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An Evaluation of Pressure Measurement Technology and Operating Performance Using Sandia's Molten Salt Test Loop

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Abstract

Sandia National Laboratories has recently completed the design, construction, commissioning, and initial operation of a Molten Salt Test Loop (MSTL) facility in Albuquerque, NM, USA. MSTL provides three parallel test loops for customers to evaluate new and existing technology in flowing molten nitrate salt at plant-like conditions of up to 70kg/s flow rate, 40bar pressure, and 300-585°C temperature. The test loop furnace contains 40metric tons of 60% sodium nitrate / 40% potassium nitrate salt that is pumped through the parallel test loops by a 9-stage, vertical turbine pump. The three parallel test legs provide locations that can accommodate small component tests such as flow instrumentation devices or valves to large solar collection systems for on-sun testing using molten nitrate salt. The system was designed with 1.4MW of heat removal capability – equivalent to the solar gain of a large aperture trough module.

During startup and commissioning of the system, the pressure transducers were identified as having a significant amount of thermally induced drift. This drift came from both diurnal ambient variations as well from operational heating from the process fluid. Exacerbating these difficulties is the requirement of MSTL that the pressure transducers operate over a wide temperature range in the course of a single test operation cycle. Sandia has taken steps to evaluate the pressure variation and to reduce this variation through temperature control. This work has greatly reduced the variability in the pressure transducers, but further improvements are on-going. The presentation will report on the efforts taken to reduce variability and the resulting performance of the transducer systems. In the course of describing the pressure transducer efforts, the system performance will also be presented along with some lessons-learned in the commissioning and startup of this test capability.

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1. Introduction

Thermal energy storage (TES) is the key differentiating technology between Concentrating Solar Power (CSP) and the other renewable energy sources. Thermal storage is a very efficient way to store energy for time periods up to several days and decouples the power production from the solar resource. This technology has been successfully applied to enable solar power plants to generate electricity around the clock or to shift the electricity generation several hours from the solar flux.

To date, the gold-standard of TES systems is nitrate molten salt storage. Nitrate salt for solar applications is either a sodium nitrate / potassium nitrate mixture (near but not at the eutectic point) or a sodium/potassium/calcium nitrate eutectic. These salts have excellent properties in the temperature range of interest, are relatively inexpensive at approximately \$1/kg, and have performed for extended time periods with no significant degradation of the heat transfer/storage fluid. These salts are typically used to a maximum temperature of 585°C because of a nitrate/nitrite disassociation that occurs more rapidly above this temperature. Though this reaction is reversible, often the oxygen from the dissociation creates metal-oxides with the fluid handling piping/tankage/pumps/valves and thus corroding the equipment.

In order to create more cost effective solutions for CSP, the US DOE has created the SunShot Initiative which seeks to reduce the cost of CSP generated electricity to 6¢/kWhr. This aggressive goal requires improvements in the entire CSP system, but is likely to require a higher efficiency power cycle which requires a higher operating temperature. The SunShot goal is above 650°C. This will require different heat transfer fluids and different thermal storage fluids. There are numerous possibilities for meeting these requirements, but each one has significant challenges that must be overcome. Two possible solutions for this are carbonate and chloride salts both of which can be made to have good temperature ranges of operation and are relatively inexpensive when compared to some of the other heat transfer options. The salts are best used for sensible heating which is advantageous for its close match to Rankine and Brayton power cycles for thermal input profile. Also, by utilizing all of the research and development that has gone into salt storage systems, high temperature salts face many fewer technical challenges than other heat transfer/storage options.

