Numerical Study on the Condensation Length of Binary Zeotropic Mixtures

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Outline

- Introduction
- Heat and mass transfer during mixtures condensation
- Equilibrium models
- Non-equilibrium models
- Results
- Conclusions
Motivation

- The study of the two-phase condensation region is important for the design of heat exchangers.

- The condensation process of binary mixtures is more complicated than that of the single component fluid.
Heat and Mass Transfer during Mixture Condensation — different from pure fluid

- Concentration shift
- Non-isothermal

Phase equilibrium diagram for R134a and R123 at 0.495 MPa
Heat and Mass Transfer during Mixture Condensation — Resistances

In practice, the process is more complicated.

- Concentration: \( Y_i > Y_V, X_L < X_i \)
- Temperature: \( T_L < T_i < T_V \)
Definitions in this work

- Equilibrium vs. non-equilibrium models
  - Equilibrium: no mass transfer resistance
    example: Silver [1] and Bell & Ghaly [2] models
  - Non-equilibrium: mass transfer resistance
    example: film theory, Colburn & Drew [3]

- Heat and mass transfer resistance
  The resistance emphasized in the present work is specific to the vapor phase. The mass transfer resistance in the liquid phase is not predominated.
Overview of the models

- Resistances considered in each model

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass</th>
<th>Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>x</td>
<td>√</td>
</tr>
<tr>
<td>3</td>
<td>√</td>
<td>x*</td>
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<td>4</td>
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</table>

- Common assumptions
  1D steady-state model; annular flow.
Equilibrium models

- Conservation equations:

  Mass: vapor
  \[ \frac{d}{dz} (\alpha \rho_v V_v) = -M_t \]

  liquid
  \[ \frac{d}{dz} ((1 - \alpha) \rho_l V_l) = M_t \]

  Momentum:
  \[ \frac{d}{dz} (\alpha \rho_v V_v^2) + \frac{d}{dz} ((1 - \alpha) \rho_l V_l^2) = -\frac{dP}{dz} - \frac{4}{D_w} \tau_w \]
Equilibrium models

- Heat balance: \( Q_w = Q_{lv} + Q_{sv} \)
  
  heat flux: \( q_w = \frac{D_v}{D_w} (q_{lv} + q_{sv}) \)

- Condensation rate:
  
  \[
  M_t = \frac{4}{D_w} \left( q_w - \left( \frac{D_v}{D_w} \right) q_{sv} \right), \quad H_{lv} = f(T_{eq}, C_0)
  \]
Equilibrium models

- Heat balance: \( Q_w = Q_{lv} + Q_{sv} \)
- Heat flux: \( q_w = \frac{D_v}{D_w} (q_{lv} + q_{sv}) \)
- Condensation rate:

\[
M_t = \frac{4}{D_w} \frac{(q_w - (D_v/D_w)q_{sv})}{H_{lv}}, \quad H_{lv} = f(T_{eq}, C_0)
\]
Equilibrium models

- **Heat balance:** \( Q_w = Q_{lv} + Q_{sv} \)
  
  **heat flux:** \( q_w = \frac{D_v}{D_w} (q_{lv} + q_{sv}) \)

- **Condensation rate:**

  \[
  M_t = \frac{4}{D_w} \left( q_w - \left( \frac{D_v}{D_w} \right) q_{sv} \right), \quad H_{lv} = f(T_{eq}, C_0)
  \]

- **Sensible heat (Del Col et al. [4])**

  \[
  \frac{Q_{sv}}{Q_w} \approx x c_{p,v} \frac{dT}{dh} \approx x c_{p,v} \frac{\Delta T_{db}}{\Delta H_m}
  \]
Non-equilibrium models

- Additional conservation equations:

  Species: \(\frac{d}{dz}(\alpha \rho_v V_v Y) = -M_1\)

  Energy:

  \[
  \frac{d}{dz}(\alpha \rho_v V_v H_v) - H_{vi} \frac{d}{dz}(\alpha \rho_v V_v) = -\frac{4D_v}{D_w^2} q_{sv}
  \]
Non-equilibrium models

