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Assessment of Condensation Heat Transfer Models for Containment Cooling with CUPID code

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1. Introduction

Steam condensation is a very important issue in various engineering fields including refrigeration, heat exchanger, and distillation system and so on. For a typical PWR which is equipped with the concrete containment, depressurization during design basis and severe accidents should be achieved by condensing steam on a cooling device called the Passive Containment Cooling System (PCCS). The PCCS consists of a number of tube banks, such that condensation occurs at the exterior surface of the tubes, and the cooling fluid comes into the tube bank from the heat sink called the Passive Containment Cooling Tank (PCCT) installed at the outside of the containment in such a way that working fluid can circulate the loop between the PCCS cooling device and PCCT in a passive way, relying only on gravitational force.

In many nuclear safety applications, steam condensation occurs in the presence of non-condensable gases. In the case of a LOCA, for example, released steam condenses on various passive heat structures in the presence of some amounts of air. For a hypothetical severe accident, hydrogen generated from core damage degrades steam condensation.

For nuclear safety analyses, lumped parameter codes have been conventionally used. In the lumped parameter codes mechanistic models or empirical correlations based on bulk physical properties are often employed, thus, relatively less computational cells than those in CFD codes are required, while this produces essential limitations in describing flow field at the same time. On the other hand, in CFD codes the boundary layer near the cooling wall is resolved using several mm cells, such that the flow field near the condensation region can be captured and this can be reflected in condensation heat transfer. However, in CFD codes a lot of computational time is typically needed and considering the nuclear containment applications a huge amount of computational resources might be required.

In the present work, existing condensation heat transfer models including mechanistic models, empirical correlation, and heat and mass transfer analogy model using the wall law are assessed in terms of the accuracy and computational time considering a large scale problem such as the PCCS.

2. Condensation Model

For assessment of condensation heat transfer models, four different models are adopted: heat and mass transfer analogy model with the wall law or empirical correlation. In the former model, the temperature profile proposed by Kader [1] is directly converted into the concentration profile from heat and mass transfer analogy. Similarly, for the latter model the well-known Dittus-Bolter correlation is used. Additionally, a diffusion layer model by Peterson [2], and Uchida correlation [3] which is widely tested in the nuclear containment codes.

3. Comparison of COPAIN and CONAN Experiments

3.1. Experimental Facility

In this section, the condensation models are compared with experiments. For model assessment, COPAIN and CONAN experiments are considered.

The COPAIN and CONAN experiments were conducted to investigate the steam condensation on the vertical wall in the presence of non-condensable gas under forced convection [4,5]. The experimental facilities are mainly composed of the primary and secondary loops. The primary loop consists of steam generator, test section and condensate vessel to collect condensate water. The secondary loop is responsible for supplying cooling water into the test section, such that the heat exchange occurs at the thin stainless steel plate between the primary and secondary loops.

For COPAIN experiment, the cross-sectional area of the rectangular test section is 0.6 m × 0.5 m and the height is 2.5 m. The cooling flat plate has 0.6 m in width and 2 m in height. On the other hand, in the case of CONAN experiment the square channel with 0.34 m in length and 2 m in height is used.

3.2. Conditions

For each COPAIN and CONAN experiment, four different experimental conditions are considered for model assessment as summarized in Tables 1 and 2.

Table 1. Computational conditions for COPAIN

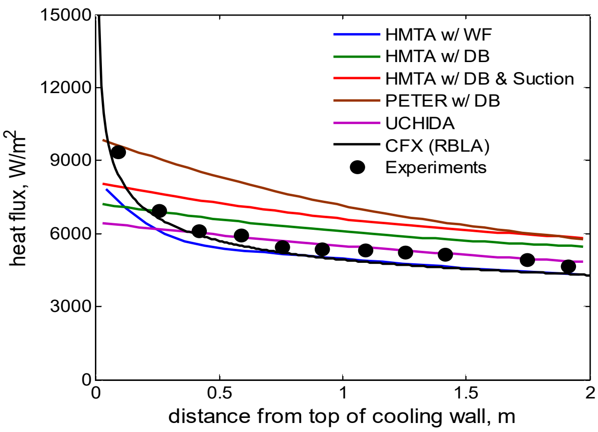
Cases	U, m/s	W_{nc}	P, bar	T_{in}, K	T_w, K
P0441	3.0	0.767	1.02	353.2	307.4
P0443	1.0	0.772	1.02	352.3	300.1
P0444	0.5	0.773	1.02	351.5	297.7
P0344	0.3	0.864	1.21	344.4	322.0

Table 2. Computational conditions for CONAN

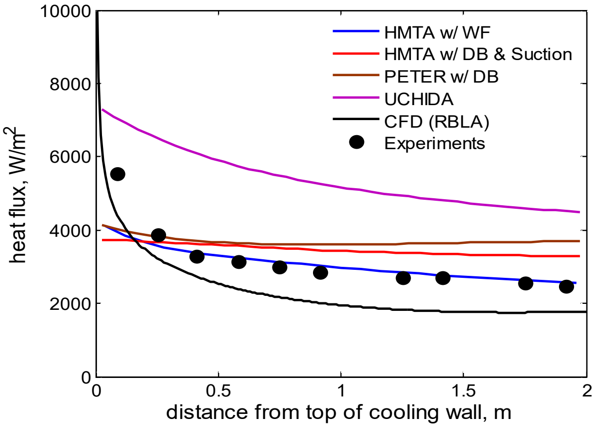
Cases	U, m/s	W_{nc}	P, bar	T_{in}, K
P10-T30-V25	2.57	0.707	1.0	348.6
P15-T30-V25	2.61	0.572	1.0	356.5
P20-T30-V25	2.59	0.359	1.0	364.5
P25-T30-V25	2.6	0.279	1.0	366.8

