

DEVELOPEMENT OF THE NEW BASIC CORRELATION “MG-S” FOR CHF PREDICTION OF THE PWR FUELS

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Abstract

It is important for core thermal-hydraulic design and plant safety analysis of PWR (Pressurized Water Reactor) to predict CHF (Critical Heat Flux) accurately. The accurate CHF prediction can enhance the reliability of the safety analysis and bring more efficient plant operations such as up-rating and higher burn-up fuel management. The new CHF correlation, MG-S (Mitsubishi Generalized correlation - for Standard grid), has been developed as a basic correlation of the new correlation series, which are for conventional and new-generation Mitsubishi fuel assemblies. Through comparisons with existing CHF data and a conventional CHF correlation, it was confirmed that MG-S can predict CHF with sufficient accuracy and extend its applicability to wider fluid parameters of interest.

Introduction

As one of the most important safety parameters for PWRs, DNBR (Departure from Nucleate Boiling Ratio) is assessed in the core thermal-hydraulic design and the plant safety analysis. This parameter is defined as a ratio of predicted CHF to actual local heat flux so as to denote the quantitative thermal margin to DNB occurrence. In the practical design work, CHF prediction actually depends on the empirical CHF correlations based on a lot of measured CHF database, since the CHF mechanism is so complicated. The CHF correlation should be developed for each specific fuel design and its corresponding CHF database since the CHF highly depends on the geometrical design of the fuel, or the conservatively derived CHF correlation is adopted.

The MIRC-1 correlation [1] has been applied to the core thermal-hydraulic design and most of the Non-LOCA (Non - Loss Of Coolant Accident) safety analyses of the core, in which the Mitsubishi designed fuels are loaded. The W-3 correlation [2] is supplementary used for the several events of safety analyses such as Main Steam Line Break, which are beyond the applicable range of MIRC-1. MIRC-1 was originally developed for Mitsubishi's conventional fuel designs and was provided as a function of the local coolant parameters such as pressure, mass velocity and thermal-equilibrium-quality, and geometrical parameters. The CHF database for MIRC-1 consists of several configurations of the rod bundles to cover various effects of key parameters on CHF, such as rod diameter, rod-to-rod gap, heated length, axial power distributions, existence of unheated rod, and axial spacing of grid spacers. Therefore, MIRC-1 has been applied to the variety of Mitsubishi fuel designs including the newly developed designs which possessed equivalent or slightly improved CHF performance than the standard fuel designs.

Although MIRC-1 has advantages of describing the various effects of key parameters on CHF based on its abundant CHF database, it is difficult to apply MIRC-1 to the new generation fuels which have specifically higher CHF performance. It is because that CHF occurrence conditions for such high performance fuels tend to shift to higher quality condition due to its enhanced mixing effects compared with conventional fuels. As be similar to other existing correlations, MIRC-1 assumes a linear relationship between CHF and thermal-equilibrium-quality. However, the linear approximation reduces its accuracy of CHF predictions in higher quality conditions. Thus, it has been recently required to develop a new CHF correlation which can adequately predict CHF even for the higher quality conditions.

In this paper, the new CHF correlation, MG-S (Mitsubishi Generalized correlation - for Standard grid), is proposed which was established as a basic equation aiming to extend its applicability to higher quality conditions. MG-S is fully compatible with MIRC-1 except higher quality conditions. MG-S will be used for the core thermal-hydraulic designs and most of the safety analyses. For the specific events of safety analyses which are beyond the applicable range of MG-S, a conservative correlation, MG-NV (Mitsubishi Generalized correlation - for Non Vane grid) which is reported in another paper [3] will be used instead of conventional W-3 correlation.

