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Development of a High Flow CHF Correlation for the KMRR Fuel

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KMRR 핵연료에 대한 고유량 임계열속 상관식 개발

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Abstract

A high flow critical heat flux (CHF) correlation, based on the single- pin CHF experimental data for finned and unfinned heated rods, was developed for the thermal-hydraulic design and safety analysis of the Korea Multi-purpose Research Reactor (KMRR) core. The correlation consists of dimensionless parameters such as Reynolds number, thermodynamic equilibrium quality, liquid-to-vapor density ratio, and hydraulic equivalent diameter ratio. The fin effect was taken into account in the correlation by a finned-to-unfinned heated perimeter ratio. The effects of a cold wall and non-uniform axial power distribution were discussed to verify the applicability of the single-pin based correlation to the KMRR fuel bundle. The correlation limit departure from nucleate boiling ratio (DNBR) was determined as 1.44 from the statistical analysis of the CHF data.

요 약

KMRR 노심의 열수력 설계 및 안전 해석을 위한 고유량 CHF 상관식을 개발하였다. 상관식 개발에는 fin이 부착된 경우와 부착되지 않은 경우의 가열봉에 대한 단일봉 CHF 실험 자료를 사용하였다. 상관식은 Reynolds 수, 열역학 평형 건도, 액상과 기상의 밀도비 및 등가 수력 직경비 등의 무차원 변수로 이루어져 있으며, fin이 있는 경우와 없는 경우의 가열 둘레비를 사용하여 fin의 영향을 고려하였다. 이처럼 단일봉에 대하여 개발된 상관식의 KMRR 핵연료 집합체에 대한 적용 타당성을 보이기 위하여 비가열면 및 축방향 비균일 출력 분포의 영향을 논의하였다. CHF 실험 자료 분석 결과, 상관식 한계 DNBR은 1.44로 결정되었다.

1. Introduction

The CHF is generally defined as the maximum heat flux from the heated surface which usually causes a temperature excursion of the heated surface due to the inordinately deteriorated heat transfer characteristics caused by a small increase in surface heat flux or inlet coolant temperature or a small decrease in inlet mass flow. The occurrence of CHF on the nuclear fuel rod surface causes a sudden rise in fuel cladding temperature which may result in its damage. Thus, whether CHF occurs or not is a very important factor to be confirmed in connection with the integrity of nuclear fuels.

The DNB design criterion as one of the thermal-hydraulic design bases for the KMRR is that the probability that DNB will not occur in the reactor core during Condition I and II events, i. e., normal operation, operational transients, and any transient conditions arising from faults of moderate frequency, should be greater than or equal to 95% with a 95% confidence level. To meet this design criterion, the minimum DNBR in the reactor core calculated by the CHF correlation developed on the basis of CHF experimental data should always be greater than the correlation limit DNBR during normal operation and transient conditions. Here, the correlation limit DNBR is determined in such a way that if the minimum DNBR calculated in the reactor core is greater than this correlation limit DNBR, the probability of CHF occurrence at the limiting rod is less than 5% with a 95% confidence level.

The KMRR is designed as an open-chimney-in-pool type to give an easy access to the reactor core for experiments. It is also designed to have a compact core and high power density to obtain high neutron flux for efficient experiments, and the 8 longitudinal rectangular fins are attached to the fuel cladding for efficient cooling at high heat flux conditions. Hence, the KMRR is operated under the conditions of low coolant temperature, high coolant velocity, and low pressure. [1] In addition to these operating conditions, the finned fuel rod is the KMRR's unique feature and is much different from the unfinned fuel rod in the heat transfer characteristics including CHF. Although many efforts have been devoted to the CHF phenomenon, it has not been clarified analytically yet even for simple vertical round tubes. Thus, the empirical correlations based on experimental data are mostly used in the complex geometries such as a reactor core. The empirical CHF correlation is usually accurate and simple to use but applicable only to the restricted ranges of parameters which are dependent on experimental data base. Furthermore, the use of CHF correlation relies on the characteristics of the thermal-hydraulic analysis code used in the calculation of local conditions at CHF locations. There is no available empirical CHF correlation which is applicable to the KMRR core conditions associated with the COBRA/KMRR subchannel analysis code. Therefore, it is necessary to develop a new CHF correlation which can be applied to the KMRR's unique operating conditions.

