REVERSE FLOW THROUGH A LARGE SCALE MULTICHANNEL NOZZLE (U)

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ABSTRACT

A database was developed for the flow of water through a scaled nozzle of a Savannah River Site reactor inlet plenum. The water flow in the nozzle was such that it ranged from stratified to water solid conditions. Data on the entry of air into the nozzle and plenum as a function of water flow are of interest in loss-of-coolant studies. The scaled nozzle was 44 cm long, had an entrance diameter of 95 mm, an exit opening of 58 mm x 356 mm, and an exit hydraulic diameter approximately equal to that of the inlet. Within the nozzle were three flow-straightening vanes which divided the flow path into four channels. All data were taken at steady-state and isothermal (300 K ± 1.5 K) conditions. During the reverse flow of water through the nozzle the point at which air begins to enter was predicted within 90% by a critical weir-flow calculation. The point of air entry into the plenum itself was found to be a function of flow conditions.

Introduction

Safety is the top priority when operating nuclear reactors. The design basis for reactor safety at the Savannah River Site (SRS) includes analyses for mitigation of loss-of-coolant accidents (LOCAs), with the most severe LOCA being a double-ended guillotine break (DEGB) of a main process coolant pipe. Computational modeling of the primary hydraulic system with RELAP5 or other codes is enhanced by benchmarking the components of the code with experimental data from separate effects experiments.

SRS reactor coolant systems have six inlet nozzles feeding cooling water to a circular plenum at the top of the reactor. One of the DEGB LOCAs under study involves a break where the pipe connects to one plenum nozzle. Single-phase liquid flow through the nozzle is easily modeled. Two-phase flow, which occurs after the hypothetical break, is more complex and is the subject of this report. An unusual feature of the plenum nozzles is that the hydraulic diameters of their entrance and exit openings are approximately equal despite the fact that the entrance is round and the exit is flat and rectangular. The internal hydraulic
diameter makes transitions to smaller values because of flow straightening vanes within the nozzles. The vanes are present to minimize flow stall during normal operation.

The purpose of this paper is to describe a scale experiment that was done to model break flow, involving air and water. The experiment was Froude number scaled because the flow regime of interest (stratified and transitions from it) is gravity dominated.

Experimental Apparatus

Test Rig. Figure 1 shows a schematic of the experimental apparatus. The actual reactor plenum is fed by six coolant process pipes. If there were a break in one of the feed pipes, the remaining pipes would still carry water to the plenum; therefore, it was necessary to study the nozzle with the water flow out of the plenum. The system consisted of the pumps, central plenum tank to feed the plenum, scaled section of plenum, nozzle, and finally a catch basin with a return line which led to the pump suction.

Reactor Plenum. A semi-curricular section of the plenum and two adjacent nozzles were used to create the correct boundary conditions on the plenum side. Having a nozzle on either side of the central nozzle under study allowed for the same flow patterns expected in the real reactor. Further, four rows of scaled reactor assemblies (33.35 mm in diameter), were included in the plenum to set up the correct pressure environment at the plenum/nozzle interface. The plenum was 55.55 mm in height and the assemblies were arranged prototypically (i.e., on a 44.45 mm triangular pitch).

Nozzle. The nozzle's shape (Fig 2) is unique in that (from entrance to exit) it converges along the horizontal axis and diverges along the vertical axis (note, Fig. 2 depicts accident flow which is exiting out what is referred to as the nozzle entrance). The nozzle is 440 mm long with a circular entrance, a diameter of 95.25 mm, and an exit opening of approximately 58 mm x 356 mm, both ends have approximately the same hydraulic diameter. Internally, there are three flow straightening vanes which reduce the hydraulic diameter. The vertical vanes span the entire nozzle height, one vane runs along the vertical centerplane of the nozzle, and each of two side vanes is angled 11.5° from the center vane, diverging from the entrance to the exit. Further, the center vane starts 10.7 mm from the exit opening and has a length of approximately 246 mm. This length means that the center vane only extends traverse 246/440 x 100% = 56% of the total length of the nozzle with the side vanes being slightly shorter, 149 mm.) The length of the prototypical nozzle was
increased by 35% but the length of the vanes was not increased; therefore, the vanes do not span the entire length of the nozzle. To cut down on flow stall, the nozzle length was increased to allow the entrance divergence angle of the nozzle to be reduced from 45° to 24°. Basically, during normal flow operation this nozzle breaks the incoming coolant water into three slightly divergent channels before the water enters into the plenum. It had been shown that stall was reduced; however, it still occurred (Harris, 1971).