1. Basic characteristics of CHF

CHF characteristics have been experimentally and theoretically investigated by many researchers. Among them, the "look up table" proposed by Groneveld, et al. [4] can provide the basic characteristics of CHF in the wide parameter range. It provides discrete CHF values for specified fluid conditions given by pressure, mass velocity and quality. The look up table was developed based on over 15,000 CHF data for single tubes to cover the CHF phenomena for the wide range of fluid conditions. At conditions where CHF data are not available, CHF values are provided by extrapolations using the applicable empirical correlations. The table was basically developed for the inner tube diameter of 8 mm, and CHF for the diameter other than 8 mm is correlated by the following;

$$\frac{CHF_D}{CHF_{D=8mm}} = \left(\frac{D}{8}\right)^n \quad (1)$$

where $CHF_{D=8mm}$ is the CHF value provided by the look up table, D the inner tube diameter and n the constant which is, for example, given by -0.5.

The look up table is quite useful database to examine the effect of each fluid condition onto CHF. Figure 1 was created from the look up table and shows quality-versus-CHF curves at 14 MPa which is close to the PWR operating condition. Several mass velocity conditions are also plotted to examine the effect of mass velocity on CHF (1000kg/m²s to 5000kg/m²s). As shown in Figure 1, CHF values linearly decreases as quality becomes larger up to the vicinity of 0.2 in quality and then approaches asymptotically to zero. The inflection points, where the linear relationships disappear in quality-versus-CHF curves, would be corresponding to the change of heat transfer characteristics due to flow pattern transitions.

In addition to the above basic characteristics of CHF, additional correlation factors are required in the practical application. For example, as shown in Table 1, Groeneveld, et al. [5] summarized the additional correlation factors if the look up table is applied to actual design work. Those factors are also taken into account in the development of the new CHF correlation.

Table 1 Correlation factors with Groeneveld, et al. [5]

(A)	Subchannel or tube diameter cross-section factor	(E)	Axial flux distribution factor
(B)	Bundle geometry factor	(F)	Radial or circumferential flux distribution factor
(C)	Mid-plane spacer factor	(G)	Flow-orientation factor
(D)	Heated length factor	(H)	Vertical low-flow factor

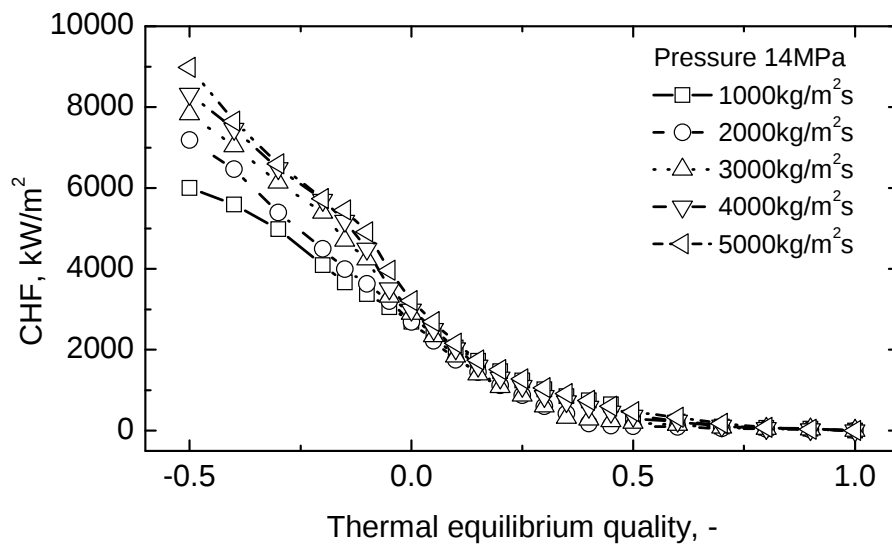


Figure 1 Look up table of CHF at P=14MPa [4]

2. Development course of CHF correlation MG-S

2.1 CHF correlation based on local parameter

The empirical CHF correlations can be classified into two types; local parameter type and system parameter type. The local parameter type correlations are described as a function of local fluid conditions such as pressure, mass velocity and quality, and local geometrical parameters such as hydraulic equivalent diameter. On the other hand, the system parameter type correlations are composed of inlet boundary fluid conditions and geometrical features such as heated length, which can combine the inlet conditions and local conditions based on the heat balance. Since the system parameter concept requires that the same heat balance (the same closed channel geometry) is available in both of the actual core and CHF test section, the CHF correlations based on the local parameters have been usually adopted in the PWR core thermal-hydraulic design. The coolant in the actual PWR core is exchanged between fuel assemblies due to its open channel structure without a channel box such as BWR fuels, whereas the partial models such as 5x5 or 4x4 rod bundle are used as the CHF test sections. The subchannel analysis can compensate the difference of geometries between actual PWR cores and CHF test sections, providing the local coolant conditions. As well as the previous CHF correlations adopted in PWR core thermal-hydraulics, MG-S has been also developed based on local parameters.

