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IMPLEMENTATION AND VERIFICATION OF MISHIMA'S CHF DATA AT LOW FLOW AND ATMOSPHERIC PRESSURE IN THE PLTEMP/ANL CODE

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ABSTRACT

Mishima performed critical heat flux (CHF) tests at near-atmospheric pressure for water flowing in annular, rectangular, and round channels. The mass velocities (G) in these tests, which are representative of natural circulation flow in research reactors, ranged from 0 to 350 kg/m^2-s for down-flow and from 0 to 70 kg/m^2-s for up-flow. Mishima's fit to his CHF data gives much smaller CHF values for G < ~350 kg/m^2-s than do the Mirshak and the Labuntsov correlations which are based on CHF test data for G > ~1500 kg/m^2-s. The present work investigates Mishima's fit to his CHF data for rectangular channels and combines it with the Mirshak and the Labuntsov correlations valid for G > ~1500 kg/m^2-s, in order to provide CHF for G from 0 to ~1500 kg/m^2-s and above, for up-flow, down-flow, and for one-sided and two-sided heating. The combined set of CHF correlations was recently implemented in PLTEMP/ANL, a thermal-hydraulics code for research reactors. The implementation was verified by PLTEMP/ANL calculations that agree with both Mishima's and Mirshak's CHF test data and reproduce the plot of CHF versus coolant velocity for an MTR-type 2 MW test reactor studied in the IAEA TECDOC-233. The combined set of CHF correlations is compared with other correlations at the thermal-hydraulic limits set by different reactor design criteria.

1. Introduction

Some research reactors are cooled during steady-state operation by the natural circulation of the coolant (water), without a pump forcing the coolant flow. A method of calculating the natural circulation flow rate is available in the PLTEMP/ANL code [1]. A thermal-hydraulic design criterion commonly checked for research reactors operating by natural circulation is a required minimum critical heat flux ratio (CHFR). This work investigates the limited CHF data (specifically Mishima's tests data [2-4] for rectangular channels) available in the literature at low flow and low pressure for calculating CHFR in PLTEMP/ANL. The investigation was needed because Mishima's tests data are much lower than the CHF values from other correlations [5-9].

2. Mishima's CHF Tests Data for Rectangular Channels at Low Flow and Atmospheric Pressure

Mishima 2-4] obtained experimental CHF data for water at atmospheric pressure in a rectangular coolant channel (2.4 mm thick and 40 mm wide), both for one-sided heating and two-sided heating of the channel. He obtained CHF data up to 350 kg/m^2-s in down-flow and up-flow for one-sided heating, and up to 280 kg/m^2-s in down-flow and 70 kg/m^2-s in up-flow for two-sided heating. Mishima's fits (i.e., Eqs. (9), (10), (14), (15), (17) and (18) of his work [2] and Eq. (41) of his work [3]) to his tests data at low mass velocities (G), i.e. ≤ 350 kg/m^2-s, can be summarized by Eqs. (1) to (3). All symbols are defined in the nomenclature at the end.

$$q_c = \begin{cases} q_f\left[1 + 2.9\,x\,10^5\left(\Delta h_i/\lambda\right)^{6.5}\right] & 0 \le G \le 200\ \text{kg/m}^2-\text{s downflow} \\ 0.001\ A_f \Delta h_i G/A_h & G \ge 200\ \text{kg/m}^2-\text{s downflow} \\ \le \text{Mirshak \& Labuntsov correls. as downflow G increases} & \end{cases} \quad (1)$$

$$q_c = \begin{cases} q_f + 0.00146\,\lambda\,G & \text{for 1-sided heating in upflow} \\ q_f + 0.00170\,\lambda\,G & \text{for 2-sided heating in upflow} \\ \le \text{Mirshak \& Labuntsov correls. as upflow G increases} & \end{cases} \quad (2)$$

$$q_f = \frac{0.007\,A_f\,\lambda\left(g\,\rho_v\,\Delta\rho\,w\right)^{1/2}}{A_h\left[1 + \left(\rho_v/\rho_l\right)^{1/4}\right]^2} \quad (3)$$

