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FLOW TESTING AND ANALYSIS OF THE FSP-1 EXPERIMENT

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ABSTRACT

The U.S. High Performance Research Reactor conversions fuel development team is focused on developing and qualifying the uranium-molybdenum (U-Mo) alloy monolithic fuel to support conversion of domestic research reactors to low enriched uranium. Several previous irradiations have demonstrated the favorable behavior of the monolithic fuel.

The Full Size Plate 1 (FSP-1) fuel plate experiment will be irradiated in the northeast (NE) flux trap of the Advanced Test Reactor (ATR). This fueled experiment contains six aluminum-clad fuel plates consisting of monolithic U-Mo fuel meat. Flow testing experimentation and hydraulic analysis have been performed on the FSP-1 experiment to be irradiated in the ATR at the Idaho National Laboratory (INL). A flow test experiment mockup of the FSP-1 experiment was completed at Oregon State University. Results of several flow test experiments are compared with analyses. This paper reports and shows hydraulic analyses are nearly identical to the flow test results.

A water channel velocity of 14.0 meters per second is targeted between the fuel plates. Comparisons between FSP-1 measurements and this target will be discussed. This flow rate dominates the flow characteristics of the experiment and model. Separate branch flows have minimal effect on the overall experiment. A square flow orifice was placed to control the flowrate through the experiment. Four different orifices were tested. A pressure differential versus flow rate curve for each orifice is reported herein. Fuel plates with depleted uranium in the fuel meat zone were used in one of the flow tests. This test was performed to evaluate flow test vibration with actual fuel meat densities and reported.

INTRODUCTION

The Full Size Plate-1 (FSP-1) experiment will be irradiated in the North East flux trap of the Advanced Test Reactor (ATR) as shown in Figure 1 at the Idaho National Laboratory (INL). The experiment consists of six full size plates approximately 48 in. in length. The fuel meat is uranium 10wt% molybdenum (U-10Mo) in the form of a monolithic foil with a uranium enrichment of 19.75% U-235. The purpose of this paper is to detail the experimental flow testing results of the FSP-1 experiment. A hydrodynamic evaluation was performed to compare with experimental results. A discharge coefficient from the square flow orifice varying with orifice size is necessary for the final design put into the reactor.

A flow test experiment [1] for FSP-1 was conducted at Oregon State University (OSU) Hydro-Mechanical Fuel Test Facility (HMFTF). This is a thermal hydraulic test loop that is designed to allow hydraulic testing of a variety of single, full-scale High Performance Research Reactor (HPRR) fuel elements. It can be utilized to facilitate the measurement of fuel plate and element plastic and elastic deformation, and vibration as a function of operating system pressure, and flow rate for a prescribed temperature. The HMFTF consists of a closed primary loop containing a separate bypass leg and secondary loop. The purpose of the primary loop is to control the system fluid (water) at a prescribed temperature, flow rate, and pressure in order to examine the response of the test specimen located in the test section of the primary loop. The purpose of the feed water system is to prepare the primary fluid (pH and conductivity), and account for all necessary heat removal and fluid makeup requirements that may be required by the test engineer for the primary loop. The test section in the primary loop accommodates testing of the FSP-1 geometric configuration. Instrumentation housed in and around the test section allows for experimental data collection to meet the requirements outlined herein.

FSP-1 has one hardware design with variable lobe power from cycle to cycle. FSP-1 has three specimen types/condition including Full Burn (FB), Intermediate Power (IP), and Thick Meat (TM), arranged in distinct fuel-meat axial length segments within swaged frame assemblies. Each frame assembly has a twin, giving a total of six fueled frame assemblies. The irradiation vehicle will house six frame assemblies; substituting fueled frame assemblies for dummy frame assemblies when needed.

Several flow tests of the FSP-1 experiment with various flow restrictor orifices were tested at OSU. These flow tests provide higher confidence flow rates as inputs for calculating experiment temperatures. This paper discusses the analyses supporting the interpretation of flow test measurements made by OSU to support these irradiation experiments.

The primary target of this analysis is to provide the best-estimate flow rates inside the fuel plate channels. The FSP-1 experiment specifies a bulk water velocity between the fuel plates of 14.0 m/s. Four flow restrictor orifices were tested. A pressure drop versus flow rate curve was obtained for each orifice. This paper shows the hydrodynamic analysis of these curves and calculates what the final orifice size should be to meet requirements.

All modeling is performed using the Mathcad and Excel software.