Central Plenum Tank. One role that the tank served was that of structural support for the model reactor plenum. The aluminum tank was approximately 1.2 m high, the inside diameter was 760 mm and the centerline of the opening, which lead to the reactor plenum, was located 0.8 m from the tank bottom. Also supported by the tank was the pump suction line used during forward flow tests. An air intake line, temperature and pressure measuring ports, and a vacuum-breaker line were connected to the top of the tank, which is made of Plexiglas to allow for visual access. To increase visual access, the back of the tank was equipped with a port hole, 150-mm inside diameter, located directly opposite and at the midpoint of the reactor plenum. Inside the tank was coiled copper tubing that domestic or house water flowed through to remove pump heat and maintain the apparatus at a constant temperature. At the bottom of tank a drain line was connected to a 4.5-m high standpipe which prevented the tank from being accidentally over pressured.

Instrumentation. A data acquisition system was used to obtain air and water temperature, pressure, volumetric flow, and water level. Visual measurements were made of the flow regime, liquid level at the nozzle entrance, and location of the air-water interface on the upper surface when one existed in the plenum-nozzle test section (for example, Fig. 2 shows an air-water interface which terminates near the nozzle exit). Specifics as to the location, range, and accuracy of the instruments used can be found below. The following are further descriptions of instrumentation.

- **Data Acquisition System (DAS):** The DAS for this experiment consisted of Macintosh IIx computer with an Motorola 68030 microprocessor and 4 Mb of RAM. The DAS had five signal-input cards available that allowed the connection of 16 analog channels per card with an analog-to-digital conversion at a 12-bit resolution. The maximum sampling rate per channel was 2.2 kHz but because the test was carried out at steady state and because channels filters were needed, a sampling rate of 1-Hz was used; that is, all 53 channels used were read once-per-second, but all the channels were read in 53/2200 = 0.024 second. A loop calibration determined that the accuracy per channel was better than ± 0.1%
of range. The settling time for all the instruments used was insignificant to the 1-Hz sampling rate.

- **Volumetric Water-flow Rate:** A venturi meter was placed on each of the two side nozzles and on a return line connected to the catch basin. The stainless-steel Herschel-type Venturis were 491.0 mm long, had an inside diameter of 97.2 mm, throat inside diameter of 47.4 mm and had a discharge coefficient of 0.96. The water temperature was monitored with thermocouples upstream of the Venturis.

- **Volumetric Air-flow Rate:** Each nozzle water-supply pipe and central-plenum tank had an air line. Each line had a turbine-type air flowmeter made of stainless steel, 139.7 mm long, inside diameter of 25.4 mm, rated for a maximum of 150-psi, and rotor's bearings were ball-type. Both air pressure and temperature were measured downstream of each flowmeter.

- **Liquid level:** It was important to know the liquid height at the entrance and at the exit of the nozzle during stratified flow. A scale was placed at the entrance of the nozzle, from which the liquid level could be measured as the water flowed out the nozzle (the water flows out the entrance for the accident scenario). At the exit of the nozzle was the model reactor plenum. The liquid level was measured in eight locations of the plenum by a float-and-rod mechanism where the movement of the rod was sensed by an induction field. Each device was located within one of the many "dummy" tubes (a hollow tube that housed a float-and-rod mechanism) that filled the plenum. Each of the eight tubes had holes just below and above the plenum, which allowed water to enter and air to escape so that the float within could be maintained at the height of the water in the plenum. When stratified flow existed for steady-state test runs in the plenum, the level sensors measured the local water height. Before the experiment was run, sensors were tested and found to measure collapsed water height so that when the flow regime was different from stratified it indicated void fraction.

