NTNU – Trondheim
Norwegian University of
Science and Technology

Numerical Study on the Condensation Length of Binary Zeotropic Mixtures

Han Deng, Maria Fernandino, Carlos A. Dorao

3rd Trondheim Gas Technology Conference
4 – 5 June, 2014
Trondheim, Norway

Outline

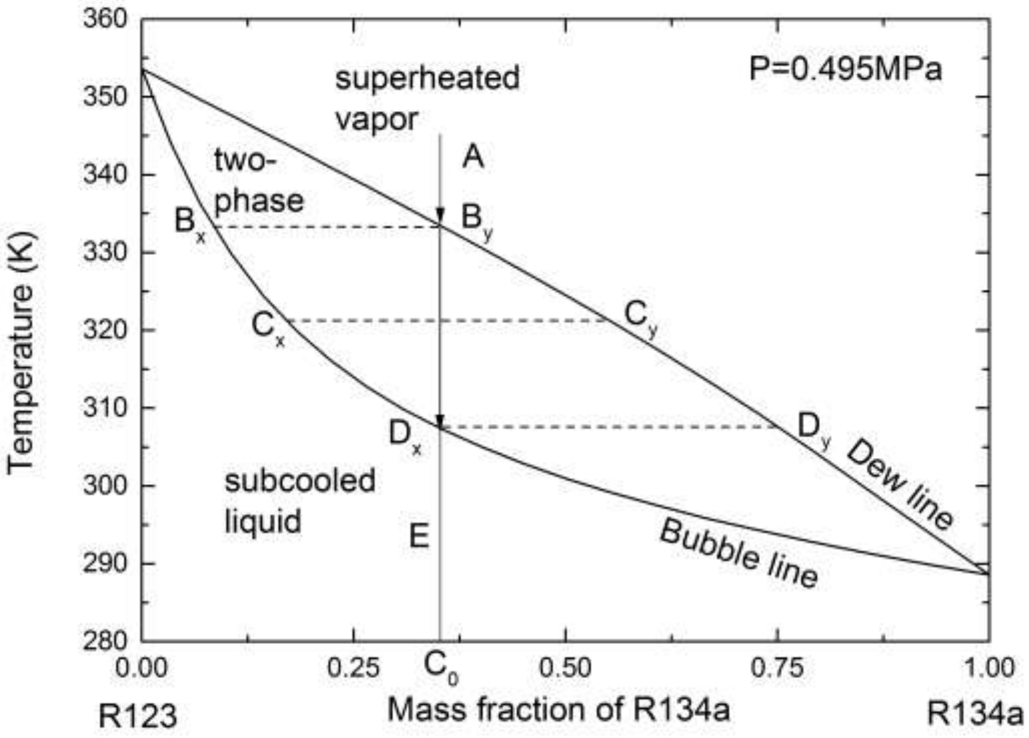
- Introduction
- Heat and mass transfer during mixtures condensation
- Equilibrium models
- Non-equilibrium models
- Results
- Conclusions

