CRITICAL FLOW EXPERIMENT AND ANALYSIS FOR SUPERCRITICAL FLUID

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The use of Supercritical Fluids (SCF) has been proposed for numerous power cycle designs as part of the Generation IV advanced reactor designs, and can provide for higher thermal efficiency. One particular area of interest involves the behavior of SCF during a blowdown or depressurization process. Currently, no data are available in the open literature at supercritical conditions to characterize this phenomenon. A preliminary computational analysis, using a homogeneous equilibrium model when a second phase appears in the process, has shown the complexity of behavior that can occur. Depending on the initial thermodynamic state of the SCF, critical flow phenomena can be characterized in three different ways; the flow can remain in single phase (high temperature), a second phase can appear through vaporization (high pressure low temperature) or condensation (high pressure, intermediate temperature). An experimental facility has been built at the University of Wisconsin to study SCF depressurization through several diameter breaks. The preliminary results obtained show that the experimental data can be predicted with good agreement by the model for all the different initial conditions.

KEYWORDS : Critical Flow, Supercritical Fluids, Water, CO_2

1. INTRODUCTION

Supercritical defines a fluid that has reached a pressure and a temperature such that the distinction between liquid and gas no longer exists. The use of such fluids combine the advantages of both a liquid and a gas in a power cycle for advanced reactor and has led to numerous possibilities. For example, within the last decade the use of supercritical fluid in power systems has resulted in a growing interest in supercritical fluids to serve as working fluids in several Next Generation Nuclear Plant (NGNP) [1] to optimize efficiency.

In the framework of Generation IV, Supercritical Water (SCW) has been proposed as a primary coolant in the Supercritical Water-Cooled Reactor (SCWR) whereas Supercritical CO_2 ($SCCO_2$) has been considered for advanced power cycles such as Brayton cycles (Dostal et al 2004). The primary motivation is to reduce the system complexity and increase the thermal efficiency of the power cycle up to 45 %. However, other advantages are associated with such improvements. First, by using a supercritical (SC) fluid, as a single-phase fluid, there is no concern about the heat transfer discontinuities; e.g., critical heat flux. Secondly, it reduces the required mass flow substantially per unit of thermal power required. Overall this simplifies the power cycle, as fewer components are required (in particular, phase separators).

Unfortunately these advantages do not come without any disadvantages. In the direct power cycle designs, the loss of flow transient becomes a major concern in the operation of the reactor system. Pump stoppage or a pipe rupture can cause a loss of flow. In both cases, the relevant parameter will be the characteristic time of depressurization, as this will specify the type of response needed to adapt and control the transient event. The only data available concerning the event of supercritical water blowdown relates to the work conducted by the United Kingdom Atomic Energy Authority (UKAEA) [2]. These experiments were, however, conducted at the boundary of the supercritical region (temperature lower than 400 ºC) in order to study the critical flow at the extreme pressure and temperature attained during an Anticipated Transient Without Scram (ATWS) event rather than at possible accident conditions for proposed advanced power cycle. Their experiments were conducted at steady state conditions avoiding phase transition.

In the present study our focus centers on the mass flow rate and the depressurization from a pipe break. Since these possible events have to be well understood, the University of Wisconsin has initiated a study to characterize the critical mass flow rate of different supercritical fluids under a large range of temperature and pressure. The present paper first describes the model used to evaluate different behaviors of the supercritical fluid in a blowdown event and to design the experiments that are to be performed with SCW and $SCCO_2$. It also presents preliminary results of blowdown for both SCW and $SCCO_2$.

2. COMPUTATIONAL MODEL

2.1 A Homogeneous Equilibrium Model Implemented in EES

In an effort to analyze this problem, a standard Homogeneous Equilibrium Model (HEM) was implemented into an Engineering Equation Solver (EES) [3] along with data from the IAPWS steam [4] and CO_2 [5] thermodynamic properties database. The calculation was performed on a reservoir at an initial pressure and temperature that depressurizes through a straight vent line of varying L/D. The critical flow rate was computed for a large range of initial conditions assuming both relative temperature and relative pressure higher than unity, both with and without friction.

