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FLOW INSTABIITY IN A VERTICAL ANNULUS UNDER STEADY STATE AND TRANSIENT CONDITIONS (U)

by

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Flow Instability in a Vertical Annulus Under Steady State and Transient Conditions

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Abstract

Experimental data have been obtained for the occurrence of flow instability in a vertical annulus under steady state and transient down-flow conditions. The results show that the primary factor affecting the onset of flow instability is the Q_{ratio} parameter. In addition, it is shown that for steady state conditions good agreement exists between the single annulus data and single tube data based upon the same L/D ratio. The results also indicate that under transient operation the Q_{ratio} can be used as a stability criterion.

Nomenclature

c_p = specific heat at constant pressure, J/kg-K
D = hydraulic diameter of channel, m
G = mass velocity, kg/sec-m^2
L = heated length of channel
S_t = Stanton Number
T_{sat} = saturation, K
T_{inlet} = inlet temperature, K
T_{outlet} = temperature, K

Introduction

A comprehensive experimental program has been conducted to investigate flow instability in vertical channels under down-flow and sub-cooled boiling conditions. As part of that program, tests were conducted in a fixed L/D ratio circular annulus. The dimensions of the annulus and the flow direction, downward, were selected to address a particular reactor application.

Flow instability is an important consideration in the design of nuclear reactors because of the possibility of flow excursion during postulated accidents. For the purposes of this paper, the onset of flow instability point (OFI) is defined as the minimum in the demand curve (i.e., the channel's pressure drop versus flow-rate curve). This is commonly referred to as a Ledinegg flow instability (see figure 1). In an operational system with alternate flow paths, an increase in the pressure drop in one channel can cause the flow to be diverted to an alternate channel. If the process continued, the channel would eventually experience burnout. For controlled flow, where the channel flow-rate is maintained independent of the pressure drop, data can be obtained beyond the minimum point.

In addition to testing a vertical annulus, the overall program involved experiments in circular tubes with varying L/D ratios, heat input profiles, and loop flow arrangements.

Background

Marshek [1] presented the earliest results based upon tests in short vertical annuli with an unheated inner tube. Johnston [2] presented flow instability results for a vertical channel in down-flow with an L/D ratio of approximately 600. The inner tube was heated, and the outer tube was transparent. This author obtained demand curve data over a range of heat fluxes. The relationship between OFI (onset of flow instability) and OSV (onset of significant voiding) was also examined.

The experimental data base for non-annular geometry is considerably larger and mostly directed toward circular tubes. Dormer and Bergles [3] investigated the pressure drop in small diameter tubes under sub-cooled boiling conditions. These experiments were conducted with controlled flow so that data were obtained well beyond the minimum point. The authors correlated a large amount of data using the ratio of the pressure drop to the zero flux pressure drop versus the ratio of surface heat flux to the flux required to raise the bulk fluid temperature to the saturation temperature at the channel exit. Using these parameters, it was shown that the only remaining effect was geometry. Maulbetsch and Griffith [4] studied flow instability in small diameter high L/D ratio channels. They determined that during parallel flow operation excursive flow instability occurred when the pressure drop versus mass flow curve reached a minimum.

Whittle and Forgan [5] examined the pressure loss in rectangular and circular channels under sub-cooled boiling conditions. These investigators determined that for a given L/D ratio the minimum in the demand curve occurred at fixed values of the ratio of the channel temperature rise to the inlet sub-cooling, $(T_{outlet} - T_{inlet})/(T_{sat} - T_{inlet})$. Whittle and Forgan also determined that flow direction did not affect the flow-rate at which the minimum point (OFI) occurred.

Duffey and Hughes [6] developed an analytical model to describe static flow instability (Ledinegg) in vertical channels. They showed that a linear relationship exists between the OFI point and power density. In this paper, the authors developed a relationship for the flow-rate at the minimum point in the pressure drop curve based upon the frictional pressure drop and the buoyancy-induced pressure drop. These investigators assumed that the friction factor including the two-phase multiplier was independent of flow-rate.

Dougherty et al. [7-8] presented results for flow instability studies in vertical tubes with down-flow for L/D ratios from 100 to 150. These authors showed that the results could be correlated using a Q_{ratio} defined by equation (1). This ratio was the same as that developed by Dormer and Bergles [3]. The Q_{ratio} is a measure of the void production in the channel. Since voids are the cause of the minimum point in the demand, this parameter is useful in correlating results.

$$Q_{ratio} = q''A_h / \dot{m}c_p\,(T_{sat} - T_{inlet}) \qquad (1)$$

Dougherty et al. [9] presented results for non-uniformly heated vertical tubes.

These investigators determined that the flow-rate at which OFI occurred was only slightly affected by the local surface heat flux. The local heat flux was established by the product of the average flux and the tube power shape factor.

Fighetti et al. [10] presented results for the steady state testing of the same single annulus test section as presented here. This paper included results for a variety of operating conditions including controlled flow, controlled pressure, and non-symmetric heating. The author established that the Q_{ratio} parameter, defined in equation (1), was valid for the annular geometry. However, the OFI for the single annulus occurred at slightly lower flow-rates than those for a single tube with the same L/D. This change was attributed to the larger hydraulic diameter in the single annulus.

The present program involved down-flow experimental studies of a vertical single annulus with an L/D ratio of 261. Both the inner and outer tube of the annulus could be heated electrically.

Test Apparatus

The experimental facility for this test program consists of a flow loop, power system, and test section. Figure 2 presents a schematic of the flow loop and test section. Table 1 presents the physical characteristics of the test section The flow loop contains a number of bypass lines which were required to achieve a variety of test configurations. The present results will be limited to controlled pressure drop operation with a transient bypass.

Table 1 Test Section Physical Characteristics

Heater Material	Inconel 625
Heated Length	3.66 m
Inner Heater Inside Diameter	56.31 mm
Inner Heater Outside Diameter	59.61 mm
Outer Heater Inside Diameter	73.63 mm
Outer Heater Outside Diameter	76.91 mm

In the controlled pressure drop mode, the test section was connected in parallel with an unheated channel. For the transient tests, the bypass consisted of an unheated 100 mm diameter pipe connecting the inlet and exit plena. The resistance of the bypass line was adjusted by means of an air-operated valve to provide the desired flow diversion from the test section. The test procedure involved first setting the test conditions (test section exit pressure, test section inlet temperature, and surface heat flux) and then establishing steady state conditions. A quick acting valve on the bypass line was then opened, and flow was diverted to the bypass line. The magnitude of flow diversion was selected to provide test section flow-rates slightly above or below the steady state OFI conditions. Unfortunately, pre-test predictions based upon steady state results did not always result in flow excursion. The procedure was, therefore, modified to yield unstable data. In some tests, the test section exit pressure was reduced for the same magnitude bypass flow diversion, and in other cases, the exit pressure was maintained, and the bypass flow increased.