However, there are still challenges that must be solved before either chloride or carbonate salts are economical to use in thermal energy storage systems. In either the 585°C nitrate salt case or the >650°C carbonate or chloride case, there is a significant challenge regarding pressure and flow instrumentation. There are currently no commercially available measurement options for either pressure or flow above 535°C. Numerous efforts have been made for developing new technology for performance at high temperature and reasonably high pressure. Ritchie [1] developed a Fabry-Perot interferometer and tested the performance to 700°C, though the system was still affected significantly by temperature and had error similar to NaK transducers. A capacitive version was also created for the work, but was overly sensitive to electrical noise from heating and pumps. Peng [2] developed a single crystal cubic zirconia method that monitored the stress in the zirconia from pressure using the phase shift of light. This work demonstrated a large range of pressure and temperature performance, but has some challenges from blackbody radiation causing background variation in the fringes. It is also not completely clear how this system would be employed in salt service due to the need for high quality seals around prisms and the precision assembly used. Fiber optic sensors have been developed [3] utilizing extrinsic Fabry-Perot in the fiber. While temperature to 900°C is predicted, demonstration was limited to 450°C by materials. This system in its current configuration has incompatible materials for salt and would not be easily adaptable. A metal coated fiber Bragg grating was developed [4-6] for petroleum recovery with impressive pressure performance, but current temperature limitations due to materials selection render this technology non-applicable to molten salt at this juncture.

This work seeks to determine the ability of current pressure and flow instrumentation to meet the challenges of high temperature measurement in mildly or highly corrosive environments. Because the newer above technologies are not commercially available, do not have the required performance, or do not have the longevity required for an industrial application in salt, this study is conducted on diaphragm type, NaK filled capillary pressure sensors. The evaluation is done with current generation technology in the Molten Salt Test Loop (MSTL) at Sandia National Laboratories.

2. Current Technology for Flow and Pressure Measurement in MSTL

The Molten Salt Test Loop (MSTL) at Sandia National Laboratories is a newly completed test facility for the testing and evaluation of components in flowing molten salt in plant-like conditions. The system is nominally capable of flow to 70kg/s, 40bar, and 585°C though these values are increased or decreased depending on the pump curve at the desired operating point. The system has 3 parallel test loops that provide locations where a customer's experiment can be attached for testing in flowing salt in plant-like conditions. Figure 1 shows a schematic of the MSTL flow path and highlights the pressure transducers (indicated as PI_...) and the flow meters.

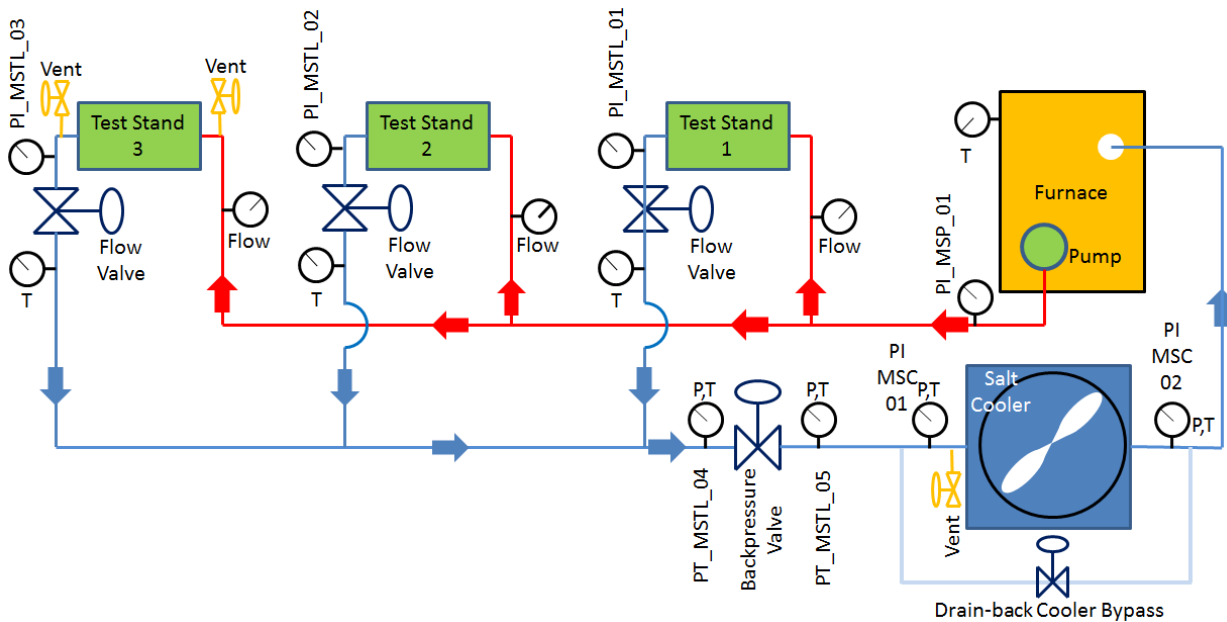


Figure 1. Flow Schematic for the Molten Salt Test Loop Showing Flow and Pressure Meters

