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HEAT TRANSFER AND PRESSURE DROP IN AN ANNULAR CHANNEL WITH DOWNFLOW

by

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ABSTRACT

The onset of a flow instability (OFI) determines the minimum flow rate for cooling in the flow channels of a nuclear fuel assembly. A test facility was constructed with full-scale models (length and diameter) of annular flow channels incorporating many instruments to measure heat transfer and pressure drop with downflow in the annulus. Tests were performed both with and without axial centering ribs at prototypical values of pressure, flow rate and uniform wall heat flux. The axial ribs have the effect of subdividing the annulus into quadrants, so the problem becomes one of parallel channel flow, unlike previous experiments in tubes (upflow and downflow). Other tests were performed to determine the effects if any of asymmetric and non-uniform circumferential wall heating, operating pressure level and dissolved gas concentration. Data from the tests are compared with models for channel heat transfer and pressure drop profiles in several regimes of wall heating from single-phase forced convection through partially and fully developed nucleate boiling. Minimum stable flow rates were experimentally determined as a function of wall heat flux and heat distribution and compared with the model (Saha and Zuber, 1974) for the transition to fully developed boiling which is a key criterion in determining the OFI condition in the channel. The heat transfer results in the channel without ribs are in excellent agreement with predictions from a computer model of the flow in the annulus and with empirical correlations developed from similar tests. The test results with centering ribs show that geometrical variations between the channels can lead to differences in subchannel behavior which can make the effect of the ribs and the geometry an important factor when assessing the power level at which the fuel assembly (and the reactor) can be operated to prevent overheating in the event of a loss-of-coolant-accident (LOCA).

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INTRODUCTION

For safe operation of low pressure and low temperature production reactors of nuclear materials, it is very important to predict thermal hydraulic conditions under which onset of flow instability (OFI) phenomenon occurs during any postulated accident or system transient. The presence of multiple parallel flow paths in the reactor core presents a potential of having such a phenomenon if any of the flow channels experience a mismatch of flow to power ratio during the postulated accident. If this should occur, the overheated channel will offer more hydraulic resistance due to the presence of two phase flow in it, thus diverting the flow to the adjacent channels still in single phase flow. Any reduction in flow to the overheated channel causes more two phase activity, leading to a complete channel dryout and potential fuel damage. This phenomenon which is commonly termed as flow excursion or Ledinegg flow instability is illustrated in Figure 1. Thus the reactors are operated at power levels such that flow instability would not occur during any accident condition and the reactor is safely scrammed to very low power levels.

For commercial power reactors this phenomenon is not power limiting due to high pressures (low specific volume of voids) and the rod bundle type of fuel assemblies. Instead, a CHF based safety criterion is applied to preclude fuel damage under accident conditions.

As discussed above, the flow instability phenomenon occurs due to an increase in flow resistance in a channel experiencing boiling. Thus it is important to determine thermal hydraulic characteristics of reactor flow channels under single phase and two phase conditions. The production reactors at Savannah River Site have fuel assemblies with concentric annular flow channels formed by fuel and target tubes. Four longitudinal ribs are co-extruded with each tube in order to maintain these tubes in nominally concentric position. In order to determine thermal hydraulic behavior of such fuel assemblies, Savannah River Laboratory initiated a comprehensive experimental program. Extensive test programs were established at Columbia University and Creare Incorporated operated to obtain fundamental thermal hydraulic data in single tubular and annular channels. In addition, a full fuel assembly mockup test program was conducted at Babcock & Wilcox to test the performance of a fuel assembly under various transient conditions.

This paper describes the results of tests conducted at Creare Inc. through a subcontract from Westinghouse Savannah River Co. The test section in these tests simulates one of the annular flow channels of the fuel-assemblies. The flow channel is a full-scale model – length, hydraulic diameter, rib dimensions, and other geometric details were preserved – which was fabricated from aluminum extrusions in order to replicate the materials and surface conditions of the prototype fuel assemblies. Instruments were installed in the test section to measure wall and fluid temperatures, pressure and pressure drop and wall heat input. The primary test variables were wall heat flux, flow rate and inlet subcooling. The testing program also included tests to examine the effects of asymmetric wall heating, non-uniform circumferential heat distribution (power tilt), and tests in an annulus without the centering ribs. Detailed test measurements provided data for evaluating a flow instability criterion and for validating models for wall heat transfer and pressure drop in the annulus.

BACKGROUND

Description of Flow Situation

Figure 2 illustrates the boiling regimes and transitions of interest in this case, with sketches of the associated pressure and temperature profiles for downflow in a uniformly heated channel. The boiling regimes and transitions include:

- Single-phase forced convection regime,
- Transition at Onset of Nucleate Boiling (ONB),
- Partially developed subcooled nucleate boiling regime,
- Transition for Onset of Significant Voiding (OSV), and
- Fully developed subcooled nucleate boiling regime.

This basic picture of flow boiling follows the approach described in detail by Collier (1986).

In the single-phase region, the fluid is subcooled as it enters the inlet to the flow channel, and the temperature increases with heat addition from the wall. The wall temperature increases in parallel, showing that the wall-to-fluid temperature difference, or the heat transfer coefficient, is approximately constant. The wall temperature can be slightly greater than the saturation temperature before nucleation of vapor bubbles occurs at the Onset of Nucleate Boiling (ONB) transition. To that point, the pressure gradient is approximately linear, with the positive pressure gradient due to hydrostatic forces outweighing the negative pressure gradient due to friction.

In the partially-developed boiling region – after vapor bubbles nucleate at the walls – the fluid continues to heat up at a linear rate (since there is not net vapor generation in this region). The temperature difference between the wall and the saturation temperature is governed by a superposition of forced convection and subcooled nucleate boiling heat transfer considerations. The frictional contribution of the pressure gradient may increase slightly because the vapor bubbles attached to the wall affect the shear, similar to rougher pipe walls.

At the Onset of Significant Voiding (OSV) transition, the vapor bubbles detach from the wall surface and enter the flow. This is the fully developed boiling region. Because some of the energy from the walls goes to making vapor, the rate of increase in the fluid temperature is proportionally decreased. The fluid remains subcooled, however. The temperature difference between the wall and saturation temperature becomes approximately constant. In this region the pressure gradient changes dramatically because (a) the vapor flow significantly decreases the positive contribution of the hydrostatic component of the pressure gradient, and (b) the frictional component of the pressure gradient becomes significantly larger (more negative) in the two-phase flow. The net pressure drop in the channel begins to increase in this boiling regime.

OFI Research

Prior Research on OSV. The Onset of Flow Instability (OFI) is related to the formation of voids in subcooled flow boiling: the Onset of Significant Voiding (OSV). OSV generally precedes the onset of the flow instability. Since the production of vapor has a strong effect on the frictional and hydrostatic components of the pressure gradient however (see above), the OFI point tends to be closely linked with the OSV transition.

Saha and Zuber (1974), Levy (1967), Staub (1968), and Rogers et al. (1987) present theoretical models to describe the conditions for departure of vapor bubbles from the surface. Saha and Zuber studied subcooled boiling in vertical channels with upflow, and they developed a useful criterion for the OSV transition which depends upon the local thermal and hydraulic conditions. Their model includes two parts. At high flow rates ($Pe = Re_f Pr_f >$ 70,000) the OSV transition depends only upon the hydrodynamics, and

$$St = \frac{\phi}{(T_{sat} - T_{fex})c_{pf}G} = 0.0065$$

At low flow rates (Pe < 70,000), the thermal conditions are more important and

$$St = \frac{454}{Pe}$$

There is evidence that the latter condition depends upon the flow direction.

The OSV investigations cited have studied the phenomenon in simple flow geometries. More recently, Kowalski et al. (1990) investigated OSV from a finned tube in upflow. That work is of interest because of the finned geometry of the annulus in the reactor fuel assemblies for the present work. They used a 0.6 m long test section, 7.8 mm in diameter, with 8 fins 1.0 mm long protruding from the surface into the flow. The finned tube was electrically heated, while the outer flow channel was transparent and unheated. Kowalski et al. correlated their OSV results in the same form used by Saha and Zuber, but obtained a different relationship which shows a slight dependence on the flow rate even at high mass flow rates.

$$St = \frac{0.0446}{Pe^{0.18}}$$

For the range of conditions in our experiments ($7x10^4 < Pe < 3x10^5$), the Stanton number calculated from Kowalski's correlation ranges from 0.0060 to 0.0046, or within 8% to 30% of the Stanton number given by Saha and Zuber for this Pe range. So, this model lies close to the Saha and Zuber result.

Research on OFI. Experiments performed on subcooled flow boiling in downflow include:

- Columbia University [Lee (1963), Dougherty et al. (1989)],
- Savannah River Laboratory [Johnston (1988)], and
- Creare Inc. [Block, et al. (1990)]

The Columbia University and Savannah River Laboratory (SRL) experiments investigated the overall pressure drop versus flow rate characteristics for controlled boundary conditions, with emphasis on locating the minimum pressure drop (OFI) point. As discussed in this paper, the Creare experiments provide detailed profiles of temperature and pressure gradients in the test section. All of these experiments were performed at prototypical pressures, temperatures, and heat fluxes.

Columbia University first studied flow boiling in an electrically heated mockup of a fuel element [Lee, 1963]. The geometry of this test section was annular, with a 30.6 mm diameter stainless steel tube forming the inner wall and a 37.4 mm aluminum tube for the outer wall, providing a 3.4 mm annular gap. The inner steel tube was electrically heated over a 3.57 m length (L/D_h = 525). More recently, additional tests [Dougherty, 1989] have been performed in 2.44 m tubes (stainless steel) ranging from 15.5 to 25.3 mm diameter (L/D_h = 100 to 160).

The Savannah River Laboratory experiments [Johnston, 1988] included an annular test section 1.83 meters long, with a 38.1 mm outer diameter and a 25.4 mm inner diameter (L/D_h = 288). The inner stainless steel tube was electrically heated while the outer wall was unheated and made of glass in order to permit visualization of the boiling behavior.