Accordingly, a CHF correlation applicable to the KMRR core design was developed on the basis of the results of the single-pin CHF experiments. The applicability of the present CHF correlation to the KMRR fuel bundle was examined and the correlation limit DNBR was evaluated with the mean and standard deviation of the measured-to-predicted CHF ratio (M/P).

2. Experiments

The single-pin CHF data for the KMRR fuel[2, 3] and for the aluminum rod[4] were employed in the development of the CHF correlation. The schematic diagram of the experimental apparatus of the Atomic Energy of Canada Limited-Whiteshell Nuclear Research Establishment (AECL-WNRE)[2, 3] for the KMRR fuel single-pin CHF test at high flow conditions is shown in Fig. 1. It consists of a pump, a heated test section, a power supply system, a surge tank, two heat exchangers, and connecting piping. The pump is mounted with a variable-speed motor to obtain various flows. The annular test section consists of a transparent glass tube of 17 mm or 24 mm inside diameter to permit visual observations of boiling phenomena, and an indirectly heated rod of 0.6 m length with 8 longitudinal fins. The heated rod is made of a thin-walled stainless steel tube clad with aluminum sheath as the actual KMRR fuel cladding. The heated rod and glass tube were chosen to have the same hydraulic equivalent diameter as that of the actual KMRR fuel bundle. The structure and dimensions of the heated rod are shown in Fig. 1. In the case of the unfinned heated rod being used, the stainless steel tube of 6.35 mm outside diameter without aluminum cladding was used.

The experiments were conducted under the conditions described in Table 1. The test section having the finned heated rod with a hydraulic equivalent diameter of 7.24 mm had a cosine-shaped non-uniform heat flux distribution. The CHF values for the finned heated rod were obtained by dividing the measured values of power by the heat transfer area without fins.

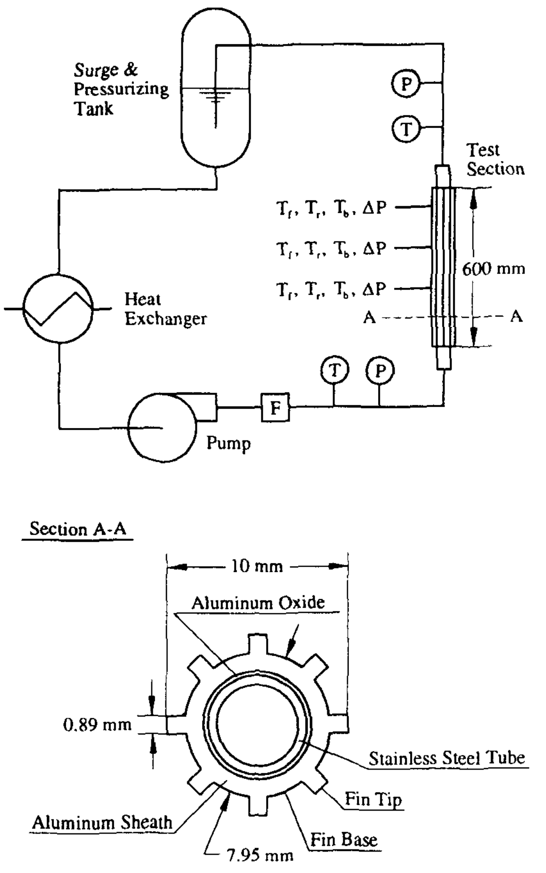

Fig. 1. Schematic Diagram of the AECL-WNRE Experimental Apparatus and Structure of Finned Heated Rod

This is because the CHF values calculated in this way are very similar to the results obtained by the two-dimensional calculation of the heat transfer phenomena considering the fin. [3] The local fluid temperature at the position of CHF occurrence was calculated from the energy balance by integrating the heat produced in the heated rod to the point of CHF occurrence. Although the data from the Savannah River Laboratory and the Columbia University (SRL-CU)[4] were obtained under the condition of downflow, these experimental data could be included in the upflow CHF data base since the buoyancy effect is negligible at high flow conditions.

