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Assessment of CHF Correlations for Internally Heated Concentric Annulus Channels

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Abstract

The existing CHF correlations for internally heated concentric annulus channels are assessed using KAIST CHF database for uniformly heated vertical annuli. Six annulus correlations (Jannsen-Kervinen, Barnett, Levitan-Lantsman, Kumamaru et al., Doerffer et al., and Bobkov et al.) are chosen for assessment based on literature survey and Groeneveld et al.'s CHF table for round tube is also assessed for comparison. Among the above correlations, two are inlet-condition type and others local conditions type. To make the comparison meaningful, the local-condition-type correlations are assessed in two ways: direct substitution method (DSM) and heat balance condition method (HBM). Totally 1174 data are classified into 10 groups based on pressure and mass flux conditions and correlations are assessed to each group separately. Prediction capability of each correlation depends on the data group and none shows the best prediction over the entire group. In overall, the correlations by Doerffer et al. and Jannsen et al. appear to be the best, but Barnett or Levitan-Lantsman correlations also show reasonable prediction for most groups. However, the low-pressure, low flow CHFs are not well predicted by any correlations. The CHF table for round tubes overpredicts the CHF in annuli at fixed local conditions.

1. Introduction

The researches on critical heat flux (CHF) have been extensively carried out during the last four decades for various geometries: round tubes, rod-bundles, annuli, rectangular channels, etc. Among these geometrical CHF studies, less investigation has been done for annulus geometries than for round tubes and rod-bundles. The interest in annular geometry experiments mainly lies in the fact that the flow structure around the rods in rod bundles is of annular type, and moreover, peripheral subchannels of rod bundles may be assimilated to a part of an annulus having an inside heated rod and an unheated shroud [1].

Generally, the CHF in annuli is small relative to that in the round tube for the same local conditions. There are several mechanisms that make differences in CHF between annuli and round tubes. One is the unheated cold wall effect which causes the liquid film thickness differences between inner and outer rod, enthalpy imbalance and the asymmetry of void distribution. Also there exist phase velocity difference, abnormal liquid exchange at vapor core interface and weak droplet deposition rate.

In this paper, existing CHF correlations for internally heated concentric annulus channels are assessed using the KAIST CHF database [2] which consists of available worldwide and KAIST experimental data. The data base is divided into 10 groups based on pressure and mass flux, in order to investigate the prediction capability according to operating conditions.

2. Correlations, Databases, and Assessment Method

There are several CHF correlations suggested for vertical concentric annuli. Table 1 shows five of them [3-7]frequently referred in the literature and a most reliable prediction method for vertical round tubes[8]. Generally, the type of the correlation can be classified as local-condition type and inlet-condition type according to whether it uses local quality or inlet subcooling. And the annulus correlations use hydraulic equivalent diameter (D_e), heated equivalent diameter (D_h) or both, to represent the cross-sectional dimension. The first column of Table 1 shows this information as well as the reference. Other columns of Table 1 summarize the data base ranges upon which the correlations were developed. It is interesting to note that Bobkov et al. [4], Doerffer et al. [5], and Levitan-Lantsman [7] correlations are derived by applying correction factors to CHF tables for round tubes. Groeneveld et al.'s 1995 CHF table [8] represents the most accurate round tube CHF values for most operating conditions. Their former table [9] has been adopted in many best-estimate thermal-hydraulic codes such as RELAP5/MOD3, CATHARE, CATHENA, etc.

Table 2 summarizes the KAIST CHF data base [2] used in correlation assessment: Becker et al. data [10] for intermediate pressure and low flow conditions, Jannsen-Kervinen data [6] for high-pressure conditions, and others [2, 11] for low-pressure, low-flow conditions. The data distributions according to pressure, mass flux and critical quality are summarized in Table 3. For correlation assessment, the operating conditions are divided into 16 regions based on pressure and mass flux, among which only 10 regions have actual experimental data for assessment. In Tables 4 and 5, the notion of each region is given as (Pressure Region)-(Mass Flux Region). For each parameter, VL, L, M and H represent "very low", "low", "medium" and "high", respectively.

The assessment of inlet-condition-type correlations can be done by substituting the inlet conditions directly into the correlations. However, there are two ways to use the local-condition-type correlations: the direct substitution method (DSM) and heat balance condition method (HBM) as illustrated in Fig. 1[12]. Prediction errors are found to be larger for DSM [12]. Actually, the use of a local-condition-type correlation by the HBM is equivalent to using one converted into the inlet-condition type. Therefore, it is reasonable to use error statistics of HBM for local-condition correlations when we compare inlet- and local-condition correlations. The local condition correlations are assessed by both DSM and HBM in this work.