It should be noted that these fits are not the same as Mishima's CHF lower bound [1]. In Eqs. (1) to (3), his fits are combined with the works of Mirshak [8] and Labuntsov [9] at G ≥ 1500 kg/m^2-s. Mirshak obtained Eq. (4) based on 65 tests using downward coolant flow in channels of rectangular and annular cross sections. The correlation has a fitting error of ±16%, a standard deviation of 8%. The range of the tests is: coolant velocity from 1.52 to 13.72 m/s with only one of 65 tests at 1.52 m/s, pressure from 1.7 to 5.8 bar, and subcooling from 5 to 75 °C at the point of CHF occurrence. Labuntsov obtained Eqs. (5) and (6) based on CHF data from 9 Russian sources. The fitting error is ±17% which was found by scaling the scatter in Fig. (a) of Labuntsov's paper [9]. The range of the tests is: coolant velocity from 0.7 to 45 m/s, pressure from 1 to 204 bar, and subcooling from 0 to 240 °C at the point of CHF occurrence.

$$q_c = 1.51\ (1 + 0.1198\ U)\ (1+0.00914\ \Delta T_{sub})\ (1 + 0.19\ P) \quad (4)$$

$$q_c = 1.454\ \theta(P)[1+2.5\ U^2 / \theta(P)]^{1/4}\ [1 + (15.1/ P^{1/2})\ (Cp\ \Delta T_{sub} / \lambda\ )], \quad (5)$$

$$\theta(P) = 0.99531\ P^{1/3}(1 - P/P_c)^{4/3} \quad (6)$$

To find CHF in the intervening range of mass velocity (i.e. 350 to 1500 kg/m^2-s), for down-flow and up-flow, Mishima's fits are extrapolated to higher G to meet the back-extrapolated Mirshak correlation (to G lower than Mirshak's data base) or the back-extrapolated Labuntsov correlation (i.e., the smaller of the two). This method of calculating CHF is implemented in the PLTEMP/ANL code, and is referred to as the Mishima-Mirshak-Labuntsov