2.2 Basic equation

The target of developing MG-S is to extend its applicability to higher quality region. Therefore, the basic equation of MG-S should adequately produce the quality-versus-CHF curves covering a wide range of quality as shown in Figure 1. The main features of quality-versus-CHF curves are that; (a) CHF values linearly decreases as quality becomes larger up to certain conditions, (b) the conditions where the linearity between CHF and quality is lost are affected by mass velocity conditions, and (c) CHF values approaches asymptotically to zero in higher quality conditions. In the existing CHF correlations, for example, exponential functions are actually adopted in relating CHF to quality [6] - [11] to consider the above features. In addition, Gambil [12] pointed out from the Maxwell-Boltzmann distribution that (d) there are upper limitations of CHF and CHF values are saturated in highly subcooled conditions.

To incorporate the features of (a) to (d) in the new CHF correlation, the following Eq. (2) based on a logistic curve [13] is proposed as a basic equation;

$$q_{CHF,U}'' = \frac{A}{1 + \exp\{K(x_{loc} - C)\}} \quad (2)$$

where $q_{CHF,U}''$ is a predicted CHF assuming the axially uniform heat flux distribution, x_{loc} local quality, and parameters A , K , and C are provided as a function of pressure, local mass velocity and geometrical parameters. The logistic curve seems suitable to fit the CHF characteristics mentioned above, because it can describe a continuous change of the gradient.

Figure 2 demonstrates the potential capability of Equation (2) to fit the CHF characteristics shown in Figure 1. The parameters A , K and C were adjusted by a conventional nonlinear parameter fitting method so as to reproduce CHF data in Figure 1. As a result, it was confirmed that Equation (2) can accurately represent the CHF values with the above features (a) to (d).

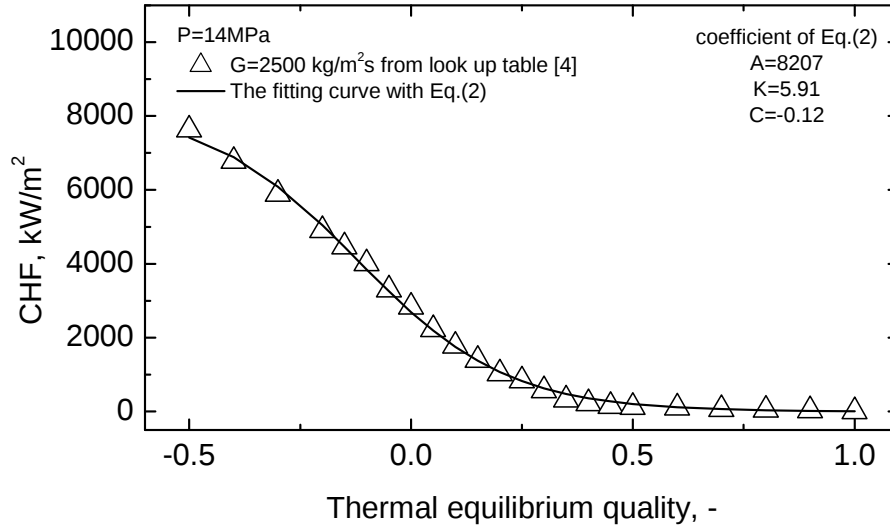


Figure 2 Quality-versus-CHF curve predicted by Eq. (2)