The test section consisted of two concentric inconel 625 tubes with a uniform wall thickness of 1.65 mm. The tube diameters were selected to simulate a specific reactor flow passage. Each tube was independently heated by a DC electric current. The center core of the inner heater tube contained ceramic plugs which were used to position the thermocouple instrumentation. In addition, thermocouples were cemented or brazed to the exterior of the outer heater. Taps for pressure measurements were located on the unheated portion of the test section just upstream and downstream of the heated section. The unheated portion was approximately 1.83 meters in length and consisted of concentric, thick-wall, nickel pipe. The test section geometry was maintained by a series of pins mounted on the inner heater, exterior stiffeners, and positioning pins from the outer heater to the inner heater.

The instrumentation of the test section and flow was extensive. A total of approximately 120 measurements were made at each test point. These measurements included flow-rate, absolute pressure, differential pressure, fluid temperature, current, voltage, and wall temperatures. The primary measurements associated with the determination of OFI were flow-rate, test section exit pressure, pressure drop, inlet temperature, and surface heat flux (test section current and voltage drop). During transient testing, approximately two dozen measurements were taken every 16 milliseconds. Table 2 presents the estimated uncertainty associated with the primary measurements.

Table 2 Uncertainty Analysis

Measurement	Estimated Uncertainty
Exit Pressure	1.6 % of full scale
Differential Pressure	1.5 % of full scale
Inlet Temperature	0.3 ^{o}C
Flow-rate	0.5 % of full scale
Power	0.44 % of full scale

Results and Discussion

Figure 3 presents a typical controlled flow demand curve for a test section inlet temperature of 50 ^{o}C. The minimum point in the pressure drop for each case is well defined. A demand curve is a useful operational tool because it identifies for a given set of conditions the point at which flow diversion would occur if a parallel flow path existed. The reactor normal operating conditions can then be controlled so that the OFI flow-rate will not be reached during a postulated accident.

To investigate correlations and trends, Dougherty et al. [8] have shown that the Q_{ratio} parameter defined in equation (1) is a more useful coordinate. The frictional pressure drop in the channel can be considered to be composed of a single phase component and a two-phase component. The former decreases as the flow-rate decreases. However, the two-phase pressure drop will increase as voids are formed with decreasing flow-rate. Since the Q_{ratio} relates the channel temperature rise to the inlet subcooling, it is a measure of the void production. Reducing the test section exit pressure with other parameters fixed will reduced the saturation and result in more voids and a large Q_{ratio}. Figure 4 presents all the controlled flow single annulus steady state heating results as a function of the Q_{ratio}. From this figure, it can be seen that the minimum point for all cases occurred at a Q_{ratio} of 0.96. In this figure, the lowest flux case has a very shallow minimum; however, a curve fit of the data shows that the Q_{ratio} at OFI is approximately 0.91. This is within 5% of the rest of the data.

Fighetti and Cheh [11] correlated data for a range of single tube tests in terms of the Q_{ratio} and L/D. Figure 5 presents their results and those obtained by Dougherty et al [8]. From this figure the importance of L/D can be seen.

$$Q_{ratio} = 1/(1 + D/(4.S_tL)) \qquad (2)$$

Saha and Zuber [12] predicted the onset of significant voiding (OSV) in terms of the Stanton number and Peclet number. Using an adiabatic calculation of the exit temperature, it is possible to represent the Q_{ratio} in terms of L/D and the Stanton number (see equation (2)). For Peclet numbers greater than 100,000 which is the case for all the data in figure 5, Saha and Zuber showed that OSV occurred for a Stanton number of 0.0065. The solid curve in figure 5 is a plot of equation (2) with Stanton number equal to 0.0065 and represents the Q_{ratio} at OSV. Since the curve fits the data quite well, the results show that OFI and OSV at least for down-flow occur at the approximately the same flow-rate. Using the L/D for the single annulus, the Q_{ratio} calculated from equation (2) is 0.87 with Stanton number equal to 0.0065. The average minimum point for the single annulus data occurs at a slightly higher ratio (0.96); however, the OFI point is still within 10% of the predicted value based upon equation (2). For comparison the single tube data for the same L/D indicates an OFI at a Q_{ratio} of 0.906. The data presented in figure 5 covers a large L/D range but were restricted to one heated length, and, therefore, no diameter effects were investigated. Dormer and Bergles [3] showed that the primary factor affecting the minimum point was the L/D ratio; however, they also determined that diameter had a secondary effect. The current results appear to agree with this observation. The hydraulic diameter of the single annulus is approximately 14 mm, compared to 9 mm for the single tube data with the same L/D.

Figure 6 presents a the test section flow-rate versus time for a series of four tests in which the flow diversion through the bypass was held constant and the exit pressure was reduced to cause flow instability. For test SAT0612M, the exit pressure was 379 kPa. The test section flow-rate dropped to the expected value after the bypass was opened and maintained this value for approximately 10 seconds, at which time the test was terminated. In test SAT0612O, the exit pressure was reduced to 365 kPa. In this case, the test section flow-rate dropped to the bypass diversion setting; however, it then continued to drop until the test was terminated by a low flow power trip. The selection of the low flow-rate trip setting was somewhat arbitary; however, the level was always well below the test section flow-rate expected after the bypass was opened. Prevention of damage to the test section was the main concern. A total of thirty five transient tests were conducted; however, only six resulted in flow instability. The test section pressure drop results oscillated violently due to the presence of subcooled boiling as can be seen in figure 7. Figure 8 presents the wall temperature history at several locations along the channel for test SAT0612O. This particular test experienced significant flow diversion after the bypass was opened; however, the wall temperature rose only slightly in proportion to the channel flow decrease.

The applicability of the Q_{ratio} to transient conditions was also investigated. Figures 9, 10, and 11 present results from several tests involving stable and unstable conditions. Each figure also presents the steady state OFI Q_{ratio}. Tests in which the Q_{ratio} was not exceeded were stable. Depending upon the degree to which the Q_{ratio} was exceeded determined whether instability or flow diversion occurred. In figure 10, the conditions for test SAT0612M resulted in a Q_{ratio}, after bypass opening, of less than 10% greater than the steady state limit, and the test section did not become unstable. However, for tests SAT0612N and SAT0612O, the Q_{ratio} after initiation of the transient was more than 10% greater than the steady state value and flow instability occurred. For these discussions, flow instabilty is identified by a power tripped within ten seconds of the bypass opening. As noted earlier, all power trips were caused by low flow conditions in the test section.

Conclusions

Down-flow experimental flow instability data have been obtained in a single annulus under controlled flow conditions and controlled pressure drop conditions. The following conclusions can be drawn from these results:

Based upon steady state results, the experimental data are well correlated using the Q_{ratio} , defined by equation (1), parameter.

The agreement between the calculated OSV Q_{ratio} and the measured OFI Q_{ratio} shows that for the present flow arrangement OSV and OFI occur at approximately the same flow-rate.

The quick opening of a bypass line, which provides an alternate flow path, can result in the test section becoming unstable and experiencing flow diversion.