Figure 3 characterizes the result of the Columbia University and SRL experiments relative to the OSV criterion developed by Saha and Zuber. As expected, the conditions at the minimum pressure drop (OFI) lie above the OSV criterion at high mass flow rate (high Peclet number). This indicates that it is possible to proceed to a smaller subcooling at the exit from the heated channel than predicted by the OSV criterion before the minimum pressure drop is encountered. Many data lie below the Saha-Zuber criterion for low mass flow rates ($Pe < 70{,}000$), but still above the criterion for high mass flow rates. This may indicate a difference between upflow – the experimental basis for the criterion – and the Columbia University and SRL downflow tests. Fortunately, the conditions of interest for the reactor are at $Pe > 70{,}000$, so this difference is not a factor in the present investigation. We do note that the analysis methods presented in this paper compare very well with the results of this OFI research in non-ribbed flow channels.

Description of Analysis Methods

This Section describes the specific analytical models used in the comparisons presented in this report. The analysis models heat transfer and pressure drop for water in a heated flow channel. The analytical models are incorporated into a computer program called ANNULUS (Barry, Crowley, and Wallis, 1989). Using input values for the inlet temperature, pressure, and velocity as well as the geometry and heat flux (axial profile), the program computes pressure, fluid temperature, wall temperature, and quality or void fraction along the length of the annulus. Following the analytical approach described by Collier (1986), the program models flow in the following boiling regimes and transitions between the regimes:

- Single-phase forced convection regime
- Transition at Onset of Nucleate Boiling (ONB)
- Partially developed subcooled nucleate boiling regime
- Transition for Onset of Significant Voiding (OSV)
- Fully developed subcooled nucleate boiling regime
- Saturated boiling.

Tables 1 and 2 summarize the regime and transition models used in the comparisons presented here.

TEST PROGRAM

The test program was carried out in a closed loop flow facility which was designed for steady-state testing with independent control of the annulus inlet flow rate, pressure, temperature, dissolved helium saturation pressure and the annulus wall heat flux. Test measurements included annulus wall and fluid temperatures, annulus pressure and pressure drop, flow rate and wall heat input. The measurements were all recorded on a computer based data acquisition system while a second computer monitored the power supply controls and numerous safety devices intended to protect the test facility in the event of a loss of cooling capability.

Test Facility. The closed cycle flow loop is shown schematically in Figure 4. Water is pumped from the Reservoir tank through an orifice flow meter to the top of the annulus test section. After being discharged from bottom of the annulus into the Separator, the water is then pumped through the heat exchangers and back to the Reservoir. Some of the cooled water is returned to the Separator in order to maintain the temperature below saturation at the annulus exit pressure. Helium gas is used for pressurizing the vapor space in the Separator in order to maintain the desired annulus inlet pressure. Helium is also supplied to the Reservoir to control the vapor pressure and concentration of gas dissolved in the water. The walls of the test section are indirectly heated with electrical resistance heaters which are provided with DC power from a six-zone, 3.75 MW power supply. To ensure water quality throughout the test program, all components in contact with the water in the flow loop are fabricated from either stainless steel or aluminum alloys. In addition, the water is de-ionized prior to filling the flow loop and oxygen content is reduced to less than 1 ppm by purging with helium.

Test Sections. Two full-scale annulus test sections are used in the testing program as shown in Figure 5. Both test sections were fabricated using aluminum alloy (6061, 6063 and 8001) extrusions for the inner and outer walls of the flow channels. One of the test sections has longitudinal centering ribs on the inner wall tube which were co-extruded with the tube in the same way as in the prototype fuel fabrication. For the second test section the central tube was fabricated without ribs; the tube was centered within the flow channel by the use of small "pins" and "buttons" placed along the length of the annulus at four locations around the circumference. Two versions of each flow channel geometry were assembled for the test program. Table 3 summarizes the key dimensional data for both types of geometries.

The test section is heated with cartridge type electrical resistance heaters installed inside the inner and outer walls as shown in Figure 5. Each heater is 9.53 mm diameter with a heated length of about 3.91 m. The resistance elements are designed to produce a uniform axial power profile and a maximum power of 98 kilowatts from each heater. The inner wall of the test section is heated by 12 heaters uniformly spaced inside the aluminum tube. These heaters are held in place and against the inside surface of the aluminum tube by metal guides and a central support tube. The outer wall of the test section has internal cavities which contain 24 heaters. The narrow spaces surrounding the heaters in the outer wall cavities and inside the inner wall tube are filled with a eutectic tin-lead solder which provides a conductive path between the heaters and the aluminum test section walls. This interface ensures sufficient heat removal from the heaters and a known and uniform wall heat flux condition. The heaters are connected in groups to separate power supply zones which allows adjusting the power in each group of heaters to set different circumferential power profiles.

Test Measurements. The test facility contains 132 instruments for measuring overall test conditions as well as the detailed conditions in the annular flow channel. These instruments are connected to a data acquisition system which computes average values for each measurement and displays the readings on a video monitor during the tests. Readings are updated approximately once each second and color coded displays are used to inform the operators that a steady condition has been achieved following a flow or power change, and to provide an alert or warning when temperatures exceed pre-determined threshold values. Approximately 50 other measurements in the test facility, primarily temperatures, are monitored by the laboratory power control computer for facility safety purposes.

Wall and fluid temperatures and pressure drop are measured in one quadrant of the annulus flow channel at 12 locations along the heated length. Spacings between the measurement locations range from 0.15 m to about 0.91 m while most of the measurements are concentrated near the end of the annulus (0.15 m spacings over the bottom 0.91 m) where boiling and two-phase flow should first occur. Similar types of measurements are made in each of the other three quadrants of the flow channel, however in these subchannels measurements are made only at the bottom of the heated length and at 0.3 m above the bottom.

All temperatures are measured with Type E thermocouples which enter the test section through the outer wall in the gaps between heaters (see Figure 5). The water temperature probes are 1 mm diameter and are inserted so that the measuring junction is at the center of the annular gap. Temperatures on the outer wall of the flow channel are measured with 1.5 mm diameter, aluminum clad thermocouples which are press fit into the wall and are flush with the wall surface. Annulus pressures and pressure drops are measured with pressure transducers connected to 0.76 mm diameter pressure taps on the outer wall of the flow channel using water-filled lines. Differential pressures transducers are connected between adjacent pressure taps on the annulus wall such that the sum of the 12 individual pressure drop measurements would be equal to the total annulus pressure drop. A transducer is also connected between the top and bottom of the test section in order to measure the overall pressure drop.

Estimated measurement uncertainties for the principal test data are given in Table 4. These estimates include the effects of instrument and calibration system errors, and errors due to thermal and noise effects in the amplifiers and in the analog-to-digital converter. The temperature probes were calibrated in-place several times during the test program. The calibrations confirmed that temperature measurements were generally within the estimated errors shown in Table 4. For those cases where the error was larger than the estimate, the data are rejected. Pressure drop data are also examined during the test to detect possible errors. The principal checks are: (1) verify the static head offset readings, and (2) compare the overall pressure drop in the annulus with the sum of the individual measurements in one quadrant. The difference between the total and sum of pressure drops is always less than 1.4 kPa (0.2 psi) and is less than 0.69 kPa (0.1 psi) for annulus velocity lower than about 3 m/s.

<u>Test Operation</u>. During the tests, the thermal/hydraulic boundary conditions at the annulus are individually and independently controlled in order to establish the desired test conditions and to maintain steady-state operation during the data acquisition interval. A test is performed by setting a high flow rate in the annulus (7.6 m/s was the highest initial value) while adjusting the inlet pressure and temperature to the specified values for the particular test (see Table 5 for the test conditions). Power to the heaters is increased gradually until the desired value of wall heat flux is reached. Conditions are allowed to stabilize and then the first data point is recorded. The data acquisition computer records data at a rate of 10 readings per second for each measurement for a period of 5 minutes. This recording process is continuous such that after the 5 minutes is reached, the data file is overwritten with the most recent data. The operator manually terminates the data recording process after a sufficient period with steady-state conditions. Successive tests usually involve a small reduction in flow rate and re-establishment of steady-state conditions at the new flow with constant values of inlet pressure and temperature, and wall heat flux. Measurements are again recorded to produce a 5 minute long data file. Flow rate is reduced in steps until the flow through the annulus becomes unstable and large excursions in pressure drop occur. At that point, flow is

increased until stability is re-established. The minimum stable pressure drop is subsequently determined by making very small reductions in flow (0.03 to 0.06 m/s) and recording data at each new flow rate. This process is continued until the pressure drop is observed to increase only slightly indicating that the minimum stable operating condition has been passed. A total of 19 test series were performed in this program. Table 5 lists the main test parameters in each series, including the geometry variables (ribbed and non-ribbed), heat flux magnitude and distribution (uniform, asymmetric and power tilt), inlet pressure (275.8 kPa and 413.7 kPa, absolute), and helium saturation pressure (6.9, 34.5 and 103.4 kPa, gauge). Five test series were performed in the two versions of the non-ribbed annulus whereas 14 of the series were performed in two versions of the ribbed annulus. Each test series produced data for a single demand curve as well as detailed measurements for validating wall heat transfer and annulus pressure drop models.

DATA ANALYSIS

Typical Demand Curve. Figure 6 shows the demand curve data for four separate test series (1, 1A, 5 and 13) at the baseline test conditions in the ribbed geometry. (The basic character of the curve is consistent with data from the simple annular geometry at SRL and the tubular geometry at Columbia University.) These four test series were performed in two different builds of the annulus test section and occurred over an interval of several months during which other tests, e.g. some at higher power, were also performed. Good repeatability is demonstrated. The small variations which do occur at high velocity are probably due to slight geometry shifts in the facility. The minimum pressure drop occurs at a velocity between 0.98 and 1.05 m/s in the four series of tests. This variation in velocity at the minima is approximately equal to the flow rate measurement uncertainty and hence the accuracy with which the velocity can be set in the tests. As described below, steady-state pressure drop data could not be obtained at lower velocities.