3. Development of the CHF Correlation for the KMRR at High Flow Conditions

3.1. Procedure for the Development of the CHF Correlation

The CHF correlation for thermal-hydraulic design and safety analysis should be developed from the CHF experimental data obtained by using the simulated fuel assembly which has the same geometrical shape as that of the actual fuel assembly, or the shape that can be substituted for it. Prior to developing a new CHF correlation, several existing CHF correlations[3 − 7] for annular geometry were examined by comparison with CHF experimental data for the KMRR. Figs. 2 and 3 show M/P predicted by each correlation plotted against mass velocity for the finned and unfinned heated rods, respectively.

As shown in Fig. 2, it can be seen that each correlation does not predict well the experimental results for the finned heated rod. For the unfinned heated rod, the prediction by Knoebel's correlation is comparatively good, but not for the finned heated rod. Shim's correlation predicts the experimental data comparatively well except for the region of very high flow, but has a weak point in its form in that the

Table 1. CHF Test Conditions

	Coolant Velocity (m/s)	Coolant Temperature (°C)	Pressure (kPa)	Heat Flux (MW/m²)
AECL-WNRE[2, 3]				
−Finned Heater				
D_e=7.24mm	1.00~5.93	61.6~108.3	106~354	2.62~10.29
D_e=13.63mm	1.09~4.56	55.2~100.8	190~230	4.99~12.75
−Unfinned Heater				
D_e=10.65mm	0.98~5.21	47.1~79.9	122~241	3.42~10.28
SRL-CU[4]				
−Unfinned Heater				
D_e=7.82mm	4.56~13.74	95.2~134.0	446	4.72~16.11
D_e=8.20mm	4.54~9.19	100.2~130.2	446	7.10~10.54

predicted CHF approaches zero as the coolant condition becomes saturated. Therefore, it is necessary to develop a new CHF correlation based on the experimental data obtained under the operating conditions of the KMRR.

The procedure for the development of the CHF correlation which will be applied to the KMRR is shown in Fig. 4. As presented in the figure, a CHF correlation for the unfinned heated rod was developed first, and then the fin effect was taken into account later by introducing a modeling parameter of the fin. To apply the CHF correlation developed in this way to the thermal-hydraulic design and safety analysis of the KMRR, the effects of the difference

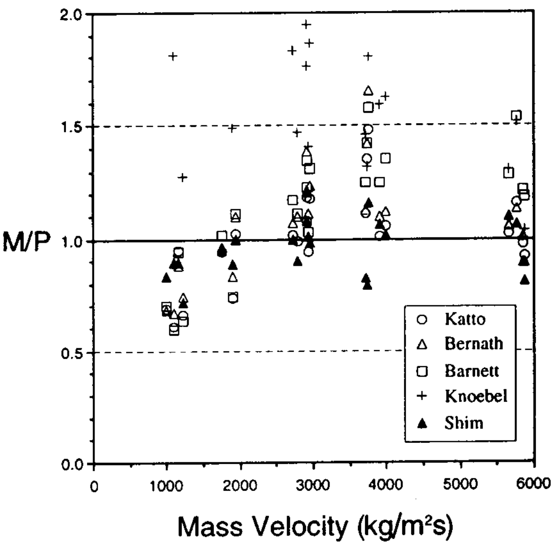

Fig. 2. M/Ps for Finned Heated Rod Predicted by Existing CHF Correlations vs. Mass Velocity