For conditions where the steady state OFI Q_{ratio} was not exceeded, flow instability did not occur. Exceeding the steady state OFI Q_{ratio} by 10% or less will not result in an unstable case.

The Q_{ratio} at OSV agrees very well with the measured Q_{ratio} at OFI. This indicates that at least for down-flow conditions, the onset of significant voiding and the onset of flow instability occur at the same flow-rate.

Acknowledgement

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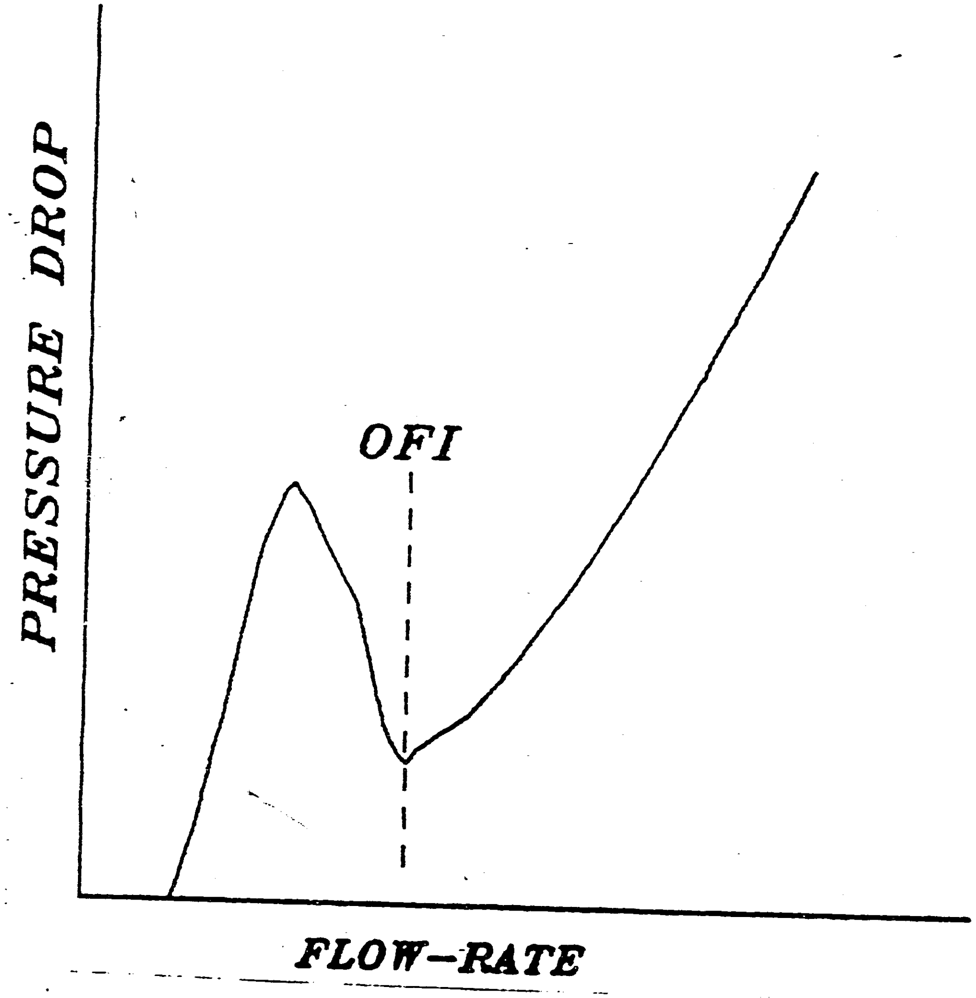

Fig 1

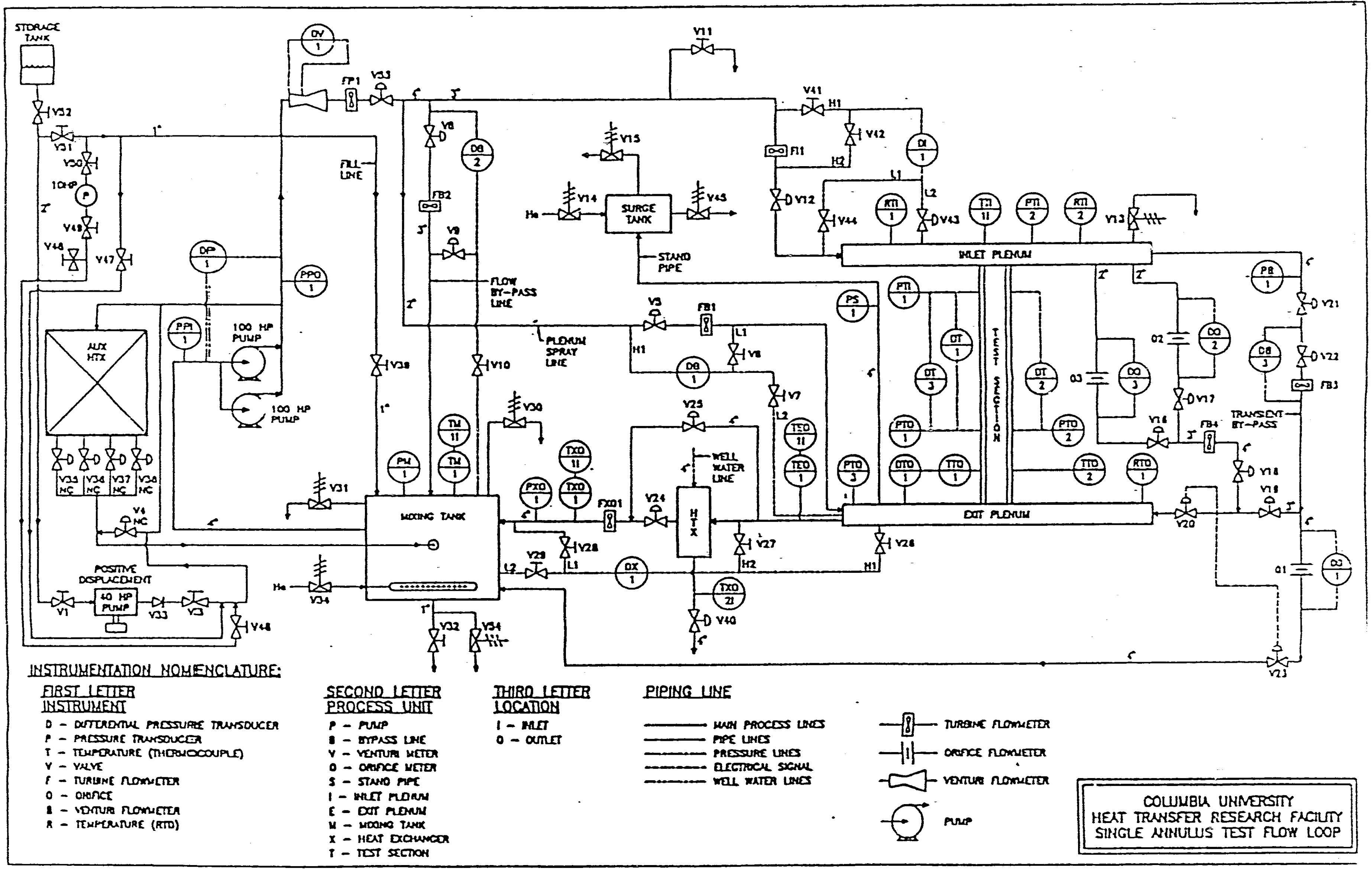
STORAGE TANK
FILL LINE
FLOW BY-PASS LINE
PLENUM SPRAY LINE
STAND PIPE
SURGE TANK
He
AUX HTX
100 HP PUMP
100 HP PUMP
10HP
POSITIVE DISPLACEMENT
40 HP PUMP
MIXING TANK
WELL WATER LINE
HTX
INLET PLENUM
EXIT PLENUM
TEST SECTION
TRANSIENT BY-PASS
V1 V3 V4 NC V5 V6 V7 V8 V9 V10 V11 V12 V13 V14 V15 V16 V17 V18 V19 V20 V21 V22 V23 V24 V25 V26 V27 V28 V29 V30 V31 V32 V33 V34 V35 NC V36 NC V37 NC V38 NC V40 V41 V42 V43 V44 V45 V47 V48 V49 V50 V51 V52 V53 V54
DV 1 FP1 DB 2 FB2 FB1 DB 1 FI1 DI 1 FX01 DX 1 FB4 FB3 DB 3 PB 1 DO 1 DO 2 DO 3 O1 O2 O3
DP 1 PPO 1 PPI 1 PM 1 TM 11 TM 1 PXO 1 TXO 11 TXO 1 TXO 21 TEO 11 TEO 1 PTO 3 PS 1 PTI 1 DT 1 DT 3 DT 2 PTO 1 PTO 2 DTO 1 TTO 1 TTO 2 RTO 1 RTI 1 TTI 11 PTI 2 RTI 2
H1 H2 L1 L2 1" 2" 3"
INSTRUMENTATION NOMENCLATURE:
FIRST LETTER INSTRUMENT
D – DIFFERENTIAL PRESSURE TRANSDUCER
P – PRESSURE TRANSDUCER
T – TEMPERATURE (THERMOCOUPLE)
V – VALVE
F – TURBINE FLOWMETER
O – ORIFICE
B – VENTURI FLOWMETER
R – TEMPERATURE (RTD)
SECOND LETTER PROCESS UNIT
P – PUMP
B – BYPASS LINE
V – VENTURI METER
O – ORIFICE METER
S – STAND PIPE
I – INLET PLENUM
E – EXIT PLENUM
M – MIXING TANK
X – HEAT EXCHANGER
T – TEST SECTION
THIRD LETTER LOCATION
I – INLET
O – OUTLET
PIPING LINE
MAIN PROCESS LINES
PIPE LINES
PRESSURE LINES
ELECTRICAL SIGNAL
WELL WATER LINES
TURBINE FLOWMETER
ORIFICE FLOWMETER
VENTURI FLOWMETER
PUMP
COLUMBIA UNIVERSITY
HEAT TRANSFER RESEARCH FACILITY
SINGLE ANNULUS TEST FLOW LOOP