The pressure drop predicted by the ANNULUS computer program is shown by the solid line in Figure 6. The minimum pressure drop and corresponding velocity are predicted reasonably well. At this low velocity, the minimum pressure drop is dominated by the hydrostatic component, so the measured and predicted values represent primarily a head of 4 m of water. The minimum pressure drop is predicted at only slightly lower velocity than is observed from the data. This is consistent with the conditions at OFI lying at lower Stanton number, i.e. at higher velocity and higher subcooling, than calculated (Figure 3).

The pressure drop predicted by the ANNULUS computer program for the heated wall tests is 5% to 15% higher than the measured values at high flow velocity. This result is consistent with single-phase pressure drop data in the annulus with no heat flux, as shown in Figure 7. In the program, a hydraulic diameter of $D_h = 0.012$ m has been estimated by strict application of the definition that the hydraulic diameter is equal to four times the cross-sectional area divided by the wetted perimeter of the channel, where the wetted perimeter also includes the surface of the ribs. If the ribs were not present, the hydraulic diameter for the annulus would be $D_h = 0.013$ m. Calculated pressure drops with these two values of the hydraulic diameter bound the data, as illustrated by the pressure drop data for the unheated annulus in Figure 7.

Pressure and Temperature Profiles. Figures 8, 9, and 10 show the detailed pressure and temperature profiles for Series 1 in the ribbed geometry for:

- Non-boiling situation at high velocity (Figure 8),
- Near the onset of nucleate boiling at the exit (Figure 9), and
- At the minimum stable pressure drop (Figure 10)

To first order, the predictive models in the ANNULUS computer program represent the data very well. If the wall heat transfer coefficient used in the code calculations was about 10% larger, the agreement would be excellent.

The calculated and measured pressure gradients are linear in each case, and agree well at all velocities. The pressure gradient predictions were improved by using the Zigrang-Sylvester (1982) model to replace the Rohsenow-Hartnett (1985) model for annular flow. Note that the measured pressure gradient given by the summation of the individual differential pressures (open circles) agrees with the measured absolute pressure drops (solid circles).

The calculated and measured fluid temperatures also show a linear heatup. Calculated and measured values agree.

Wall temperature calculations illustrate a systematic trend observed in all of the data: the calculated wall-to-fluid temperature difference is about 10% larger than the measured value in the single-phase heat transfer region, i.e. before the wall temperature reaches saturation. As a result, in the calculation the wall temperature reaches saturation nearer to the beginning of the heated length than is observed from the data (see Figures 9 and 10).

Two other effects also account for some of the difference between the ANNULUS calculations and the data:

> *The measured fluid temperatures are in one of the colder subchannels.* Even with uniform heat flux, the fluid temperatures at the exit of the instrumented channel (136 degree location in Figure 5) are 2.8 °C to 5.6 °C colder than the average of the measured temperatures at the annulus exit. The nonuniform temperature distribution is possibly due to a geometry variation from subchannel to subchannel as a result of the radial clearance gap between the ribs and the outer wall.
>
> *The measured fluid temperatures at the subchannel centerline are lower than the actual bulk fluid temperatures because of the temperature gradient across the subchannel.* The average of the measured fluid temperatures at the annulus exit is about 2.8 °C less than the bulk fluid temperature predicted by ANNULUS (using an energy balance). This is clearly shown in Figures 9 and 10 where the ANNULUS prediction (dotted line) lies at higher temperature at the annulus exit (L = 4 m) than the measured data in the subchannels (open symbols). The difference between the average of the measured fluid temperatures and the calculated temperature is due to the temperature gradient across the subchannel. The temperature gradient can be illustrated by reference to the analytical solution for fully developed turbulent flow in a tube with constant heat flux (Kays, 1966). Substituting typical measured values of wall and centerline temperatures for the baseline condition (T_w = 135 °C, T_f = 121 °C) yields a bulk fluid temperature of 123 °C which is 2 °C higher than the measured centerline temperature.

Combining the fact that most of the measured temperatures are in one of the colder subchannels with the effect of the temperature gradient across the subchannel suggests that the measured fluid temperatures in the instrumented flow channel are about 5 °C to 8 °C lower than the bulk fluid temperatures. Therefore, the average fluid temperatures should be higher than the measured data and in better agreement with the analysis.

Parametric Effects. The parametric investigations are briefly summarized below:

- The effect of ribs in the test geometry seems to be the most important with respect to the key result -- the location of OFI. This is a result of asymmetry among the four subchannels with the least stable (hottest) subchannel controlling the behavior (see below Discussion of Results).

- The effect of power tilt requires further study. The experiments show little effect of power tilt, however that may be a function of the particular configuration tested.

- The effects of heat flux, inlet pressure, and asymmetric heating are consistent with expected trends based upon the analytical work.

- The effect of dissolved helium does not appear to be significant.

In addition, since the baseline test conditions were repeated four times during the course of the experiments in the ribbed geometry (from early May to mid-August 1990), and since the results are repeatable, there did not seem to be any significant effect of aging of the annulus wall surface on the results, within the time scale of this test program.

Evaluation of OFI. A key objective in the Creare experiments is to assess the conditions at OFI in each test series. Figure 11 is a plot of Stanton number versus Peclet number which summarizes the data for the minimum stable flow condition from each of the 19 test series and compares them with the OSV prediction of the Saha-Zuber model. Measured data and calculated fluid properties are used to evaluate the Stanton number and the Peclet number for the conditions at the annulus exit in the test selected as the minimum in each series. In this evaluation the definition of the Stanton number is:

$$St = \frac{\phi}{(T_{sat} - T_f)c_{pf}G}$$

and the Peclet number is:

$$Pe = GD_h/k_f$$

The results indicate that:

- The minima for the ribbed geometry generally lie at lower Stanton number (larger subcooling) than the minima for the non-ribbed geometry in our tests or in previous tests (Figure 3).

- The minima for the power tilt tests do not differ significantly from the minima for the uniform heat flux tests in the ribbed geometry. (However, this result may be because we located the peak heat flux region in the most stable subchannel.)

- A Stanton number of about 0.003, or about 50% lower than the Saha-Zuber model bounds all of the experimental data, including tests with ribs and power tilt.

Discussion of Results. It is believed that because of the geometrical tolerances in the annulus diameter and the rib-to-wall clearance gap, one flow subchannel can be created which has a somewhat different geometry than the other subchannels. For instance, if the inner assembly is positioned such that two adjacent ribs touch the outer annulus wall, the resulting subchannel between these ribs will have a smaller flow area (about 25% smaller) than the subchannel on the opposite side of the annulus. Assuming a share of the heat flux which is one-quarter of the total, but a share of the inlet flow which is less than one-quarter of the total in this subchannel, this subchannel might (apparently) become unstable before the others, when the flow conditions are based upon the average flow and heat flux in the four subchannels. In these experiments, the subchannel at the 312° location was hotter (Figure 12) and generally became unstable first in the tests with uniform heat flux.

The results from the power tilt tests indicate that the subchannel with the highest heat flux (136° location) became unstable first, but the temperatures in that subchannel did not differ significantly from those in the unstable (312°) channel with uniform heat flux. This may explain why the demand curves and OFI points in the power tilt experiments do not differ significantly from the tests at uniform circumferential wall heat flux.

The overall uncertainty in the Stanton number based on uncertainties in the instrument readings is estimated to be about 10% to 20%. This uncertainty takes into account a measurement uncertainty of 1 °C in the fluid temperature out of a subcooling of 10 °C (10%) 5% to 15% uncertainty in the inlet velocity (larger values at the lower end of the velocity range tested), and about 2% uncertainty in the heat flux.

CONCLUSIONS

The results from these experiments in a full-scale model of a flow channel indicate that the conditions for OFI in a ribbed annulus may lie at somewhat higher average velocity (higher average subcooling) than in the geometry without ribs. The Creare data from the non-ribbed annulus are in agreement with other data obtained or compiled by SRL also in geometries without ribs.

Because of the possibility for geometrical variations in the annulus (due to the combined effects of diameter and rib height tolerances) each subchannel could have a somewhat different flow area and hence different mass flow rate. Thus, one subchannel might apparently become unstable before the others when the flow conditions are based on the averages flow rates in the four subchannels of the ribbed geometry.

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NOTATION

c_{pf}	specific heat capacity of the liquid (J/kg-K)
D_h	hydraulic diameter of the flow channel (m)
G	mass flux = $\rho_f V_f$ (kg/m^2-s)
k_f	thermal conductivity of the liquid (W/m-K)
Pe	Peclet number
St	Stanton number
T_f	temperature of the liquid (K)
T_{fex}	temperature of the liquid at OSV location (K)
T_{sat}	saturation temperature at OSV location (K)
V_f	velocity of the liquid in the annulus (m/s)
ρ_f	mass density of the liquid (kg/m^3)
ϕ	wall heat flux (W/m^2)

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NOTE TO REVIEWERS:

The Tables and Figures in this technical paper will be revised to contain only SI units for the final manuscript.

