Modeling Steam Condensation on Passive Heat Sinks within Containment for Realistic Analysis of Heat Removal Behavior

Jia Yu [a], Yeon-Gun Lee [a*]
[a]*Department of Quantum and Nuclear Engineering, Sejong University, 209, Neungdong-ro, Gwangjin-gu, Seoul, Republic of Korea*
[*]*Corresponding author: yglee@sejong.ac.kr*

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1. Introduction

In the event of accidents like loss-of-coolant accidents (LOCA) in nuclear reactors or main steam line break accidents (MSLB), passive heat sinks within containment structures, such as containment liner plates, play a critical role as the initial sink for heat removal. Therefore, it is essential to analyze the condensation heat transfer of passive heat sinks accurately. The Colburn-Hougen model [1], a gas kinetics-based model developed in 1934, was the first to propose a method for calculating the condensation rate of steam without detailed analysis of the gas boundary layer governing equations. The Colburn-Hougen model is a stagnant film model that assumes that the gas mixture around the condensation surface is in a static state. This does not take into account the increase in mass transfer rate due to turbulence effects that occur when a strong flow field is formed. Furthermore, since it does not consider various local phenomena occurring within the gas boundary layer, improvements are necessary to reflect the influence of flow fields and local phenomena for a more realistic analysis of containment behavior affected by passive heat sinks. In this study, a turbulent diffusion coefficient was introduced into the Colburn-Hougen model, and a modified Sherwood number correlation equation was derived for laminar flow and turbulent flow to define the mass transfer coefficient according to the introduction of the turbulent diffusion coefficient. The developed model was validated against flat plate condensation experiments conducted under forced convection conditions, and it was compared with the previous model.

2. Modeling

2.1 The introduction of turbulent diffusion coefficients

In the original Colburn-Hougen model, the condensation rate was calculated using the molecular diffusion coefficient. To account for the turbulent effects induced by the flow field, the developed model used an effective diffusion coefficient, which combines the molecular diffusion coefficient with the turbulent diffusion coefficient, when calculating the condensation rate:

$$D_{eff} = D_m + \overline{D}_T \tag{1}$$

where D_{eff} is the effective diffusion coefficient, D_m is the molecular diffusion coefficient, $\overline{D}_T$ is the turbulent diffusion coefficient. The turbulent diffusion coefficient was calculated using the Cebeci-Smith model [2], and for the inner region of the diffusion boundary layer, it is as follows:

$$D_T = l_m^2 \left|\frac{\partial \bar{u}}{\partial y}\right| \tag{2}$$

The turbulent mixing length l_m in Eq. (2) is calculated using the Van-Driest mixing length model proposed by Cebeci [3] as:

$$l_m = ky[1 + exp(-y^+/A^+)] \tag{3}$$

where k is the Von-Karman mixing length constant (0.4), A^+ is the Damping constant (26), y is the distance from the wall, y^+ is the dimensionless distance from the wall. The velocity gradient in the diffusion boundary layer is determined by the law of the wall, which depends on the dimensionless distance from the wall y^+. The velocity profile for laminar regime is calculated by:

$$u^+ = y^+ \tag{4}$$

For turbulent flow regime follow as:

$$u^+ = 2.44 \ln y^+ + 5.0 \tag{5}$$

The u^+ is the dimensionless velocity:

$$u^+ = u/u^* \tag{6}$$

u is the velocity, u^* is the shear velocity defined by:

$$u^* = \sqrt{|\tau_i|/\rho_i} \tag{7}$$

where τ_i is the interfacial shear stress, ρ_i is the fluid density at interface. Using the biquadratic blending function, known as the 'Automatic wall treatment', to combine Eq. (4) and Eq. (5), allows for the use of u^+ across the entire range of y^+:

$$\frac{1}{u^{+4}} = \frac{1}{u_l^{+4}} + \frac{1}{u_t^{+4}} \tag{8}$$

The turbulent diffusion coefficient for the outer region of the diffusion boundary layer defined by:

$$D_T = \frac{0.0168 U_\infty \delta_1}{\left[1+5.5\left(y/\delta_g\right)^6\right]} \tag{9}$$

, where U_∞ is the velocity of the mixture bulk, δ_1 is the displacement thickness of the boundary layer, δ_g is the thickness of the boundary layer. The turbulent diffusion coefficient at a distance from the inlet L (m) was determined by dividing the boundary layer into multiple sections and averaging the values obtained at each local point:

$$\bar{D}_T = \frac{1}{\delta_g}\int_0^{\delta_g} D_T\, dy = \frac{1}{\delta_g}\left(\int_0^{\delta_{tb}} D_{T,in}\, dy + \int_{\delta_{tb}}^{\delta_g} D_{T,out}\, dy\right) \quad (10)$$