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

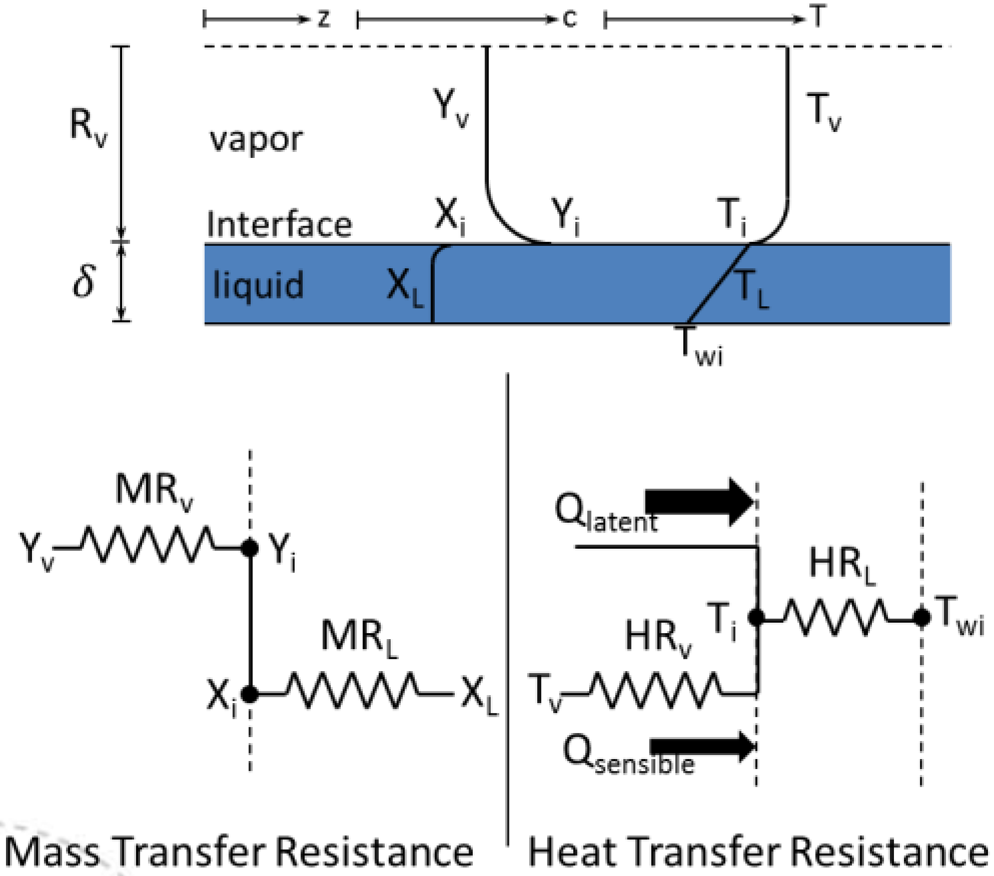


Phase equilibrium diagram for R134a and R123 at 0.495 MPa

- Concentration shift
- Non-isothermal

NTNU – Trondheim
Norwegian University of
Science and Technology

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:

  $T_L < T_i < T_V$

NTNU – Trondheim
Norwegian University of Science and Technology

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.

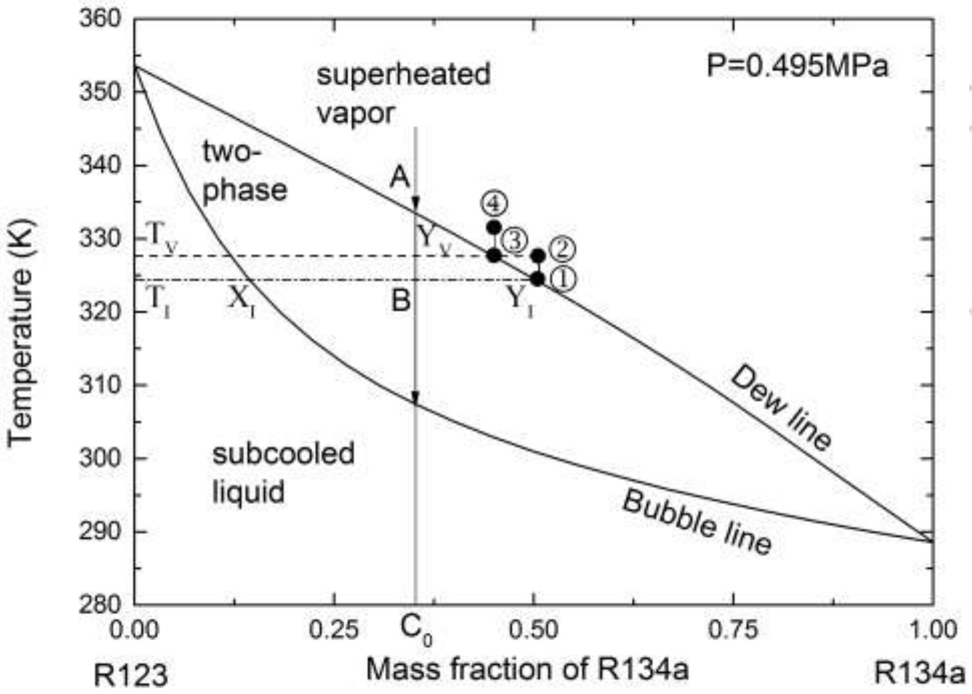
  The mass transfer resistance in the liquid phase is not predominated.

