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STEADY STATE THERMAL HYDRAULIC CHARACTERISTICS
OF ONE-INCH OVERBORE FUEL

A. M. Sutey, D. E. Fitzsimmons
and C. W. Angle

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STEADY STATE THERMAL HYDRAULIC CHARACTERISTICS
OF ONE-INCH OVERBORE FUEL

OBJECTIVE

The purpose of this study is to experimentally determine the thermal hydraulic characteristics of the One-Inch Overbore fuel geometry under both single and two-phase flow conditions. Results of these experiments demonstrate the relation between pressure drop and flow at various tube power levels and will be utilized to establish process tube operating limits and trip margins.

INTRODUCTION

Successful operation of a nuclear reactor requires complete knowledge of the thermal-hydraulic behavior of the reactor fuel charge. Knowledge of the pressure-drop flow demand characteristics of a fuel is essential to provide necessary cooling to the fuel. Although the single pass reactors operate under single-phase subcooled conditions, their operation requires knowledge of the pressure demand curves under both single phase and two phase flow conditions. Such curves are of special significance in defining conditions of flow instability which form the basis for process tube operating limits and trip margins. Since analytical methods are presently unavailable to adequately determine such pressure demand curves for complex fuel charges, laboratory tests with prototypic models are required.

SUMMARY

In this study, single and two-phase pressure losses were determined for a full scale, electrically heated, prototypic model of the One-Inch Overbore fuel column with associated downstream and rear hardware. Boiling demand curves were established using two different downstream dummy-fuel charges. For the One-Inch Overbore fuel loading, the characteristic two-phase portion of the pressure demand curve was due entirely to two-phase pressure losses in the rear fittings and pigtail of the downstream

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hardware. Two-phase losses were not measurable in the active and dummy portions of the fuel column prior to the onset of parallel channel instability.

Parallel channel instability consisted of a transient flow shift from the inner to the outer subchannel of the Overbore fuel model. The transient flow shift commenced when local saturation conditions were reached at the top of the inner flow subchannel. As voids formed in the inner subchannel, flow diversion continued, and film boiling occurred in the inner subchannel. Consequently, the steady state pressure demand curve could not be extended to lower flows subsequent to the onset of parallel channel instability. If desired, the operational effects of parallel channel instability can be reduced by redesign of the Overbore fuel to increase flow to the inner subchannel and by increased hydraulic resistance in the downstream or rear hardware to increase pressure in the active fuel column and thus suppress boiling there.

Generalized boiling curves which relate Panellit pressure to flow were constructed from the experimental pressure-drop flow data. In the past, such curves have been used to establish process tube operating limits and trip settings based on the trip-after-instability concept. In this study, system instability was first reached near 1500 kW for the standard dummy charge and near 2500 kW for the non-standard case. System instability occurred at lower power levels with the standard dummy charge than with the non-standard dummy charge due to pressurization in the active assembly afforded by the increased pressure demand of the standard dummy charge. At power levels, less than 1500 kW for the standard dummy charge and 2500 kW for the non-standard dummy charge, parallel channel instability and film boiling occurred before system instability could be established.

Results indicate that the conventional trip-after-system-instability concept provides minimal low trip and high trip backup protection for the power levels of interest, and thus, should not be used to establish

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trip settings for the present design of the One-Inch Overbore fuel charge. If desired, appropriate increases in the hydraulic resistance of the downstream or rear hardware would make the conventional trip-after-system-instability concept applicable to this fuel. However, such changes may not be practical.

Since the conventional trip-after-system instability method of setting trip limits will not provide safe operation for the present One-Inch Overbore fuel design, a new trip limit concept which will not necessitate additional design changes is recommended. An empirical equation relating the Panellit pressure to flow and to either the rear header pressure or the saturation pressure at the end of the active section, whichever is greater, has been shown to conservatively predict the generalized boiling curves of the Overbore fuel. The minimum of this generalized empirical relation provides a low trip limit independent of tube power. This concept will not provide high trip backup except for power levels greater than 3000 kW; however, it will provide low trip protection for both fast and slow upstream plugs for tube powers greater than 500 kW for the standard dummy charge and 1500 kW for the non-standard dummy charge.

