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INTRODUCTION

The Advanced Neutron Source (ANS) is a state-of-the-art research reactor facility that will be built at the Oak Ridge National Laboratory (ORNL) and is designed to become the world's most advanced thermal neutron flux source for scientific experiments. Therefore, the core of the ANS reactor (ANSR) must be designed to accommodate very high power densities using very high coolant mass fluxes and subcooling levels. The nominal average and peak heat fluxes in the ANSR are approximately 6 and 12 MW/m², respectively, with a nominal total thermal power of 303 MW. Highly subcooled heavy-water coolant (1.7 MPa and 85°C at the core exit) flows vertically upward at a very high mass flux of almost 27 Mg/m²-s. The cooling channels in each fuel assembly are all parallel and share common inlet and outlet plenums, effectively imposing a common pressure drop across all the channels. This core configuration is subject to flow excursion (FE) and/or flow instability that may occur once boiling is initiated in any one of the channels. The FE phenomenon constitutes a different thermal limit than a true critical heat flux (CHF) or departure from nucleate boiling (DNB). In such a system, initiation of boiling in one of the channels (i.e., the hot channel) can result in flow redistribution to the other cooler channels. In practice, there are three distinct flow zones along the channel. The first is of convective single-phase flow where the pressure gradient actually decreases in the flow direction because of a reduction in fluid viscosity with increased temperature. In the second zone, which starts at the point of incipient boiling

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(IB), the pressure gradient starts increasing very gradually up to a certain point, called onset of net vapor generation (ONVG) point or the point of onset of significant void (OSV), where both void generation and pressure gradient starts increasing sharply. It is normally assumed that at the OSV point, bubbles begin to detach from the wall and move into the core of the fluid. In the third zone, both void generation and pressure gradient increases rapidly, leading to a fast reduction of flow in the channel. The flow reduction promotes more boiling, which rapidly leads to FE [also referred to as the onset of flow instability (OFI)]. Because of the sharp acceleration in void generation occurring at the OSV, the third zone is normally short, and therefore it is normally accepted that FE or OFI will most likely occur soon after the OSV is established. This process can very rapidly lead to flow starvation, which, in turn, leads to DNB in the hot channel at flows lower than the nominal flow rate. It therefore becomes important to be able to identify and to predict the OSV as an early (conservative) warning to the expected occurrence of FE.

The current correlations and experimental data bases for FE and CHF seldom evaluate the specific combination of ANSR operating parameters. In addition, many investigators in the past did not distinguish between FE and true CHF, which adds to the inconsistencies in the available FE and CHF data base, since both are very complex but different phenomena.

A thermal hydraulic test loop (THTL) was designed and built to provide known thermal hydraulic (T/H) conditions to a simulated full-length coolant subchannel of the ANS reactor core, allowing experimental determination of the thermal limits (both FE and CHF) under anticipated ANS T/H conditions. A detailed description of the test facility is given by Felde, Yoder, and Skrzyckie (1992), Siman-Tov, et al. (1993) and Felde et al. (1994) and will not be repeated here. The test section simulates a single subchannel in the ANS reactor core. The FE or OFI conditions are determined in most of the THTL FE experiments by detection of the test section pressure-drop minimum as the flow to the test section was reduced in steps under a constant heat flux. To be able to perform the tests in this mode, a "stiff" system is required and used, where the bypass around the test section was closed or minimized to maintain a near-constant flow through the test section. For confirmation and comparison, limited experiments were performed with an actual FE burnout using a "soft" system. In this mode, a large bypass around the test section was fully open to maintain an almost constant common pressure-drop across the test section, thus closely simulating the ANSR configuration. Some experiments for true CHF burnout were also run in a "stiff" system with the bypass completely closed (securing constant flow in the test section) by reducing the flow until actual burnout occurred.

Most of the tests were conducted in a test section with a reduced span of 12.7 mm (vs 87 and 70 mm for the two ANSR cores) to limit the necessary power. Tests with double that span (25.4 mm) were also performed to remove

concerns about the scalability of the results to wide-span parallel channels as in the ANSR. The concern relates to possible end effects from the channel corners, which operate at a heat flux level about 36% of the heat flux at the flat portion. Non-uniform spanwise fluid bulk temperature, spanwise fluid mixing (or lack of it) in the channel and heat redistribution by thermal conduction in the test section aluminum walls could be dependent on span size and correspondingly effect the test results.

