:** prior to moving to CFD deposition/plugging modeling, the SPPL was first modeled with no plugging conditions (no oxygen within the system) to gain confidence in liquid metal modeling and understand the level of accuracy with which the SPPL test section thermal-hydraulics can be modeled prior to any deposition phenomena taking place. This was accomplished in two steps:
 - a. Test Section CFD Model Validation: A CFD model of the test section was built and calibrated against a set of four no-plugging tests conducted with the SPPL. Due to the fact that the SPPL was not originally built for CFD model validation purposes (but for a more “qualitative” deposition phenomena identification purpose), large uncertainties characterized sodium flow rate measurements and heat transfer on the test section outer surfaces exposed to air. Thus, during the calibration of the CFD model, the two parameters of focus were the sodium flow rate through the semi-

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circular channels, and the heat transfer coefficient on bare test section surfaces (lumping several uncertainties under one parameter). The CFD simulation results were found to reproduce the experimental measurements in an acceptable way, especially considering the uncertainties mentioned, particularly on sodium flow rate. Various sensitivity studies were conducted as well to account for other uncertainties within SPPL, to understand their impacts.

- b. Loop CFD Modeling: Since the test section CFD model did not include/resolve the inlet boundary condition effects due to upstream features of SPPL, a loop CFD model was built. The main purpose of the loop CFD model is to be combined with the sodium oxide deposition CFD methodology to build the overall plugging CFD tool.

2) Plugging CFD Model Development: Once the no-plugging CFD modeling methodology was developed, and a loop CFD model was ready for the plugging CFD methodology implementation, the next step was the development of the sodium oxide modeling approach. An important challenge in modeling sodium oxide deposition is that there is very little applicable data in literature regarding the deposit. The plugging methodology was undertaken in two steps.

- a. Sodium oxide deposition as a function of temperature only: First step was to develop the multi-component approach to model the deposition in CFX and simplify the deposition initiation and growth mechanism. A 2D model was built and several different studies were conducted to test the methodology and the effect of important parameters (e.g. Re number, deposit's thermal conductivity, cooled section length to initiate deposit formation).
- b. Sodium oxide deposition as a function of temperature and oxygen concentration: Once the multi-component methodology was established, and the impacts of various parameters determined, the effect of oxygen concentration on the deposition process was added. The methodology was tested on the same 2D domain, as well as on a representative 3D domain with promising results.

Due to the challenges with SPPL mentioned in Section 2.1, plugging data were not collected during the project period. As a result, the plugging CFD methodology could not be validated. However, this methodology was built with enough flexibility to accommodate experimental data once made available, e.g. deposit porosity which will inform the methodology itself, and to perform the ultimate validation.

Below is a list of suggested future work and improvements to the deposition CFD model presented herein:

- The main challenge with the current deposition model is the integration of quantities within ANSYS CFX, specifically the deposit mass within each control volume. Although there are unsupported ways of resolving some integration challenges, due to the recursive nature of the deposition calculation and interdependencies, a more stable and robust approach is needed. This may require eventual use of a beta release of CFX with changes made in solver settings.

- Once the previous integration challenges are solved, the appropriate mass sources and sinks based on the sodium and oxygen inventories, and on the generated sodium oxide mass, need to be adequately updated for the next time step calculation.
- An investigation on the energetics of the sodium oxide formation is recommended. This investigation will inform the potential addition of adequate energy sources or sinks in the energy equation, to take into account the energy needed to form sodium oxide.
- The current deposition model is demonstrated with fluid-only domain and temperature boundary conditions are directly applied to the sodium channel surfaces. Addition of solid steel wall domains and application of conjugate heat transfer (as done for the developed loop CFD model) will help to smooth sharp temperature changes at the sodium channel surfaces that cause stability issues.
- In the current CFD deposition model, the inlet velocity and oxygen concentrations are provided as constant values. In reality, as sodium oxide is deposited on the channel walls:
 - portion of the flow to the channel will be redirected to the cold trap bypass channel due to the backpressure increase due to plugging, and
 - the fixed initial oxygen concentration in the loop will start to decrease as oxygen is removed from the flow with the deposit.

Hence, these boundary condition values need to be continuously adjusted throughout the transient run, at the inlet of the test section.

- Inclusion of turbulence sinks to account for the deposit formation.
- If computational resources are available, the mesh can be further refined in the area of oxide formation, resulting in an increase of the resolution of the applied methodology.
- If mesh refinement becomes prohibitive because of memory and processing time limits, introduction of methods to track the formation of the interface (transitional zone) between the sodium and sodium oxide, as well as mesh readjustments, might be considered.

4. Ultrasonic Time Domain Reflectometry development

This chapter is organized as follows:

- Section 4.1: Summary of development work.
- Section 4.2: Theory. This section discusses the theory behind using ultrasonic waves for detecting material discontinuities and quantifying thicknesses.
- Section 4.3: Testing methodology.
- Section 4.4: Experimental results and insights.
- Section 4.5: Recommendations for future work.

4.1 Summary of development work

The Ultrasonic Time Domain Reflectometry (UTDR) technique has been investigated at ANL to assess its capability to characterize sodium oxide deposits growing inside of small channels, like those in the SPPL. It was concluded that it might be feasible to determine the sufficiently large thicknesses of sodium oxide deposits precipitated upon the near and far sodium channel walls in the SPPL, although the intensities of the signals returning from the deposit-sodium and sodium-deposit interfaces were estimated to be low.

To validate the UTDR technique and to determine the measurement resolution of the thickness, three experimental tasks were planned:

- 1) capability and calibration tests;
- 2) laboratory mockup test;
- 3) in-situ¹⁸ high-temperature test.

Tasks 1) and 2) have been completed. Task 3) was not entirely completed since, as discussed in Section 2.1, the SPPL was not available to run in plugging mode before the end of the project. However, an extensive assessment on the needs related to instrumentation setup in the SPPL was performed, including the design and fabrication of two transducer-waveguide holder fixtures suited for installation on the SPPL test section (once the SPPL becomes available) and their laboratory mockup testing, which was conducted at room temperature.

A high-frequency ultrasonic system, using the pulse-echo (PE) and/or through-transmission (TT) mode, was set up for all the three tasks. Potentially, the sodium oxide thickness could be measured through the time-of-flight (TOF) or attenuation of the transmissions and reflections of ultrasonic acoustic waves. Laboratory tests were conducted using a stainless steel (SS) tube removed from the SPPL following sodium plugging testing. The tests demonstrated that the UTDR technique is capable to estimate the thickness or the total amount of the sodium oxide-bearing deposits. Moreover, to allow future calibration of the UTDR technique, x-ray computer tomography (CT) was investigated, as discussed in Appendix C. This technique is capable of locating sodium oxide and

¹⁸ "In situ" should be intended as either testing of a mockup fixture that is prototypical of that to be ultimately installed on the SPPL test section, or the actual testing on the SPPL test section.

argon gas pocket. However, without a density variation scale (i.e. a calibration equation or curve) of known quantity or thickness of sodium oxide, it is difficult to accurately determine the deposition dimensions or their total amount of sodium oxide in the sodium-filled tube from the CT images between these three tubes.

Two mockups were developed and tested for laboratory feasibility study, and are available for in-situ high-temperature testing of the UTDR technique once the SPPL becomes operational. The laboratory tests demonstrated that it is possible to determine the thickness of sodium oxide thin film with an ultrasonic transducer mounted on a standoff on the outside of the SS test section by observing the time delay between reflections off of the sodium film-gas/vapor core interface versus the SS-sodium film interface. The mockup of the in-situ high-temperature test apparatus was successfully tested under ambient conditions and is ready for an in-situ, continuous high-temperature test which will be performed once the SPPL can be operated in a plugging mode.

4.2 Theory

The UTDR technique was proposed for the measurement of the thickness of sodium oxide film. Although theoretically it is feasible to measure the thicknesses of sodium oxide-bearing deposit and sodium thin film by using UTDR technique, the minimum detectable thickness depends on the tradeoff between operating frequency, ring-down cycles¹⁹, and output power of the transducer. Therefore, selection an adequate transducer is very important.

When an acoustic wave propagates perpendicularly from one medium into another medium, the strengths of the reflected and transmitted waves are determined by the impedances of the two media at the boundary. The intensity reflection (R) and transmission (T) coefficients of the incident sound wave reflected from the interface is given by the following respectively,

$$R = \frac{Z_1 - Z_2}{Z_1 + Z_2}, \quad (1)$$

$$T = 1 - R = \frac{2 Z_2}{Z_1 + Z_2}, \quad (2)$$

where $Z (= \rho c)$: acoustic impedance

ρ : density of medium,

c : sound speed in medium,

1: subscript denoting medium from which wave is incident on interface,

2: subscript denoting medium into which wave is transmitted through interface.

The attenuation of waves in a homogeneous Newtonian liquid is given by the sum of viscous and thermal diffusion terms as

$$\beta = \frac{2\pi^2 f^2}{c^3} \left[\frac{4}{3} \frac{\mu}{\rho} + (\gamma - 1) \alpha \right], \quad (3)$$

where β : inverse attenuation length,

¹⁹ The rise and decay cycles which a transducer takes to get up to 90% of maximum amplitude, or down to 10% above zero amplitude.

f : transducer operating frequency,
 μ : liquid viscosity,
 γ : liquid specific heat ratio,
 α : liquid thermal diffusivity.

Assumed densities and sound speeds for the three media of interest are shown in Table 4.1 ([19], [20], [21]). A sodium oxide-bearing deposit can actually be a highly porous precipitate of sodium oxide crystals with the interstitial volume filled by liquid sodium. No information is available for the speed of sound through sodium oxide. It is assumed here that the speed of sound through a deposit is the same as that through liquid sodium. In this regard, it is noted that the sound speed for solid sodium hydroxide, NaOH, is stated to be 2441 m/s that is similar to that for liquid sodium. Thus, the assumed impedance for a deposit differs from that for liquid sodium solely due to the difference in density of the deposit versus liquid sodium.

Table 4.1: Assumed densities and sound speeds

Medium	Density (ρ), kg/m ³	Sound Speed (c), m/s	Impedance (Z), kg/(m ² ·s)
Type 304 SS at 200°C	7833	5660	44.330×10 ⁶
Liquid sodium at 200°C	903	2462	2.223×10 ⁶
Na ₂ O deposit with volume fraction of 0.18	1149	2462 (by assumption)	2.829×10 ⁶
Na ₂ O deposit with volume fraction of 0.12	1067	2462 (by assumption)	2.627×10 ⁶

For a frequency of 5 MHz, an inverse attenuation length of 0.31 m⁻¹ is estimated corresponding to an attenuation length scale of 3.2 m. Increasing the frequency to 20 MHz, the length scale decreases to 0.20 m due to the dependency of the inverse attenuation length upon the square of the frequency. These lengths are many times the span of a sodium channel inside of a compact diffusion-bonded heat exchanger.

The wavelength (λ) is related to the sound speed (c) and frequency (f) by

$$\lambda = \frac{c}{f} \quad (4)$$

At 5 MHz, the wavelength in liquid sodium is 0.49 mm. Increasing the frequency to 20 MHz reduces the wavelength to 0.12 mm.

Table 4.2 shows, as an example, the reflection and transmission coefficients for an incident wave passing from the first medium into the second medium for a sodium oxide volume fraction in the deposit assumed equal to 0.18 [3]. Treating the density of a gas/vapor core as negligible, there is no effective transmission into the gas/vapor core. If larger than one-fourth of wavelength²⁰, the

²⁰A film with thickness of quarter-wavelength results in maximum (or complete) energy transmission. Thicknesses smaller or larger than this value result in partial energy transmission and reflection. If the thickness is smaller than quarter-wavelength, the echoes from the tube internal wall and the thin film might couple together thus resulting in a TOF extremely difficult to measure accurately.

thickness of a thin-film deposit could be estimated by the reflection and transmission coefficients. For example, at 20 MHz, one-fourth of a wavelength is 0.03 mm.

Table 4.2: Reflection and transmission coefficients for deposit with a 0.18 Na₂O volume fraction

Transition	Reflection Coefficient, <i>R</i>	Transmission Coefficient, <i>T</i>
SS-to-sodium	0.9045	0.0955
Sodium-to-gas/vapor	1.0000	0.0000
SS-to-deposit	0.8800	0.1200
Deposit-to-sodium	0.1199	0.8801
Sodium-to-SS	-0.9045*	1.9045
Deposit-to-SS	-0.8800	1.8800
Sodium-to-deposit	-0.1199	1.1199

* The negative sign indicates that the reflected wave is 180 degrees out of phase with the incident wave.

Table 4.3 shows the intensities calculated inside of the SS in front of the transducer for reflections off of the various interfaces assuming sodium-oxide bearing deposits on the near and far walls of a sodium channel. Also shown, in the last row, is the intensity of a wave that transits across the channel into the SS on the opposite side of the channel. The signal reflected from the near deposit-sodium interface has an intensity of only 0.027 and 0.0176 relative to the signal emitted by the transducer into the SS for a sodium oxide volume fraction of 0.18 and 0.12, respectively. The dependency upon the deposit net density suggests that the reflected signal intensity could perhaps provide an indication of the net sodium oxide volume fraction provided that signals are correlated with independent measurements of the deposit thickness and sodium oxide volume fraction. Interestingly, the signal reflected from the opposite sodium-deposit interface (0.0267 and 0.0175 for Na₂O volume fractions of 0.18 and 0.12, respectively) is comparable in size to that from the near deposit-sodium interface, such that if the near interface can be identified, then the far interface should also be identifiable. A relatively strong signal is calculated from reflection off of the opposite deposit-SS interface (0.193 and 0.185 for Na₂O volume fractions of 0.18 and 0.12, respectively).

Table 4.3. Reflection and transmission coefficients for steel at transducer

Signal	Na₂O volume fraction of 0.18	Na₂O volume fraction of 0.12
Reflection from SS-deposit interface	0.8800	0.8880
Reflection from deposit-sodium interface	0.0270	0.0176
Reflection from opposite sodium-deposit interface	0.0267	0.0175
Reflection from opposite deposit-SS interface	-0.1930	-0.1850
Reflection from opposite SS-gas interface	0.0494	0.0440
Transmission into SS on opposite side of channel	0.2220	0.2100

4.3 Testing methodology

The theoretical study discussed in the previous section shows that it might be feasible to measure the thicknesses of sodium films and sodium oxide-bearing deposits by using the UTDR technique. Three experimental tasks were planned and conducted to validate the technique and to determine

the measurement resolution of the thickness: 1) capability and calibration test, 2) laboratory mockup test, and 3) in-situ high-temperature test.

4.3.1 Capability and calibration test

Before water mockup and in-situ high-temperature tests, a feasibility study of the UTDR technique was conducted to evaluate its capability of measuring sodium oxide-bearing depositing on the internal surface of a SS tube. Then an investigation was carried out to establish a calibration process for the quantitative determination of the thickness of sodium oxide film and the total amount of sodium oxide depositing on the tube.

A high-frequency ultrasonic system, shown schematically in Figure 4-1 with its actual realization in Figure 4-2, was designed to resolve the sodium film thickness. The system consists of a high-frequency ultrasonic pulser/receiver (Olympus 5072PR-15-U), a pair of ultrasonic delay-line transducers (Olympus V202RM or V208-RM), a pair of ultrasonic waveguides, and a data acquisition system. All the control, data acquisition, and data analysis were developed in-house on the LabView platform. Due to the high-temperature envisioned for the ultimate application, transducers are mounted on waveguides using dry coupling technique and gold foil is used as the coupling material. The waveguides are then mounted on the opposite sides of the tubing²¹. The system was tested in both pulse-echo and through transmission modes:

- *Pulse-echo mode*: the transmitter sends out initial pulse and receives the reflection echoes from the waveguide, SS tubing, and the interface between sodium oxide and liquid sodium. By calculating the time-of-flight (TOF) of each echo and combining it with temperature measurements, the thickness of the sodium oxide film can be estimated.
- *Through transmission mode*: the transmitter sends an ultrasonic pulse through the SS tubing, to a receiver located on the opposite side. The overall amount of sodium oxide depositing on the internal surface of the tubing can be determined by measuring the TOF and the intensity change.

²¹ To mount waveguides on a round tube, the surface of each waveguide attaching to tube was machined to have the exact curvature as the tube to provide a tight fitting for optimal acoustic coupling/transmission. To achieve consistent and repeatable measurement, it is essential to be able to keep the transducers and waveguides in good contact, alignment, and positioning. A holder, which consists of a detachable SS collar and a mini mechanical clamp, was designed and fabricated. The collar can move along and rotate around the tube for easy repositioning. The two thorough holes, which have about 0.002" larger than the waveguide's diameter (~0.19"), were drilled at the opposite sides on the collar to keep a precise alignment. The mini mechanical clamp is used to clamp the two transducers and waveguides in place as well as keep appropriate pressure, i.e. coupling.

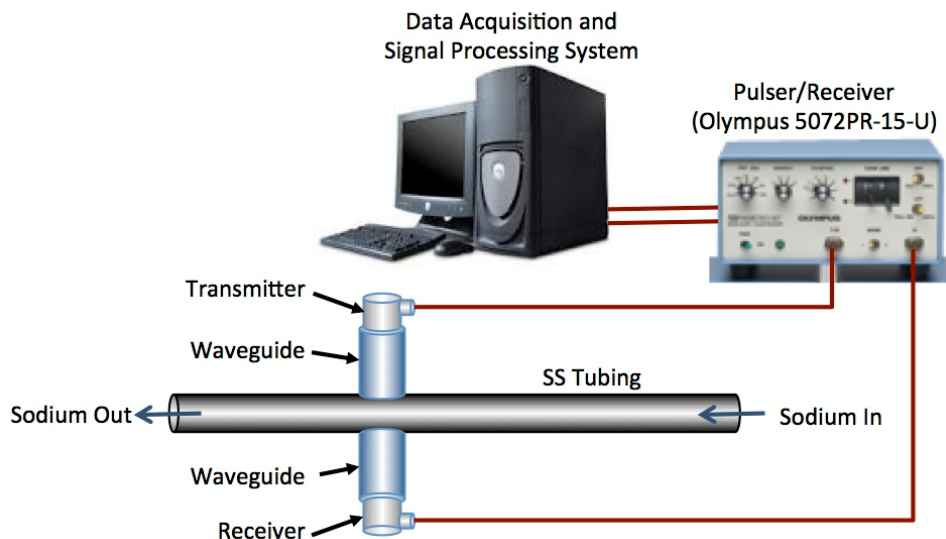


Figure 4-1: Schematic of high-frequency ultrasonic system and experimental setup



Figure 4-2: High-frequency ultrasonic system and experimental setup

The minimum detectable thickness depends on the tradeoff between operating frequency, ring-down cycle, and output power of a transducer. To evaluate the optimal operating frequency both ultrasonic delay-line transducers (V202-RM and V208-RM) were tested using SS steel plates with thickness of 1.22 and 0.39 mm (50 and 15 mills). V208-RM has higher operating frequency at 20 MHz and was selected because of its cleaner signal and echo separations. Tests were conducted to determine the optimal ring-down cycles and gain of the transducer for optimizing its output power and still maintaining signal clearness. Two different waveguides, high-temperature (HT) plastic (DLHT-3G) and SS waveguides, were evaluated²².

²² The DLHT-3G has an operating temperature up to 480°C with high ultrasonic attenuation and non-continuous contact. The SS waveguide has higher operating temperature and lower ultrasonic attenuation. However, it generates a more complex receiving signal due to mode conversions, which make signal processing and thickness determination more difficult.

Figure 4.2 shows the RF signals of multiple reflections from a DLHT-3G waveguide contacting SS plates with thicknesses of 1.22 mm and 0.39 mm, respectively. It shows that the selected high-frequency transducer has very little ring-down cycles. However, if the thickness is too small (right plot), the multiple reflected signals of the thin SS plates are cluster together and make the accurate thickness measurement very difficult.

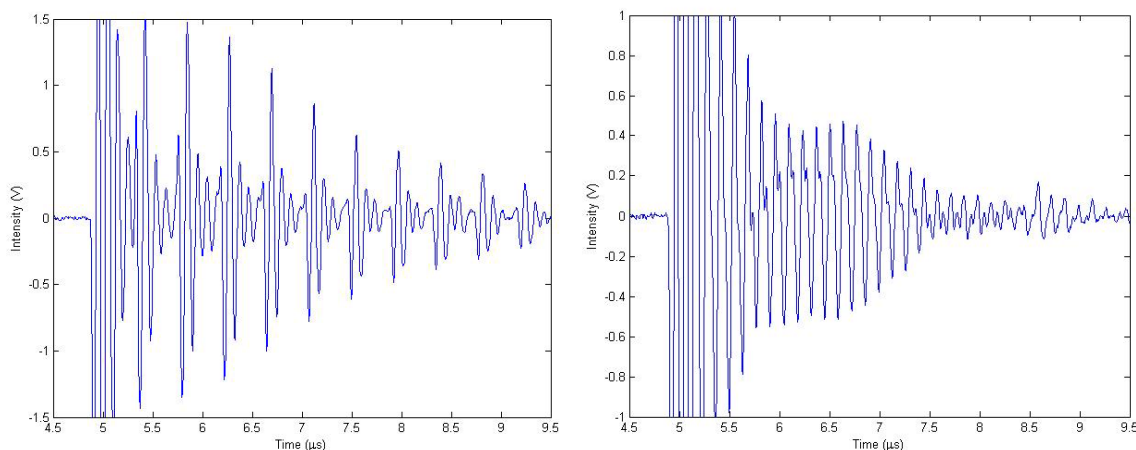


Figure 4-3: RF signal (V) of multiple reflections from SS plates vs. time (μ s), for 1.22 mm (left) and 0.39 mm (right) thickness

Three tube samples, shown in Figure 4.3, are used in the lab to evaluate and calibrate the system²³. These tubes have the same material (SS), ID and OD. The two shorter tubes, one clean and another filled with water, are used for calibration purposes. The ultrasonic signal acquired from the clean tube provides the reflection baseline of the tube wall for the pulse-echo mode. There were multiple reflections from the tube wall that cause some complexity in the thickness measurement of sodium oxide thin deposition. By applying the baseline subtraction technique using the reflection baseline result, the unwanted echoes were then cleared out resulting in an easier and more accurate thickness measurement. The tube filled with water will be used, for the through transmission mode, to simulate liquid sodium in a tube to evaluate the TOF of a tube filled with liquid sodium only. The longer tube, used to evaluate the capability of the system, was removed from the SPPL following sodium plugging testing and was assumed to contain sodium/sodium oxide and some pockets of argon cover gas. Figure 4.5 is a close view of the experimental setup.

²³ These tubes were also used for assessing the capability of a third diagnostic technique, x-ray Computer Tomography, whose results are summarized in Appendix C since they were inconclusive.

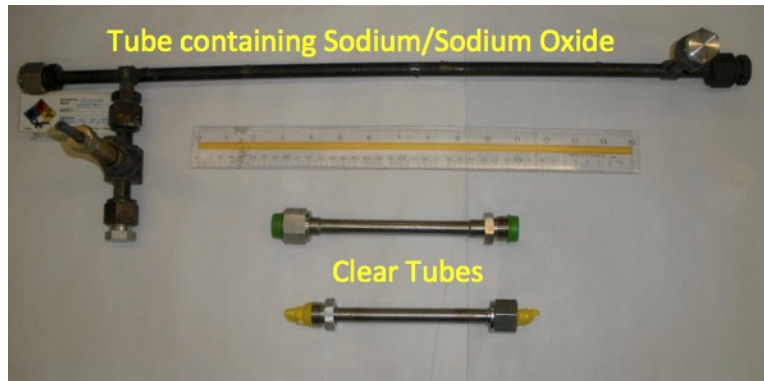


Figure 4-4: Sample tubes for UTDR capability evaluation and calibration tests

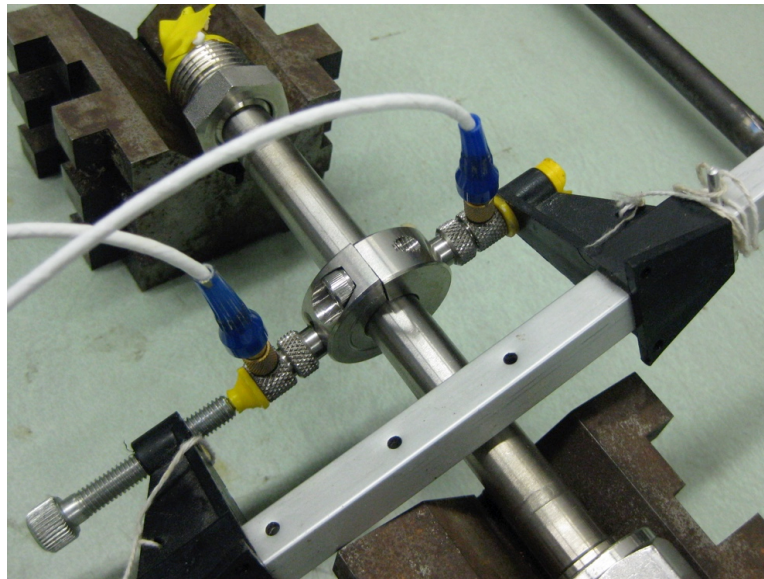


Figure 4-5: Transducer-tube holder for capability evaluation and calibration tests.

4.3.2 Laboratory mockup test

Before conducting in-situ high-temperature testing, a laboratory mock-up test was conducted to validate the UTDR feasibility. This investigation addressed waveguide material and length, signal intensity, mode conversion and multiple echoes caused by long waveguides, background substation algorithms and transducer/waveguide mounting and coupling mechanism. A mockup of a single channel was fabricated to evaluate the technique and prepare for the in-situ high-temperature test. The mockup tests, including both PE and TT modes, were used to test the transducer/waveguide mounting mechanism, and then to optimize the ultrasonic energy transmission efficiency. A pair of ultrasonic delay-line transducers (Olympus V208-RM @ 20MHz) and DLHT-3G waveguides are used for this evaluation. A holder was fabricated to provide good contact and alignment of the transducers. A transducer/waveguide holder was fabricated to provide good contact and alignment of the transducers. Figure 4-6 shows the single-channel mockup sample.

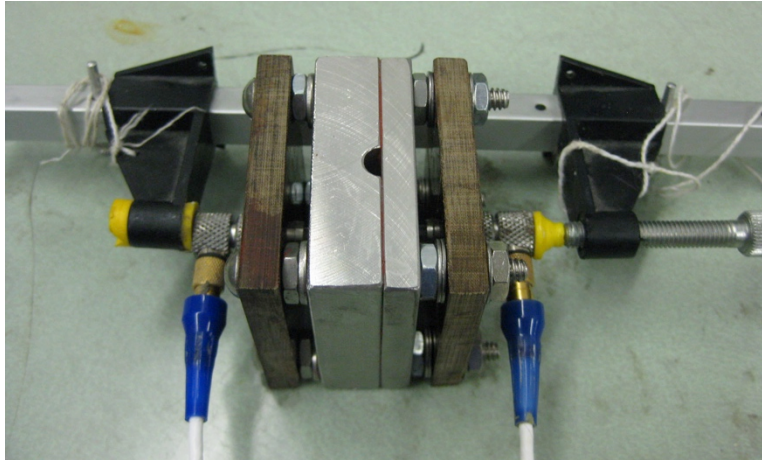


Figure 4-6: Laboratory mockup test setup of a single-channel mockup sample

4.3.3 In-situ mockup test

Because of the impossibility, by the end of the project, to run plugging tests at the SPPL, the ultimate in-situ *high-temperature* testing was not performed. However, an extensive evaluation was made to address the instrumentation setup challenges that will need to be faced once the SPPL becomes operational for conducting plugging tests, which led to the manufacture of two prototypical transducer-waveguide holder fixtures. This work is discussed below.

For an in-situ high-temperature test, an evaluation was first conducted to identify a suitable location for the transducer-waveguide (TD-WG) holder fixture mounting on the SPPL test section, as this installation should result in minimum impact to the SPPL performance (especially not causing a cold spot). The proposed location is shown in Figure 4-7, while Figure 4-8 shows the top surface of the channel test area at this location.

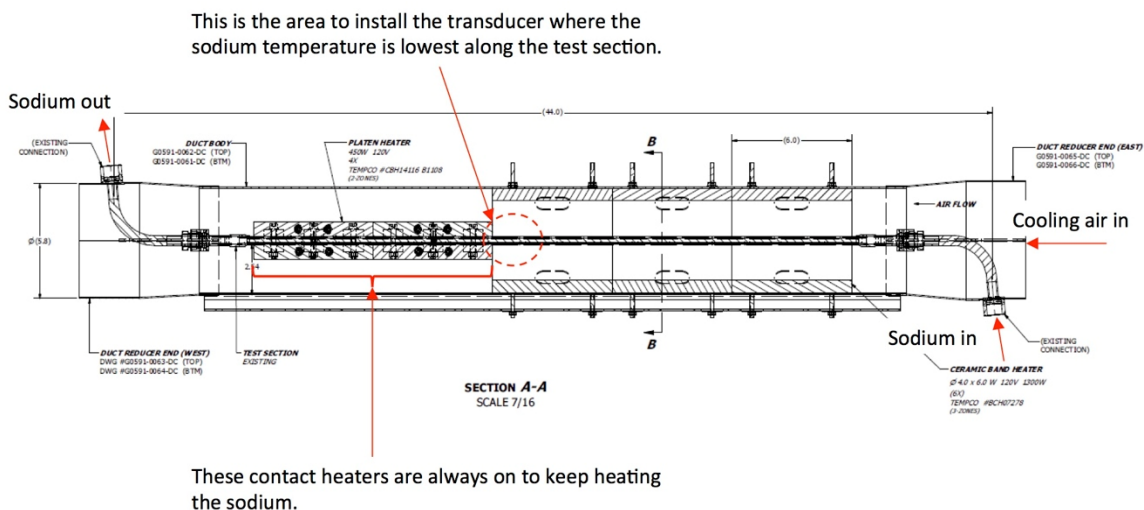


Figure 4-7: Proposed location in the test section for mounting a pair of ultrasonic transducers and waveguides

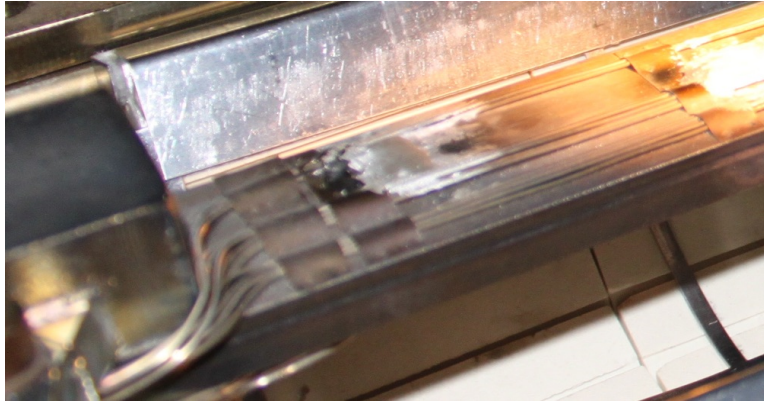


Figure 4-8: Picture of the proposed location for mounting an ultrasonic transducer pair

Three main challenges exist in mounting the holder fixture:

- As evident from Figure 4-8, there are several thermocouples mounted on the top surface of the test section, which should not be compressed by the new installation. To avoid this, the space between the holder and the surface of the test section can be adjusted by the properly designing the penetration depth of the waveguide and the two fixture mounting screws.
- The clearance between the test section and the ceramic band heater is very small ($<3\text{mm}$), thus challenging the mounting of the alignment blocks. Special band heaters were designed to give flexibility of mounting the TD-WG holder fixture as well as keep consistent heating to minimize the impact on the SPPL performance. Possible solutions are to either modify the test section or use a band heater with a larger ID. The former could be accomplished by either reducing the wall thicknesses of the test section or making a transducer recess hole on each side. The latter could be addressed by using longer waveguides or by replacing the third band heater with a modified heater having larger ID.
- The in-situ test will be conducted at a temperature of at least 200°C , which is higher than the operating temperature of most commercially available ultrasonic transducers ($\sim 50^{\circ}\text{C}$). To protect the transducer from excessive heat, a waveguide needs to be used as a thermal buffer. Depending on the waveguide material, it might decrease the overall received signal intensity (if it has high ultrasonic attenuation potential) or generate unfavorable mode conversions (more likely in low attenuation potential materials). A pair of specially designed SS waveguide and a transducer/waveguide holder was designed to protect the transducers from high temperature and to provide not only good and consistent contact between the waveguides and the test section, but also accurate alignment of the transducer pair mounted on the opposite surface of the SPPL test section. Figure 4-9 illustrates the envisioned setup of the holder fixture on the SPPL test section.

Two prototypes of the holder fixture were fabricated, to essentially address the challenge of the small clearance existing between the test section and the band heater, with one having twice the holder's thickness of the other. Figure 4-10 shows the dimensions of the prototype with thicker holder. A screw hole ($1/4\text{-}28$ ") was machined in the middle of the two holders. In order to be an effective buffer in protecting the transducer from high temperatures, while limiting its

invasiveness in the SPPL,, the length of the waveguides should be approximately 3 inches. Hence, two SS waveguides, 3" in length and 0.25" in rod diameter, were designed to have the same geometry as the Olympus DLHT-3G waveguide for the mounting of ultrasonic delay line transducers (Olympus V202-RM). The rod body of the waveguide was machined with thread (1/4-28), which will reduce the mode conversion and reflection that are caused by the long waveguide. The thread waveguide will allow for easy adjustment of the contact of the waveguide tip onto the surface of the channel block to ensure precise alignment and to maintain optimal ultrasonic coupling, which in turn will provide maximum energy transmission between the transducers and accurate and consistent measurements.

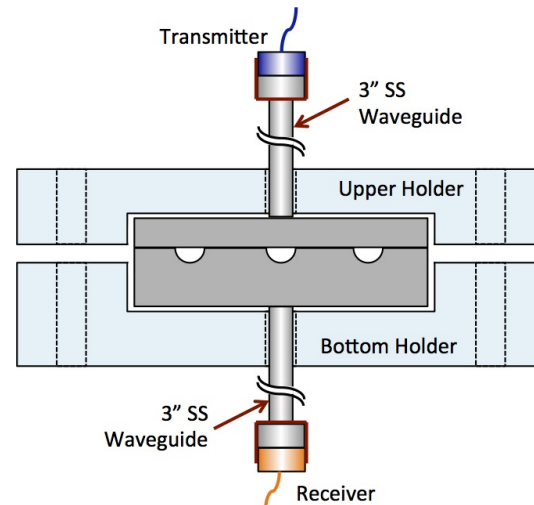


Figure 4-9: Design of the transducer-waveguide holder fixture for in-situ test

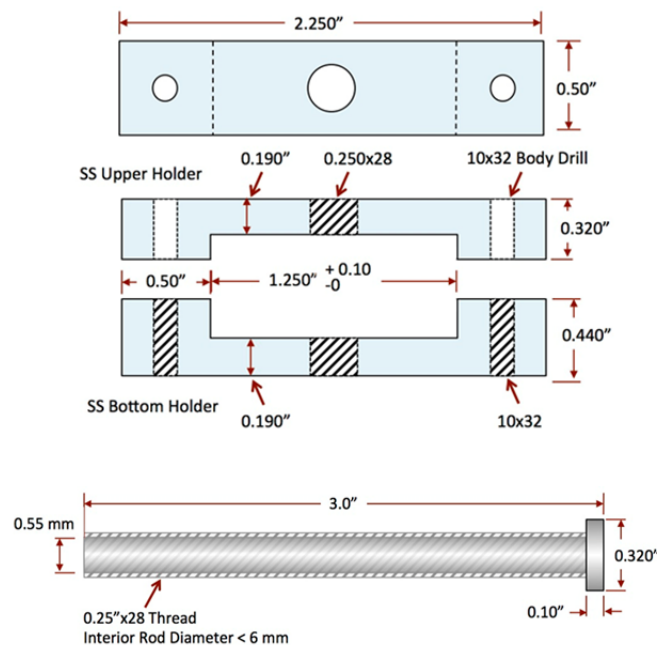


Figure 4-10: Dimensions of the transducer-waveguide holder (top) and of the stainless steel waveguide (bottom)

4.4 Experimental results and insights

Mock-up tests were conducted to validate the UTDR technique feasibility and to prepare for the in-situ high-temperature test. In addition to the laboratory mockup (shown in Figure 4-6), a mockup for in-situ high-temperature testing was fabricated and successfully tested although at room temperature. It was therefore demonstrated that the TOF and the attenuation of the ultrasonic signals could be used to estimate the thickness of sodium oxide-bearing deposits.