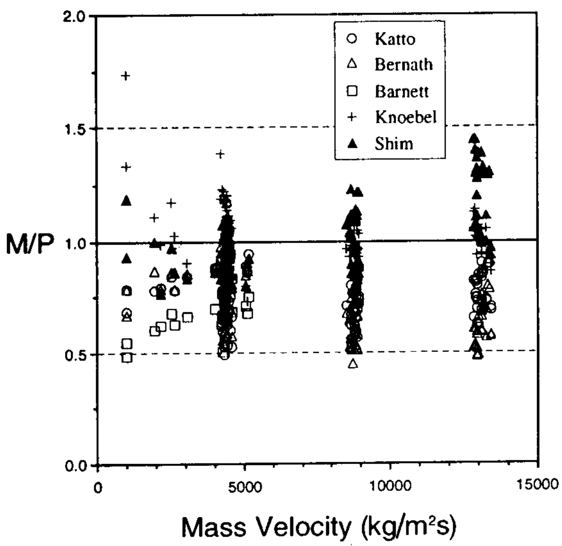

Fig. 3. M/Ps for Unfinned Heated Rod Predicted by Existing CHF Correlations vs. Mass Velocity

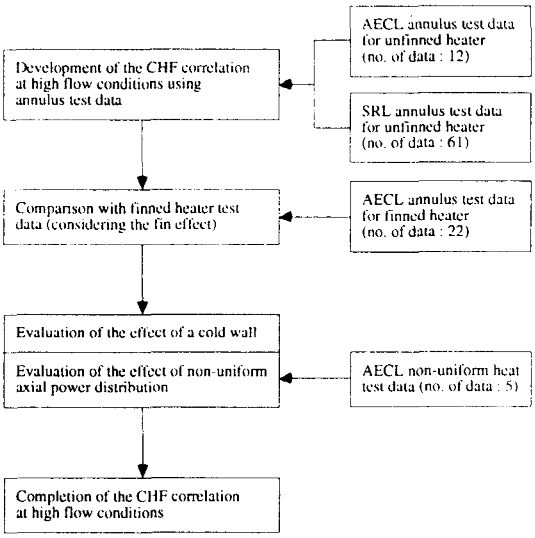

Fig. 4. Procedure for Development of CHF Correlation for the KMRR at High Flow Conditions

between the annulus and the rod bundle in geometry, especially, a cold wall, and non-uniform axial power distribution on CHF should be considered.

3.2. CHF Correlation Based on the Experimental Data for the Unfinned Heated Rod

It was made clear through a large number of experiments and theoretical analyses that the CHF is the function of the various parameters such as pressure, mass velocity, quality, and geometry, etc. The effects of these parameters on CHF were studied by many investigators. [8−11] As the major independent variables determining CHF, pressure, hydraulic equivalent diameter, thermodynamic equilibrium quality, mass velocity, liquid-to-vapor viscosity ratio, and liquid-to-vapor density ratio were selected. From these variables, the dimensionless parameters to form the CHF correlation were determined by surveying the various literatures[8−13] as Reynolds number, thermodynamic equilibrium quality, liquid-to-vapor density ratio, and hydraulic equivalent diameter ratio. The CHF correlation represented as the following Eq. (1) was determined from the experimental data for the unfinned heated rod by multiple linear regression analysis using the International Mathematical and Statistics Library (IMSL)[14].

$$q''_{CHF} = 1.81722\times10^{-2}\, Re^{0.454741}\, (1-\chi_e)^{7.05122}\, (\rho_f/\rho_g)^{-0.0015188}\, (8/D_e)^{\frac{1}{3}}, \qquad (1)$$

In this correlation, the thermodynamic properties are calculated at saturated conditions, and the units of CHF and hydraulic equivalent diameter are MW/m^2 and mm, respectively.