3. MG-S based on rod bundle CHF data

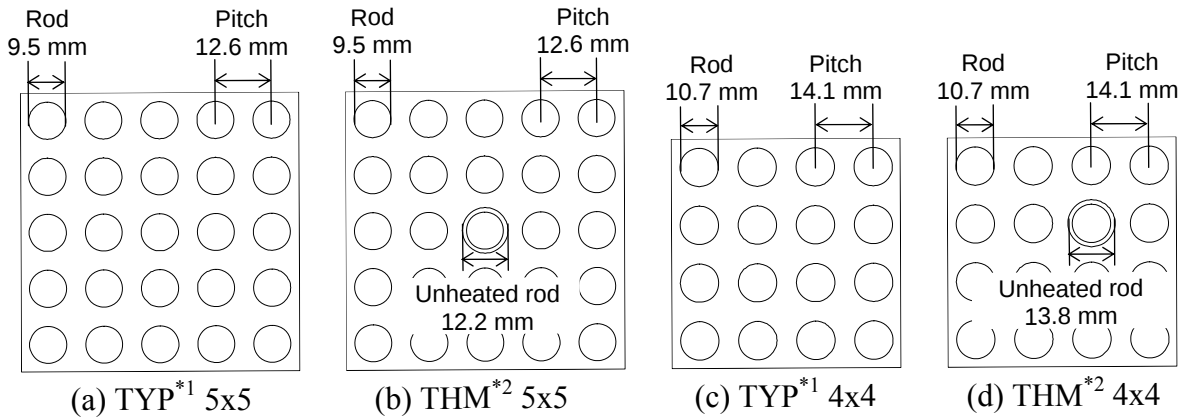
3.1 CHF database

The CHF database used for developing MG-S was collected from the CHF test data acquired at the Heat Transfer Research Facility of Columbia University [14] as well as those of MIRC-1 correlation [1]. Finally, the database of MG-S consists of the original MIRC-1 database and the CHF data for the current Mitsubishi fuel (Z2 grid spacer). The test sections are 4x4 or 5x5 rod bundles with mixing vane grid spacers and include various fuel assembly configurations such as rod diameter, rod-to-rod gap, grid spacing, axial power distributions and heated length. The test conditions can sufficiently cover the parameter ranges of pressure, mass velocity and quality which are required for the core thermal-hydraulic design and plant safety analysis in PWR. Totally, more than 1000 data points were used to develop MG-S. The test section geometries and the test conditions are summarized in Table 2 and Figure 3.

Table 2 Test specification of Rod Bundle CHF data [14]

Test No.	Channel Layout ^{*1}	Heated Length (m)	Axial Power Shape	Grid Spacing (m)	Number of Data	Pressure (MPa)	Inlet Mass Velocity (kg/m ² s)	Inlet Temperature (°C)
161	Fig.3 (a)	4.27	uniform	0.56	71	10.3 - 16.7	1300 - 4800	195 – 331
156	Fig.3 (a)	4.27	uniform	0.66	78	10.3 - 16.7	1300 - 4700	184 - 319
160	Fig.3 (a)	2.44	uniform	0.56	66	10.3 - 16.7	1400 - 4800	196 – 321
157	Fig.3 (a)	2.44	uniform	0.66	77	10.3 - 16.7	1300 - 4800	198 – 331
164	Fig.3 (a)	4.27	cosine	0.56	73	10.3 - 16.7	1300 - 4800	196 – 320
124	Fig.3 (c)	2.44	cosine	0.51	32	10.4 - 16.7	2000 - 5100	235 – 328
125	Fig.3 (c)	2.44	top skew	0.51	32	10.4 - 16.7	2700 - 4800	251 – 327
127	Fig.3 (c)	2.44	top skew	0.66	34	10.4 - 16.7	2400 - 4800	247 – 329
131	Fig.3 (c)	4.27	top skew	0.66	37	10.3 - 16.7	2600 - 4800	227 – 318
133	Fig.3 (c)	4.27	top skew	0.33	37	10.3 - 16.7	2000 - 4700	228 – 321
134	Fig.3 (c)	4.27	top skew	0.81	37	10.2 - 16.7	2600 - 4800	227 – 320
140	Fig.3 (c)	2.44	top skew	0.81	29	10.3 - 16.6	2700 - 4800	258 – 325
148	Fig.3 (c)	4.27	top skew	0.66	69	10.3 - 16.7	2000 - 4800	202 - 320
153	Fig.3 (c)	4.27	uniform	0.66	40	10.3 - 16.7	1900 - 4100	190 – 320
139	Fig.3 (d)	4.27	top skew	0.81	37	10.3 - 16.6	2500 - 4700	227 – 318
162	Fig.3 (b)	4.27	cosine	0.56	70	10.3 - 16.7	1400 - 4800	221 - 321
166	Fig.3 (d)	4.27	top skew	0.66	44	10.3 - 16.6	2000 - 4800	205 - 319
114	Fig.3 (c)	2.44	cosine	0.66	33	10.3 - 16.9	2700 - 5000	248 – 330
145	Fig.3 (c)	4.27	top skew	0.66	41	10.3 - 16.6	2700 - 4700	227 - 320
108	Fig.3 (c)	2.44	top skew	0.51	29	10.4 - 16.7	2600 - 4900	241 – 331
144	Fig.3 (d)	4.27	top skew	0.66	38	10.0 - 16.6	2700 - 4800	206 – 316
M01 ^{*1}	Fig.3 (a)	3.66	cosine	0.45	107	9.7 - 17.3	1400 - 4800	177 - 331
M02 ^{*1}	Fig.3 (b)	3.66	cosine	0.45	115	9.7 - 17.2	1400 - 4700	181 - 329