**Measurement Uncertainty.** The uncertainties listed below are generally larger than the true uncertainties. These values are target values that were maintained throughout the experiment.
Water flow rate (70-1150 lpm) = \pm 2.0\% \text{ full scale} = \pm 23 \text{ lpm}
Water flow rate (< 70 lpm)= \pm 0.5 \text{ lpm}
Manually measured liquid levels = \pm 1.5 \text{ mm}
Electrically measured liquid levels = \pm 5 \text{ mm}
Temperature = \pm 1 \text{ K}
Diff. pressure (0-129 mmHg) = \pm 0.2\% \text{ full scale} = \pm 0.25 \text{ mmHg}

The law of propagation of errors was used to determine the measurement uncertainties (Mandel, 1984)

Test Procedure

The first phase of the test was to verify that all instrumentation was in proper working order. This phase consisted of checking the electrical conductivity of the water, which was maintained between 2 and 5 \mu\text{S/cm}. Higher conductivities allowed galvanic corrosion to occur among the metallic components. The zero outputs of the many differential pressure transducers were measured and inputted in the DAS to compensate for drift. Upon verifying that everything was in working order the pumps were turned on so that the closed loop of the apparatus ran water solid. The water temperature was allowed to increase to 26.5°\text{C} by pump heat (typical of the reactor temperature), then was maintained constant (\pm 1.5°\text{C}) by a copper cooling coil located in the central plenum tank. With the apparatus warm the water flow was stopped, and the water level in the plenum was reduced and held at two points so that the outputs of the eight liquid-level sensors were verified for accuracy. Three of the eight sensors worked on electrical capacitance, and were adjusted daily (if necessary) to compensate for the changing electrical properties of the water. This first phase of the test was completed by taking data at high and low flow rates. These two flow rates were the same as measured during the shakedown phase of the experiment, (i.e., before any testing was done). These shakedown data allowed comparison of the outputs of all the devices while in active operation. Since the majority of the devices had linear outputs, this two-point check indicated zero, and span drift that may have occurred over time. The second phase of the test began when all checks and adjustments were made.

The actual test data were taken in the second phase. Water at a pre-determined flow rate was set and the system was allowed to come to steady state, as indicated when the average output of all instruments not did not change in time. When ready, the DAS was initiated to take one minute of data at 1 Hz of the more than 60 instruments on line. While
data were being obtained the flow through the nozzle and the plenum was filmed at
different angles to determine flow regimes, air-water interfaces, etc. Manual data were
taken of:
  • the height of the water in the catch basin
  • the liquid level in the central plenum tank
  • the position of the air-water interface at the top of the nozzle (if it existed)
  • the ambient pressure.
Results and Discussion

In a 1-D scoping calculation by McLaughlin and Nash (1989) the flow rate of water, as it poured out the nozzle entrance, was determined to be 397 lpm. This was the minimum reverse flow necessary to maintain the entrance of the nozzle water solid; that is, a lower water flow rate would allow air to enter into the top of the nozzle. Under the same conditions, the measured flow rate from the nozzle-flow-characteristics test rig was 435 lpm ($\sigma = \pm 25$ lpm). This measured flow rate is approximately 9% greater than the calculated result, an excellent agreement when considering the simple method of calculation. It means that the scaled model of the nozzle accurately reproduces separated flow effects for the prototypic nozzle. Both calculated and measured results are shown in Figures 3, 4, and 5.

As water flowed out the nozzle entrance the air-water interface remained relatively smooth (there were small waves). For all axial locations, except right at the mouth of the nozzle entrance (i.e., $x/L < 1$, see Fig. 2), the critical point (where Froude = 1) was always internal to the nozzle. As the reverse-flow rate increased, the critical point moved closer to the nozzle entrance. This is evident in Figure 5 which shows the increasing effect of the gravitational force as the liquid at the nozzle entrance increases in height resulting from an increase in volumetric flowrate. At the minimum flowrate which just maintains the nozzle entrance water solid, the inertial and gravitational forces are equivalent. As the flowrate is further increased the inertial forces continue to grow but since the height of water is now restricted the Froude number loses meaning. This explains the increasing value of the Froude number after the abscissa value of 1.0.

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