EQUIPMENT DESCRIPTION

TEST FACILITY

The experiments were performed in the Low Pressure Heat Transfer Facility at 189-D Laboratory of the Pacific Northwest Laboratory. The test assembly consisted of a full scale, prototypic, electrically heated model of a One-Inch Overbore fuel column with associated downstream hardware. Electrical energy for resistance heating of the model was supplied via a D-C silicon rectifier bank rated at 4.0 megawatts.

The Overbore fuel model simulated 32 C-Overbore fuel elements which have been used to a limited extent in C-Reactor. A cross section of the simulated fuel element is presented in Figure (1) along with the fuel element dimensions and heat split. As shown in Figure (1), a tubular sandwich construction was used to simulate the fuel element. This design was used to simulate the proper fuel surface heat fluxes and the required

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SIMULATED FUEL ELEMENT

FUEL ELEMENT DIMENSIONS

Fuel slug length	8.870 in.
Tube O.D.	2.451 in.
Tube I.D.	1.234 in.
Rod O.D.	0.957 in.
Zircaloy process tube I.D.	2.651 in.
Total heated length	23.7 ft.

HEAT SPLIT

Inner channel	
Rod (O.D.)	.132
Tube (I.D.)	.310
Outer channel	
Tube O.D.	.558

FIGURE 1. ONE-INCH OVERBORE DESIGN

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maximum power generation of the fuel using the available low voltage-high current power supplied by the D-C rectifiers. The heated model consisted of Inconel and K-Monel tubular sections having various inside dimensions to provide the stepped-cosine heat flux distribution shown in Figure (2). The assembly details of the heater rod are presented in Drawing H-1-14959.

Considerable effort was taken to simulate as close as possible the hydrodynamics of the fuel column. An elaborate electrical connector providing an almost exact simulation of the end of the active fuel column was used at the downstream end of the heated section. Fuel element spacers were simulated using prototypic ceramic supports. Interchannel flow holes were used at appropriate axial locations along the heated test section to simulate flow at fuel element junctions. On the basis of a previous analytical analysis (1), one round hole with a cross-section area of 0.0120 in^2 was located at axial positions corresponding to every other fuel element junction.

The experiments were run using a closed loop system as shown in the schematic diagram, Figure (3). Cold de-ionized water from the pump was split into two streams prior to entering the heated test section at approximately 66°F . The flow split was adjusted so that equal pressure drops occurred across the heated subchannels. Fluid exhausting from the fuel model passed through standard C-Reactor hardware including a dummy tube, nozzle, pigtail, and rear header, respectively. After passing through the test section installation, the flow was recirculated to the pump through the loop condenser. A description of the rear header hardware is given in Drawing No. H-1-71214.

In this study, the hydraulic characteristics of both standard and non-standard C-Reactor dummy charges were studied. The standard dummy charge consisted of five perfs, two tubulars, five solids* and one insert. The solids were located in the extreme downstream part of the process tube and were utilized to decrease flow, yet maintain pressure

*Solid dimensions: Length of 8.0 inches, Outside diameter of 2.491 inches.

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FIGURE 3. SCHEMATIC FLOW DIAGRAM

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in the active section. The non-standard dummy charge consisted of four perfs, eight tubulars and one insert.

INSTRUMENTATION

Sixteen thermocouples were located along the downstream half of the heated test section to continuously monitor surface temperatures. None of these thermocouples were located along the low heat flux inner rod of the test section. These thermocouples were used to detect the transition to film boiling during the steady state tests.

Locations of the loop flow, pressure and fluid temperature measurements are indicated in Figure (3). Rates of coolant flow into the active section subchannels were measured via calibrated Potter turbine flow meters in the two subchannel supply lines. Total flow to the model was also measured with a calibrated 0.524 in. I.D. venturi in the inlet piping upstream of the point where the subchannel supply lines separated. Total flow measurements compared within 1.0% in all cases.

Fluid temperatures were measured along the active length and at various locations along the downstream hardware. Circumferential fluid temperatures of both the inner and outer annuli were measured at the end of the active section. These circumferential temperatures were measured to indicate the effect of local subchannel temperature disparities on instability and burnout. Fluid temperature measurements were considered accurate within $\pm 2^\circ\text{F}$.