*1: Mitsubishi fuel (Z2 grid spacer) data



*1 TYP: Typical cell test section which is composed only of heated rods.

*2 THM: Thimble cell test section which is composed of a single unheated rod and heated rods.

Figure 3 Geometry of test sections [14]

3.2 Subchannel analysis code

Mitsubishi-developed subchannel analysis code, MIDAC (Mitsubishi Three Dimensional Drift-flux Code for Analysis of Core Two-Phase Flow) [15] [16], was adopted to evaluate local fluid parameters which are inputs to the CHF correlation. MIDAC can provide local fluid parameters for every computational node, such as pressure, local mass velocity and local quality. The following constitutive models are selected so as to provide best estimate predictions. In the design analysis, the explicit margin can be created by adopting conservative model options.

- Subcooled void detach model: Modified Saha-Zuber model
- Subcooled void generation: Lahey model
- Drift flux correlation: Homogeneous model (Pressure ≥ 12.5 MPa)
Chexal model (Pressure ≤ 10 MPa)
Interpolation between homogeneous and Chexal models
(10MPa < Pressure < 12.5MPa)

3.3 MG-S

Based on the discussion in Subsections 3.1 and 3.2, the new CHF correlation, MG-S, has been developed based on the basic equation Eq. (2), which can apply for core thermal-hydraulic design and plant safety analysis. MG-S is provided in the following.

$$q_{CHF,U}'' = \frac{A}{1 + \exp\{K(x_{loc} - C)\}} \quad (3)$$

$$A = A_0 A_{GRID} A_{CW}$$

$$A_0 = A_0(P, G_{loc}, De)$$

$$A_{GRID} = \text{mixing vane grid spacer factor}$$

$$A_{CW} = \text{unheated wall factor}$$

$$K = K(P, G_{loc})$$

$$C = C(P, G_{loc})$$

The parameters A , K , C were obtained by a conventional non linear parameter fitting method so as to reproduce CHF database specified in Subsection 3.1. The parameter A is a function of pressure P , local mass velocity G_{loc} , hydraulic equivalent diameter De , and several factor which are representative of fuel design, i.e., mixing vane grid spacer factor A_{GRID} and unheated wall factor A_{CW} . The parameters K and C are given as functions of P and G_{loc} .