Figure 2

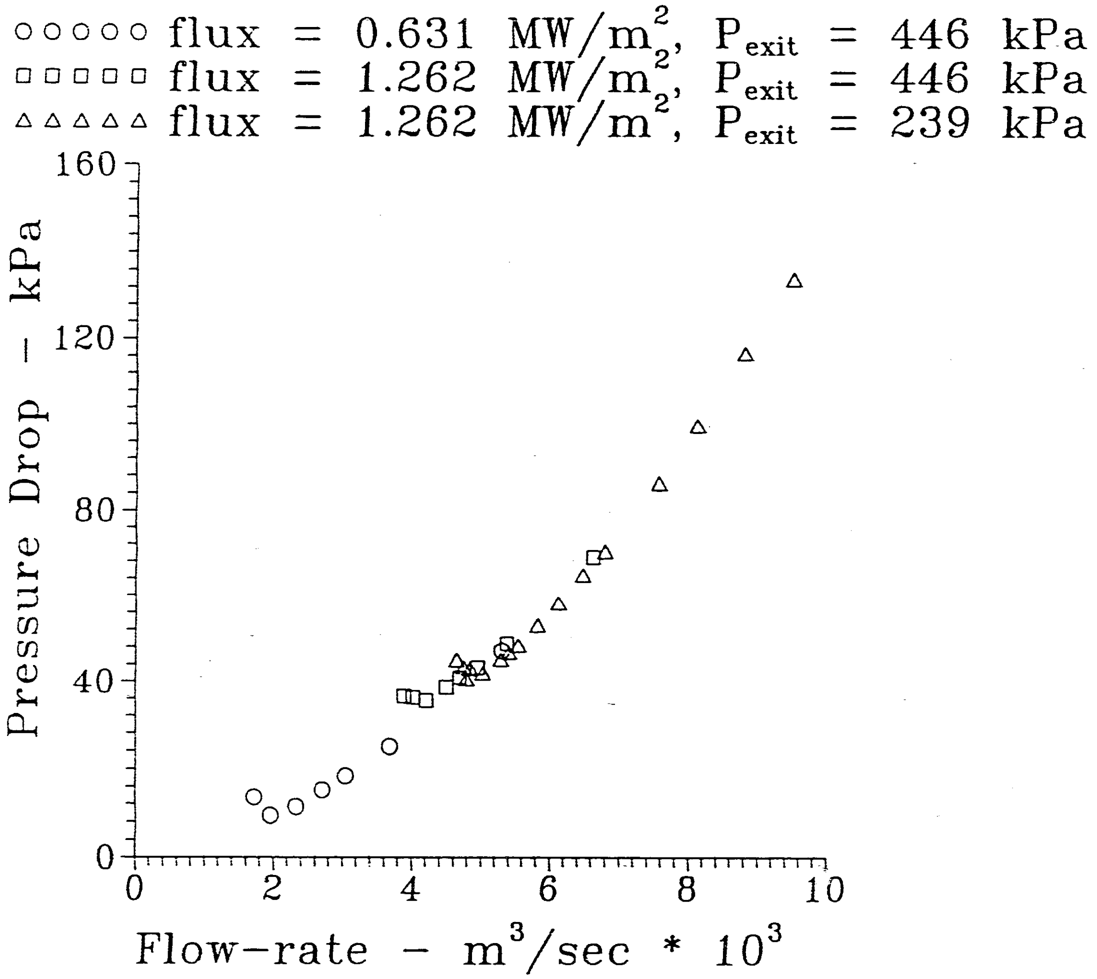

Figure 3 Pressure drop vs. flow-rate single annulus test section rev. 4 T_{inlet} = 25°C, symmetric heating

