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COMPARISON OF BABELLI-ISHII FLOW INSTABILITY CRITERION WITH 75 TESTS DONE BY WHITTLE AND FORGAN

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ABSTRACT

The maximum operating power of research reactors is usually determined by flow instability. According to the Babelli-Ishii flow instability criterion, the flow in a channel is *stable* if the ratio of the Subcooling number to the Zuber number N_{sub}/N_{zu} on the left side of the following equation is greater than the quantity on the right hand side, and *unstable* if the ratio N_{sub}/N_{zu} is smaller.

$$\frac{N_{sub}}{N_{zu}} = \left(\frac{L_{nvg}}{L}\right)_{critical} + \frac{A_F}{\zeta_H L} \begin{Bmatrix} 0.0022\,Pe & \text{if} & Pe < 70000 \\ 154 & \text{if} & Pe > 70000 \end{Bmatrix}$$

This criterion was verified using a program developed to apply the criterion and a simpler form of this criterion to 75 tests (having uniform heat flux) reported by Whittle and Forgan. The comparison between the measured and calculated coolant inlet velocities at the onset of flow instability in these tests is good. The mean error in the inlet velocities calculated by the main criterion or its simpler form is 0.38 m/s or 0.36 m/s (higher). Both criteria have been implemented in the PLTEMP/ANL code. The derivation of the correlation, all the test data, and the comparison will be presented.

1. Introduction

The maximum operating power of research reactors is usually determined by Ledinegg flow instability in which a small random decrease in flow leads to a large decrease in flow, i.e., a flow excursion (all-vapor flow) causing a rapid heatup of the heater material, ending in its melting and failure if left unprotected [1]. This instability is due to the S-shape of the flow versus pressure drop characteristic of a boiling heated coolant channel that operates at low pressures (1 to ~20 bar) [2]. At higher pressures (> ~60 bar), the flow versus pressure drop characteristic is not S-shaped and hence there is no Ledinegg instability. To predict the onset of this instability in research reactors, some criteria are available, e.g., the Whittle and Forgan criterion [3], and the ORNL criterion [4]. In 2001, Babelli and Ishii reported another criterion [5] for flow instability

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based on the Subcooling number and the Zuber number which is the subject of this work.

In this work, two forms of the Babelli-Ishii flow instability criterion were verified using a program developed to apply the criterion to the 75 flow instability tests (using uniform heat flux) reported by Whittle and Forgan [3]. The comparison of the measured and calculated (using either form of the criterion) coolant inlet velocities at the onset of flow instability in these tests shows that both forms predict slightly higher inlet velocities. Both the main criterion, Eq. (8), and the simpler criterion, Eq. (9), have been implemented in the PLTEMP/ANL code [6] for steady-state thermal hydraulic analysis of research reactors.

1. Derivation of Babelli-Ishii Criterion for Flow Instability

Babelli and Ishii obtained Eq. (8) given below as a criterion for excursive flow instability due to boiling inception in a coolant channel heated by a *uniform* wall heat flux, based on their theoretical and experimental work, and the experimental data of Dougherty [7]. The criterion is applicable to both downward and upward flows. By heat balance, the coolant flow rate times the enthalpy change from channel inlet to the net vapor generation (NVG) position (defined as the point where bubble departure from the channel wall is initiated[8]) equals the power generated in the fuel and transferred to the coolant over the non-boiling length, $q_w^{''} \zeta_H L_{nvg}$.

$$\left(h_{nvg} - h_{in}\right) = \frac{q_w^{''} \zeta_H L_{nvg}}{\rho_{in} V_{in} A_F} \tag{1}$$

See nomenclature given at the end. Assume the coolant pressure P_{in} at the start of the heated section to be a *reference pressure* for calculating coolant subcooling at inlet and at the NVG position. Then the enthalpy difference between any pair of axial positions exactly equals the corresponding subcooling difference. The inlet subcooling $\Delta h_{in} = h_f(P_{in}) - h_{in}$, the subcooling at the NVG position $\Delta h_{nvg} = h_f(P_{in}) - h_{nvg}$, and the left hand side of Eq. (1) is

$$(h_{nvg} - h_{in}) = \Delta h_{in} - \Delta h_{nvg} \tag{2}$$

If the coolant pressure at the NVG position (instead of the pressure P_{in} at the start of the heated section) were used as the system *reference pressure*, then inlet subcooling $\Delta h_{in} = h_f(P_{nvg}) - h_{in}$, the subcooling at the NVG position $\Delta h_{nvg} = h_f(P_{nvg}) - h_{nvg}$, and Eq. (2) remains unchanged. With this assumption, the subcooling at the NVG position is accurate and the subcooling at inlet is approximate, whereas with the former assumption, the subcooling at the NVG position is approximate and the subcooling at inlet is accurate (the reverse is true). Substituting Eq. (2) into Eq. (1), and solving for the non-boiling length L_{nvg}, one gets

$$\frac{L_{nvg}}{L} = \frac{\rho_{in} V_{in} A_F \left(\Delta h_{in} - \Delta h_{nvg}\right)}{q_w^{''} \zeta_H L} \tag{3}$$