Overview of the models

- Resistances considered in each model

Model	Mass	Heat
1	×	×
2	×	√
3	√	×*
4	√	√

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



Equilibrium models

- Conservation equations:

Mass: vapor $$\frac{\mathrm{d}}{\mathrm{d}z}(\alpha\rho_\mathrm{v}V_\mathrm{v}) = -M_\mathrm{t}$$

liquid $$\frac{\mathrm{d}}{\mathrm{d}z}((1-\alpha)\rho_\mathrm{l}V_\mathrm{l}) = M_\mathrm{t}$$

Momentum:

$$\frac{\mathrm{d}}{\mathrm{d}z}\left(\alpha\rho_\mathrm{v}V_\mathrm{v}^2\right) + \frac{\mathrm{d}}{\mathrm{d}z}\left((1-\alpha)\rho_\mathrm{l}V_\mathrm{l}^2\right) = -\frac{\mathrm{d}P}{\mathrm{d}z} - \frac{4}{D_\mathrm{w}}\tau_\mathrm{w}$$

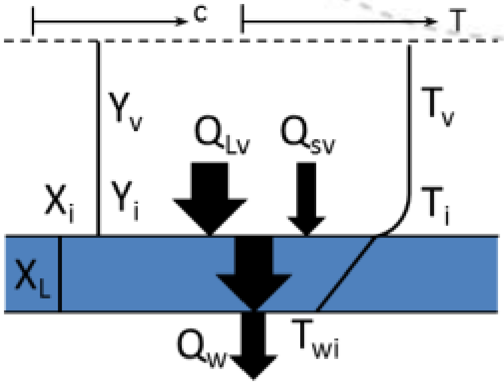
Equilibrium models

- Heat balance: $Q_{\mathrm{w}} = Q_{\mathrm{lv}} + Q_{\mathrm{sv}}$

  heat flux: $q_{\mathrm{w}} = \dfrac{D_{\mathrm{v}}}{D_{\mathrm{w}}}(q_{\mathrm{lv}} + q_{\mathrm{sv}})$

- Condensation rate:

$$M_{\mathrm{t}} = \frac{4}{D_{\mathrm{w}}} \frac{(q_{\mathrm{w}} - (D_{\mathrm{v}}/D_{\mathrm{w}})q_{\mathrm{sv}})}{H_{\mathrm{lv}}}, \;\; H_{\mathrm{lv}} = f(T_{\mathrm{eq}}, C_0)$$



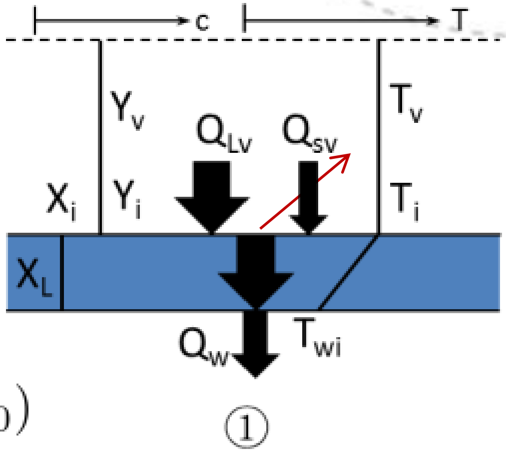
Equilibrium models

- Heat balance: $Q_{\mathrm{w}} = Q_{\mathrm{lv}} + \cancel{Q_{\mathrm{sv}}}$

  heat flux: $q_{\mathrm{w}} = \dfrac{D_{\mathrm{v}}}{D_{\mathrm{w}}}(q_{\mathrm{lv}} + \cancel{q_{\mathrm{sv}}})$