2.1. Flow Measurement in MSTL

The flowmeters utilized in MSTL are double-pass, ultrasonic flow meters manufactured by Krohne?????. These flowmeters are installed on each of the 3 test loops in the MSTL system. The performance of these flowmeters has been tested by using the pump speed to determine the expected flow from the pump curve. The pump curve is derived from measured data in a water test at ambient conditions and then scaled for molten nitrate salt's specific gravity and for temperature. Also, a test was performed in which the pump was run at a constant speed, the backpressure control valve put at a specific position, and 25kg/s flow run through each test leg individually. Though imperfect in testing due to differences in pipe length of more than 24m, this test showed the flowmeters to agree under flow control with pump speed matching within 6%. An additional potential error source in this test is the valves which could have slightly different limits positions and a 0.5% measurement resolution in the valve position. Throughout the operation of MSTL, the flow meters have not appeared to exhibit noticeable drift, their output appears to be very consistent meter to meter and, so far as can be determined, the flow measurement appears to be accurate. However, these flowmeters have a temperature limit in the technical specifications of 535°C. For the operation of MSTL, Sandia was given a special guarantee that the meters would perform accurately and safely up to the maximum design temperature of MSTL of 585°C. So, while these meters were acceptable for this application, they likely would not be acceptable for a CSP plant that had to meet production guarantees. These flowmeters are not capable of meeting the >650°C goals of the SunShot program. The reason for this temperature limitation is not completely clear. It is likely at least partly due to the material challenges at temperatures above 600°C where stainless steel loses much of its strength and the materials of choice are high temperature nickel superalloys. It may be difficult, or at the very least expensive, to provide flowmeters in these materials. Additionally, few electronics devices will operate at these temperatures, requiring remote mounting. This requires the use of temperature controlled dead-legs or intermediate fluids in the transducer to remove the electronics to a cooler area. In fact, the MSTL flow meters require that the flow meter not be insulated. So in contrast to the rest of the piping, valves, furnace, and MSTL equipment which is heavily insulated, the flow meters are open to atmosphere. The meters must still be heat traced to prevent salt freezing in the main flow path and therefore the flow meters consume considerable amounts of energy when the system is not flowing salt. This point is illustrated by Figure 2, taken during construction, which shows the piping with only half of its insulation thickness installed.



Figure 1. A flowmeter in MSTL, shown during construction, remains uninsulated and is contrasted with the highly-insulated piping.

2.2. Pressure Measurement in MSTL- First Attempt

In contrast to the flow meters which have been fairly successful in MSTL, the pressure sensors have given significant challenges. The transducers used are technology originally developed for the injection molding industry and utilize a diaphragm that is in contact with the heat transfer/storage fluid on one side. Because of the contact with salt, the materials that can be used for this diaphragm are limited. Behind this diaphragm is a very small capillary filled with sodium-potassium (NaK) fluid. Pressure waves in the salt impinge on the diaphragm which transmits the wave to the capillary fluid. After traveling the length of the capillary in the capillary fluid, the pressure wave impinges on a diaphragm whose deflection is measured by capacitance or laser measurement. The advantage of these sensors is that they remove the sensitive electronics package from direct contact with the high heat and potential corrosion experienced at the HTF end of the transducer.