3. Results and Discussions

Table 5 summarizes the assessment results. Each correlation shows different prediction capability according to operating conditions. Figure 2 illustrates the performance of the correlation that shows the least prediction error for each region. The results are discussed in more detail in the following paragraphs.

(a) *Region VL-VL (pressure 100-1000 kPa, mass flux 0-500 kg/m^{2}s)*: Most correlations show very large errors. Kumamaru correlation gives the least but still large prediction errors. This reveals the need for a new correlation for this region. The correlation of El-Genk et al.[11] specific to this region is not adequate for general applications; therefore it is not assessed in this work.

(b) *Region L-VL (pressure 1000-5000 kPa, mass flux 0-500 kg/m^{2}s)*: Prediction capability is improved especially for Barnett and Babkov et al. correlations. However, most other correlations still show very large errors.

(c) *Region L-L (pressure 1000-5000 kPa, mass flux 500-1000 kg/m^{2}s)*: Doerffer et al., Barnett, and Levitan-Lantsman correlations show excellent prediction. Jannsen-Kervinen correlation also give reasonable prediction.

(d) *Region L-M (pressure 1000-5000 kPa, mass flux 1000-3000 kg/m^{2}s)*: Jannsen-Kervinen and Doerffer et al. correlation predict the data excellently. Levitan-Lantsman and Barnett correlations also show reasonable prediction.

(e) *Region M-VL (pressure 5000-8000 kPa, mass flux 0-500 kg/m^{2}s)*: Jannsen-Kervinen and Barnett correlations show excellent prediction. In this region, Doerffer et al. and Levitan-Lantsman correlations based on tube correlations do not show good accuracy. This would be related to the fact that the tube CHF tables do not accurately predict the tube CHF itself at very low flow conditions[8].

(f) *Region M-L (pressure 5000-8000 kPa, mass flux 500-1000 kg/m^{2}s)*: Doerffer et al., Barnett, Jannsen-Kervinen and Levitan-Lantsman correlations all show good accuracy.

(g) *Region M-M (pressure 5000-8000 kPa, mass flux 1000-3000 kg/m^{2}s)*: The accuracy is deteriorated to some degree, but four correlations by Doerffer et al., Barnett, Jannsen-Kervinen and Levitan-Lantsman show good prediction capability.

(h) *Region M-H (pressure 5000-8000 kPa, mass flux 3000-8500 kg/m^{2}s)*: Levitan-Lantsman, Doerffer et al., and Barnett correlations show excellent prediction; however, Jannsen-Kervinen correlation does not show good accuracy.

(i) *Region H-M (pressure 8000-110000 kPa, mass flux 1000-3000 kg/m^{2}s)*: Doerffer et al., Jannsen-Kervinen, and Levitan et al. correlations shows excellent prediction. Barnett correlation also give reasonable prediction.

(j) *Region H-H (pressure 8000-110000 kPa, mass flux 3000-8500 kg/m^{2}s)*: Doerffer et al. correlation shows the best prediction; but all the correlations overpredicts the CHF in the region.

In overall, Doerffer et al. correlation is assessed to show the best prediction capability over wide operating conditions; it can be used for most conditions with reasonable prediction error. Jannsen-Kervinen correlation also shows reasonable prediction errors except for low-pressure, low-flow conditions. Levitan-Lantsman correlation and Barnett correlation show a little higher prediction errors than Doerffer et al. correlation. Bobkov et al. and Kumamaru et al. correlations are not assessed to improve the prediction accuracy of previous correlations; however, their data bases can be quite different from ours.

It is shown that the CHF table for round tubes overpredicts the annulus CHF data for the same local (but area averaged at the same elevation) conditions. This is primarily due to the enthalpy imbalance caused by the unheated outer wall. The difference in CHF between tubes and annuli decreases with pressure. On the other hand, the good performance of Doerffer et al. and Levitan-Lantsman correlations which apply some correction factors to the CHF tables for round tubes, indicates the feasibility of a well-established tube correlation (or table or mechanistic model) as a basis for annulus CHF prediction models. As the experimental data are very extensive and there exist some very reliable prediction models for most regions, the CHF prediction for other geometries (annuli, rod bundles, etc.) can be developed by fully utilizing this information.