RESULTS AND DISCUSSION

The THTL experimentation for the ANSR T/H correlations is still in its initial stages with emphasis placed on the FE phenomena and CHF, as was reported by Siman-Tov, et al. (1993). Since then, additional experiments were performed that cover higher heat fluxes and velocities. The experiments completed so far include the following T/H conditions:

- coolant: light water,
- channel configuration: rectangular 1.27×12.7 and 25.4×507 mm,
- inlet coolant temperature: 45 (& 40) °C,
- exit coolant pressure: 1.7 (& 0.45, 0.17) MPa,
- exit heat flux range: 0.7-18 MW/m² (most within 11-15 range), and
- corresponding exit velocity range: 2.8-28.4 m/s (most within 10-20 range).

Acquiring FE data at this level of heat fluxes and velocities is significant for two reasons. First, to the authors' knowledge, very few data are available for FE at velocities higher than 10 m/s. In the initial part of this activity, the range was extended to 21 m/s as reported earlier by Siman-Tov, et al. (1993) and has now been extended further to 28.4 m/s (at the exit), which is above the maximum expected in the ANSR, including uncertainties. Second, the high heat flux achieved in this study is well above both the ANSR nominal average heat flux of 5.9 MW/m² and the nominal peak heat flux of 12 MW/m², and is almost as high as the "hot channel peaking factor" heat flux (e.g., peak heat flux with all uncertainties) of 18 MW/m². The limiting velocity corresponding to the ANSR nominal peak of 12 MW/m² is about 20 m/s (at a subcooling of 23°C), well below the ANSR nominal velocity of 25 m/s.

Preliminary results from tests with a test section of wider span (25.4 mm) indicates some effects on tests results from increased span dimension. Final conclusions on the subject, however, were not yet revealed.

DATA COMPARISON AND CORRELATION

Although the final correlation of the FE data will not be made until the remainder of the experiments are performed, the collected data were compared with correlations by Costa (1967), Whittle & Forgan (W&F) (1967), and Saha & Zuber (S&Z) (1974) as shown in Fig. 1. In the Costa correlation, the FE heat flux is proportional to the square-root of velocity, whereas both W&F and S&Z (as well as most other FE correlations) show a linear dependence. The S&Z correlation shows the best agreement with the data whereas the Costa correlation becomes increasingly conservative with increases in the mass flux. The FE heat flux dependence on velocity seems to be between 0.5 power (Costa) and 1.0 (S&Z and W&F), more nearly in the 0.8-0.9 range

The above data comparison and discussion supports a shift from the Costa correlation to the S&Z correlation for the ANSR, especially since for most of the ANSR scenarios analyzed (including nominal conditions) the mass fluxes are quite high. Plotting both the THTL data and the rest of the ANS database for FE [see Table 1 and Siman-Tov, et al. (1991)] in terms of St number (which is the selected dimensionless group for $Pe > 70,000$ in the original S&Z correlation) against subcooling reveals a clear trend for St number (and to a lesser degree also Nu number) to increase with decreasing subcooling, a trend which becomes stronger at lower subcoolings. In addition, it should be observed that by definition both St number and Nu number must become infinite for zero subcooling, which contradicts constant values for these parameters, as suggested by the original S&Z correlation. This observation, in combination with the trend observed in the data, provides a strong case for modifying the S&Z constant St number (0.0065) and constant Nu number (455) criteria, especially in the low subcooling range. Based on best-fit with the ANS database ($2^\circ\text{C} \leq \Delta T_{\text{sub}} \leq 48^\circ\text{C}$), the following correlations were developed and proposed for ANSR applications:

$$St = q'' / (G C_p dT_{\text{sub}}) = 0.0065 [0.55 + 11.21 / (dT_{\text{sub}})], \quad Pe > 70,000 \quad \text{Eq. 1}$$

$$Nu = q'' D_h / (k dT_{\text{sub}}) = 455 [0.55 + 11.21 / (dT_{\text{sub}})], \quad Pe < 70,000 \quad \text{Eq. 2}$$

Figure 2 shows the selected modified correlations in terms of St number and Nu number, respectively, against the ANS database, including the THTL data of the present study. Table 2 provides the statistics for the modified S&Z correlation in terms of mean and standard deviation as well as for the original S&Z and Costa correlations

ENERGY BALANCE METHOD vs. DIRECT SUBSTITUTION

Predictive equations like the S&Z correlation for OSV can create some confusion as to their proper application for determining uncertainties or their proper incorporation in predictive computer codes. The discussion by Inasaka and Nariai (1992) on such methodology for evaluating CHF against data is a good example of such confusion. Most of the difficulties on the subject arise from a confusion in nomenclature, physical interpretation, and implementation of the various parameters of the correlation. The two major options are the use of either the "Direct Substitution Method" (DSM) or the "Energy Balance Method" (EBM). The S&Z, Costa, and other similar correlations are all DSMs, while the W&F and other "global" correlations are EBMs.