Table 1. BOILING REGIME MODELS USED IN ANNULUS PROGRAM CALCULATIONS				
Regime	Wall Heat Transfer	Fluid Heating/ Vapor Generation	Pressure Drop	Friction Factor
Single-Phase	(a) Dittus-Boelter (1930)	Energy Balance	1ϕ	(a) Rohsenow-Hartnett (1985)
	(b) Bjorge-Hall Rohsenow (1982)	Energy Balance	1ϕ	(b) Zigrang-Sylvester (1982)
Partially Developed Nucleate Boiling	Bowring (1962) (with Thom) (1965)	Energy Balance	1ϕ	(a) Levy (1967) (with Colebrook 1938)
				(b) Zigrang-Sylvester (1949)
Fully Developed Nucleate Boiling	Thom (1965)	Energy Balance, (with Ivey-Morris (1962) energy partition)	Homogeneous 2ϕ	McAdams

(a) = original model
(b) = revised model

Table 2. TRANSITION MODELS USED IN ANNULUS PROGRAM CALCULATIONS	
Transition	Model
Onset of Nucleate Boiling (ONB)	Davis-Anderson (1966)
Onset of Significant Voiding (OSV)	Saha-Zuber (1974)

Table 3. GEOMETRIC DATA FOR ANNULUS TEST SECTIONS		
PARAMETER	AVERAGE VALUE	AVERAGE VALUE
ANNULUS CONFIGURATION	RIBBED	NON-RIBBED
OUTER WALL DIAMETER	73.56 mm	73.51 mm
INNER WALL DIAMETER	59.78 mm	60.15 mm
FLOW AREA	1394 mm2	1403 mm2
HYDRAULIC DIAMETER	11.86 mm	13.35 mm
HEATED LENGTH	3.91 m	3.91 m
OUTER WALL SURFACE AREA	0.902 m2	0.902 m2
INNER WALL SURFACE AREA	0.736 m2	0.741 m2
OUTER WALL MATERIAL	Al 6063	Al 6063
INNER WALL MATERIAL	Al 8001	Al 6061

Table 4. ESTIMATED MEASUREMENT UNCERTAINTIES	
MEASURED PARAMETER	UNCERTAINTY IN AVERAGE VALUE
TEMPERATURE	1.1 °C + 0.16%
TOTAL ANNULUS PRESSURE DROP	1.22 kPa + 0.25%
LOCAL ANNULUS PRESSURE DROP	0.22 to 0.42 kPa + 0.25%
ANNULUS PRESSURE	4.0 kPa + 0.25%
PROCESS PRESSURE	5.17 kPa + 0.25%
FLOW METER PRESSURE DROP	0.05 to 0.12 kPa + 0.25%
POWER SUPPLY VOLTAGE	0.81 V + 0.60%
POWER SUPPLY CURRENT (ZONES 1 TO 3)	8.1 A + 0.79%
POWER SUPPLY CURRENT (ZONES 4 TO 6)	2.0 A + 0.79%
HEATER CURRENT	4.1 A + 1.0%

Table 5. TEST CONDITIONS FOR FLOW INSTABILITY EXPERIMENTS IN THE ANNULUS GEOMETRY					
Test Series Number	Test Parameter	Geometry	Heat Flux (Btu/hr-ft^2)	Inlet Pressure (psia)	Helium Saturation Pressure (psig)
1	Baseline	Ribbed(3)	100,000	40	5
1A	Baseline	Ribbed(4)	100,000	40	5
5	Baseline	Ribbed(4)	100,000	40	5
13	Baseline	Ribbed(4)	100,000	40	5
4	Heat Flux	Ribbed(4)	200,000	40	5
6	Heat Flux	Ribbed(4)	300,000	40	5
9	Heat Flux	Ribbed(4)	375,000	40	5
2	Pressure	Ribbed(3)	100,000	60	5
7	Pressure	Ribbed(4)	300,000	60	5
3	Helium	Ribbed(3)	100,000	40	1
3A	Helium	Ribbed(4)	100,000	40	15
15	Power Tilt	Ribbed(4)	100,000±20%	40	5
16	Power Tilt	Ribbed(4)	200,000±20%	40	5
10	Asymmetric	Ribbed(4)	200,000/0	40	5
1	Ribs	Non-ribbed(1)	100,000	40	5
1A	Ribs	Non-ribbed(2)	100,000	40	5
4	Ribs	Non-ribbed(2)	200,000	40	5
2	Ribs	Non-ribbed(2)	100,000	60	5
3	Ribs	Non-ribbed(2)	100,000	40	1

* All tests were performed with inlet water temperature of 86 °F.