The pressure sensors currently used in the MSTL system are like the one shown in Figure 2a. The HTF diaphragm is at the end of the rigid stainless tubing at the upper left of the Figure. The capillary transmits the pressure wave through the length of the stainless tubing and the electronics unit is shown at the upper right of the Figure. The transducers are temperature compensated and the thermocouple connection at the lower left of the Figure is for this purpose. It is important to note, however, that the temperature measured is at the tip of the transducer and the remainder of the transducer, including the capillary, is not temperature compensated or temperature controlled. The transducers have an upper temperature limit of 535°C which is due to the strength reduction of the PH15-5 stainless steel used in the threaded portion of the transducer end as well as temperature limitations of the diaphragm. Because this is a potential safety and performance issue, there has been no approval to take these sensors above 535°C.

As of the 9th month of operation, the Gefran transducers have shown good reliability as far as returning signals of somewhat reasonable magnitude. However, upon first using the transducers, it quickly became apparent that they were significantly affected by ambient temperature conditions and with no salt in the line (and no pressure change) the pressure readings would vary by more than 12 bar day to night (see Figure 4.)

2.3. Pressure Measurement with Insulated Capillaries

The first attempt to counteract this temperature sensitivity was to place insulating sun covers over the transducers to eliminate the solar input from directly affecting the transducer. Though this may have helped some, the change was relatively ineffective. The second attempt was to wrap insulation around the capillary and the J-box holding the electronics unit.

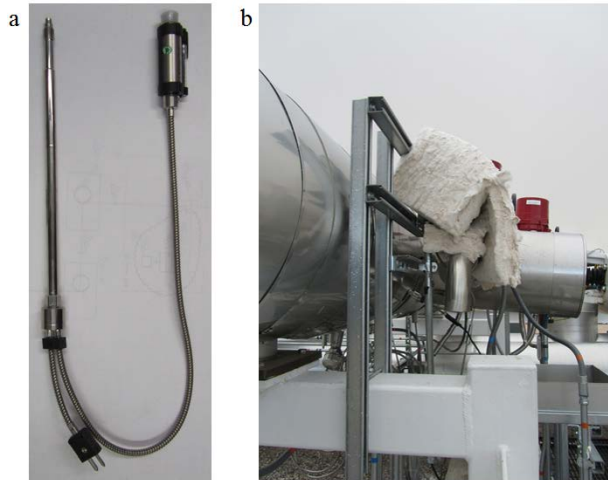


Figure 2. a) NaK-filled capillary transducer, b) insulation placed on the electronics box to reduce diurnal temperature variation.

Figure 4 shows pressure data measured during testing of MSTL. The blue and green lines in the Figure are pressure measurements throughout the night of September 20, 2012 and values for these measurements are in bar on the right scale of the graph. It can be seen that the pressure transducers indicate a pressure drop at the pump outlet of 12 bar. It is important to remember that throughout the night represented by this graph, the pipes were actually at 0 bar and the temperature of the pipe was maintained at 300°C by the heat trace system. Obviously, pressure indicators that show 12 bar pressure change that doesn't exist are not performing satisfactorily.

2.4. Pressure Measurement with Heated Electronics and Insulated Transducers and Electronics

Testing with the insulated capillary showed that the heat from the pipe and salt system had a significant effect on the measured pressure values. The salt flowing in the pipe heated the capillary and caused a large increase in the reported pressure. Additionally, even with the capillary insulated, the diurnal temperature swing caused a matching pressure change. This result indicated that insulating the capillary was not sufficient and that the electronics package would have to be fully insulated as well. In addition, it was apparent that the capillary and electronics package would have to be heated to such an extent that the pressure transducer would maintain a constant temperature whether salt was flowing or not. To test this theory, an electronic junction box was attached to the end of the pressure transducer protection pipe and the entire capillary and electronics package were placed in the box. A heater was placed in the bottom of the box as can be seen as a flat metal strip with terminal posts shown in the Figure. For the test, the box was then insulated externally. The results of this test were positive, so a more permanent solution was developed.