For a uniform heat flux distribution, the proper physical interpretation in the EBM is confusing but possible, but for a non-uniform heat flux distribution as in the ANSR, such interpretation in the EBM becomes extremely difficult if not entirely impossible. It is shown that the DSM is preferable over the EBM for use in statistical evaluation of correlations against experimental data and for incorporation in design and analysis procedures such as is often used in thermal hydraulic design and analysis codes where evaluations are based on local conditions.

Table 1. Summary of FE/OSV database used in present analysis.

Author (Year), Org.	# of Data Points	Velocity m/s	Pressure MPa	ΔT_{wall} °C	Heat Flux MW/m ²
THTL	26	2.8 - 23.6	0.18 - 1.74	15.1 - 31.6	0.7 - 14.8
Lafey et al (1965)	34	0.5 - 4.5	0.17	2.1 - 25.0	0.3 - 2.4
Lafey & Costa et al (1967)	117	2.2 - 7.7	0.17 - 0.39	2.3 - 42.1	0.7 - 4.6
Courtaud et al, (March 1966)	6	2.5 - 9.0	0.3	11.3 - 22.2	2.0 - 4.0
Courtaud et al, (Jan. 1966)	15	1.8 - 7.0	0.28 - 0.32	11.8 - 24.7	2.0 - 4.0
Courtaud et al, (June 1967)	12	4.8 - 8.8	0.29 - 1.08	11.0 - 22.4	4.0 - 7.0
Vernier (1965)	19	2.1 - 10	0.15 - 0.29	6.6 - 16.5	1.0 - 4.5
Courtaud et al, (June 1966)	12	2.0 - 6.2	0.3	17.6 - 47.2	2.0 - 4.0
Whittle & Forgan (1967)	23	1.6 - 4.5	0.10 - 0.12	3.7 - 9.7	0.7 - 2.1
Whittle & Forgan (1967)	65	0.8 - 11.4	0.12 - 0.17	4.6 - 16.3	0.4 - 3.5
Schleisiek & Dumaine (1966)	14	3.6 - 9.0	0.39 - 0.49	11.2 - 18.8	2.5 - 5.1
Lafey et al (1968)	18	1.6 - 9.2	0.49	5.4 - 33.6	2.0 - 6.0
Waters (1966)	18	0.5 - 17.8	0.27 - 2.52	6.0 - 24.6	0.1 - 6.5
Cheh & Fighetti (1990)	86	1.3 - 7.9	0.24 - 0.46	2.2 - 43.7	1.1 - 3.2
Egan (1957)	7	0.5 - 1.3	0.41 - 1.65	4.4 - 21.1	0.4 - 1.6
Ferrel (1964)	11	0.1 - 1.4	0.98 - 5.0	10.6 - 18.9	0.2 - 0.7
Griffith et al (1958), BETTIS	12	0.5 - 1.2	8.2 - 13.6	6.1 - 41.7	0.3 - 1.9
Rouhani (1965), BMI	11	0.5 - 1.1	13.8	11.1 - 32.2	0.3 - 0.9

Table 2. U factor¹ statistics for Costa, S&Z, and modified S&Z correlations.

Peclet Range	Correlation	Data Range	# Points	Average	S.D.	S.D.%
Pe > 70,000 (Stanton Correlation)	Costa	THTL Data	24	1.452	0.326	22.45%
		All Data	403	1.042	0.596	57.20%
		V > 8 m/s	46	1.679	0.609	36.25%
		V < 8 m/s	357	0.960	0.543	56.60%
	Saha & Zuber	THTL Data	24	0.951	0.142	14.98%
		All Data	403	1.375	0.722	52.51%
		V > 8 m/s	46	1.276	0.531	41.64%
		V < 8 m/s	357	1.388	0.743	53.52%
	Modified Saha & Zuber	THTL Data	24	0.933	0.093	9.92%
		All Data	403	1.000	0.274	27.43%
		V > 8 m/s	46	0.991	0.163	16.41%
		V < 8 m/s	357	1.001	0.286	28.56%
Pe < 70,000 (Nusselt Correlation)	Saha & Zuber	THTL Data	2	0.535	0.267	49.96%
		All Data	56	1.328	1.185	89.23%
	Modified Saha & Zuber	THTL Data	2	0.474	0.277	58.30%
		All Data	56	0.679	0.481	70.92%

¹ U = Experimental Heat Flux / Predicted Heat Flux

Fig. 1. Comparison of flow excursion data from thermal-hydraulic test loop experiments. Bars represent uncertainty related to axial and lateral internal heat redistribution by conduction.