- Condensation rate of each component
  Based on film theory and Fick’s law,
  \[
  M_1 = M_t Y_i - \frac{4D_v}{D_w^2} k_v (Y_i - Y) \\
  M_2 = M_t - M_1
  \]

- Heat flux
  Latent: \[ q_{lv} = \frac{D_w^2}{4D_v} (M_1 H_{lv,1} + M_2 H_{lv,2}) , \quad H_{lv} = f(T_i) \]
  Sensible: \[ q_{sv} = h_v (T_v - T_i) \]
## Summary of the models

<table>
<thead>
<tr>
<th>Model</th>
<th>Conservation Eq.s solved</th>
<th>Information needed</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>mass, momentum</td>
<td>T-C diagram</td>
</tr>
<tr>
<td>2</td>
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<td>T-C diagram</td>
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Results

- Study case
  Mixture: R134a/R123 0.349/0.651 by mass
  Inlet pressure: 495 kPa
  Mass flux: 300.5 kg/m²s
  Tube: diameter 8.4 mm, horizontal
Results

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Heat transfer resistance (without mass transfer effect)
Heat transfer resistance (with mass transfer effect)

$L_2 = 1.13L_1$
$L_4 = 1.09L_3$
Results

Mass transfer resistance (without heat transfer effect)

Mass transfer resistance (with heat transfer effect)

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$L_3 = 1.39L_1$

$L_4 = 1.35L_2$
Results

![Graph showing condensation length vs. quality with model lines and experimental points.]

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Mass transfer resistance > Heat transfer resistance

\[ L_3 = 1.24L_2 \]
Results

Composition of R134a in vapor vs. Condensation length [m]

Condensation flux and diffusion [kg/m²s] vs. Quality

Model 1, Model 2, Model 3, Model 4

Diffusion, Model 3, Diffusion, Model 4

Condensation, Model 1, Condensation, Model 2, Condensation, Model 3, Condensation, Model 4
Conclusions

- The non-equilibrium models give better predictions than the two equilibrium models.
- The mass transfer resistance in the vapor phase has a significant effect on the condensation length, and it overweighs the influence of heat transfer resistance.
- The equilibrium models are simpler, computationally cheaper and faster than the non-equilibrium models, but it may under-predict the required length for full condensation.
- A method that can predict mass and heat transfer accurately and efficiently is highly demanded for the reliable design.
References

Thank you for your attention!
Appendix: closure relations

- Pressure drop model

\[ \Phi_{lo}^2 = (1 - x)^2 + x^2 \frac{\rho_{l} f_{v0}}{\rho_{v} f_{lo}} + 3.24A_2A_3Fr^{-0.045}We^{-0.035} \]

\[ A_2 = x^{0.78} (1 - x)^{0.224}, \quad A_3 = \left( \frac{\rho_{l}}{\rho_{v}} \right)^{0.91} \left( \frac{\mu_{v}}{\mu_{l}} \right)^{0.19} \left( 1 - \frac{\mu_{v}}{\mu_{l}} \right)^{0.7} \]

\[ \tau_{w} = f_{lo} \frac{G^2}{2\rho_{l}} \Phi_{lo}^2. \]

- Heat transfer coefficients

\[ h_{v} = 0.023Re_{v}^{0.8}Pr_{v}^{0.4} \frac{\lambda_{v}}{D_{v}} \]

\[ h_{l} = 0.023Re_{l}^{0.8}Pr_{l}^{0.4} \left( 1 + \frac{2.22}{X_{t}^{0.89}} \right) \frac{\lambda_{l}}{D_{w}} \]

- Mass transfer coefficient

\[ k_{v} = \frac{\rho_{v} D_{v}}{D_{v}} S h_{v} = \frac{\rho_{v} D_{v}}{D_{v}} 0.023Re_{v}^{0.8} Sc_{v}^{1/3} \]