The M/P predicted by Eq. (1) is plotted against mass velocity in Fig. 5. As shown in the figure, the CHF correlation predicts the experimental data for the unfinned heated rod within the error range of 20%.

3.3. CHF Correlation Considering the Fin Effect

As shown in Fig. 5, the experimental results for the

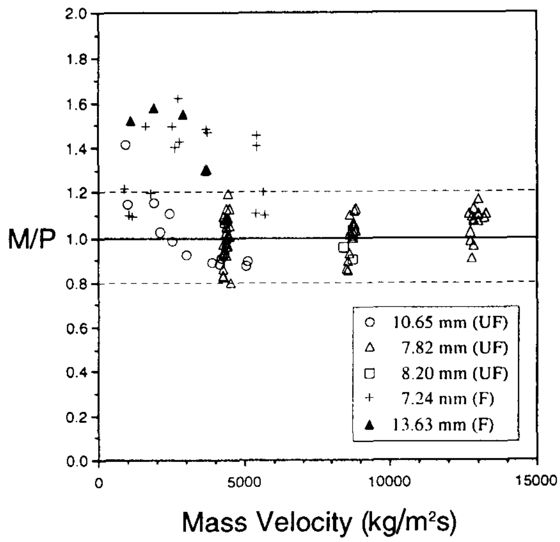

Fig. 5. M/P for Finned and Unfinned Heated Rods Predicted by Eq. (1) vs. Mass Velocity

finned heated rod are mostly distributed above the line of +20%, and this means that the CHF correlation of Eq. (1) generally underpredicts the CHF values for the finned heated rod. The enhancement of CHF due to the existence of the fin was modeled by using a finned-to-unfinned heated perimeter ratio as the following Eq. (2):

$$q''_{CHF} = 1.81722\times10^{-3}\,Re^{0.45474}\,(1-\chi_e)^{7.05122}\,(\rho_f/\rho_g)^{-0.0015186}\,(8/D_e)^{\frac{1}{3}}\,(P_{ht}/P_{hu})^{0.6}, \quad (2)$$

where

P_{ht} = heated perimeter with fins,

P_{hu} = heated perimeter without fins.

The parametric ranges of the experimental data for the finned and unfinned heated rods are as follows:

Re : 28057~576360,

χ_e : −0.13~−0.03,

ρ_f/ρ_g : 383.4~1536.5,

D_e(mm) : 7.24~13.63.

The parametric trends of M/P predicted by Eq. (2) are shown in Figs. 6 through 8 for mass velocity, thermodynamic equilibrium quality, and liquid-to-vapor density ratio, respectively. As shown in the figures, the CHF correlation of Eq. (2) predicts the experimental results well within the error range of 20%.

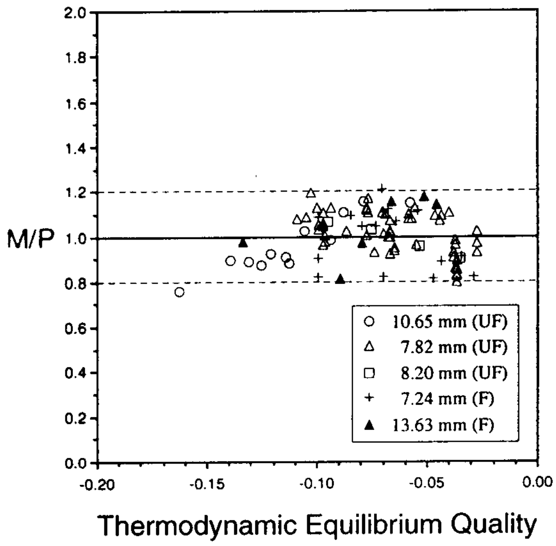

Fig. 7. Parametric Trend of M/P Predicted by Eq. (2) for Thermodynamic Equilibrium Quality