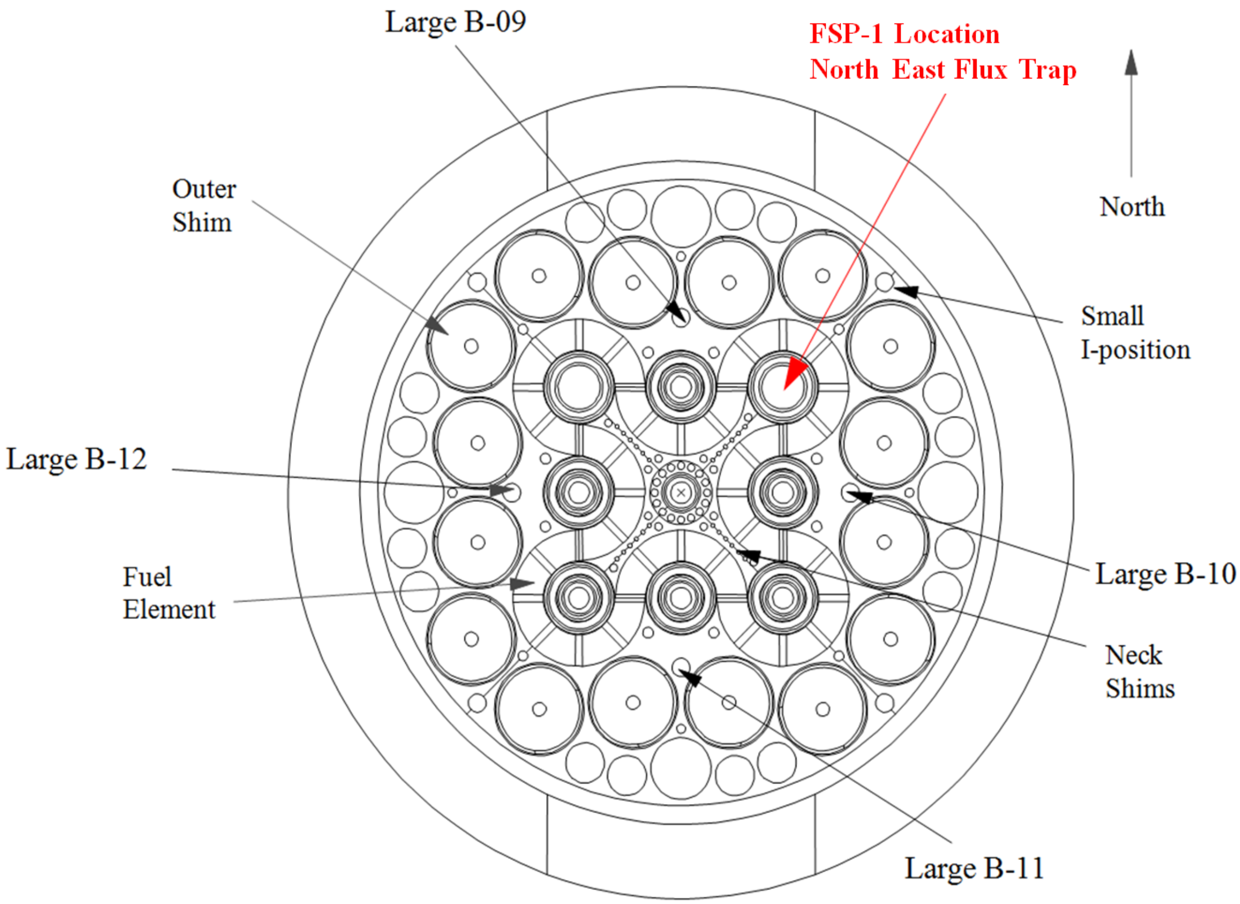

Figure 1. ATR core cross section showing the northeast flux trap position containing the FSP-1 experiment.

MODEL DESCRIPTION

FSP-1 hydraulic model will be discussed in this section. For the OSU data, the nominal temperature and pressure is 170 °F and 400 psig. The nominal coolant inlet temperature and pressure in ATR is 125 °F and 360 psig, while the core pressure drop is 77 psid.

All measurement uncertainties are documented in Appendix B of the previously mentioned OSU report. The main flow rate uncertainty varies between 2.04% and 2.09%, while the pressure differential uncertainty varies between 0.90 and 0.94 psid. The FSP-1 experiment is designed to yield appropriate fluence levels to support the development of the uranium-molybdenum alloy fuel. The vehicle comprises four main components as shown in Figure 2 and Figure 3.

Flow Simulator – The flow simulator is a cylindrical body with an outer diameter of nominally 6 inches, an inner diameter of 5.25 inches and a total length of 74.88 inches. The flow simulator is the interfacing component between the Hydro-Mechanical Fuel Test Facility (HMFTF) and the remaining components which comprise the FSP-1. The inner geometry of the Flow Simulator is designed to reflect similar conditions found within the ATR.

Outer Basket – The Outer Basket is the outer-most geometry which will be placed within the ATR. The outer basket has an outer diameter of 5.125 inches, an inner diameter of 4.00 inches, and is 66.92 inches in length. An orifice plate is located on the lower most surface of the outer basket. Use of an appropriately sized orifice plate will lead to the desired hydraulic balance (flow rate and pressure drop) that satisfies safety basis and in-pile irradiation conditions. The orifice plate is secured to the outer basket via 6 socket head cap screws.