Equation (3) is Eq. (2) of the Babelli and Ishii paper [5]. Using the Subcooling number and Zuber number defined below by Eqs. (5) and (6), Babelli and Ishii recast Eq. (3) as

$$\frac{N_{sub}}{N_{zu}} = \frac{L_{nvg}}{L} + \frac{A_F}{\zeta_H L}\left\{\frac{\rho_{in} V_{in} \Delta h_{nvg}}{q''_w}\right\} \tag{4}$$

where

N_{sub} = Subcooling number = $\dfrac{\Delta h_{in}}{h_{fg}} \dfrac{(\rho_{f,nvg} - \rho_{g,nvg})}{\rho_{g,nvg}}$ (5)

N_{zu} = Zuber number = $\dfrac{q''_w \zeta_H L}{\rho_{in} V_{in} A_F h_{fg}} \dfrac{(\rho_{f,nvg} - \rho_{g,nvg})}{\rho_{g,nvg}}$ (6)

N_{sub}/N_{zu} = Ratio of Subcooling number to Zuber number = $\dfrac{\rho_{in} V_{in} A_F \Delta h_{in}}{q''_w \zeta_H L}$ (7)

The ratio inside the curly brackets on the right hand side of Eq. (4) is obtained from the Zuber correlation for the net vapor generation. For an accurate application of the Zuber correlation, it is preferred that the system *reference pressure* is assumed equal to the coolant pressure at the NVG position (rather than the pressure P_{in} at the start of the heated section), making the value of the subcooling at the NVG position accurate. Substituting the value of $\rho_{in} V_{in} \Delta h_{nvg} / q''_w$ in Eq. (4) from Eq. (6) of the Babelli and Ishii paper [5] which is basically the Saha-Zuber correlation [8] for net vapor generation, one gets Eq. (8), the desired flow instability criterion. The channel flow is *stable* if the ratio N_{sub}/N_{zu} on the left hand side of Eq. (8) is greater than the quantity on the right hand side, and *unstable* if the ratio N_{sub}/N_{zu} is smaller.

$$\frac{N_{sub}}{N_{zu}} = \left(\frac{L_{nvg}}{L}\right)_{critical} + \frac{A_F}{\zeta_H L}\begin{Bmatrix} 0.0022\,Pe \quad \text{if} \quad Pe < 70000 \\ 154 \quad \text{if} \quad Pe > 70000 \end{Bmatrix} \tag{8}$$

where

$(L_{nvg}/L)_{critical}$ = Critical value of the dimensionless non-boiling length. Based on experimental data for freon-113 and water, it is plotted in Fig. 4 of Ref. [5] as function of the Subcooling number, and the same data is tabulated here in Table 1.

Table 1. Critical Value of Dimensionless Non-boiling Length $(L_{nvg}/L)_{critical}$ as Function of Subcooling Number

Subcooling Number, N_{sub}	Experimental Value of $(L_{nvg}/L)_{critical}$		Subcooling Number, N_{sub}	Experimental Value of $(L_{nvg}/L)_{critical}$	
	Lower Limit	Upper Limit		Lower Limit	Upper Limit
2.69	0.0232	0.0232	43.03	0.594	1.297
5.38	0.0684	0.414	53.78	0.711	1.222
8.07	0.141	0.594	64.54	0.905	1.083
10.76	0.256	0.756	69.92	1.00	1.00
21.51	0.440	1.083	160.00	1.00	1.00
32.27	0.527	1.222			

In the case of *upward flow*, the quantity is calculated as shown in Eq. (8) given above. However, in the case of *downward flow*, Babelli and Ishii suggest (based on the experimental data of Johnston [9]) that the quantity is always 154.
A simpler criterion for flow instability due to boiling inception may also be inferred from Fig. 5 of Ref. [5] which is a plot on the N_{sub}-N_{zu} plane of several flow instability test data for Freon-113 and water. The plot suggests the following simple criterion for flow instability.

$$\frac{N_{sub}}{N_{zu}} = \begin{cases} > 1.36 & \text{clearly stable} \\ < 1.36 \text{ to } 1.0 & \text{may be stable or unstable} \\ < 1.0 & \text{clearly unstable} \end{cases} \tag{9}$$

2 Application of Flow Instability Criterion of Equation (8) to Whittle and Forgan Tests

The Babelli-Ishii criterion for the onset of flow instability (OFI) was applied to all 75 tests performed by Whittle and Forgan at a uniform heat flux [3]. The test data used in the present calculation of these 75 tests are listed in Table 2. Eight tests (Test Numbers 17 to 24) performed in test section 1A using non-uniform heat fluxes were not analyzed. A program was developed to calculate for each test, the coolant exit temperature, single-phase pressure drop, Subcooling number, Zuber number, and other needed quantities, for an *assumed* coolant inlet velocity. The program found the coolant inlet velocity at OFI by iteration, as described below.