The mass, momentum, and energy conservation equations are implemented in the model assuming steady state and adiabatic conditions. When the fluid stays single phase, the computation can be interpreted as a Fanno flow for a real gas that is expected to choke at the outlet of the exiting tube. Note that, at supercritical condition, the ambient pressure/initial pressure ratio for both SCW and $SCCO_2$ is much lower than what the choking conditions require. The model switches to the HEM (Homogenous Equilibrium Model) when the properties are such that the gas at a specific cell would be inside the vapor dome. If the second phase appears and the HEM is employed the density and the viscosity are calculated as follows:

$$\frac{1}{\rho} = \frac{x}{\rho_g} + \frac{1-x}{\rho_f} \qquad \text{(1) HEM}$$

$$\frac{1}{\mu} = \frac{x}{\mu_g} + \frac{1-x}{\mu_f} \qquad \text{(2) Isbin correlation}$$

The friction factor is estimated locally, along the length of the pipe, using the Blasius correlation:

$$C_f = 0.0791.\mathrm{Re}^{-0.25} \qquad (3)$$

The HEM assumes thermal equilibrium between the phases and the same velocity in the pipe, which leads to an underestimation of the critical flow. The results are useful, however, for the design of the experiment and as a first approximation of the critical mass flow to determine the depressurization rate. At the vicinity of the critical point, the property for fluid and gas are similar, this fact substantiates our choice of using the HEM as a first approach. From a computational point of view, the model involves four inputs: pressure, temperature, diameter and mass flow rate. Due to the formation of a very high gradient at the choking exit, it is more convenient to calculate the critical length of the pipe associated with a given mass flow rate and iterate to match the physical geometry of the experiment. For example, knowing the initial pressure, temperature, and the geometry of the problem, one can guess a critical mass flow rate and obtained a critical length. If the critical length is greater than the actual pipe length, the mass flow rate is increased. This routine is iterated upon until both length match.

2.2 Comparison with Previous Work

In an effort to initially validate our model, calculations were performed at the same initial conditions as those of the UKAEA experimental data (374 to 400ºC and 22 to 31MPa). In these experiments, four different exiting nozzles were considered. The critical mass flow rate was measured using a flow meter and conditions were such that the system was running at a steady state. The temperature and pressure measurements were only used to estimate the heat transfer coefficient. Nozzle A is a sharp edged 1.7-mm diameter orifice. Nozzle B and D are round edge short nozzles with similar length-to-diameter ratios. Nozzle B has a 1.7-mm diameter whereas nozzle D has a 2.5-mm

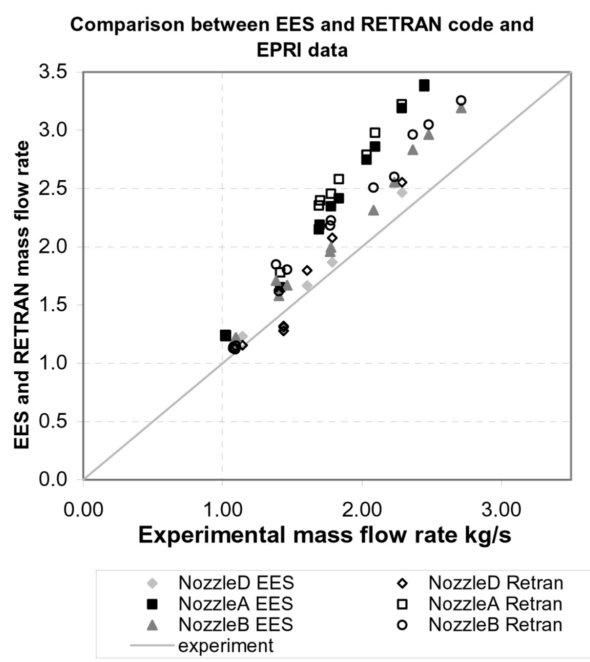

Fig. 1. Comparison of EES Code with RETRAN Calculation and Data from UKAEA

diameter. At this stage of calculation, the model does not take into account the geometry of the nozzles, and an isentropic flow assumption is implemented. The nozzle geometry is such that, the friction effects are mostly due to entrance pressure loss in the nozzle associated with the formation of a vena contracta, however this was not included in the initial calculation.

The results of these experiments and the current calculations were also compared to calculations performed with the RETRAN code [6]. The RETRAN-02 and RETRAN-3D computer programs were developed by the Electric Power Research Institute (EPRI) to perform licensing and best-estimate transient thermal-hydraulic analyses of light water reactors, which has been approved by the United States Nuclear Regulatory Commission.