4.4.1 Results of laboratory mockup test

Laboratory mockup testing was performed on the fixture shown in Figure 4-6. Figure 4-11 shows the ultrasonic signal received from the PE mode using the Olympus V202-RM transducer pair with an operating frequency of 20MHz and DLHT-3G waveguides. The reflected signals of a sodium oxide-bearing deposit would show up in between the first and the second echoes from the channel wall. The thickness of the deposit could be estimated by measuring the TOF between the two consecutive echoes resulting from the deposit.

Figure 4-12 shows instead the ultrasonic signal received from the TT mode, using the same setup as the PE mode. To conduct the test in TT mode, one side of the channel was sealed, and then filled with water. The thickness of the deposit could be obtained from either the TOF or from the intensity changes of the first through-transmission signal. It can be seen that the intensity of the received PE signal (≤ 3 V) is much stronger than that received from the TT mode (≤ 0.04 V), making signal detection easier in PE mode.

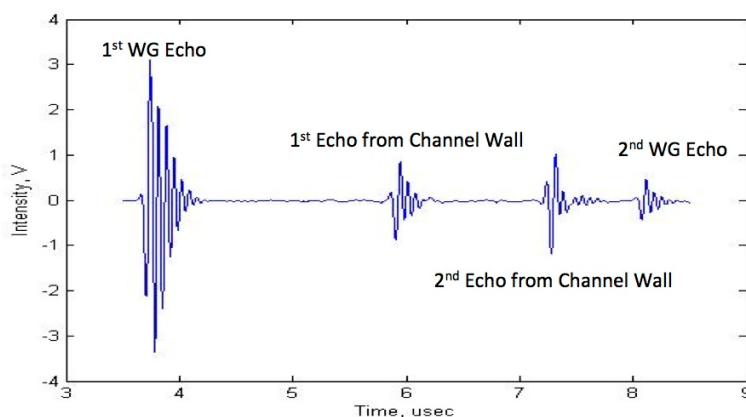


Figure 4-11: Ultrasonic signal received from pulse-echo mode of channel sample

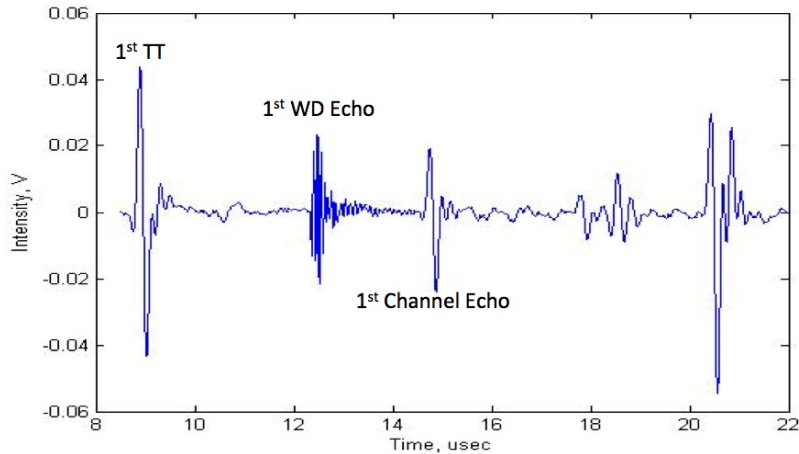


Figure 4-12: Ultrasonic signal received from through-transmission (TT) mode of channel sample

4.4.2 Results of in-situ mockup test at room temperature

Laboratory mockup tests were conducted on the fixture prototype shown in Figure 4-9 and Figure 4-10 to evaluate the capability of the waveguide mounting mechanism to ensure a consistent contact and accurate alignment of the waveguides. The tests were also used to optimize the overall ultrasonic energy transmission efficiency of both PE and TT modes. The mockup system consisted of a high-frequency ultrasonic pulser/receiver (Olympus 5072PR-15-U), a programmable gain-filter (Krohn-Hite 3945), a pair of ultrasonic delay-line transducers (Olympus V202-RM), a pair of ultrasonic waveguides, and a data acquisition system. Figure 4-13 shows the prototypical, i.e. for in-situ high-temperature testing, fixture on top of the pulser/receiver. The long waveguides can be noticed, which differentiate this fixture from the laboratory mockup (Figure 4-6), which adopted much shorter waveguides and is not suited for high-temperature applications.

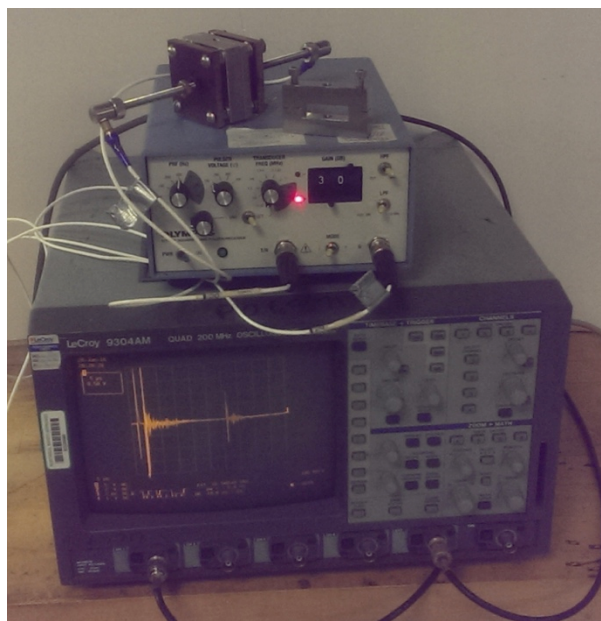


Figure 4-13: In-situ mockup test of the specially designed SS UT-WG

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The 3" long SS waveguides have higher operating temperature and lower ultrasonic attenuation. However, they might generate a much complex receiving signal due to mode conversions²⁴, which makes signal processing and thickness determination more difficult. To assess this, the prototypical fixture was tested on a step-standard (see Figure 4-14), which consists of two steel plates one on top of the other.

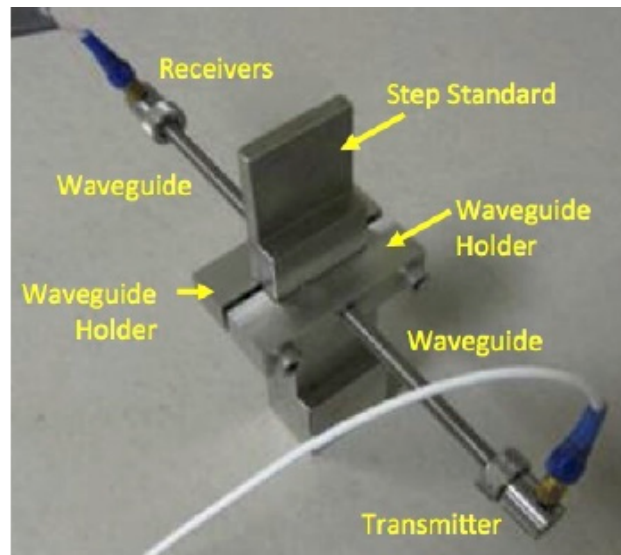


Figure 4-14. Setup of the prototypical TD-WD holder fixture on step standard

Figure 4-15 shows the ultrasonic signal received from the PE mode. It can be seen that the mode conversions of the waveguide are minimized. The first echo is the reflection from the interface of the end of the transmitter's waveguide and the front surface of the step standard. The second one is from the opposite surface of the step standard. The reflected signal of sodium oxide deposition would follow the first echo. The thickness of the deposition could be estimated by measuring the TOF between the two consecutive echoes resulting from the deposition. Figure 4-16 shows the ultrasonic signal received from TT mode using the same setup. As observed for the laboratory mockup tests (see Figure 4-11 and Figure 4-12), the intensity of the received TT signal (~ 2 V) is much stronger than that received from the PE mode (~ 0.5 V). The thickness of the deposit could be estimated by either the TOF or the intensity changes of the first TT signal.

²⁴ The mode conversions and reflections from the waveguide's walls generate unwanted echoes, which will interfere with the signal of the film and make accurate TOF measurement difficult. A baseline subtraction technique may be able to eliminate them, resulting in an easier and more accurate thickness measurement.

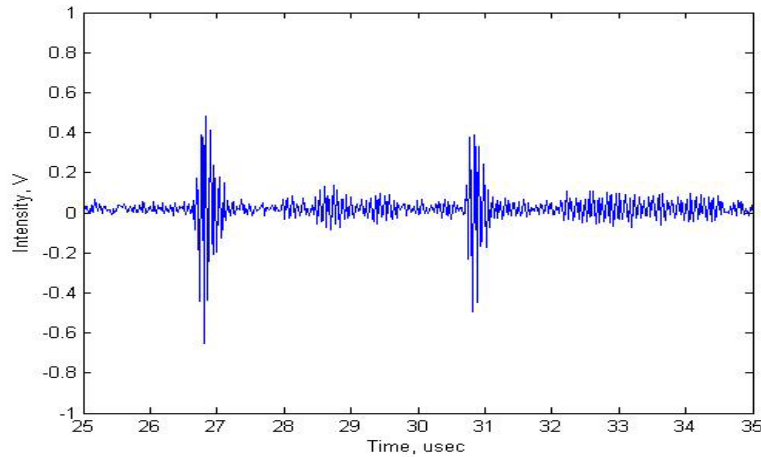


Figure 4-15: Ultrasonic signal received from pulse-echo mode

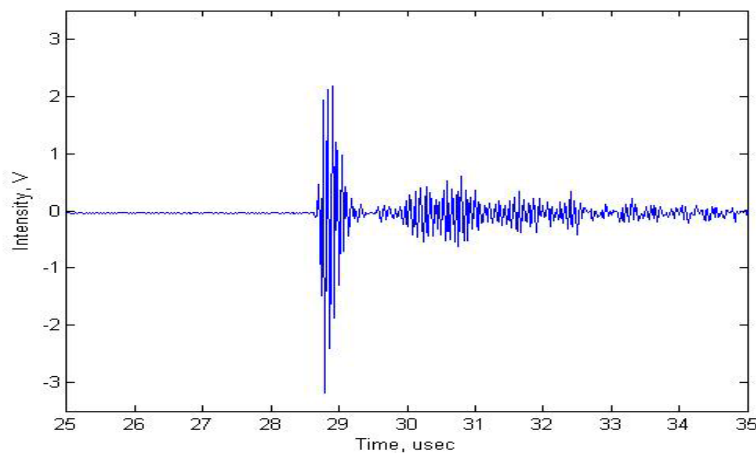


Figure 4-16: Ultrasonic signal received from through-transmission mode

4.5 Recommendations for future work

The mockup of the in-situ high-temperature test apparatus was successfully tested under ambient conditions. Some work is however needed to 1) ensure accuracy in deposit thickness measurement and 2) adjust the SPPL configuration as to allow installation of the transducer-waveguide holder fixture. The system accuracy could be assessed by validating thickness measurements against, for example, artificially-made deposits of known size. However, the purpose is not to build more delays into the progress but to put instrumentation onto the test section and determine the feasibility of the UTDR technique during actual sodium plugging runs. The following are recommended:

- Replace the third band heater with a new one, to allow installation of the 3" SS waveguides. The new heater can be procured using design drawings made as part of this project, ultimately not used because it has not been possible to identify a vendor willing to manufacture such a custom-made heater. It might be necessary for ANL to create a suitable heater through modification of an existing type.

- Test the fitting and installation mechanism of the TD-WG holder fixture onto the SPPL test section;
- Conduct preliminary testing of the UTDR while the system is at room temperature;
- Conduct in-situ high-temperature testing of the UTDR at elevated temperature;
- Calibrate or correlate the test results with the plugging indicator(s) of the SPPL, such as flow rate variations.

5. Potential Drop technique development

This chapter is organized as follows:

- Section 5.1: Summary of development work
- Section 5.2: Theory and analytical/computational verification
- Section 5.3: Experimental work
- Section 5.4: Conclusions on PD technique
- Section 5.5: Recommendations for future work.

5.1 Summary of development work

Studies have been conducted at ANL to assess the viability of potential drop (PD) measurement technique for in-situ monitoring of sodium oxide deposition in the flow channels of the SPPL. The adverse environment of SPPL (i.e., high temperature, vibration, limited space, etc.) limits the use of many conventional nondestructive evaluation (NDE) methods that might otherwise be used for on-line monitoring. The probing method for this application should withstand high temperatures and operate over extended periods of time. In view of these constraints, the well-established PD method was selected for evaluation. This electromagnetic NDE method offers good sensitivity to changes in electrical properties (i.e., conductivity and permeability) of layered structures and is well-suited for operation in high temperature environments. Analytical evaluations based on a simplified model of the sodium channel were initially performed to assess the effect of test parameters on the measurement results. Limited numerical studies were later performed to gain a better understanding of current flow through the medium. A PD measurement system was subsequently assembled for experimental studies on a small-scale mockup of the sodium channel. All the necessary hardware and software modifications to allow multi-channel PD measurements were implemented in-house. A number of tests have been performed to help determine the optimum excitation frequency and probe configuration. The results of applied research efforts conducted to date suggest that PD method could be a viable approach to on-line monitoring of sodium oxide deposition in sodium flow channels. Follow-on R&D efforts in this area should conceivably include electromagnetic model-based optimization of the PD measurement parameters and experimental validation of the alternate current (AC) PD diagnostic technique through on-line monitoring of SPPL during operation.

5.2 Theory and analytical/computational verification

The PD technique, as a tool to diagnose the presence of sodium oxide deposits and to characterize them, relies on the capability to detect variations in electrical resistance along selected current paths due to the high electrical resistance of the oxide relative to both stainless steel (SS) and liquid sodium. Before conducting experiments, analytical formulations and computational models were used to first understand whether this technique has the capability to resolve sodium oxide deposits.

5.2.1 Analytical verification

Analytical formulations for direct current and alternate current potential drop (DCPD and ACPD) using a simplified two-layer model–SS and liquid sodium–were initially implemented in MATLAB™ to assess the effect of different test parameters (e.g., material properties, probe arrangement, spacing and frequency) on the expected PD measurement parameters. The model used in the study was a liquid Na half-space covered with a layer of 304SS. In reference to Figure 5-1, a coated half space is a fairly good approximation of the SPPL geometry for a measurement setup in which the largest dimension of the collinear probe is aligned with the axis of the channel. The current injected at the surface will penetrate a finite depth into the conducting medium. The penetration depth for DCPD measurement is governed primarily by probe spacing and for ACPD measurement is governed by both the probe spacing and the operating frequency. Therefore, the electrodes can be arranged to probe into the sodium with a reduced flow into the SS layer underneath. This implies that the lack of bottom layer of steel (3rd layer) in the EM model should not significantly affect the results. Additionally, most of the current will flow in a small channel between the probes with little lateral leakage. As a result, it is expected that the finite lateral dimensions of the vessel would not cause significant deviation between the estimated and the measured values.

In all the test cases here, a conductivity of $\sigma_{SS}=0.14e7$ S/m was used for layer 1 (304SS) and a conductivity of $\sigma_{Na}=0.57e7$ S/m was used for layer 2 (Na). A relative permeability of $\mu_r=1$ (non-ferromagnetic material) was used for both layers. In reference to Figure 5-2(a) the thickness of SS layer was set to $D=0.125$ in. (~ 3.175 mm). To emulate the effect of non-conducting oxide layer in the model, the conductivity of the liquid sodium half-space was varied between zero and its nominal value. This effectively is equivalent to averaging the conductivity of the entire channel as the oxide layer deposition increases. Both DC and AC measurements were simulated and analyzed to observe how the measured resistance/impedance would change with respect to probe spacing, conductivity of the bottom layer and the excitation frequency (in the case of ACPD).

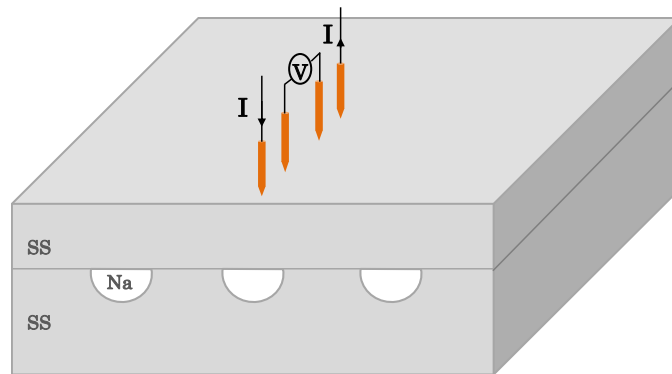


Figure 5-1: Collinear probe arrangement for four-point PD measurement along a sodium channel.

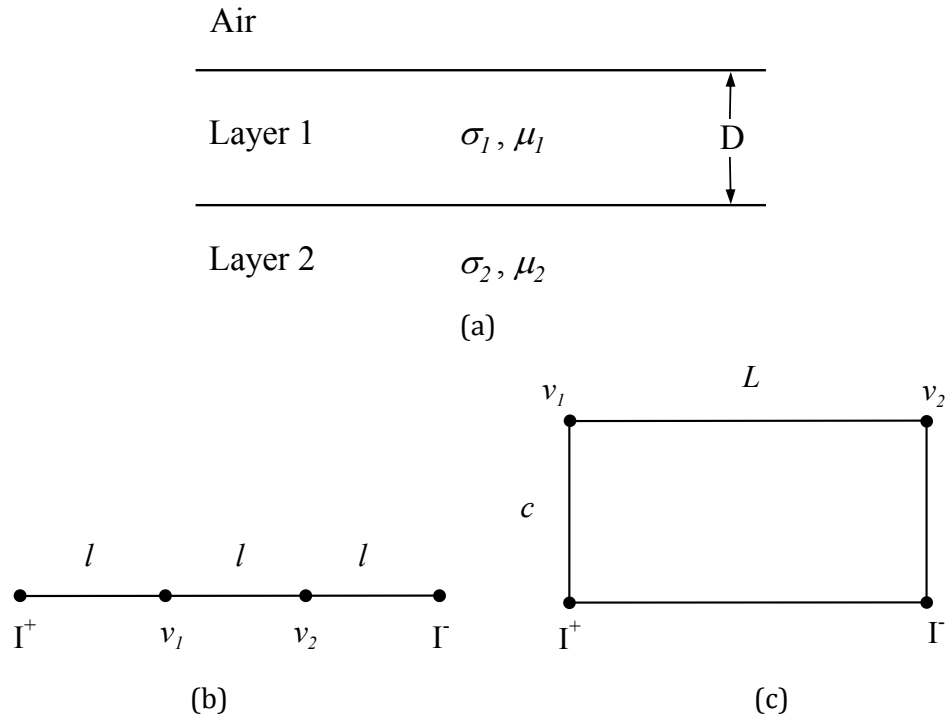


Figure 5-2: (a) Cross section of the layered media (1=SS; 2=Na) and electrode arrangement for (b) collinear equidistant probe and (c) rectangular probe

The calculated resistance as a function of conductivity of the sodium layer (layer 2) for different values of collinear probe spacing is shown in Figure 5-3. The electrode spacing, in reference to Figure 5-2(b), was varied between two and six times the thickness of the SS layer (D). Resistance increases exponentially with decreasing conductivity as seen in Figure 5-3. This indicates the possibility of a useful relationship between the thickness of the sodium oxide layer and the surface resistance of the vessel. As the probe spacing increases, the slope of the curves at the low conductivity range also increases, indicating that larger probe spacing could provide better sensitivity to changes in the amount of oxide film in the sodium channel. Similar results are shown in Figure 5-4 for the predicted change in PD resistance as a function of the conductivity of liquid sodium for a rectangular probe arrangement with $c=D$ and varying L values ($D/3$ to $2D$). The electrode configuration and the denoted parameters for four-point PD measurement with a rectangular probe arrangement were shown in Figure 5-2(c). The graphs in Figure 5-4 generally exhibit a similar shape to those in Figure 5-3 for the collinear probe. In this case, however, there is a stronger dependence of the measured PD on the change in probe spacing.

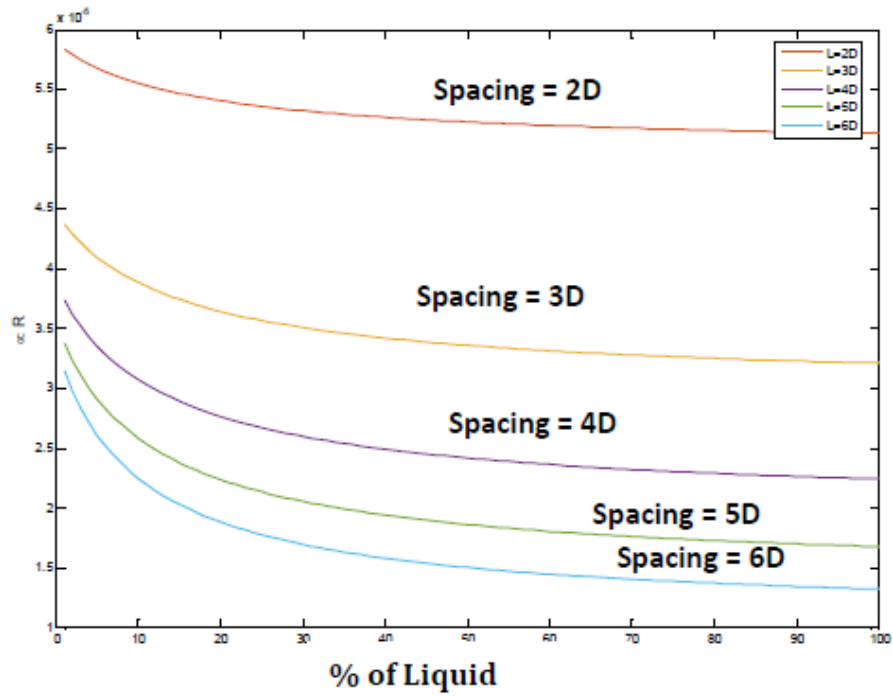


Figure 5-3: Resistance vs. conductivity of liquid Na (as a % of liquid Na) for various collinear probe spacings

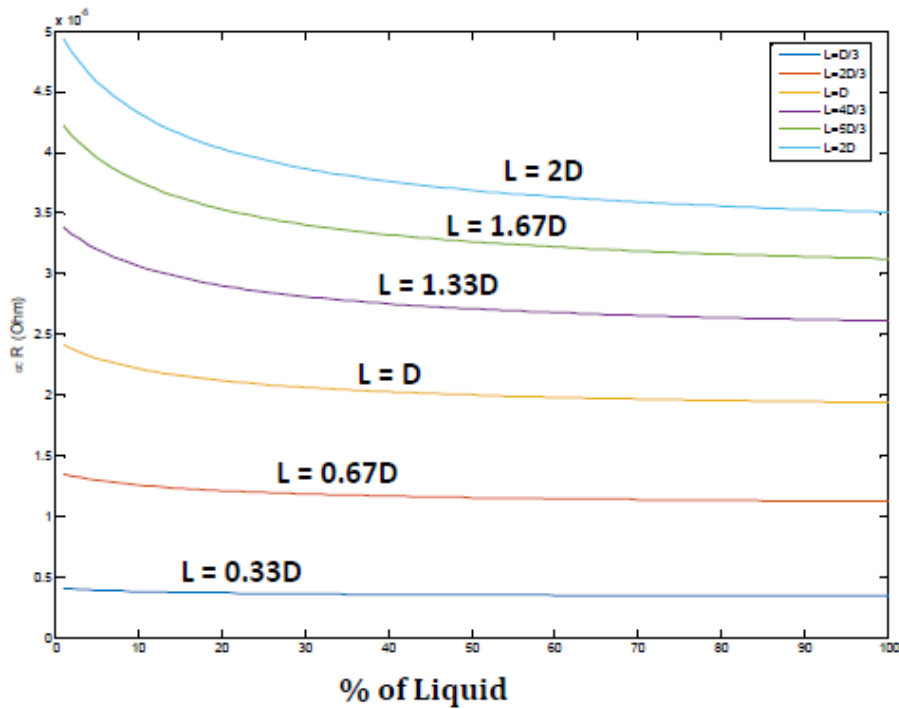


Figure 5-4: Resistance vs. conductivity of liquid Na (as % of liquid Na) for rectangular probe arrangement with $c=D$ (see Figure 5-2) and varying L values ($D/3$ to $2D$).

Simulations were also carried out to assess potential improvement in sensitivity for monitoring of oxide layer buildup using ACPD measurement. While the simulation code can handle arbitrarily placed electrode configurations, representative data are shown here only for the case of collinear probe arrangement. For ACPD measurement, the real and imaginary parts of the impedance change were examined as a function of change in conductivity of the sodium layer and at different frequencies. The total probe spacing for these calculations is three times the thickness of layer 1 (SS). Figure 5-5 shows the change in PD resistance and reactance of as a function of frequency from DC to 10 kHz for a single layer of SS (i.e., layer 2 being air). Both components of impedance show an exponentially increasing PD response as frequency increases. Simulation of change in impedance components for the two-layer geometry is shown in Figure 5-6. In this case resistance and reactance are plotted as a function of conductivity of liquid sodium at different frequencies in the range of 1 to 9 kHz. Once again, the real part of impedance increases rapidly with decrease in the conductivity of the sodium layer, and increases with respect to frequency. The magnitude of the imaginary component also increases rapidly with increasing conductivity and frequency. The penetration depth of the injected currents at a frequency of $f=10$ kHz is sufficient to penetrate through the top SS layer and into the sodium channel. With skin depth defined as $\delta = \sqrt{1/\pi f \mu \sigma}$, the value of δ at $f=10$ kHz is ~ 4.3 mm which is greater than the thickness of SS layer ($D \sim 3$ mm). Variation of resistance and reactance as a function of the conductivity of liquid sodium at $f=5$ kHz are shown in Figure 5-7 for various probe spacing. As in the DC case, the results generally indicate the dependence of measured PD values with electrode spacing. It should be noted that while an increase in frequency is expected to increase measurement sensitivity to oxide layer deposition, it could also increase the sensitivity to other test variables. Therefore, selection of optimal probe spacing and excitation frequency will always be a tradeoff between sensitivity and stability for conventional ACPD measurements.

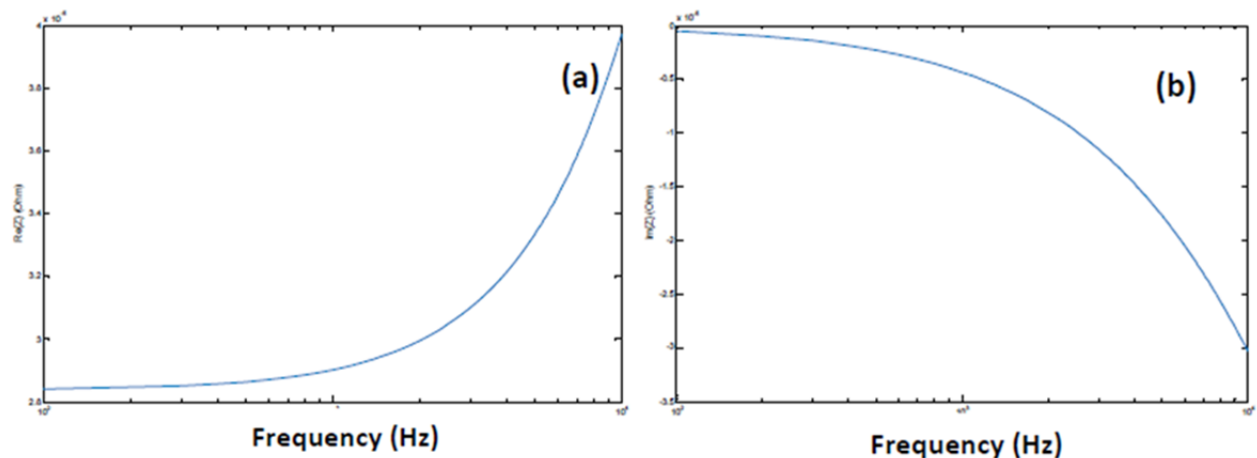


Figure 5-5: Change in resistance (a) and reactance (b) of SS plate as a function of frequency from DC to 10 kHz

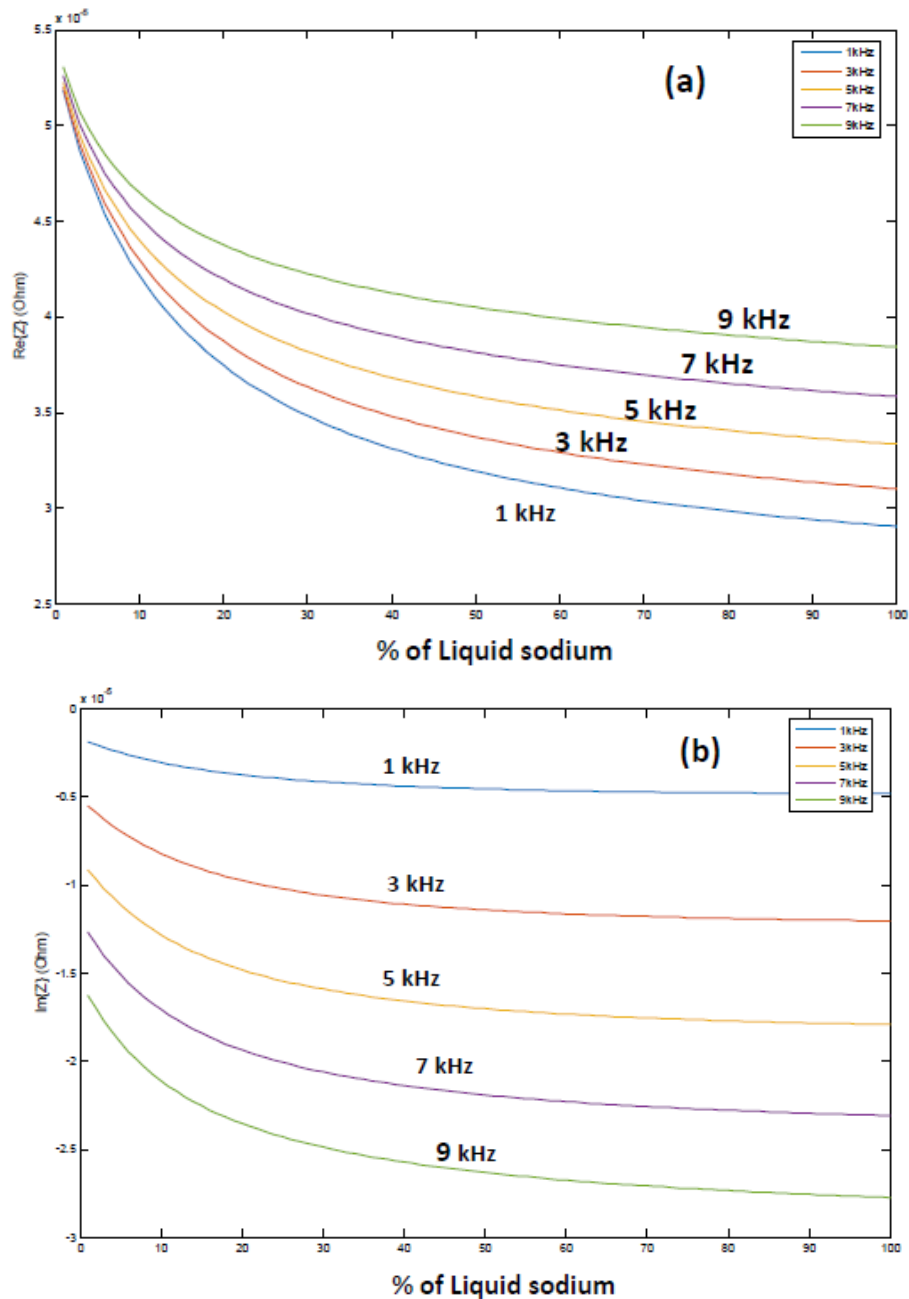


Figure 5-6: Resistance (a) and reactance (b) as a function of conductivity of liquid Na at different frequencies from 1 kHz to 9 kHz

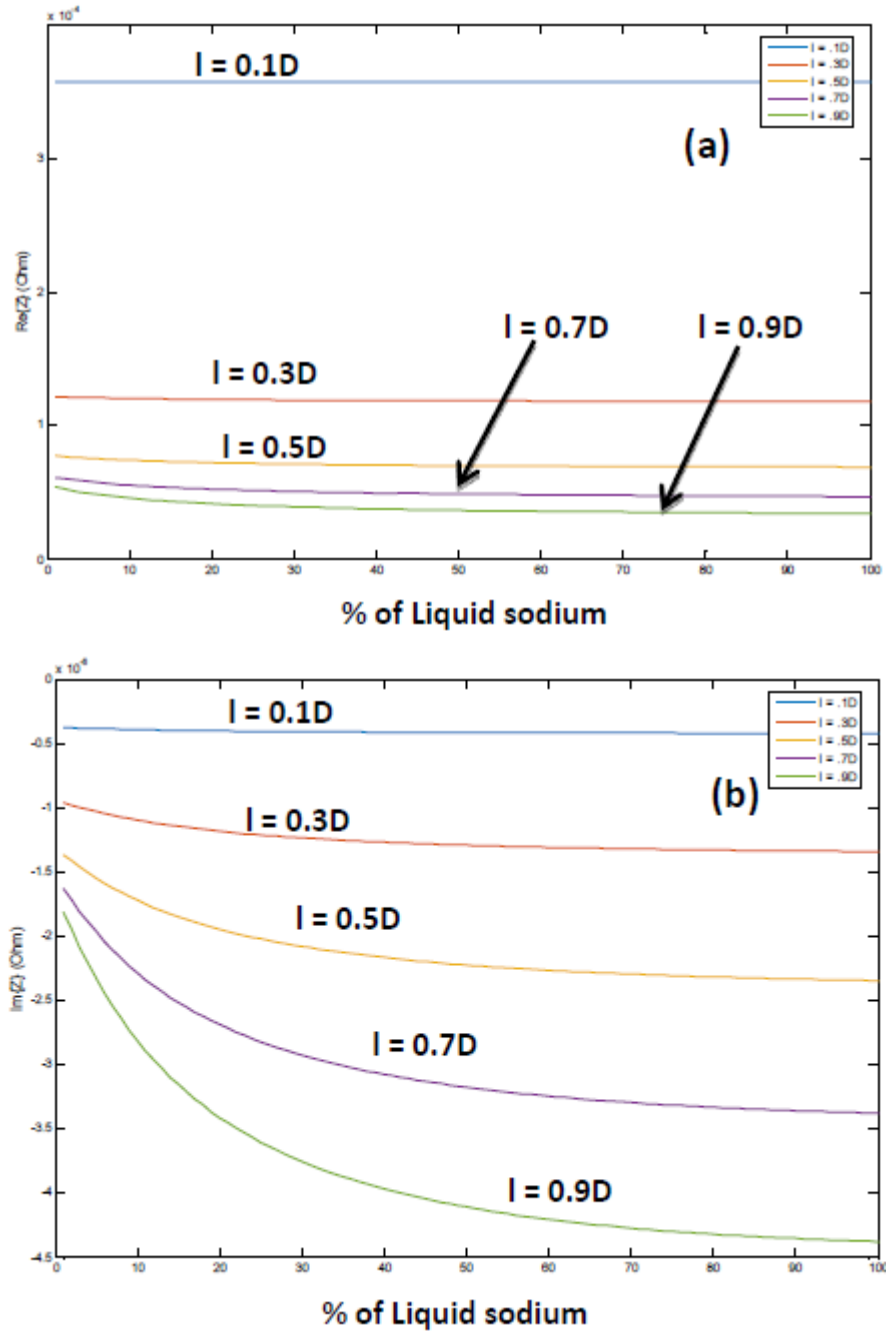


Figure 5-7: Resistance (a) and reactance (b) as a function of conductivity of liquid Na at 5 kHz for various probe spacing

5.2.2 Computational verification

As a follow-up to analytical modeling efforts, limited numerical modeling studies were also carried out later in this project in an attempt to determine the effect of change in conductivity of sodium channel on PD measurements by using a more realistic model of the problem geometry. The AC/DC module of the COMSOL® Multiphysics software was utilized to perform the numerical simulations. This finite element analysis (FEA) based modeling tool allows detailed simulation of complex geometries using a CAD-based model construction interface.

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In reference to Figure 5-8, a 3D model of a section of the sodium plugging loop was constructed to evaluate the effect of different test parameters on PD measurements. The overall dimensions of the simulated geometry are close to the actual dimensions of the SPPL. For the limited number of test cases shown here the outer-most electrodes (1 and 6) were used both as the excitation and as the measurement elements. It should be noted that, based on the numerical results, this injection and pick-up electrode configuration produced the highest sensitivity for ACPD measurement of change in conductivity of the sodium channel.