The effect of non-uniform axial power distribution on CHF is considered by applying widely used Tong's non-uniform power shape factor F [17], which denotes the ratio of the equivalent uniform heat flux to the actual local heat flux. Finally, MG-S with the Tong's F -factor [17]

deduces the predicted CHF for non-uniform axial heat flux distribution, $q''_{CHF,NU}$, by following.

$$q''_{CHF,NU} = \frac{q''_{CHF,U}}{F} \quad (4)$$

The applicable range of MG-S is determined based on the fluid parameters and the geometrical parameters covered by the CHF database. Table 3 shows a summary of applicable range of MG-S. The applicable range can sufficiently cover typical parameters such as core thermal-hydraulic design and plant safety analysis of interest.

Table 3 Applicable range of MG-S

Pressure (MPa):	9.7	through	17.3
Local mass velocity (kg/m ² s):	1200	through	4900
Local quality (-):	-0.22	through	0.39
Grid spacing (mm):	330	through	813
Hydraulic equivalent diameter (mm):	9.5	through	12.9

3.4 Effects of key parameters on CHF

As described in Section 1, it should be confirmed that MG-S adequately takes into account the several additional factors listed in Table-1, which are required in the practical application. Table 4 shows the compatibility of MG-S with additional correlation factors listed in Table1. Since MG-S belongs to the local parameter type correlations, most of the additional correlation factors are automatically provided by subchannel analysis. In addition, it is notable that MG-S doesn't include a heated length factor in Eq. 3. Although MIRC-1 belongs to the local parameter type correlations as well as MG-S, it remains the heated length as an input parameter of the correlation. MG-S has been successfully developed as a fully local parameter based correlation by eliminating such a macro parameter effect.

Table 4 Compatibility of MG-S to the proposed correlation factors

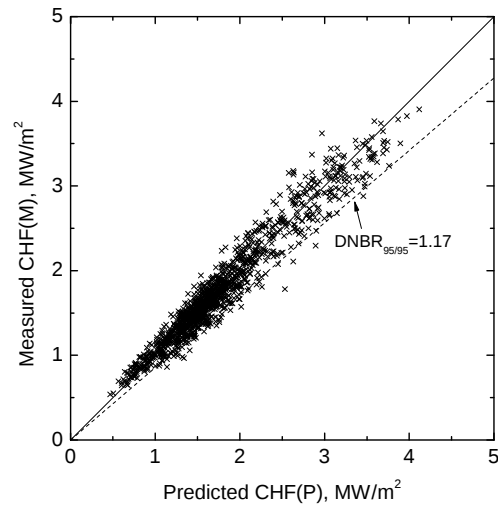
(A)	The effect of hydraulic equivalent diameter is modeled in MG-S (see Eq. 3).	(E)	Tong's non-uniform factor, F, in Eq. (4) can take into account the effect of axial heat flux distribution.
(B)	All of CHF database for the development of MG-S was based on the CHF data with rod bundle geometries.	(F)	Radial heat flux distributions are inputs to subchannel analysis code and implicitly considered in MG-S via local fluid parameters.
(C)	All of CHF database for the development of MG-S was based on the CHF data with mixing grid spacers. The spacing of mixing grid spacers is modeled in MG-S (see Eq. 3).	(G)	The flow distribution induced by the non-uniform pressure distribution and void generation can be evaluated by subchannel analysis and implicitly considered in MG-S via local fluid parameters.
(D)	The effect of heated length can be evaluated in subchannel analysis and implicitly considered in MG-S via local fluid parameters.	(H)	The CHF database doesn't include the vertical low-flow rate conditions such as downward flow.