The results depicted in show a reasonable agreement between the current model (EES), and RETRAN code, however, for high mass flow rates both models diverge from the experimental data. The calculated mass flow rates are higher than experimental mass flow rates due to the isentropic flow assumption made in the EES model. Because of the friction, the mass flow rate would decrease. Two trends can also be observed corresponding to the geometries of the nozzle used during the experiment. Nozzle A diverges from the experiments more than the short nozzles B and D. The difference between the simulations and the experiment suggest a secondary effect due to the geometry of the nozzle. The sharp edge orifice A has a higher entrance pressure loss, inducing an additional friction component that tends to reduce the critical mass flow compared to the round edge entrance nozzles B and D. Both the experiment and theory suggest that the higher the pressure and the lower the temperature, the higher the mass flow rate. As the mass flow rate increases, the error between calculation and experiment increases. This is due to the fact that as the mass flow increases, the friction effects become more significant.

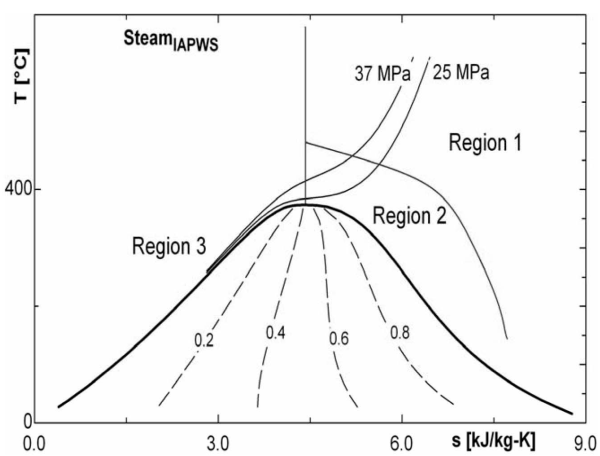

Fig. 2. Blowdown Map Depicted in a T-S Diagram for SCW

2.3 Behavior Map Prediction

Depending upon the initial conditions, three regions of behavior have been identified. In the first region (Region 1 shown in Figure 2), the fluid remains in a single phase during the blowdown event, going from a supercritical condition to subcritical, superheated steam. In the second and third regions, a second phase appears. Condensation is expected in Region 2 whereas vaporization occurs in Region 3.

This map shows the range of behaviors that one could expect to observe during a blowdown event. In a typical power cycle operating with a SC fluid, any of these regimes could exist, and thus it is necessary to understand the specifics of depressurization from each region.

3. EXPERIMENTAL SET UP AND DATA ANLYSIS PROCEDURE

3.1 Supercritical Water Facility

Several preliminary critical flow experiments have been conducted with SCW and $SCCO_2$ on two different facilities. The first series of tests made use of the University of Wisconsin supercritical water loop used for corrosion and heat transfer study, which is a rectangular loop 3-meters tall and 2.5-meters wide, constructed of schedule 160 2-inch Inconel 625 pipe. In these experiments the loop was maintained at a constant pressure and temperature until a fast opening pneumatic gate was opened, initiating the blowdown event through a 0.28-m long 1.59-mm inside diameter smooth sapphire tube. This gate was designed to actuate at the extremity of the tube to avoid in-line ball valve pressure losses. A series of experiments were conducted to verify the reliability of the measurement technique and to obtain preliminary results of the discharge time from the supercritical region to the sub critical region.

The temperature and the pressure transient were measured respectively with E-type thermocouples and a PCB Series 1501 dynamic pressure transducer attached the loop. The pressure was measured within 0.3% error with a standard deviation of 14-kPa. The thermocouple accuracy is about 1.7˚C or 0.5%, whichever is greater, with a standard deviation of 0.3˚C. The recording rate was 1000 samples per second.

