# SIMULATION OF CONDENSATION OF BINARY VAPOR MIXTURE ON A VERTICAL FLAT PLATE

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## Introduction

Condensation of binary vapor mixture is a fundamental separation process. Although many theoretical[4] and experimental[5] studies have been made on this process, little is known about the transition from partial to total condensation. The purpose of the present work is to make theoretical and experimental approaches to the transition from partial to total condensation.

## 1. Simulation

In our previous papers[1,2], experimental studies of the condensation of a binary vapor mixture of the methanol-steam system on a small vertical flat plate were described. On the basis of these results, the following simplifying assumptions were made for simulation of the condensation of binary vapor mixture on a vertical flat plate.

1) Flow is laminar in the vapor and the condensate.
2) The Nusselt model corrected for the effect of vapor shear stress[3] is applied to heat transfer in the condensate film.
3) The laminar boundary layer theory is applied to heat and mass transfer in the vapor phase.
4) The surface temperatures of the condensate are at their bubble points.
5) The liquid-phase resistance is negligibly small[2].

The basic equations for the present model are summarized in **Table 1.** Axial distributions of the concentrations and flow rates of the condensate were calculated by a step-by-step method with the inlet vapor flow rate, vapor concentration and coolant temperature as initial values.

**Table 1.** Basic equations

Vapor-phase local diffusion flux

$$Sh_{GZ}(J_{AZ}/N_{AZ}) = 0.332 Re_G^{1/2} Sc_{Gs}^{1/3} g_M C_Z \tag{1}$$

$$g_M = 1 + 1.2F(0)^{1.04} Sc_{Gs}^{0.68} \tag{2}$$

$$F(0) = 2(\upsilon_s/U_\infty) Re_G^{1/2} \tag{3}$$

$$C_Z = 1.03\left\{1-\left(\frac{Z_0}{Z_0+Z}\right)^{3/4}\right\}^{-1/3} \tag{4}$$

Vapor-phase local heat flux

$$Nu_{GZ} = 0.332 Re_G^{1/2} Pr_{Gs}^{1/3} g_H C_Z \tag{5}$$

$$g_H = 1 + 1.2F(0)^{1.04} Pr_{Gs}^{0.68} \tag{6}$$

Heat flux through condensate film

$$h_c/(1+C_V) = 0.943\left\{\frac{g\rho_L^2 k_L^3 h_{fg}}{\mu_L (T_s - T_w) Z}\right\}^{1/4} \tag{7}$$

$$C_V = 0.679\left\{\left(\frac{\rho_G \mu_G}{\rho_L \mu_L}\right)^2 \frac{Pr_L h_{fg} U_\infty^6}{g^3 c_L (T_s - T_w) Z^3}\right\}^{1/2} \tag{8}$$

$$h_{fg} = N_A \lambda_A + N_B N_B + (3/8) c_L (T_s - T_w) \tag{9}$$

**Table 2.** Ranges of variables

| $y_{in}$ [-] | $Re_G$ [-] | $T_{cwin}$ [K] |
|---|---|---|
| 0.45 - 0.48 | 2560 - 9520 | 283 - 335 |
| 0.68 - 0.71 | 2740 - 6100 | 287 - 332 |

## 2. Experimental Apparatus and Procedures

The experimental apparatus was a vertical flat-plate condenser with a 50 mm-long, 16 mm-wide, 0.5 mm-thick copper condensing wall, the upper edge of which was 25 mm from the lower edge of a divergent-convergent nozzle with a calming grid. On the opposite side of the condensing wall, a 0.25 mm-outer diameter sheathed Cromel-Alumel thermocouple located 28 mm from the upper edge of the wall was mounted on a traversing mechanism for measurements of the vapor-phase temperature profile. Details of the experimental apparatus were shown elsewhere[2].