Finite element solutions were obtained over a range of frequencies using different collinear injection and pick-up electrode configurations shown in Figure 5-8. It should be noted that in order to reduce the computational run time, only the sodium-filled channel was considered in the model geometry. Representative test cases on distribution of normalized current density J (A/m²) within the conducting medium are presented first. The change in impedance as a function of frequency is also presented for the optimum collinear probe configuration.

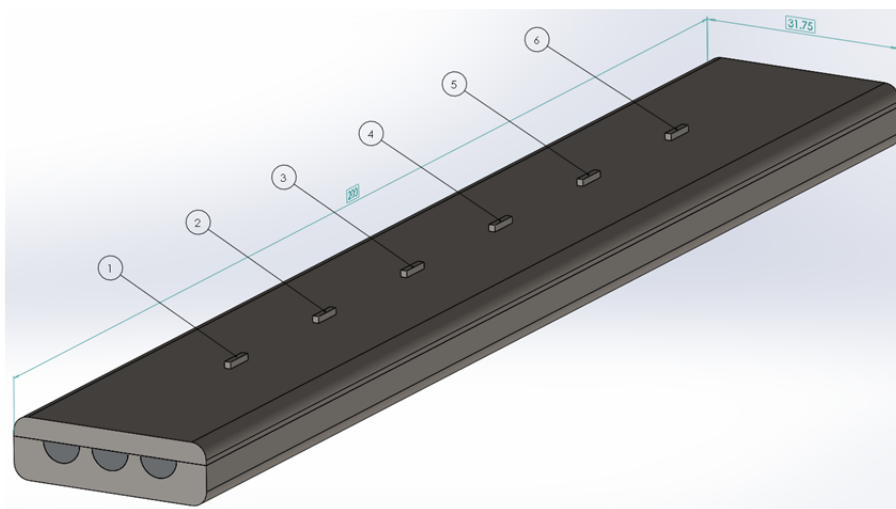


Figure 5-8: 3D model of a section of SPPL constructed for FEA

The post-processor module of the simulator allows various EM field components to be displayed over any arbitrary cross section of the model geometry. Figure 5-9 through Figure 5-11 show the calculated current density at 1Hz, ~180Hz and ~56 kHz, respectively. The three frequencies shown are arbitrarily selected elements of the discretized frequency vector that was used as input to the FEA batch solver. The current density distribution in Figure 5-9 is displayed over an axial cross section through the middle of the sodium channel which is also the plane intersecting the collinear electrodes. The distribution of J over the entire volume of the channel is shown in Figure 5-10 and Figure 5-11. As expected, while the current flow is mainly along the path between the two electrodes, the current density at low frequencies is distributed more uniformly throughout the volume of the channel. The current distribution at the highest frequency on the other hand is confined mostly to a thin layer near the surface. The ACPD probe response is therefore expected to increase as frequency increases. The upper limit of the usable test frequency, however, would be dictated by the skin depth attenuation due to finite conductivity SS layer. Figure 5-12 displays the FEA results for the normalized magnitude of impedance as a function of frequency, from DC to 100kHz. The results of numerical simulations suggest that the measured impedance at frequencies

significantly higher than 10kHz will not provide sufficient sensitivity to changes in conductivity of the sodium channel. This is consistent with the analytical simulation results performed earlier using a simplified model geometry.

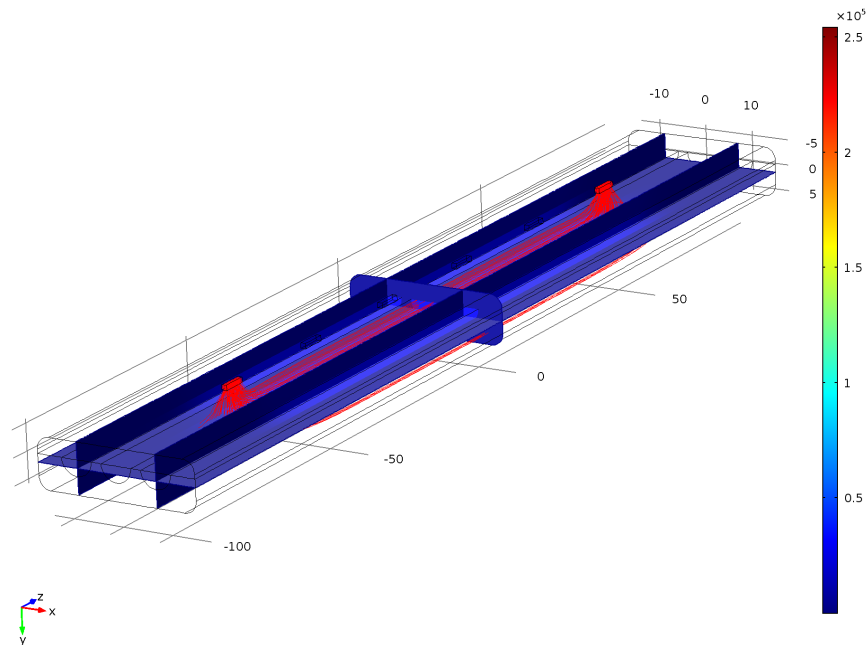


Figure 5-9: Distribution of normalized current density at $f=1$ Hz over an axial cross section through the middle of the sodium channel along the collinear electrodes.

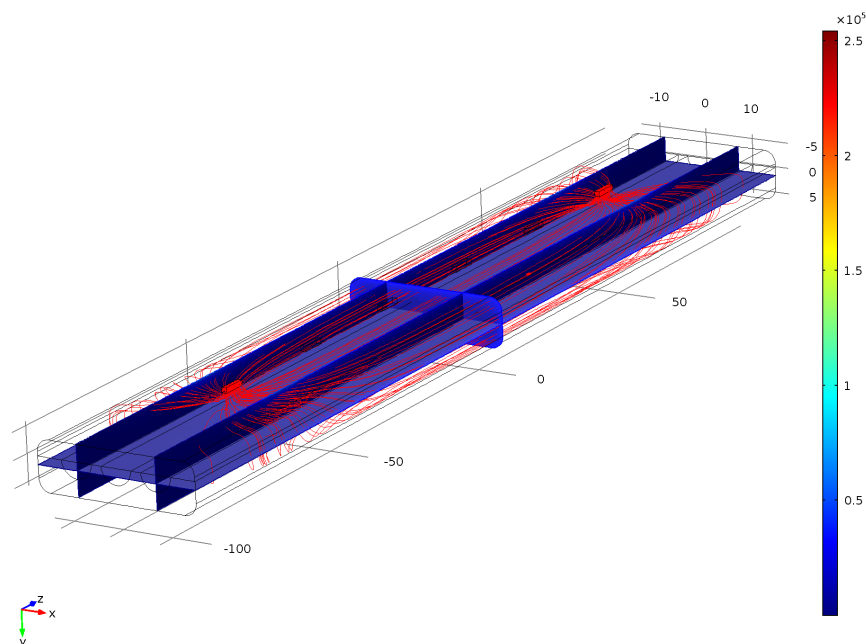


Figure 5-10: Distribution of normalized current density at $f \sim 180$ Hz along the volume of the geometry with the current being injected through the outer-most collinear electrodes.

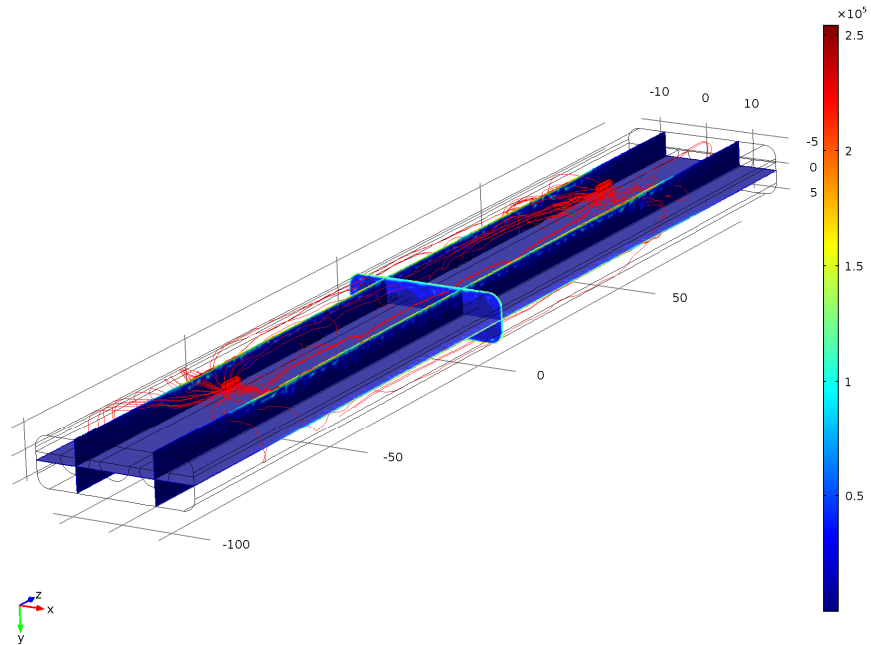


Figure 5-11: Distribution of normalized current density at $f \sim 56$ kHz along the volume of the geometry with the current being injected through the outer-most collinear electrodes.

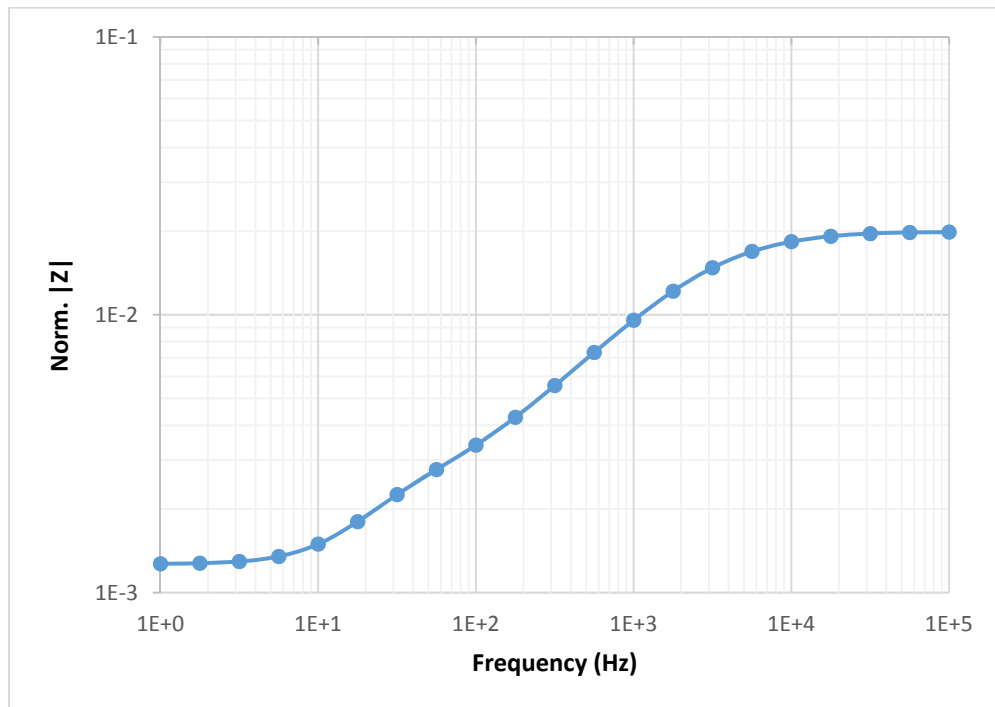


Figure 5-12: Normalized magnitude of impedance as a function of frequency obtained by FEA with the electrodes 1 and 6 of Figure 5-8 used for both signal injection and pick-up.

5.3 Experimental work

Small-scale experiments were conducted to assess the viability of the PD measurement technique for in-situ monitoring of Na_2O deposition in the flow channels of the SPPL. A mockup of the sodium channel fabricated in-house and fitted with SS electrodes at various locations was used to test different excitation and detection configurations for four-point ACPD measurements. Results of bench-scale experiments conducted at ANL are summarized below.

5.3.1 PD measurement system setup

The PD measurement system used for experiment evaluations consists of a wide bandwidth Solartron SI1287 potentiostat/galvanostat, an 8-channel multiplexer (1281), and a frequency analyzer unit (1252A). The block diagram of the system is shown in Figure 5-13. All instruments are interfaced through a GPIB BUS and controlled via a PC. With incorporation of the multiplexer (MUX) unit, current or voltage controlled measurements can be performed sequentially on up to eight devices under test. The PD measurement system connected to the mockup test piece is shown in Figure 5-14. The mockup of the sodium channel is made of 3"x6" (76.2mmx152.4mm) plates separated by two 0.125" (~3.175 mm) SS spacer plates. The thicknesses of the top and the bottom plate are 0.125" (~3.175 mm) and 0.25" (~6.35mm), respectively. To allow testing of different PD excitation and detection configurations, SS wires were welded at ~1" spacing on the top and bottom plates in a collinear probe arrangement as well as to the sides of the upper and lower plate. To simulate the sodium channel, two copper bars with 0.125"x0.125" (~3.175x3.175mm) square cross section were placed side-by-side in between the two SS plates along the channel axis. The separation of the top and bottom plate is adjusted by a series of screws to create a tight contact between the copper channel and the SS plates. In reference to Figure 5-14, the two sets of SS probe wires attached to the top plate run along the copper channel and along an empty channel. This collinear probe configuration is intended to allow for differential ACPD measurements. It is worth noting that a differential probe configuration will most likely be implemented for the planned tests on the SPPL to help reduce the effects of noise from the environment.

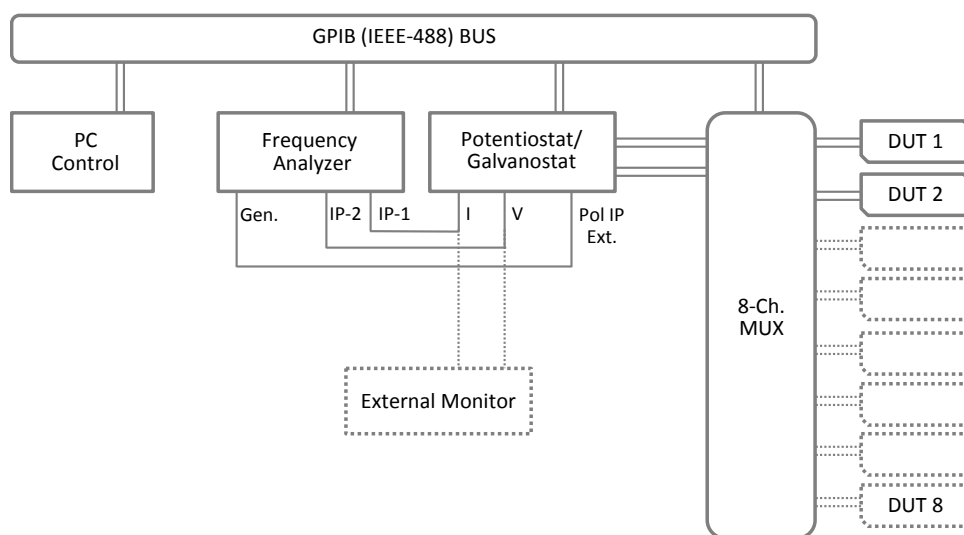


Figure 5-13: Block diagram of the PD measurement system

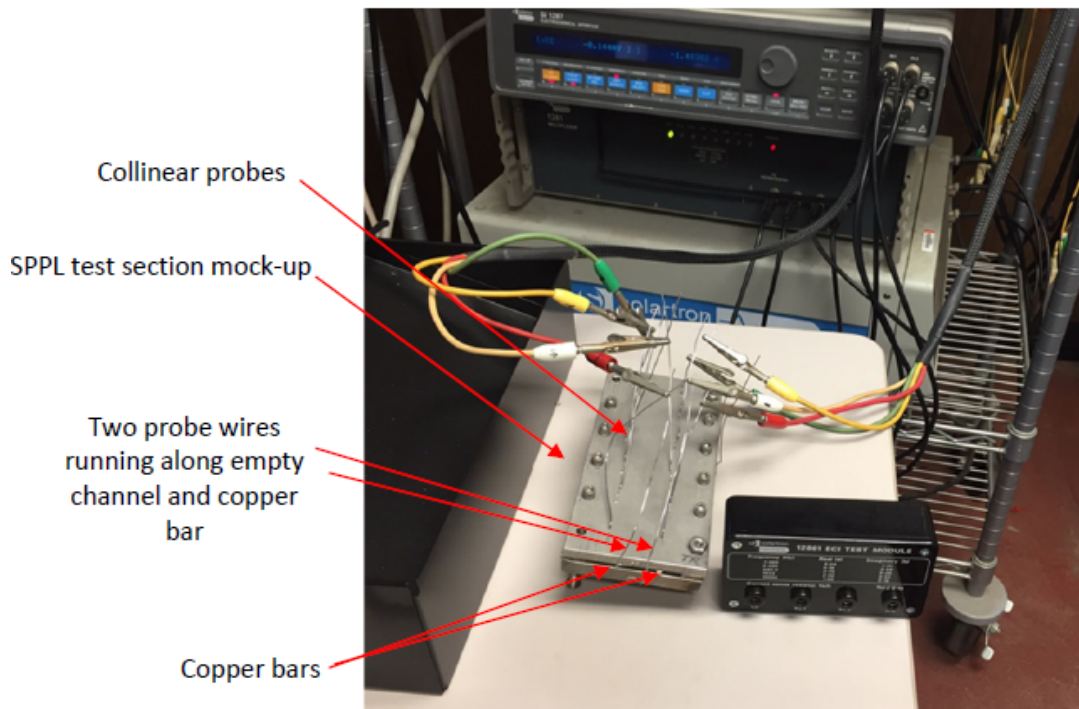


Figure 5-14: Photo of the PD measurement system and the mock-up test piece. Also visible in the foreground is the calibration test module (black box)

Prior to testing of the sodium channel mockup, a series of tests were conducted to confirm proper operation of the PD measurement system. It should be noted that the impedance measurement and analysis software were recently upgraded in preparation for the SPPL tests. Additionally, a software interface was written in the MATLAB environment to load both data file types written by the commercial software used for operating the PD system (CorrWare™ and ZPlot™). A companion MATLAB display program was also implemented that allows tracking of file changes for multiple files (channels) and displaying the data live as files are written, thus allowing for an active display and processing interface for data created by the ZPlot™ software.

The circuit diagram of the calibration module is shown in Figure 5-15. The module is visible in the foreground in Figure 5-14. Results from one of the swept frequency impedance ($Z=R+jX=Z'+jZ''$) measurements is shown in Figure 5.16. Comparison of the impedance plane plot as well as the impedance magnitude and phase over the frequency range of 0.5 Hz to 9.5 kHz matches closely with the prescribed values.

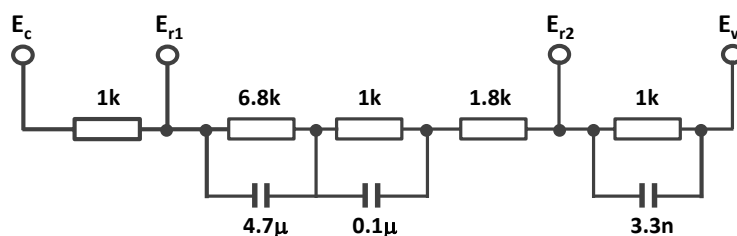


Figure 5-15: Circuit components of the calibration test module.

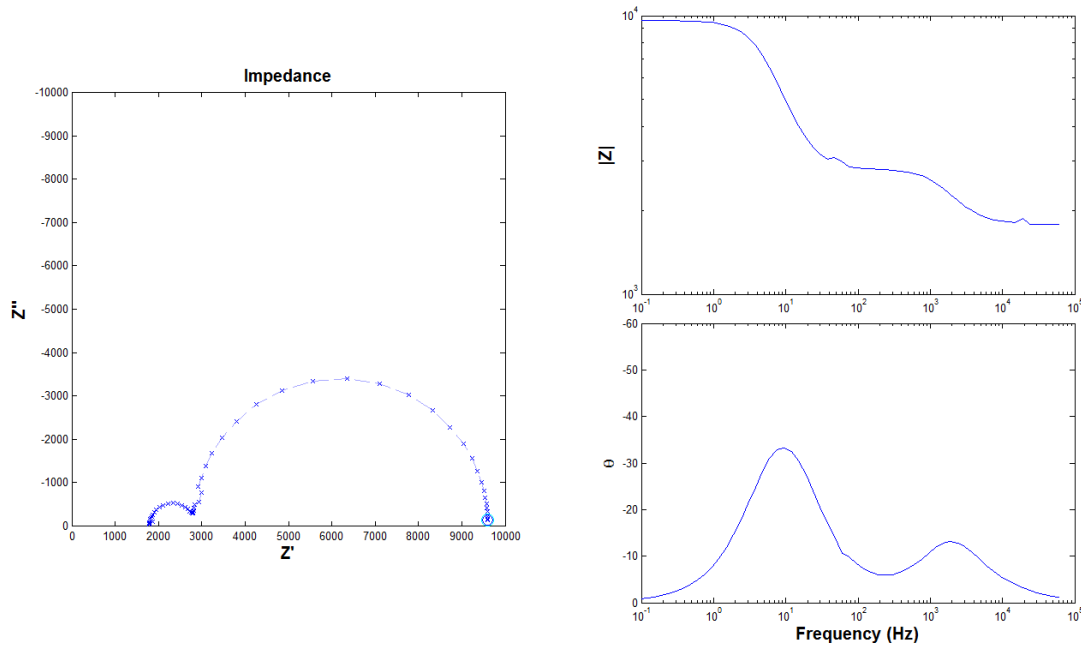


Figure 5-16: Swept frequency response of the calibration module showing (left) impedance plane plot (top right) magnitude and (bottom right) phase of the measured impedance.

Preliminary ACPD measurements were subsequently conducted on the mockup test piece displayed in Figure 5-14. As noted previously, two-channel four-point probe measurements were performed with one set of collinear probes positioned along the copper bars and the other set sensing the airgap in between the plates. For the initial tests, swept-frequency measurements were carried out over the range of 0.1 Hz to 10 kHz. It should be noted that the selection of the upper frequency range was based on the results of analytical investigations conducted previously. In summary, the skin depth at that highest test frequency allows penetration into the copper bar and in turn the ability to sense changes in conductivity of the channel. Representative impedance measurement results for a case in which two copper bars were placed underneath one of the collinear probe sets is shown in Figure 5-17. Similar tests were also conducted by placing a single copper bar under one of the collinear probe sets. The magnitude of the measured differential impedance for the test cases in which one and two copper bars were sequentially placed under one set of collinear probes is shown in Figure 5-18. These preliminary results are qualitatively in good agreement with the analytical modeling results performed earlier. The ACPD measurement results also indicate the ability of the technique to sense small changes in the conductivity of the channel. Furthermore, operation at higher frequencies may be necessary to obtain acceptable sensitivity to changes in the sodium channel. Follow-on studies on determination of optimum operating frequency range as well as PD probe configuration are discussed in the next section.

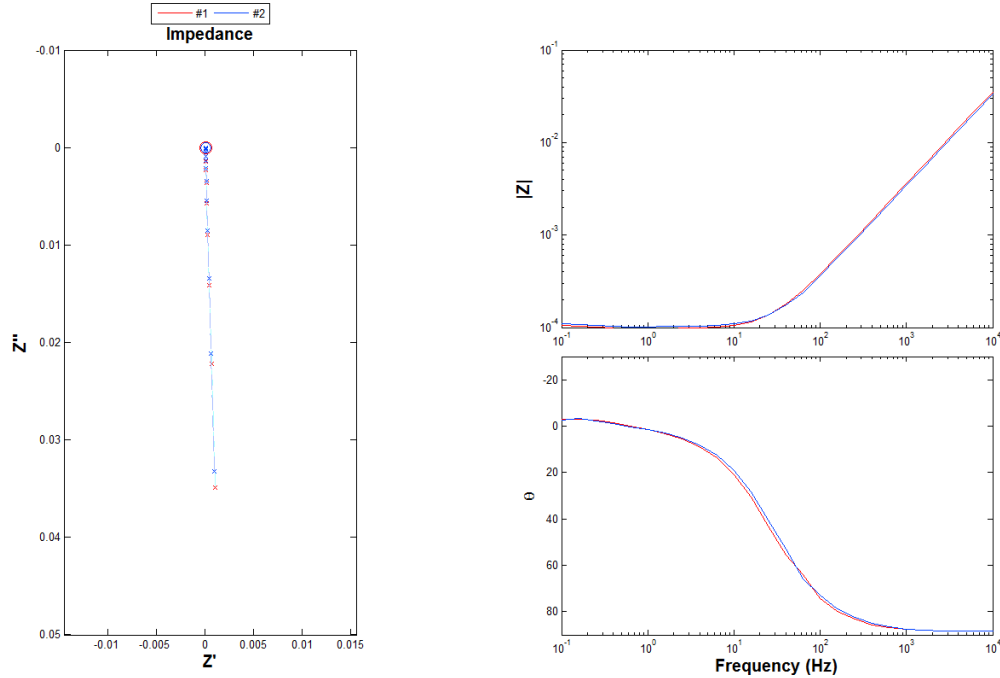


Figure 5-17: Swept frequency ACPD measurement of impedance components over the range of 0.1 Hz to 10 kHz

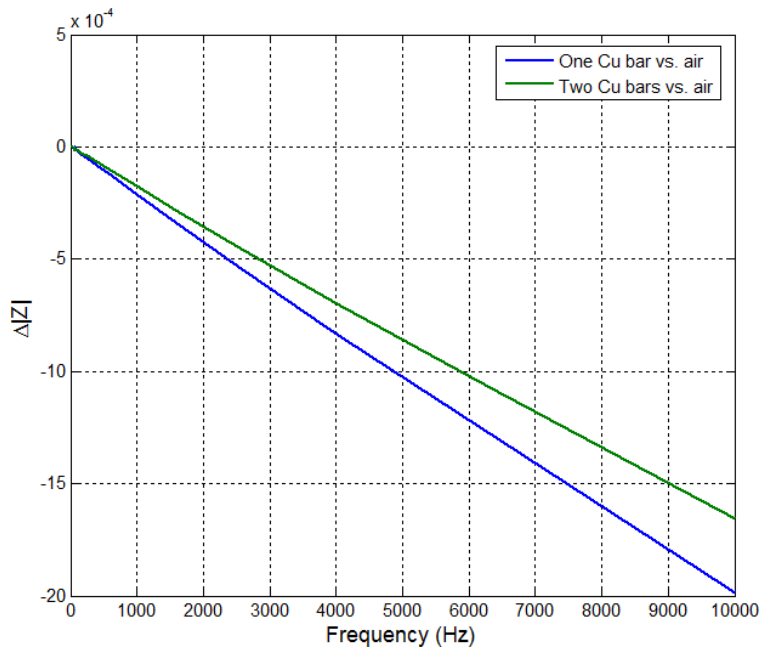


Figure 5-18: Swept frequency ACPD measurement of the differential impedance magnitude over the range of 0.1 Hz to 10 kHz

5.3.2 Bench-scale experiments on four-point PD measurement

Description of the PD measurement system used for bench-scale experimental evaluations was provided in the previous section. The system consists of a wide bandwidth

potentiostat/galvanostat, an 8-channel multiplexer, and a frequency analyzer unit. Figure 5-19 shows the complete rack-mounted system. All instruments are interfaced through a GPIB BUS and controlled via a PC. A software interface was implemented under the MATLAB environment to load both data file types written by the commercial software used for operating the PD system. A companion MATLAB display program was also implemented that allows tracking of file changes for multiple files (channels) and displaying the data live as files are written, thus allowing for an active display and processing interface for data created by the commercial software. Further refinements have since been incorporated into the MATLAB-based tools used for the analysis and visualization of the impedance data.

As described previously, the small-scale mockup of the sodium channel used for PD experiments (inset in Figure 5-19) is made of 3"x6" (76.2mmx152.4mm) plates separated by two 0.125" (~3.175 mm) SS spacer plates. The thicknesses of the top and the bottom plates are 0.125" (~3.175 mm) and 0.25" (~6.35mm), respectively. To allow testing of different PD excitation and detection configurations, SS wires were welded at ~1" spacing on the top and bottom plates in a collinear probe arrangement as well as to the sides of the upper and lower plate. To simulate the sodium channel, two copper bars with 0.125"x0.125" (~3.175x3.175mm) square cross section were placed side-by-side in between the two SS plates along the channel axis. The two sets of SS probe wires attached to the top plate run along the copper channel and along an empty channel. This collinear probe configuration is intended to allow for differential ACPD measurements. Based on the studies conducted so far, it has been determined that a differential probe configuration is a more suitable approach for the planned tests on the SPPL as it can help reduce the effect of noise from the environment.

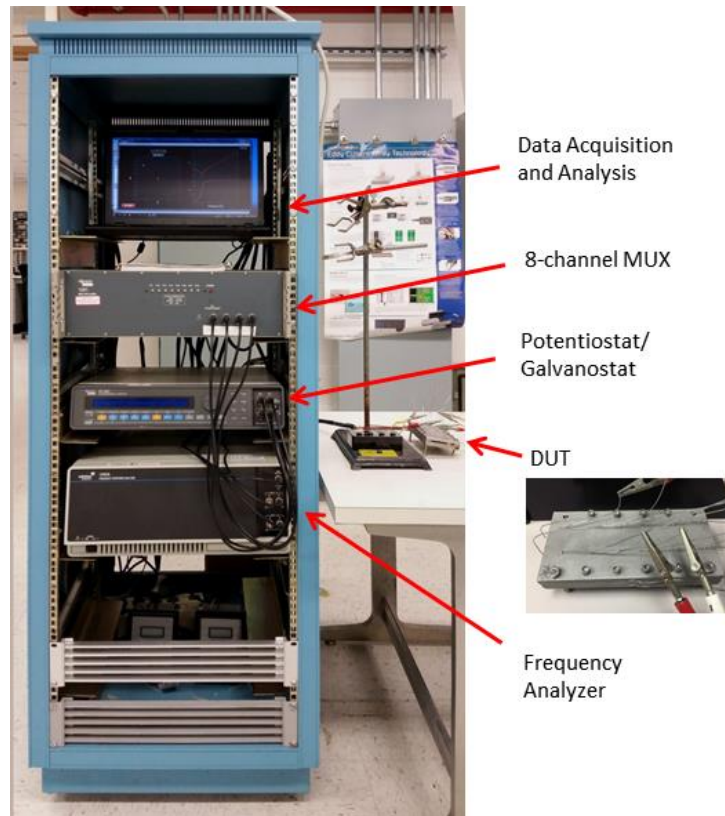


Figure 5-19: Photo of the rack-mounted PD measurement system and the mockup test piece. The instrumentation and the device under test are marked on the figure.

A series of tests were conducted to evaluate the effect of probe configuration on the measurement results. The ACPD measurements were made on the mockup test piece with the excitation electrodes placed on the top, bottom, and the sides of the upper and lower plates as shown in Figure 5-20). The E_c and E_w are the input signal ports and E_{r1} and E_{r2} are the pickup signal ports. In all cases, the two-channel four-point probe PD measurements were performed with one set of collinear probes positioned along the copper bars and the other set sensing the airgap in between the plates.

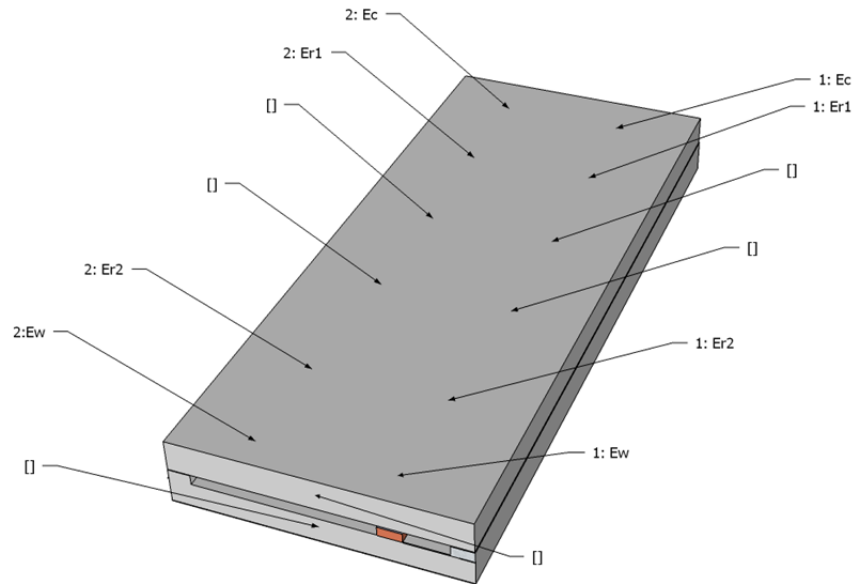


Figure 5-20: Drawing of the mockup test piece showing the location of signal injection electrodes (E_w and E_c) and signal pickup electrodes (E_{r1} and E_{r2}). Not shown are the electrodes placed at the bottom and the side (along the length) of the plate.

Swept frequency measurements with a constant current of 1A were made over the range of 0.1 Hz to 10 kHz. Figure 5-21 shows a representative display of the measured frequency response of the test piece displaying the impedance plane plot as well as the magnitude and phase of the measured impedance, $Z=R+jX=Z'+jZ''$, over the range of 0.1 Hz to 10 kHz. In this case, the top and bottom electrodes were used as the excitation ports. The MATLAB-based GUI implemented at Argonne displays the impedance data in near real time. An accompanying MATLAB script is used for subsequent analysis of the data.

Figure 5-22 displays a series of swept frequency differential impedance measurements using different excitation and pickup electrode configurations. As marked on the figure, from top to bottom legend, the configurations include 1) E_w and E_c at outermost electrodes on top plate and E_{r1} and E_{r2} at the nearest inner electrodes on top plate (see Figure 5-23), 2) same as Configuration 1 with all electrodes moved 1" inward, 3) E_w and E_c at outer most electrodes on top plate and E_{r1} and E_{r2} at the innermost electrodes on top plate, 4) E_w and E_c along the width of the top and bottom plates and E_{r1} and E_{r2} at the innermost electrodes on the top plate, 5) same as Configuration 4 but with E_w and E_c reversed (i.e., opposite polarity), 6) E_c along the width of the top plate, E_w on the bottom plate (far side), and E_{r1} and E_{r2} at the innermost electrodes on top plate, and 7) E_c along the width of the top plate, E_w on the bottom plate (near side), and E_{r1} and E_{r2} at the innermost electrodes on top plate. The results shown in Figure 5-22 suggest that for the test cases examined so far the collinear probe arrangement for which the excitation and pickup electrodes are on the same side (i.e., Configurations 1 to 3) and along the channel length provide the largest differential impedance values. Furthermore, the magnitude of the differential impedance is larger when the excitation electrodes are farther apart and the pickup electrodes are closer to the excitation electrodes (i.e., Configuration 1).