3.2 Supercritical Carbon Dioxide Experimental Set Up

To study the fundamental of critical flow over a wider range of conditions, we employ $SCCO_2$ with a much simpler geometry. It is composed of a 0.125m^3 cylindrical vessel with a length of 2.5m and a diameter of about 0.26m. The entire vessel is weighed on a 5g-resolution Sartorius scale (with maximum weight of 800kg) and has an output rate of 10 samples/sec. The opening gate initiating the blowdown is similar to that used for the SCW blowdown experiments. In this case the gate valve sealed the end of a constant diameter 0.335m long 2mm ID quartz tube. The entrance of the tube was rounded and the roughness was measured to be Ra=0.007μm,which for the purpose of the model can be considered as smooth. Figure 3 illustrates the range of conditions that can be achieved with the $SCCO_2$ setup compared to proposed designs for a $SCCO_2$ power cycle. Unfortunately due to the high pressures and temperatures the vessel cannot be used for direct comparison of SCW critical flow rates.

Our design can reach any initial condition depicted below the design limit, which is determined by the maximum input mass in the vessel and the maximum pressure that can be reached following the ASME safety factor criteria. In the $SCCO_2$ experiment presented in this work the critical mass flow rate is determined using two separate approaches; the first consists of measuring the temperature and the pressure transient inside the vessel yielding to the density change with time, the second records the actual mass lost as a function of time based on the high accuracy scale measurements.

3.3 Data Processing Procedure

Supercritical water

To estimate the supercritical water critical flow the temperature and pressure transient in the loop were measured. Both the temperature and pressure signal were filtered and smoothed using a low pass filter with a 2Hz cutoff frequency and a moving average of 200 points. The values for temperature and pressure were then input in EES to calculate the density transient, which, multiplied by the loop volume, leads to the mass transient. The mass curve was then fitted with an order 4 polynomial function over the first 5 seconds.

Supercritical Carbon dioxide

For the $SCCO_2$ experiment, the critical flow has been estimated using the pressure and temperature transient similarly to the SCW experiment. However, the pressure and temperature change with time were much more smaller so that the mass transient could be estimated by assuming a linear fit.

A second more accurate method for measuring the mass flow rate uses the mass measurements obtained from the scale. Figure 4 shows a typical graph of the mass versus time for an experimental run. Few distinct patterns can be discussed. The opening and closure transient are due to the exiting jet hitting the plug of the valve as it is retracted from the end of the exit tube. The upward force induced, leads to an error in the initial mass measurement, however after this initial transient the mass loss becomes very linear with respect to depressurizing time.

The critical mass flow is extracted from data similar to that shown in the figure above (Figure 4.). In order to correct for the initial transient induced by the operation of the valve a linear average over the first 5 seconds of the depressurization was calculated using the initial mass and the mass measured after 5 seconds.

4. RESULTS

4.1 Supercritical Water Critical Flow

As a first approach, the initial conditions of the preliminary tests were set up such that they all belong to the Region 1 where only a single phase is expected through out the blowdown event. Preliminary results have been obtained with SCW for temperatures ranging