2.2 Modification of mass transfer correlation

In the original Colburn-Hougen model, turbulent effects were incorporated in the empirical expression for the Sherwood number used to calculate mass transfer coefficients. Due to the incorporation of turbulent diffusion coefficients in the developed model, the mass transfer coefficients were redefined accordingly. The modified Sherwood correlation was derived from the condensation rates measured in flat plate condensation experiments such as COPAIN [4], CONAN [5], and SETCOM [6] experiments. The Sherwood number was estimated from experimental data for each condition as follows:

$$Sh = \frac{\dot{m}''_{v,i-exp}}{\left(\frac{\rho}{Y_v}\frac{D_{eff}}{L}\right)\ln\left(\frac{1-Y_{v,i}}{1-Y_{v,b}}\right)} \quad (11)$$

, where Y_v is the molar fraction of vapor, $Y_{v,i}$ is the molar fraction of vapor at interface, $Y_{v,b}$ is the molar fraction of vapor at bulk, $\dot{m}''_{v,i-exp}$ is the mass flux calculated from the measured heat flux q''_{exp} in the experiments and defined by:

$$\dot{m}''_{v,i-exp} = \frac{q''_{exp} - q''_{fs}}{h_{fg,i}} \quad (12)$$

q''_{fs} is the sensible heat flux, $h_{fg,i}$ is the latent heat of evaporation at the interface. With the introduction of turbulent diffusion coefficients, the newly defined Sherwood number correlation equations for both the laminar (Eq. (13)) and turbulent (Eq. (14)) flow regions are derived as:

$$Sh_l^* = 2.27 Re_L^{0.330} Sc^{1/3} \quad (13)$$

$$Sh_t^* = 4.03 \cdot 10^2 Re_L^{-0.145} Sc^{1/3} \quad (14)$$

, where Re is the Reynolds number, Sc is the Schmidt number. In the transition flow region, Sherwood number was calculated using linear interpolation as follows:

$$Sh_{trans}^* = (1-R)\cdot Sh_l + R \cdot Sh_t \quad (15)$$

$$R = \frac{Re_L - 5\cdot 10^5}{5\cdot 10^5} \quad (16)$$

2.3 The modified Colburn-Hougen model

Finally, by introducing turbulent diffusion coefficients and using the modified Sherwood number correlation, the condensation model was proposed as follows.

$$\dot{m}''_{v,i} = Sh^* \frac{D_{eff}}{L}\left(\frac{\rho_v}{Y_v}\right)\ln\left(\frac{1-Y_{v,i}}{1-Y_{v,b}}\right) \quad (17)$$

, where Sh^* is the newly defined Sherwood number, ρ_v is the density of vapor in the boundary layer.

3. Results

The developed model was validated using flat plate condensation experiments conducted under forced convection conditions, such as the CONAN, COPAIN, and SETCOM experiments. Table I shows the key specifications for each experiment.

Table I: The key specifications for condensation tests.

	COPAIN	CONAN	SETCOM
Length (m)	2.0	2.0	6.0
Duct size (m)	0.6×0.5	0.34×0.34	0.44×0.44
NC Gas type	Air / Helium	Air	Air
Steam flow (m/s)	0.1-3.0	1.5-3.5	0.5-5.0
Inlet NC mass fraction	0-1.0	0-0.75	0.51-0.94
Pressure (MPa)	0.1	0.1	0.1
Inlet gas temperature (K)	344.0-353.2	348.8-370.7	333.2-353.2

3.1 CONAN experiments

The CONAN experiments, conducted at the University of PISA in Italy, studied the effect of non-condensable gases inside containment structures during hypothetical accidents. Fig. 1 presents the heat flux measured in the CONAN experiments compared to the predicted heat flux using the previous model and the developed model. The accuracy of the model was represented by the standard deviation of relative error (STDV) calculated as:

$$STDV = \sqrt{\frac{\sum_i^N \left|\frac{C_i - M_i}{M_i}\right|^2}{N-1}} \quad (18)$$

The standard deviation of relative error (STDV) decreased from 21.7% for the previous model to 9.8% for the developed model, confirming that the developed model predicts condensation heat flux more accurately.

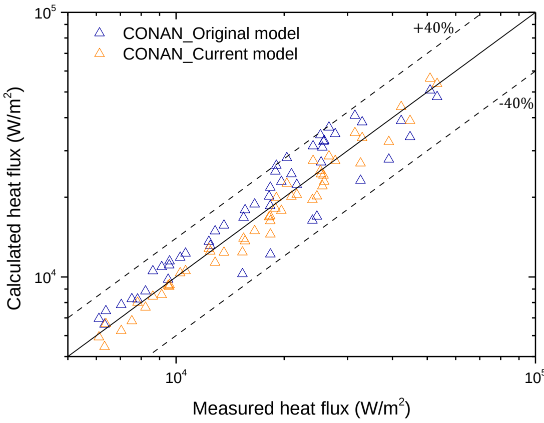

Fig. 1. The results of calculations for CONAN experiments.