4. Conclusions

Following conclusions can be drawn from this study:

(a) Four correlations, i.e., Doerffer et al.[5], Jannsen-Kervinen[6], Levitan-Lantsman[7] and Barnett[3] correlations, show reasonable prediction capability over most operating conditions of common interests. Among them, the Doerffer et al. correlation shows the best prediction capability in overall sense and Jannsen-Kervinen correlation shows the least error for some specific regions.

(b) There is no reliable correlations for very low pressure conditions ($P < 1000$ kPa); there is a strong need for new correlations with enhanced prediction capability.

(c) The tube CHF table overpredicts the annulus CHF due to the effect of unheated wall in internally heated annuli. The degree of overprediction decreases with the increase of pressure.

(d) The success of tube-table-based correlations by Doerffer et al. and Levitan-Lantsman indicates the feasibility of a well-established tube correlation (or table or mechanistic model) as a basis for future development of annulus CHF prediction models.

As a result of this work, it is suggested that Doerffer et al. correlation be used for reliable assessment of the annulus CHF for most conditions. However, further assessment with a more extensive data base covering the wider operating conditions and the improvement of models for some specific regions are needed as future work.

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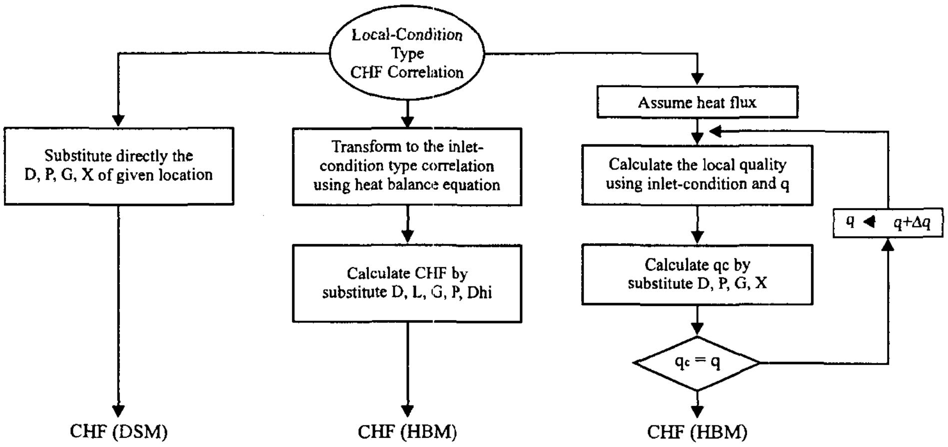

Figure 1. Prediction of CHF by Local-Condition Type Correlation

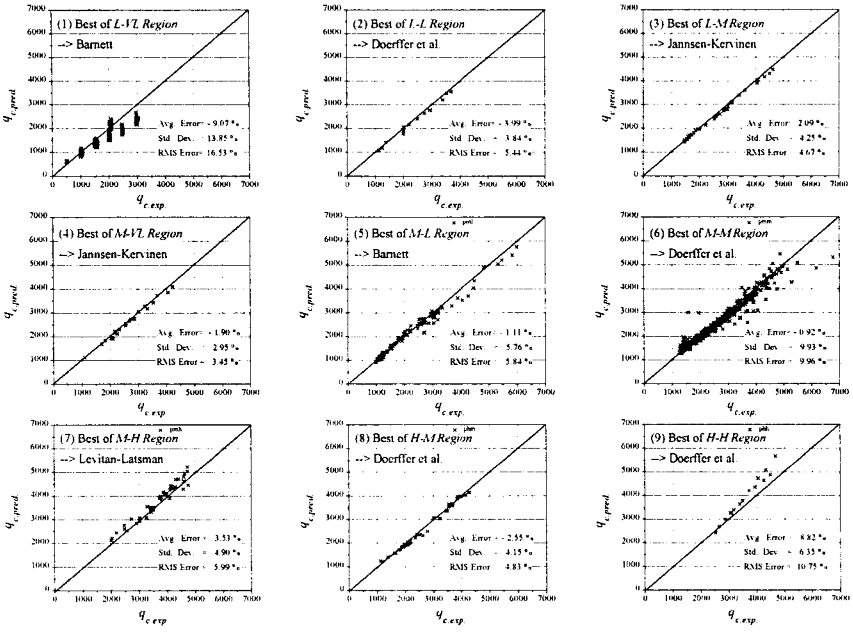

Figure 2. Comparison Results of Annulus CHF Correlations According to Divided Regions