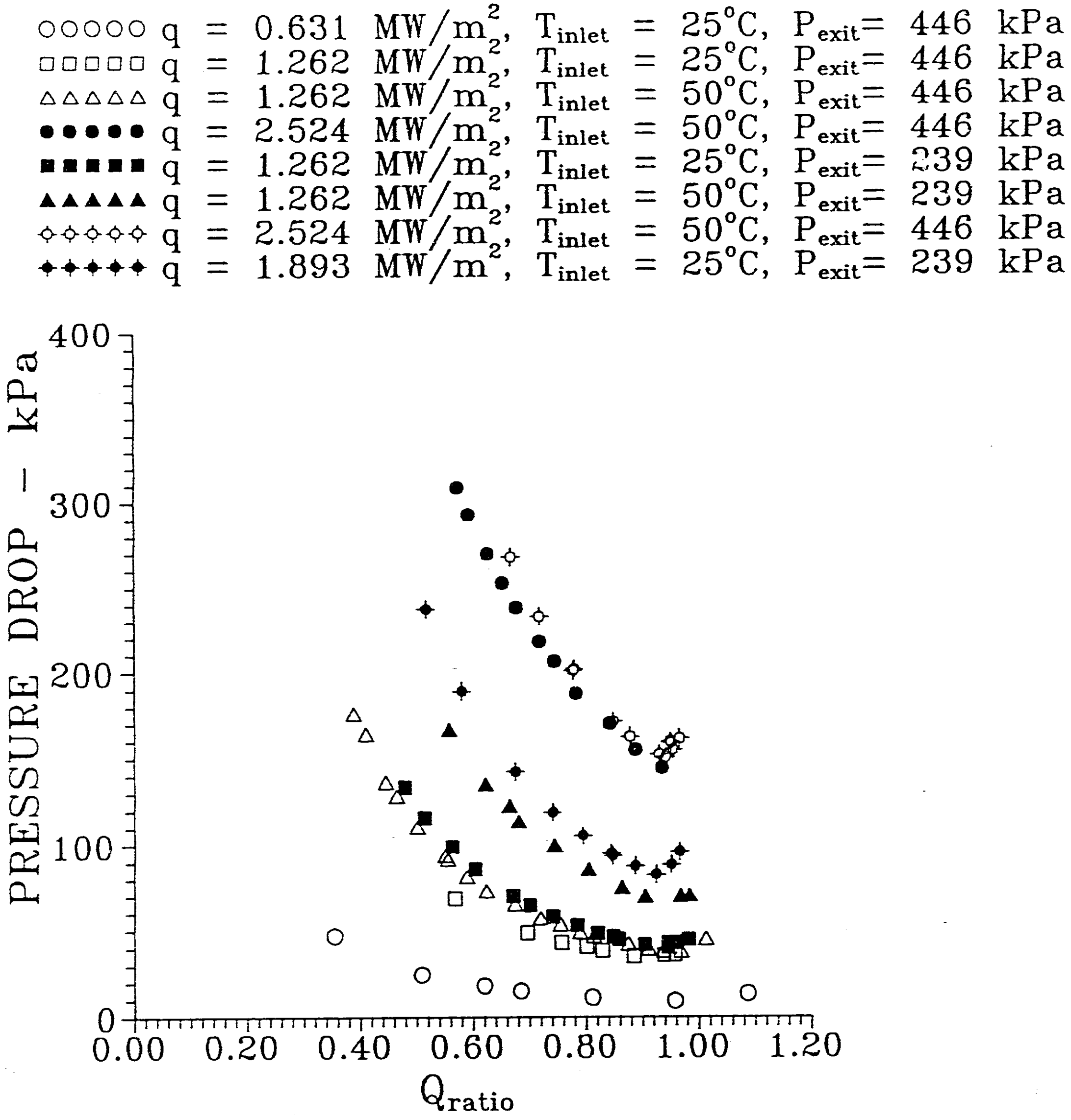

Figure 4 Pressure drop versus Q_{ratio} single annulus test section rev. 4 symmetric heating