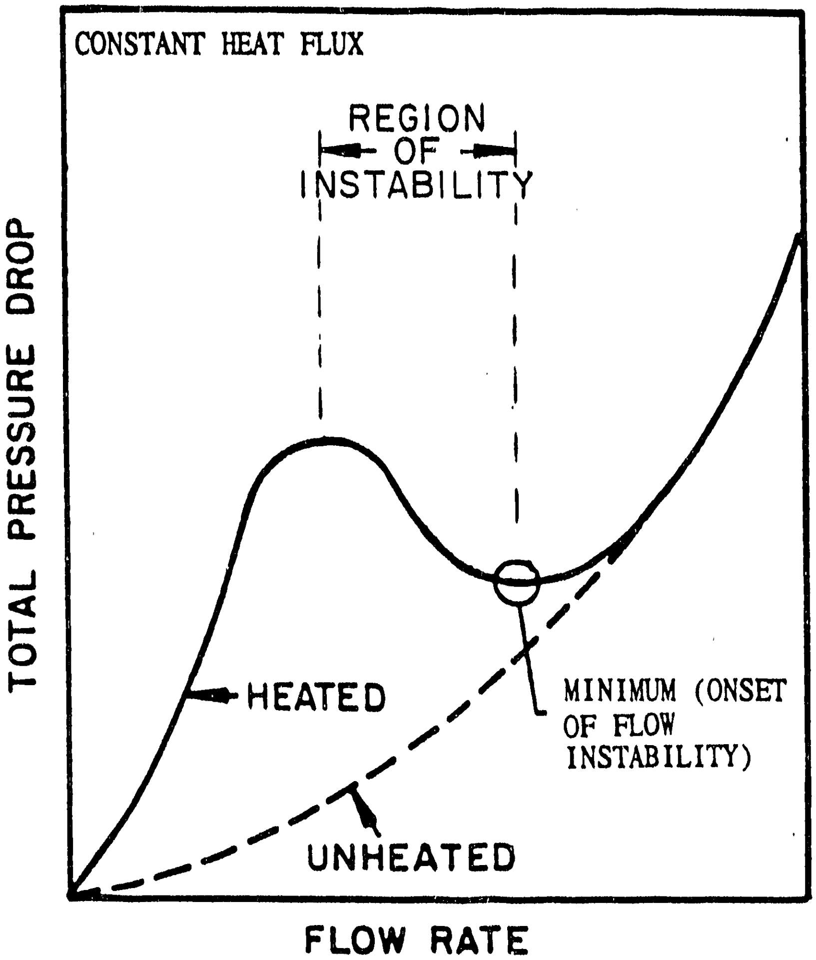


Figure 1. ONSET OF FLOW INSTABILITY LOCATED ON THE DEMAND CURVE FOR A HEATED FLOW CHANNEL

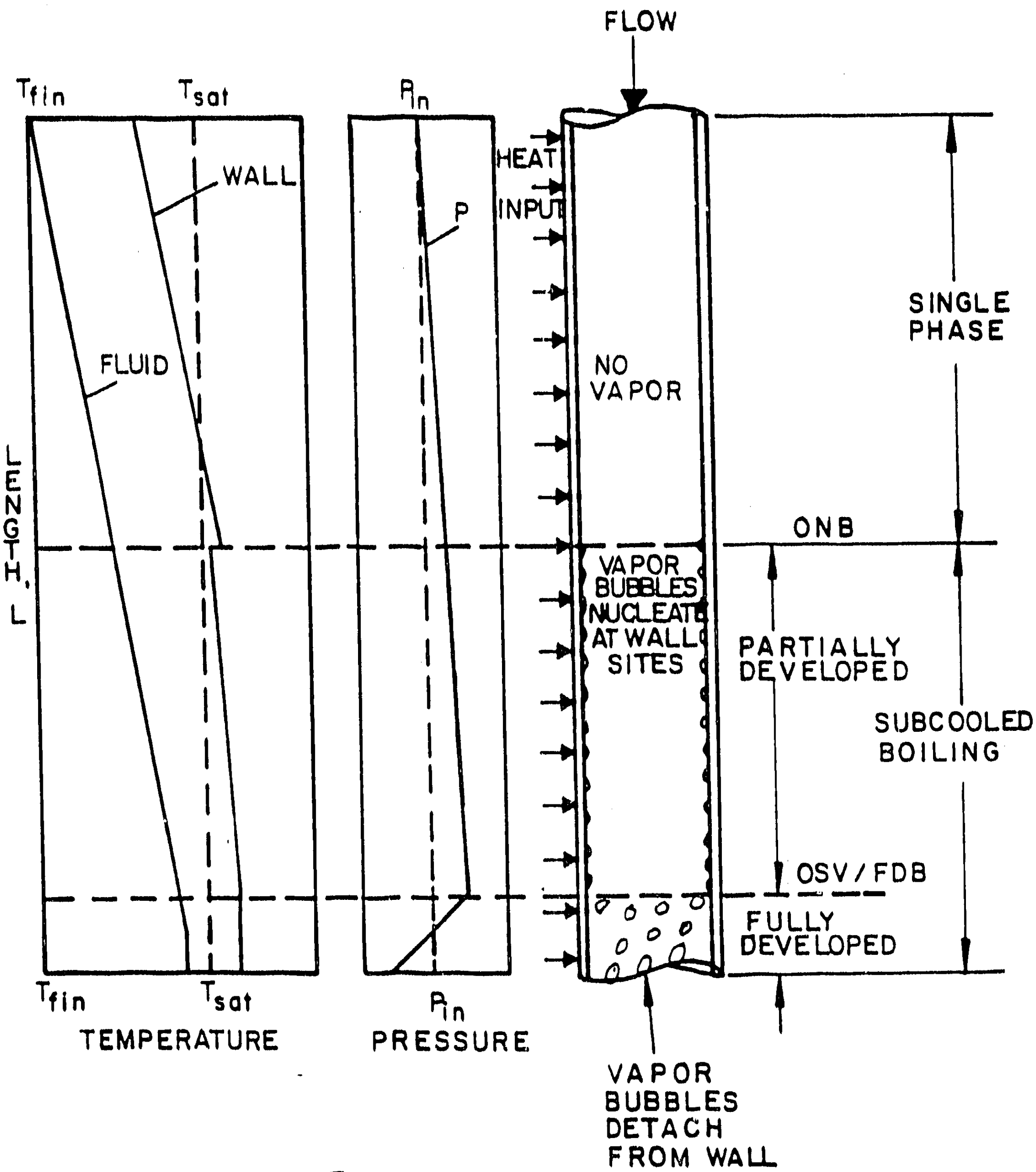


Figure 2. ILLUSTRATION OF BOILING FLOW PHENOMENA IN DOWNFLOW

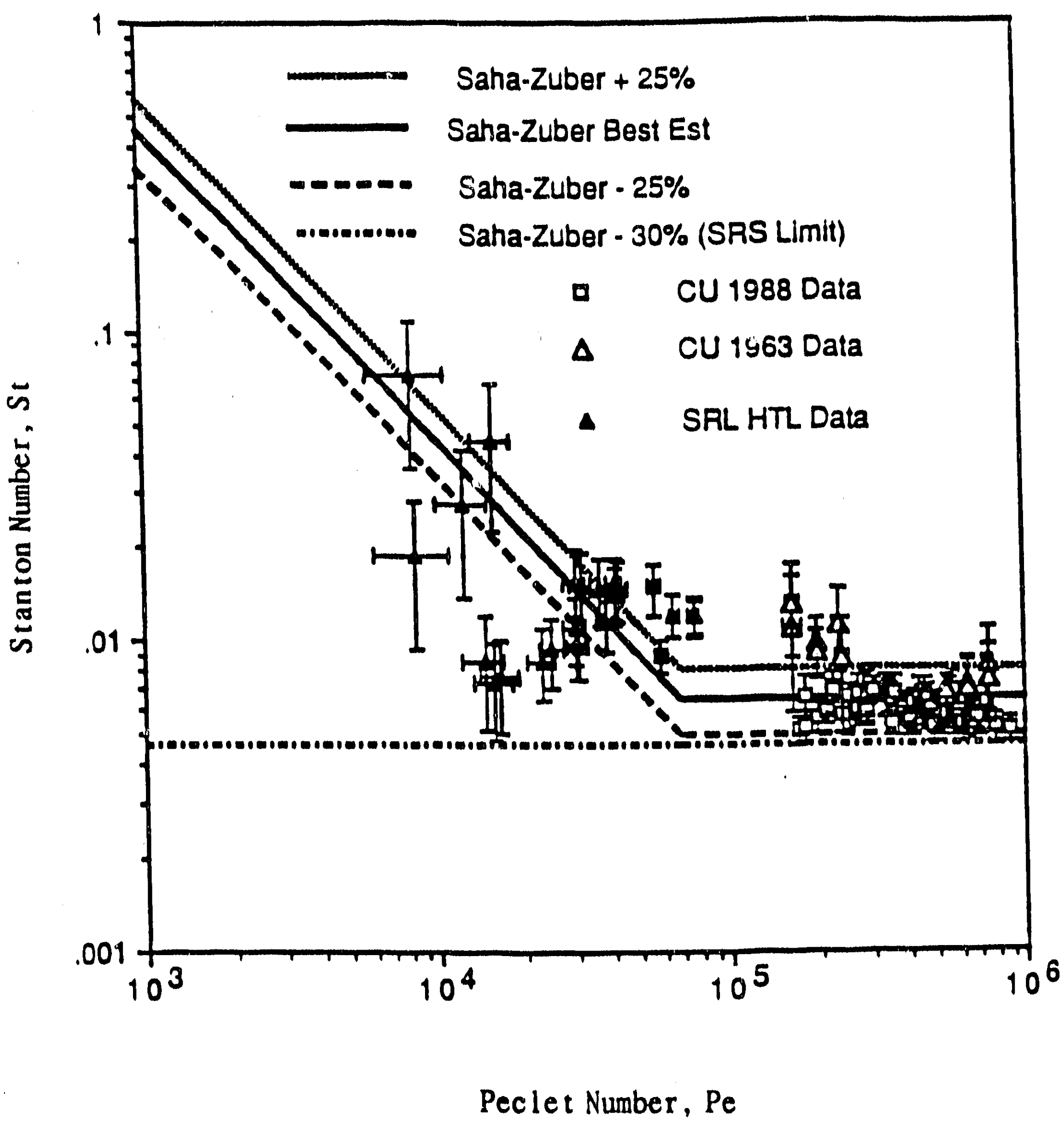


Figure 3. SUMMARY OF OFI RESULTS FROM OTHER SRL PROGRAM EXPERIMENTS (CHEN ET AL., NOVEMBER, 1989)

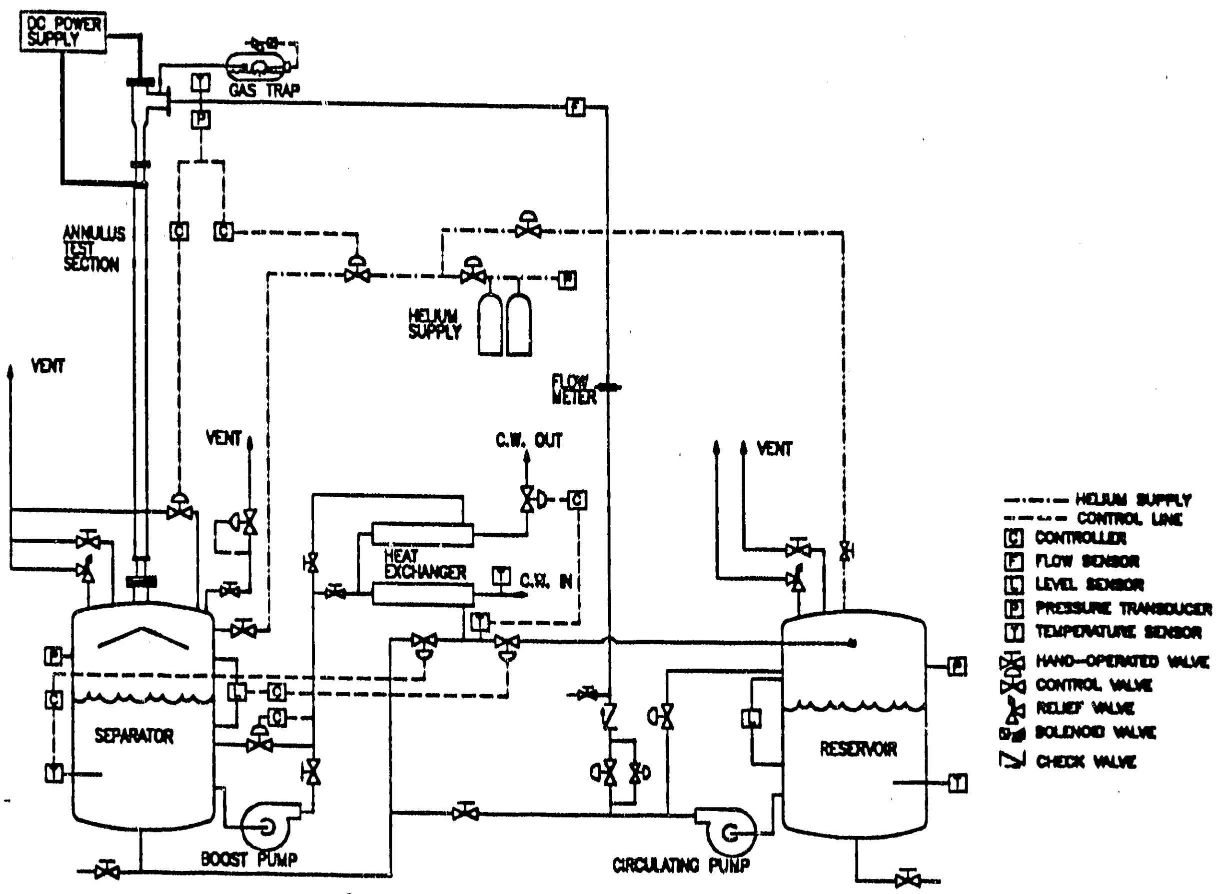
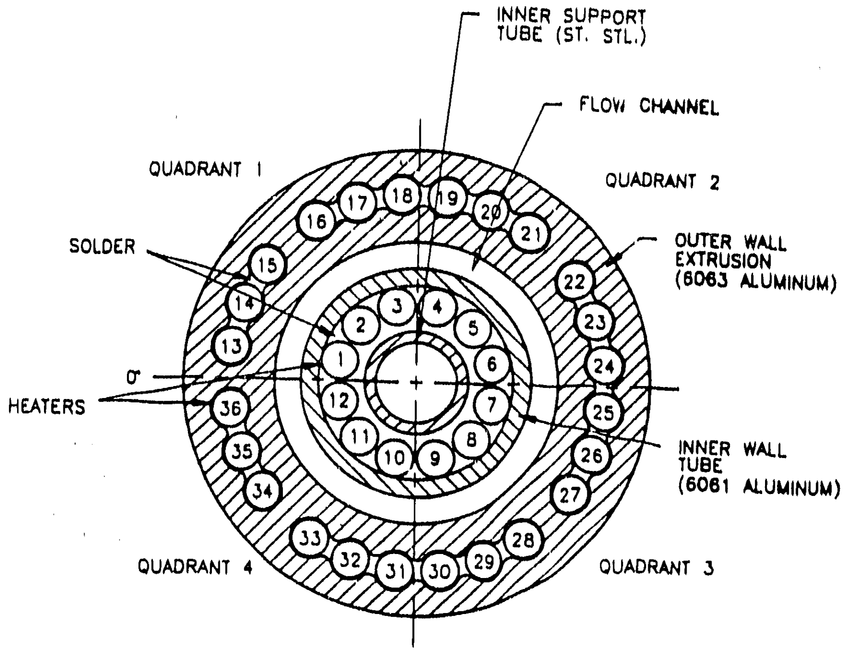
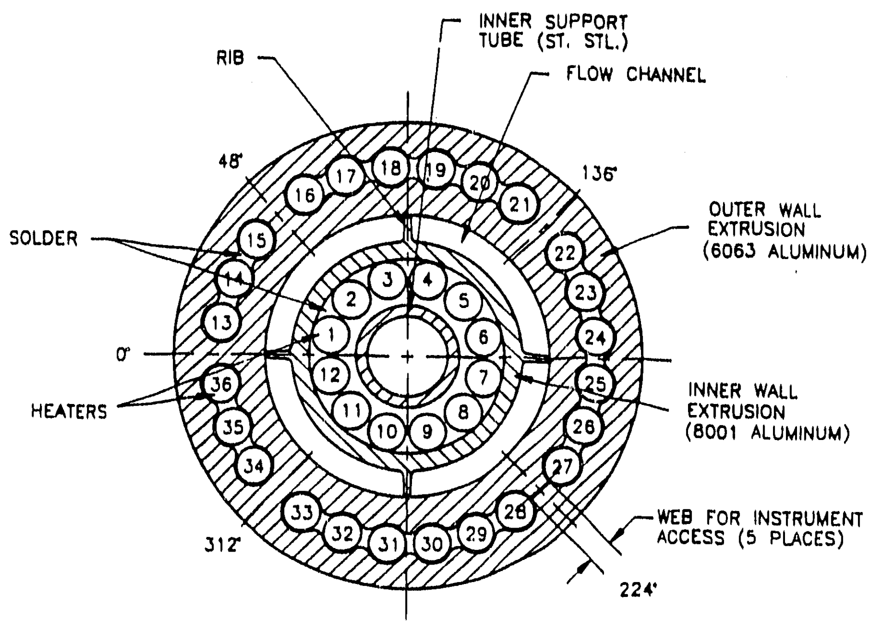