Based on the success of the above test, a box-in-a-box concept was developed as shown in Figure 3. The inner electrical box is connected to the pipe that protects the pressure transducer. This inner box contains the capillary, electronics package, and a PID controlled heater. This inner box is surrounded by a larger outer box which has a 50mm spacing for insulation all around the inner box. In the Figure, the insulation can be seen behind the inner box, but the insulation has not yet been added to the sides and in-front of the inner box. A completed box is shown in the Figure, though the Figure shows Temporary lagging on the insulation surrounding the transducer protection pipe. This configuration has significantly improved the pressure transducer performance over previous configurations. Two tests were conducted to determine the effects of this modification. The “before” modification test was performed in September of 2012 and the “after” modification test was performed in January when the temperature change overnight is at its extreme. Figure 4 shows the results of the two 17 hour stability tests beginning at 2:00pm and going through the night to 7:00am. The Figure shows data for the two most critical pressure transducers for the operation of MSTL. Pressure sensor 1 is at the pump outlet and sensor 4 is just before the backpressure control valve. Before the electronics enclosure was insulated and heated, the pressure transducers indicated a pressure change of up to 12bar overnight. It is important to note that over this time, the piping was maintained at 300°C by resistive heat trace and the gage pressure in the pipe was 0bar throughout the entire test. After implementing

the change to insulate and heat the electronics enclosure, the indicated pressure change overnight was less than 1.4 bar. In actuality, while the graph only displays 17 hours, the “after modification” test was conducted over 24 hours and the indicated pressure change still remained under 1.4 bar. This performance improvement is marked, but one would hope for single digit variation or better. Therefore, a test was performed to see if the pressure transducers in this state were sufficient to use as another flow meter.

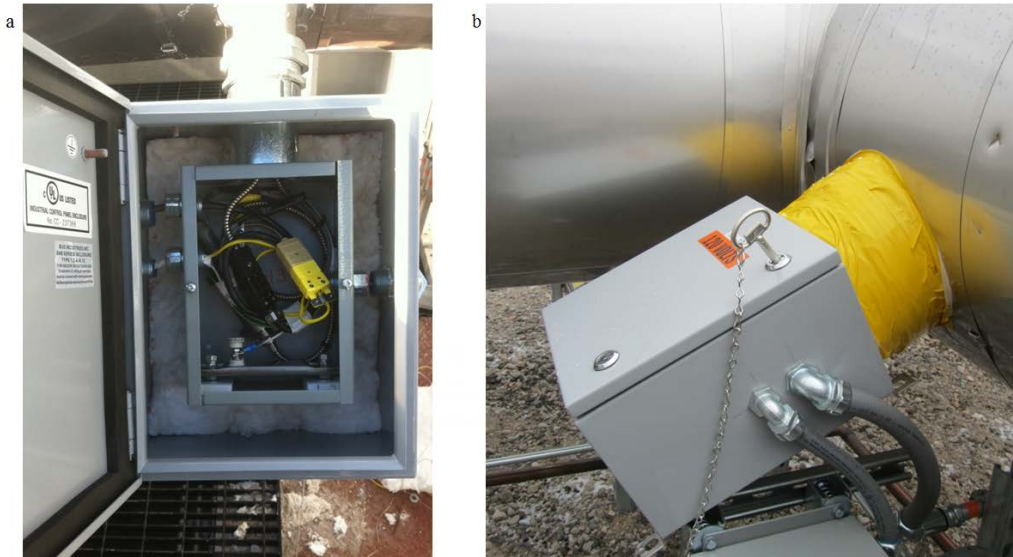


Figure 3. a)the modified electronics enclosure is heated and insulated, b) a completed, modified electronics enclosure