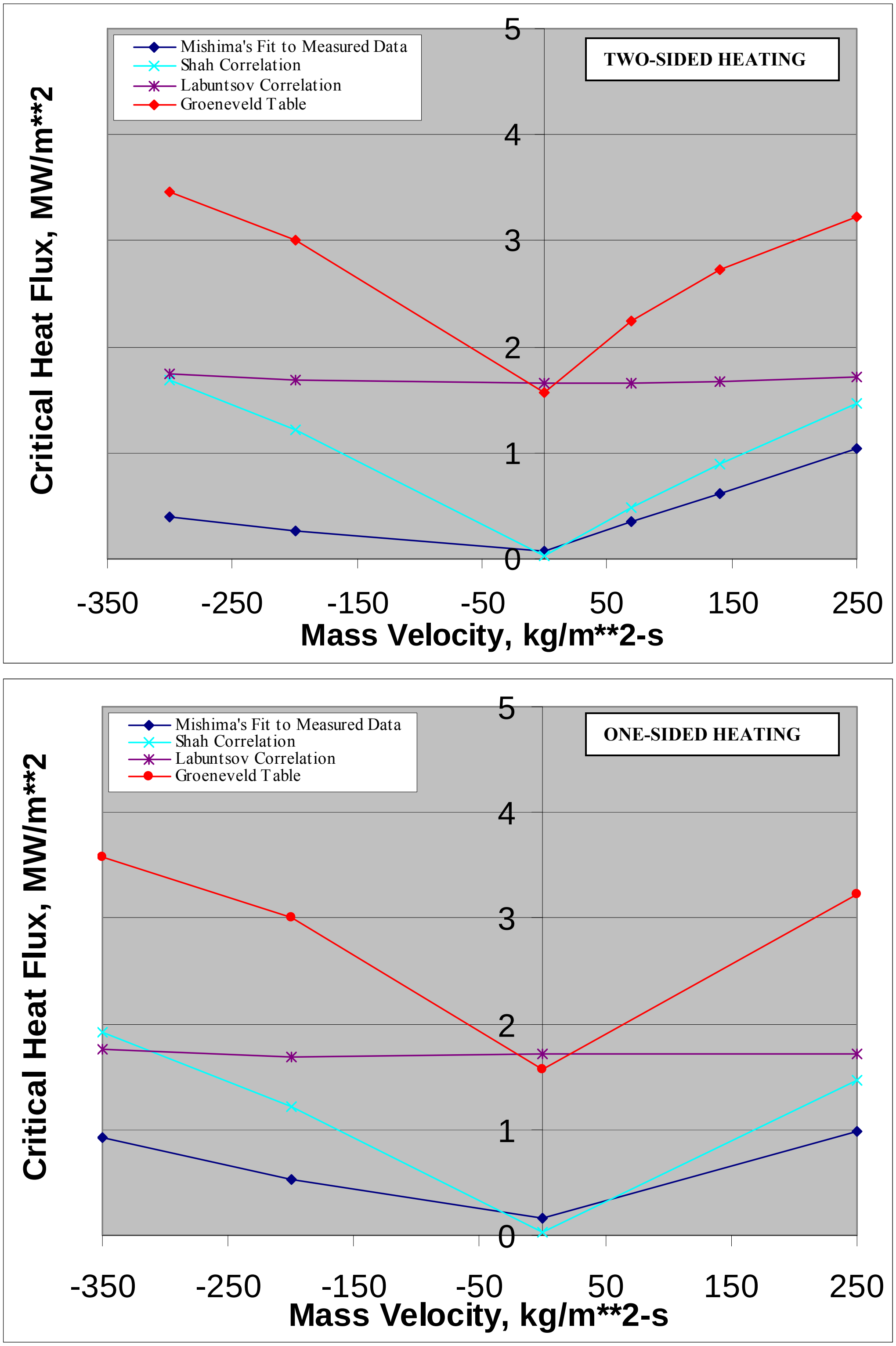


Fig. 1. Comparison of Mishima's CHF Data for a Rectangular Channel with Other Correlations (T_{in}=31 °C, T_{out} = 95 °C for Mishima's Test Section)

option (option 6). In the intervening range, the smallest of the three CHF values is used.

Mishima's tests data are compared in Fig. 1 with PLTEMP/ANL-calculated [1] CHF values based on 3 correlations reportedly valid for low flow: Shah correlation (valid for G > 4 kg/m^2-s), Labuntsov correlation (valid for G > 700 kg/m^2-s), and Groeneveld Table (valid for G > 0). To make the comparison under *the same thermal-hydraulic conditions*, the CHF was calculated when the power had been adjusted (using the code's search capability) to achieve a fixed coolant exit temperature of 95 °C. The measured value of CHF at zero flow agrees with the value calculated by the code using Eq. (3). This equation implies that the value of CHF at zero flow in a rectangular channel heated from both sides is exactly half of its value in the same channel if heated from only one side. The CHF at zero flow is 0.08 MW/m^2 for two-sided heating, and 0.16 MW/m^2 for one-sided heating. These CHF values at zero flow are much smaller than the established value of CHF in pool boiling (~1.25 MW/m^2 at 1 bar). Mishima[4] has discussed this, and pointed out that the CHF at zero flow in a coolant channel increases with increasing diameter/length ratio until it reaches the pool-boiling CHF.

The Shah and Labuntsov correlations and Groeneveld Table give higher CHF values than Mishima's measured data, the Shah correlation being the closest and the Groeneveld Table being the highest. However, Mishima's CHF test data are considered to be reliable at velocities below 0.4 m/s at which the tests were done; the Labuntsov correlation is considered to be reliable at velocities above 0.7 m/s at which the underlying CHF tests for the correlation were done; and the Mirshak correlation is considered to be reliable at velocities above 1.5 m/s at which the CHF tests for this correlation were done. The sequence of several papers by Mishima [2-4] on CHF at very low velocities in channels of different cross sections and inclinations indicates his high confidence in his data. Therefore, it is not prudent to ignore his data, and instead just extrapolate the Labuntsov and Mirshak correlations far out of their underlying test base.

3. Verification of the Mirshak and Labuntsov CHF Correlations in PLTEMP/ANL

The Mirshak and Labuntsov CHF correlations are included in the recommended CHF option, and their implementation in PLTEMP/ANL needed to be verified. The Mirshak correlation was verified by comparison with his CHF tests data (described in the next two paragraphs). In addition, both correlations were verified by calculating the CHF as a function of coolant velocity and comparing it with the CHF plot for an MTR-type 2 MW research reactor shown in Fig. A15 in the International Atomic Energy Agency (IAEA) Guidebook [10] TECDOC-233 (described in the 4th paragraph below).

Mirshak [8] has reported all his 65 CHF test data along with the corresponding prediction by his CHF correlation, Eq. (4). A hand calculation of the first CHF test is provided below for verification. The data for the first test are [8]: P = 38.0 psia = 2.62 bar, U = 18.8 ft/s = 5.730 m/s, ΔT_{sub} = 46.0 °C, q_c = 875,000 pcu/(hr)(ft^2) measured, and 954,000 pcu/(hr)(ft^2) predicted.