Inner Basket – The inner basket acts as a holder for the test plates. The inner basket has an outer diameter of 3.88 inches and a total length of 65.45 inches. The interior of the inner basket has been machined to a square slot to provide a mating surface for the test plates. The inner basket comprises two assemblies; the top region is the handle assembly which is connected to the body assembly via a hinge point. This hinge allows for the rotation of the handle assembly to be placed out of concentricity with the body assembly which provides sufficient space for the test plates to be slid into their appropriate location.

Test Plates & Ram Rod – Six test plates are located in the FSP-1. These test plates all have a width of 2.24 inches (2.40 inches including the side rail), thickness of 0.05 inches (0.25 inches including the side-rail), and a length of 48.75 inches nominally. These plates are placed adjacent to one another inside the square slot that is located within the inner basket. They are held secure in-place via a ram rod. The ram rod is a 0.725 inch thick aluminum square plate which is placed between the outer-most test plate and the inner surface of the inner basket. The ram rod mechanically secures the test plates both horizontally and vertically within the inner basket through a compression fit against the plates' side-rails. The outer primary surface of the ram rod contains a number of ball plungers which compress the ram rod against the side rails of the test plates, securing them horizontally. The test plates are secured vertically by a small arm located on the top of the ram rod which mates against the top surface of each test plate's side rail.

Flow Orifice– A square orifice plate as shown in Figure 2 and Figure 3 is placed to control the flow rate through the experiment. OSU tested four orifice plates during the experiment. Square holes of 1.44, 1.30, 1.16, and 1.244 inches were respectively tested. These will be noted as tests 1, 2, 4, and 5 in this paper. OSU did a total of six experiments and we will be referring to the above mentioned tests.

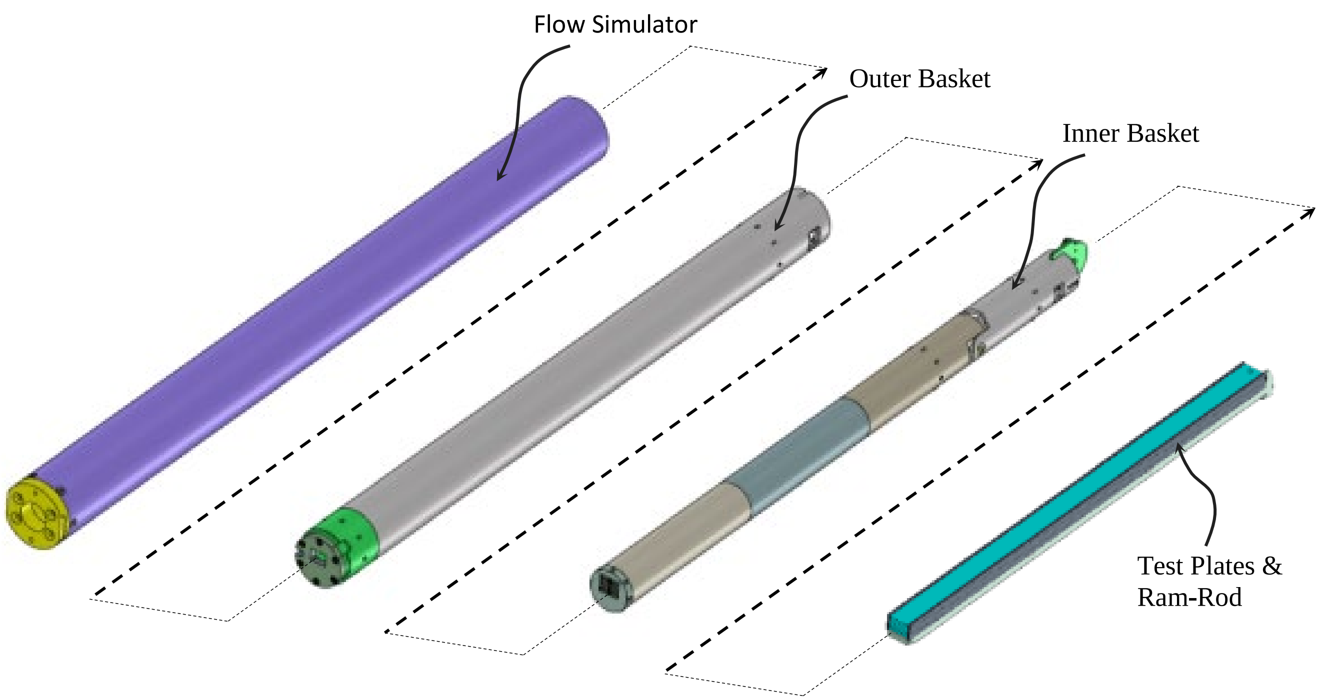

Figure 2. Description of the FSP-1 experiment.