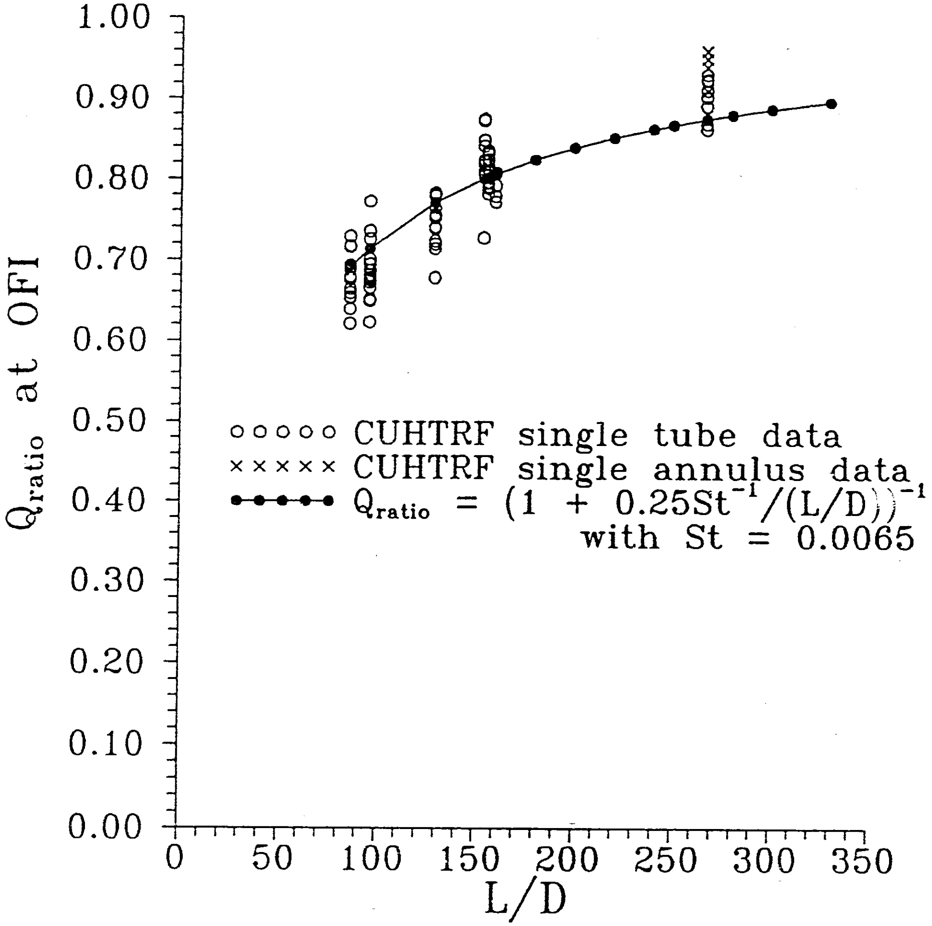

Figure 5 Q_{ratio} at OFI vs. L/D

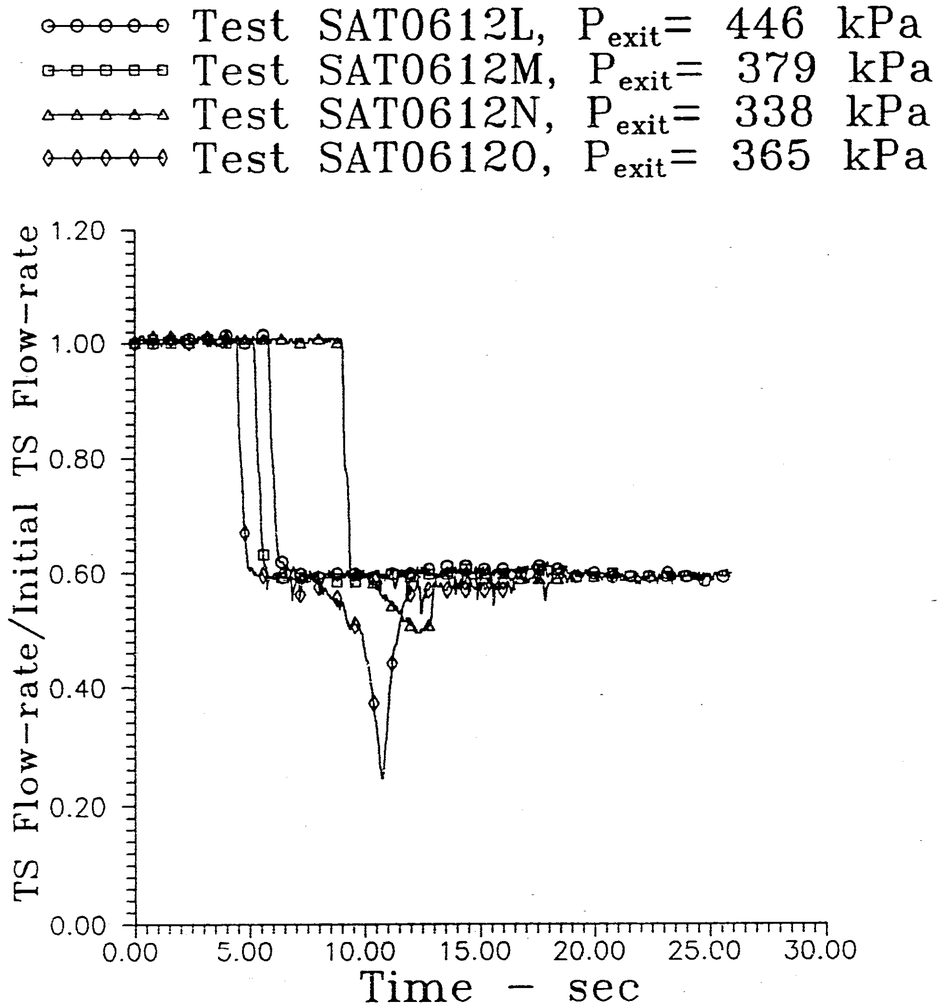

Figure 6 Normalized flow-rate versus time flux = 1.893 MW/m^2, T_{inlet}= 25°C

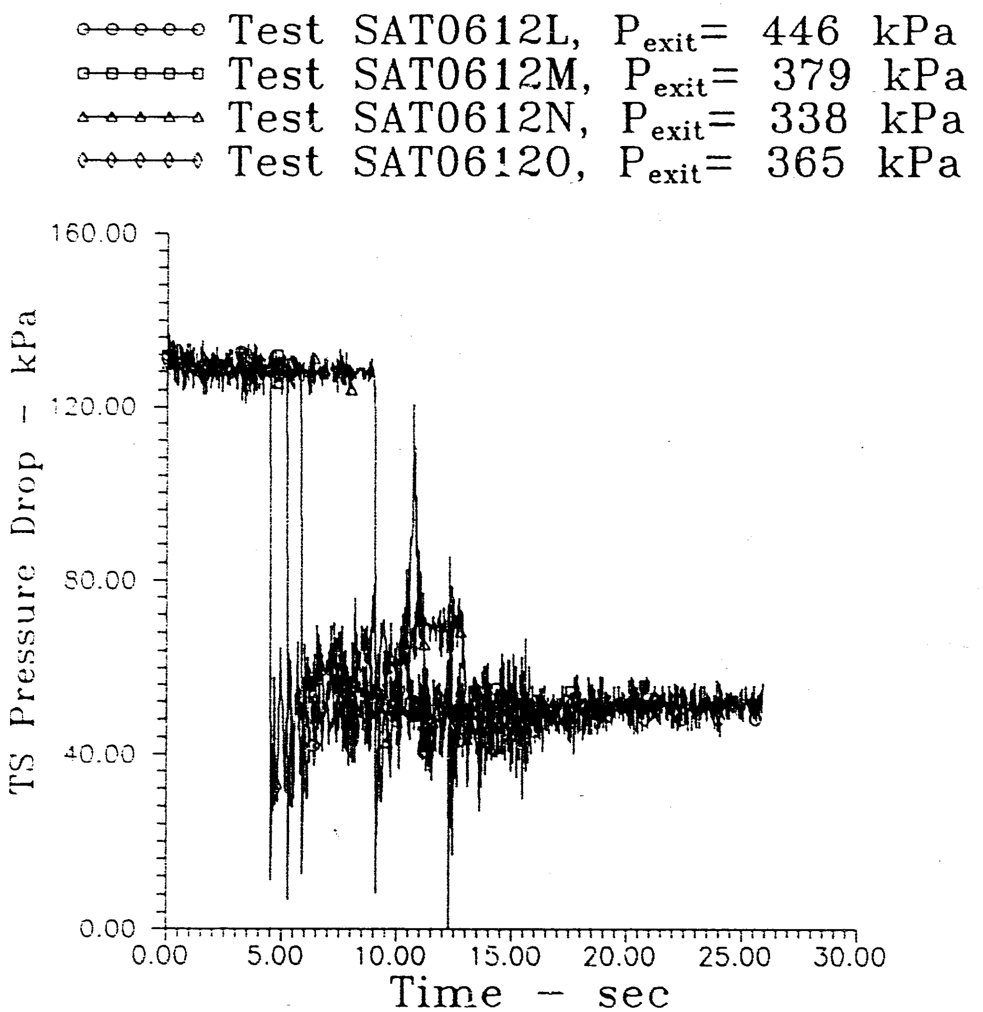