The coolant inlet velocity was varied in steps of 0.001 m/s from a suitable low value to a higher value, in search of the inlet velocity at which the ratio N_{sub}/N_{zub}, the left hand side of Eq. (8) becomes higher than the right hand side, i.e., the flow becomes stable. The inlet velocity just before the flow becomes stable is the inlet velocity at OFI. The inlet velocity at OFI was calculated for each test, and the results are shown in Table 2. The results for all 75 tests remain unchanged irrespective of whether the upper or the lower limit of $(L_{nvg} / L)_{critical}$ (given in Table 1) is used in the calculation. This is because the two limits exist only if the Subcooling number is less than 69.92. However, in all the 75 tests the Subcooling number is greater than 69.92, as shown in Table 2.

The measured flow rate (W) and inlet velocity at OFI (V_{in}), found from the measured exit coolant temperature using the heat balance Eq. (10), are also shown in Table 2. The exit temperature was itself calculated from the measured ratio $r = (T_{sat,out} - T_{out})/(T_{out} - T_{in})$ reported by Whittle and Forgan [3], using Eq. (11). The measured flow rates at OFI thus obtained were found to be in agreement with those obtained by A. P. Olson using a different approach during an earlier analysis of these tests [6].

$$\rho_{in} V_{in} A_F = W = \frac{Q}{h(P_{out}, T_{out}) - h(P_{in}, T_{in})} \tag{10}$$

$$T_{out} = \frac{T_{sat,out} + r\,T_{in}}{1+r} \tag{11}$$

A statistical analysis was done to find the mean and the standard deviation of the difference between the calculated and measured inlet velocities at OFI (calculated – measured). The mean error was 0.384 m/s with a standard deviation of 0.242 m/s. Figure 1 shows a comparison of the calculated versus the measured coolant inlet velocity at OFI. The data points are generally above the line of slope 1, indicating that the criterion is conservative. The mean value of the Whittle and Forgan parameter η at OFI is found to be 37.55 with a standard deviation of 3.16.

3. Application of Flow Instability Criterion of Eq. (9) to Whittle and Forgan Tests

The simple flow instability criterion of Eq. (9) was also applied to the same 75 tests reported by Whittle and Forgan. The coolant inlet velocity was varied in steps of 0.001 m/s from a suitable low value to a higher value, in search of the inlet velocity at which the ratio N_{sub}/N_{zub} becomes greater than 1.36, i.e., the flow becomes stable according to Eq. (9). The inlet velocity just before the ratio N_{sub}/N_{zub} becomes greater than 1.36 is the inlet velocity at OFI. The inlet velocity at OFI was calculated for each test. Figure 2 shows a comparison of the calculated versus the measured coolant inlet velocity at OFI. A statistical analysis was done to find the mean and the standard deviation of the difference between the calculated and measured inlet velocities (calculated – measured). The mean error was 0.363 m/s with a standard deviation of 0.319 m/s. Again, the mean error is positive, implying that the criterion is conservative.

For the 12 tests done by Whittle and Forgan in their test section number 3 (with $L/D_H = 190.9$), the simple criterion finds the parameter η at OFI to be about 68.2 which is about two times the values of η at OFI found for all other tests. This is because the parameter η at OFI *calculated based on Eq. (9)* equals $0.36(L/D_H)$, as explained in Section 4 below.