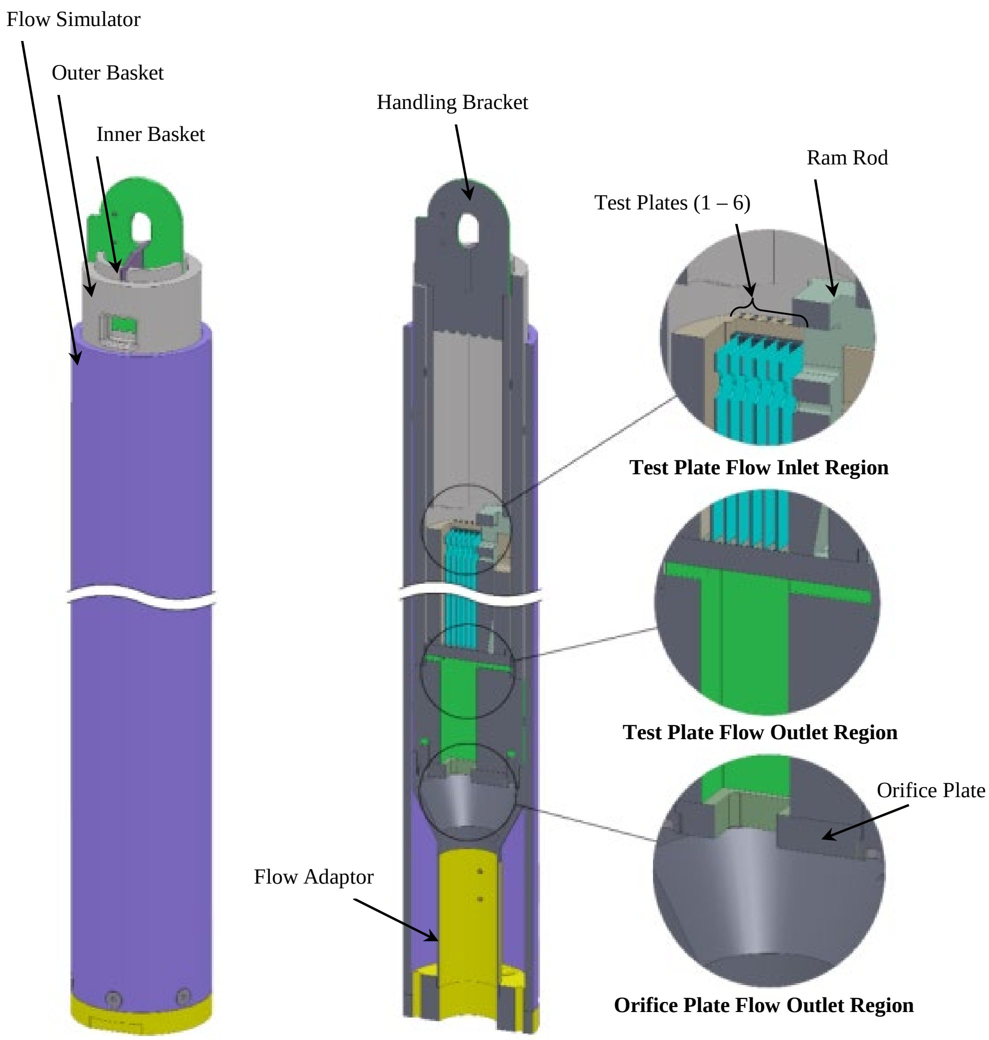

Figure 3. Arrangement of components in the FSP-1 experiment.

A flow resistance diagram is shown in Figure 4. A flow condition of 14.0 m/s is set as the bulk water velocity between the fuel plates as a programmatic requirement. The bypass flow is between the inner and outer baskets. The flow along the fuel plates, ram bypass, and edge rail bypass all have the same pressure drop. These three flows combine and go through the flow disrupter. The flow disrupter lines up with the seven water channels with a divider down the middle for a total of 14 channels. The flow disrupter is put in to keep vortices from shedding off of the bottom of the fuel plates and causing vibration. The flow through the bypass joins with the flow through the flow disrupter and goes through the rectangular area. This total flow then goes through the flow restrictor. Just over half (~52%) of the pressure drop occurs along the fuel plates, while about 43% occurs through the flow restrictor. Values displayed in Figure 4 are for the final design with an orifice plate square hole size of 1.244 inches. This analysis shows a total experiment pressure drop of 73.27 psid. This value comes from the 77 psid across the ATR core minus 3.73 psid across the flux trap support tube at the bottom of the ATR. There is no flow between the outer basket and the flow simulator. A total flow through the experiment of 411.7 gpm is calculated.

Figure 5 shows a cross section of the flow area within the inner basket of the FSP-1 assembly. The plates are assembled into the inner basket and then the ram-rod is then placed down into the inner basket, forcing the plates together tightly and fixing them in place. Fluid can then pass through the voids between plates, the inner basket, and the ram rod. The FSP-1 experiment was designed to allow for the test plates to be changed out. This allows for testing with both aluminum (6061-T6) and aluminum clad, depleted uranium (DU) plates.

Nominal dimensions are the same for all geometric configurations tested, whether the dummy aluminum, or surrogate DU plates are used. All flow channels have an equal nominal span width of 1.905 ± 0.03 inches and thickness of 0.200 ± 0.02 inches. All plates range in thickness from 0.050 to 0.048 inches.