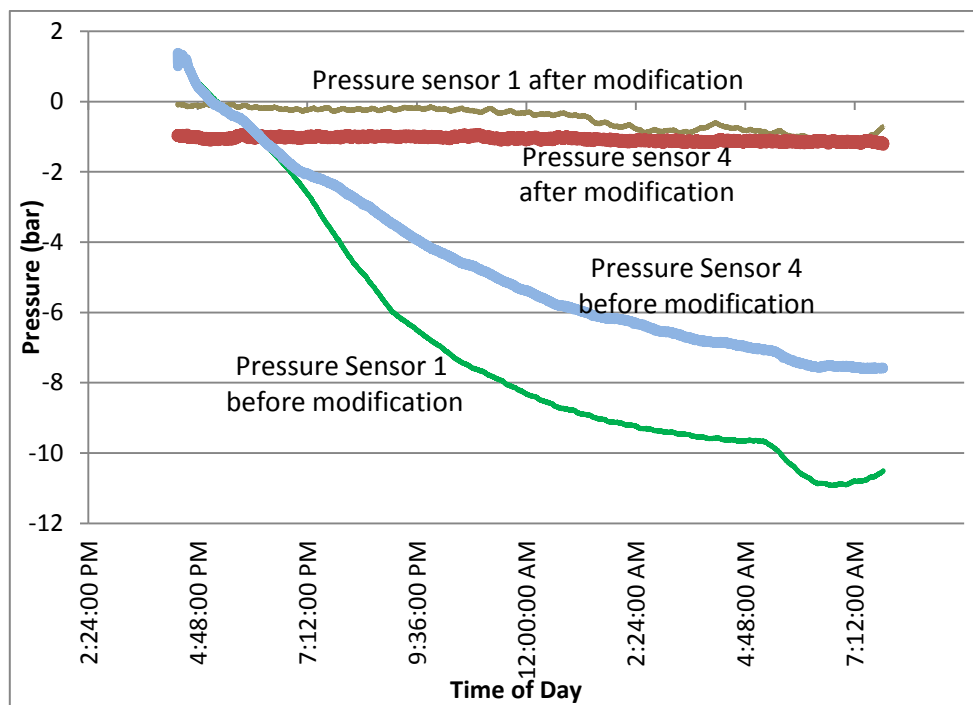


Figure 4. A comparison of 15 hours over night shows the improvement in the pressure reading after modifying the electronics enclosure.

3. An Evaluation Using Pressure to Measure Flow in MSTL

When the initial Failure Mode and Effects Analysis (FMEA) was performed for MSTL, the loss of flow measurement was determined to be a severe failure mode because of the need to determine quickly and accurately if there is a breach in a customer’s test. With the improved performance of the pressure transducers, a test was performed to determine if the pressure transducers could measure the flow on both sides of a valve to accurately determine flowrate. The use of a pressure drop to measure flow is a very common practice, though it is usually done with a device having a single flow coefficient, Cv, such as a knife-edge orifice plate or a Venturi. Because these devices have not been successful in salt applications (due primarily to poor pressure measurement) there is not an orifice or Venturi flow meter installed in the MSTL system. Without this fixed-Cv component, a characterized variable Cv device is the next best choice and the valves were provided with Cv curves at different valve positions. A test was run in which a broad set of flow and pressure conditions were evaluated with the pressure drop measured across Flow Control Valves 1 and 4 (FCV-1 and FCV-4). FCV-1 is used to set flow and an initial pressure drop within test loop 1. FCV-4 is used to set the back pressure of the entire system. Both of these valves have pressure transducers on both the upstream and downstream sides of the valve. The transducers are not optimally positioned, however, as they are not designed as a flow meter. The nominal test conditions are shown in Table 1. The results of the test are shown in Figure 5. The Figure shows that the valve 4 gives reasonable results around 6.9 bar operating pressure (tests 4 and 8) but the flow values get worse with increasing system pressure. The tests indicate that it will not be possible to rely on the valves and pressure transducers as a corroborating flow measurement, and so another method is required, especially above 535°C where the pressure transducers are not rated for operation.