Figure 7 Pressure drop versus time
flux = 1.893 MW/m^2, T_{inlet}= 25°C

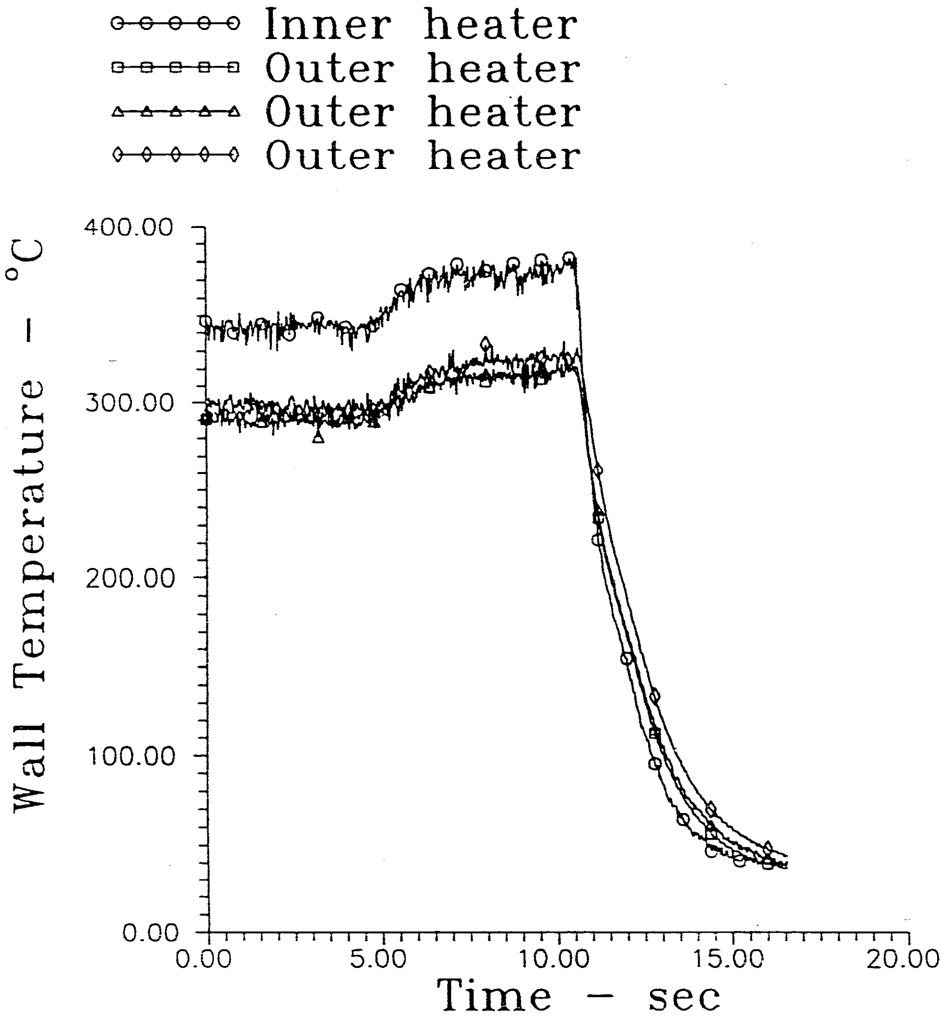

Figure 8 Wall temperature versus time
flux = 1.893 MW/m^2, T_{inlet}= 25°C
P_{exit}= 365 kPa