Pressure losses were measured for the entire fuel column and for various components within the column. Pressure taps were located to measure pressures along the active section, dummy length and rear header hardware. For the most part, absolute pressures were obtained using Heise pressure gauges and are considered accurate within $\pm 1/2$ psi.

EXPERIMENTAL PROCEDURE

Isothermal, single-phase, hydraulic experiments were performed with the model fuel column and associated downstream hardware prior to the two-phase boiling-curve experiments. The isotherms provided (1) an estimate of the heat losses from various parts within the flow system; (2) a check of the system instrumentation over a wide range of

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temperature, pressure drop, and flow rate; (3) a cold (66°F) pressure drop-flow relation which was used as an instrumentation reference for each loop start-up during testing and (4) a comparison of the pressure-flow characteristics and flow split of the simulated fuel model with that of an actual fuel column as measured in the hydraulics laboratory.

The boiling curves were determined by throttling the pump flow to the fuel assembly while tube power and rear header pressure were held constant. Following each adjustment of flow, steady state conditions were reached, and complete readings of flow, pressure, and temperature were obtained at appropriate locations along the fuel column assembly. Flow reductions were continued until a rapid excursion in rod surface temperatures indicated a transition to film boiling at which time the test section power was reduced. In this manner, boiling curves of the Overbore fuel assembly were obtained for several different dummy charges over a wide range of tube power levels. Power levels considered ranged from 500 to 3500 kW with the standard dummy charge and 1500 to 3500 kW with the non-standard dummy charge. Tube inlet temperature and rear header pressure were maintained constant at 66°F and 45 psig, respectively.

EXPERIMENTAL RESULTS

Steady State Boiling Curves

The experimental pressure drop-flow curves obtained in this study for the One-Inch Overbore fuel model are presented in Figures 4 to 9. The boiling demand curves for the entire fuel assembly from the tube inlet to the rear header are presented in Figures 4 and 5. Contributions to the total column thermal hydraulic behavior are presented for the active-heated length, the dummy hardware and rear fittings in Figures 6-9. Boiling demand curves were established for two different dummy fuel charges which have been previously described.

Characteristic low pressure hydraulic demand curves are presented in Figures 4 and 5 for power levels greater than 1500 kW for the standard dummy charge and 2500 kW for the non-standard dummy charge. For a given tube power, the pressure drop across the fuel column and downstream

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Pressure Drop - Tube Inlet Minus Rear Header - Psi

FIGURE 4: STEADY STATE HYDRAULIC DEMAND CURVES
(STANDARD DUMMY CHARGE)

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Pressure Drop - Tube Inlet Minus Rear Header (Psi)

FIGURE 5. STEADY STATE HYDRAULIC DEMAND CURVES
(NON-STANDARD DUMMY CHARGE)

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components decreased linearly with decreasing single phase flow. Once boiling commenced in the rear fittings, the data deviated from the single phase (straight) line. The overall pressure drop continued to decrease until the two phase flow contribution was sufficient to increase the pressure drop with decreasing flow. At low power levels interchannel instability occurred before steady two-phase flow conditions could be established. As shown in Figures 6 and 7, steady state two phase demand curves were not established for the active section of the assembly. Steady state two-phase pressure drop-flow data were not obtainable after the occurrence of parallel channel instability which lead to film boiling conditions.

The shaded symbols in Figure 4 and 5 represent the flow at which parallel channel flow instability commenced. This type of instability consisted of a transient shift of flow from the inner to the outer subchannel in the Overbore fuel model. Flow diversion occurred at both the inlet to the test assembly and at the interjunction holes due to the formation of voids in the inner annulus. Transient flow diversion continued until film boiling conditions were reached in the inner subchannel. The flow diversion was most severe at low power levels. At high power levels the pressure in the active section was greater, and therefore, the extent of voiding and resulting flow diversion was less.

For the One-Inch Overbore fuel geometry, the characteristic two-phase portion of the pressure demand curve was due entirely to two-phase pressure losses in the rear fittings and pigtail of the downstream hardware as described in Figures 8-9. Two-phase losses were not experienced in the dummy length prior to interchannel instability; however, the type of dummy charge greatly affected the flow at which interchannel instability occurred. Due to the pressurization in the active fuel assembly afforded by the increased pressure-demand of the standard dummy charge, the boiling curves were extended to much lower flow rates than possible with the non-standard dummy charge. Pressure losses of the non-standard dummy charge were negligible in comparison to the standard dummy charge.