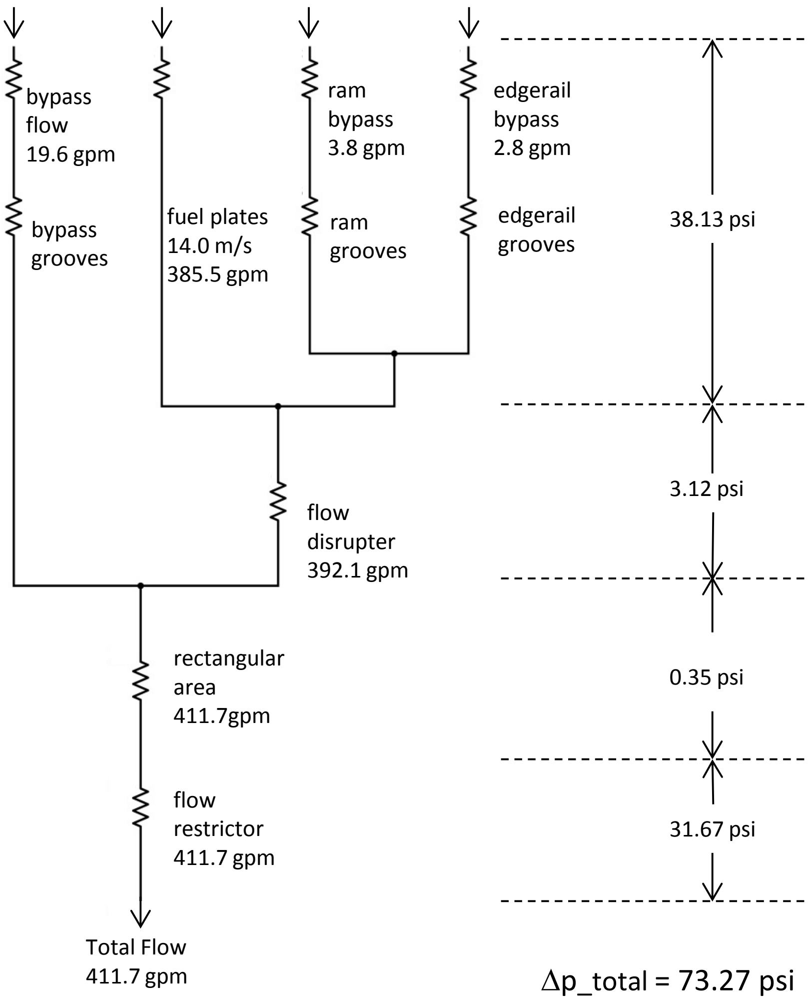

Figure 4. Flow and resistance diagram of the FSP-1 experiment.

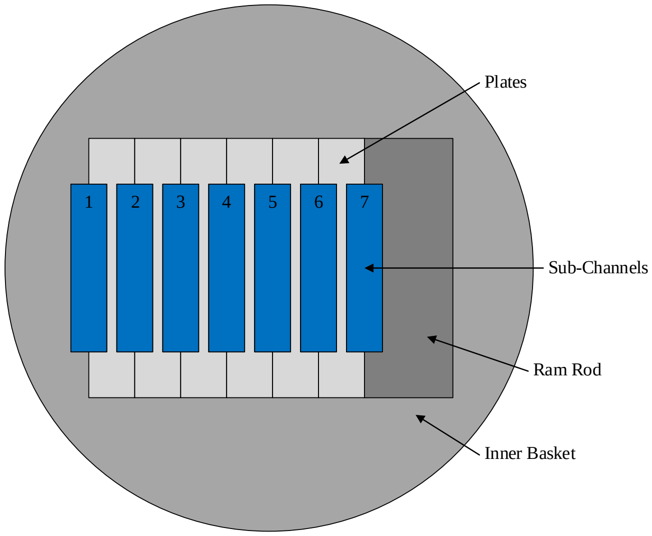

Figure 5. Cross section of inner basket

To solve the hydrodynamic equations, a find function with 48 non-linear equations was setup in the Mathcad software to find the velocities, Reynolds numbers, friction factors, K value loss coefficients, and pressure drops for all four separate channels. The fuel plates, outer annulus, outer annulus return grooves, ram bypass, ram bypass return grooves, edge rail and edge rail return grooves, flow disrupter, and rectangular area all had 5 unknown quantities mentioned above. The flow restrictor had three unknown quantities of: velocity, K value, and pressure drop. These are the 48 equations (9x5+3) simultaneously solved for. Initial guesses for all 48 values were employed to solve the equations in Mathcad. Three input variables of orifice size, experiment flow rate, and experiment pressure drop were used. To solve these simultaneous non-linear equations, all values had to be non-dimensionalized by dividing the area by in^2 and velocity by in/s. Constraints were taken from Figure 4 for equalizing pressure drops, total pressure drop, and conservation of flow at the junctions of the channels. As an example, the channels containing the fuel plates had the following calculations to determine the pressure drop.