4. Validation of MG-S

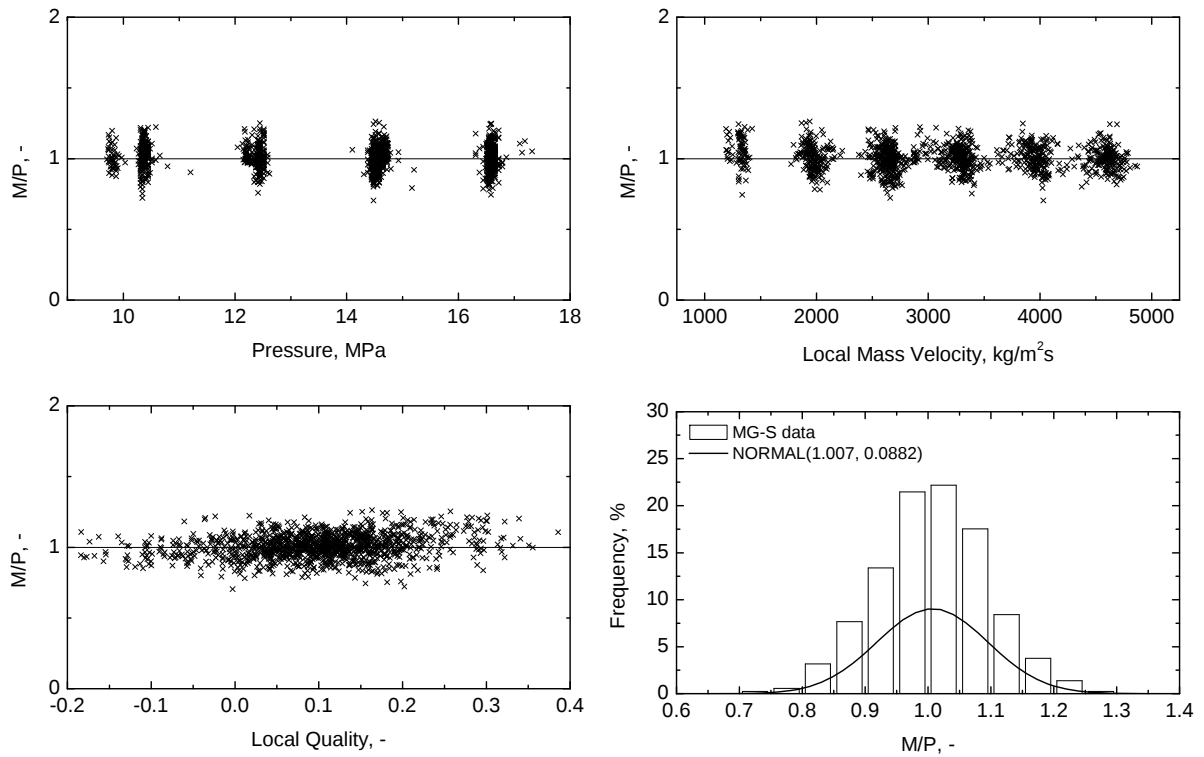
The CHF values predicted by MG-S were compared with CHF database described in Subsection 3.1 to confirm whether MG-S can adequately predict CHF for various fluid conditions. Figure 4(a) shows measured (M) versus predicted (P) CHF values. The predicted CHF values were obtained from the CHF test analyses based on the combination of MG-S and MIDAC subchannel analysis code. The figure shows that the plots are gathering around a diagonal line and the predicted CHF values are in reasonable agreement with the measured ones. The Figure 4(b) shows M/P versus pressure, M/P versus local mass velocity and M/P versus local quality, respectively. Here, M/P denotes a measured-to-predicted CHF ratio. It can be confirmed from the figures that M/P distributions show no significant dependency on the fluid conditions. The histogram based on all the M/P is presented in Figure 4(b). The M/P distributions can be assumed a normal distribution of which mean value is approximately 1.0. As a result, it was confirmed that MG-S can predict CHF values with sufficient accuracy for various fluid conditions and its prediction accuracy is independent on the fluid conditions.

Average of M/P and standard deviation by MG-S are 1.007 and 0.0882, respectively. DNBR correlation limit with 95% probability and 95% confidence level is deduced based on the M/P values, and resulted in 1.17. The DNBR correlation limit includes prediction uncertainties of MG-S and is adopted as a design limit for core designs and safety analyses to prevent DNB with 95% probability and 95% confidence level.