One pcu is the amount of energy that raises the temperature of 1 pound of water by 1 °C. A heat flux of 1 pcu/(hr)(ft^2) = 5.6746 W/m^2. Therefore, the reported q_c = 4.965 MW/m^2 measured, and 5.414 MW/m^2 predicted. For these values of parameters, the value of CHF obtained from Eq. (4) is $q_c = 1.51\ (1 + 0.1198 \times 5.730)\ (1+0.00914 \times 46.0)\ (1 + 0.19 \times 2.62) =$ 5.418 MW/m^2. This value is nearly equal to the predicted value of CHF reported by Mirshak [8] (5.414 MW/m^2). This provides a verification of Eq. (4) which is implemented in PLTEMP/ANL.

For verification by comparison with the IAEA Guidebook TECDOC-233, one standard fuel assembly of the reactor was modeled by the PLTEMP/ANL code assuming an axially uniform power shape and a *specified* coolant velocity (2.0, 3.0, 4.0, 5.0, or 6.0 m/s in different runs). The fuel assembly has 19 fuel plates and 20 coolant channels (18 inner channels of thickness 2.916 mm and 2 outer channels of half thickness 1.458 mm). The search option of the code was used to adjust the reactor power in order to achieve a CHFR of 1.58, equal to the peak-to-average heat flux ratio specified for the reactor [10]. All coolant channels are identical. The code calculates identical coolant temperatures and critical heat fluxes for all coolant channels. The CHF values calculated by the code (column 7) are compared in Table 1 with those reported in the IAEA Guidebook TECDOC-233 (column 8). They are identical, both for the Mirshak correlation and the Labuntsov correlation. This provides a verification of these correlations as implemented in the PLTEMP/ANL code.

Table 1. Verification of Mirshak and Labuntsov CHF Correlations by Comparing Them with IAEA-TECDOC-233 for an MTR-Type 2 MW Reactor at CHFR = 1.58

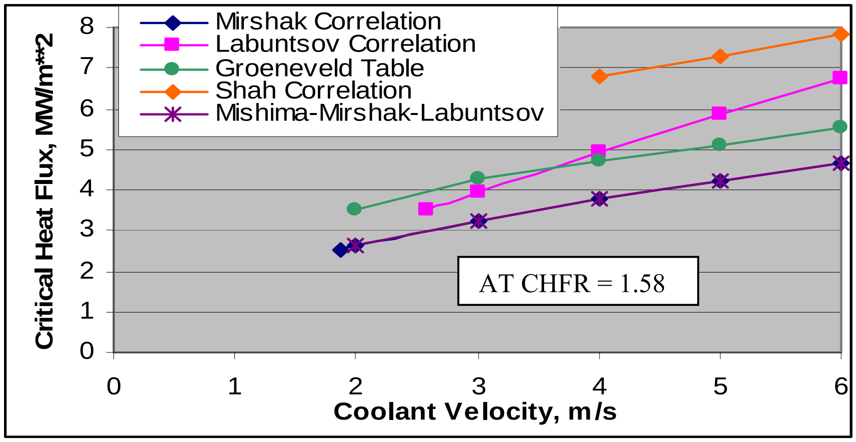
Coolant Velocity, m/s	Mass Velocity, kg/m^2-s	Flow per Assembly, kg/s	Power at CHFR=1.58, MW	Coolant Exit Temp., °C	Exit Subcool-ing, °C	CHF by PLTEMP, MW/m^2	CHF[a] in TECDOC-233, MW/m^2
1	2	3	4	5	6	7	8
Mirshak Correlation, PLTEMP Input Option = 0							
1.88	1826.4	6.72	2.308	119.6	0.0	2.54	2.56
2.0	1953.4	7.19	2.391	117.1	2.5	2.63	2.61
3.0	2930.1	10.78	2.947	103.1	16.5	3.24	3.21
4.0	3906.8	14.37	3.418	94.7	24.9	3.76	3.77
5.0	4883.5	17.97	3.847	89.0	30.6	4.23	4.27
6.0	5860.2	21.56	4.251	85.0	34.6	4.68	-
Labuntsov Correlation, PLTEMP Input Option = 2							
2.59[b]	2516.5	9.26	3.180	119.6	0.0	3.50	3.50
3.00	2930.1	10.78	3.590	117.1	2.5	3.95	3.93
4.00	3906.8	14.37	4.498	112.4	7.2	4.95	4.95
5.00	4883.5	17.97	5.343	108.7	10.9	5.88	5.88
6.00	5860.2	21.56	6.136	105.7	13.9	6.75	6.79

(a) Scaled from an enlarged copy of Fig. A15 of Ref. 10.
(b) IAEA-TECDOC-233 reports that the exit sub-cooling is zero at a coolant velocity of 2.52 m/s whereas PLTEMP finds that it occurs at a velocity of 2.59 m/s.