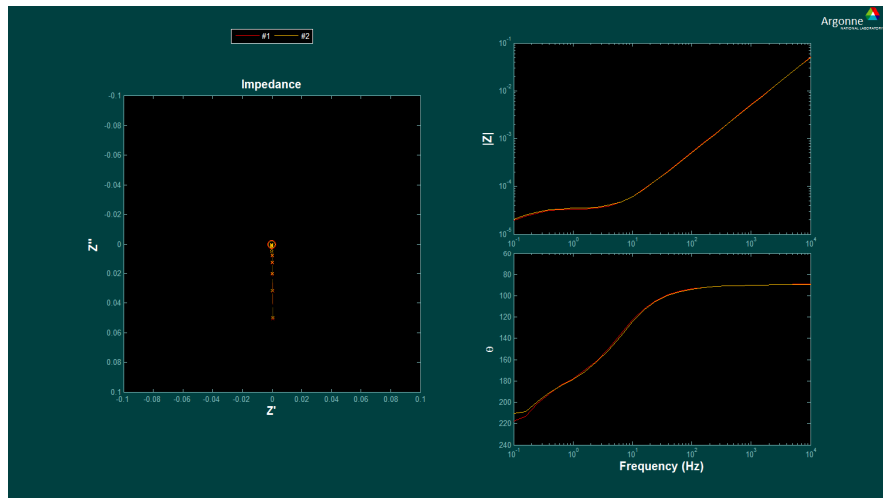


Figure 5-21: Representative display of the measured frequency response on the test piece showing (left) impedance plane plot (top right) magnitude and (bottom right) phase of the measured impedance over the range of 0.1 Hz to 10 kHz

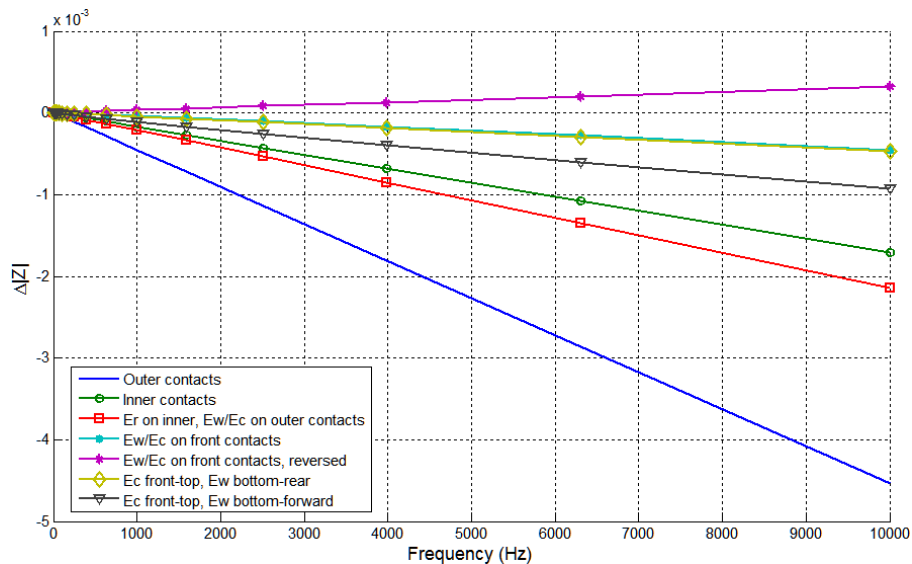


Figure 5-22: Swept frequency ACPD measurements showing the differential impedance magnitude over the range of 0.1 Hz to 10 kHz using different excitation and pickup electrode configurations

A set of experiments were last conducted to further assess the sensitivity of the ACPD monitoring method to changes in flow channel conductivity. Four-point probe measurements were performed on the mockup test piece by using the same voltage and current leads for PD measurements on the reference (airgap) and on the test (Cu bar) channel. The electrode numbering along the airgap and the Cu bar insert that was used for these tests is shown in Figure 5-23. The tests in all cases were performed by applying a current of 2A across the outer most electrodes on both the airgap (A1 and A6) and the Cu (B1 and B6) channel. The potential was measured between different sets of electrodes along the airgap (A1-A6, A2-A5, A3-A4) and along the Cu insert (B1-B6, B2-B5, B3-B4). It

is worth noting that unlike the previous test cases for which a differential measurement configuration was used, the tests here were performed in an absolute manner. This was done to more directly assess the sensitivity of the measurement system by minimizing the influence of variables such as the differences among probe leads. However, as discussed previously, a differential configuration is more likely to be implemented for actual on-line monitoring applications.

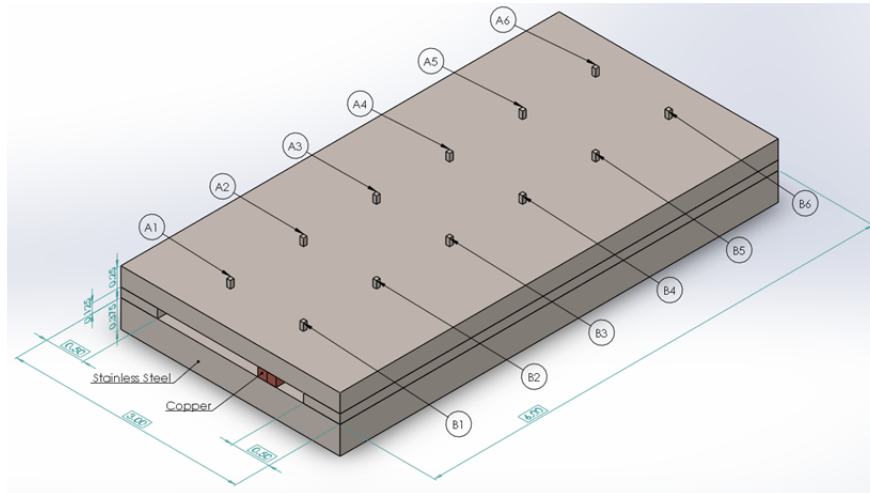


Figure 5-23: Location and labeling of electrodes on the mockup test piece.

ACPD measurements were performed in absolute mode over the frequency range of 10Hz to 40kHz. Potential drop measurements across each pair of pick-up electrode were repeated several times to estimate the error bounds associated with measurement variability. Based on past experience, the use of temporary connectors is often the primary source of measurement variability. The data for the test case in which the potential was measured across the outer-most electrodes (A1/A6 and B1/B6) is plotted in Figure 5-24. The magnitude and phase of the complex impedance as a function of frequency is shown in Figure 5-24 (a). The same data plotted as real and imaginary component of impedance is shown in Figure 5-24 (b). Both the mean value and the deviation (error bars) are plotted on each graph. The difference in measured absolute PD values between the two channels is clearly distinguishable up to about 10kHz. Similar measurements were also conducted using the inner pairs of electrodes for PD measurement. Although not shown here, the experimental results indicate that the highest sensitivity among the test cases examined is achieved when the outer-most electrodes are used for both excitation and pick-up. The sensitivity here is defined as the largest difference between the measured PD between the airgap and the Cu channel. In agreement with the numerical simulation results, the experimental data also indicate that at frequencies above 10kHz the difference in effective impedance between the two channels becomes difficult to measure reliably.

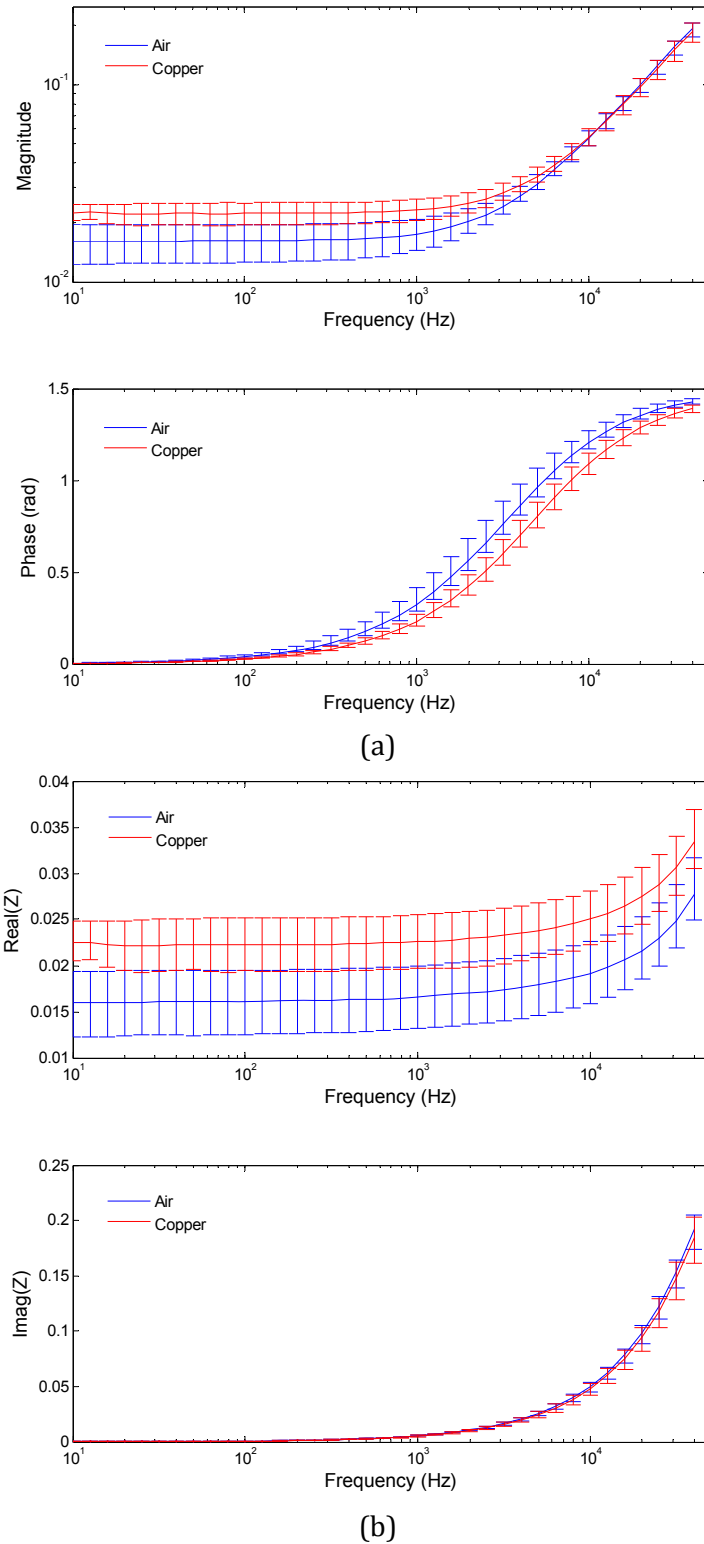


Figure 5-24: Measured (a) magnitude and phase and (b) real and imaginary components of impedance as a function of frequency using the outer-most electrodes in Figure 5-23

5.4 Conclusions on PD technique

Theoretical and experimental investigations were conducted at ANL to assess the viability of ACPD measurement technique for in-situ monitoring of sodium oxide deposition in the flow channels of the SPPL. The challenging environment of SPPL limits the use of many conventional on-line monitoring techniques. Proof-of-concept studies were carried out on the use of PD method as a potential on-line diagnostic technique as it offers good sensitivity to changes in electrical properties of layered structures and is well suited for operation in high temperature environments. The viability of the PD method was evaluated through sensitivity analysis studies using analytical and computational modeling. A PD measurement system was assembled for bench-scale experiments using a small-scale mockup of the sodium channel. The results of applied research efforts conducted to date suggest that the ACPD method is a viable approach to on-line monitoring of sodium flow channels.

5.5 Recommendations for future work

Viability of ACPD method as a potential candidate for on-line monitoring of sodium flow channels has been demonstrated under this project through theoretical studies and through small scale mockup experiments. Further evaluations, however, are needed to fully demonstrate the utility of the ACPD method as an on-line monitoring technique for the diagnosis of sodium oxide deposition. Follow-on R&D efforts in this area should conceivably include the following tasks:

- Experimental validation of ACPD diagnostic technique through on-line monitoring of SPPL during actual plugging testing
 - Install the ACPD instrumentation onto the test section determining the most appropriate probe placement and coupling method based on the actual test section constraints;
 - Evaluate the system developed at ANL under actual deposit formation conditions during plugging tests;
 - Calibrate the results versus results from the UTDR measurements and flow meter measurements; and
 - Refine system hardware and software based on feedback from the experiment investigations.

6. Project products

Table 6.1 is a summary of the publications and presentations originated from the project.

Table 6.1: List of products originated from the project

	Type of product	Event/journal title	Product title	Author(s)	Date
1	Panel presentation	Panel on “Department of Energy Investments in Advanced Nuclear Power” at ANS 2013 Winter Meeting	Modeling and Validation of Sodium Plugging for Heat Exchangers in Sodium-cooled Fast Reactor Systems	P. Ferroni, J. Sienicki	Nov 13, 2013
2	Conference paper	ANS Winter meeting, Anaheim, CA	CFD Modeling of Heat and Mass Transfer in Heat Exchangers of Sodium-Cooled Fast Reactor Systems	E. Tatli, M. Dzodzo, P. Ferroni	Nov 9-13, 2014
3	Conference paper	American Institute of Chemical Engineers annual conference, Atlanta, GA	Evaluation of Liquid Sodium Impurity Deposition Models for Sodium-Cooled Fast Reactor Heat Exchangers	J. P. Mazzocchi, E. Tatli	Nov 16-21, 2014
4	Internal presentation	Westinghouse internal meeting with Bob Hill, Technical Director of Advanced Reactor R&D at ANL	Modeling and Validation of Sodium Oxide deposition and Heat Exchanger plugging in SFR Systems	P. Ferroni et al.	March 23, 2015
5	Internal presentation	Westinghouse internal meeting with Toshiba	Advanced Non-light Water Reactors: some activities in Westinghouse	P. Ferroni et al.	March 26, 2015
6	Conference paper	16th International Topical Meeting on Nuclear Reactor Thermal Hydraulics (NURETH-16), Chicago, IL	CFD Modeling of Sodium-Oxide Deposition in Sodium-Cooled Fast Reactor Compact Heat Exchangers	E. Tatli, J. Mazzocchi, P. Ferroni	Aug 30 – Sept 4, 2015
7	Presentation	DOE ARC-13 Program Review Meeting, Argonne National Laboratory	Modeling and Validation of Sodium Plugging for Heat Exchangers in Sodium-cooled Fast Reactor Systems	P. Ferroni, E. Tatli, M. Dzodzo, L. Czerniak, J.J. Sienicki, Y. Momozaki, H-T Chien, S. Bakhtiari	Nov. 19, 2015

7. Conclusions and recommendations for future work

The project “Modeling and Validation of Sodium Plugging for Heat Exchangers in Sodium-cooled Fast Reactor Systems” was conducted jointly by Westinghouse Electric Company and Argonne National Laboratory (ANL), over the period October 1, 2013- March 31, 2016. With the ultimate goal of informing the design of small-diameter sodium heat exchanger (HX) channels, such as those in the diffusion bonded HXs proposed for SFR-sCO₂ systems, a state-of-the-art CFD model with Na₂O deposition prediction capabilities was developed. This model accurately reproduces the key features of the Sodium Plugging Phenomena Loop (SPPL), which was designed and built at ANL to obtain fundamental data on channel plugging induced by the precipitation of oxygen impurities in liquid sodium flowing through prototypical sodium-to-CO₂ HX channels under well-controlled experiment conditions. This tool incorporates a first-principles Na₂O deposition model developed by ANL, and combines it with predictive capabilities for the spatial and temporal variation of temperature, velocity, dissolved oxygen concentration, and wall temperature under flowing sodium conditions. The CFD model was validated under no-deposition conditions using experimental data collected with the SPPL, demonstrating the model’s capability to predict the thermal-hydraulics of the SPPL test section within the measurement uncertainty characterizing the SPPL instrumentation. The model’s deposition prediction capability was not, however, validated as the SPPL could not be operated under plugging conditions during the project, resulting in the lack of deposition data with adequate pedigree for a CFD model validation. However, in preparation for when plugging tests will be conducted, the project developed two novel diagnostic techniques, namely Ultrasonic Time Domain Reflectometry (UTDR) and Potential Drop (PD) techniques, to detect and characterize Na₂O deposits, particularly their thickness, thus providing a fundamental tool for the CFD model validation under plugging conditions.

After analytically and/or computationally demonstrating these techniques’ capability to diagnose Na₂O deposits inside of small channels, prototypical UTDR and PD instrumentation was fabricated and tested. The testing, performed on mockups of the SPPL test section, demonstrated the capability of these techniques to detect and characterize material discontinuities like those induced by sodium oxide deposition on stainless steel channel walls. Because of the mentioned impossibility to run the SPPL in a plugging mode, the developed instrumentation could not be tested in-situ, i.e. at the SPPL while deposits are being formed inside of the SPPL test section.

Recommended future work is discussed below for the CFD modeling and for the in-situ, high-temperature testing of the UTDR and PD techniques, respectively.

Recommended future work for CFD modeling

Below is a list of suggested future work and improvements to the deposition CFD model:

- The main challenge with the current deposition model is the integration of quantities within ANSYS CFX, specifically the deposit mass within each control volume. Although there are unsupported ways of resolving some integration challenges, due to the recursive nature of the deposition calculation and interdependencies, a more stable and robust approach is needed. This may require eventual use of a beta release of CFX with changes made in solver settings.

- Once the previous integration challenges are solved, the appropriate mass sources and sinks based on the sodium and oxygen inventories, and on the generated sodium oxide mass, need to be adequately updated for the next time step calculation.
- An investigation on the energetics of the sodium oxide formation is recommended. This investigation will inform the potential addition of adequate energy sources or sinks in the energy equation, to take into account the energy needed to form sodium oxide.
- The current deposition model is demonstrated with fluid-only domain and temperature boundary conditions are directly applied to the sodium channel surfaces. Addition of solid steel wall domains and application of conjugate heat transfer (as done for the developed loop CFD model) will help to smooth sharp temperature changes at the sodium channel surfaces that cause stability issues.
- In the current CFD deposition model, the inlet velocity and oxygen concentrations are provided as constant values. In reality, as sodium oxide is deposited on the channel walls:
 - portion of the flow to the channel will be redirected to the cold trap bypass channel due to the backpressure increase due to plugging, and
 - the fixed initial oxygen concentration in the loop will start to decrease as oxygen is removed from the flow with the deposit.

Hence, these boundary condition values need to be continuously adjusted throughout the transient run, at the inlet of the test section.
- Inclusion of turbulence sinks to account for the deposit formation.
- If computational resources are available, the mesh can be further refined in the area of oxide formation, resulting in an increase of the resolution of the applied methodology.
- If mesh refinement becomes prohibitive because of memory and processing time limits, introduction of methods to track the formation of the interface (transitional zone) between the sodium and sodium oxide, as well as mesh readjustments, might be considered.

Recommended future work for in-situ, high-temperature testing of UTDR and PD techniques

Recommended future work aims at in-situ, high-temperature testing of the developed UTDR and PD instrumentation, data collection and ultimately completion of the CFD model validation. To this end, the following tasks are recommended:

- Installation of the developed UTDR and PD instrumentation on the SPPL test section followed by plugging tests. This will allow collection of Na₂O deposition data after the onset of deposition to nearly complete channel plugging.
- Reduction in SPPL flowmeter measurement uncertainty through re-calibration efforts, for example by installing an electrical contact-type probe in the expansion tank, together with an ultrasonic-type surface detection probe.
- If, as demonstrated analytically/computationally, satisfactory signals are detected during plugging tests by the installed instrumentation, UTDR and PD techniques will need to be calibrated against, for example, a piece of tubing containing a deposit of known size.

- Refinement of UTDR and PD system hardware and software based on feedback from the experiment investigations.
- CFD model validation under plugging conditions, using experimental data collected by calibrated UTDR and/or PD instrumentation during plugging tests. This validation will include CFD model refinement.

Appendix A: Analyses in support of CFD modeling

A.1 Early mesh and turbulence model validations for the no-plugging CFD model

This section presents the early validation studies for the base no-plugging CFD modeling approach candidates tested against the available experimental data in literature. The focus geometry of these comparisons is the step contracting pipe as an acceptable representation of the thermal-hydraulics characterizing the SPPL transition piece between the SPPL main line and the semi-circular test channels as presented in Figure A- 1.

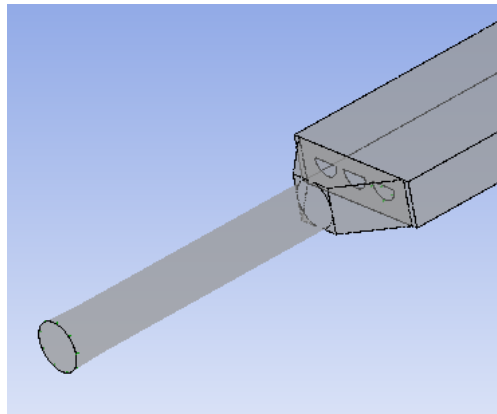


Figure A- 1: Inlet transition piece to the test sections in the CFD model

The CFD results for the contracting pipe case with fully turbulent flow with constant liquid sodium properties and constant wall heat flux are presented, and compared to the correlations in literature. Three different turbulence models and two meshes were used.

The computational domain analyzed for the contracting pipe case is shown in Figure A- 2.

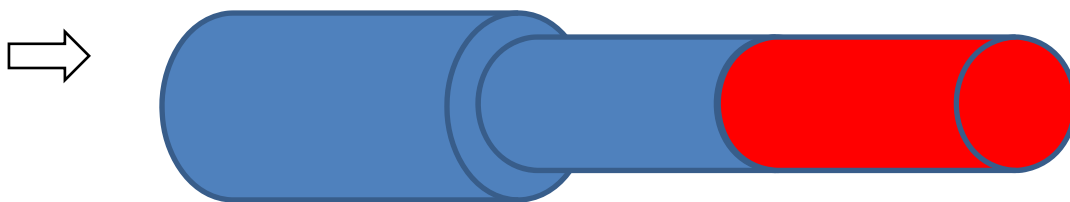


Figure A- 2: Contracting pipe domain (not drawn to scale)

The cross sectional dimensions were chosen to mimic the dimensions of the transition piece connecting to the test section as shown in Figure A- 1. The length dimensions were chosen to allow the flow to hydro-dynamically fully develop in each of the individual section.

Section 1: Diameter = 0.275 in, Length = $150 \times D = 41.25$ in

Section 2: Diameter = 0.236 in (=6 mm), Length = $200 \times D = 47.2$ in

Section 3: Diameter = 0.236 in (=6 mm), Length = $100 \times D = 23.6$ in

The inlet flow rate was set to 1 m/s, providing a Re number of $\sim 15,500$ simulating a fully turbulent case. Inlet temperature was set to 300°C based on [2], and the constant sodium properties used in the simulation were based on this temperature. These values are provided below, extracted from [26].

- Density = 879.31 kg/m^3
- Dynamic viscosity = $0.000341 \text{ Pa}\cdot\text{s}$
- Thermal conductivity = 76.670 W/mK
- Heat capacity = 1309.205 J/kgK

These values, in addition to the Re number given above, provide a Prandtl number (Pr) of 0.006 and Peclet number (Pe) of 90.089.

Section 3 shown in Figure A- 2 is the cooled section of interest of the domain and all other walls were set to adiabatic. The value for the uniform heat flux applied (cooling) to the walls of Section 3 was extracted from [28], and was calculated to be $\sim 12,500 \text{ W/m}^2$. Outlet was set as a pressure outlet with gage pressure of 0 psi.

CFX was used for the simulations. Three turbulence models were chosen: SST k- ω with automatic wall treatment, k- ϵ with scalable wall function and RNG k- ϵ with scalable wall function (improved wall heat transfer compared to standard k- ϵ). Wall y^+ values were in the range of the used turbulence models ($y^+ < 1$).

Two separate meshes were generated using TrueGrid. The fine mesh included ~ 20.6 million hexahedral computational cells, whereas the coarse mesh included ~ 3.4 million hexahedral computational cells (no difference in cell density along the flow direction for both meshes). Figure A- 3 presents sample cut planes perpendicular to the flow direction in Section 3 of the CFD model.

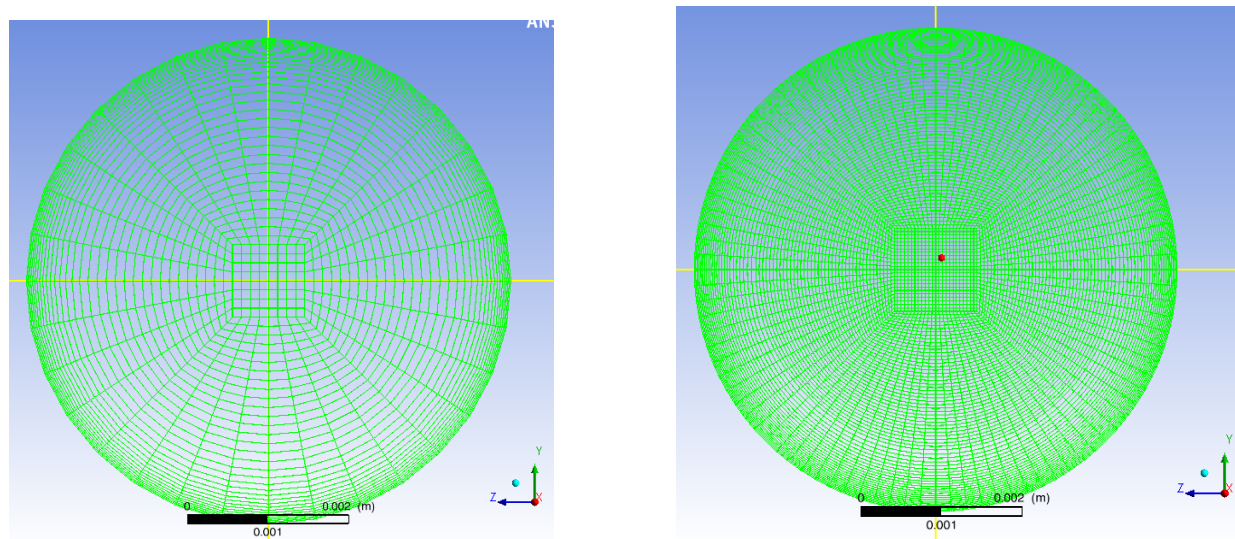


Figure A- 3: Coarse (left) and fine meshes on cut planes, showing cell density

There is great scatter in the heat transfer correlations in the literature due to reasons explained prior. Ref. [22] provides various correlations for liquid metals (and not just sodium), some of most commonly used are presented below for constant wall heat flux case.

- Lyon (1951)

$$Nu = 7.0 + 0.025x(Pe/Pr_t)^{0.8} \quad \text{for } 0 < Pr < 0.1 \text{ and } 4000 < Re < 3.2 \times 10^6$$
- Notter and Sleicher (1972)

$$Nu = 6.3 + 0.0167x(Pe)^{0.85} \quad \text{for } 0.004 \leq Pr \leq 0.1 \text{ and } 10^4 \leq Re \leq 3.2 \times 10^6$$
- Lee ([23])

$$Nu = 3.01xRe^{0.0833} \quad \text{for } Pe < 100$$

The results of the CFD analyses and comparison to correlations are given below in Table A- 1. Note that the Nusselt number (Nu) value presented for the CFD studies is the average taken after the flow was fully developed in Section 3 of the pipe. Based on the comparison with CFD results the SST k- ω model, with both fine and coarse mesh, produces results closest to the literature correlations considered.

Table A- 1: Nu values from correlations and CFD analyses

Source	Nu
Lyon	7.03
Notter and Sleicher	7.07
Lee	6.72
CFD Case 1: SST k- ω , fine mesh	7.28
CFD Case 2: k- ϵ , fine mesh	8.94
CFD Case 3: RNG k- ϵ , fine mesh	8.85
CFD Case 4: SST k- ω , coarse mesh	7.32
CFD Case 5: k- ϵ , coarse mesh	8.99
CFD Case 6: RNG k- ϵ , coarse mesh	8.89

A.2 Turbulent Prandtl number sensitivity study

In order to determine the dependence of the simulation results on the turbulent Prandtl number (Pr_t), sensitivity studies were conducted with different Pr_t values with an earlier SPPL CFD model (different than the model documented in Section 3.3). It is widely known that the default 0.9 value (which is suitable for water and air flow simulations) used in commercial CFD software including CFX (in which many of the widely used turbulence models are based on the eddy diffusivity concept) may not allow accurate modeling and that the Pr_t for liquid metals is expected to be greater than 1 (exact values being case-dependent). But there are very few data points in literature in the Peclet (Pe) number range (less than 10 to 100) expected to be observed in the SPPL that document Pr_t values for liquid metals.

Due to the flow rate ranges expected in the SPPL, the flow regime in the test channels may either be laminar, turbulent, or even transitional (especially with the possible presence of sodium oxide deposits). And even with low enough flow rates in the loop that may demonstrate a laminar profile in the test sections, other parts of the loop (T-junctions, contractions before the test sections, etc.) may show turbulence (as presented earlier in the transition regions). For this reason, a turbulence model (SST k- ω) was used for both laminar and turbulent cases. Thus, to cover the range of flow

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rates, a total of six simulations were conducted on the domain shown in Figure A- 4 to test Pr_t sensitivity: Three simulations were conducted with constant Pr_t values, implemented for the fully turbulent case: 0.9 (CFX default), 4.12 [24], and 5.6 (extrapolated for Pe from [25]), and three cases were conducted again with constant Pr_t values but implemented for the laminar case (using a turbulence model), and with the same three Pr_t values used for the turbulent case. The Pr_t values presented in Ref. [25] are given at 300°C, but since Pr_t decreases with increasing Pe (thus increasing temperature at constant velocity for sodium), the Pr_t values of 5.6 and 6.5 (for turbulent and laminar, respectively) were selected as high limiting values.

The conditions for the six tests are presented below.

- $Re \approx 900$ and 11,000 (in test channels)
- $Pr_t = 0.9, 4.12$ and $5.6/6.5$ (for turbulent and laminar, respectively)
- $h = 2 \text{ W/m}^2\text{K}$ for laminar and $100 \text{ W/m}^2\text{K}$ for turbulent, with $T_{\text{ambient}} = 15^\circ\text{C}$

(In addition to the above six cases, a case with $Re \approx 900$ was also run in laminar settings and the results were same as the SST $k-\omega$ model results.)

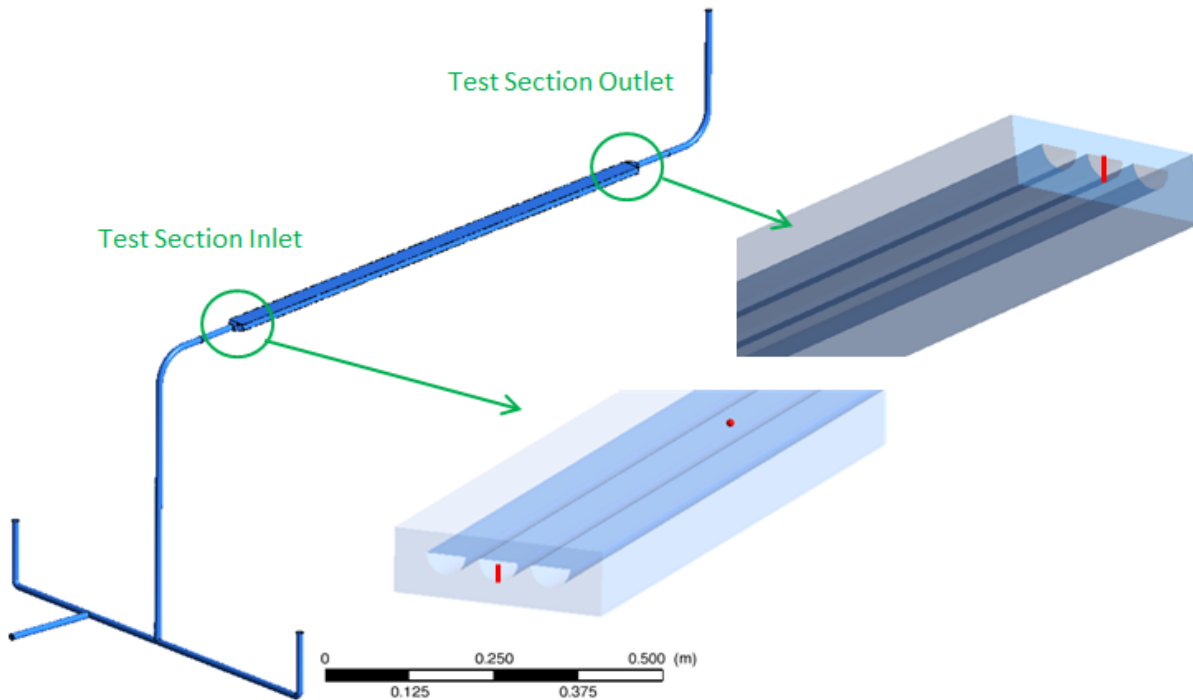


Figure A- 4: CFD domain and post-process lines shown in red

Overall, there were no appreciable differences observed in either temperature or velocity profiles, as shown in Figure A- 5 and Figure A- 6, respectively, which refer to the $Re \approx 11000$ case at the inlet and outlet of the center test channel. Hence, due to small differences in results observed between Pr_t values of 4.12 and 5.6/6.5, the value of 4.12 was selected to be used for the validation studies as this was the value directly provided in Ref. [24] for $Pe \leq 1000$, thus not requiring any extrapolation and any temperature dependency assumptions.

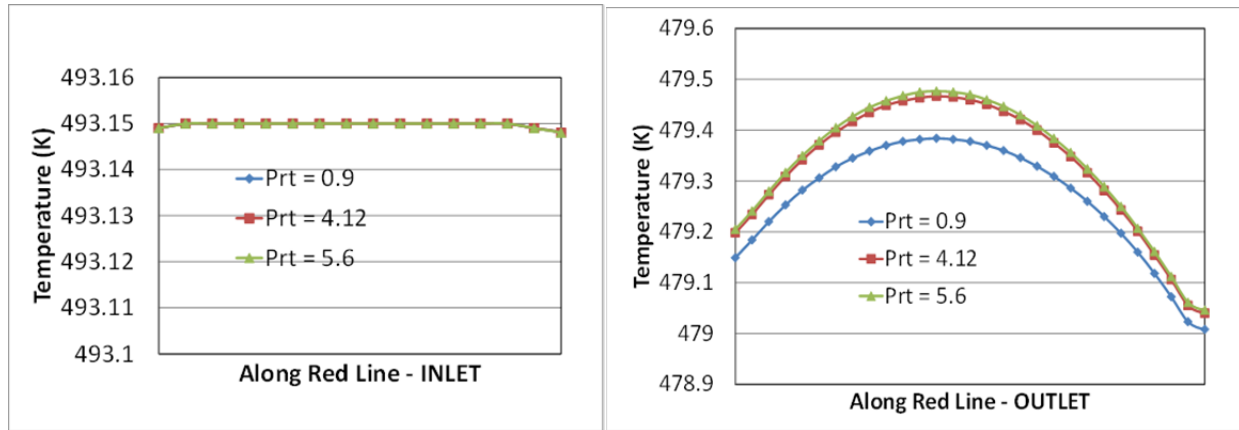


Figure A- 5: Temperature profile along the post-processing red line at the inlet (left) and outlet (right) of the middle test section

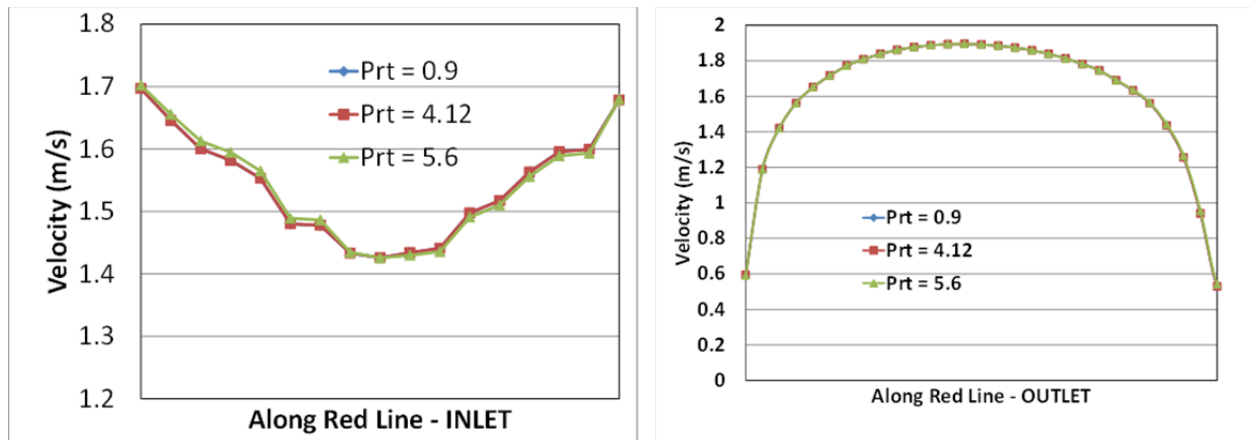


Figure A- 6: Velocity magnitude profile along the post-processing red line at the inlet (left) and outlet (right) of the middle test section

A.3 Turbulence model versus laminar settings sensitivity for the early stage plugging CFD model

The SST $k-\omega$ turbulence model was used for all the cases within the first stage plugging CFD model sensitivity studies regardless of Re values and possible flow regime changes due to the channel narrowing and possible recirculation zones downstream of the deposits. To evaluate applicability of turbulence modeling for low Re number (in fact laminar flow) cases, Case 5 presented in Table 3.4 was simulated with both SST $k-\omega$ turbulence model and with no turbulence model. Figure A- 7 presents the contour plots of sodium mass fraction around the cooled wall, showing no visually significant difference.

