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Parametric Analysis of Various Condensation Models Applicable for Passive Containment Cooling System

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1. Introduction

Recently, the passive engineering components such as PCCS, PAFS etc. have been adopted in new advanced Light Water Reactors (LWR) and Boiling Water Reactors (BWR). Typical reactors designed with the concept of passive safety features are AP1000, VVER-1200, ESBWR, AES-2006, APR +, etc. Especially the development of passive containment cooling system (PCCS) of APR+ has been progressing in in Korea. The most important physical phenomena determining the performance of PCCS is wall condensation on outside surface of PCCS heat exchangers.

In this work, the relative performances and parametric behaviors of a selected number of condensation models are investigated using a simple package program, in which the available those are included. Two type of models are considered; a mechanistic and experimental ones.

2. Design Concept of PCCS

Figure 1 shows the conceptual design of PCCS in brief. Bundle of PCCS heat exchangers are installed at the top of containment building. Tube outside will be contacted with containment atmosphere and condensation will be also happened. Thanks to the buoyancy driven force, cooling water from PCCS tank through tube inside is naturally circulated. After the LOCA accident, huge amount of water steam carrying a lot of energy from the primary side is blown out and immediately mixed with air (non-condensable gas) already existing in containment. In initiation period of accident, hot steam flume will hit the top part of dome and its flow pattern is unlikely to be directly affected by heat transfer through PCCS and passive heat sink. In long term period, however, PCCS plays a key role to determine the flow pattern (expected to play a certain part) and depressurization of containment.

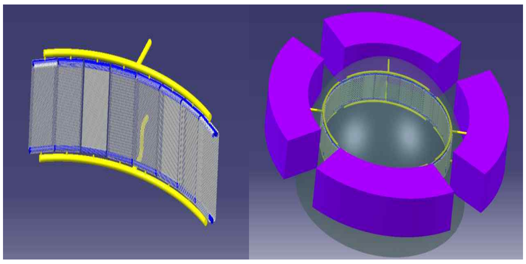

Fig 1 Conceptual design of PCCS

3. Condensation Model

More than a few theoretical and experimental studies of condensation have been carried out so far. Among these, what we need to be interested is in case of non-condensable gas mixture. As a point of view of surface shape on that condensation happen, our interests lie in the outside of tube, rather than the inside of tube and plate surface. Usually a significant part of the literature about condensation has been focused on the flat plate surface. A couple of experiments interested in tube outside condensation, however, were carried out; for example, Dehbi, Kawakubo, Liu, Su, Lee's experiments. Those experiments were carried in condition of similar configurations; single condensation tube in a certain size of container, secondary water cooling through tube, steam suppling from a separate steam generator or immersion heater which sank to the bottom pool.

3.1. Mechanistic Models

One of the most common mechanistic models is Collier's model which is based on the HTMA for the gas mass transfer coefficient. During the LOCA accident, film-wise condensation is expected on PCCS heat exchanger surface. Film formation on the surface plays as a resistance of heat flow. It, therefore, must be considered to complete the heat and mass balance and requires the iterative solution. It results in the thermodynamic conditions of diffusion boundary layer on condensate film. The transfer of heat from the bulk gas mixture to the interface is made up two components; the sensible heat and latent heat through the layer. In other to decide the condensation mass transfer coefficient, the head and mass transfer analogy (HMTA) is mostly used. This type of condensation model is adopted in many system codes and containment codes. RELAP, MELCOR, GOTHIC, CONTAIN etc., even though models of these codes shows no evidence that can be applicable to PCCS.