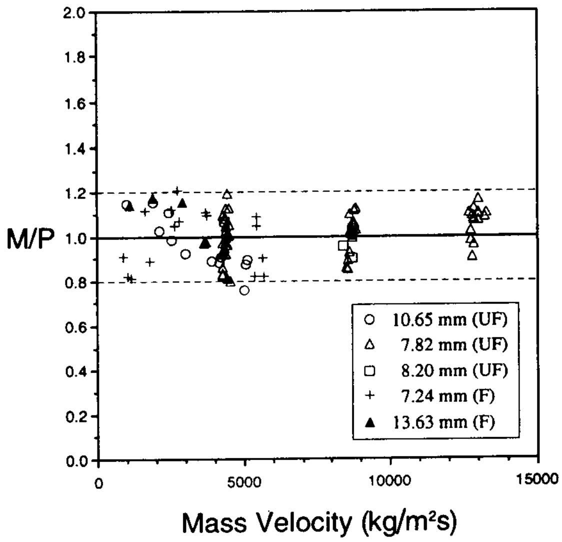

Fig. 6. Parametric Trend of M/P Predicted by Eq. (2) for Mass Velocity

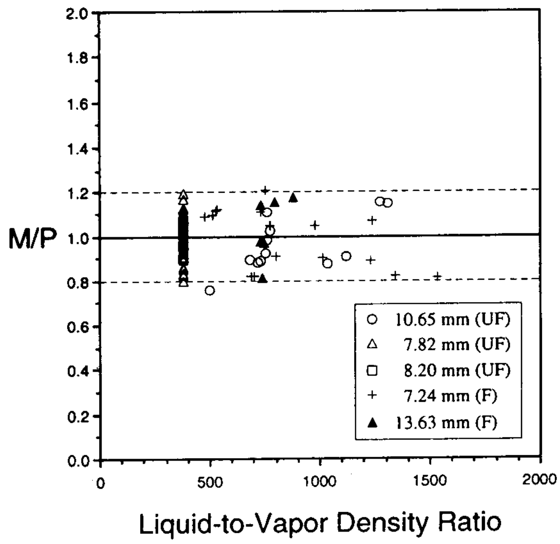

Fig. 8. Parametric Trend of M/P Predicted by Eq. (2) for Liquid-to-Vapor Density Ratio

4. Results and Discussion

4.1. Effect of a Cold Wall

It is found that the differences in CHF behavior between a uniformly heated single channel and a non-uniformly heated rod bundle can be attributed to; (a) boundary of unheated wall, (b) shape of axial and radial power profile, (c) flow mixing between neighboring subchannels, and (d) geometry of spacer grid and mixing vane. The effects of radial power distribution and flow mixing can be appropriately reflected in the calculation of CHF through subchannel analysis.

The CHF with a cold wall is normally less than that without a cold wall under the same thermal-hydraulic conditions. As one of the existing studies on the effect of a cold wall, Tong[15] obtained the cold wall factor from the CHF experimental data for the round tube and the annulus, and applied it to the prediction of CHF in the fuel assemblies. Tong's cold wall factor is generally less than 1, but this factor is inadequate to apply to the KMRR since it was obtained in the high pressure conditions ranged from 68.9 to 158.6 bar. On the other hand, Mishima, et al. [16] evaluated the effect of a cold wall under the conditions of very low pressure and low flow, and they proposed the relationship between the critical quality in the presence of a cold wall, χ_{ec}, and that in the round tube, χ_{er}, as follows:

$$\chi_{ec} = \chi_{er}(P_h/P_w)$$

where P_h and P_w represent heated perimeter and wetted perimeter, respectively. As shown in the above equation, the presence of a cold wall reduces the critical quality compared with that in the round tube, and decreases CHF.

Since the KMRR is operated under the conditions of low pressure and high flow, the above-mentioned correction factors for a cold wall cannot be applied to the KMRR. Also, the CHF experimental data for the conditions of the KMRR are insufficient to quantify this correction factor. Therefore, qualitative evaluations were made to confirm the conservatism of the application of the present CHF correlation to the KMRR fuel bundle.