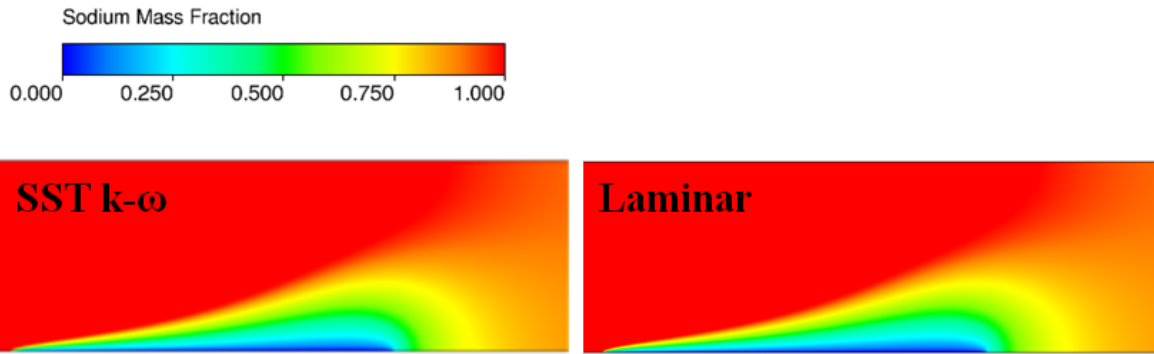


Figure A- 7: Comparison of sodium mass fraction contour plots on center vertical cut plane near the cooled wall for Case 5 turbulent and laminar models

Figure A- 8 presents the comparison of sodium mass fraction values for Case 5 turbulent and laminar models across a line perpendicular to flow (shown in black in figure inset) at a distance of 251 mm from the inlet (cooled section extends from 240 mm to 252 mm). It can be noticed that the difference between the curves is negligible.

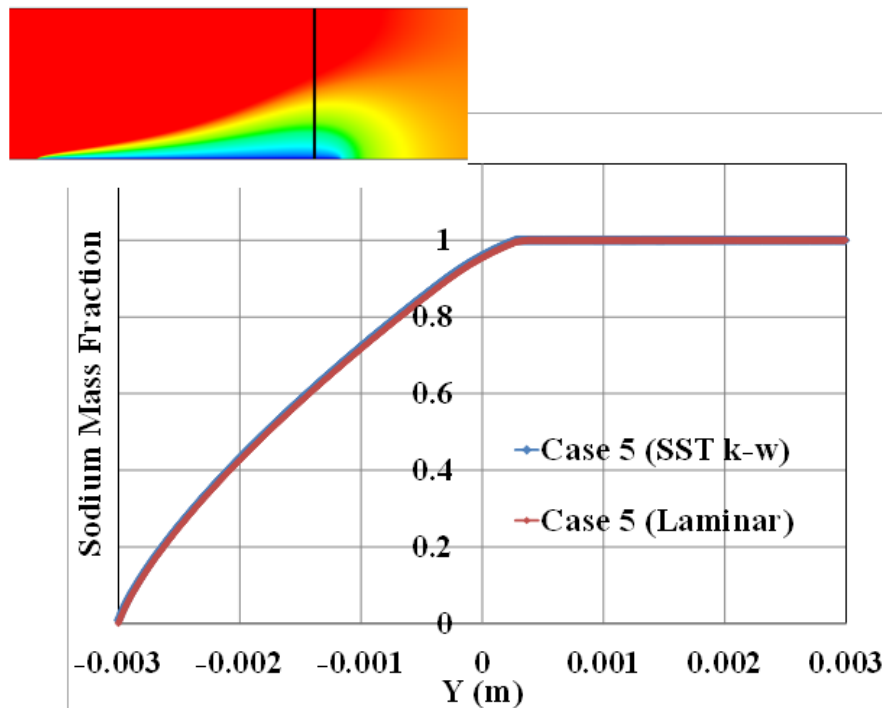


Figure A- 8: Comparison of sodium mass fraction values at $X = 251$ mm along the black line shown in insert contour plot ($Y = 0$ mm is the channel centerline) for Case 5 turbulent and laminar models

A.4 No-plugging CFD model sensitivities

This section presents various sensitivity studies undertaken for the no plugging CFD model.

A.4.1 Mesh sensitivity

Due to the large number of CFD simulations that were needed for the no-plugging CFD model calibrations, it was important to be able to keep the number of computational cells small to optimally use the computational resources available. The fluid region mesh in the CFD model needed to be very fine due to the need to capture the boundary layer details with the SST k- ω model, especially once the deposit formation was to be simulated. In addition, the mesh on the test section solid walls, where only conduction occurs, could be kept with larger cell sizes. But this combination created large jumps in cell sizes across the interface between solid and fluid domains, as presented in Figure A- 9 on a vertical cut plane perpendicular to the flow direction.

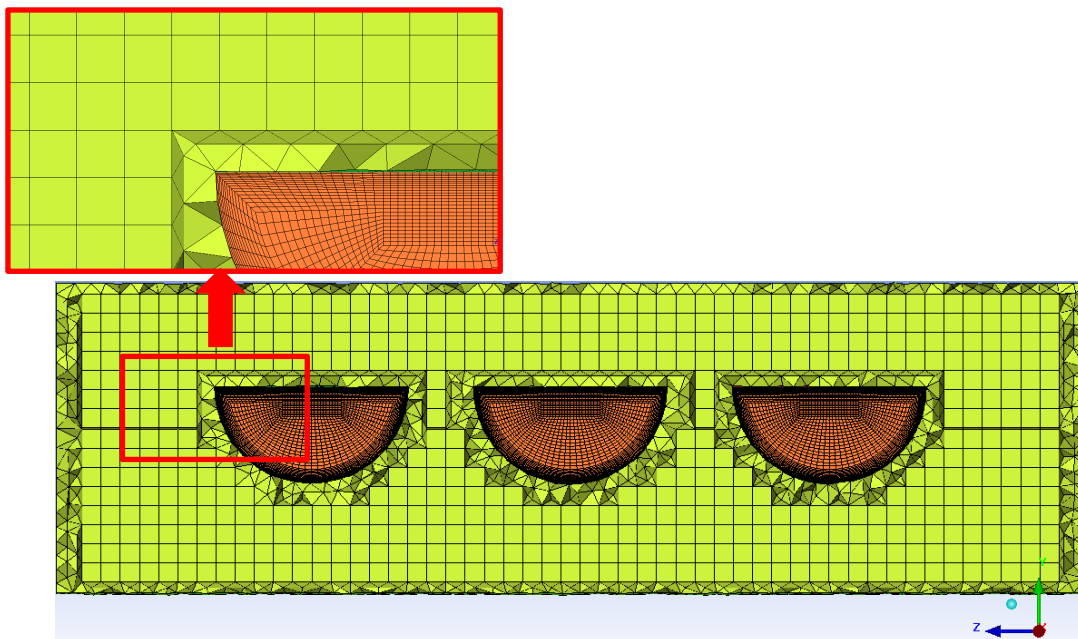


Figure A- 9: Vertical cut plane perpendicular to the flow direction showing mesh density

In order to make sure this didn't affect the CFD simulation results, a sensitivity study was conducted where the fluid domain mesh was coarsened, as shown in Figure A- 10, while still keeping $y^+ < 2$. This mesh, although still within the limits of the SST k- ω model's strength to capture boundary layer details, is not ideal for the eventual plugging simulations in which the calibrations are intended to be eventually implemented, but was built solely to demonstrate the effects. The coarse mesh for the fluid domain provided a smoother transition in cell sizes between solid and fluid domains across the interface.

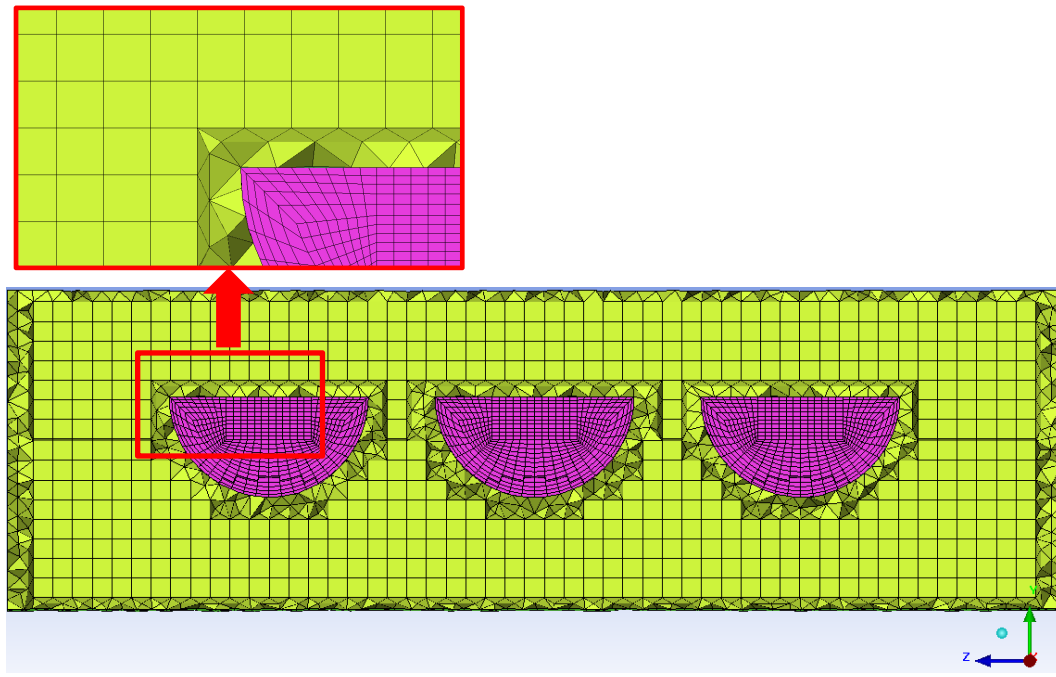


Figure A- 10: Vertical cut plane perpendicular to the flow direction showing mesh density

Simulation results for Test #3 with fine and coarse meshes are presented in Figure A- 11 and Figure A- 12, with the latter zooming-in in the initial part of the transient. The quantities of interest, T/C #12, #15 and #17, are plotted. There was no difference observed, and thus the decision was to continue using the fine mesh for the fluid domain to be eventually used for the plugging CFD tool.

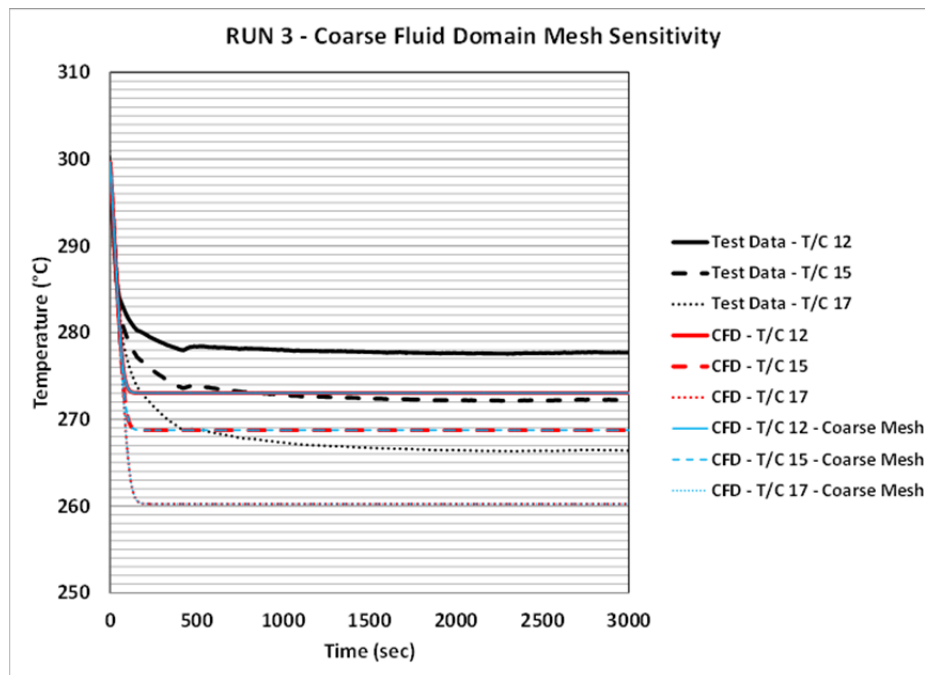


Figure A- 11: Mesh sensitivity results for Test #3 with fine (red) and coarse (blue) fluid meshes

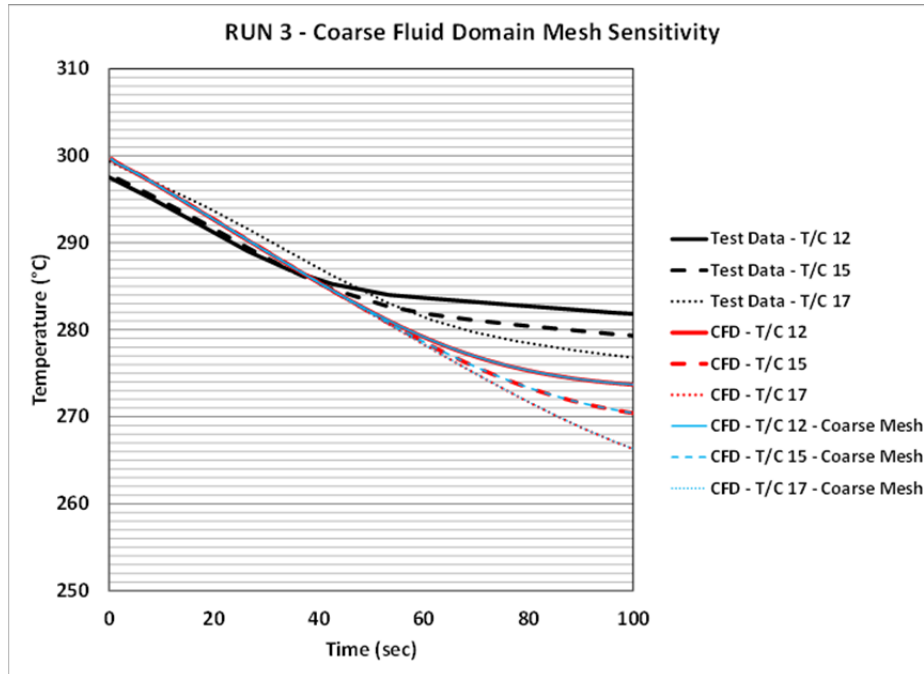


Figure A- 12: Mesh sensitivity results for Test #3 with fine (red) and coarse (blue) fluid meshes – focus on initial cooling period

A.4.2 Inlet boundary conditions sensitivity

Inlet boundary condition (temperature and turbulence intensity) sensitivities for the CFD model were conducted on Test #3 to account for uncertainties in the SPPL setup.

Inlet temperature sensitivity

In order to account for the possible variations in the flow temperature entering the test section due to temperature control challenges that may affect the SPPL, the inlet temperature to the test section CFD model for Test #3 was raised 1% (to 303°C), and the results are compared to the base case run, presented in Figure A- 13 and Figure A- 14. One can observe 2-3 °C difference in T/C #12, #15 and #17 readings between the two models, showing the importance of inlet temperature measurement accuracy.

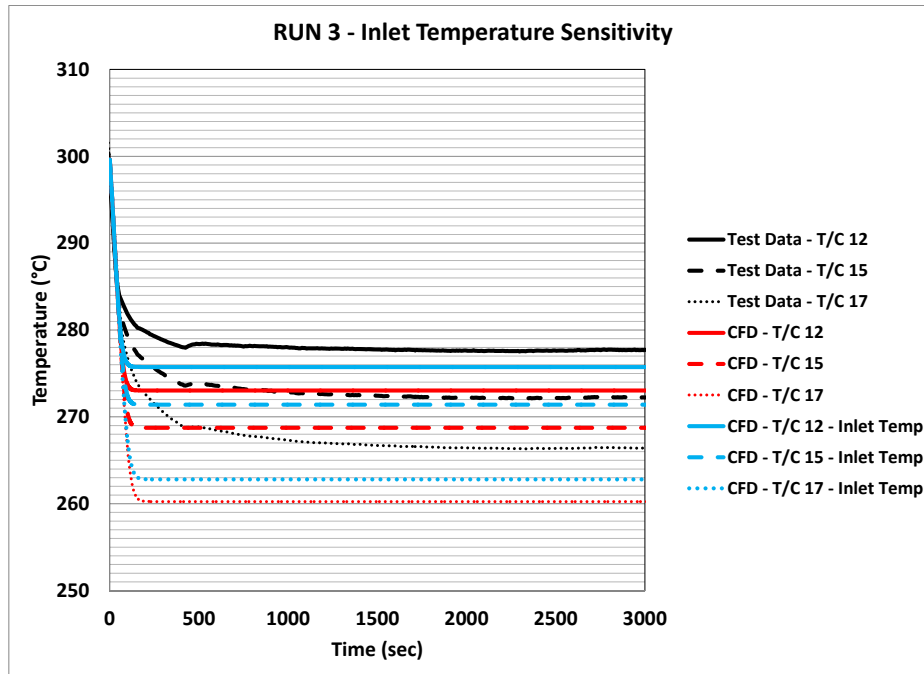


Figure A- 13: Inlet temperature sensitivity simulation results for Test #3. Measured inlet T (red); +3°C (blue)

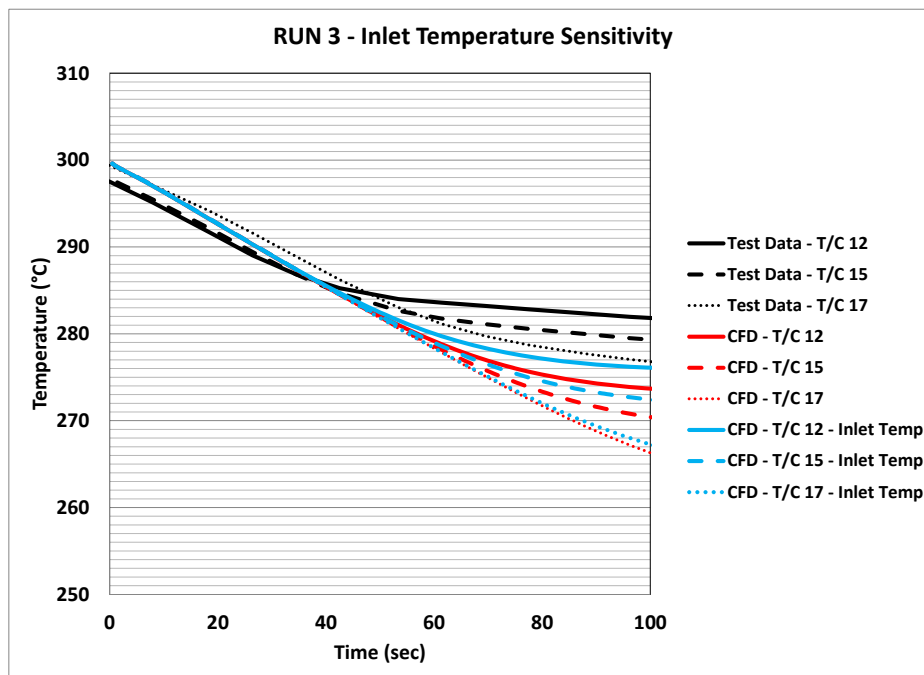


Figure A- 14: Inlet temperature sensitivity simulation results for Test #3 – focus on initial cooling period. Measured inlet T (red); +3°C (blue)

Inlet turbulence intensity sensitivity

Since the calibration studies were conducted only on the test section, the inlet turbulence intensity that would be entering the channels due to upstream loop conditions (such as elbows) were not

immediately taken into account (but are provided with the loop CFD model separately). Thus, a sensitivity study was conducted on the inlet turbulence intensity specified for the CFD model. A 1% inlet turbulence intensity was specified for all the calibration runs and Test #3 was repeated with a 5% inlet turbulence intensity to observe the effects. Figure A- 15 and Figure A- 16 present the results (blue curves represent the case with 5% inlet turbulence intensity), and no difference was observed within the two cases.

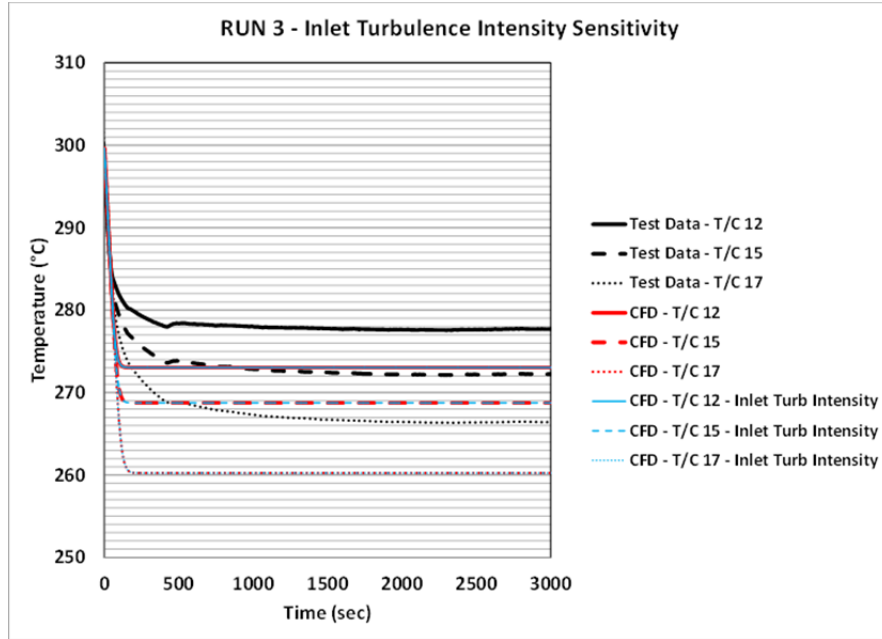


Figure A- 15: Inlet turbulence intensity sensitivity simulation results for Run 3

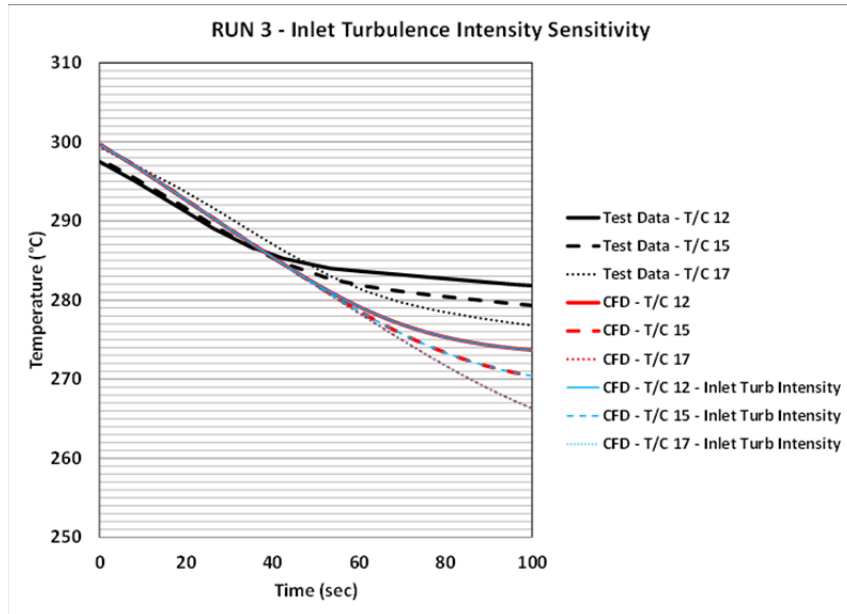


Figure A- 16: Inlet turbulence intensity sensitivity simulation results for Run 3 – focus on initial cooling period

A.4.3 Contact heater temperature sensitivity

A sensitivity study was conducted for Test #3 for the contact heater temperatures specified as boundary conditions within the CFD model at the top and bottom surfaces of the last 2/5th's of the test section (see Figure 1-4).

In the original Test #3 calibration model, the heater temperatures were set to 303 °C (average reading of all T/C readings on the surfaces during the test). For the sensitivity study, the temperatures were increased by 1%, and the results are presented in Figure A- 17 and Figure A- 18. No difference was observed on T/C #12, #15 and #17 readings as expected since the contact heaters are downstream of regions of interest, and their purpose is to avoid any solidification and plugging downstream of the test section.

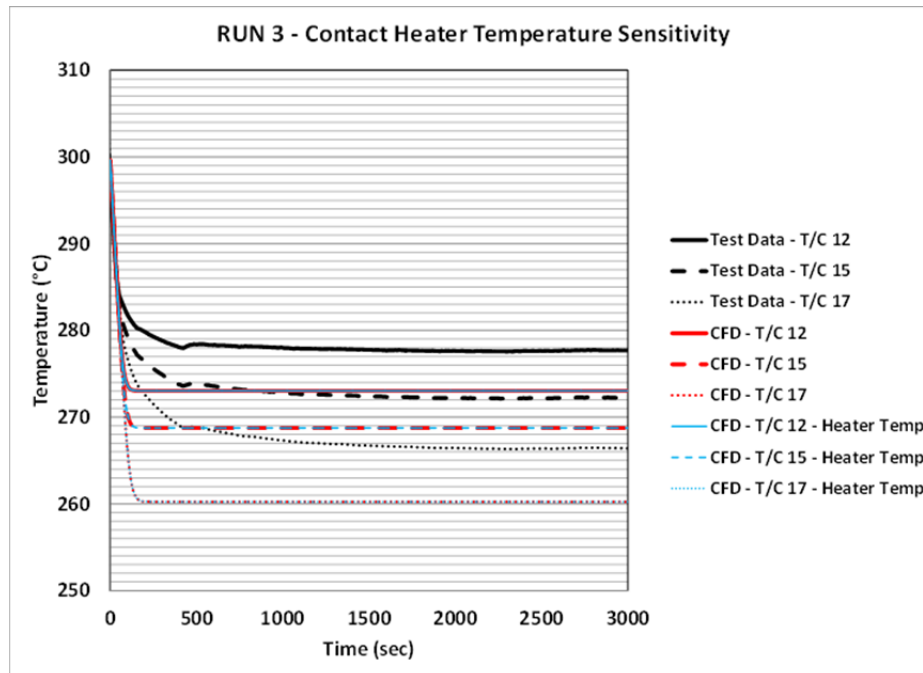


Figure A- 17: Heater temperature sensitivity simulation results for Test #3 (using measured T: red; with 1% increased T: blue)

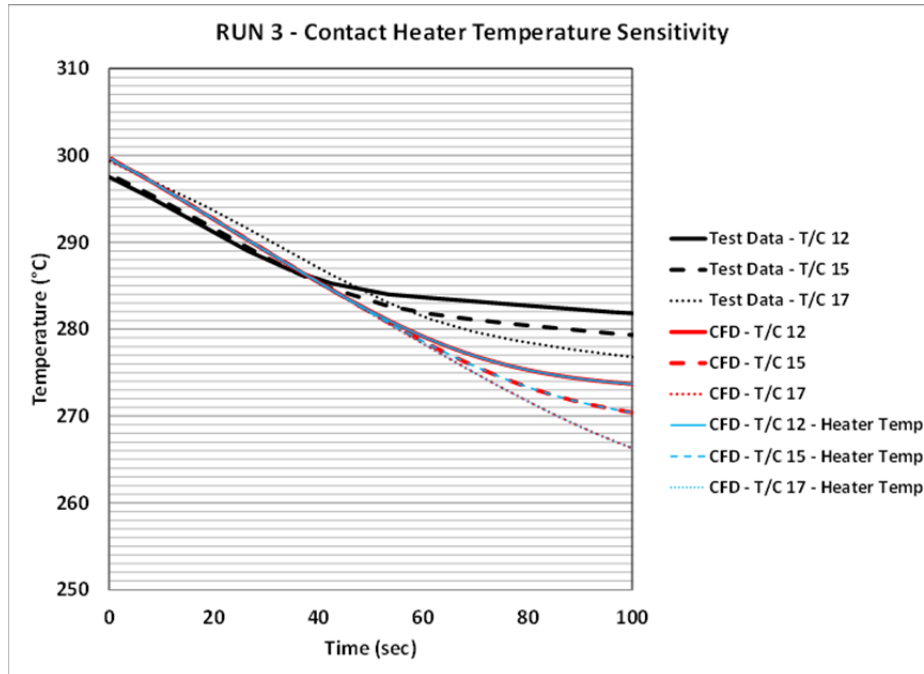


Figure A- 18: Heater temperature sensitivity simulation results for Run 3 – focus on initial cooling period (using measured T: red; with 1% increased T: blue)

A.4.4 Run time sensitivity

Since the calibration runs were conjugate heat transfer simulations (where solid and fluid domains were both modeled), it was important to make sure the run duration was chosen long enough to achieve full convergence, but short enough to be able to accommodate the large number of calibration runs to be conducted. Thus, a very long duration simulation was conducted for Test #3 to make sure no unexpected transients were observed. Figure A- 19 presents the results for the longer run overlapped with the original simulation results for T/C #12, #15 and #17. Note that no further changes were observed despite running the simulation twice as long.

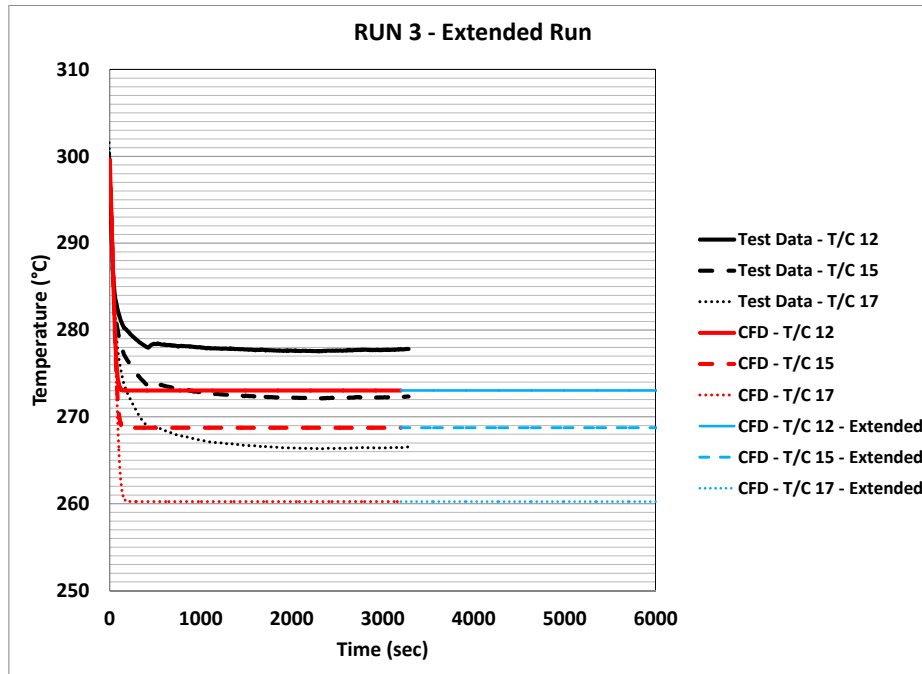


Figure A-19: Extended Run 3

A.4.5 Solver settings sensitivities

The following subsections document the solver setting sensitivities for the transient runs conducted for the validations. Sensitivities are presented on the maximum number of coefficient loops, time step size and convergence limits.

Maximum number of coefficient loops

The transient simulations conducted for the calibrations had the number of maximum coefficient loops set to 5 for convergence control. And although the inner loop convergences were checked and were satisfactory, an additional sensitivity run was conducted on Test #3 where the maximum number of inner coefficient loops was increased to 15. Figure A- 20 and Figure A- 21 present the results, and no difference was observed between the two cases.

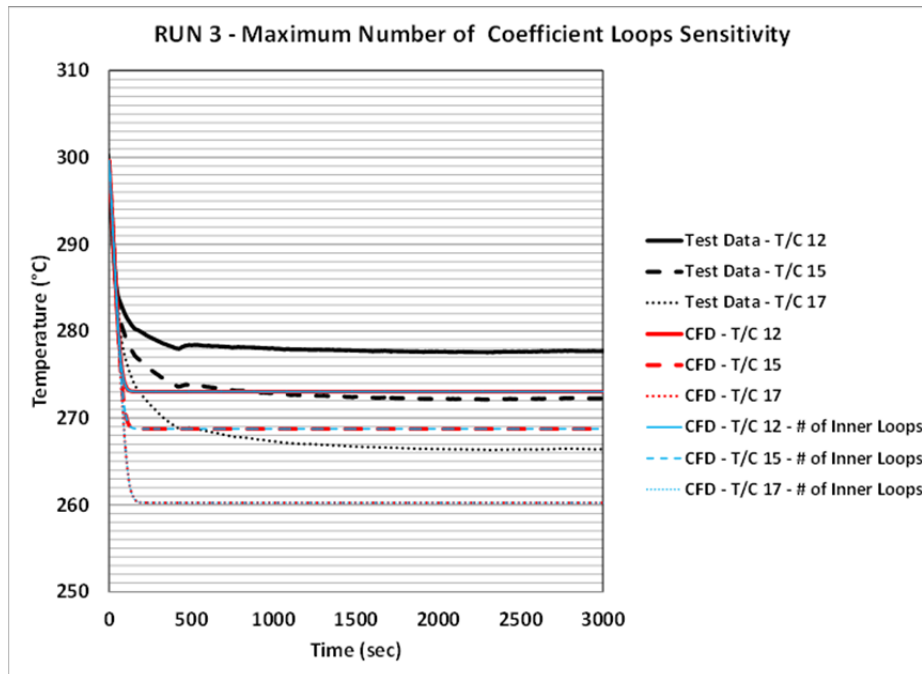


Figure A- 20: Maximum number of coefficient loops sensitivity simulation results for Test #3 (red: 5; blue: 15)

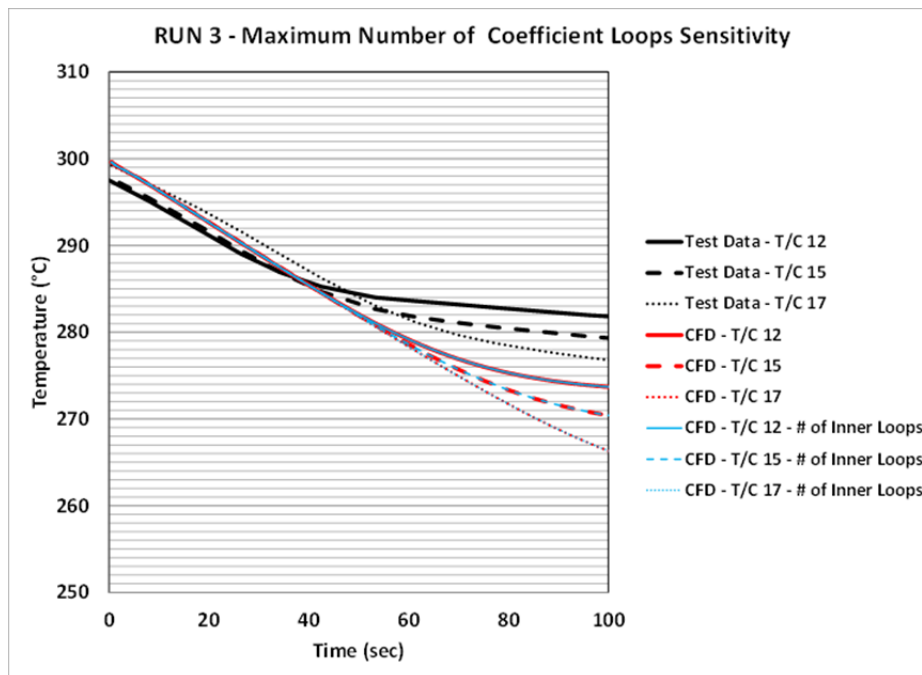


Figure A- 21: Maximum number of coefficient loops sensitivity simulation results for Test #3 – focus on initial cooling period (red: 5; blue: 15)

Time Step Size

In order to determine the time step size to be used for the large number of transient calibration simulations - to be able to use as large time step as possible to speed up solution without compromising resolving the details, a sensitivity study was conducted to determine the effects. Two time step sizes were considered – a time step size of 0.05 seconds (which provided an RMS Courant number of ~9), and a time step size of 0.5 seconds (as expected provided an RMS Courant number of ~90). Although these numbers are larger than recommended for Courant number, CFX is an implicit solver thus much larger values can be utilized without affecting numerical stability of the solver. In addition, as long as convergence within each time step is reached within 5-6 coefficient loops, the details will also be resolved. Figure A- 22 Figure A- 23 present the results and show no difference between the two cases for Test #3. Note that this is expected based on the maximum number of coefficient loop sensitivity study presented prior. Thus, in order to speed up simulations, a time step size of 0.5 seconds was utilized in the calibration runs.