$$q''_{film} = q''_{conv} + q''_{cond}$$

$$q''_{film} = h_f \Delta T_f$$

$$q''_{cond} = K_c \rho_g \frac{(P_{sb} - P_{si})}{P_{am}} h_{fg}$$

$$q''_{conv} = h_s \Delta T_s$$

Table 1 Experimental correlations of condensation heat transfer coefficient

Author	Correlation	Applicable Range
Dehbi(1991)	$\bar{h}=\frac{L^{0.05}\left[(3.7+28.7P)-(2438+458.3P)\log W_a\right]}{\Delta T_w^{0.25}}$, *where P in atm*	$0.3\le L\le 3.5m$ $0.152\le P\le 0.456MPa$ $10\le T_b-T_w\le 50^oC$
Liu(2000)	$\bar{h}=55.635X_s^{2.344}P^{0.252}\Delta T_w^{0.307}$, *whter P in Pa*	$0.2533\le P\le 0.4559MPa$ $0.395\le W_a\le 0.873$ $4\le T_b-T_w\le 25^oC$
Kawakubo(2008)	$\bar{h}=\left(1/\bar{h}_f+1/\bar{h}_i\right)^{-1}$ $\bar{h}_f$: Film HTC evaluated by Nusselt's therory $\bar{h}_i=\min\left[0.33X_a^{-0.8}\Delta T_w^{0.25},\ X_a^{-0.1}\Delta T_w^{-0.2X_{air}^{-0.25}}\right]\cdot(P+0.5)$, *where P in MPa*	$0.33\le L\le 1.0m$ $0.2\le P\le 0.4MPa$ $0.05\le X_a\le 0.5$ $5\le T_b-T_w\le 50^oC$
Su(2013)	$\bar{h}=\left[10189.3+90416.4P-(4314.4+46537P)\log10(100W_a)\right]\Delta T_w^{-0.6}$	$0.2\le p\le 0.6MPa$ $0.20\le W_a\le 0.80$ $27\le T_b-T_w\le 70^oC$
Su(2014)	$\bar{h}=\left[-2913.62+7957.3P-(7841.62+3051.85P)\log10(W_a)\right]\Delta T_w^{-0.35}$	$0.4\le p\le 0.6MPa$ $0.07\le W_a\le 0.52$ $13\le T_b-T_w\le 25^oC$
Lee(2017)	$\bar{h}=Nu_Dk/D_0$ $Nu_D=890Gr_L^{0.125}W_s^{*0.966}Ja^{-0.327}$ $Gr=\frac{g\rho(\rho_w-\rho_b)L^3}{\mu^2},\ W_s^*=1-W_a^{0.01},\ Ja=\frac{c_p(T_b-T_w)}{h_{fg}}$	$0.1\le L\le 3.5m$ $1.36\cdot 10^{10}\le Gr_L\le 5.05\cdot 10^{12}$ $1.16\cdot 10^{-3}\le W_s\le 2.35\cdot 10^{-2}$ $0.009\le Ja\le 0.035$

Another mechanistic condensation model considered in this research is the condensation conductivity model by Peterson. Peterson derived the conductivity between the bulk temperature and film temperature; it's equivalent to mass transfer coefficient based on concentration difference as a driving force. Modified version of Peterson's one is proposed by Herranz who improving the Peterson's model based on the Anderson's experimental data targeting AP600 PCCS.

$$q''_{cond}=h_c\left(T_b^s-T_i^s\right)=Sh\frac{k_c}{L}\left(T_b^s-T_i^s\right)$$

$$h_c=Sh\frac{k_c}{L}=C_c\left(Gr\cdot Sc\right)^{1/3}\frac{k_c}{L}$$

$$k_c=\frac{1}{\phi T_{avg}}\left(\frac{h_{fg}^2P_0M_v^2D_0}{R^2T_0^2}\right)$$

$$\phi=\frac{y_{a,avg}}{y_{s,avg}}=-\frac{\ln\left[(1-x_{ab})/(1-x_{ai})\right]}{\ln\left[x_{ab}/x_{ai}\right]}$$

In this research, Collier's model implemented in GOTHIC and RELAP code and condensation conductivity model by Peterson and Herranz are considered.

