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Assessment and Improvement of Condensation Models in RELAP5/MOD3.2

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Abstract

The condensation models in the standard RELAP5/MOD3.2 code are assessed and improved based on the database, which is constructed from the previous experimental data on various condensation phenomena. The default model of the laminar film condensation in RELAP5/MOD3.2 does not give any reliable predictions, and its alternative model always predicts higher values than the experimental data. Therefore, it is needed to develop a new correlation based on the experimental data of various operating ranges in the constructed database. The Shah correlation, which is used to calculate the turbulent film condensation heat transfer coefficients in the standard RELAP5/MOD3.2, well predicts the experimental data in the database. The horizontally stratified condensation model of RELAP5/MOD3.2 overpredicts both cocurrent and countercurrent experimental data. The correlation proposed by H.J.Kim predicts the database relatively well compared with that of RELAP5/MOD3.2. The RELAP5/MOD3.2 model should use the liquid velocity for the calculation of the liquid Reynolds number and be modified to consider the effects of the gas velocity and the film thickness.

1. Introduction

The best estimate safety analysis code, RELAP5/MOD3.2, which was developed at INEL(Idaho National Engineering Laboratory) for the U. S. NRC(Nuclear Regulatory Commission), is used to analyze the transients and the LOCA(LOss of Coolant Accident) of a nuclear power plant. A lot of heat transfer correlations in RELAP5/MOD3.2 are known to have much uncertainties. In particular, there is no reliable model on condensation phenomena with noncondensable gases in a vertical tube of IC(Isolation condenser), which is applicable to the design of the PCCS(Passive containment cooling system) and SC(Secondary Condenser). It is also needed to assess the models for direct contact condensation phenomena in a CMT(Core Makeup Tank) and in a DVI line(Direct Vessel Injection line) of CP-1300 with RELAP5/MOD3.2.

The objective of this research is to minimize the uncertainties of the condensation models in RELAP5/MOD3.2 code through the assessment with the experimental data of the database.

The condensation models of the standard RELAP5/MOD3.2 code are divided into the wall film condensation and the interfacial condensation. Each modes are analyzed separately in this paper.

A condensation heat transfer database is constructed from the previous data on the various condensation experiments in a vertical condensing tube with laminar and turbulent condensate films, and on the horizontally and vertically stratified condensation. Based on the constructed database, the condensation models in RELAP5/MOD3.2 are assessed and improved.

2. Condensation Models in RELAP5/MOD3.2

The heat transfer phenomena are modeled in two distinct way in RELAP5/MOD3.2. The one is the wall heat transfer, providing energy to either the liquid or vapor phase, or both, and the other is the interfacial heat transfer through an assumed interface as a result of differences in the bulk temperature of the liquid and vapor phases.

2.1 Wall Film Condensation Heat Transfer Correlations

Two wall condensation models, the default and the alternative, are used in RELAP5/MOD3.2. The default model is to use the maximum of Nusselt's and Shah's with a diffusion calculation when noncondensable gases are present. The Nusselt expression for the vertical surfaces uses the film thickness.

$$h_{Nu} = \frac{k_f}{\delta},$$

where from Nusselt's derivation the film thickness is

$$\delta = \left[\frac{3\mu_f \Gamma}{g\rho_f \Delta\rho}\right]^{1/3}.$$

The alternative model is the Nusselt model with UCB multipliers, which is revised to include the effects of the interfacial shear and the presence of the noncondensable gas in a vertical tube as follows.

$$\frac{h_{UCB}\delta}{k_f} = f_1 \cdot f_2$$

The enhancement factor, f_1, accounts for the effects of the shear of the gas on the liquid film, and the degradation factor, f_2, accounts for the effects of the noncondensable gas on the heat transfer coefficient.

For a horizontal tube with laminar flow the Nusselt correlation is replaced by the Chato correlation.

The detailed descriptions of the correlations are given in RELAP5/MOD3.2 code manual.[1]

2.2 Interfacial Condensation Heat Transfer Correlations

The interfacial condensation heat transfer is divided into the horizontally and the vertically stratified flow. For the horizontal stratified flow, the Dittus-Boelter correlation is used for the smooth interface, and for the vertical stratified flow the McAdams correlation is used. The detailed descriptions of the correlations are also given in RELAP5/MOD3.2 code manual.[1]

The degradation factor, f_2, of the UCB multiplier is also used to consider the effect of the noncondensable gas like the wall condensation heat transfer.