Table 1. Test conditions for the pressure sensor / flow meter evaluation at 340°C

Test Number	Pressure bar (psig)	Flow kg/s (gpm)	Pump Speed (RPM)
1	13.8 (200)	47.3 (400)	1130
2	20.7 (300)	47.3 (400)	1321
3	27.6 (400)	47.3 (400)	1489
4	6.9 (100)	59.1 (500)	1065
5	13.8 (200)	59.1 (500)	1237
6	20.7 (300)	59.1 (500)	1401
7	27.6 (400)	59.1 (500)	1536
8	6.9 (100)	59.1 (500)	1037
9	6.9 (100)	70.9 (600)	1187
10	13.8 (200)	70.9 (600)	1355
11	20.7 (300)	70.9 (600)	1488
12	27.6 (400)	70.9 (600)	1604

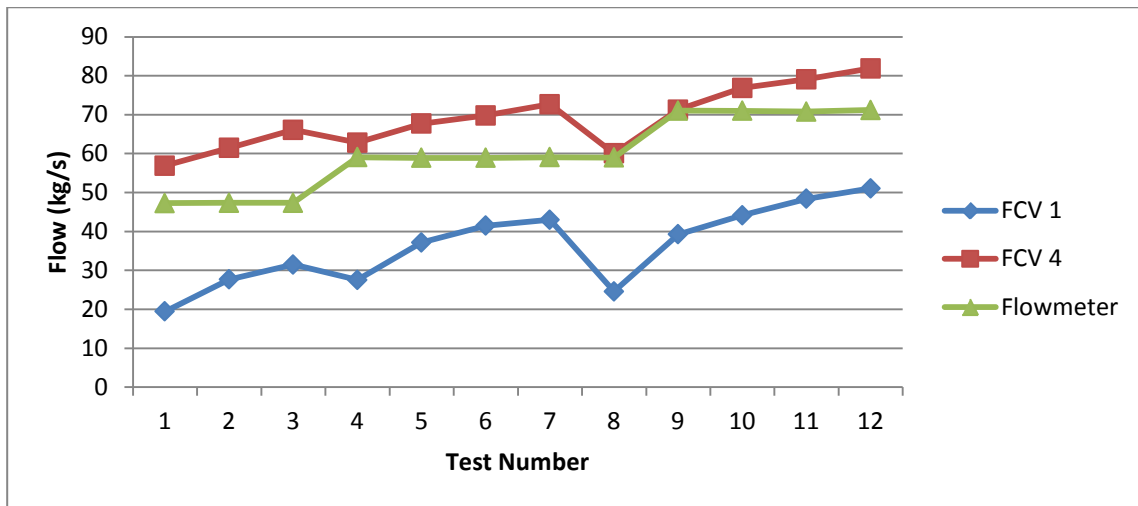


Figure 5. Flow results from flowmeter and pressure drop test showing poor agreement between the pressure drop and flow meter values

Further modifications to the pressure sensors are currently underway at the Molten Salt Test Loop. We are implementing horizontal dead-legs for the transducers with temperature control of the salt in the dead leg based on manufacturer recommendations. Because the MSTL piping system fully fills and drains every time it is operated, it is not clear that these dead legs will effectively fill with salt or whether they will maintain an air pocket but this method will be tested in the near future in an attempt to further reduce variability in pressure measurements.

4. Conclusions

The pressure sensors provided with the Molten Salt Test Loop (MSTL) have not proven to give reliable pressure measurement. The sensors are severely affected by ambient temperature changes indicating pressure changes of 12 bar when the pressure was in fact ambient. To counteract this pressure variation, several methods of reducing ambient temperature change were implemented including insulation, co-location of sensor and transmitter, and heating. A solution has been implemented that corrects much of the pressure variation and testing has shown the pressure transducers to change less than 1.4 bar over a 17 hour time period.

At the same time, an alternative flow measurement method was needed as a back-up method for the MSTL flowmeters. Though the flowmeters have been reliable thus far, they are extremely important for the operation of the test loop and determining if there are salt leaks in a customer's test apparatus. Therefore, an additional method of measuring flow was determined to be important. Based on the improved pressure transducer measurements, an evaluation was conducted to see if the pressure drop across valves with known Cv would be accurate enough to utilize. A test was performed and the flow measurement using the pressure drop was not sufficiently accurate to be usable.

There remains a significant need to develop both pressure and flow metering equipment that will be usable in temperatures over 535°C. This missing capability will have a deleterious effect on efforts to achieve the SunShot goals with sensible fluid heat transfer and storage materials.

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