4. Value of Parameter η According to the Simple Instability Criterion

The Whittle and Forgan parameter η at OFI is defined by Eq. (12). Here, the ratio of temperature differences, $\Delta T_{sub,o}/\Delta T_c$ equals the ratio of the corresponding enthalpy differences, $\Delta h_{out}/\Delta h_c$.

$$\eta = \frac{\Delta T_{sub,o}}{\Delta T_c}\frac{L}{D_H} = \frac{\Delta h_{out}}{\Delta h_c}\frac{L}{D_h} \quad \text{at OFI} \qquad (12)$$

In the simple instability criterion of Eq. (9), the ratio N_{sub}/N_{zub} equals 1.36 at OFI. The ratio N_{sub}/N_{zub} is defined by Eq. (7) whose numerator can be written as $W\Delta h_{in}$, and the denominator is the total heat transferred, Q, to the coolant in the channel. So the ratio N_{sub}/N_{zub} equals $W\Delta h_{in}/Q$. Noting that Q/W is the coolant enthalpy rise in the channel Δh_c , the ratio N_{sub}/N_{zub} equals $\Delta h_{in}/\Delta h_c$ and this ratio equals 1.36 at OFI based on the criterion of Eq. (9) as shown in Eq. (13).

$$\frac{N_{sub}}{N_{zub}} = \frac{W\Delta h_{in}}{Q} = \frac{\Delta h_{in}}{\Delta h_c} = 1.36 \qquad \text{at OFI} \qquad (13)$$

Thus, $\Delta h_{in} = 1.36\ \Delta h_c$ at OFI. Noting that $\Delta h_{in} = \Delta h_{out} + \Delta h_c$, one gets $\Delta h_{out} = 0.36\ \Delta h_c$, and using this value of Δh_{out} in Eq. (12), one gets from Eq. (12) the parameter $\eta = 0.36\ L/D_H$. It means that the Whittle and Forgan parameter η at OFI based on the simple flow instability criterion of Eq. (9) varies linearly with the heated length-to-hydraulic diameter ratio. That is why the parameter η at OFI calculated based on Eq. (9) for Test Numbers 63 to 74 (with L/D_H = 190.9) is about 68.2 . The values of parameter η at OFI for Test Numbers 63 to 74 are about twice the values of η at OFI found for all other tests. The reason is that Test Numbers 63 to 74 were performed in a test section having an L/D_H nearly twice the L/D_H in all other tests (see L/D_H of all tests in Table 2).

5. Conclusions

The Babelli-Ishii flow instability criterion of Eq. (8) and the simple criterion of Eq. (9) were applied to 75 Whittle and Forgan tests. The comparison of the calculated and measured coolant inlet velocities at OFI in these tests shows that both criteria are slightly conservative. Both criteria are implemented in the PLTEMP/ANL V3.4 code [6].

Nomenclature

A_F = Flow area of channel, m^2
C_p = Specific heat of the coolant, J/kg-°C
D_h = Hydraulic diameter based on the *wetted* perimeter of the channel, m
D_H = Hydraulic diameter based on the *heated* perimeter of the channel, m
$h(P,T)$ = Liquid coolant enthalpy as a function of coolant pressure P and temperature T, J/kg
h_{in} = Coolant enthalpy at the heated length inlet = $h(P_{in}, T_{in})$, J/kg
h_{out} = Coolant enthalpy at the heated length exit = $h(P_{out}, T_{out})$, J/kg
$h_{f,in}$ = Saturated liquid enthalpy at the heated length inlet pressure = $h(P_{in})$, J/kg
$h_{f,out}$ = Saturated liquid enthalpy at the heated length exit pressure = $h(P_{out})$, J/kg
$h_{fg}(P)$ = Latent heat of vaporization as a function of coolant pressure P
Δh_c = $h_{out} - h_{in}$ = Coolant enthalpy rise in the channel, J/kg
Δh_{in} = Subcooling at the start of heated length, J/kg = $h_f(P_{in}) - h_{in} \approx h_f(P_{nvg}) - h_{in}$
Δh_{out} = $h_{f,out} - h_{out}$ = Exit subcooling in terms of enthalpy, J/kg
Δh_{nvg} = Subcooling at the NVG position, J/kg = $h_f(P_{in}) - h_{nvg} \approx h_f(P_{nvg}) - h_{nvg}$
K = Coolant thermal conductivity, W/m-°C
L = Channel heated length, m
L_{nvg} = Non-boiling length, i.e., the distance from start of heated length of channel to the position of net vapor generation, m
N_{zu} = Zuber number
N_{sub} = Subcooling number
P = Coolant pressure, Pa
Pe = Peclet number = Re Pr = $\rho_{in} C_p V_{in} D_h / K$
Pr = Prandtl number = $\mu C_p / K$
P_{in} = Channel inlet pressure, Pa
P_{out} = Channel outlet pressure, Pa
q''_w = Wall heat flux (assumed uniform over the channel length), W/m^2
Q = $q''_w \zeta_H L$ = Total power input to the coolant, W
Re = Reynolds number = $\rho_{in} V_{in} D_h / \mu$
ρ = Coolant density, kg/m^3
T = Coolant temperature, °C
T_{in} = Coolant temperature at the channel inlet, °C
T_{out} = Coolant temperature at the channel outlet, °C