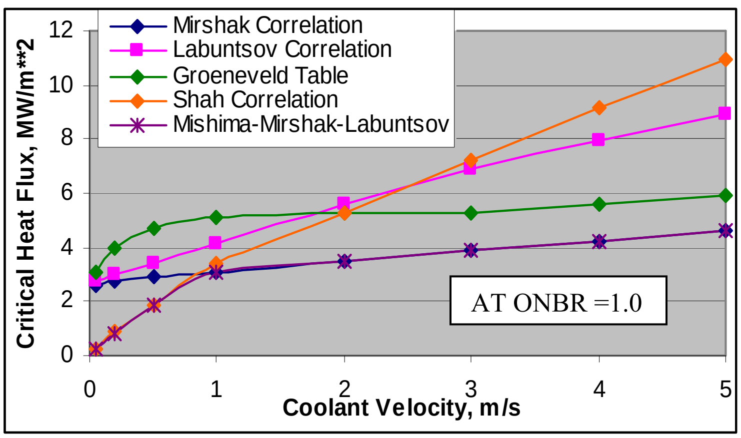
In Table 1, the *smallest* coolant velocity (1.88 m/s) used in the case of the Mirshak correlation was determined by PLTEMP/ANL so that the exit sub-cooling is zero, with a CHF of 2.54 MW/m^2. This compares accurately with IAEA-TECDOC-233 which reports that the exit sub-cooling is zero at a coolant velocity of 1.88 m/s, with a CHF of 2.56 MW/m^2. This comparison provides another verification of the Mirshak correlation as implemented in PLTEMP/ANL. The smallest coolant velocity (2.59 m/s) used in the case of the Labuntsov correlation was determined by PLTEMP/ANL so that the exit sub-cooling is zero, with a CHF of 3.50 MW/m^2. IAEA-TECDOC-233 reports that the exit sub-cooling is zero at a coolant velocity of 2.52 m/s, with a CHF of 3.50 MW/m^2. This comparison provides a verification of the Labuntsov correlation as implemented in PLTEMP/ANL.

4. Comparison of Mishima-Mirshak-Labuntsov CHF Option with Groeneveld Table

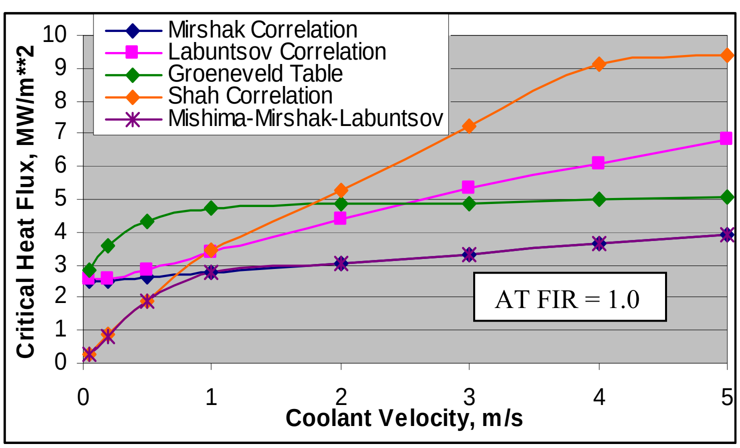
Figure 2 compares the Mishima-Mirshak-Labuntsov option (option 6 of PLTEMP/ANL) with the Groeneveld Table for a 2 MW research reactor studied in IAEA-TECDOC-233. The



(a)



(b)



(c)

Fig. 2. Comparison of Mishima-Mirshak-Labuntsov CHF Option with the Groeneveld Table for a 2 MW Research Reactor Studied in IAEA-TECDOC-233

comparison is done at the thermal-hydraulic limit set by each of the following 3 research reactor design criteria. Each CHF value in Fig. 2 was calculated by PLTEMP/ANL by adjusting the power to achieve one of the design criteria.

Criterion 1: CHFR = 1.58 (the peak-to-average heat flux ratio of the reactor).
Criterion 2: ONBR = 1.0 using Bergles-Rohsenow ONB temperature.
Criterion 3: Whittle and Forgan FIR = $\frac{(T_{sat} - T_{in})}{(1 + \eta\, D_{hh}/L_h)\,(T_{out} - T_{in})}$ = 1.0 using η = 32.5.