3.2. Results

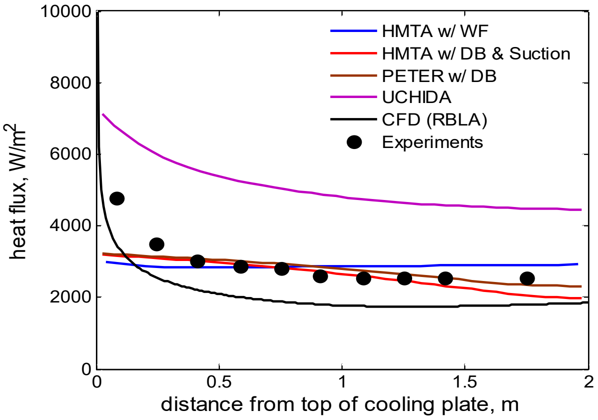
Figure 1 shows the comparison results of heat flux along the cooling wall for COPAIN test, and Table 3 shows the relative errors of each model from experimental data for the averaged heat flux.



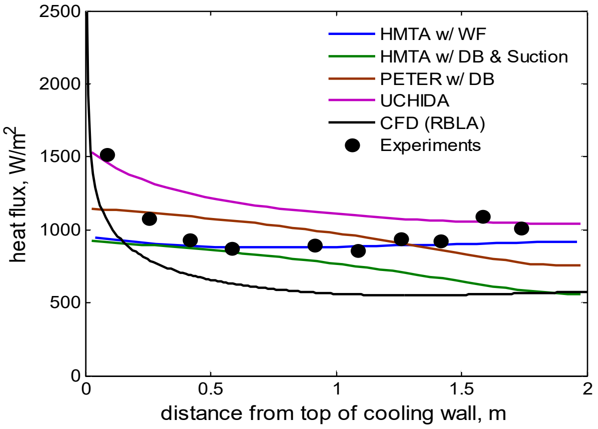
(a) P0441



(b) P0443



(c) P0444



(d) P0344

Figure 1. Comparison of heat flux along the cooling wall

Table 3. Relative errors for averaged heat flux

Cases	Exp. (W/ m^2)	1st model[1]	2nd model[2]	3rd Model[3]	4th Model[4]
P0441	5992.05	-13%	+18%	+35%	-2%
P0443	3214.66	-5%	+10%	+15%	+81%
P0444	2974.23	-3%	-3%	+0.1%	+82%
P0344	1011.95	-18%	-24%	-5%	+10%

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[1] Heat and mass transfer analogy with wall function (or HMTA w/ WF in Fig. 1)
[2] Heat and mass transfer analogy with empirical correlation (or HMTA w/ DB in Fig. 1)
[3] Diffusion layer model by Peterson (or PETER w/ DB in Fig. 1)
[4] Uchida correlation (or UCHIDA in Fig.1)

It should be noted that the number of mesh is 5,000 and y+ is set to about 30 for heat and mass transfer analogy model with wall function (or HMTA w/WF in Fig. 1). While for other models about 1,000 cells with y+ > 100 are used since these models are calculated based on bulk properties.

It is indicated from Fig. 1 and Table 3 that the heat mass transfer analogy model with the Dittus-Boelter correlation gives comparable predictions (-24% maximum relative error) to the wall function based model using relatively fine mesh with y+ ~ 30 (-18% maximum relative error). Meanwhile, the Uchida correlation shows the worst performance giving +82% maximum deviation from experimental data. This can be explained by the fact that the Uchida experiments were conducted under the natural convection condition and the correlation was fitted using only density ratio of steam to non-condensable gas. Thus, any effects related to gaseous mixture velocity were not included in the Uchida correlation.

Figure 2 shows the comparison of condensation rate for CONAN test. Similarly to previous COPAIN cases, the heat and mass transfer analogy model with the Dittus-Bolter correlation (HMTA w/ DB) and Peterson's DLM (PETER w/ DB) show comparable predictions to CFD using resolved boundary layer and experimental measurements. For CONAN case, the maximum relative errors are +4% for HMTA w/ DB and +6% for PETER w/ DB, respectively.

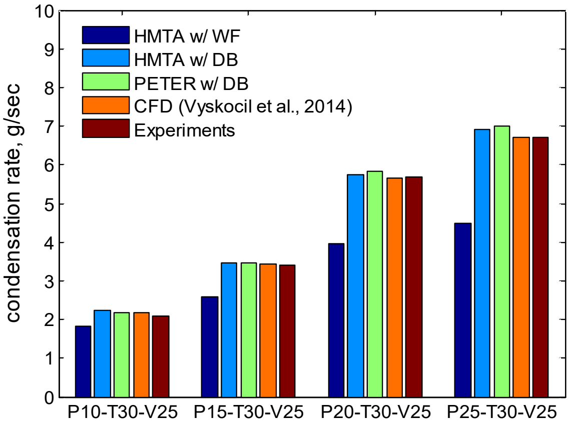

Figure 2. Comparison of condensation rate

3. Conclusions

In this work, some exiting condensation models including heat and mass transfer analogy model, diffusion layer model, and Uchida's correlation are implemented into CUPID code and compared with the COPAIN and CONAN experiments. The comparison results imply that even though the heat and mass transfer analogy model with an empirical correlation and diffusion layer model use coarse meshes with y+ over 100, their prediction performance for heat flux and condensation rate are comparable to wall function based model and CFD model using well resolve boundary layer. This indicates that for large scale problems such as the nuclear containment pressure and temperature analyses a condensation model based on fine mesh would be unnecessary.

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