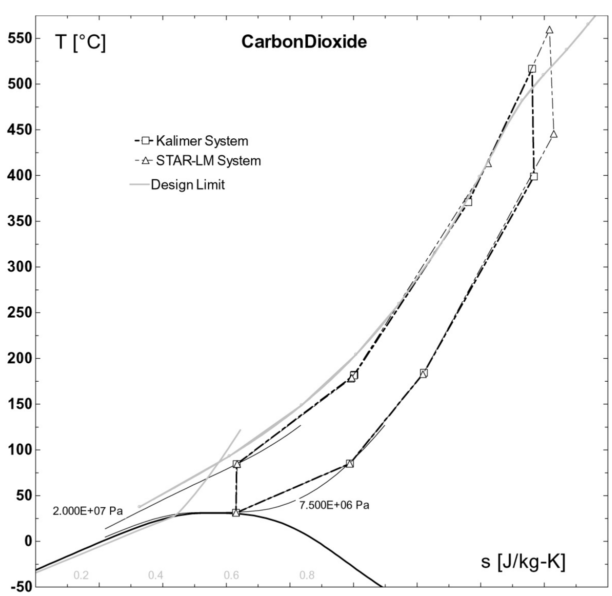

Fig. 3. Power Cycle Design and Design Limit Depicted in a CO_2 T-S Diagram

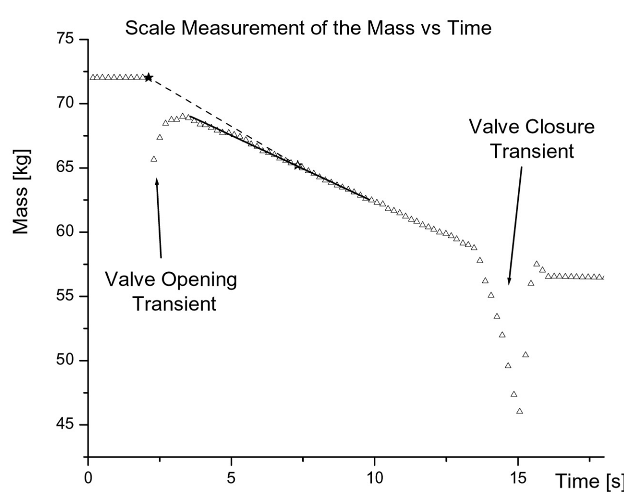

Fig. 4. Graph Depicting Scale Measurement of Mass vs Time

between 488 and 515˚C at a pressure of 25 MPa. They are tabulated in Table 1.

The complexity of the geometry and the heating system of the SCW corrosion loop has made it difficult to reproduce exactly the same initial thermodynamic conditions. Although a temperature of 500˚C and a pressure of 25MPa were desired, a spread of points around these conditions has been obtained. One can notice that the critical flow predicted by the EES model only slightly underestimates that calculated from the P and T measurements in the vessel. This will be discussed more in detail in the light of the $SCCO_2$ results

4.2 Supercritical Carbon Dioxide Critical Flow

The $SCCO_2$ experimental results conducted for a stagnation pressure of 100 bars with various stagnation temperatures are presented. Figure 5 summarizes the results of the data, which encompasses conditions corresponding to all three of the regions discussed above.

The mass flow rate uncertainty obtained with the scale measurement is directly linked to the resolution of the scale and is between 6 and 10 % for this data. The critical flow has also been estimated using the pressure and temperature transient similarly to the water experiment. However, the critical mass flow rate determined with by this method is not accurate due to the thermocouple response time in the low velocity gas volume of the tank. Techniques are being implemented to allow fast time response optical measurement of the temperature; however results are not available at this time.

5. DISCUSSION

The results obtained with supercritical water show good reproducibility of the experimental test procedure. Table 1 also suggests that the EES calculation underpredicts the critical flow when compared to the test values estimated from the density under similar initial conditions. We expect the critical flow to be underestimated as the HEM assumptions may be restrictive when compared to the real behavior. However, this comparison does not account for all the differences between the model and the experiments. The temperature measurement, similarly to the $SCCO_2$ experiment, was biased due to the heat capacitance effect of the thermocouple inducing a higher measured critical mass flow. The SCW results have enabled us to improve the test apparatus design currently use for the $SCCO_2$ experiment also since these were conducted with similar L/D ratios a comparison of the critical flow rate of SCW and $SCCO_2$ is possible.

The ability to use the high-resolution mass scale for the $SCCO_2$ experiment resulted in a more accurate time resolved measurement of the critical mass flow rate and more precise results due to lower noise compared to the T and P measurements. The implementation of the EES

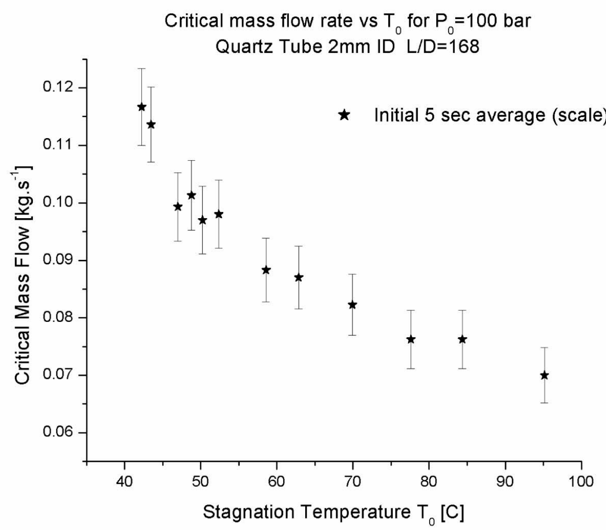

Fig. 5. Experimental Critical Mass Flow Rate for 2mm ID Quartz Tube

Table 1. Mass Flow Rate for SCW: D=1.59mm L=0.28m (L/D=176)