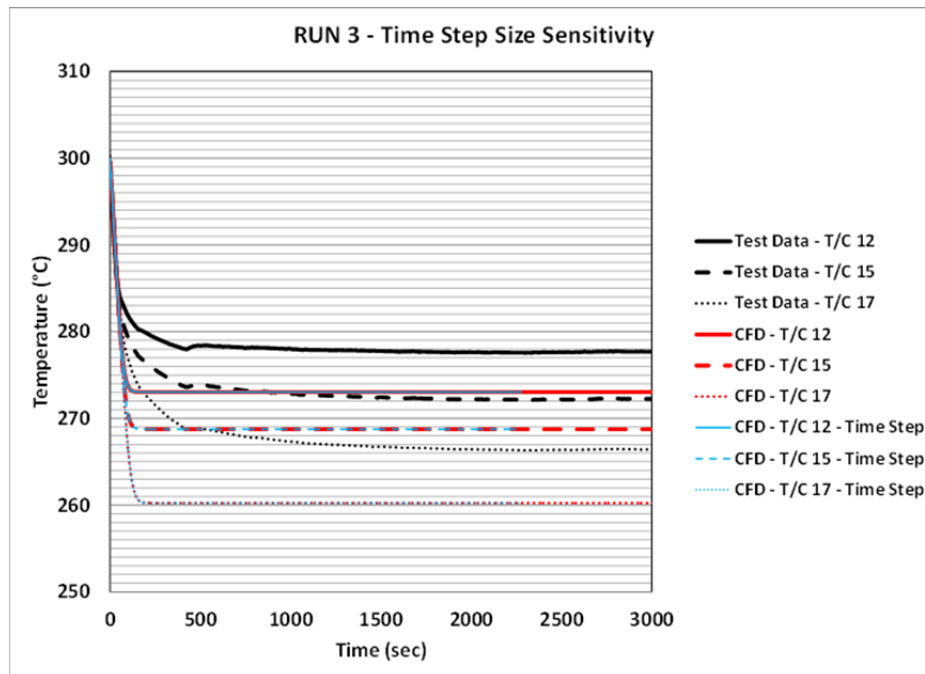


Figure A- 22: Time step size sensitivity simulation results for Test #3 (red: 0.5 s; blue: 0.05 s)

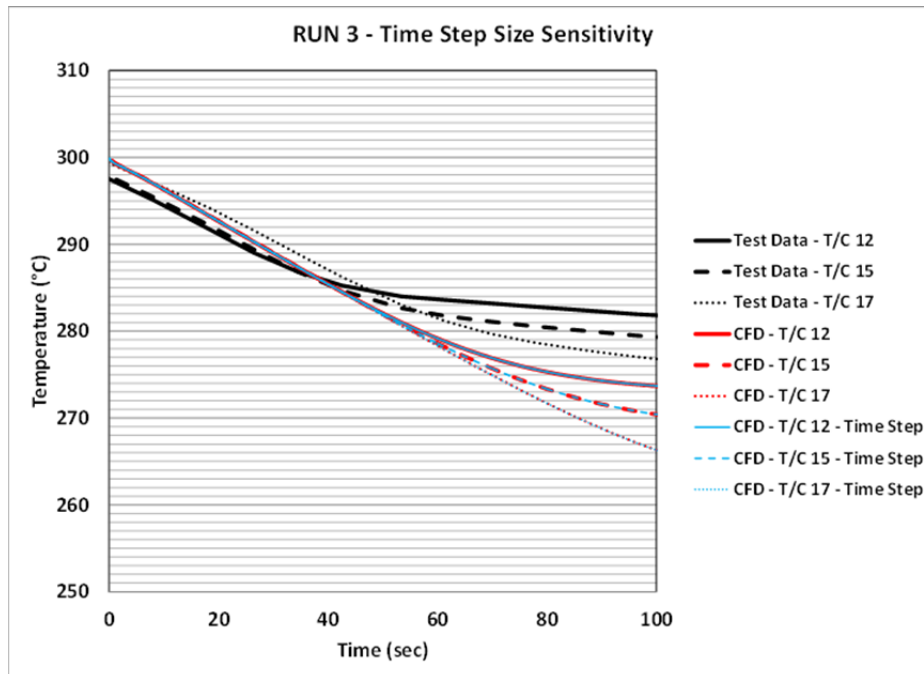


Figure A- 23: Time step size sensitivity simulation results for Test #3 – focus on initial cooling period (red: 0.5 s; blue: 0.05 s)

Convergence limits

In order to determine the sensitivity of the results to convergence limits implemented for the transient runs, an additional simulation was conducted where the convergence criteria was much less strict. In the calibration runs, the RMS residual target was set to 1.e-10, and a conservation (domain imbalance) target was set to 1.e-3. In the sensitivity simulation for Test #3, the RMS residual target was lowered to 1.e-6, and no conservation target was specified. Figure A- 24 and Figure A- 25 present the results. As it can be observed, no differences were seen on the results of interest. The main purpose of this sensitivity was to determine starting convergence criteria limits that could be applied in building the CFD plugging model (and to eventually determine if these criteria might need to be tightened for the plugging methodology).

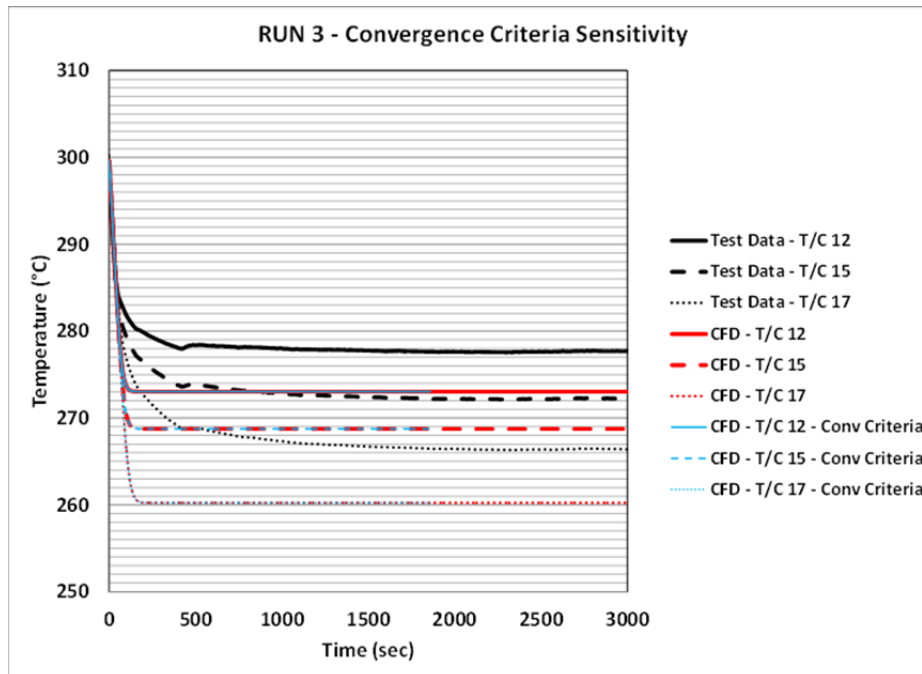


Figure A- 24: Convergence criteria sensitivity simulation results for Test #3 (blue represents less strict convergence criteria)

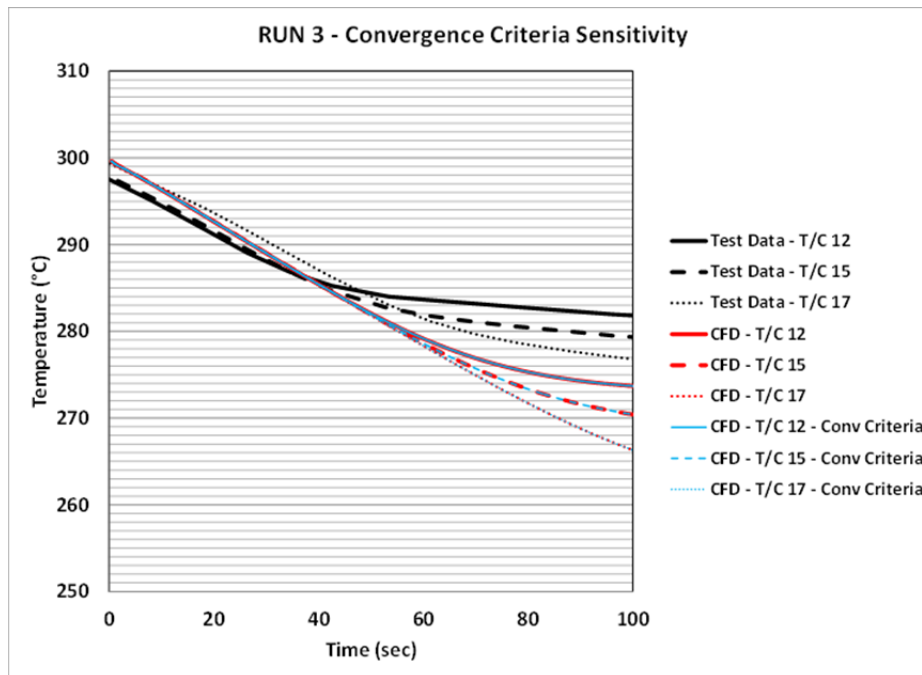


Figure A- 25: Convergence criteria sensitivity simulation results for Test #3 – focus on initial cooling period (blue represents less strict convergence criteria)

A.5 Example of plugging methodology application to a 3D domain

The plugging methodology developed and later demonstrated on the 2D rectangular domain (see Section 3.4) was also applied to a sample 3D domain representative of a single 6mm diameter semi-circular test channel in the SPPL test section. The domain used in the CFD simulation is presented in Figure A- 26. Again similar to the SPPL and the 2D plugging case presented prior, a small section in the center of the domain, at the bottom circular region, was cooled to initiate deposition.

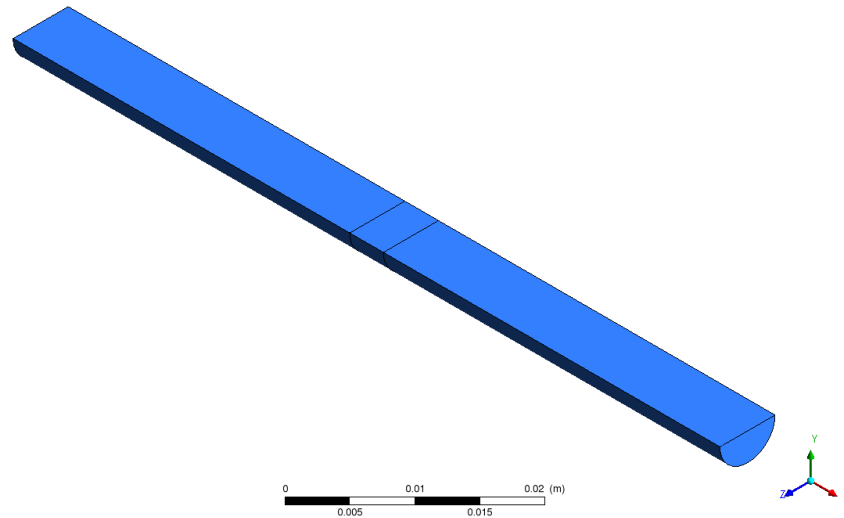


Figure A- 26: CFD domain used in the example application of plugging model to a 3D domain

The domain length was a total of 21 hydraulic diameters ($D_H = 3.666$ mm), with $10D_H$ entry section, D_H cooled section, and $10D_H$ exit section. Only sodium flow was simulated, and the solid test section walls were not included within this simulation. A fully hexahedral coarse mesh was built for this sample simulation with TrueGrid (first cell thickness of 0.45 mm, total number of computational cells 112,200). Figure A- 27 presents mesh density across the channel and also on the surfaces.

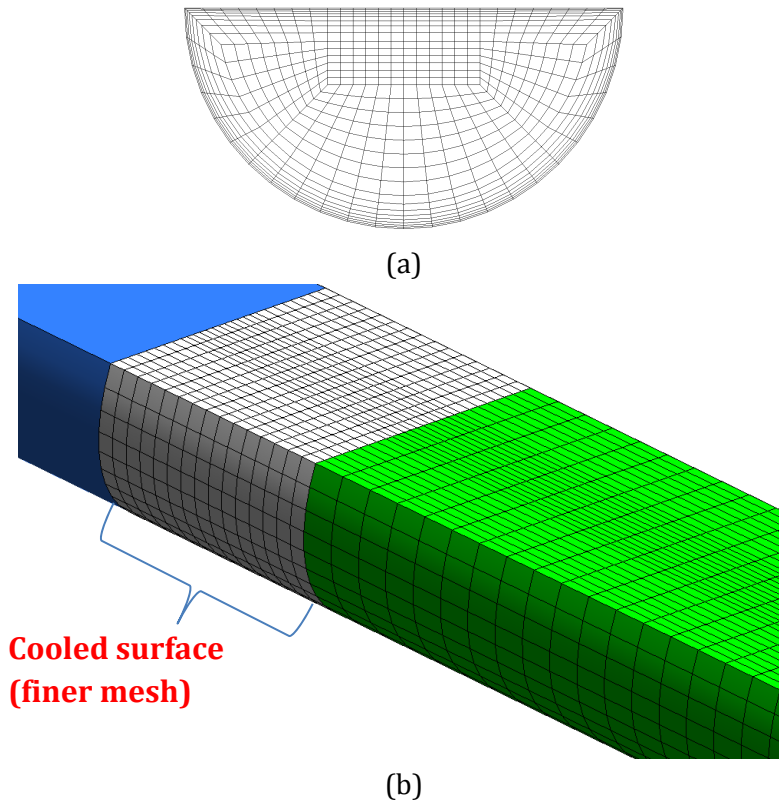


Figure A- 27: Mesh densities (a) across flow channel and (b) on outer surfaces

Figure A- 28 presents the boundary conditions applied to the CFD model, also showing the monitoring points within the domain with yellow asterisks. The inlet velocity was set at 0.5 m/s at 300°C, with a turbulence intensity of 1% and oxygen concentration of 40 ppm. All top walls were kept at 300°C, and bottom semi-circular walls of the entrance and exit sections were set to adiabatic. The bottom semi-circular cooled surface (at the center of the domain) was set to 150°C (marked in green in Figure A- 28). Same modeling setup described in the main report with regards to the second stage of the plugging methodology is applied herein as well.

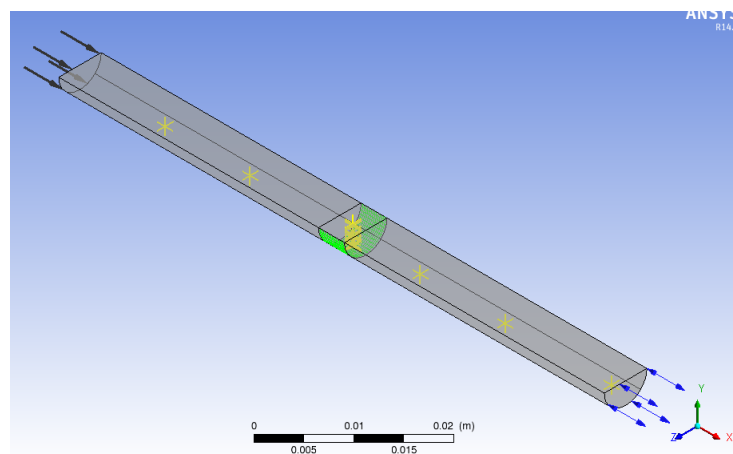
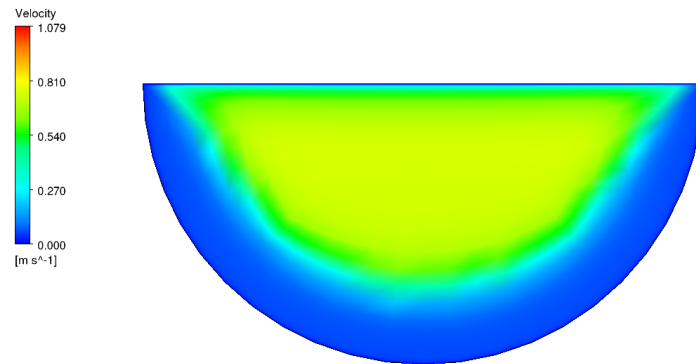


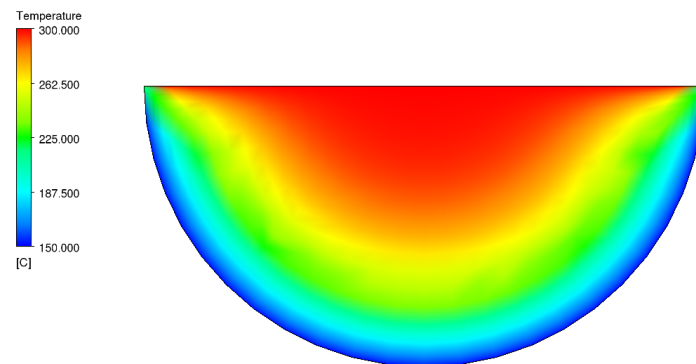
Figure A- 28: Boundary conditions and monitor point locations

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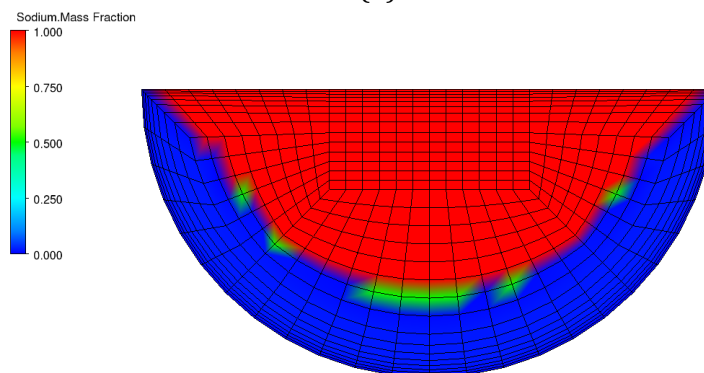
CFX was used as the solver, and a steady state simulation was conducted with a pseudo-time step of 0.01 seconds. Figure A- 29 shows the velocity magnitude, temperature, and sodium mass fraction contours across a vertical cut plane perpendicular to the flow placed in the middle region of the cooled section. Note the sodium mass fraction distribution is sharp (mainly either 0 or 1) due to reasons described in Section 3.4.1.2 with respect to time integration challenges.



(a)



(b)



(c)

Figure A- 29: Contours across a vertical cut plane perpendicular to the flow placed in the middle region of the cooled section (a) velocity magnitude, (b) temperature, and (c) sodium mass fraction

Figure A- 30 presents the velocity magnitude, temperature, and sodium mass fraction contours across a vertical cut plane parallel to the flow placed in the center of the channel (the area between the vertical black lines represent the cooled section).

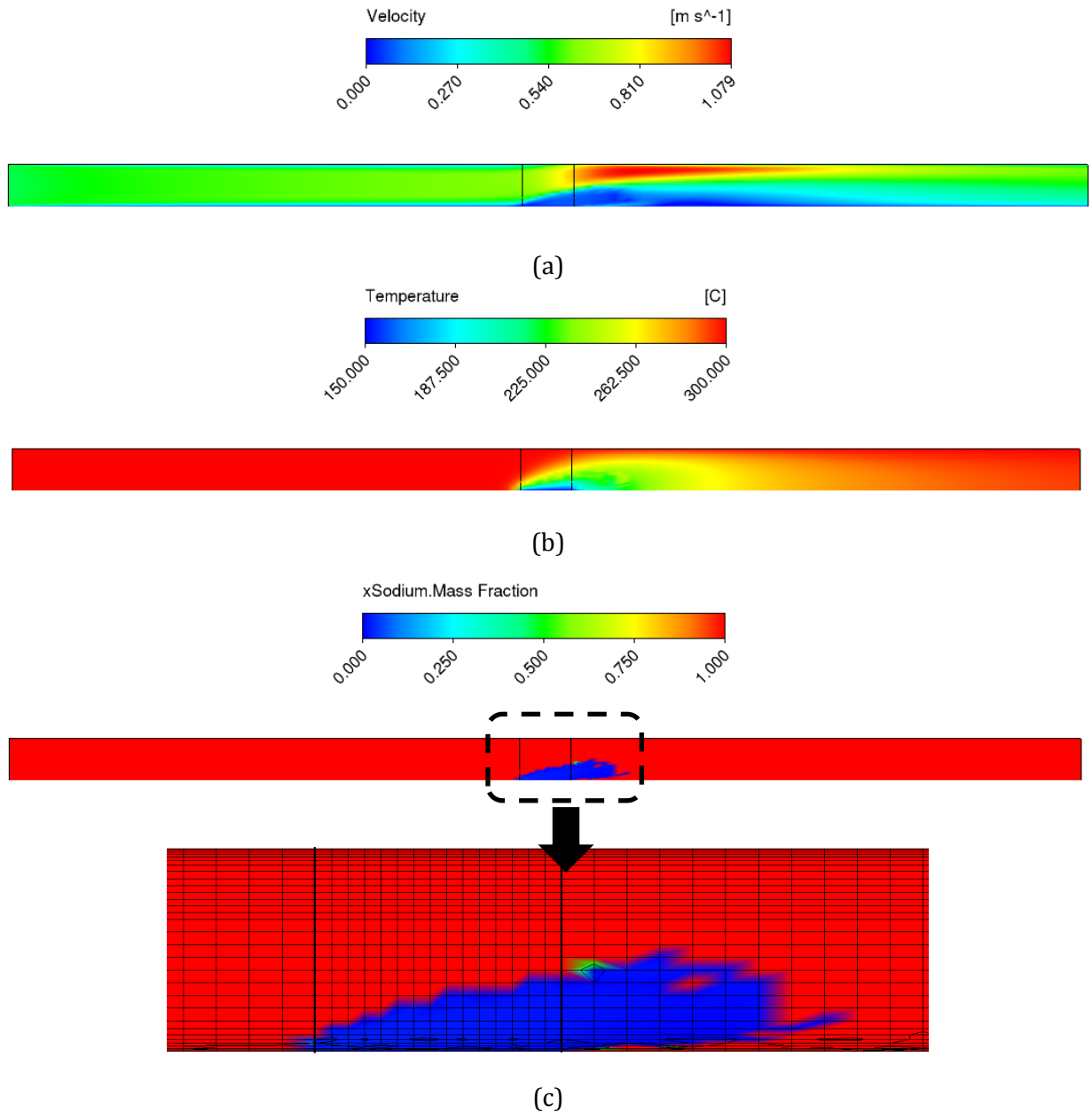


Figure A- 30: Contours across a vertical cut plane parallel to the flow placed in the center of the channel (a) velocity magnitude, (b) temperature, and (c) sodium mass fraction

One can observe the recirculation region in the velocity magnitude contour after the deposit (shown in the sodium mass fraction contour). Two interesting observations can be made regarding results presented in Figure A- 30. The temperature contour clearly shows the reduction in temperature slightly upstream of the cooled section due to the high thermal conductivity of sodium. This causes, although very small, deposition upstream of the cooled section as observed by the

sodium mass fraction contour. In addition, due to sodium cooling downstream, one can observe the deposit growth, but eventually detached growth from the wall.

Figure A- 31 presents the sodium oxide mass fraction iso-surface at 0.999, representing the outer “shell” of the deposit, colored by temperature. Rough surfaces are due to the coarse mesh density.

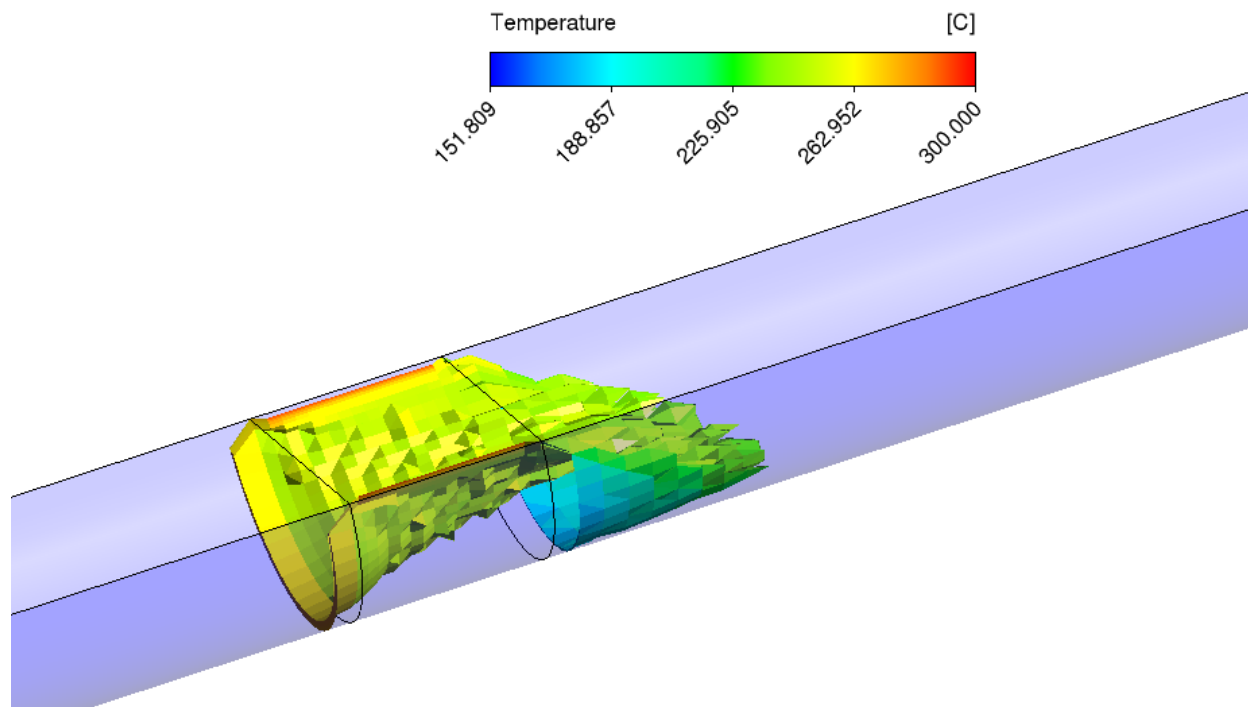


Figure A- 31: Sodium oxide mass fraction iso-surface of 0.999, colored with temperature

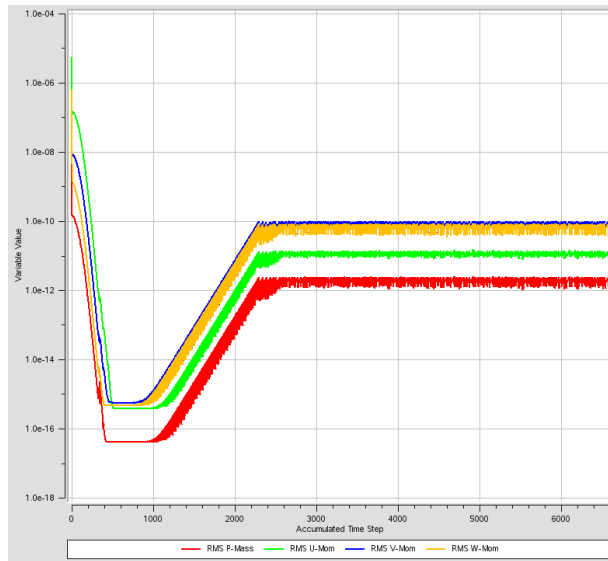
A.6 Convergence plots

The following subsections present the convergence plots for the no-plugging validation runs, loop CFD run and 2D plugging run.

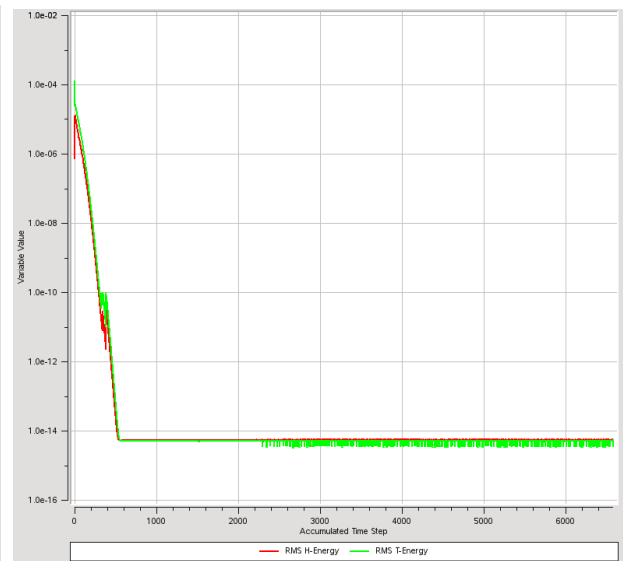
A.6.1 No plugging validation runs

Four convergence plots are presented in Figure A- 32 through Figure A- 35 for each of the no-plugging CFD simulations conducted for Tests 1, 2, 3 and 4 (see Section 3.2).

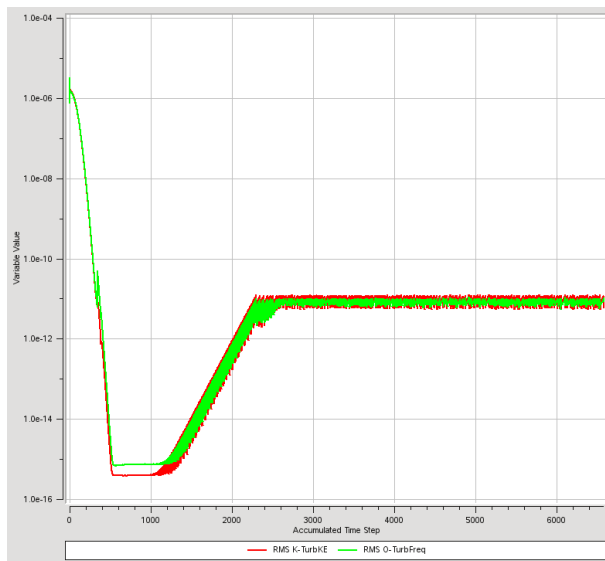
- RMS P-Mass, U-/V-/W-Mom
- RMS H-Energy, T-Energy
- RMS K-Turb KE, O-Turb Freq
- Monitors NPV_T1/T2/T3/T4 (temperatures along the channel)



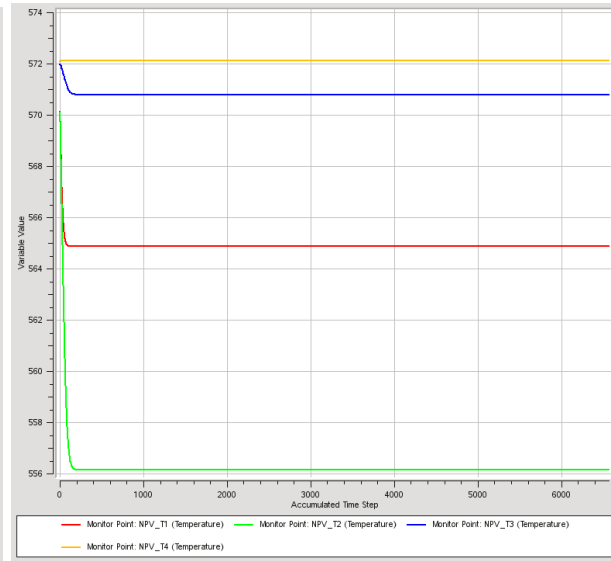
(a)



(b)



(c)



(d)