Figure 5 shows a comparison between CHF data coming from different heated length and predictions by MIRC-1 and MG-S. The CHF data are well predicted by either MIRC-1 or MG-S. As described in Subsection 3.4, a heated length factor was eliminated from the MG-S. Therefore, MG-S can draw a quality-versus-CHF curve by a single line without depending on heated length, whereas two different lines are needed in MIRC-1. As a result, it was confirmed that a heated length factor (macro factor) could be successfully eliminated from MG-S with maintaining good prediction accuracy. Figure 6 shows an applicability of MG-S to high quality condition, which is the most important target in the development of MG-S. The CHF data for high quality conditions were picked up from the Mitsubishi fuel with higher CHF performance (Z3 grid spacer) just for the purpose of this discussion. Obviously, the CHF data in Figure 6 shows larger CHF than the predictions due to its high CHF performance. However, MG-S could well predict the trend of quality-and-CHF curve shown by the CHF data. When MG-S is modified for the fuel with higher CHF performance in the near future, only simple modification will be required by considering the enhanced CHF performance, e.g. constant multiplier represented by parallel line in Figure 6.



(a) Measured versus Predicted CHF



(b) M/P versus pressure, local mass velocity, local quality, and histogram of M/P

Figure 4 CHF prediction of MG-S

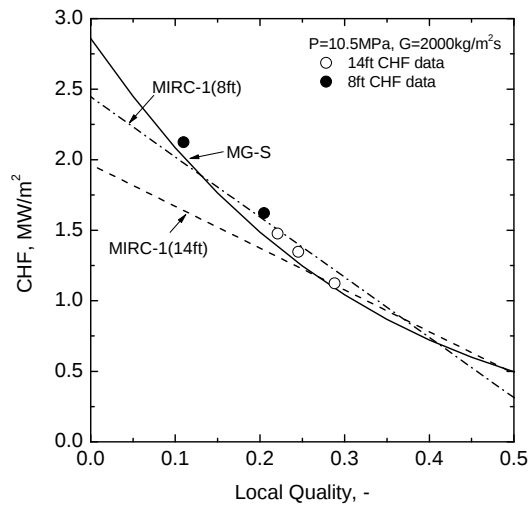


Figure 5 Effect of heated length for CHF

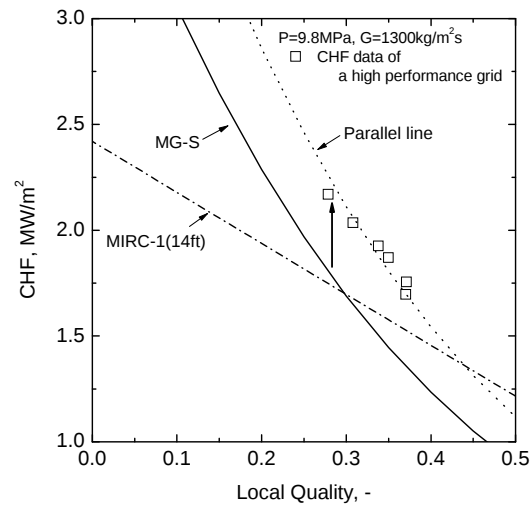


Figure 6 MG-S applicability to high quality

5. Conclusion

In this paper, the new CHF correlation, MG-S (Mitsubishi Generalized correlation - for Standard grid), was proposed which was established as a basic equation aiming to extend its applicability to higher quality conditions. The main features of MG-S are as follows;

- (1) MG-S is used for the core thermal-hydraulic design and most of the safety analyses as a replacement of the conventional MIRC-1 correlation.
- (2) MG-S was developed fully based on local parameters. The subchannel analysis code, MIDAC (Mitsubishi Three Dimensional Drift-flux Code for Analysis of Core Two-Phase Flow), can provide local parameters which are inputs to MG-S.
- (3) The CHF database for the development of MG-S was composed of MIRC-1 database and the CHF data of current Mitsubishi fuel (Z2 grid spacer).
- (4) MG-S can predict CHF values with sufficient accuracy for various fluid conditions and its prediction accuracy is independent on the fluid conditions. DNBR correlation limit with 95% probability and 95% confidence level was deduced based on the M/P values, and resulted in 1.17.
- (5) MG-S possesses potential capability to CHF predictions for high quality conditions. Simple modifications to MG-S can realize the CHF predictions for the next fuel with high CHF performance.

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