3. Condensation Heat Transfer Database

The condensation heat transfer database is constructed by collecting the local data, including the wall film and the interfacial condensation and by calculating the local values from the correlations published. However, most literature reports an averaged values rather than the local ones. Futhermore, the correlations for the condensation heat transfer coefficient in literature are based on their own data reduction method. It makes the construction of the condensation database based on the local values difficult. Therefore, the number of usable data for assessment is restricted and the assessment is limited.

The condensation phenomena are divided into 4 categories depending on the test geometry and film characteristics; 1. Vertical Laminar Film Condensation Heat Transfer, 2. Vertical Turbulent Film Condensation Heat Transfer, 3. Horizontal stratified condensation heat transfer, and 4. Vertical stratified condensation heat transfer.

The above-mentioned condensation phenomena are so different from the others that they have each unique condensation mechanisms. Also the definitions of the local variables such as the heat transfer coefficient and the nondimensional parameters, which describe and simulate each condensation phenomena, has its own meanings. However most of the variables are common except for a few variables which depend on the specific condensation phenomena.

Using the similarity between each condensation phenomena, a database of condensation heat transfer coefficient is constructed with the same format to maximize usefulness.

The used variables are described briefly and each data point has 27 fields which have the meanings as shown in table 1. H.C.NO et al.[2] give the detailed descriptions such as the types of the noncondensables, the substance of the condensing fluid, the definition of the nondimensional numbers and the identification of the experimental data.

Table 1. Parameters of the condensation heat transfer database

Col.	Field	Meaning
A	#	sequential number of data points
B	htc	local heat transfer coefficient (KW/m^2°C)
C	z	location from the liquid entrance (m)
D	Tf	local bulk mean temperature of the liquid phase (°C)
E	Tg	local bulk mean temperature of the mixture (°C)
F	Ti	local interfacial temperature (°C)
G	Tw	local wall temperature(°C)
H	Wf	local mass flow rate of the liquid phase (kg/s)
I	Wg	local mass flow rate of the condensing vapor or mixture (kg/s)
J	x	local flow quality
K	alpha	local void fraction
L	P	local pressure (MPa)
M	h	local liquid film thickness (m)
N	D1	hydraulic diameter(if circular tube), etc
O	D2	channel width, inner tube diameter, etc
P	L	length of the test section or submergence, etc
Q	theta	inclination angle between flow direction
R	Non	type of the noncondensables
S	X	mass fraction of the noncondensables
T	fluids	substance of the condensing phase
U	Ref	liquid or nozzle Reynolds number
V	Reg	gas phase Reynolds number
W	Pr	liquid phase Prandtl number
X	Ja, τ_i^*	Jacob number, or dimensionless interfacial shear stress
Y	Sc, Fr, Ri	Schmidt number, Froude number, or Richard number
Z	Nu	Nusselt number
AA	I.D.	identifier of the data point

For the laminar film condensation inside a vertical condensing tube, experimental data are collected from the studies by Vierow, Siddique, Hasanein, Kuhn, and Park. For the vertical turbulent film condensation Carpenter, Goodykoontz and Kuhn give the local data . Also Lim, Segev, Kim and Kim give the horizontal stratified condensation heat transfer data.

The local heat transfer coefficient data are not acquired for the vertical stratified condensation, but it needs explanations for that phenomena. There are three separate models; 1. McAdams' model for the vertical stratified heat transfer without surface perturbation, 2. Brown-Khoo-Sonin's model, Brown-Helmick-Sonin's model, and Theofanous model for the vertical stratified heat transfer by the water jetting from the bottom, 3. A model based on the KAIST CMT experimental data for the vertical stratified heat transfer by the water jetting from the top.

4. Assessment of the Condensation Models in RELAP5/MOD3.2

The condensation models in RELAP5/MOD3.2 are assessed and improved based on the constructed database, including models of the laminar film condensation heat transfer, the turbulent film condensation heat transfer, and the horizontal stratified condensation heat transfer.

4.1 Laminar Film Condensation Heat Transfer

Both the default model and the alternative model used for the laminar condensation heat transfer inside a vertical condensing tube are assessed. In case of the default model, it is compared with the Hasanein's steam-helium experimental data. The model underpredicts the experimental data for the low heat transfer coefficient range, but it overpredicts the experimental data for the high heat transfer coefficient range as shown in figure 1. As the heat transfer coefficients calculated from the default model do not agree with the heat transfer coefficients of the database and show much large scattering, the default model is inadequate to predict the laminar film condensation with noncondensable gas.

In case of the alternative model, it is compared with steam-helium experimental data of Hasanein and Kuhn. As the enhancement factor f_1 is always highly evaluated, the model predicts higher values than both Hasanein's and Kuhn's experimental data as shown in figure 2.

As the Vierow's experimental data used for the development of the UCB multiplier in the alternative model shows great scattering, it is desirable to be based on more experimental data to develop a new correlation.