Figure A- 32: Run 1 residual and monitoring point values convergence plots

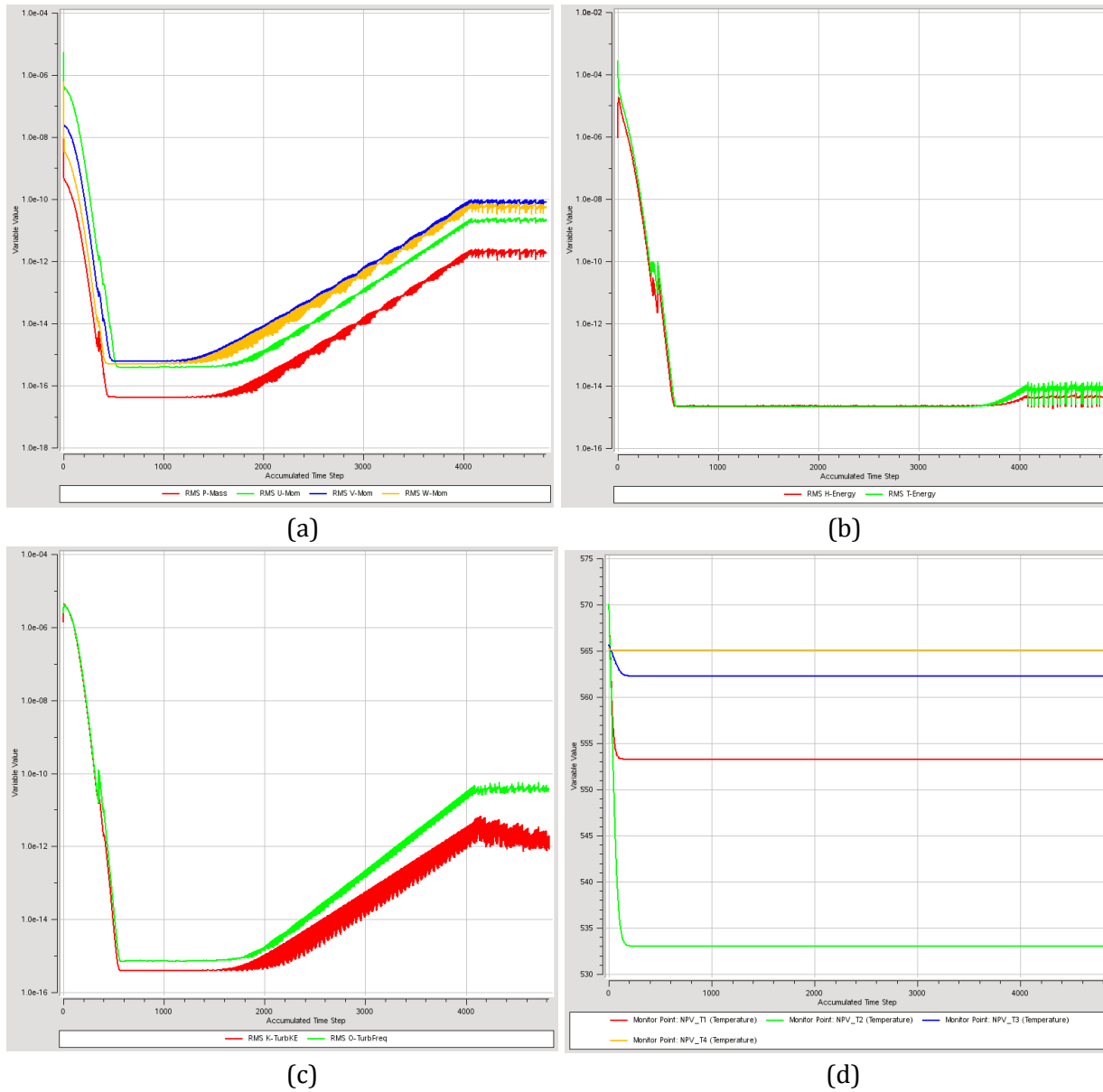


Figure A- 33: Run 2 residual and monitoring point values convergence plots

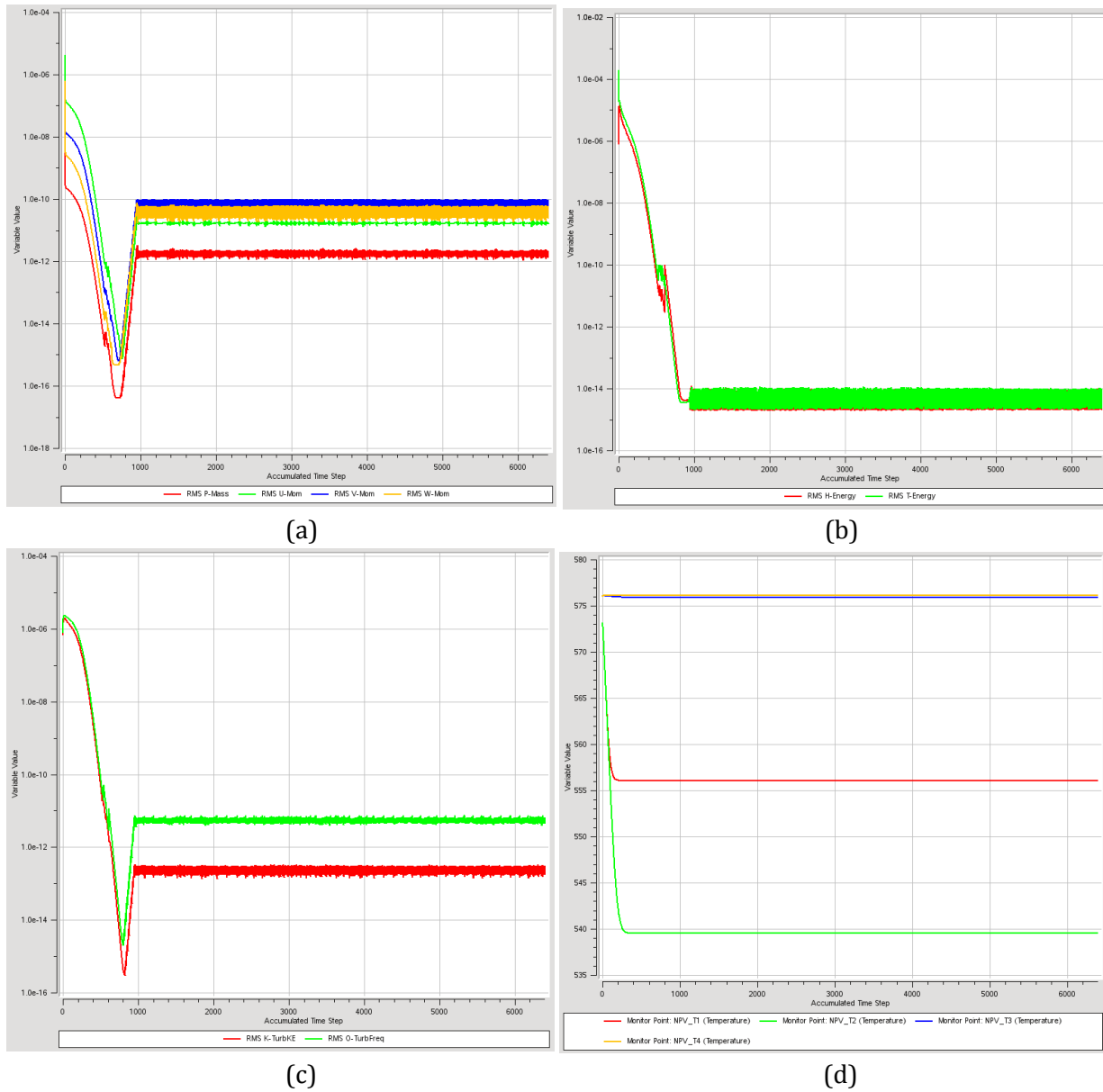


Figure A- 34: Run 3 residual and monitoring point values convergence plots

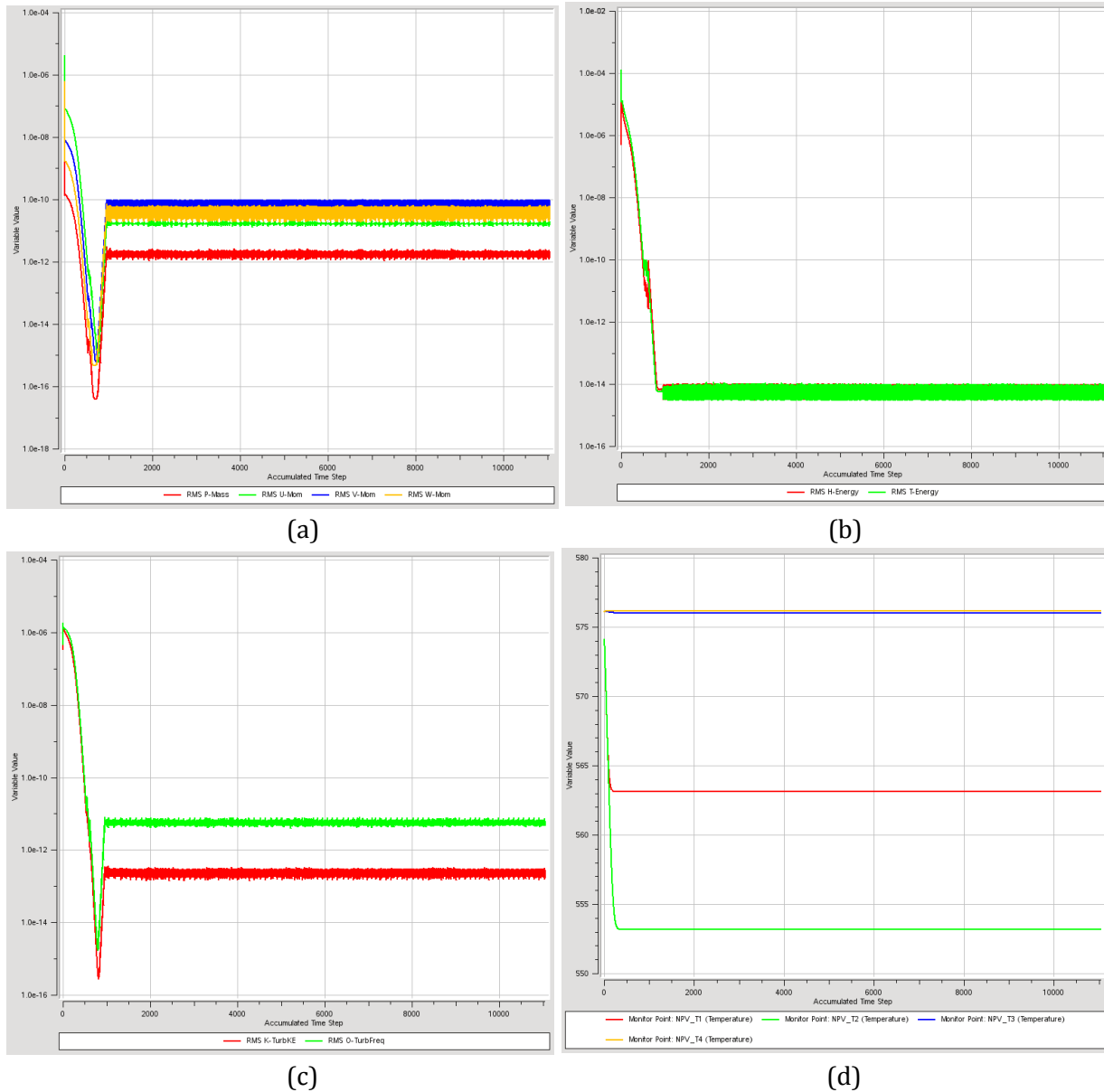


Figure A- 35: Run 4 residual and monitoring point values convergence plots

A.6.2 Loop CFD run

Four convergence plots are presented in Figure A- 36 for the loop CFD simulation.

- RMS P-Mass, U-/V-/W-Mom
- RMS H-Energy, T-Energy
- RMS K-Turb KE, O-Turb Freq
- Monitors NPV_T1/T2/T3/T4 (note that the monitor points were scattered within the solid/fluid domains)

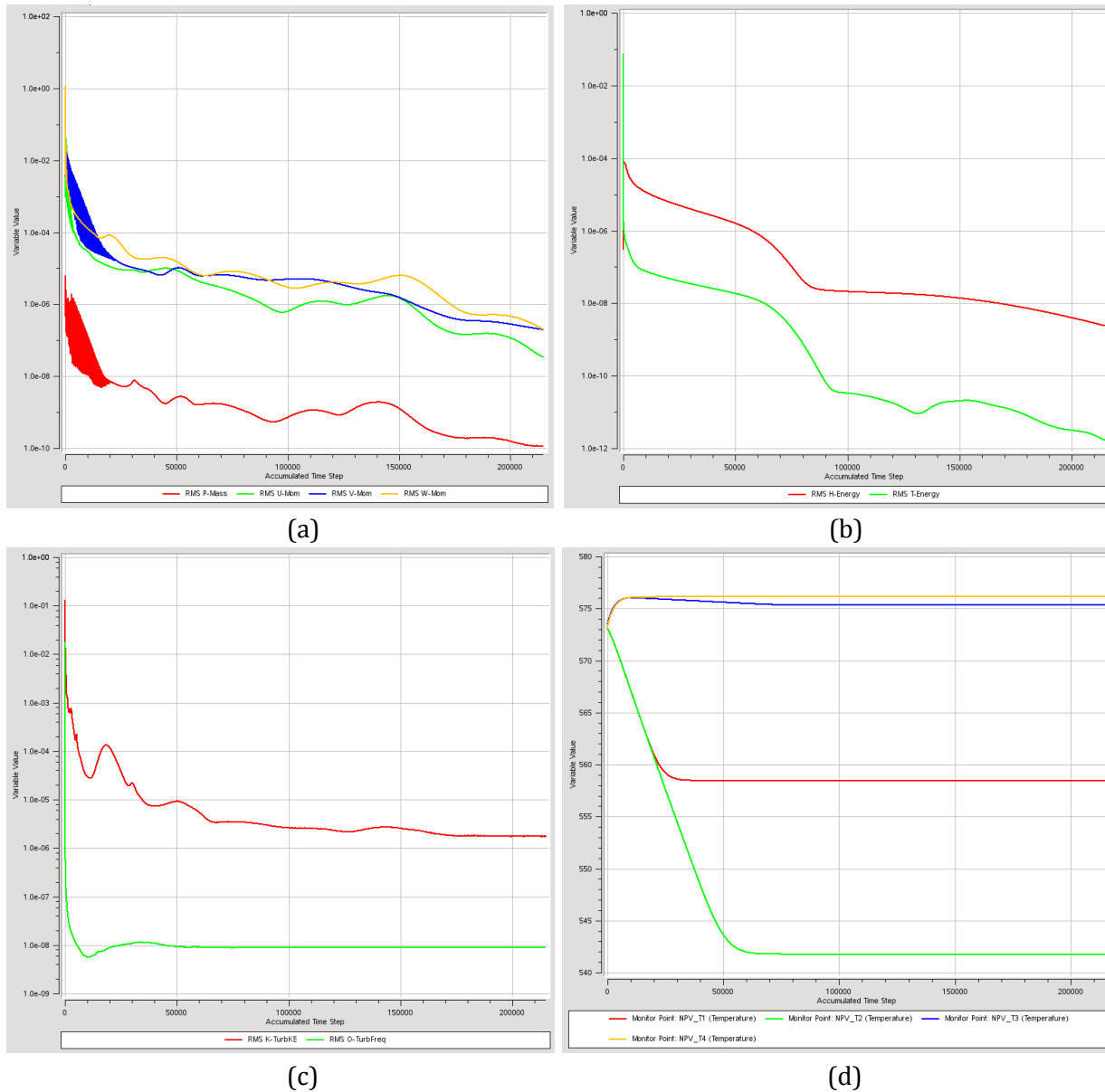
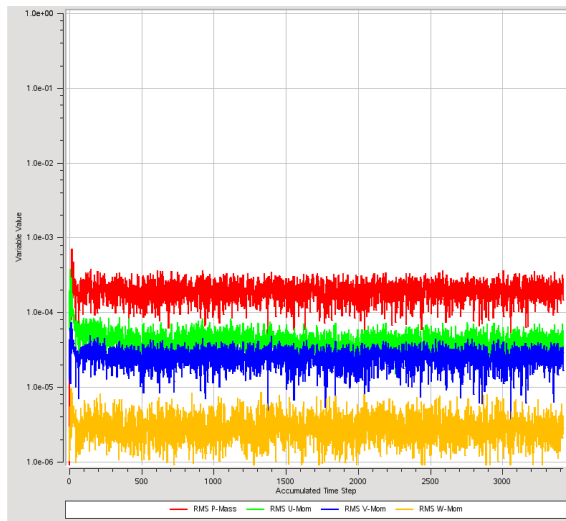


Figure A- 36: Loop CFD run residual and monitoring point values convergence plots

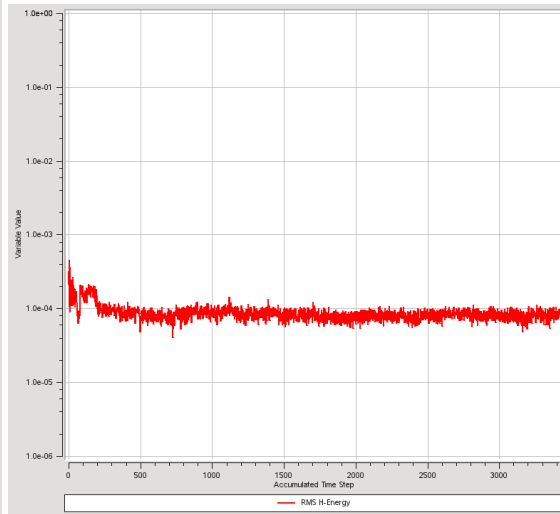
A.6.3 Plugging run (2D domain)

Five convergence plots are presented in Figure A- 37 for the plugging CFD simulation (left to right then down).

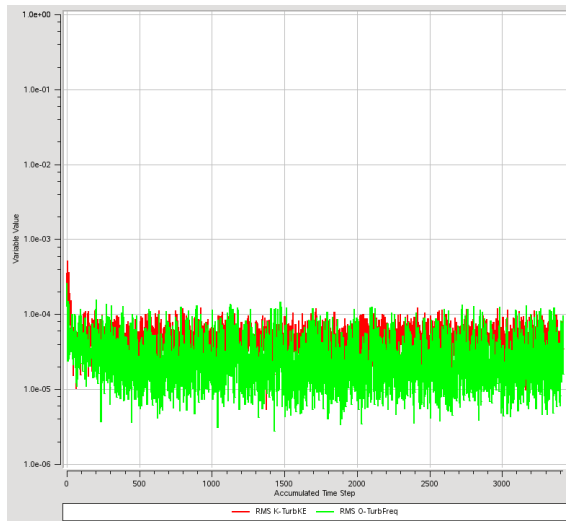
- RMS P-Mass, U-/V-/W-Mom
- RMS H-Energy
- RMS xConc (transport equation solved for the oxygen concentration)
- RMS K-Turb KE, O-Turb Freq
- Monitors of Velocity u, Vel 1/2/3_DepositTop/4/5/6 (u velocities along the flow channel)



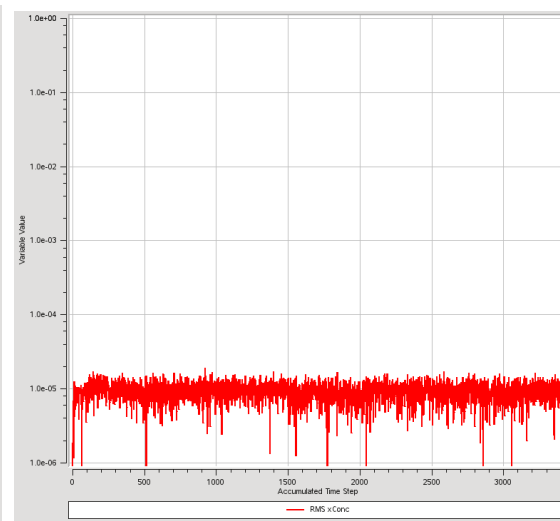
(a)



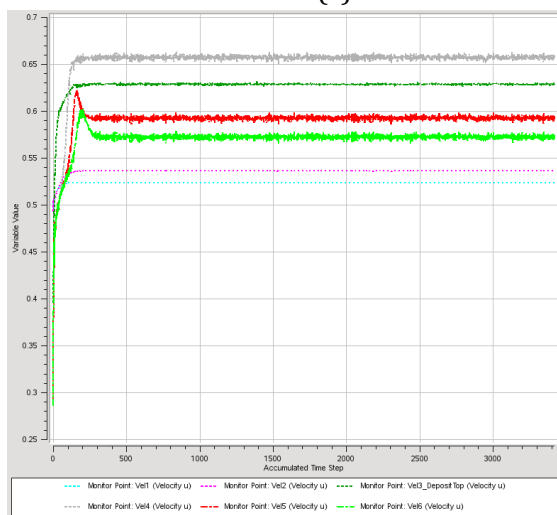
(b)



(c)



(d)



(e)

Figure A- 37: Plugging CFD run residual and monitoring point values convergence plots

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A.7 Computational mesh information

Mesh reports, generated using ICEM-CFD, are reported below for the no-plugging validation runs, loop CFD run and 2D plugging run.

A.7.1 No-plugging CFD validation runs (same fluid and solid domain meshes used for all four cases)

Mesh Info

Element types :

TETRA_4 : 4946263
HEXA_8 : 11107590
TRI_3 : 1042112
QUAD_4 : 443880
PYRA_5 : 327212

Element parts :

CENTER-SIDE-1 : 143520
CENTER-SIDE-2 : 141593
C_INLET : 2220
C_OUTLET : 2220
HEATEDBOTTOM : 94154
HEATEDTOP : 94110
LEFT-SIDE-1 : 143520
LEFT-SIDE-2 : 143982
L_INLET : 2220
L_OUTLET : 2220
RIGHT-SIDE-1 : 143520
RIGHT-SIDE-2 : 140995
R_INLET : 2220
R_OUTLET : 2220
SODIUM : 10389600
SOLID_BOTTOM : 139374
SOLID_ENDS : 5610
SOLID_SIDES : 142717
SOLID_TOP : 139577
STAINLESSSTEEL : 5991465

Total elements : 17867057

Total nodes : 12516741

Min : -0.000276719 -0.00632584 -0.015875

Max : 0.777366 0.0711252 0.015875

Mesh check

Running diagnostics for Duplicate elements in subset "all"

No problems were found for Duplicate elements

Running diagnostics for Uncovered faces in subset "all"

No problem volume elements were found for Uncovered faces
Running diagnostics for Missing internal faces in subset "all"
No problems were found for Missing internal faces
Running diagnostics for Volume orientations in subset "all"
No problems were found for Volume orientations
Running diagnostics for Surface orientations in subset "all"
 no orientation errors
 faces are correctly oriented
Surface orientations are OK
Running diagnostics for Hanging elements in subset "all"
No problems were found for Hanging elements
Running diagnostics for Multiple edges in subset "all"
No problems were found for Multiple edges
Running diagnostics for Triangle boxes in subset "all"
No problems were found for Triangle boxes
Running diagnostics for Single edges in subset "all"
No problems were found for Single edges
Running diagnostics for Non-manifold vertices in subset "all"
No problems were found for Non-manifold vertices
Running diagnostics for Unconnected vertices in subset "all"
0 unconnected vertices were found.
Unconnected vertices are OK

A.7.2 Loop CFD run

Mesh Info:

Element types :

TETRA_4 : 4946263
HEXA_8 : 9862202
TRI_3 : 1042112
QUAD_4 : 367808
PYRA_5 : 327212

Element parts :

ADIABATICPIPES : 191860
CENTER-SIDE-1-1 : 39200
CENTER-SIDE-2 : 141593
HEATEDBOTTOM : 94154
HEATEDTOP : 94110
LEFT-SIDE-1-1 : 39200
LEFT-SIDE-2 : 143982
RIGHT-SIDE-1-1 : 39200
RIGHT-SIDE-2 : 140995
SODIUMLOOP : 9144212
SOLID_BOTTOM : 139374
SOLID_ENDS : 5610
SOLID_SIDES : 142717

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SOLID_TOP : 139577
STAINLESSSTEEL : 5991465
XINLET : 29174
XOUTLET : 29174

Total elements : 16545597
Total nodes : 11230902
Min : -0.015875 -0.466353 -0.25598
Max : 0.159004 0.50052 0.947116

Mesh check

Running diagnostics for Duplicate elements in subset "all"

No problems were found for Duplicate elements

Running diagnostics for Uncovered faces in subset "all"

No problem volume elements were found for Uncovered faces

Running diagnostics for Missing internal faces in subset "all"

No problems were found for Missing internal faces

Running diagnostics for Volume orientations in subset "all"

44 problems were found for Volume orientations

Running diagnostics for Surface orientations in subset "all"

no orientation errors

faces are correctly oriented

Surface orientations are OK

Running diagnostics for Hanging elements in subset "all"

No problems were found for Hanging elements

Running diagnostics for Multiple edges in subset "all"

No problems were found for Multiple edges

Running diagnostics for Triangle boxes in subset "all"

No problems were found for Triangle boxes

Running diagnostics for Single edges in subset "all"

No problems were found for Single edges

Running diagnostics for Non-manifold vertices in subset "all"

No problems were found for Non-manifold vertices

Running diagnostics for Unconnected vertices in subset "all"

0 unconnected vertices were found.

Unconnected vertices are OK

Note (in **bold** above) that 44 problems were found for volume orientations for the loop CFD model mesh. Volume orientation check in ICEM-CFD looks for "left handed elements due to incorrect connectivity (node numbering of cell)." The fully conformal, fully hexahedral mesh for the loop sodium domain was built using TrueGrid, with significant manual translations of nodes (especially at the inlet/outlet transition regions of the test section, and also elbows), thus the reason for the volume orientation problems. CFX solver was able to overcome these problems, but it did require significantly more iterations to drop the residuals to convergence limits. Improvement of mesh quality is suggested for future work to speed up the runs.

A.7.3 Pugging run (2D domain)

Mesh Info

Element types :

HEXA_8 : 336000

QUAD_4 : 344720

Element parts :

DEFAULT-DOMAIN : 336000

XBOTTOMWALLLEFT : 2000

XBOTTOMWALLRIGHT : 2000

XCOOLED : 200

XINLET : 160

XLEFTSYMMETRY : 168000

XOUTLET : 160

XRIGHTSYMMETRY : 168000

XTOPWALL : 4200

Total elements : 680720

Total nodes : 510543

Min : 0 -0.003 -0.00024

Max : 0.126 0.003 0.00024

Mesh Check

Running diagnostics for Duplicate elements in subset "all"

No problems were found for Duplicate elements

Running diagnostics for Uncovered faces in subset "all"

No problem volume elements were found for Uncovered faces

Running diagnostics for Missing internal faces in subset "all"

No problems were found for Missing internal faces

Running diagnostics for Volume orientations in subset "all"

No problems were found for Volume orientations

Running diagnostics for Surface orientations in subset "all"
faces are correctly oriented

Surface orientations are OK

Running diagnostics for Hanging elements in subset "all"

No problems were found for Hanging elements

Running diagnostics for Multiple edges in subset "all"

No problems were found for Multiple edges

Running diagnostics for Triangle boxes in subset "all"

No problems were found for Triangle boxes

Running diagnostics for Single edges in subset "all"

No problems were found for Single edges

Running diagnostics for Non-manifold vertices in subset "all"

No problems were found for Non-manifold vertices

Running diagnostics for Unconnected vertices in subset "all"

0 unconnected vertices were found.

Unconnected vertices are OK

A.8 Wall Y+ contours

Wall y+ contours are presented below for the no-plugging validation runs, for the loop run and for the 2D plugging model.

A.8.1 No-plugging CFD validation runs (same meshes used for all four cases)

Run 3

Run 3 test was conducted with 'nominal' loop sodium flow rate of 'A' (same as Run 4). Wall Y+ values on the semi-circular channel walls were below 1 (except a very small region at the entrance of the channels as shown in Figure A- 38(c)).

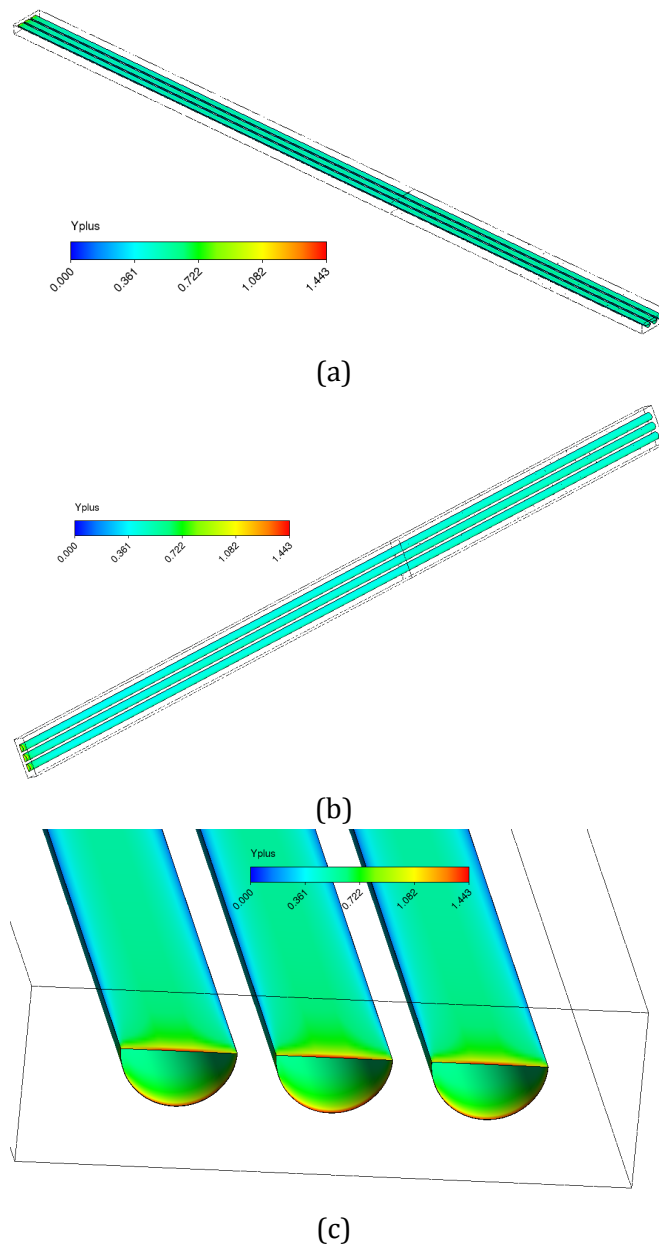


Figure A- 38: Wall Y+ contours on the semi-circular channel walls for Run 3 (a) top view, (b) bottom view, and (c) entrance

Run 1

As shown in Table 2.1, Test #1 test was conducted with double the 'nominal' loop sodium flow rate with '2A' (same as Test #2). Wall Y^+ values on the semi-circular channel walls were below 1 (except a very small region at the entrance of the channels as shown in Figure A- 39(c)).

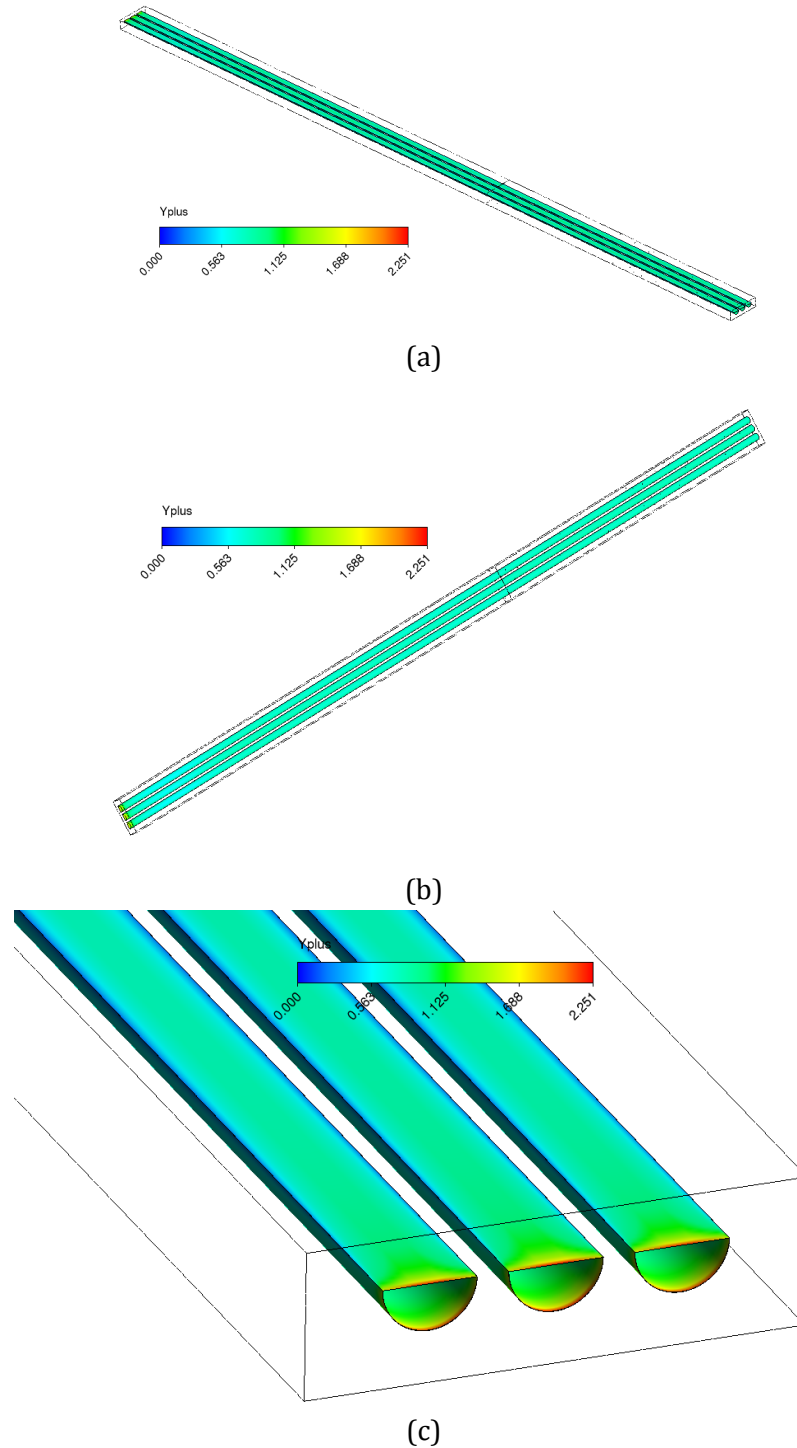


Figure A- 39: Wall Y^+ contours on the semi-circular channel walls for Run 1 (a) top view, (b) bottom view, and (c) entrance

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Run 3 Coarse Mesh

This coarser mesh for Run 3 was used for the mesh sensitivity study conducted to observe the effects of cell size jump between fluid and solid domains (see Section A.4). Wall Y^+ values on the semi-circular channel walls were ~ 2 (except a very small region at the entrance of the channels as shown in Figure A- 40(c)). A wall Y^+ value of 2, although slightly above the desired value for the SST k- ω turbulence model of 1, is still acceptable taking full advantage of this turbulence model's boundary layer resolution through the viscous sub-layer.

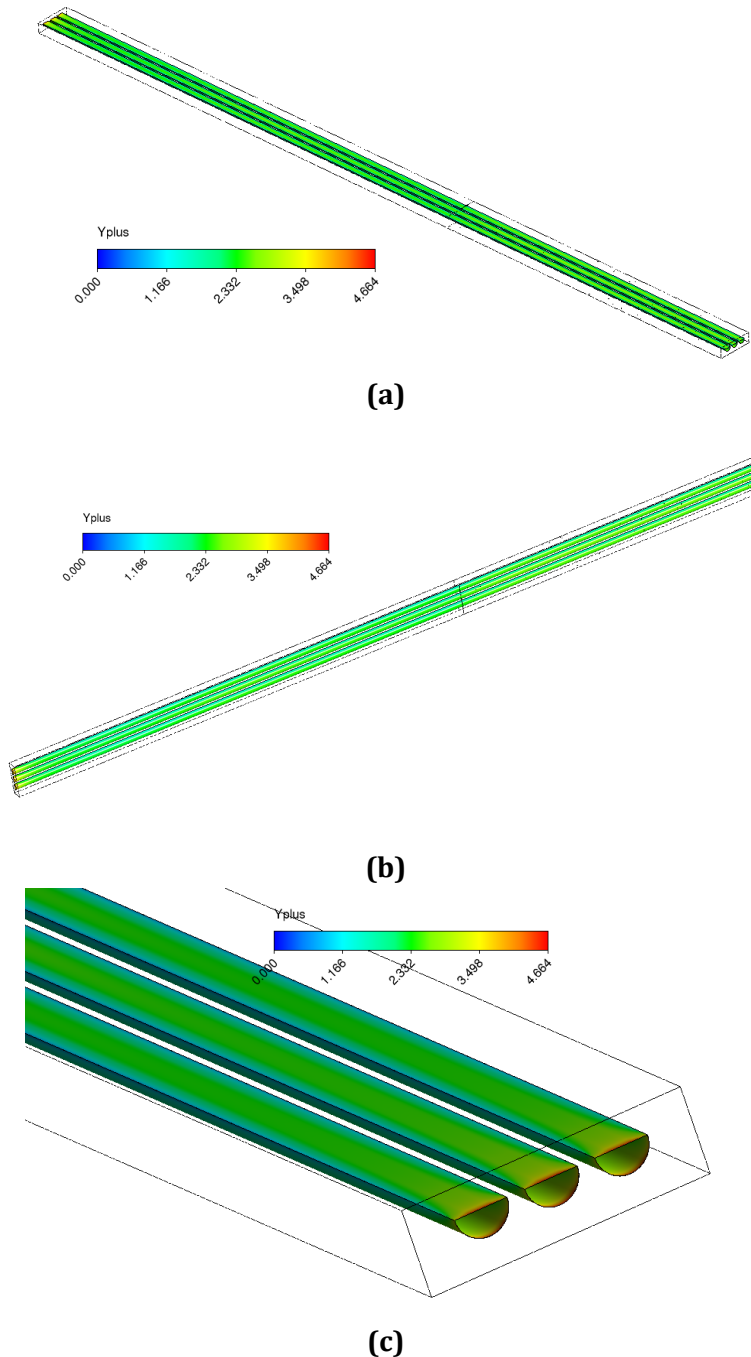


Figure A- 40: Wall Y^+ contours on the semi-circular channel walls for Run 3 coarse mesh (a) top view, (b) bottom view, and (c) entrance

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A.8.2 Loop CFD run

Figure A- 41 shows the wall Y^+ values for the loop CFD simulation. All wall Y^+ values, including loop main line, transition pieces before and after the test section, and the semi-circular channels, are below 1.

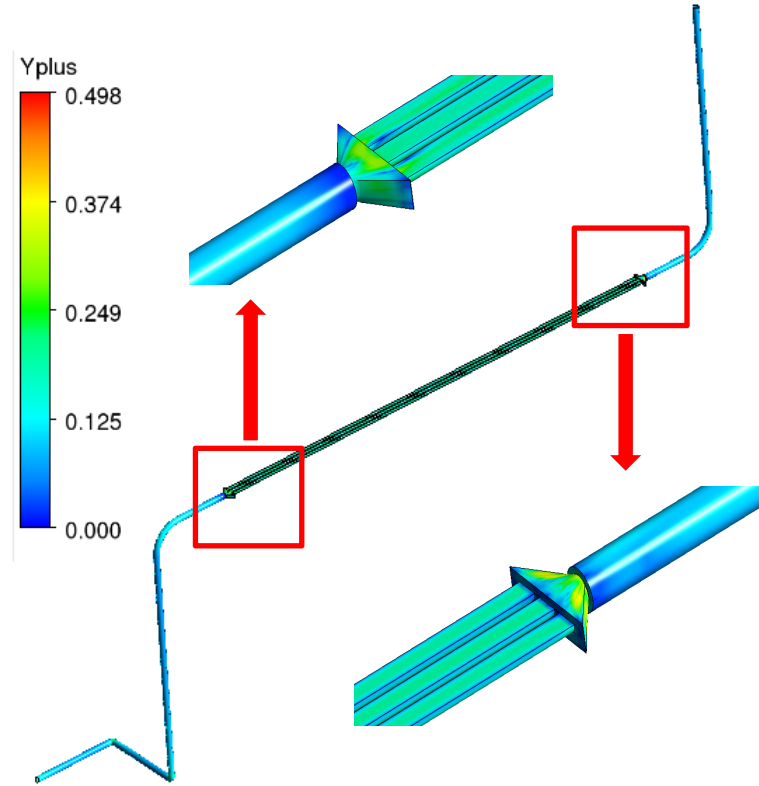


Figure A- 41: Wall Y^+ contours on the loop CFD model

A.8.3 Plugging run (2D domain)

Figure A- 42 presents the wall Y^+ contours on the bottom two cell thick walls of the 2D plugging CFD simulation, end of transient. Note that the surface upstream of the deposit has a wall Y^+ of ~ 3.5 , and the surface downstream of the deposit has a wall Y^+ value of ~ 3 . The SST $k-\omega$ model fully resolves the boundary layer for Y^+ values less than or equal to 1-2 (within the viscous sublayer). For these cases, the SST $k-\omega$ model switches to a low-Re formulation instead of using a wall function. For Y^+ values greater than 11 (basically in the log law region), the SST $k-\omega$ model will function as $k-\epsilon$ and use wall functions. Anything in between these Y^+ limits, it will be a blend of both formulations. Since the focus was testing the CFD plugging methodology herein, the domain mesh count was kept as low as reasonably possible (such as using a 2D domain). So although the Y^+ values for the plugging CFD model are still acceptable in taking advantage of the more sophisticated SST $k-\omega$ model to a large degree, a finer mesh in the future to bring the value down to 1 or lower is suggested.