Po	To	Mass flow rate EES model	Mass flow PT transient	Tr	Pr
Pa	C	Kg/s	Kg/sec	T/Tc	P/Pc
2.443E+07	480	0.041	0.048	1.16	1.10
2.472E+07	514	0.040	0.046	1.22	1.12
2.475E+07	479	0.042	0.043	1.16	1.12
2.480E+07	482	0.042	0.05	1.17	1.12
2.492E+07	511	0.040	0.043	1.21	1.13
2.495E+07	514	0.040	0.042	1.22	1.13
2.509E+07	511	0.041	0.042	1.21	1.14

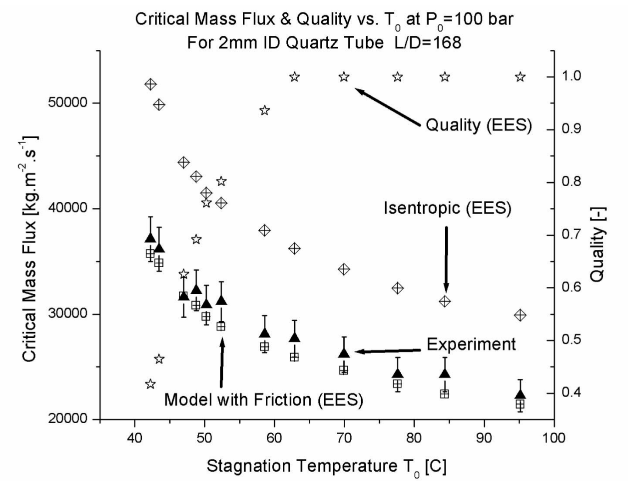

Fig. 6. Comparison Between Experimental Data and Model (EES)

model assumed friction in a straight smooth pipe flow with a round edged entrance. The additional assumption of adiabatic flow is justified by the high thermal resistance of the thick wall quartz tube and by the short time during which the flow is in contact with the wall (on the order of 1 ms). Similar to the SCW experiments the model predictions of the $SCCO_2$ flow appears to be slightly underpredicting the data as it can be seen in Figure. However in this series two-phase flow appears for stagnation temperatures below about 62ºC. Thus under these conditions, we expect that the HEM enthalpy and density definitions would lead to a lower bounding of our experimental data. This is due to the fact that the thermodynamic equilibrium and the no slip assumption result in an overprediction of the momentum pressure drop.

As we can see in Figure 6 the critical flow increases with a decrease in temperature for a given pressure. This is expected as the density of the fluid increases quickly as we approach the pseuso-critical line (45°C for a stagnation pressure of 100 bars). Also shown on the above figure (Figure 6) is a calculation assuming isentropic flow. Obviously this would result in an over prediction in actual flow rate and as can be seen the data is bounded by the calculation assuming a HEM with friction and a calculation assuming isentropic processes. The calculated quality evolution as we move toward the high temperature region is plotted on the right hand side of Figure 6. From this curve one can observe that at temperatures lower than 45ºC, vaporization is expected leading to low exit quality (< 0.5). For temperatures between 45ºC and 62ºC condensation is expected, leading to higher exit quality. Finally, for temperatures higher than 62ºC a single-phase flow exists along the entire tube. Even though these various behaviors are very different from one another the HEM calculation captures the trend of the critical flow as a function of stagnation temperature.

6. CONCLUSIONS

The Homogeneous Equilibrium model implemented in EES, to estimate the critical mass flow rate of water with and without friction, shows good agreement with the UKAEA RETRAN calculations.

Both simulations overpredict the test data for critical mass flow rate by as much as 40% for the orifice nozzle A and as much as 25% for the short nozzles B and D. This discrepancy is attributed to frictional effects.

A map of flow behavior was obtained for supercritical fluid depending on the initial conditions. It shows that complex behaviors can be expected, involving single and two phase flow, vaporization or condensation. Preliminary results for SCW and $SCCO_2$ show the reliability of the scale measurement over the P and T measurement. Model predictions implemented in EES were found to yield predicted results with less than 8% deviation from experiments for both SCW and $SCCO_2$ despite the restrictive assumptions. The present results have validated our approach for modeling the critical flow in the simple geometry of a long straight smooth pipe and have not found any curious behavior with respect to supercritical blow down events. More experiments are being conducted to characterize the effect of roughness, diameter to length ratio, and entrance pressure drop. These will include additional diagnostics to measure the temperature and density of the fluid through the length of the quartz tube.

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