At a fixed CHFR of 1.58 (Criterion 1), Fig. 2(a) shows that the CHF values in option 6 are smaller than those given by the Groeneveld Table, with a maximum difference of 25%. The CHF values obtained in option 6 are identical to those given by the Mirshak correlation. This is because the CHF in option 6 is defined to be the smaller of the values given by the Mirshak and the Labuntsov correlations, and at coolant velocities > ~1.5 m/s for this reactor, the CHF value given by the Mirshak correlation is smaller than that given by the Labuntsov correlation.

At a fixed ONBR of 1.0 (Criterion 2), Fig. 2(b) shows that the CHF values in option 6 at coolant velocities <1.0 m/s agree with those given by the Shah correlation, but are much smaller than those given by the Groeneveld Table, being one-tenth at a velocity of 0.05 m/s (i.e., 0.256 compared to 3.06 MW/m^2). At coolant velocities ≥1.0 m/s, the former are smaller than those given by the Groeneveld Table, with a maximum difference of 39%.

The CHF values obtained in option 6 are identical to those given by the Mirshak correlation at velocities ≥1.0 m/s, but are much smaller than the Mirshak correlation at velocities <1.0 m/s. At a coolant velocity of 0.05 m/s, the CHF value in option 6 is 0.256 MW/m^2, equal to one-tenth of the CHF value (2.58 MW/m^2) given by the (extrapolated) Mirshak correlation. This is because, at velocities <1.0 m/s, the CHF of option 6 is determined by the Mishima CHF test data which are much smaller than the *extrapolation* of other correlations. At velocities ≥1.0 m/s, the CHF of option 6 is determined by the Mirshak correlation which gives the smaller of the CHF values calculated from the Mirshak and the Labuntsov correlations.

At a fixed FIR of 1.0 (Criterion 3), Fig. 2(c) shows that the CHF values in option 6 at coolant velocities <1.0 m/s agree with those given by the Shah correlation, but are much smaller than those given by the Groeneveld Table, being one-tenth at a velocity of 0.05 m/s (i.e., 0.256 compared to 2.82 MW/m^2). At coolant velocities ≥1.0 m/s, the former are smaller than those given by the Groeneveld Table, with a maximum difference of 42%.

The CHF values obtained in option 6 are identical to those given by the Mirshak correlation at velocities ≥1.0 m/s (i.e., 2.75 to 3.93 MW/m^2), but are much smaller at velocities <1.0 m/s. At a coolant velocity of 0.05 m/s, the CHF value in option 6 is 0.256 MW/m^2, equal to one-tenth of the CHF value (2.47 MW/m^2) given by the (extrapolated) Mirshak correlation. These comparisons are like those discussed above in the case of design Criterion 2.

5. Importance of CHF Data in Research Reactor Design

To make an assessment of the importance of CHF data in research reactor design, this section collectively examines the power-versus-coolant velocity data accumulated in this work for the 2 MW reactor studied in IAEA-TECDOC-233. This is done by finding the order in which the three design criteria (discussed above in Section 4) are exceeded when the reactor power is increased at a fixed coolant velocity. The power-versus-coolant velocity data accumulated in this work are all plotted in Fig. 3. The first 4 plots (numbered 1 to 4) show the power at which Criterion 1 (CHFR = 1.58) is exceeded using 4 different CHF correlations. The remaining 2 plots (numbered 5 and 6) show the power at which Criterion 2 (ONBR = 1.0) and Criterion 3 (FIR = 1.0) are exceeded.