$T_{sat}(P)$ = Coolant saturation temperature at a specific pressure P, °C
$T_{sat,in}$ = Coolant saturation temperature at channel inlet , °C
$T_{sat,out}$ = Coolant saturation temperature at channel outlet, °C
ΔT_c = $T_{out} - T_{in}$ = Coolant temperature rise at OFI, °C
ΔT_{sat} = $T_{sat,out} - T_{in}$ = Saturation temperature at exit minus inlet temperature at OFI, °C
$\Delta T_{sub,o}$ = $T_{sat,out} - T_{out}$ = Exit subcooling at the onset of flow instability, °C
η = $\frac{T_{sat,out} - T_{out}}{T_{out} - T_{in}} \frac{L}{D_H}$ = A parameter used by Whittle and Forgan in their analysis of the flow instability tests
μ = Absolute viscosity of the coolant, Pa-s
V = Coolant velocity, m/s
W = $\rho_{in} V_{in} A_F$ = Coolant flow rate, kg/s
ζ_H = Heated perimeter, m

Subscripts

c = coolant
F = flow
f = saturated liquid
g = saturated vapor
fg = liquid to vapor phase change
H = heated
h = hydraulic
in = channel heated length inlet
nvg = position of net vapor generation
out = channel heated length outlet
sat = saturated

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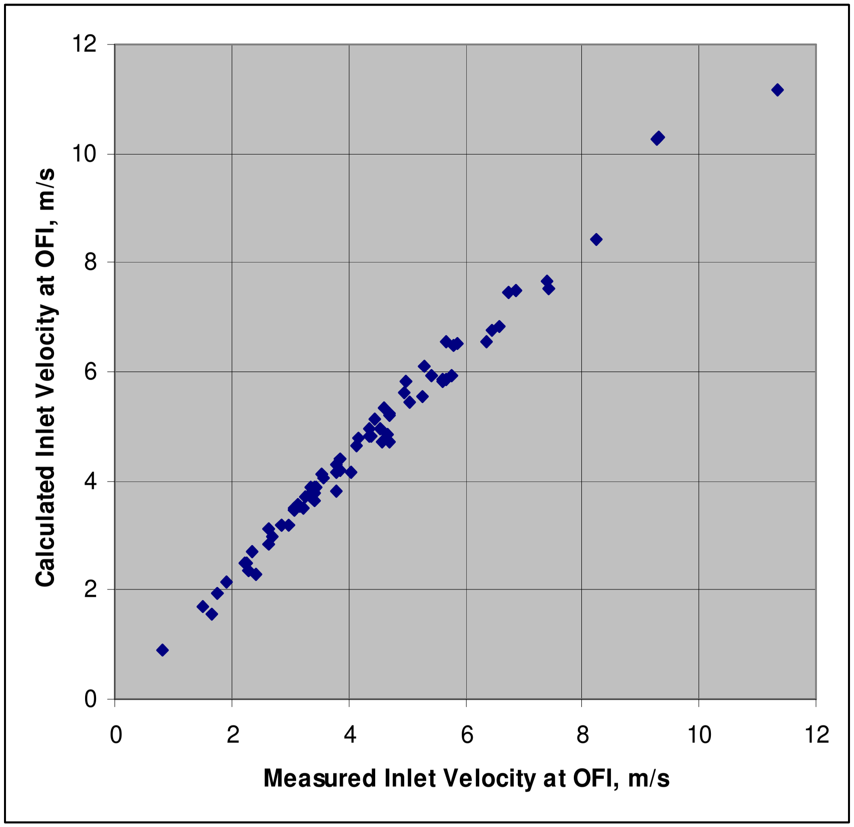

Fig. 1. Comparison of Coolant Inlet Velocity at OFI Calculated
Using Eq. (8) Versus its Measured Value in 75 Tests
Reported by Whittle and Forgan