The condensate flow rates were measured by a stopwatch and a measuring cylinder. The concentrations of the condensate were measured by a gas chromatograph. The surface temperatures of the condensate were

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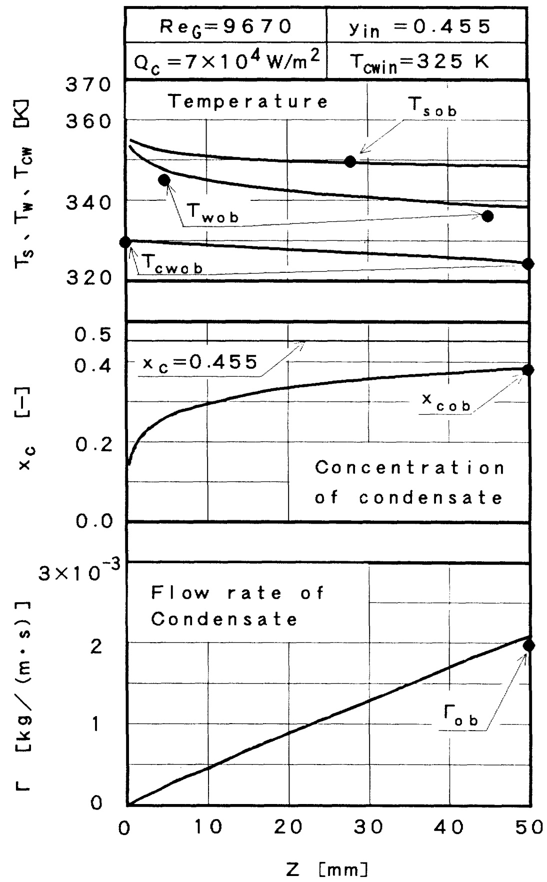


**Fig. 1** An example of axial distributions of surface temperatures, concentration of condensate and condensate flow rates

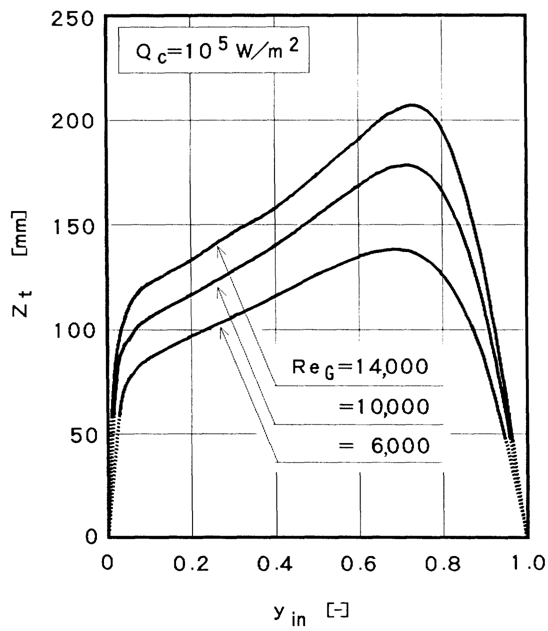


**Fig. 3** Predicted minimum length of condensing wall at total condensation with condition of $Q_c = 10^5$ W/m$^2$

estimated by extrapolation of the observed vapor-phase temperature profile to the liquid surface.

Condensation runs of binary vapor mixture were made for the methanol-steam system. Ranges of the experimental variables are shown in **Table 2.**

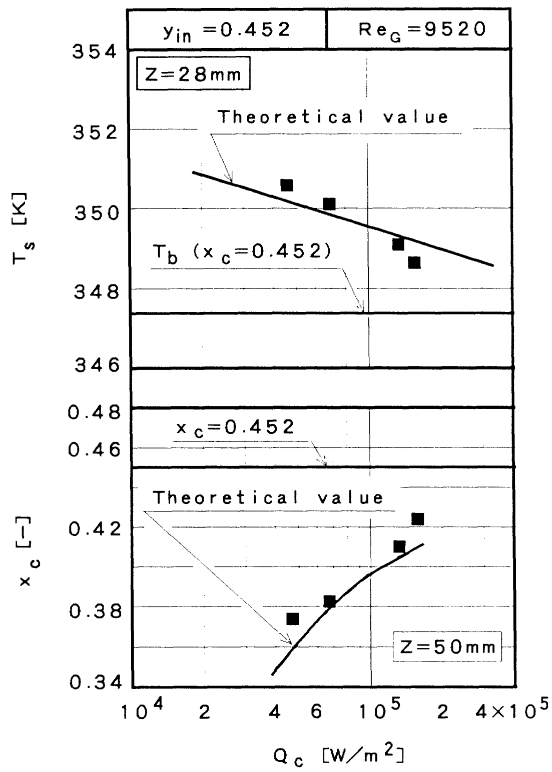


**Fig. 2** Effect of heat flux in condensation on outlet concentration of condensate at $Z$ = 50 mm and surface temperature at $Z$ = 28 mm