- Condensation rate:

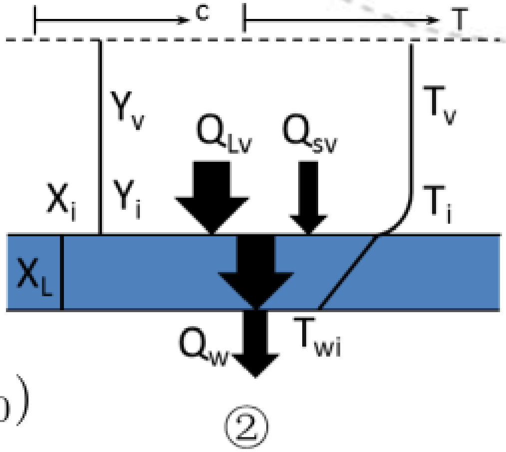
$$M_{\mathrm{t}} = \frac{4}{D_{\mathrm{w}}}\frac{(q_{\mathrm{w}} - \cancel{(D_{\mathrm{v}}/D_{\mathrm{w}})q_{\mathrm{sv}}})}{H_{\mathrm{lv}}}, \quad H_{\mathrm{lv}} = f(T_{\mathrm{eq}}, C_0)$$



Equilibrium models

- Heat balance: $Q_{\mathrm{w}} = Q_{\mathrm{lv}} + Q_{\mathrm{sv}}$

  heat flux: $q_{\mathrm{w}} = \frac{D_{\mathrm{v}}}{D_{\mathrm{w}}}(q_{\mathrm{lv}} + q_{\mathrm{sv}})$



- Condensation rate:

$$M_{\mathrm{t}} = \frac{4}{D_{\mathrm{w}}}\frac{(q_{\mathrm{w}} - (D_{\mathrm{v}}/D_{\mathrm{w}})q_{\mathrm{sv}})}{H_{\mathrm{lv}}}, \quad H_{\mathrm{lv}} = f(T_{\mathrm{eq}}, C_0)$$

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

$$\frac{Q_{\mathrm{sv}}}{Q_{\mathrm{w}}} \approx x c_{\mathrm{p,v}} \frac{dT}{dh} \approx x c_{\mathrm{p,v}} \frac{\Delta T_{\mathrm{db}}}{\Delta H_{\mathrm{m}}}$$

Non-equilibrium models

- Additional conservation equations:

Species: $\frac{\mathrm{d}}{\mathrm{d}z}(\alpha\rho_\mathrm{v}V_\mathrm{v}Y) = -M_1$

Energy:

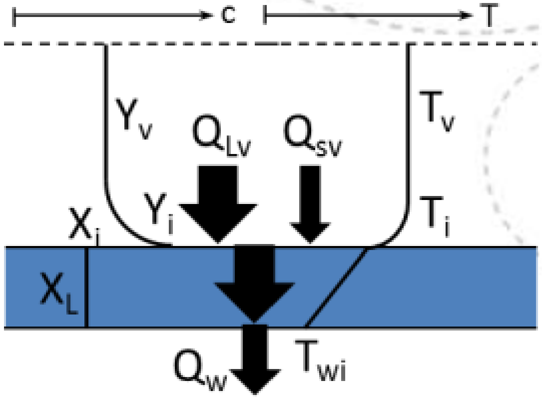
$$\frac{\mathrm{d}}{\mathrm{d}z}\left(\alpha\rho_\mathrm{v}V_\mathrm{v}H_\mathrm{v}\right) - H_\mathrm{vi}\frac{\mathrm{d}}{\mathrm{d}z}\left(\alpha\rho_\mathrm{v}V_\mathrm{v}\right) = -\frac{4D_\mathrm{v}}{D_\mathrm{w}^2}q_\mathrm{sv}$$