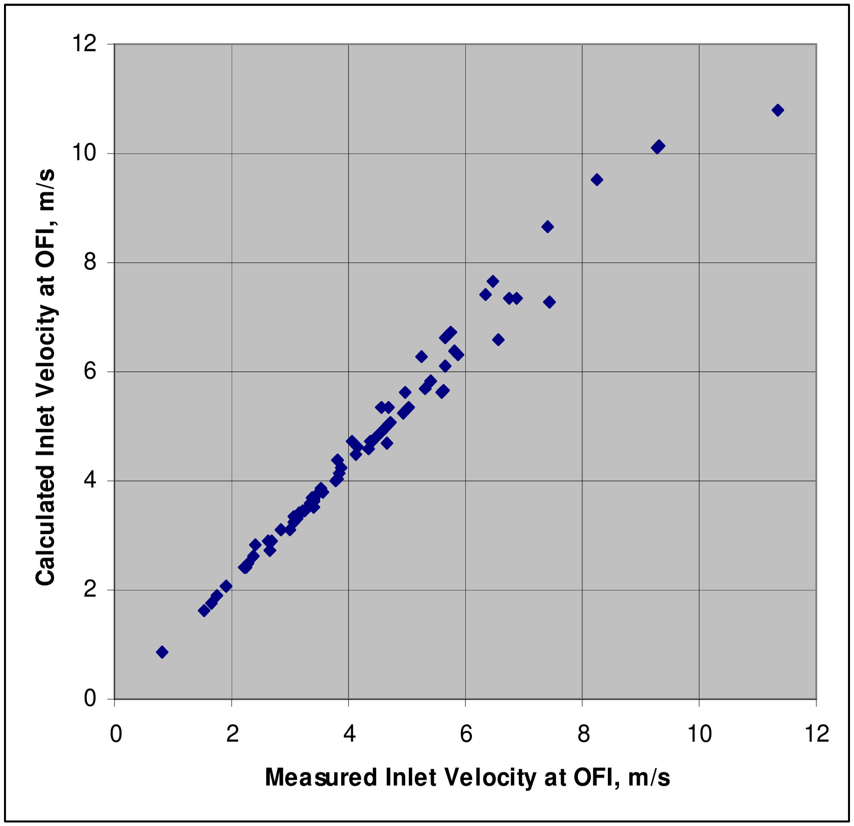

Fig. 2. Comparison of Coolant Inlet Velocity at OFI Calculated
Using Eq. (9) Versus its Measured Value in 75 Tests
Reported by Whittle and Forgan

Table 2. Comparison of Coolant Inlet Velocity at OFI Calculated Using Eq. (8) Versus its Measured Value in 75 Tests Reported by Whittle and Forgan