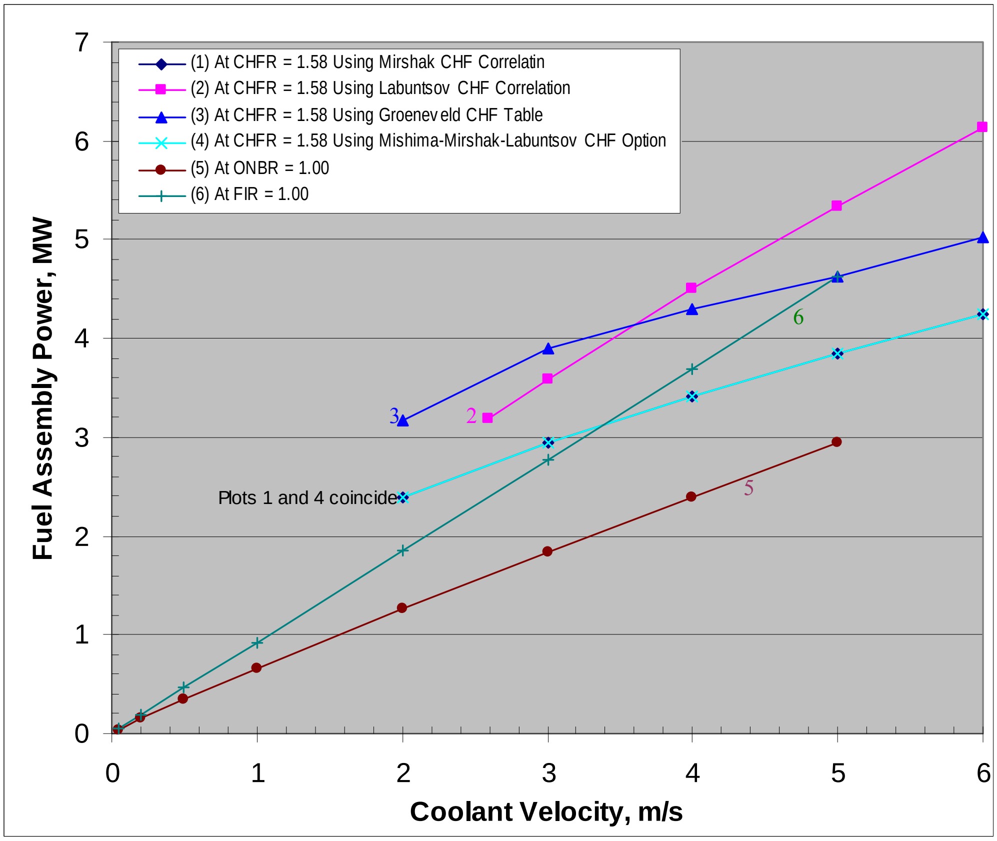


Fig. 3. PLTEMP/ANL-Calculated Power at a Given Design Limit for the 2 MW Research Reactor Studied in IAEA-TECDOC-233

First, it is noted in Fig. 3 that plots 2 and 3 are above all other plots, implying that the limit of the design criterion CHFR=1.58 with CHF found from the Labuntsov correlation and the Groeneveld Table is reached last, after the limits of the design criteria ONBR=1.0 and FIR=1.0 are already exceeded. Plots 1 and 4 coincide because the Mishima-Mirshak-Labuntsov CHF option equals the smaller of the Mirshak and the Labuntsov correlations at higher velocities, and for this reactor the Mirshak correlation is smaller.

Second, plot 5 based on the design criterion ONBR=1.0 lies below all the plots in Fig. 3. This means that the ONBR-based design criterion is reached at the lowest power and is the most limiting (conservative) compared to the other two design criteria.

Third, the relative position of the 6 plots in Fig. 3 shows the following order in which the three design limits are exceeded when the power is raised at a fixed coolant velocity < 3.0 m/s: first, ONBR=1.0 using Bergles-Rohsenow ONB temperature is exceeded; second, Whittle and Forgan FIR=1.0 using η = 32.5; and third, CHFR=1.58 using the CHF option 6 or the Mirshak correlation. The design criterion FIR=1.0 determines the maximum allowed reactor power at velocities < 3.0 m/s. This order of exceeding design limits means that the value of CHF is not of key importance in determining the maximum allowed power of research reactors operating at coolant velocities < 3.0 m/s.

At coolant velocities > 3.0 m/s, the CHFR=1.58 design criterion determines the reactor power if the CHF option 6 or the Mirshak correlation is used, whereas the design criterion FIR=1.0 (not the criterion CHFR = 1.58) determines the reactor power if the Labuntsov CHF correlation or the Groeneveld CHF Table is used. This means that the value of CHF *may be* of key importance in determining the maximum allowed power of research reactors operating at coolant velocities > 3.0 m/s.

6. Conclusions and Recommendations

The Mishima-Mirshak-Labuntsov CHF option (option 6 in PLTEMP/ANL) gives much smaller CHF values at coolant velocities below 1.0 m/s, compared to the *extrapolated* Mirshak correlation or Labuntsov correlation. These smaller CHF values come from Mishima's CHF test data used in this option at velocities below 0.4 m/s. Mishima's CHF test data are considered to be reliable at velocities below 0.4 m/s at which the tests were done, and the CHF option 6 is recommended at low velocities in natural circulation.

The Mirshak and the Labuntsov correlations in PLTEMP/ANL were verified by comparison with Mirshak's tests data and with CHF versus coolant velocity plots reported in IAEA-TECDOC-233 for an MTR-type 2 MW research reactor.