3.2. Experimental Correlations

Experimental correlations for the condensation outside circular tube have been proposed by several authors so far. Dehbi proposed the condensation correlations on outside of a vertical-oriented single tube, in actual, this geometrical configuration is the same as considered in APR+. Dehbi's correlation is as function of several variables such as non-condensable concentration, subcooling and pressure. After Dehbi's experiment, several workers conducted similar experiments such as Liu, Kawakubo, Su, Lee, etc. These experimental correlations are listed in Table 1.

4. Result and Discussion

A simple package program including models and correlation mentioned in chapter 3 was developed. Within a certain range and interval entered by user, the package program calculates and prints out the condensation rate, sensible heat transfer rate, interfacial temperature, etc. for each model and correlation. Typical results are shown in Figure 2. Each model and correlation showed the different heat transfer coefficient with variation of air mass fraction which is most sensitive factor to condensation of non-condensable gas mixture.

Another example which results from this package program is shown in Table 2. Total nine test cases from three series are selected from Dehbi's experimental database. For the mechanistic models, GOTHIC and Peterson's model shows the best applicability. On the other hand, for the experimental correlations, JNU correlation, of course, except for Dehbi's correlation, shows the best applicability.

From those analyses, the sensitiveness of each models and correlation and practicability for PCCS component against major parameters and previous experimental database are quantitatively derived.

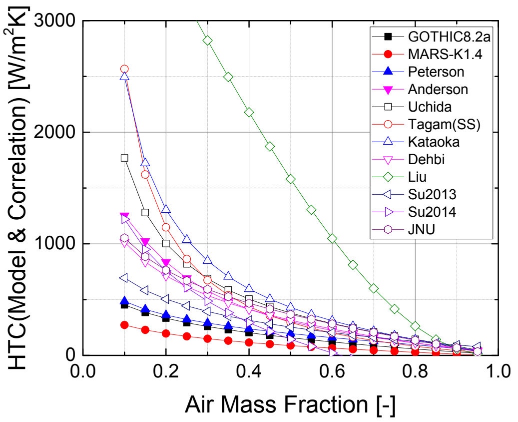

Figure 2 Comparison of HTC with air mass fractions (P = 1.5 bar, T_b = 423 K, T_w = 300 K, W_a = 0.1 ~ 0.95)

Table 2 Comparison of HTC on Dehbi's test conditions

	Series A			Series B			Series C		
	A38	A30	A25	B39	B33	B28	C25	C16	C9
Experimental Conditions and HTC									
P(bar)	1.5			3.0			4.5		
T_b(°C)	101	94	79	125	113	85	137	127	95
T_w(°C)	72	65	60	90	88	62	100	82	60
W_{air}(-)	0.33	0.56	0.80	0.34	0.59	0.85	0.35	0.58	0.88
HTC	644	367	200	854	446	189	888	491	144
HTC of Mechanistic Models									
GOTHIC	572	299	119	683	385	145	801	420	125
RELAP	424	209	77	506	269	88	594	277	70
Peterson	544	341	197	710	478	195	808	465	180
Anderson	860	448	215	1076	591	211	1197	610	192
HTC of Experimental Correlations									
Uchida	624	321	144	605	295	113	586	303	94
Tagami	588	235	82	563	209	62	539	217	50
Kataoka	758	355	142	731	321	107	706	332	87
Dehbi	712	383	178	821	459	174	943	492	168
Liu	1685	803	148	2073	801	102	2276	1112	79
Su2013	875	531	386	1105	718	313	1361	646	209
Su2014	700	114	-327	1030	480	31	1376	751	340
Lee	799	448	206	906	516	175	985	516	140

5. Conclusion

In this study, comprehensive and quantitative analysis of condensation mechanistic models and experimental correlations has been conducted to express the practicability for PCCS. Firstly, available models and correlations were investigated. For these, a simple condensation model and correlation package program including these is developed and it allows analysis easily to be quantitative and statistical.

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