Test No.	Calc. Inlet Vel,m/s	Inlet Temp C	Heat Flux W/cm^2	L/D_H Ratio	Exit Press psia	Exit Temp C	Ratio $\Delta T_c/\Delta T_{sat}$	η W&F	Measured at OFI		Peclet Number	Subcool Number	Zuber Number	Ratio N_{sub} $/N_{zub}$
									Inlet Vel,m/s	Flow kg/s				
1	2.712	55.000	104.000	94.488	17.000	89.971	0.712	38.260	2.361	0.1908	94905.	129.406	91.950	1.407
2	3.781	55.000	145.000	94.488	17.000	89.974	0.712	38.248	3.406	0.2752	132314.	129.402	91.954	1.407
3	4.798	55.000	184.000	94.488	17.000	89.975	0.712	38.244	4.164	0.3365	167903.	129.397	91.953	1.407
4	6.520	55.000	250.000	94.488	17.000	89.975	0.712	38.246	5.872	0.4745	228166.	129.384	91.938	1.407
5	2.138	55.000	82.000	94.488	17.000	89.976	0.712	38.240	1.902	0.1537	74818.	129.406	91.964	1.407
6	3.546	55.000	136.000	94.488	17.000	89.977	0.712	38.236	3.154	0.2549	124090.	129.402	91.962	1.407
7	4.172	55.000	160.000	94.488	17.000	89.977	0.712	38.238	3.806	0.3075	145996.	129.397	91.957	1.407
8	5.216	55.000	200.000	94.488	17.000	89.972	0.712	38.257	4.697	0.3796	182532.	129.393	91.939	1.407
9	3.455	45.000	160.000	94.488	17.000	87.105	0.712	38.210	3.073	0.2494	121664.	155.577	110.556	1.407
10	3.887	45.000	180.000	94.488	17.000	87.103	0.712	38.214	3.457	0.2806	136876.	155.577	110.552	1.407
11	4.405	45.000	204.000	94.488	17.000	87.107	0.712	38.201	3.868	0.3139	155117.	155.572	110.559	1.407
12	3.200	60.000	110.000	94.488	17.000	91.406	0.712	38.284	2.845	0.2293	111606.	116.295	82.629	1.407
13	4.654	60.000	160.000	94.488	17.000	91.412	0.712	38.262	4.138	0.3336	162317.	116.290	82.638	1.407
14	5.236	60.000	180.000	94.488	17.000	91.412	0.712	38.261	4.715	0.3801	182616.	116.286	82.634	1.407
15	5.818	60.000	200.000	94.488	17.000	91.410	0.712	38.267	4.982	0.4016	202915.	116.286	82.631	1.407
16	2.505	35.000	136.000	94.488	17.000	84.247	0.712	38.152	2.229	0.1816	88704.	181.713	129.155	1.407
25	1.684	45.000	78.000	94.488	17.000	87.108	0.712	38.200	1.517	0.1232	59299.	155.590	110.578	1.407
26	2.505	45.000	116.000	94.488	17.000	87.100	0.712	38.226	2.257	0.1832	88210.	155.585	110.551	1.407
27	3.196	45.000	148.000	94.488	17.000	87.100	0.712	38.225	2.843	0.2307	112543.	155.585	110.552	1.407
28	2.998	55.000	115.000	94.488	17.000	89.979	0.712	38.228	2.701	0.2183	104912.	129.410	91.977	1.407
29	1.955	55.000	75.000	94.488	17.000	89.982	0.712	38.219	1.762	0.1424	68413.	129.415	91.987	1.407
30	3.807	55.000	146.000	94.488	17.000	89.973	0.712	38.251	3.386	0.2736	133223.	129.406	91.956	1.407
31	0.907	45.000	42.000	94.488	17.000	87.097	0.712	38.233	0.827	0.0672	31939.	155.590	110.550	1.407
32	3.512	55.000	147.000	83.333	17.000	88.671	0.685	38.263	3.084	0.1884	95608.	129.402	88.514	1.462
33	4.061	55.000	170.000	83.333	17.000	88.675	0.685	38.249	3.566	0.2178	110553.	129.402	88.525	1.462
34	4.300	55.000	180.000	83.333	17.000	88.674	0.685	38.252	3.776	0.2307	117060.	129.402	88.522	1.462
35	5.136	55.000	215.000	83.333	17.000	88.676	0.685	38.244	4.454	0.2721	139819.	129.397	88.524	1.462
36	3.878	45.000	196.000	83.333	17.000	85.534	0.685	38.233	3.406	0.2090	106263.	155.577	106.414	1.462
37	4.946	45.000	250.000	83.333	17.000	85.539	0.686	38.218	4.344	0.2665	135528.	155.572	106.423	1.462
38	3.561	45.000	180.000	83.333	17.000	85.539	0.686	38.218	3.128	0.1919	97576.	155.577	106.427	1.462
39	5.331	65.000	177.000	83.333	17.000	91.812	0.685	38.288	4.621	0.2808	144098.	103.170	70.576	1.462
40	6.115	65.000	203.000	83.333	17.000	91.810	0.685	38.299	5.300	0.3221	165290.	103.166	70.566	1.462
41	6.566	65.000	218.000	83.333	17.000	91.813	0.685	38.284	5.669	0.3445	177481.	103.166	70.575	1.462
42	3.704	65.000	123.000	83.333	17.000	91.813	0.685	38.283	3.252	0.1976	100119.	103.179	70.588	1.462
43	4.137	45.000	250.000	83.333	25.000	93.422	0.686	38.159	3.543	0.2174	112790.	130.125	89.009	1.462
44	5.629	65.000	242.000	83.333	25.000	99.683	0.686	38.231	4.943	0.3004	151549.	93.463	63.930	1.462
45	3.116	65.000	134.000	83.333	25.000	99.690	0.686	38.207	2.634	0.1601	83891.	93.469	63.949	1.462

Table 2. Cont'd.