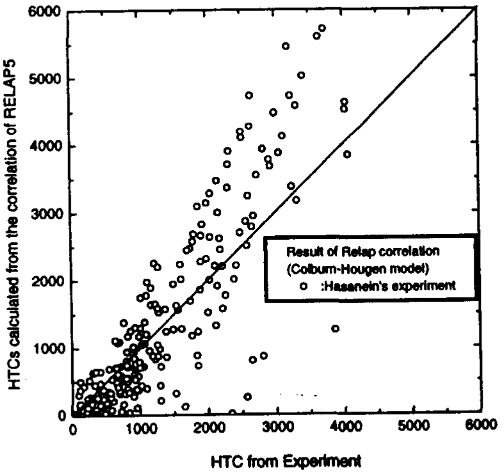

Figure 1. Assessment of RELAP5/MOD3.2 model (Default model)

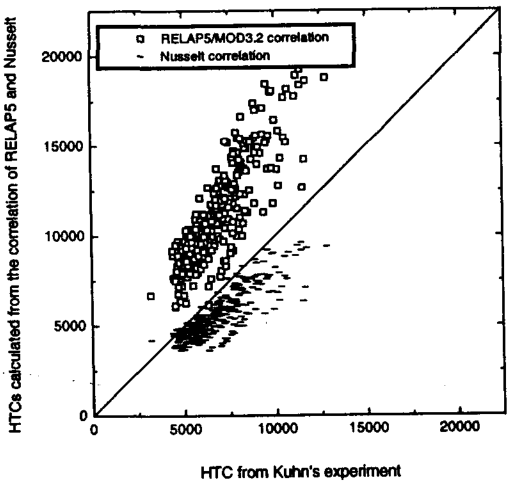

Figure 2. Assessment of RELAP5/MOD3.2 model (Alternative model)

4.2 Turbulent Film Condensation Heat Transfer

It is found that there is much scattering of the experimental data depending on Prandtl number and the interfacial shear stress in the turbulent film condensation region, but little scattering in the laminar film condensation region. Generally, as Prandtl number and the interfacial shear stress increase, the film condensation heat transfer coefficient increases in the turbulent film condensation region as shown in figure 3.

Shah's correlation which is used to calculate the turbulent film condensation heat transfer coefficients in the standard RELAP5/MOD3.2, shows good agreement with the experimental data in the database, although it does not consider the effect of interfacial shear stress, which is the most important parameter in the turbulent film condensation. It is needed to revise the correlation of Shah, considering the effect of the interfacial shear stress.

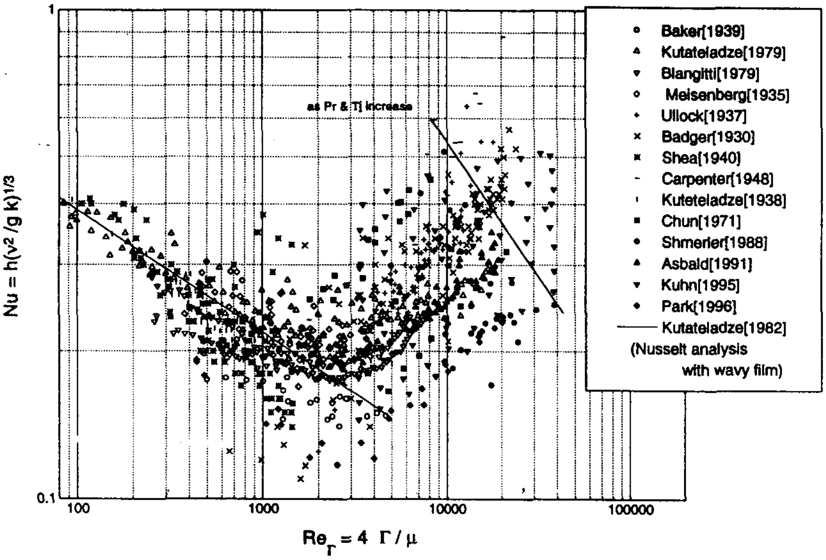

Figure 3. Film condensation heat transfer database

4.3 Horizontal Stratified Condensation Heat Transfer

The assessment for the horizontal stratified heat transfer model in RELAP5/MOD3.2 is carried out with the experimental database both for the cocurrent and the countercurrent stratified flow. The experimental data by I.S.Lim and H.J.Kim are used for the reference database for the cocurrent and the countercurrent flow, respectively. Figures 4 and 5 show the assessment results that the model in RELAP5/MOD3.2 overpredicts the database both for cocurent and countercurrent cases.