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Pressure Drop (Psi)

FIGURE 6. STEADY STATE PRESSURE LOSSES
FOR ACTIVE AND DOWNSTREAM SECTIONS
(STANDARD DUMMY CHARGE)

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FIGURE 7. STEADY STATE PRESSURE LOSSES FOR ACTIVE AND DOWNSTREAM SECTIONS (NON-STANDARD DUTY CHARGE)

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FIGURE 2. DOWNSTREAM HARDWARE PRESSURE LOSSES
(STANDARD DUMMY CHARGE)

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FIGURE 9. DOWNSTREAM HARDWARE PRESSURE LOSSES
(NON-STANDARD DURNY CHARGE)

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The Overbore fuel model assembly simulated very closely the hydraulic behavior of the actual fuel column. Isothermal single phase losses of the active length of the fuel model were only 9% lower than values previously obtained in the 189-D Hydraulics Laboratory for an actual column of 32 one-inch C-Overbore fuel elements. Differences were due primarily to surface roughness and slug junction roughness which the fuel model did not simulate. The dashed lines in Figures 6 and 7 represent the pressure losses of the active length of the fuel column corrected to account for these differences. These dashed lines were used to establish the overall pressure demand curves of the Overbore fuel assembly presented in Figures 4 and 5.

Circumferential Water Temperatures

To better understand the thermal hydraulic nature of the One-Inch Overbore fuel, the thermal conditions at the exit of the active section are presented in Figure (10) for a typical power level. Circumferential fluid temperatures were measured in both the inner and outer subchannels. Temperatures at all circumferential locations compared within less than 1°F under isothermal conditions. As shown in Figure (10), local and average fluid temperatures are higher in the inner annulus than in the outer annulus, and these differences increase slightly as the flow rate is decreased. As expected, fluid temperatures at the bottom of the eccentric outer annulus are highest for that subchannel. In the inner concentric annulus, fluid temperatures are highest at the top of the subchannel. Fluid temperatures at the top of the inner annulus are the highest of any location in the fuel. Due to gravity effects, the heated fluid layers tend to rise to the top of the horizontal heated subchannels. This phenomena has been commonly reported in concentric horizontal heated systems studied in the past.

In the Overbore fuel, the enthalpy rise of the inner annulus is greater than that of the outer annulus which is a result of the hydraulic flow split not matching the designed power split. In addition, the inner surface of the tubular element operates at the highest heat flux of any of the fuel surfaces. Consequently, as shown by the steady state hydraulic demand study, parallel channel flow instability was always

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initiated in the inner annulus followed by film boiling at the outer surface of that subchannel. The transient flow diversion was found to consistently occur once local saturation was reached at the top of the inner annulus.

Aside from stimulating subchannel instability, the aforementioned temperature disparities are also important to evaluate corrosion problems in the fuel charge. These temperature disparities can be reduced by re-design of the fuel to allow additional flow in the "hot" inner subchannel and by means of several mixer spools placed along the fuel charge length.

Generalized Boiling Curves

The experimental pressure drop-flow data presented in Figures 4 and 5 were used to construct generalized boiling curves which relate Panellit pressure to flow. In the past, these curves were used to determine conditions of system instability by which operating limits were established for various tube powers. The generalized curves are presented in Figures 11 and 12 with Panellit pressure plotted versus the square of a flow ratio (F/F^*). The techniques used to develop these curves are discussed in previous reports (2-6). The following relations were used to construct the generalized curves.

$$F^* = \frac{Q}{.2535 (t_o^* - t_i)} \quad (1)$$

$$P_{AI} = P_{TI} + (P_{AI}^* - P_{TI}^*) (F/F^*)^{2.0} \quad (2)$$

where

F = tube inlet flow rate (gpm)	t _i = tube inlet temperature (°C)
P _{AI} = Panellit pressure (psig)	t _o = tube outlet temperature (°C)
P _{TI} = tube inlet pressure	(F/F*) = $\frac{t^* - t_i}{t_o - t_i}$
Q = tube power level (kW)	

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FIGURE 11. GENERALIZED HYDRAULIC DEMAND CURVE
(STANDARD DUMMY CHARGE)

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10 X 10 TO 1/2 INCH 46 1320
7 X 10 INCHES
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An empirical relation which has been previously used to predict the generalized curve is written as follows and is presented in Figures 11 and 12.

$$P_{AH} = K (F/F^*)^{1.8} + [P_{RH} \text{ or } P_{\text{sat EOAS}}] \text{ whichever is greatest} \quad (3)$$

where P_{RH} = rear header pressure, and $P_{\text{sat EOAS}}$ = saturation pressure at the end of the active length.