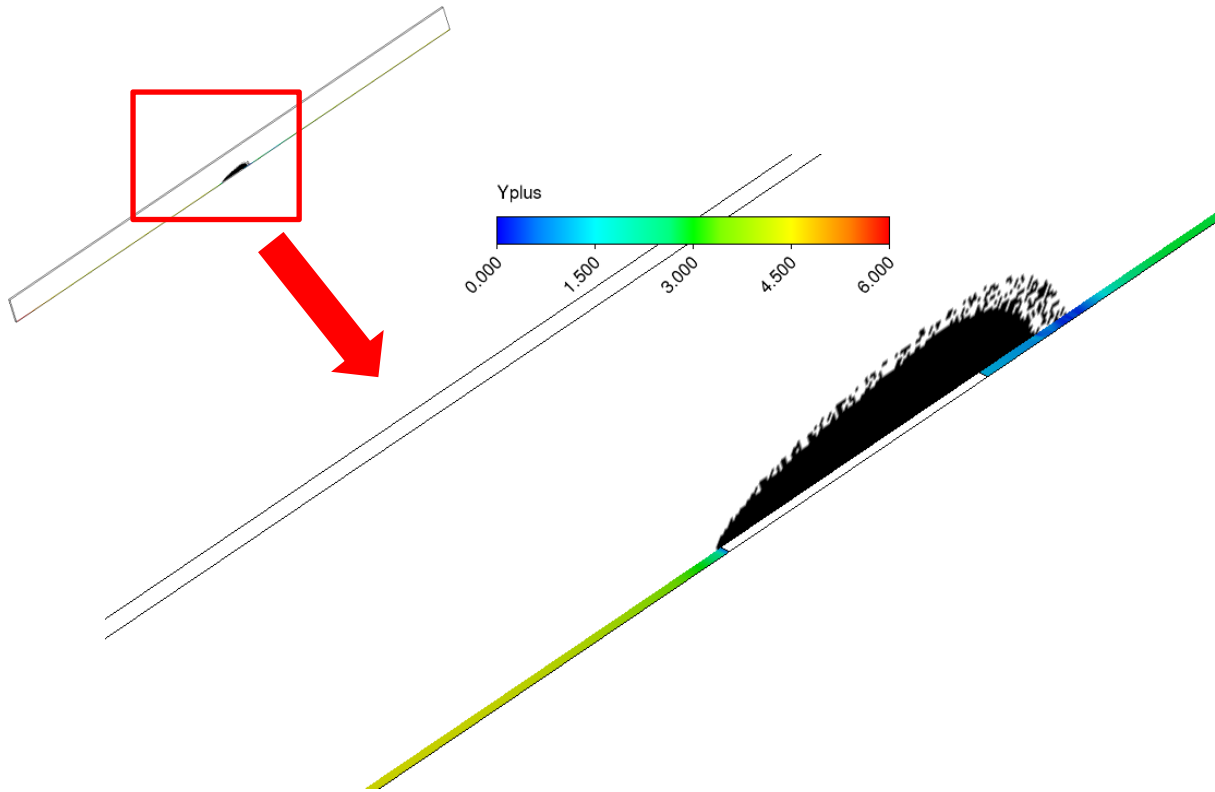


Figure A- 42: Wall Y^+ contours on the 2D plugging CFD simulation

A.9 Bibliography (documents consulted but not referenced in the report)

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Appendix B: Material properties used in CFD analysis

B.1 Sodium properties

Temperature-dependent properties for sodium were extracted from Ref. [26]. This reference is a resource for collected databases of thermophysical properties of liquid metal coolants and suggested correlations.

Density (Ref. [26], pg. 56)

The following correlation is recommended for the density of liquid sodium between normal melting and normal boiling points at atmospheric pressure:

$$\rho_{Na}(T) \left[\frac{kg}{m^3} \right] = 1014 - 0.235 \cdot T$$

with T in K. Figure B- 1 presents the CFX input to the model of the above equation.

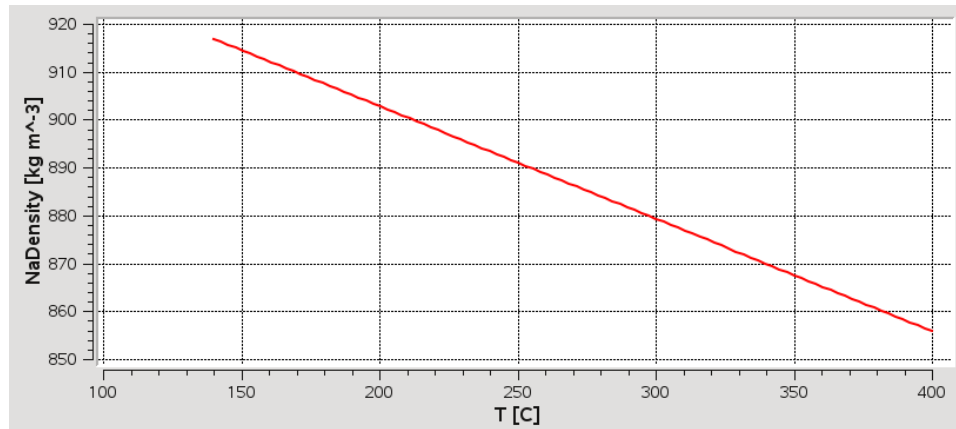


Figure B- 1: Liquid sodium density (only temperature range of interest is plotted)

Dynamic viscosity (Ref. [26], pg. 119)

The following correlation, by Shpil'rain [27], is suggested for liquid sodium dynamic viscosity:

$$\ln \eta_{Na}(T) = \frac{556.835}{T} - 0.3958 \cdot \ln(T) - 6.4406 \quad (\eta \text{ in } Pa \cdot s)$$

with T in K. Figure B- 2 presents the CFX input to the model of the above equation.

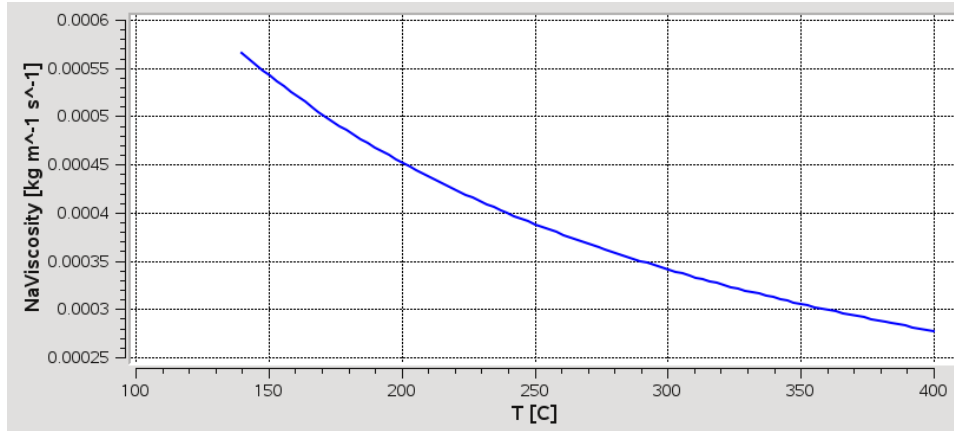


Figure B- 2: Liquid sodium dynamic viscosity (only temperature range of interest is plotted)

Thermal conductivity (Ref. [26], pg. 142)

The following correlation is suggested for thermal conductivity of sodium between the normal melting temperature and the normal boiling temperature:

$$\lambda_{Na}(T) \left[\frac{W}{mK} \right] = 104 - 0.047 \cdot T$$

with T in K. Figure B- 3 presents the CFX input to the model of the above equation.

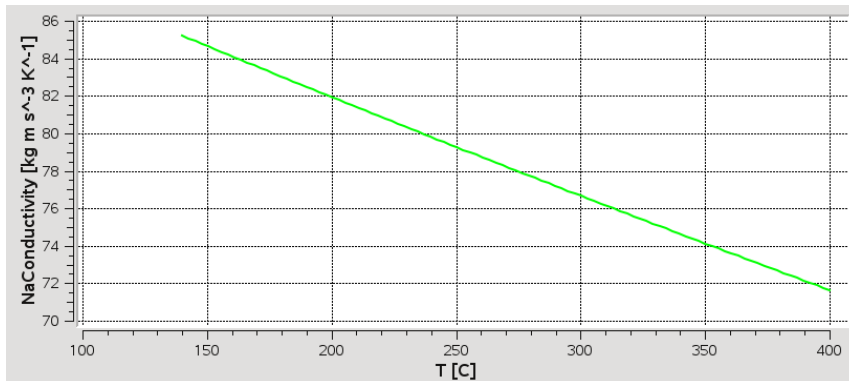


Figure B- 3: Liquid sodium thermal conductivity (only temperature range of interest is plotted)

Specific heat (Ref. [26], pg. 100)

The following correlation is suggested for sodium specific heat at atmospheric pressure:

$$C_{p(Na)}(T) \left[\frac{J}{kgK} \right] = (-3.001e6)T^{-2} + 1658 - 0.8479 \cdot T + (4.454e - 4)T^2$$

with T in K. Figure B- 4 presents the CFX input to the model of the above equation.

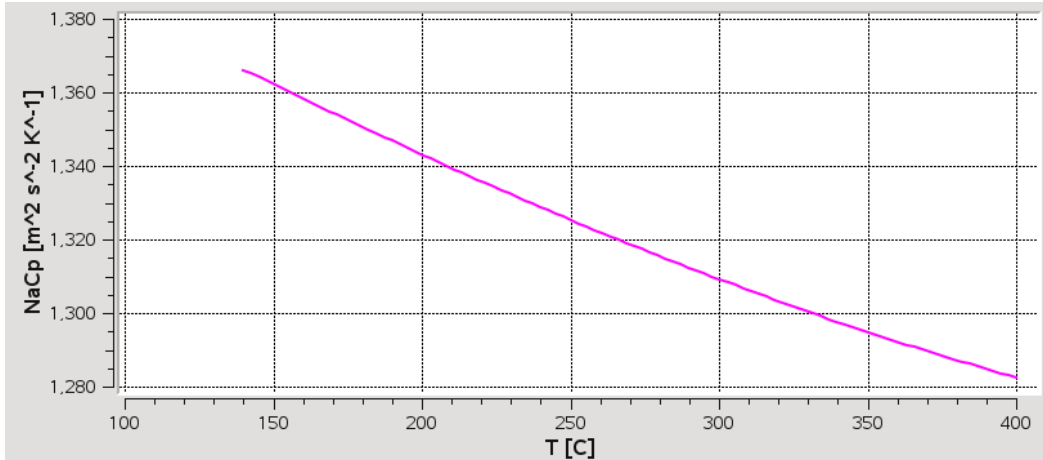


Figure B- 4: Liquid sodium specific heat (only temperature range of interest is plotted)

B.2 Stainless steel properties

The properties of SS304 stainless steel were taken from Ref. [29] and digitized to extract the data points to be included in the CFD model. This reference is a resource collecting the most widely used material property data in literature for structural materials found in light water reactor vessels. For both the thermal conductivity and specific heat, among the multiple data sets presented in Ref. [29] for SS304, Touloukian [30] data were chosen for the CFD model.

Thermal conductivity (Ref. [29], pg 23)

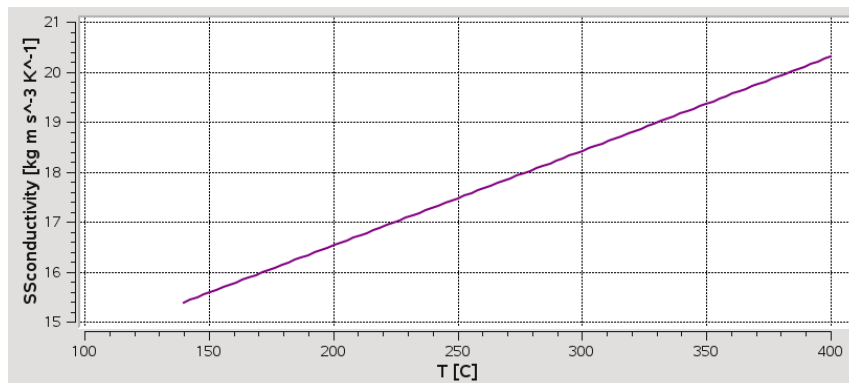


Figure B- 5: Stainless steel SS304 thermal conductivity (only temperature range of interest is plotted)

Specific heat (Ref. [29])

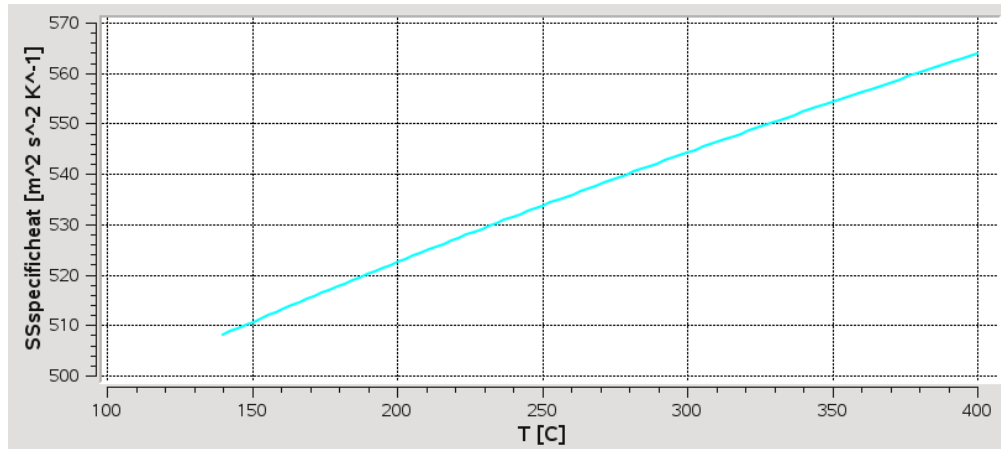


Figure B- 6: Stainless steel SS304 specific heat (only temperature range of interest is plotted)

B.3 Sodium oxide properties

The following subsections discuss how the properties for Na_2O are computed to be used in the simulations. Note that the same properties for sodium explained in Section B.1 are used for the deposit modeling presented here.

Density (Ref. [31])

The solid oxide volume fraction of the deposit was assumed to have a temperature-independent density equivalent to the theoretical density of 2270 kg/m^3 [31].

Specific heat (Ref. [32], [33])

Specific heat data are available in literature for solid sodium oxide ([32], [33]).

$$\text{Specific heat } \left(\frac{J}{kgK}\right) = -0.0013568 * [T(K)]^2 + 2.1272 * T(K) + 593.02$$

Thermal conductivity

A literature search provided no direct data for the thermal conductivity of pure sodium oxide, and little thermal conductivity data was found for oxides of similar composition materials such as pure Li_2O or K_2O . However, thermal conductivity data for solid sodium-sodium oxide cermets was available at a single temperature of 55°C ([30], [34]) as a function of sodium oxide composition (5-60 wt %). The thermal conductivity data for solid sodium is also available at temperatures below the sodium melting point of 97.7°C ([31], [34]). Using this data, the thermal conductivity of pure sodium oxide at 55°C was calculated using relationships provided in [35] that estimate the thermal conductivity of mixed solid materials. In this approach, it was assumed that the structure of the cermet could be described using a cubic geometry, in which sodium oxide is the continuous phase and sodium is the discrete phase. Since the thermal conductivity of the sodium - sodium oxide cermet and its solid sodium fraction were known at 55°C from the literature, it was possible to back calculate the thermal conductivity of the sodium oxide fraction using an effective thermal conductivity relationship that is composition dependent (Eq. 3 in [35]). A thermal conductivity value for the sodium oxide fraction of the cermet was calculated for each cermet composition

reported in Refs. [30] and [34], and the values were averaged. The resulting thermal conductivity value for solid sodium oxide was equal to 9.5 W/m.K ($\pm 42\%$). While the intrinsic value of the sodium oxide thermal conductivity should be independent of the cermet composition (recognizing the overall cermet thermal conductivity will be a function of specific sodium and sodium oxide compositions), this method provided a preliminary estimate of sodium oxide conductivity at a single temperature of 55°C.

However, the temperature in the heat exchanger channel desired to be modeled will typically be above the melting point of sodium (i.e. $>\sim 98.0^\circ\text{C}$), and therefore the sodium oxide thermal conductivity value calculated at 55 °C was scaled to higher temperatures using the thermal conductivity behavior of MgO at temperatures between 27°C and 277°C [36] (MgO is the closest similar oxide with available data). A polynomial regression for MgO thermal conductivity as a function of temperature was plotted. A “base” thermal conductivity of 56.2 W/m.K was extrapolated for MgO at 55°C. The percentage change in MgO thermal conductivity from this base value to higher temperatures was then used to scale the sodium oxide thermal conductivity of 9.5 W/m.K for the same temperature change. Using this approach, a temperature dependent curve for the thermal conductivity of sodium oxide was extrapolated between 150 °C and 300 °C as shown in the equation below (thermal conductivity decreases from ~ 6.5 W/m.K to ~ 4 W/m.K, from 150°C to 300°C, respectively).

$$\text{Thermal conductivity } \left(\frac{W}{m \cdot K} \right) = -2.519e - 7 * [T(K)]^3 + 3.91e - 4 * [T(K)]^2 - 0.2176 * T(K) + 47.66$$

Appendix C: Investigation on x-ray Computer Tomography as calibration tool for UTDR and PD techniques

This Appendix summarizes results obtained while using x-ray Computer Tomography (CT) as a diagnostic technique to characterize sodium oxide deposits inside of stainless steel tubing. This technique was developed at ANL and has been previously used for high-resolution volumetric imaging of engineering materials using high power and microfocus sources, as it provides high accuracy measurement of density variations within materials. Within this project, this technique was investigated essentially to provide a tool for the calibration of the diagnostic techniques which represented the focus of the development work performed at ANL, i.e. UTDR and PD techniques.

C.1 Experimental setup

A high-energy Philips MG-450 industrial x-ray source was used for this study. The system is capable of generating a beam spot size of 1,500 μm with a beam energy range between 20 kVp (peak kilovoltage) and 420 kVp at up to 4,200 Watts. The system employs two high-spatial resolution x-ray detectors that may be used to generate standard, two-dimensional, projection images and three-dimensional, volume datasets. Figure C- 1 shows the x-ray CT experimental setup. The same tubes as those discussed in Section 4.3.1 for UTDR testing were used here (see Figure C- 2): two shorter tubes, one clean and another filled with water, are used for calibration purposes, whereas a longer tubes removed from the SPPL following sodium plugging testing and assumed to contain sodium/sodium oxide and some pockets of argon cover gas was used for the more prototypical test. These tubes have the same material (SS), ID and OD.

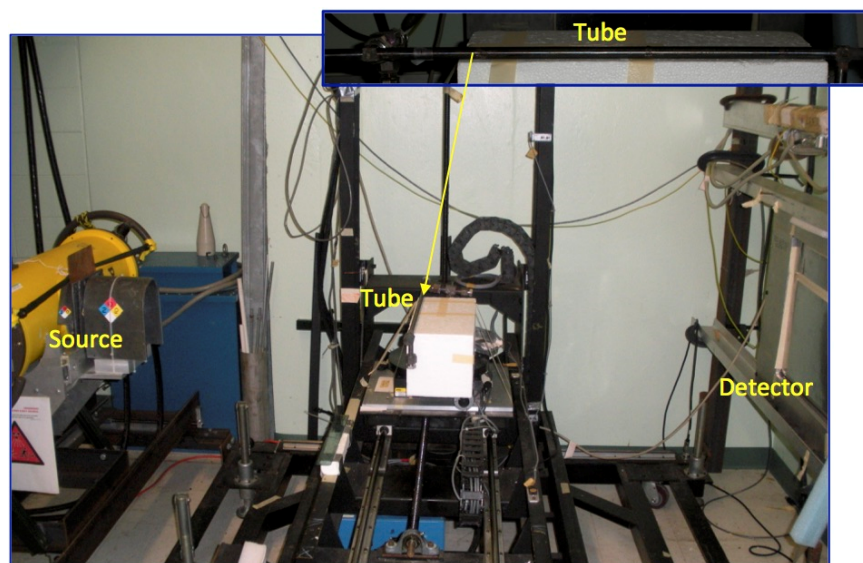


Figure C- 1: X-ray CT test setup of a tube filled with sodium/sodium oxide

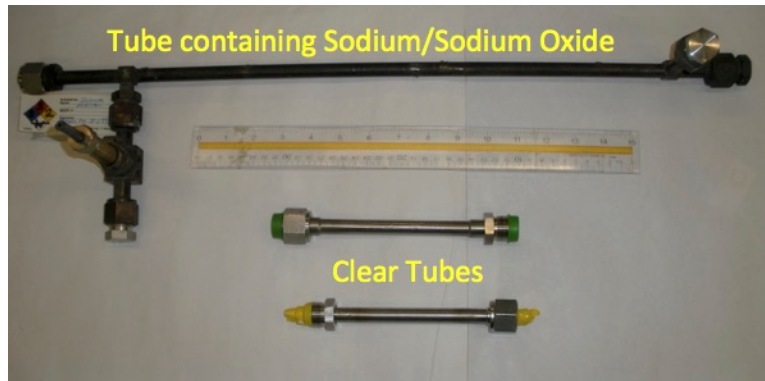


Figure C- 2: Sample tubes for x-ray CT testing

A preliminary x-ray CT test of the tube filled with sodium/sodium oxide was conducted. X-ray CT images and photos of different sections of the tube are shown in Figure C- 3. Images show some dark shaded areas that might be sodium oxide depositions and some light bubbles that might be argon gas pockets. To better locate sodium oxide films depositing on the inner surface of a tube, additional x-ray CT of the sodium/sodium oxide filled tube were conducted with tube oriented at 0 and 90 degrees axially along the tube length. Also to help calibration process for the quantitative determination of the thickness and the total amount of each sodium oxide film, all three tubes were imaged all together.

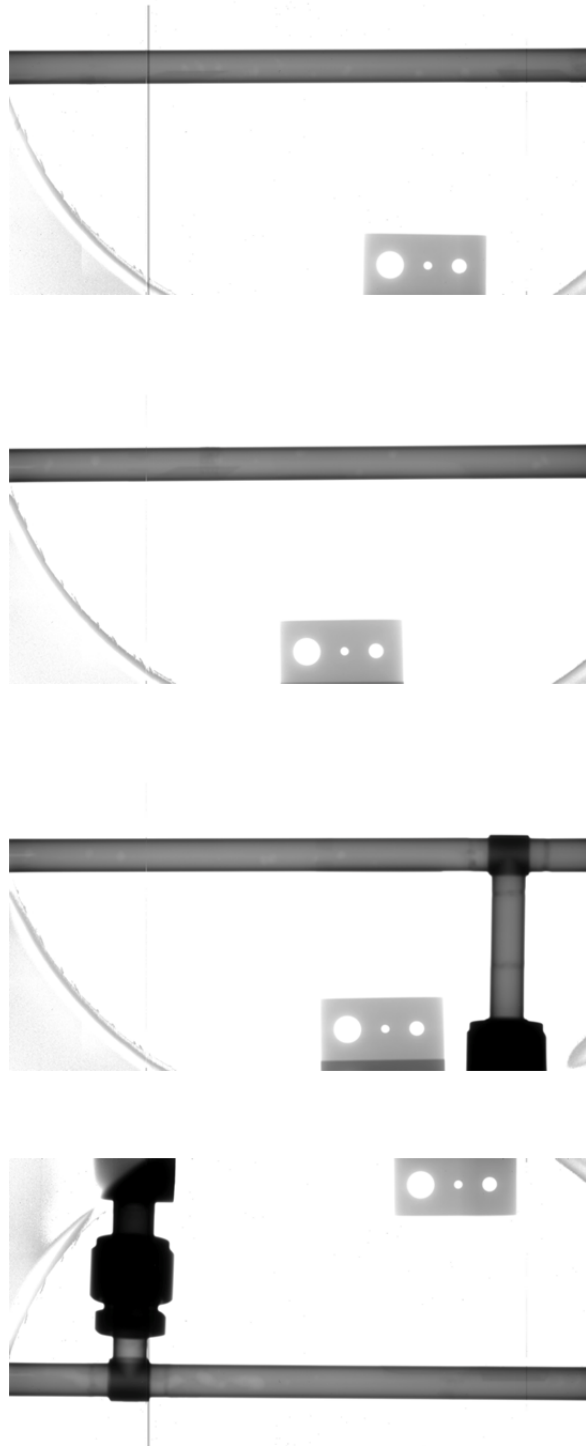


Figure C- 3: X-ray CT images of a tube filled with sodium/sodium oxide

Figure C- 4 shows a typical x-ray raw image of the three tubes “as produced” by the detector without any correction. Figure C- 5 through Figure C- 13 show instead the x-ray images obtained by operating in saturation and subsequently using Contrast Enhancement in Photoshop to augment the density differences in the sodium tube and stretch the contrast and limit/shift the gray scale²⁵. In each image, the top one is the sodium filled tube, the middle the air tube, and the bottom the water tube. Each image shows ~5 inches of tubing. Two different x-ray powers (170 and 213 kVp) were used to evaluate the effect between x-ray power and density image resolution. Figure C- 5 through Figure C- 10 were obtained in “saturation” mode at 170 kVp, 3.5 mA, It=4.0 sec whereas Figure C- 11 through Figure C- 13 were obtained also in saturation at 213 kVp, 2.5 mA, It = 4.0 sec.

The corrected images show some dark shaded areas that might be sodium oxide depositions and some light bubbles that might be argon gas pockets²⁶. Hence, the x-ray CT technique is capable of locating sodium oxide and argon gas pocket. However, without a density variation scale (i.e. a calibration equation or curve) of known quantity or thickness of sodium oxide, it is difficult to accurately determine the deposition dimensions or their total amount of sodium oxide in the sodium-filled tube from the CT images between these three tubes.

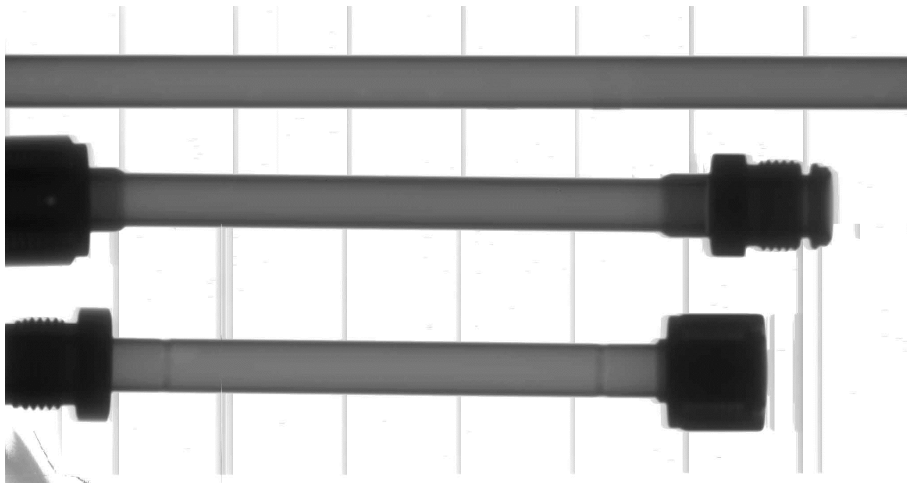


Figure C- 4: Typical X-ray CT raw image without any correction (top: sodium filled tube, middle: air tube, and bottom: water tube).

²⁵ The corrected images have the dark level raised and the bright level lowered to remove the vertical artifacts. Additionally, midrange gray scale was shifted to further enhance image contrast.

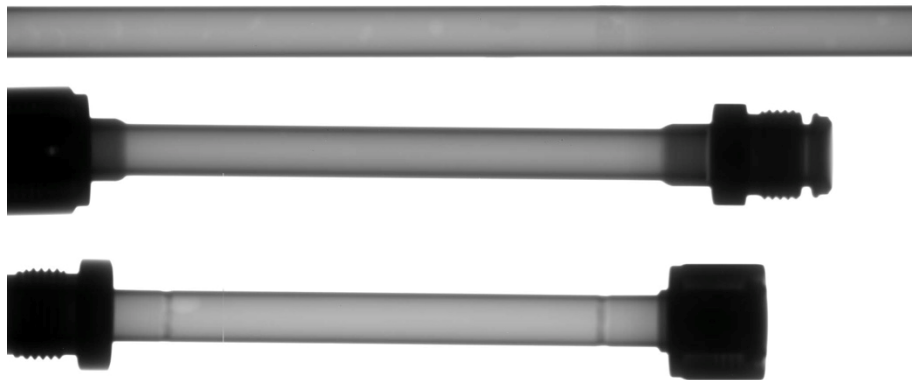
²⁶ Through the evaluation of the images, ANL suspected that the air tube (middle) has a thicker wall than the other two tubes, which needed to be verified.



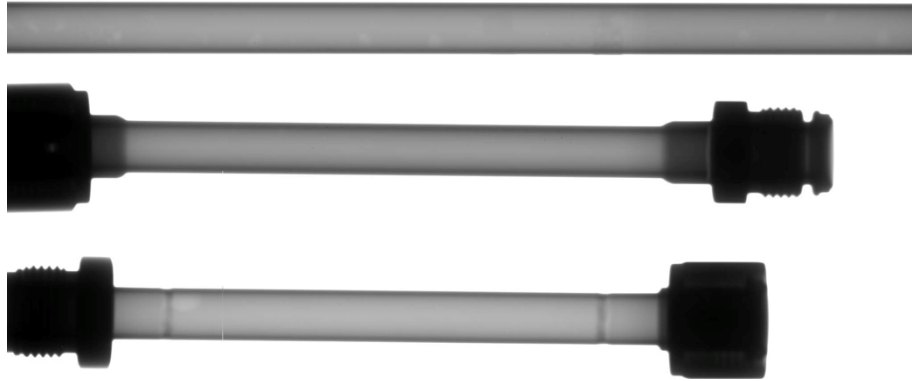
Figure C- 5: X-ray CT image at plug end (reference angle: 0°) of the three sample tubes in “saturation” mode at 170 kVp, 3.5 mA, It=4.0 sec (top: sodium filled tube, middle: air tube, and bottom: water tube).



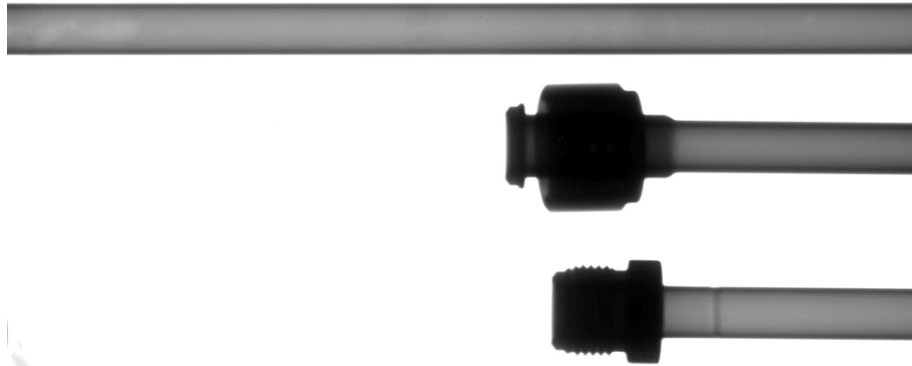
Figure C- 6: X-ray CT image at plug end (reference angle: 90°) of the three sample tubes in “saturation” mode at 170 kVp, 3.5 mA, It=4.0 sec (top: sodium filled tube, middle: air tube, and bottom: water tube).



*Figure C- 7: X-ray CT image at middle (reference angle: 0°) of the three sample tubes in “saturation” mode at 170 kVp, 3.5 mA, It=4.0 sec (top: sodium filled tube, middle: air tube, and bottom: water tube).
Note: air bubble on left-top end of water tube.*



*Figure C- 8: X-ray CT image at middle (reference angle: 90°) of the three sample tubes in “saturation” mode at 170 kVp, 3.5 mA, It=4.0 sec (top: sodium filled tube, middle: air tube, and bottom: water tube).
Note: air bubble on left-top end of water tube*



*Figure C- 9: X-ray CT image at valve end (reference angle: 0°) of the three sample tubes in “saturation” mode at 170 kVp, 3.5 mA, It=4.0 sec (top: sodium filled tube, middle: air tube, and bottom: water tube).
Note: valve of the top tube is out of view on left.*

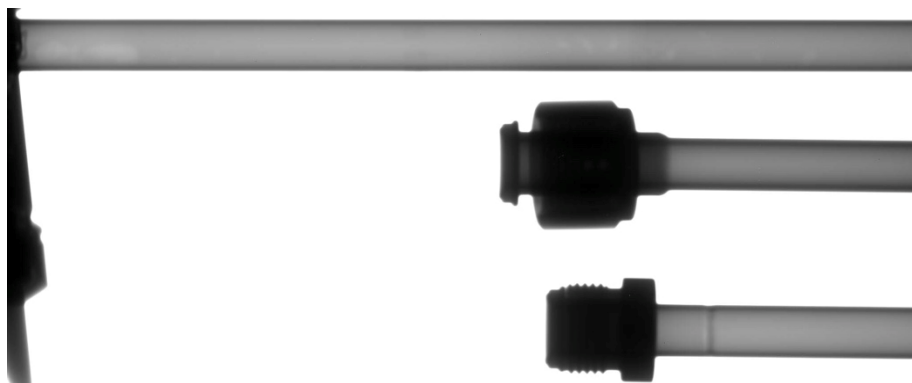


Figure C- 10: X-ray CT image at valve end (reference angle: 90°) of the three sample tubes in “saturation” mode at 170 kVp, 3.5 mA, It=4.0 sec (top: sodium filled tube, middle: air tube, and bottom: water tube).

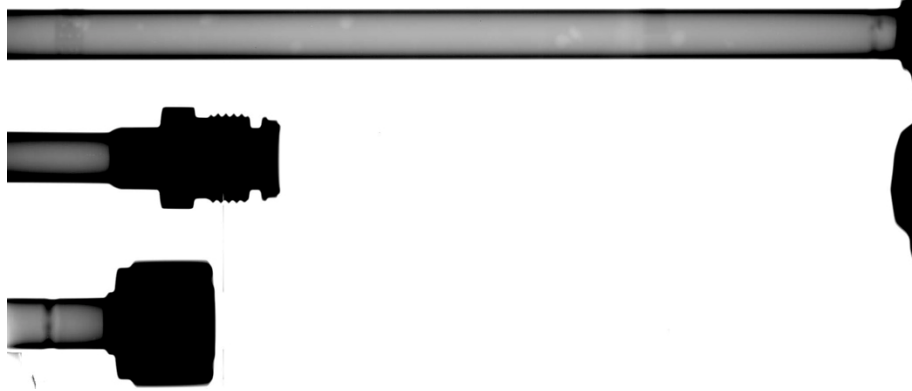


Figure C- 11: X-ray CT image at plug end (reference angle: 0°) of the three sample tubes in “saturation” mode at 213 kVp, 2.5 mA, It=4.0 sec (top: sodium filled tube, middle: air tube, and bottom: water tube).

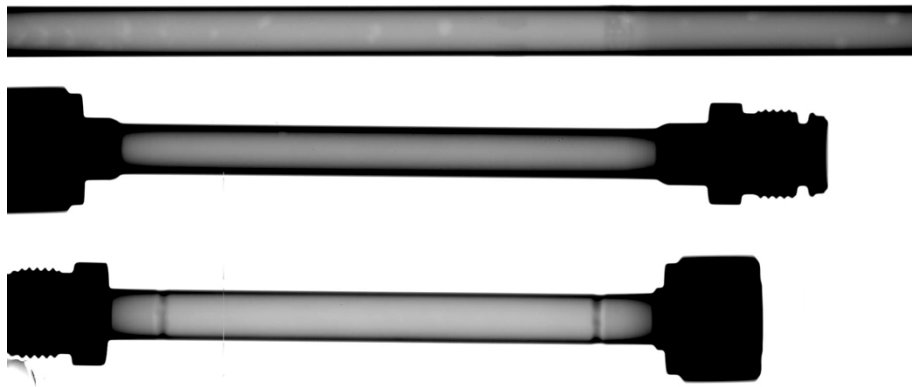


Figure C- 12: X-ray CT image at middle (reference angle: 0°) of the three sample tubes in “saturation” mode at 213 kVp, 2.5 mA, It=4.0 sec (top: sodium filled tube, middle: air tube, and bottom: water tube).



Figure C- 13: X-ray CT image at valve end (reference angle: 0°) of the three sample tubes in “saturation” mode at 213 kVp, 2.5 mA, It=4.0 sec (top: sodium filled tube, middle: air tube, and bottom: water tube).

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