NTNU – Trondheim
Norwegian University of
Science and Technology

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: $q_{lv} = \frac{D_w^2}{4D_v}(M_1 H_{lv,1} + M_2 H_{lv,2}),\ H_{lv} = f(T_i)$

Sensible: $q_{sv} = h_v (T_v - T_i)$

Summary of the models

Model	Conservation Eq.s solved	Information needed
1	mass, momentum	T-C diagram
2	mass, momentum	T-C diagram
3	mass, momentum, species	T-C diagram, diffusivity data
4	mass, momentum, species, energy	T-C diagram, diffusivity data

Results

- Study case

Mixture: R134a/R123 0.349/0.651 by mass

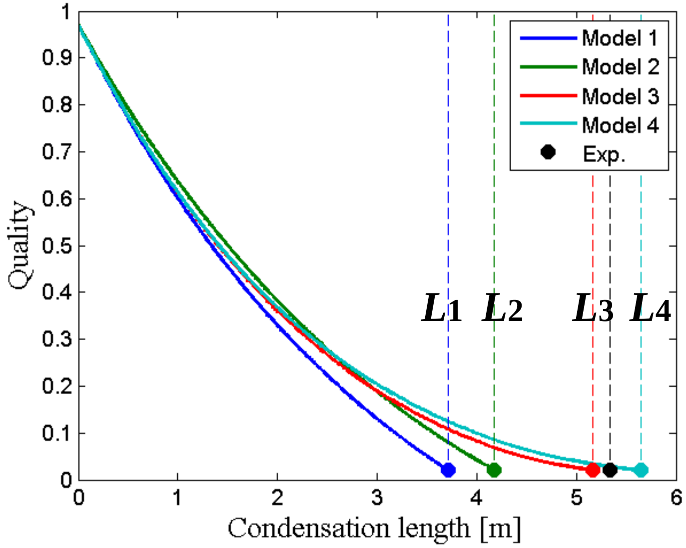
Inlet pressure: 495 kPa

Mass flux: 300.5 kg/m^{2}s

Tube: diameter 8.4 mm, horizontal

Wall heat flux: interpolated from Kogawa's [5] experimental data with quadratic polynomials

Results



Model	Mass	Heat
1	×	×
2	×	√
3	√	×*
4	√	√

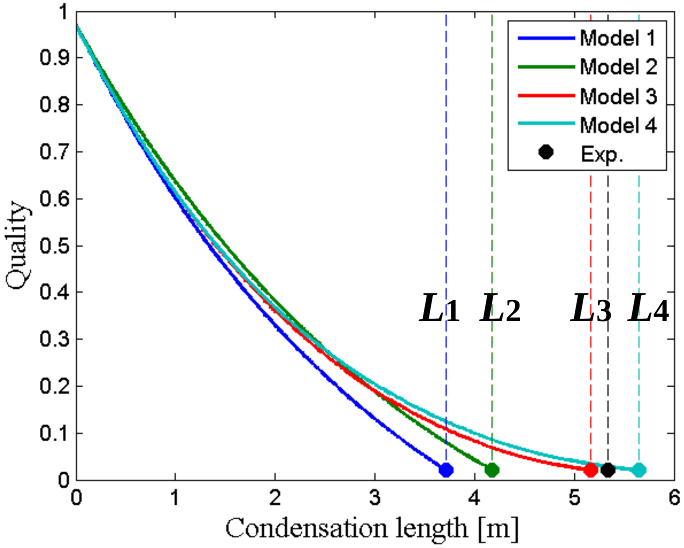
Heat transfer resistance (without mass transfer effect)

Heat transfer resistance (with mass transfer effect)