Given geometry of water between fuel plates

L_{fp} = 48.75 in	length of fuel plate
w_{fp} = 1.905 in	width of water channel between fuel plates
h_{fp} = 0.201 in	height of water channel between fuel plates

The hydraulic diameter of the rectangular fuel channel is given by Eq (1) with the Reynolds number given in Eq (2).

$$D_{hy\_fp} = \frac{2w_{fp}h_{fp}}{w_{fp}+h_{fp}} \qquad D_{hy\_fp} = 0.364\ in \tag{1}$$

$$Re_{fp} = \frac{\rho D_{hy\_fp} V_{fp}}{\mu} \tag{2}$$

where ρ is the water density, V_{fp} is the bulk water velocity along the fuel plates, and μ is the molecular viscosity. The entrance loss coefficient K_{c_fp} is 0.5, while the exit loss coefficient K_{e_fp} is estimated to be 0.1 as the water immediately transitions to the flow disrupter. The Fanning friction factor [2] was calculated as:

$$f_{fp} = \left\{-4log\left[\frac{0.27\epsilon}{D_{hy\_fp}} + \left(\frac{7}{Re_{fp}}\right)^{0.9}\right]\right\}^{-2} \tag{3}$$

where f_{fp} is the Fanning friction factor, and ε is the surface roughness of machined aluminum taken to be 63 μin from [2]. The frictional loss coefficient K_{f_fp} is defined in Eq (4) as:

$$K_{f\_fp} = \frac{4f_{fp}L_{fp}}{D_{hy\_fp}} \tag{4}$$

The total pressure drop along the fuel plates is defined in Eq (5) as:

$$\Delta p_{fp} = \frac{1}{2}\rho V_{fp}^2\left(K_{c\_fp} + K_{f\_fp} + K_{e\_fp}\right) \tag{5}$$

The frictional loss coefficient dominates Eq (5). Typical values are about 37. The total loss is not very sensitive to the estimated exit loss coefficient of 0.1 (could be a maximum of 1.0). Similar equations were calculated for each flow channel and return grooves.

The non-linear equation solver adjusted the loss coefficient of the flow restrictor orifice so that the pressure drop and conservation of flow were maintained. The square orifice had rounded corners with a radius R of 0.13 in. and side lengths of X. The area and hydraulic diameter of the orifice are described in Eqs (6), and (7) as:

$$A_{fr} = X^2 - R^2(4-\pi) \tag{6}$$

$$D_{hy\_fr} = \frac{4A_{fr}}{2\pi R + 4(X-2R)} \tag{7}$$

The pressure drop across the flow restrictor orifice is noted in Eq (8) as:

$$\Delta p_{fr} = \frac{1}{2}\rho V_{fr}^2 K_{fr} \tag{8}$$

where K_{fr} is the total loss coefficient of the flow restrictor, including entrance, friction, and exit loss coefficients. V_{fr} is the bulk water velocity through the flow restrictor. These loss coefficients (K values) for the orifice will be discussed in the Results section.

RESULTS

The FSP-1 flow test results are shown in Figures 6 through Figure 12. Traditional hydrodynamics flow calculations for contracting and expanding flows are evaluated. The final orifice plate size of 1.244 inches is the final recommended orifice size to accomplish the goal of 14.0 m/s bulk water velocity along the fuel plates.

Flow versus delta P results from Appendix A of Reference [1] are the basis for this analysis. These results show a nominal value with an associated uncertainty. Figure 6 shows the pressure drop of the test varying with flow rate for each orifice. These are the nominal curve fit values for each test. Flow rate error bars are shown based on the associated uncertainty values. Modified flow rates within the bounds of the uncertainty are shown as dotted lines. These modified flow rates were adjusted to make the K value across the orifice plate consistent. The modified flow rates for the 1.244 inch orifice are almost identical to the nominal flow rates. The modifications affected the test data for the two largest orifices (1.30 and 1.44 inches) and therefore had a small effect on the final orifice size (1.244 inches) for the FSP-1 experiment.

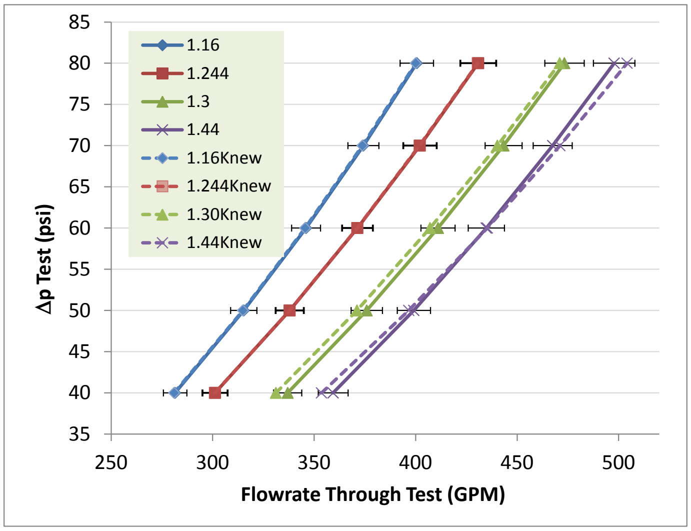

Figure 6. Pressure drop versus flow rate of test.

