• Propose new condensation flow pattern map and simplified flow structure heat transfer model for horizontal tubes.
• Model should not only be accurate for broad database but use a minimum of empirical constants and correctly predict trends in the data.
• Model should fit into my unified approach for describing intube two-phase flows, evaporation and condensation heat transfer and pressure drops.

This lecture is based on two-part paper by Thome, El Hajal and Cavallini in Int. J. Heat Mass Transfer, Vol. 46, 3349-3387 (2003).
Shortcomings of Older Methods for Intube Condensation:

- **Annular flow methods**: Do not actually model the flow as a liquid film, but apply a vapor fraction correction to the liquid Reynolds number in the Dittus-Boelter single-phase turbulent flow correlation, which is for *tubular* not *film* flow;

- **Transition problem**: Models ignore annular to stratified flow transition or use unreliable, simplistic transition criteria;

- **Discontinuity problem**: Some give *jump* in h.t.c. at transition.

- **Optimization problem**: Trends in local experimental heat transfer coefficient vs. controlling variables are usually **not** respected; hence maximum heat exchanger performance is **not** attained.

---

Recent Developments for Condensation in Horizontal Tubes

**Cavallini et al (2002)**: proposed a new flow pattern based condensation model (*ASHRAE Trans.*):
- Good accuracy for large database but *large* number of empirical correction factors (>20) and one *jump* in h.t.c.

**Thome-El Hajal-Cavallini (present lecture)**: developed a new flow pattern based model for Cavallini’s large database plus *new South African data and hydrocarbon data*:
- Based on variation of Kattan-Thome-Favrat flow pattern map and flow *boiling* model with interfacial effects.
- Same accuracy as above but with *few* empirical factors and **no jumps** in h.t.c.

- Predicts 85% of database to within ±20% taken from *nine* labs, reduced pressures from 0.02 to 0.8, mass velocities from 24 to 1022 kg/m²s, tube diameters from 3.1-21.4 mm, 0.03 < x < 0.97, covering 15 fluids including *four* hydrocarbons.
Comments on Dobson-Chato Model for Horizontal Tubes

- Best available method in 1998 (J. Heat Transfer, 1998);
- Soliman (1982) stratification equation used to determine transition from annular to stratified-wavy flow (okay);
- Zivi void fraction equation used for liquid level height for stratified flow (not a function of mass velocity);
- Stratified angle calculated from this height (this height ignores any liquid film left by waves on the side walls);
- Nusselt film solution applied to top perimeter of tube (okay);
- Convective eqn. applied to stratified liquid layer (okay);
- A tubular flow (Dittus-Boelter) expression used with $X_{tt}$ parameter to get convection (not a film flow model).
- Gives a huge jump in h.t.c. at transition from annular to stratified flow (should be avoided).

Flow Regimes for Intube Condensation (Horizontal Tubes)

- HIGH FLOW
  - Annular mist
  - Annular
  - Annular with high stratification
  - Slug elongated bubble

- LOW FLOW
  - Annular mist
  - Annular
  - Annular with high stratification
  - Wave
  - Stratified
Kattan-Thome-Fawrat Flow Pattern Map for Horizontal Tubes

Existing Map for *Adiabatic* and *Evaporating* Flows.

New Condensation Flow Pattern Map

- Strafied=S
- Strat-Wavy=SW
- Intermittent=I
- Annular=A
- Mist=MF
Choice of Void Fraction Models:

Homogeneous void fraction model for high pressures:

\[ \varepsilon_h = \frac{1}{1 + \left(\frac{1-x}{x}\right) \rho_v \rho_L} \]

Rouhani-Axelsson drift flux model for low pressures:

\[ \varepsilon_{ra} = \frac{x}{\rho_v} \left[ (1 + 0.12(1-x)) \left( \frac{x}{\rho_v} + \frac{1-x}{\rho_L} \right)^{-1} \right. \\
\left. + 1.18(1-x) \left[ g \sigma (\rho_L - \rho_v) \right]^{0.25} \right] \]

New log mean void fraction expression for complete range of pressures:

\[ \varepsilon = \frac{\varepsilon_h - \varepsilon_{ra}}{\ln(\varepsilon_h / \varepsilon_{ra})} \]

Void Fraction: Comparison of 3 Models

R410A, T=40°C, G=400 kg/m²s, d=6mm
Results of Liebenberg (2003) for R-407C at 40°C: he observed very good agreement to the new map.