The annulus CHF experimental data obtained under the conditions similar to the conditions of the KMRR were predicted by the CHF correlations for the round tube and for the fuel bundle in the absence of a cold wall. If the effect of a cold wall exists, the predicted CHF will be greater than the measured one. To compare the predicted with the measured, the annulus CHF experimental data were obtained from Becker[17] and Knoebel[4], and EPRI-1 correlation[18] for the fuel bundle and Katto's correlation[5] for the round tube were chosen. From data analysis with the assumption that the effect of a cold wall is independent of the materials used in the fin or the heated rod, the existence of a cold wall decreases the CHF for the conditions of low pressure and high flow, and the measured CHF is less than the predicted one by 20~40%.

Furthermore, the CHF experimental data for the round tube and the annulus obtained under the similar conditions were directly compared. The CHF data for the round tube were obtained from the Korea Advanced Institute of Science and Technology (KAIST) data bank[19], and the annulus CHF data were obtained from the experimental data of Becker [17]. The characteristics of the two compared experimental data group are as follows:

	Annulus	Round Tube
Heated Length(m)	0.61	0.6
L/D_e	81	60
Pressure(bar)	15.5~20.6	10.1~16.5
Mass Velocity(kg/m^2-s)	406~483	417~490
Inlet Subcooling(kJ/kg)	525~644	518~642

As a result of the comparison of the two experimental data group, the CHF for the round tube is greater than that for the annulus by about 10%.

By evaluating the effect of a cold wall as above, the conservatism of the present CHF analysis method of the KMRR core was confirmed. For the present, these cannot be quantified due to the insufficiency in experimental data, but, if the experimental data are obtained later, these can be quantified and used for increasing the thermal margin.

4.2. Effect of Non-Uniform Axial Power Distribution

As in the case of the KMRR, most CHF correlations are developed from the experimental data obtained under the condition of uniform axial power distribution. However, the axial power distribution in the actual reactor core is not uniform. There are various interpretations as to the effect of axial power distribution on CHF, and, among them, Tong's correction methodology by the F-factor[20] is most generally used. According to Tong's interpretation, the CHF mechanism in a subcooled state is influenced by the upstream power distribution, and this is due to the effect of the bubble layer existing on the heated surface. That is, the occurrence of CHF is caused by the crowded and thickened bubble layer on the heated surface which prevents the coolant from coming into contact with the heated surface, when the crowdedness of the bubble layer on the heated surface is influenced by the upstream power distribution. It is found that the effect is not significant in the low-quality region while it becomes more important as the quality becomes higher. Since the KMRR core is always kept in a subcooled state, the effect of non-uniform axial power distribution will not be significant.

The five data with cosine-shaped axial power distribution are included in the annulus CHF experimental data for the KMRR fuels. Using the CHF correlation developed for uniform axial power distribution, these five CHF experimental data were analyzed. The result shows the sample mean of M/P as 1.32 and the sample standard deviation as 33%. Fig. 9 compares the performance of the present CHF correlation for non-uniform axial power distribution with that for uniform distribution, and it can be seen that most of the predicted CHF values for non-uniform distribution are lower than the measured ones as compared with those for uniform distribution.

Tong's F-factor cannot be applied to the analysis of the KMRR core since its applicable range is restricted to comparatively high pressure conditions. As a result of applying the existing F-factor to the KMRR fuels having non-uniform distribution, the predicted CHF had less values. In particular conditions such as the case of the KMRR, the appropriate method to correct non-uniform axial power distribution has not been developed yet. However, since the present CHF correlation, on the whole, conservatively predicts the CHF for non-uniform axial power distribution as shown in Fig. 9, it is considered that the present CHF correlation can be applied conservatively to the analysis of the KMRR core.