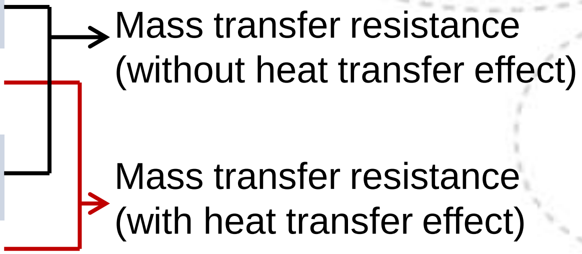
$$L_2 = 1.13L_1$$

$$L_4 = 1.09L_3$$

Results



Model	Mass	Heat
1	×	×
2	×	√
3	√	×*
4	√	√

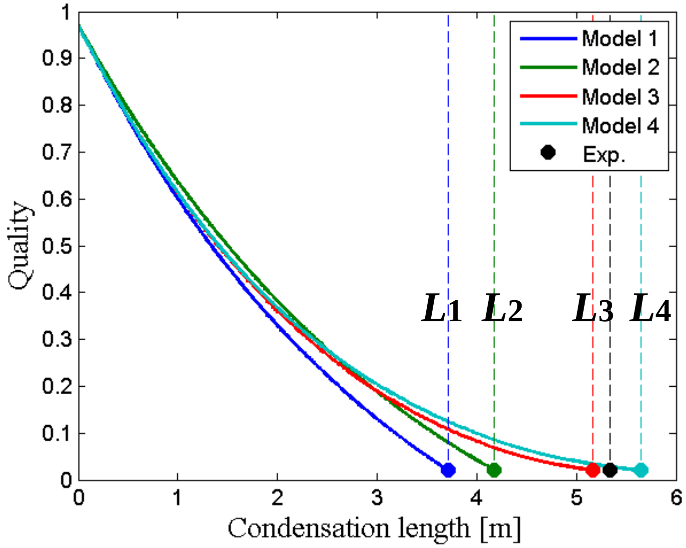

Mass transfer resistance (without heat transfer effect)

Mass transfer resistance (with heat transfer effect)