3.2 SETCOM experiments

The SETCOM experiments, conducted at Forschungszentrum Juelich GmbH in Germany, aimed to obtain precise experimental results to deepen understanding of turbulent heat and mass transfer in the boundary layer during condensation. Fig. 2 shows the comparison between the measured heat flux in the SETCOM experiments and the predicted heat flux by the previous model and the developed model. The standard deviation of relative error decreased from 52.8% with the previous model to 36.8% with the developed model. This indicates that the developed model provides higher accuracy in predicting local heat flux due to forced convection condensation on a flat surface.

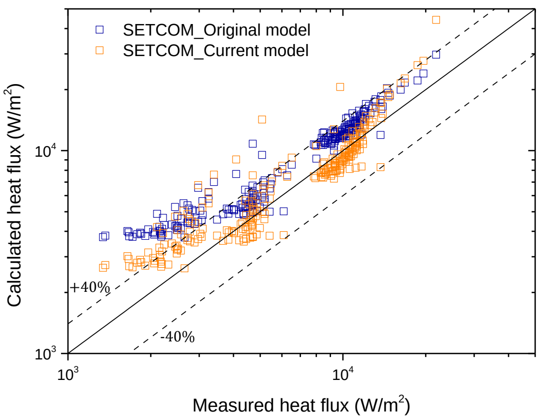

Fig. 2. The results of calculations for SETCOM experiments.

3.3 COPAIN experiments

The COPAIN experiments, conducted at the CEA research institute in France, investigated steam condensation phenomena on vertical plates in the presence of non-condensable gases. Fig. 3 shows the comparison between the measured heat flux in the COPAIN experiments and the heat flux calculated by the previous model and the developed model based on experimental conditions. The standard deviation of relative error decreased from 29.3% when calculated with the previous model to 25.6% when calculated with the developed model, confirming that the developed model predicts heat flux more accurately. The decrease in errors indicates that the developed model, which introduces turbulent diffusion coefficients to consider flow field effects, predicts forced convection condensation heat transfer more accurately than the original Colburn-Hougen model.

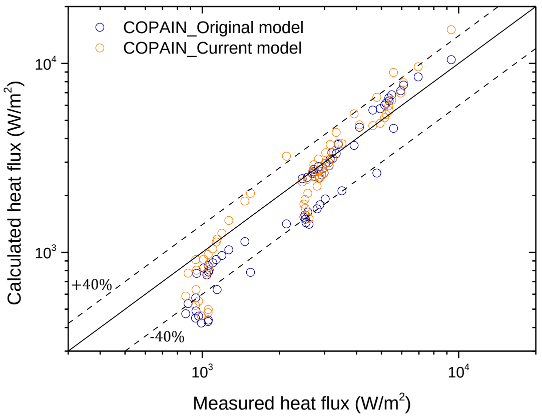

Fig. 3. The results of calculations for COPAIN experiments.

4. Conclusions and Future Works

In this study, turbulent diffusion coefficients were introduced into the Colburn-Hougen model to develop a new mechanistic model of steam condensation on passive heat sinks. To validate the developed model, the calculated heat flux was compared with measured values from flat plate condensation experiments under forced convection condition such as COPAIN, CONAN, and SETCOM experiments. The local heat flux calculated with the developed model showed a decrease in the standard deviation of relative error compared to that calculated with the previous model. This confirmed the successful prediction of condensation heat transfer by incorporating the concept of flow field effects modeled by the introduction of turbulent diffusion coefficients. We plan to expand and validate the developed model for natural convection conditions in the future. Additionally, we plan to implement physical models to account for local phenomena such as suction effect and fog formation, and evaluate their effects under various experimental conditions.

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NOMENCLATURE

A^+ Damping constant, 26

D	Diffusion coefficient ($\mathrm{m}^2\ \mathrm{s}^{-1}$)
h_{fg}	Latent heat ($\mathrm{J\ kg}^{-1}$)
k	Von-Karman mixing length constant, 0.4
L	Distance from the inlet (m)
l_m	Turbulent mixing length
$\dot{m}''$	Mass flux ($\mathrm{kg\ m}^{-2}\ \mathrm{s}^{-1}$)
q''	Heat flux ($\mathrm{W\ m}^{-2}$)
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
Sh^*	Sherwood number newly defined
U_∞	Velocity of the mixture bulk ($\mathrm{m\ s}^{-1}$)
u	Velocity ($\mathrm{m\ s}^{-1}$)
u^*	Shear velocity ($\mathrm{m\ s}^{-1}$)
Y	Molar fraction
y	Distance from the wall (m)

Greek letters

δ_1	Displacement thickness of the boundary layer
δ_g	Thickness of the boundary layer
ρ	Density ($\mathrm{kg\ m}^{-3}$)
τ	Shear stress ($\mathrm{kg\ m}^{-1}\ \mathrm{s}^{-2}$)

Sub- and Superscripts

b	bulk conditions
eff	Effective
exp	Measured in the experiments
fs	Sensible
i	Interface of liquid-gas
L	Distance from the inlet (m)
l	Laminar
m	Molarcular
T, t	Turbulent
v	Vapor
$+$	Dimensionless quantity

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