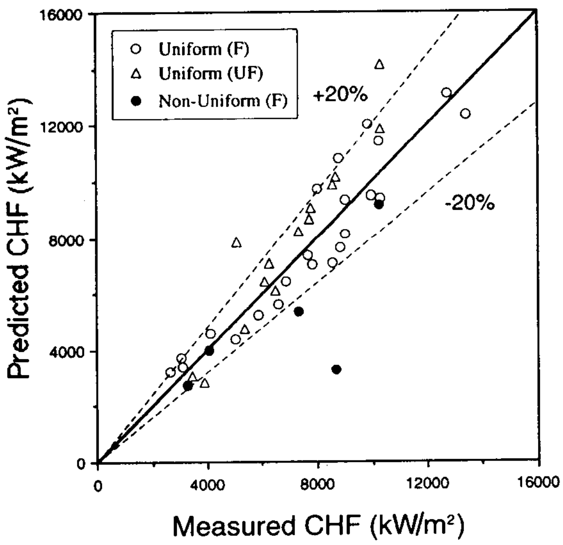

Fig. 9. Comparison of Performance of the Present CHF Correlation for Non-Uniform Axial Power Distribution with That for Uniform Distribution

4.3. Determination of the CHF Correlation Limit DNBR

To prevent CHF from occurring in the reactor core, the actual heat flux from the fuel rod surface should be less than the measured CHF. That is, CHF does not occur if the minimum DNBR in the reactor core satisfies the following inequality:

$$\mathrm{DNBR} = \frac{\dot{q}_{CHF,P}}{q_A} > \left(\frac{\dot{q}_{CHF,M}}{q_{CHF,P}}\right)^{-1}, \tag{3}$$

where,
$q''_{CHF,M}$ = measured CHF,
$q''_{CHF,P}$ = predicted CHF,
q''_{A} = actual heat flux.

Due to the uncertainties related to the CHF prediction model and measurement, the right hand side of the inequality is expressed by the statistical method rather than the deterministic one. If the distribution of M/P is a normal distribution, the minimum DNBR where the probability of CHF occurrence is 5% with a 95% confidence level can be expressed as which is called the correlation limit DNBR. The normality of the M/P distribution was checked using the W-test[21] which is applicable to small-sized sample. As the result with a 1% significance level, the distribution of M/P can be treated as a normal distribution. For a properly determined correlation, the mean of the residual, i. e., the measured value minus the predicted one, is close to zero and the distribution is normal. Applying the t-test for the mean, the hypothesis that the mean equals zero is accepted with a 5% significance level. Also, from the W-test, the distribution of the residual can be treated as a normal distribution with a 5% significance level.

The correlation limit DNBR for the KMRR fuels was determined, based on the CHF data for the finned heated rod, as follows:

Number of Data	=22
Mean of M/P, $\overline{X}$	=1.00279
Standard Deviation of M/P	=0.13117
One-Sided Tolerance Limit Factor[22], $K_{95/95}$	=2.349
Correlation Limit DNBR	=1.44

5. Conclusion

The KMRR core is different from the conventional PWR core due to the finned fuel rod with aluminum cladding and the operating conditions of low pressure, low coolant temperature, and high coolant velocity. A high flow CHF correlation applicable to the KMRR core was developed on the basis of the single-pin CHF experimental data for the finned and unfinned aluminum heated rods. The basic form of the CHF correlation consists of dimensionless parameters such as Reynolds number, thermodynamic equilibrium quality, liquid-to-vapor density ratio, and hydraulic equivalent diameter ratio. The fin effect was taken into account in the correlation using a finned-to-unfinned heated perimeter ratio. The effects of a cold wall and non-uniform axial power distribution were discussed to verify the applicability of the single-pin based correlation to the KMRR fuel bundle. Though these effects were not quantified due to lack of data, qualitative analysis showed that the present CHF correlation could be applied conservatively to the analysis of the KMRR. The developed CHF correlation limit DNBR, based on a 95% confidence level and a 95% probability, was evaluated as 1.44 for the finned heated rod CHF data.

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