Figure 4. TEST FACILITY FOR FLOW STABILITY EXPERIMENTS IN ANNULAR FLOW CHANNELS

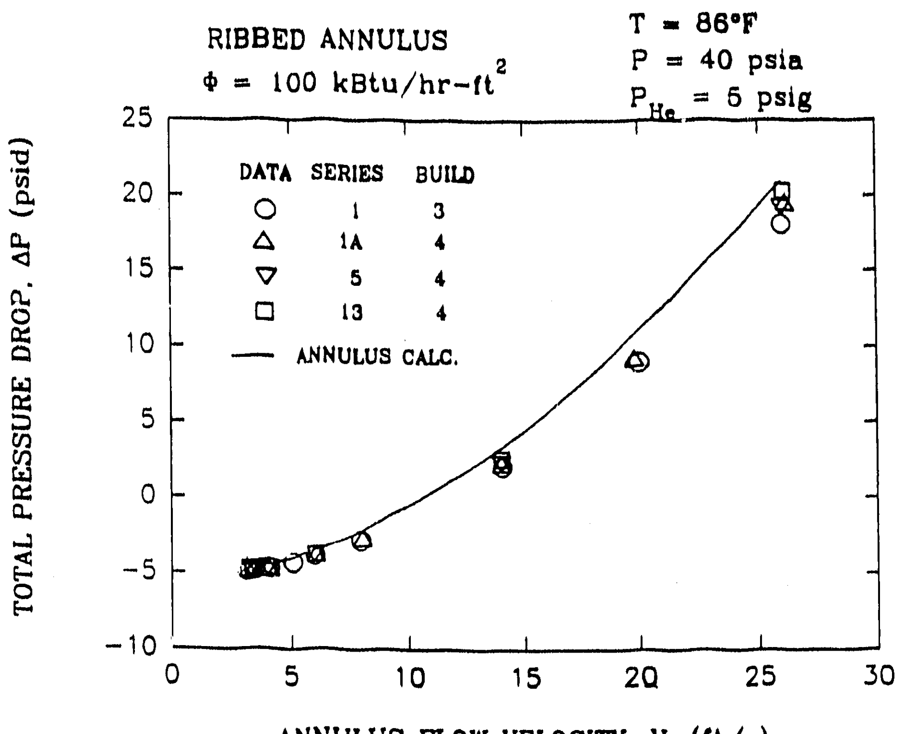


Non-Ribbed

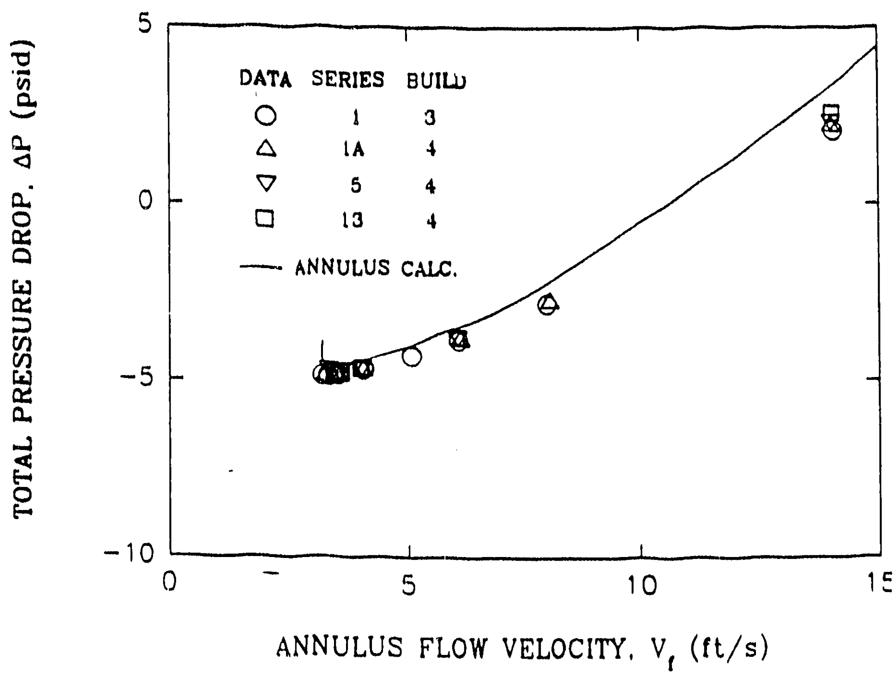


Ribbed

Figure 5. TEST ANNULUS CROSS-SECTIONS



(a) Full Scale



(b) Expanded Scale

Figure 6. DEMAND CURVE FOR BASELINE TESTS IN THE RIBBED GEOMETRY

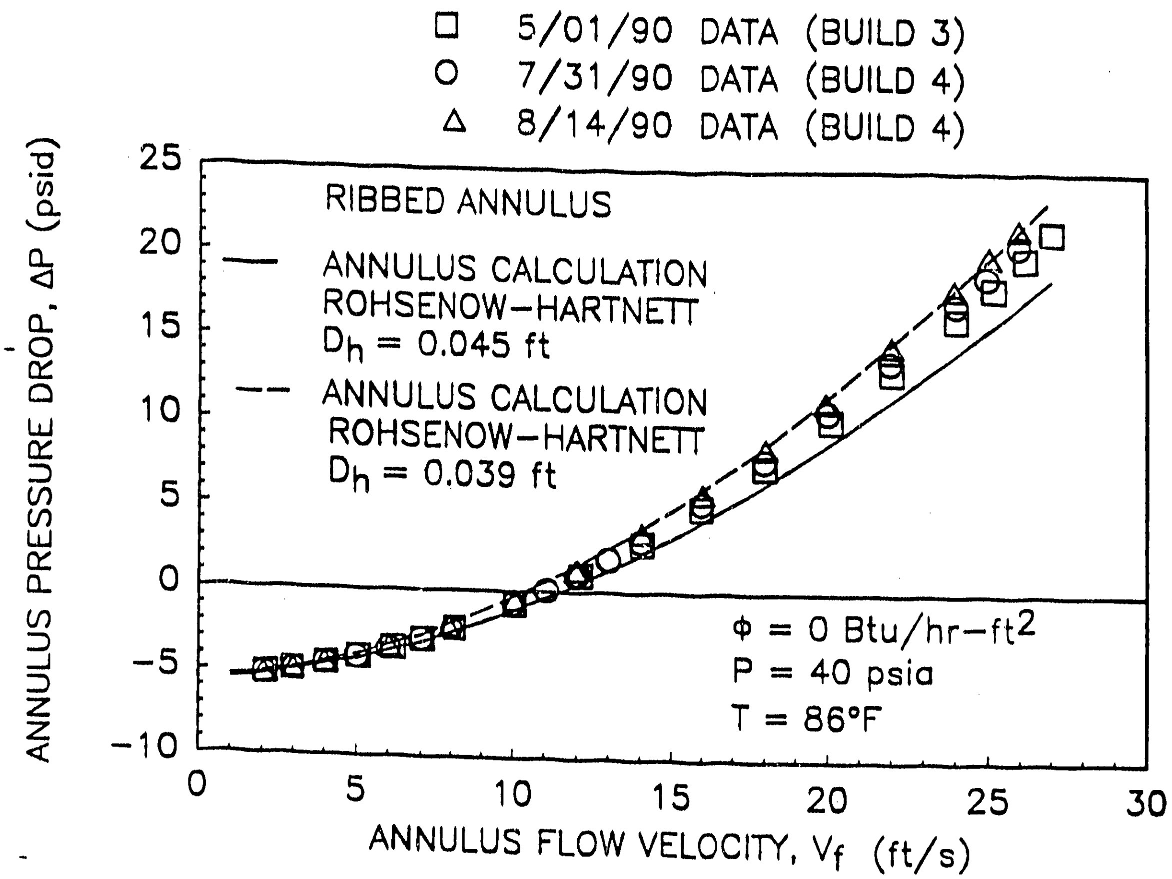