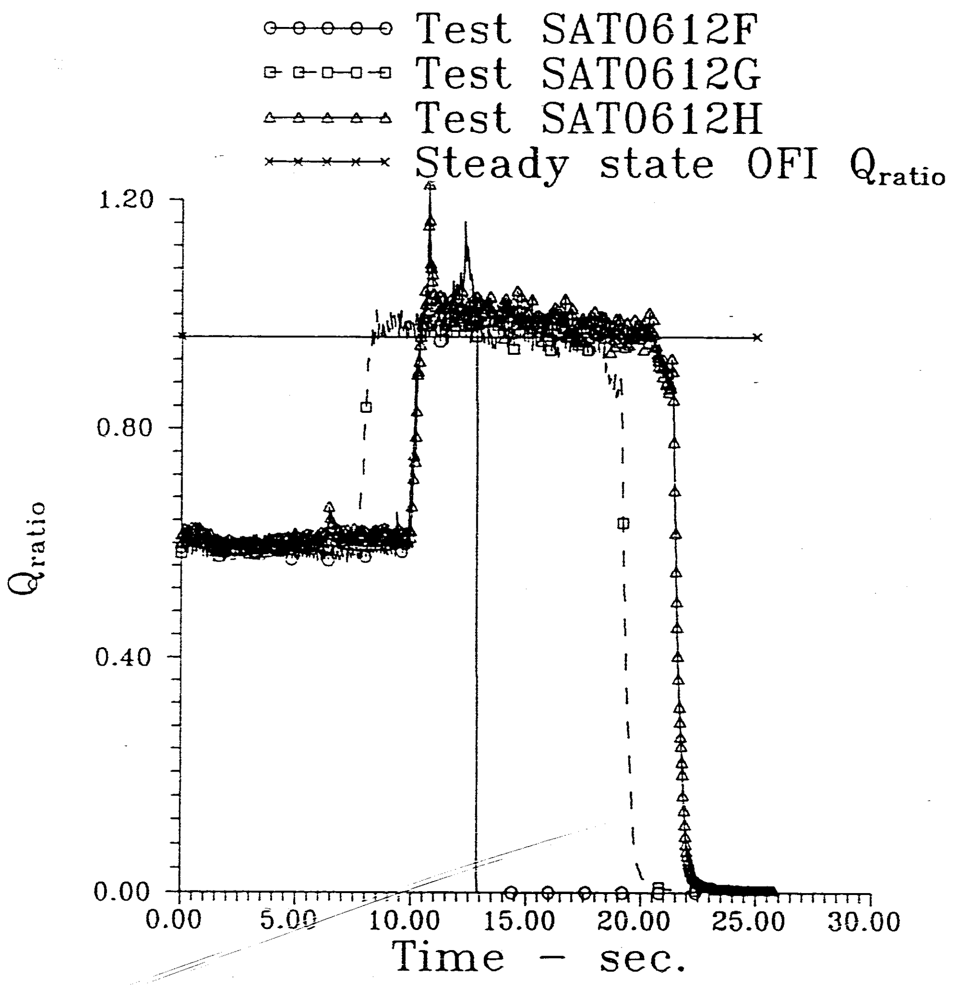

Figure 9 Single annulus transient, flux = 1.262 Mw/m^2, T_{inlet}= 50°C

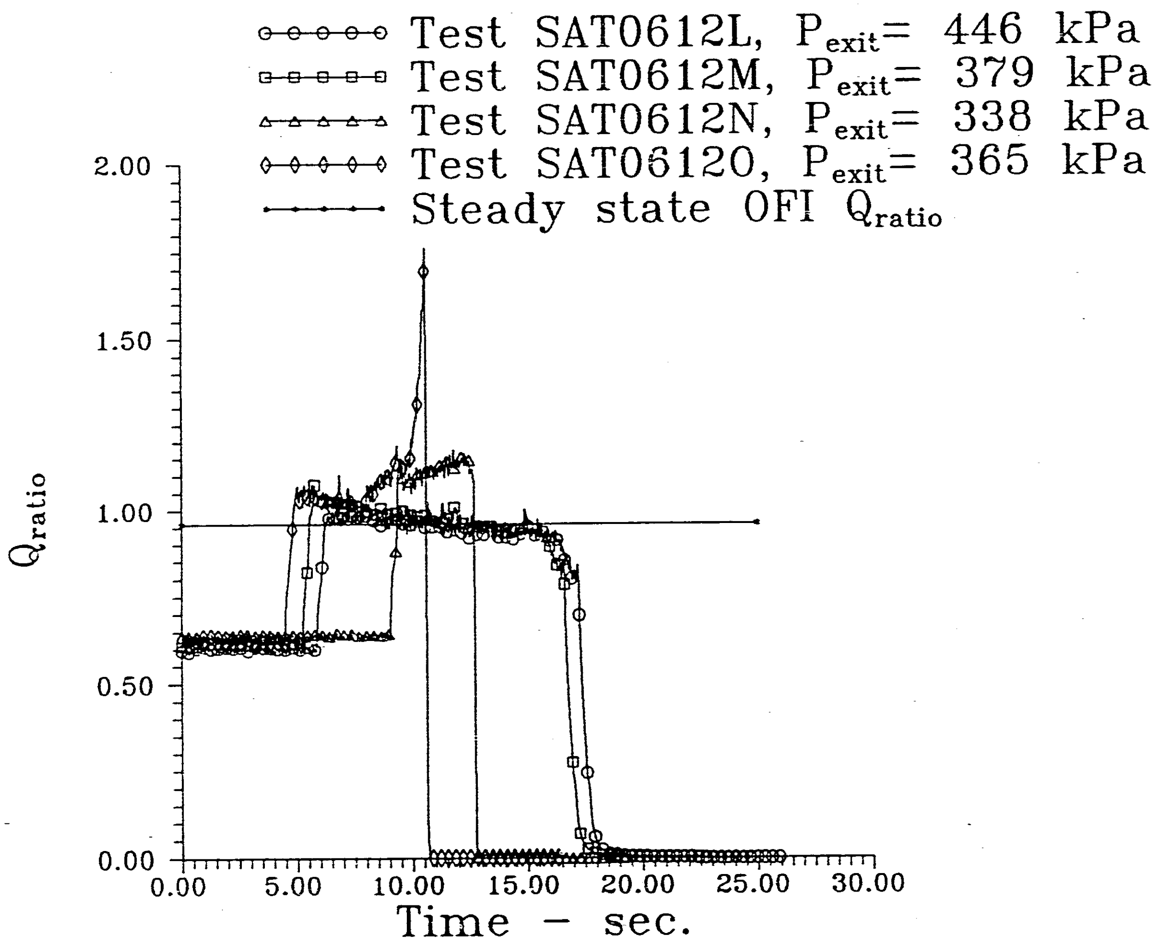

Figure 10 Single annulus transient, flux = 1.893 Mw/m^2, T_{inlet} = 25°C

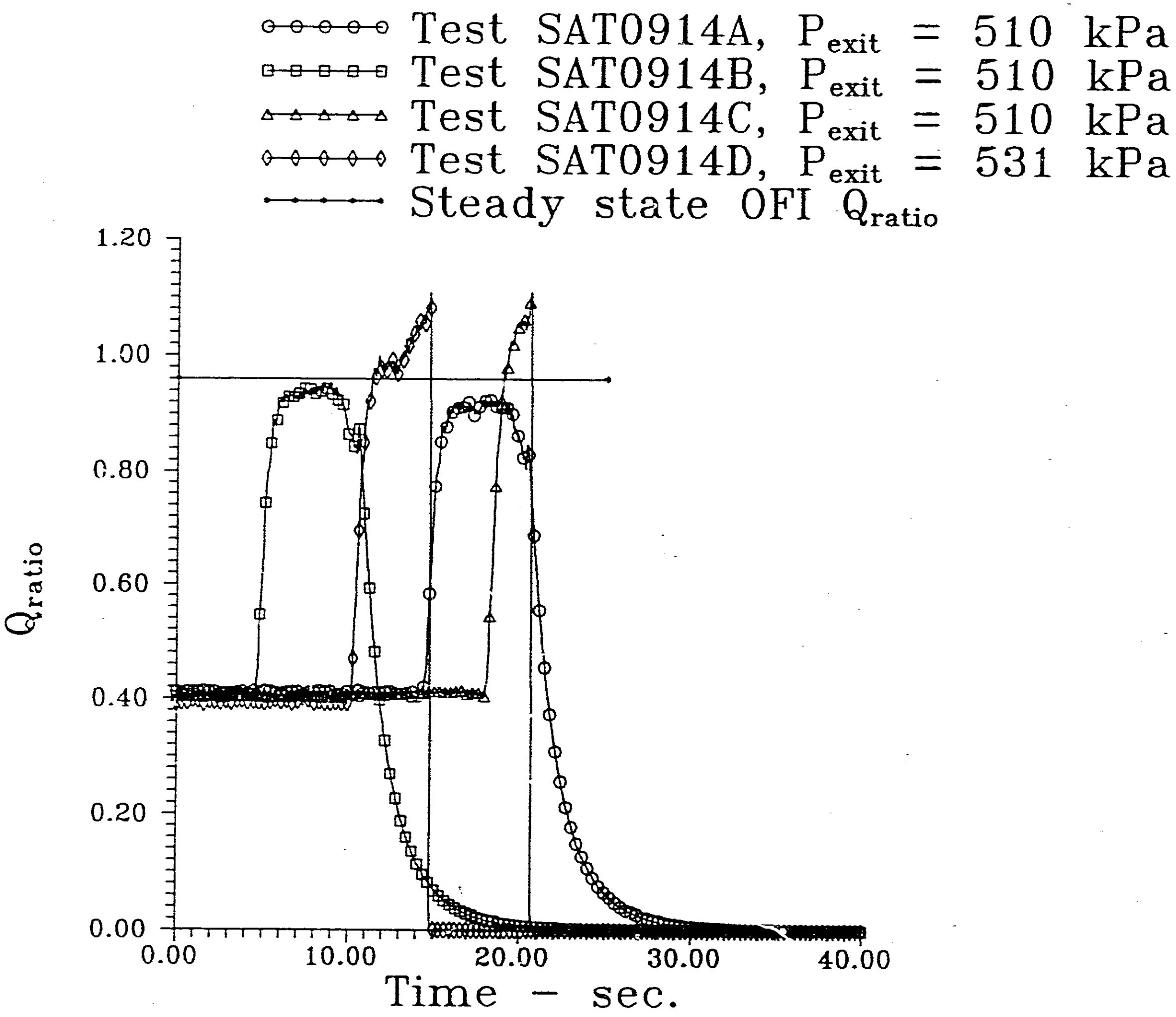

Figure 11 Single annulus transient, flux = 1.893 Mw/m^2, T_{inlet}= 25°C

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