For the curves presented in Figures 11 and 12, values of 200 psig and 130°C were chosen for P_{AH}^* and t_o^* , respectively. Values of $(P_{AH}^* - P_{TI}^*)/F^*$ determine the inlet orificing required so that each tube operates at the same Panellit pressure independent of power level.

If applicable to a given fuel geometry and its associated hardware, the theory of generalized boiling curves is very useful since it provides a simple means of setting safety trip limits. Using the empirical prediction of the generalized curves and the trip-after-system-instability concept, only one low trip limit is required for all reactor tubes independent of power level. Based on this limit, maximum tube outlet temperatures can be determined. Using this method, tube flows are matched to tube power via inlet orificing to provide safe, efficient, hydraulic operation of the reactor. Except for specific fuel geometries operated at very low power levels at which system instability did not occur, this method has been used extensively in the past.

In Figures 11 and 12, system instability at which the supply curve is tangent to the two phase demand curve, was first reached at 1500 kW for the standard dummy charge and at 2500 kW for the non-standard case. It occurred at lower power levels with the standard dummy charge than with the non-standard dummy charge due to the greater pressure demand of the standard dummy charge. At low power levels, parallel channel instability leading to film boiling occurred before system (overall) instability could be established.

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Results in Figures 11 and 12 show that the trip-after-system-instability concept, it not directly applicable to the present design of the One-Inch Overbore fuel charge. Using this method, low trip and high trip backup protection is minimal for the power levels of interest. The reason for this is that parallel channel instability leading to film boiling conditions occurs before substantial pressurization at the Panellit gauge can occur due to two phase flow in the fuel column and downstream hardware. The effect of parallel instability can be reduced by redesign of this fuel to increase flow to the inner subchannel, and by increased orificing in the rear fittings of the reactor. Proper orificing in the rear fittings will also make the trip-after-instability concept applicable to the One-Inch Overbore fuel.

Since the usual trip-after-system-instability method of setting trip limits will not provide safe operation for the present One-Inch Overbore fuel design, a new trip limit concept is recommended. Equation 3 which relates the Panellit pressure to flow and to either the rear header pressure or the saturation pressure at the end of the active section, whichever is greater, has been shown to conservatively predict the generalized boiling curves of the One-Inch Overbore fuel. The minimum of this generalized empirical curve provides a low trip limit independent of tube power for a given tube inlet temperature. Consequently, maximum tube outlet temperatures can be determined based on this limit. This concept will not provide high trip backup protection except for power levels greater than 2500 kW; however, it will provide low trip protection for both fast and slow upstream plugs for tube powers greater than 500 kW for the standard dummy charge and 1500 kW for the non-standard dummy charge. For lower tube powers, some sort of trip-before-instability concept may be applied. High trip may be set as in the past to trip after a 30% or greater flow reduction due to downstream plugging.

Another method of setting trip limits can also be used. For individual tubes, Equation (3) can be written in a non-generalized form to conservatively predict the experimental pressure demand curves in Figures 4 and 5.

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$$P_{\text{Tube Inlet}} = aF^b + [P_{RH} \text{ or } P_{\text{sat. EOAS}}] \text{ whichever is greatest} \quad (4)$$

For the standard dummy charge, $a = 0.044$ and $b = 1.95$ and for the non-standard dummy charge, $a = 0.0405$ and $b = 1.85$. Further sophistication of Equation (4) is not warranted since the curves in Figures 4 and 5 can easily be curve fitted if desired. For the tubes previously charged with One-Inch Overbore fuel in C-Reactor, the minimum of these empirical relations was used to determine low trip "limits" as a function of tube power and inlet temperature. Using this approach, different trip limits were required for each tube power, whereas, the generalized concept requires only one limit independent of power level. Consequently, the generalized approach provides more easily administered trip limits and is thus, preferable.

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