At a fixed coolant velocity < 3.0 m/s, the commonly used design limits on reactor power are exceeded in the following order: the ONBR=1.0 limit is exceeded first, then the FIR=1.0 limit, and lastly the limit CHFR=1.58 (see Fig. 3). For research reactors operating at coolant velocities < 3.0 m/s, CHF is not of key importance in determining the maximum allowed power. The design criterion FIR = 1.0 determines the maximum allowed power. However, at coolant velocities > 3.0 m/s, the CHFR-based design criterion, depending upon the CHF correlation used, may determine the maximum allowed reactor power.

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NOMENCLATURE

A_f = Flow area, m^2
A_h = $P_h L_h$ = Heated area, m^2
C_p = Specific heat of the coolant, kJ/kg-°C
D_{hh} = Heated hydraulic diameter of coolant channel, m
G = Mass velocity, kg/m^2-s
g = 9.80665 m/s^2 = Acceleration due to gravity, m/s^2
Δh_i = $C_p(T_{sat} - T_{in})$ = Inlet sub-cooling, kJ/kg
L_h = Heated Length, m
P = System absolute pressure, or Pressure at the point of CHF, bar
P_c = Critical pressure of the coolant, bar
P_h = Heated perimeter of the channel, m
q_c = Critical heat flux, MW/m^2

q_f = Critical heat flux at zero mass velocity, MW/m^2
T_{in} = Coolant inlet temperature, °C
T_{out} = Coolant exit temperature, °C
T_{sat} = Coolant saturation temperature, °C
U = Coolant velocity, m/s
w = Width (larger dimension) of the channel rectangular cross section, m
$\Delta\rho$ = $\rho_l - \rho_v$ = Density difference between saturated liquid and saturated vapor, kg/m^3
ΔT_{sub} = $T_{sat} - T_{out}$ = Coolant sub-cooling at the point of CHF (i.e., the heated length exit), °C
λ = Latent heat of vaporization, kJ/kg
ρ_l = Saturated liquid density at the system pressure, kg/m^3
ρ_v = Saturated vapor density at the system pressure, kg/m^3

REFERENCES

[1] A. P. Olson and M. Kalimullah, “A Users Guide to the PLTEMP/ANL V3.8 Code,” Reduced Enrichment for Research and Test Reactors (RERTR) Program, Argonne National Laboratory, Nuclear Engineering Division, Illinois, USA (June 20, 2009).

[2] K. Mishima, H. Nishihara, and T. Shibata, “CHF Correlations Related to the Core Cooling of a Research Reactor,” Proc. Int. Meeting on Reduced Enrichment for Research and Test Reactors, Oct. 24-27, 1983, Tokai, Japan, JAERI-M 84-073, pp.311-320 (1983).

[3] K. Mishima and H. Nishihara, “The Effect of Flow Direction and Magnitude on CHF for Low Pressure Water in Thin Rectangular Channels,” Nucl. Eng. and Design, Vol. 86, pp. 165-181 (1985).

[4] K. Mishima and H. Nishihara, “Effect of Channel Geometry on Critical Heat Flux for Low Pressure Water,” Int. J. Heat and Mass Transfer, **30**, 6, pp. 1169-1182 (1987).

[5] M. M. Shah, “Improved General Correlation for Critical Heat Flux during Upflow in Uniformly Heated Vertical Tubes,” Int. J. Heat and Fluid Flow, **8**, 4, pp. 326-335 (1987).

[6] J. G. Collier and J. R. Thome, “Convective Boiling and Condensation,” Third Edition, Clarendon Press, Oxford (1994).

[7] D. C. Groeneveld, J. Q. Shan, A. Z. Vasic, L. K. H. Leung, A. Durmayaz, J. Yang, S. C. Cheng, and A. Tanase, “The 2006 CHF Look-up Table,” Nucl. Eng. & Design, Vol. 237, No. 15, pp. 1909-1922 (2007).

[8] S. Mirshak, W. S. Durant, and R. H. Towell, “Heat Flux at Burnout,” E. I. du Pont de Nemours & Co., DP-355, Available from Office of Tech. Services, U. S. Dept. Commerce, Washington, D. C. (February 1959).

[9] D. A. Labuntsov, “Critical Thermal Loads in Forced Motion of Water Which is Heated to a Temperature Below the Saturation Temperature,” Soviet J. of Atomic Energy (English Translation) Vol. 10, No. 5, pp. 516-518 (May 1961).

[10] “Research Reactor Core Conversion from the Use of Highly Enriched Uranium to the Use of Low Enriched Uranium Fuels Guidebook,” IAEA-TECDOC-233, Appendix A, pp. A-26 to A-36, International Atomic Energy Agency, Vienna (1980) .