K value loss coefficients were calculated across the flow restrictor for the orifices varying with pressure drop and flow rate from Eq (8). A plot of K value for the flow restrictor versus Reynolds number is shown in Figure 7. The small orifices show a constant value near 0.65, with the smallest orifice of 1.16 inches being the highest. The K values for the 1.30 and 1.44 inch orifices show some increase with Reynolds number. This seems to go against intuition. The unmodified K values of the 1.30 and 1.44 inch orifices also cross each other at a Re number of 2.0 E+06. Further discussion of how these K values were modified is presented in Figure 9

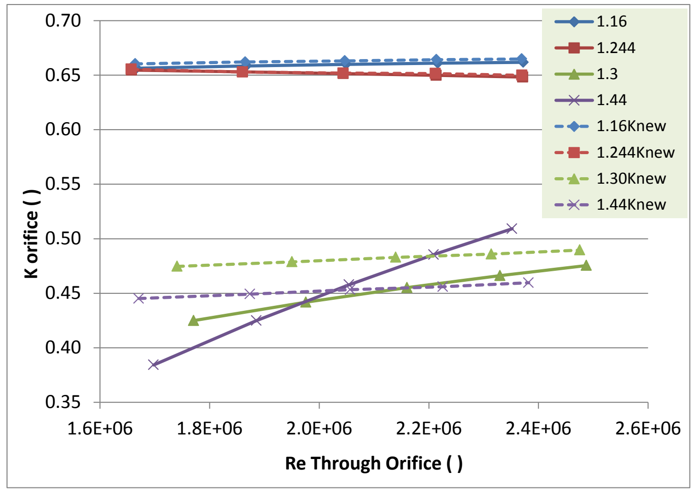

Figure 7. K values of orifice versus Reynolds number through flow restrictor orifice for nominal flow rates.

A plot of the K values of the orifice versus the experiment flow rate is shown in Figure 8. This is essentially the same information as Figure 7.

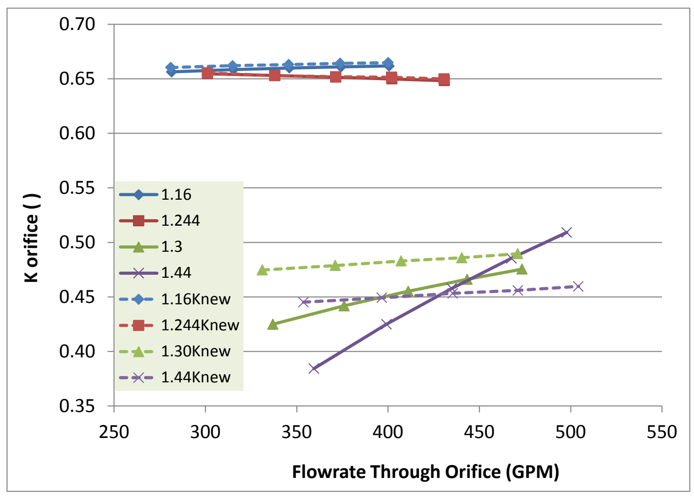

Figure 8. K values of orifice versus flow rate through experiment.

Figure 9 shows a plot of the orifice K value versus Reynolds number for all of the orifices. Each orifice has three lines on the plot. The minimum and maximum K value based on the uncertainty of the flow rate is plotted for each orifice as a solid color line. By adjusting the flow rate within the bounds of the uncertainty, the plot was made to be consistent. These adjusted K values are shown as dotted lines. The adjusted values lie within the uncertainty band defined by the minimum and maximum flows. The smallest orifices have the largest K values and they vary very little with Reynolds number.

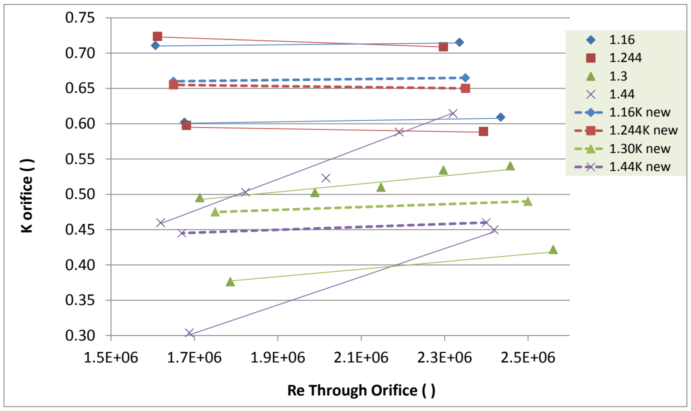

Figure 9. K values of orifice plate versus Reynolds number for minimum and maximum flow rates.

Figure 10 shows a plot of pressure drop across the orifice versus flow rate through the orifice for various flow rates and all orifice sizes. Nominal and modified flow rate values are plotted. The smallest orifice has the highest pressure drop across the orifice and hence a higher proportion of the total experiment pressure drop compared to the largest orifice.