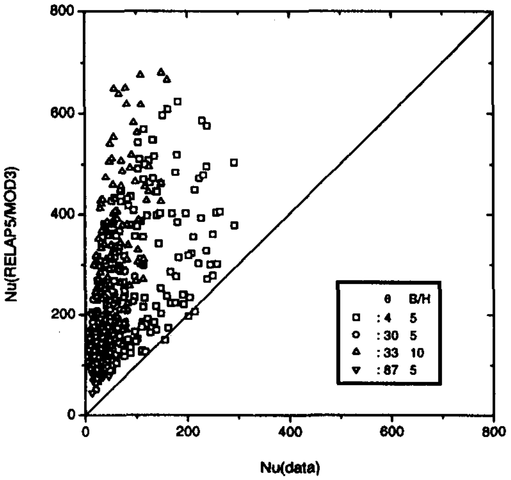

Figure 4. Comparison of RELAP5/MOD3.2 correlation with H.J.Kim's data

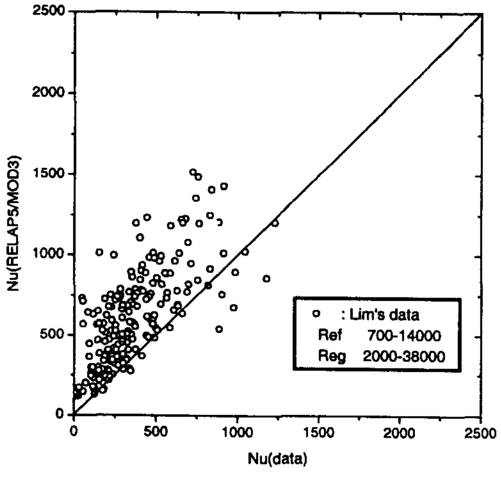

Figure 5. Comparison of RELAP5/MOD3.2 correlation with I.S.Lim's data

In particular, the overprediction for the countercurrent flow is much larger than that for the cocurrent flow. The deviation of the predicted value from the database is found to be larger with the increase of the gas velocity. In RELAP5/MOD3.2, the liquid Reynolds number is spuriously defined based on the relative velocity between the gas and the liquid phases. It appears not to be valid physically. It is reasonable that the liquid Reynolds number should be defined based on the liquid velocity only. The effects of the gas velocity, the liquid film thickness and the geometry can be considered with Froude number, Fr, like the correlation by H.J.Kim. It is interesting that the correlation by H.J.Kim predicts all data of this database better than the model in RELAP5/MOD3.2 even for the cocurrent flow.

5. Results and Discussion

The condensation models in the standard RELAP5/MOD3.2 code are investigated, and based on the database constructed from the experimental data on various condensation phenomena, the condensation models in the code are assessed and improved. Followings are concluded from the above results.

A. The default model of the laminar film condensation in RELAP5/MOD3.2 overpredicts the experimental data in the higher heat transfer region, but underpredicts the experimental data in the lower heat transfer region. In case of the alternative model, the predicted values are always higher than the experimental data. As the enhancement factor, f_1, is always calculated to have a higher value in RELAP5/MOD3.2, it is needed to develop a new correlation based on the experimental data of various operating ranges.

B. The Shah correlation of the turbulent film condensation model in RELAP5/MOD3.2 well predicts the experimental data in the database. However, as it does not consider the effect of the interfacial shear stress, it is necessary to develop a correlation which includes the effect of the interfacial shear stress.

C. The horizontally stratified condensation model of RELAP5/MOD3.2 overpredicts both the cocurrent and the countercurrent experimental data. The deviation from the database is found to be large with the high gas velocity. The correlation proposed by H.J.Kim predicts the database relatively well compared with that of RELAP5/MOD3.2. The RELAP5/MOD3.2 model should use the liquid velocity for the calculation of the liquid Reynolds number and be modified to consider the effects of the gas velocity and the film thickness.

It is needed to expand the constructed condensation heat transfer database, and improve the correlations of RELAP5/MOD3.2. As each experimental results and developed correlations, whose local data is included in the present database, has limited applicable ranges, new models with wide applicable ranges for the various condensation phenomena can be developed from the constructed condensation database, and be applicable to the RELAP5/MOD3.2.

References

1. "RELAP5/MOD3 Code Manual, Volume IV: Models and Correlations" NUREG/CR-5535, INEL-95/0174, IV, INEL, June 1995

2. Hee Cheon NO, Sang Il LEE, Ki Yong CHOI, Hyun Sik PARK, and Sang Jae KIM, "Assessment and Improvement of Condensation Model in RELAP5/MOD3", KINS/HR-176, 1996.