$$L_3 = 1.39 L_1$$

$$L_4 = 1.35 L_2$$

Results

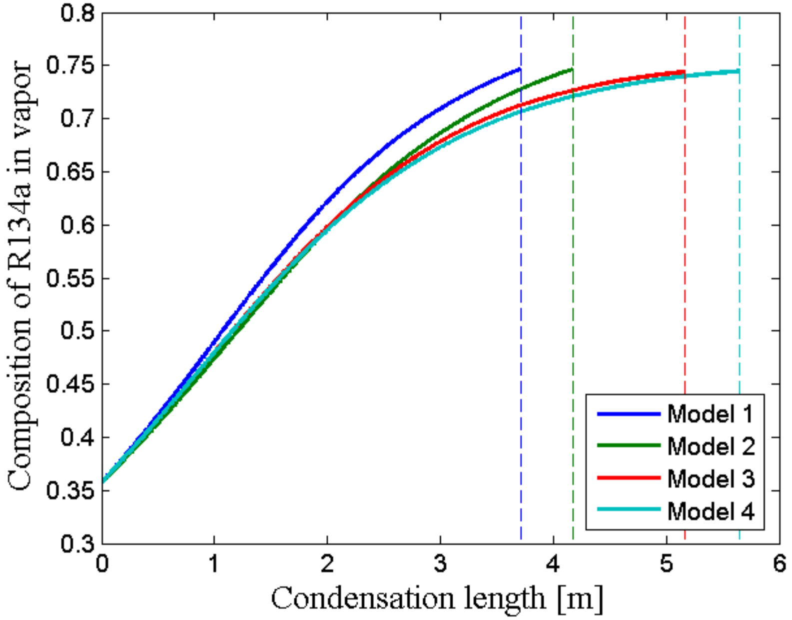


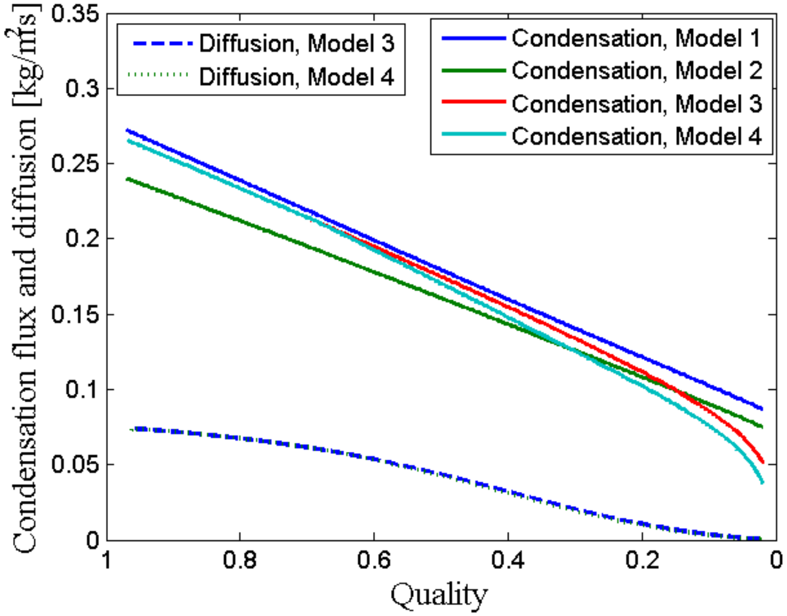
Model	Mass	Heat
1	×	×
2	×	√
3	√	×*
4	√	√

Mass transfer resistance
>
Heat transfer resistance

$$L_3 = 1.24 L_2$$

Results





NTNU – Trondheim
Norwegian University of Science and Technology

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

[1] L. Silver, Gas cooling with aqueous condensation, Transactions of the Institution of Chemical Engineers 25 (1947) 30–42.

[2] K.J. Bell, M.A. Ghaly, An approximate generalized design method for multicomponent/partial condensers, AIChE Symposium Serie 69 (1973) 72–79.

[3] A.P. Colburn, T.B. Drew, The condensation of mixed vapors. Trans. AIChE 33 (1937) 197–215.

[4] D. Del Col, A. Cavallini, J.R. Thome, Condensation of zeotropic mixtures in horizontal tubes: new simplified heat transfer model based on flow regimes, Journal of Heat Transfer 127 (3) (2005) 221–230.

[5] K. Kogawa, An experimental study on condensation of R134a/R123 mixtures inside horizontal smooth and micro-fin tubes, MS thesis, Kyushu University, Fukuoka, Japan.

Thank you for your attention!

Appendix: closure relations

- Pressure drop model

$$\Phi_{\mathrm{lo}}^2 = (1-x)^2 + x^2\frac{\rho_\mathrm{l} f_{\mathrm{vo}}}{\rho_\mathrm{v} f_{\mathrm{lo}}} + 3.24 A_2 A_3 Fr^{-0.045} We^{-0.035}$$

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

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

- Heat transfer coefficients

$$h_\mathrm{v} = 0.023\mathrm{Re_v}^{0.8}\mathrm{Pr_v}^{0.4}\lambda_\mathrm{v}/\mathrm{D_v}$$

$$h_\mathrm{l} = 0.023\mathrm{Re_l}^{0.8}\mathrm{Pr_l}^{0.4}\left(1+\frac{2.22}{X_{\mathrm{tt}}^{0.89}}\right)\frac{\lambda_\mathrm{l}}{\mathrm{D_w}}$$

- Mass transfer coefficient

$$k_\mathrm{v} = \frac{\rho_\mathrm{v}\mathcal{D}_\mathrm{v}}{D_\mathrm{v}} Sh_\mathrm{v} = \frac{\rho_\mathrm{v}\mathcal{D}_\mathrm{v}}{D_\mathrm{v}} 0.023 Re_\mathrm{v}^{0.8} Sc_\mathrm{v}^{1/3}$$