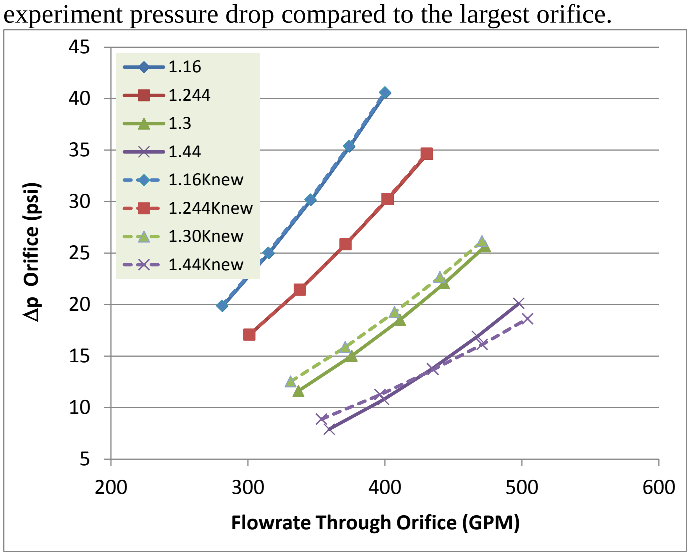

Figure 10. Pressure drop across orifice versus flowrate through orifice.

A plot of pressure drop across the orifice versus pressure drop across the entire test for all orifices for various flow rates is shown in Figure 11. This plot shows the relative pressure drop of each orifice. Nominal values in solid lines and adjusted flow values with dotted lines are plotted.

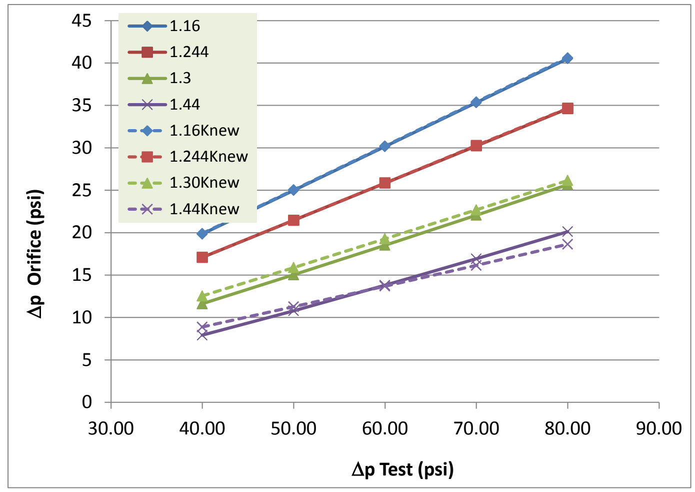

Figure 11. Pressure drop across orifice versus pressure drop across test.

Figure 12 shows a plot of water velocity in the fuel plate channels versus pressure drop of the four tests for all four orifices. A pressure drop of 73.27 psid yields a water velocity of 14.06 m/s for the 1.244 inch orifice. This was close enough to the target of 14.0 m/s to call it good and not change the orifice size for the ATR experiment.

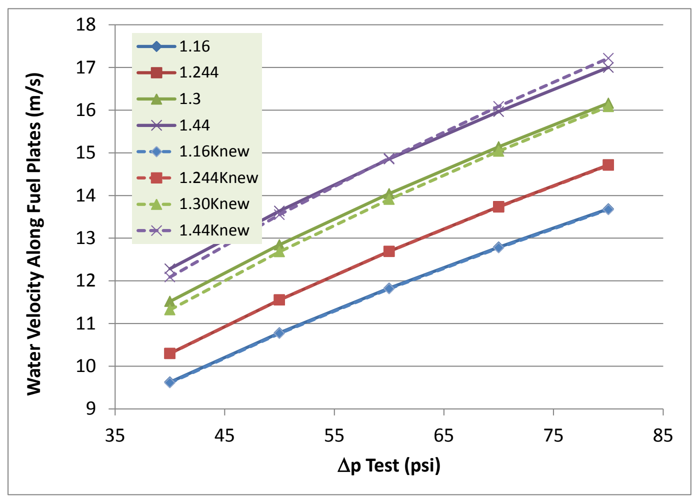

Figure 12. Water velocity in fuel channels versus pressure drop of tests.

CONCLUSIONS

A hydrodynamic analysis has been performed on the FSP-1 flow tests performed at OSU. Tests 001, 002, 004, and 005 were considered with corresponding orifice plate values of 1.44, 1.30, 1.16, and 1.244 inches respectively. Nominal flow values were adjusted within the bounds of the flow rate uncertainty to modify the K values of the flow restrictor orifice. These modified flow rates were used to size the orifice. The final orifice size is the same as the final test of 1.244 inches.

This orifice will ensure a water channel bulk velocity between the fuel plates of 14.0 m/s. Pressure drop and flow rate calculations were obtained for all four flow paths in the FSP-1 hardware.

ACKNOWLEDGMENTS

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