Figure 7. SINGLE PHASE PRESSURE DROP DATA IN ANNULUS GEOMETRY AGREE WITH FRICTION FACTOR CORRELATION

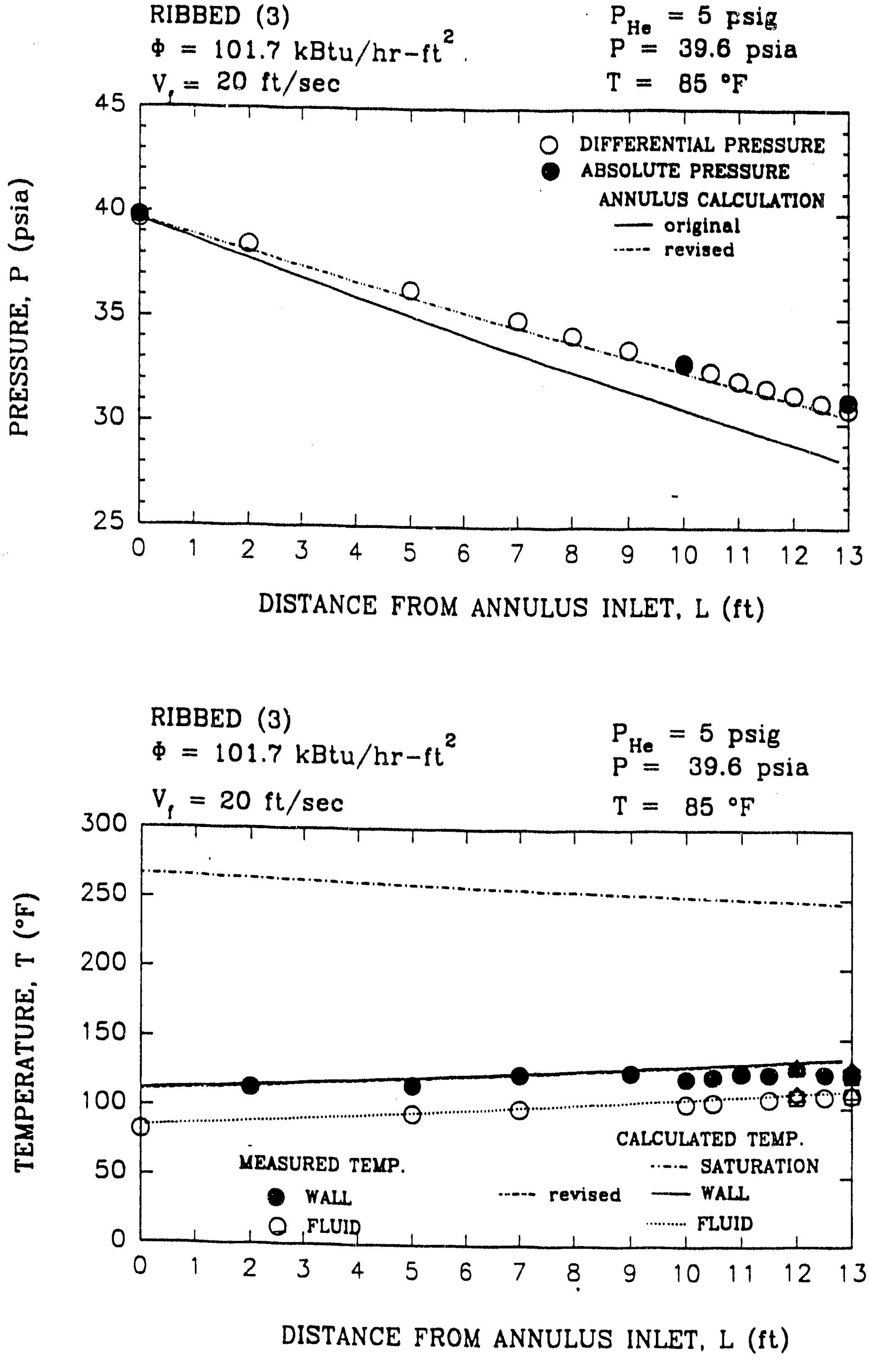
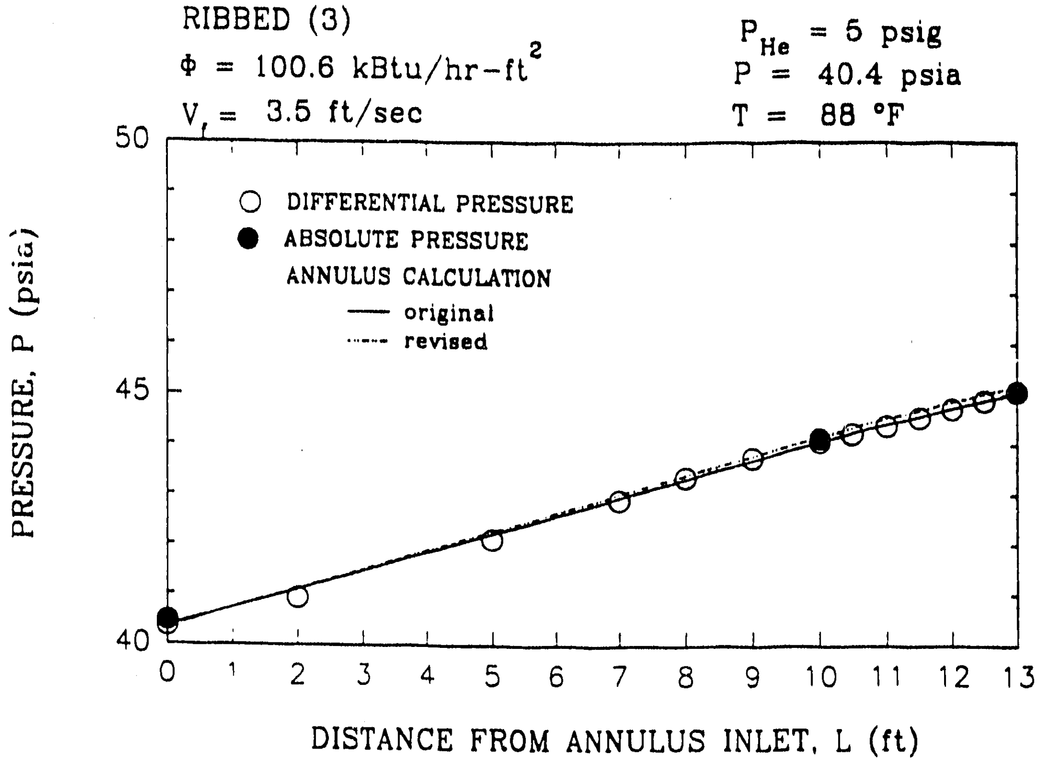


Figure 8. DATA PROFILES AND ANNULUS CALCULATIONS AT BASELINE CONDITIONS (V_f = 20 FT/S)



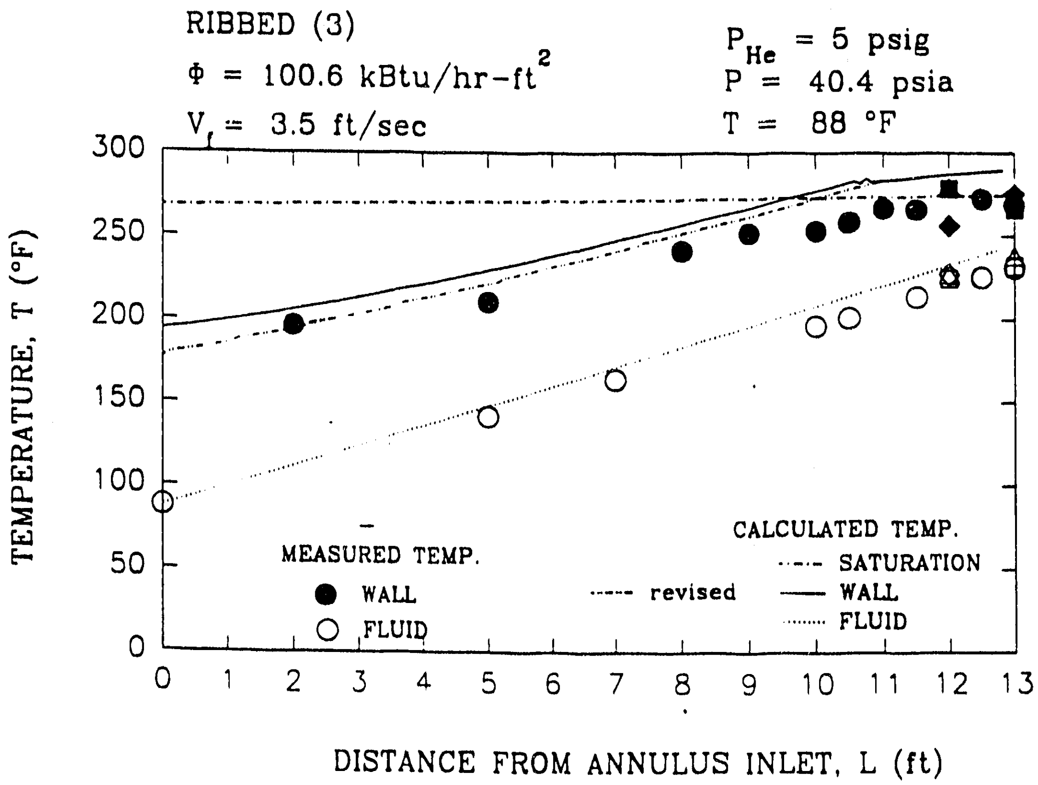
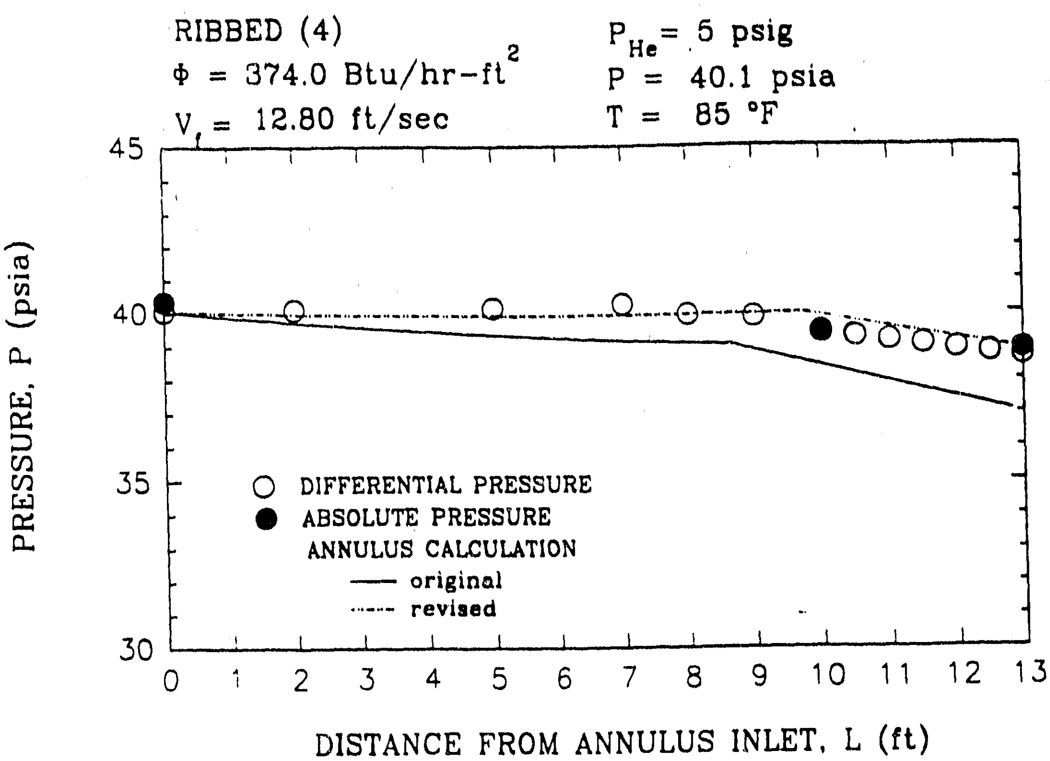