## 3. Results and Discussion

**Figure 1** shows an example of axial distributions of the surface-, wall- and coolant temperatures, $T_s$, $T_w$, $T_{cw}$, the concentrations of the condensate, $x_c$, and the condensate flow rates, $\Gamma$. The abscissa is the distance from the upper edge of the condensing wall, $Z$. The solid lines in the figure are the theoretical values by the present model and the solid keys are the observed data. The theoretical values agree well with the observed ones. Similar results were obtained for all the data.

The concentration of the condensate, as shown in Fig. 1, increases with increasing distance from the upper edge of the wall and asymptotically approaches the concentration of total condensation, $x_c$ = 0.455. In other words, partial condensation takes place near the entrance of the condenser and approaches total condensation toward the exit.

**Figure 2** shows the effect of heat flux in condensation, $Q_c$, on the outlet concentrations of the condensate at $Z$ = 50 mm and the surface temperatures at $Z$ = 28 mm. The solid keys are the observed data. The outlet concentrations at $Z$ = 50 mm approach the concentration of total condensation, $x_c$ = 0.452, with increase of heat flux, but is still lower than the concentration of total condensation for $Z$ = 50 mm.

The calculated concentration of the condensate asymptotically approaches the concentration of total condensation in the strict sense, but a finite length of the condensing wall can be found where the concentration of the condensate is in practice assumed to be the concentration of total condensation. This length gives the minimum one for total condensation. **Figure 3** shows the calculated minimum length of the condensing wall, $Z_t$, which is defined as the length at $x_c = 0.99y_{in}$. The abscissa is the inlet vapor concentration, $y_{in}$, and a parameter is the vapor-phase Reynolds number, $Re_G$, where $Z$ = 50 mm was used as a characteristic length. The minimum length of the condensing wall at total condensation is affected by the inlet vapor concentrations and increase with increasing $Re_G$. Similar results were obtained for different heat fluxes, $Q_c$, where the minimum length of the wall decreased with increasing $Q_c$.

## Conclusion

A new method for simulation of condensation of binary vapor mixture on a vertical flat plate was proposed. The simulation results showed that a minimum length of the condensing wall is required for the condition of total condensation.


### Acknowledgment

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### Nomenclature

| | | |
|---|---|---|
| $c_L$ | = specific heat of the liquid | [J/(kg· K)] |
| $C_V$ | = correction factor for the effect of vapor shear stress defined by Eq. (8) | [-] |
| $C_Z$ | = correction factor for the effect of entry length defined by Eq. (4) | [-] |
| $F(0)$ | = dimensionless stream function at the vapor-liquid interface | [-] |
| $g_H$ | = function of F(0) defined by Eq. (6) | [-] |
| $g_M$ | = function of F(0) defined by Eq. (2) | [-] |
| $h_c$ | = heat transfer coefficient | [W/(m²· K)] |
| $J_i$ | = vapor-phase diffusion flux for the *i*-th component | [kg/(m²·s)] |
| $N_i$ | = vapor-phase mass flux for the i-th component | [kg/(m²·s)] |
| $Nu_{GZ}$ | = vapor-phase Nusselt number | [-] |
| $Pr$ | = Prandtl number | [-] |
| $Re_G$ | = vapor-phase Reynolds number ($= \rho_G U_\infty (Z+Z_0)/\mu_G$) | [-] |
| $Sc_G$ | = vapor-phase Schmidt number | [-] |
| $Sh_{GZ}$ | = vapor-phase Sherwood number ($= N_A(Z+Z_0)/\rho_G \mathscr{D}_{GA}(\omega_s-\omega_\infty)$) | [-] |
| $U_\infty$ | = free stream vapor velocity | [m/s] |
| $v_s$ | = normal component of surface velocity | [m/s] |
| $Z_0$ | = distance between the lower edge of the calming nozzle and the upper edge of the condensing wall | [m] |
| $\kappa$ | = thermal conductivity | [W/(m·K)] |
| $\lambda$ | = latent heat of vaporization | [J/kg] |
| $\mu$ | = viscosity | [Pa·s] |
| $\rho$ | = density | [kg/cm³] |

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