Table 1. Ranges of Available Annulus CHF Correlations

Prediction model	D_i (m)	D_o (m)	D_e (m)	L (m)	P (kPa)	G (kg/m²s)	X (-)	Note
Annulus CHF correlations								
Barnett (1966) [3] <Inlet. D_h, D_e>	0.00952 ~ 0.0965	0.014~ 0.1016	-	0.61~ 2.74	6895	190~ 8430	-	Δh_i 0 to 958
Bobkov et al. (1995) [4] <Local, D_h>	-	-	-	-	100~ 20000	0~ 8000	-0.5~ 0.9	Using look -up table
Doerffer et al. (1994) [5] <Local, D_e>	-	-	-	-	100~ 20000	0~ 8000	-0.5~ 0.9	1986 AECL-UO
Jannsen-Kervinen [6] (1963) <Local, D_e>	-	-	0.00635 ~ 0.02223	-	4137~ 9998	190~ 8430	-0.12~ 0.45	q_c > 1103.8
Levitan-Lantsman (1977) [7] <Local, D_h>	0.002~ 0.096		0.002~ 0.022		3500~ 20000	500~ 5000	-0.4~ x_{bo}	L/D_e > 50
Round Tube CHF correlations								
New LOOK-UP (1995) [8] <Local>	-	-	-	-	100~ 20000	0~ 8000	-0.5~ 0.9	New LOOK-UP

Table 2. KAIST CHF Data Base for Internally Heated Concentric Vertical Annulus Channels

Data source	D_i (m)	D_o (m)	L (m)	P (kPa)	G (kg/m^{2}s)	q_c (kW/m^2)	X_c (-)	No. of data
KAIST [2]	0.019	0.029~ 0.035	0.6	110	0~ 198	34~ 553	0.1~ .525	58
Jannsen-Kervinen [6]	0.00635~ 0.01372	0.01410~ 0.03175	0.737~ 2.743	4089~ 10011	189.9~ 8408.6	829~ 6770	-0.129~ 0.655	630
Becker et al.[10]	0.00992~ 0.01012	0.01742~ 0.02495	0.608~ 1.216	1000~ 3620	49.7~ 661.0	498~ 3032	0.099~ 0.564	247
El-Genk et al.[11]	0.013	0.02~ 0.025	0.5	118	0~ 260	157~ 1122	0.4~ 0.85	190
Total	0.00635~ 0.019	0.01410~ 0.035	0.5~ 2.743	110~ 10011	0~ 8408.6	34~ 6770	-0.129~ 0.85	1125

Table 3. Data Distribution of KAIST Annulus CHF Database

Pressure Range	100 to 1000 (kPa)				1000 to 5000 (kPa)				5000 to 8000 (kPa)				8000 to 11000 (kPa)			
	Quality Range				Quality Range				Quality Range				Quality Range			
Mass Flux (kg/m^{2}s)	-0.5 ~ -0.1	-0.1 ~ 0.2	0.2 ~ 0.5	0.5 ~ 1.0	-0.5 ~ -0.1	-0.1 ~ 0.2	0.2 ~ 0.5	0.5 ~ 1.0	-0.5 ~ -0.1	-0.1 ~ 0.2	0.2 ~ 0.5	0.5 ~ 1.0	-0.5 ~ -0.1	-0.1 ~ 0.2	0.2 ~ 0.5	0.5 ~ 1.0
0 to 500	0	36	153	59	0	105	129	8	0	13	12	4	0	0	0	0
500 to 1000	0	6	0	0	0	9	6	0	1	24	90	0	0	0	0	0
1000 to 3000	0	0	0	0	0	17	16	0	0	252	93	0	0	36	5	0
3000 to 8500	0	0	0	0	0	0	0	0	0	42	0	0	1	14	0	0

Table 4. Divided KAIST Annulus CHF Database According to Pressures and Mass Velocities

Pressure Range	100 to 1000 kPa	1000 to 5000 kPa	5000 to 8000 kPa	8000 to 11000 kPa	
Mass Flux Range (kg/m^{2}s)	Data Name & Number	Data Name & Number	Data Name & Number	Data Name & Number	Total Number
0 to 500	(*VL-VL*) 248	(*L-VL*) 242	(*M-VL*) 29	(*H-VL*) 0	519
500 to 1000	(*VL-L*) 0	(*L-L*) 15	(*M-L*) 115	(*H-L*) 0	130
1000 to 3000	(*VL-M*) 0	(*L-M*) 33	(*M-M*) 345	(*H-M*) 41	419
3000 to 8500	(*VL-H*) 0	(*L-H*) 0	(*M-H*) 42	(*H-H*) 15	57
Total Number	248	290	531	56	1125