Figure 9. DATA PROFILES AND ANNULUS CALCULATIONS AT BASELINE CONDITIONS (V_f = 3.5 FT/S)



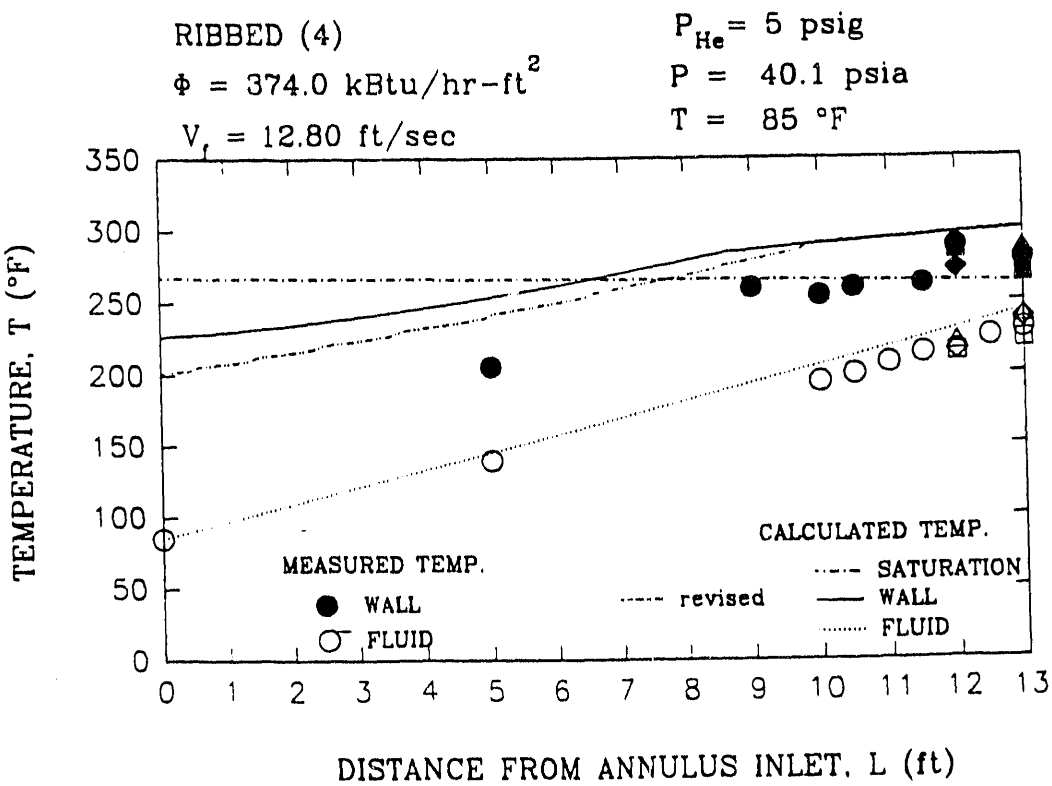


Figure 10. DATA PROFILES AND ANNULUS CALCULATIONS AT BASELINE CONDITIONS (V_f = 3.2 FT/S)

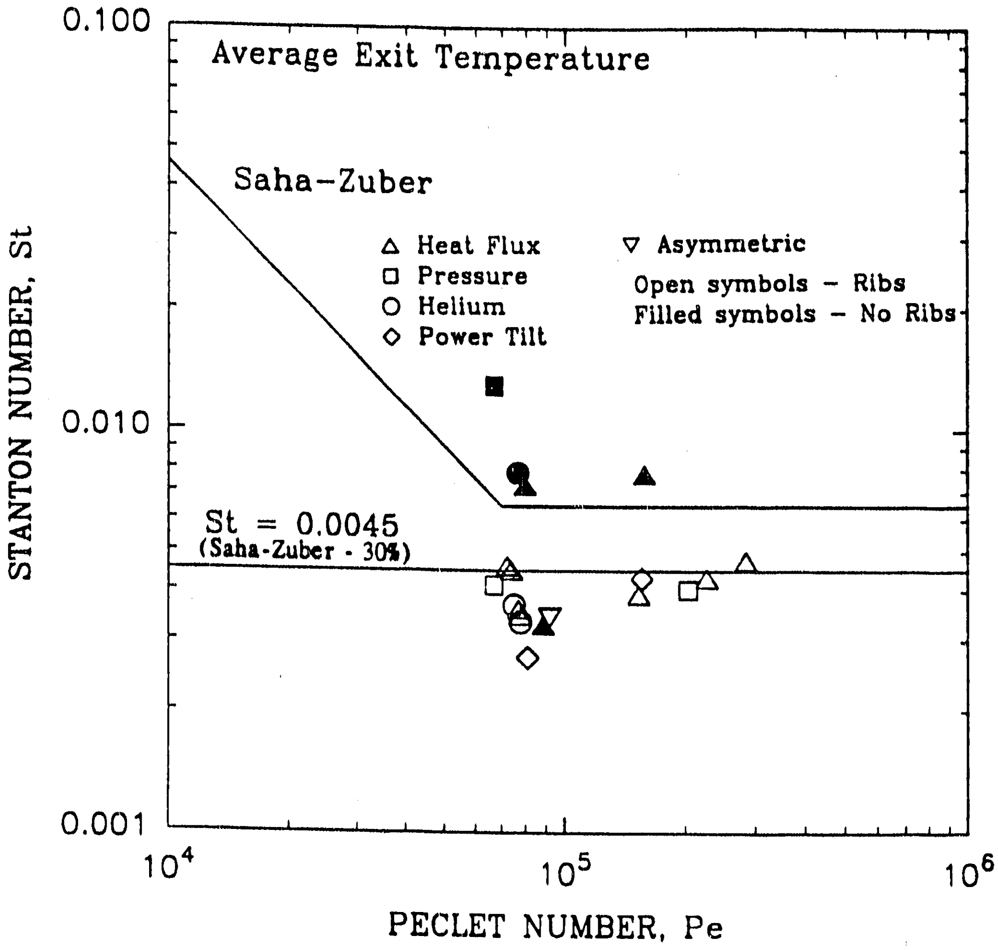


Figure 11. SUMMARY OF OFI RESULTS FROM CREARE EXPERIMENTS

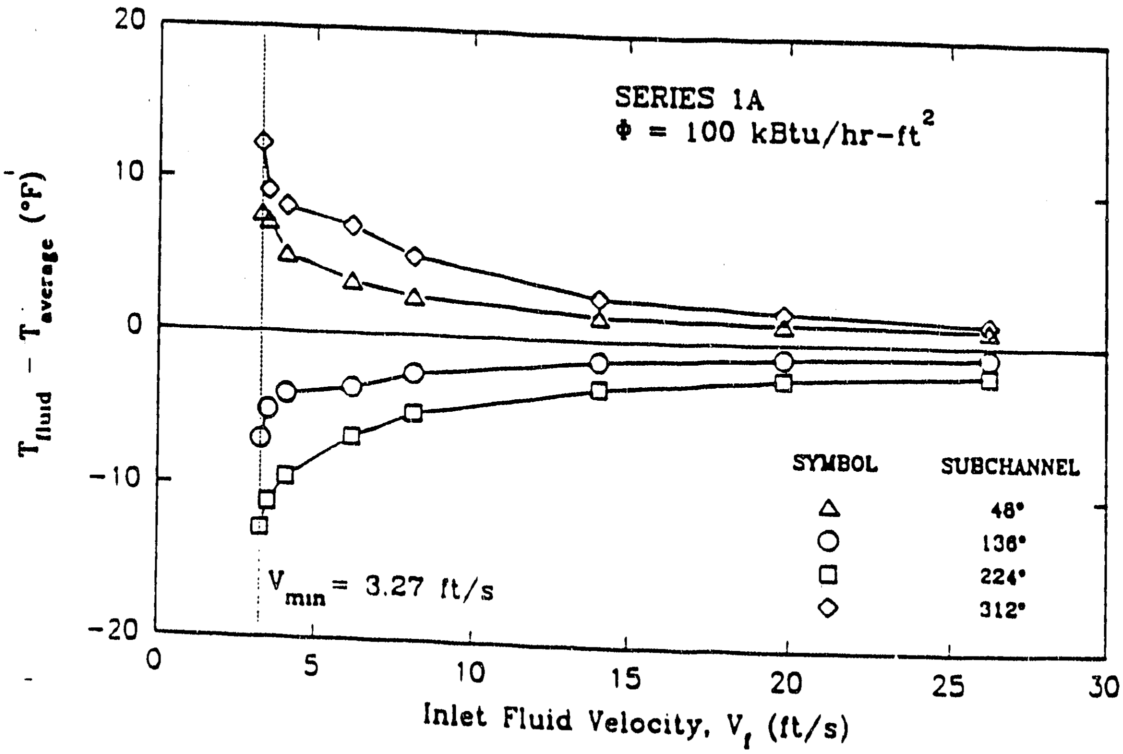


Figure 12. NONUNIFORMITY IN SUBCHANNEL FLOW AND/OR GEOMETRY MAY BE KEY TO INTERPRETATION OF THESE DATA

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