Test No.	Calc. Inlet Vel,m/s	Inlet Temp C	Heat Flux W/cm^2	L/D_H Ratio	Exit Press psia	Exit Temp C	Ratio $\Delta T_c/\Delta T_{sat}$	η W&F	Measured at OFI		Peclet Number	Subcool Number	Zuber Number	Ratio N_{sub}/N_{zub}
									Inlet Vel,m/s	Flow kg/s				
46	3.868	55.000	200.000	83.333	25.000	96.556	0.686	38.180	3.355	0.2050	104826.	111.814	76.493	1.462
47	3.481	55.000	180.000	83.333	25.000	96.558	0.686	38.173	3.058	0.1868	94338.	111.814	76.497	1.462
48	4.807	55.000	177.000	100.000	17.000	90.538	0.723	38.249	4.400	0.2240	110537.	129.397	93.439	1.385
49	5.921	55.000	218.000	100.000	17.000	90.538	0.723	38.249	5.419	0.2759	136154.	129.389	93.430	1.385
50	7.497	55.000	276.000	100.000	17.000	90.540	0.723	38.244	6.861	0.3493	172396.	129.376	93.421	1.385
51	4.828	65.000	141.000	100.000	17.000	93.296	0.723	38.295	4.361	0.2209	110269.	103.170	74.495	1.385
52	7.466	65.000	218.000	100.000	17.000	93.296	0.723	38.291	6.743	0.3415	170522.	103.153	74.480	1.385
53	10.276	65.000	300.000	100.000	17.000	93.299	0.723	38.276	9.279	0.4699	234706.	103.131	74.466	1.385
54	3.766	65.000	110.000	100.000	17.000	93.298	0.723	38.283	3.402	0.1723	86013.	103.175	74.506	1.385
55	4.971	45.000	221.000	100.000	17.000	87.779	0.723	38.226	4.550	0.2327	115013.	155.568	112.326	1.385
56	6.500	45.000	289.000	100.000	17.000	87.785	0.724	38.205	5.799	0.2965	150390.	155.559	112.334	1.385
57	5.430	35.000	283.000	100.000	17.000	85.033	0.724	38.172	5.035	0.2584	126321.	181.699	131.215	1.385
58	4.202	35.000	219.000	100.000	17.000	85.032	0.724	38.175	3.848	0.1974	97753.	181.704	131.216	1.385
59	3.511	35.000	183.000	100.000	17.000	85.034	0.724	38.169	3.215	0.1650	81677.	181.708	131.226	1.385
60	2.369	55.000	93.000	100.000	17.000	92.875	0.771	29.718	2.282	0.1162	54400.	129.406	99.621	1.299
61	10.311	75.000	223.000	100.000	17.000	96.062	0.723	38.311	9.308	0.4686	233771.	76.856	55.494	1.385
62	1.546	55.000	66.000	100.000	17.000	96.172	0.838	19.331	1.661	0.0846	35439.	129.406	108.335	1.195
63	7.651	55.000	170.000	190.909	17.000	95.934	0.833	38.233	7.408	0.2593	123456.	129.341	107.638	1.202
64	4.154	55.000	93.000	190.909	17.000	96.226	0.839	36.608	4.053	0.1418	67016.	129.389	108.460	1.193
65	5.849	55.000	130.000	190.909	17.000	95.937	0.833	38.215	5.665	0.1983	94377.	129.367	107.673	1.201
66	4.732	45.000	127.000	190.909	17.000	94.269	0.833	38.214	4.691	0.1649	76753.	155.555	129.453	1.202
67	6.558	45.000	176.000	190.909	17.000	94.275	0.833	38.189	6.352	0.2233	106373.	155.533	129.445	1.202
68	2.300	45.000	67.000	190.909	17.000	98.442	0.904	20.323	2.418	0.0850	37229.	155.577	140.510	1.107
69	8.423	45.000	226.000	190.909	17.000	94.274	0.833	38.193	8.255	0.2902	136627.	155.503	129.412	1.202
70	3.803	35.000	122.000	190.909	17.000	93.738	0.850	33.779	3.803	0.1341	61920.	181.695	154.190	1.178
71	6.751	65.000	119.000	190.909	17.000	97.600	0.833	38.249	6.457	0.2248	108283.	103.131	85.836	1.201
72	5.559	65.000	98.000	190.909	17.000	97.597	0.833	38.266	5.257	0.1830	89163.	103.149	85.847	1.202
73	4.708	65.000	83.000	190.909	17.000	97.595	0.833	38.281	4.559	0.1587	75513.	103.157	85.850	1.202
74	5.945	35.000	187.000	190.909	17.000	92.610	0.833	38.178	5.759	0.2032	96859.	181.669	151.183	1.202
75	4.851	55.000	186.000	94.488	17.000	89.971	0.712	38.261	4.663	0.1504	145126.	129.393	91.936	1.407
76	6.833	55.000	262.000	94.488	17.000	89.976	0.712	38.241	6.569	0.2118	204422.	129.380	91.937	1.407
77	3.651	55.000	140.000	94.488	17.000	89.972	0.712	38.256	3.416	0.1102	109225.	129.397	91.944	1.407
78	3.196	45.000	148.000	94.488	17.000	87.103	0.712	38.215	2.991	0.0969	96212.	155.577	110.552	1.407
79	5.831	45.000	270.000	94.488	17.000	87.106	0.712	38.206	5.607	0.1816	175538.	155.559	110.542	1.407
80	7.517	45.000	348.000	94.488	17.000	87.102	0.712	38.218	7.431	0.2407	226297.	155.546	110.519	1.407
81	2.827	65.000	86.000	94.488	17.000	92.848	0.712	38.284	2.645	0.0848	83993.	103.179	73.321	1.407
82	5.853	65.000	178.000	94.488	17.000	92.846	0.712	38.295	5.624	0.1804	173901.	103.162	73.298	1.407
83	11.184	65.000	340.000	94.488	17.000	92.853	0.712	38.262	11.357	0.3643	332305.	103.114	73.268	1.407

Mean error in calculated inlet velocity at OFI, m/s = 0.384

Standard deviation of the error in calculated inlet velocity at OFI, m/s = 0.242