Results of Liebenberg (2003) for R-134a at 40°C compared to new map.
Idealized Flow Structures for Condensation in Horizontal Tubes

<Flow types

h.t.c. model>

![Image of flow>

Waves

Local condensing coefficient: \( \alpha_w = \alpha_c r^0 + (2\pi - 0)r\alpha_c \)

Nusselt for iso-T coefficient: \( \alpha_f = 0.728 \left[ \frac{\rho_L (\rho_L - \rho_v) g h_L \lambda_L}{\mu_L D (T_{sat} - T_w)} \right]^{1/4} \)

Nusselt for iso-q coefficient: \( \alpha_f = 0.655 \left[ \frac{\rho_L (\rho_L - \rho_v) g h_L \lambda_L}{\mu_L D q} \right]^{1/3} \)

Convective cond. coefficient: \( \alpha_c = 0.003 \text{Re}_L^{0.74} \text{Pr}_{Li}^{0.5} \frac{\lambda_{L}}{\delta} f_i \)

Interfacial roughness factor: \( f_i = 1 + \left( \frac{u_v}{u_L} \right)^{1/2} \left( \frac{\rho_v - \rho_L}{\sigma} \right)^{1/4} \left( \frac{G}{G_{strat}} \right) \)

Stratification angle around top: \( \theta = \theta_{strat} \left[ \frac{(G_{wavy} - G)}{(G_{wavy} - G_{strat})} \right]^{0.5} \)
Condensation Model Auxiliary Equations:

Reynolds number: \( Re_L = \frac{4G(1-x)\delta}{(1-\varepsilon)\mu_L} \)  
Prandtl number: \( Pr_L = \frac{c_pL\mu_L}{\lambda_L} \)

Area occupied by liquid: \( A_L = (1-\varepsilon)A \)

Solve iteratively for \( \theta_{strat} \):  
\( A_L = \frac{D^2}{8} \left[ (2\pi - \theta_{strat}) - \sin(2\pi - \theta_{strat}) \right] \)

(a new eq. avoids this)

Liquid film thickness: \( \delta = \frac{D}{2} - \frac{1}{2} \left[ D^2 - \left( \frac{8A_L}{2\pi - \theta} \right) \right]^{1/2} \)

Liquid & vapor velocities:  
\( u_L = \frac{G(1-x)}{\rho_L(1-\varepsilon)} \) \( u_v = \frac{G_x}{\rho_v\varepsilon} \)

Void fraction equation:  
\( \varepsilon = \frac{\varepsilon_h - \varepsilon_{ra}}{\ln(\varepsilon_h/\varepsilon_{ra})} \)

Example of Padova Data (for R-22)
Comparison to Padova Data Only

Cavallini data without interfacial effect

Comparison to Padova Data Only

Cavallini data with interfacial effect
Comparison to All Refrigerant Data

1850 pts.

85% of data within ±20%

9 different labs in database

Comparison of All Refrigerant Data vs. Vapor Quality

\[
\% \text{ error} = 100 \% \cdot \frac{\alpha_{\text{pred}} - \alpha_{\text{meas}}}{\alpha_{\text{meas}}}
\]
Comparison of All Refrigerant Data vs. Void Fraction

Comparison of All Refrigerant Data vs. Film Thickness
Comparison of All Refrigerant Data vs. Film Reynolds No.

Liquid Reynolds Number

Comparison of All Refrigerant Data vs. Reduced Pressure

Reduced Pressure
Comparison of All Refrigerant Data vs. Mass Velocity

Comparison of All Refrigerant Data vs. Tube Diameter
Comparison of All Refrigerant Data vs. Roughness

Comparison of All Refrigerant Data by Flow Regime
Comparison to Kim Hydrocarbon + R-22 Data (oops!)

Plot Showing Kim Hydrocarbon Data at Low G
Comparison to Kim Hydrocarbon Data (OK except at low G)

Simulation of New Condensation Model for R-410A:

\[ q = 40 \text{ kW/m}^2 \]
Attributes of new method are as follows:

- New Map/Model is statistically very accurate;
- Method utilizes a minimum of empirical constants so physical model must be reasonably correct;
- Method faithfully predicts trends in important variables, which is important for optimizing heat exchanger performance;
- Method has just now been extended to handle zeotropic mixtures with glides up to about 30K with modification of Bell&Ghaly method to include effects of interfacial roughness and non-equilibrium effects in Del Col, Thome and Cavallini, *J. Heat Transfer*, in review.
Recommendations:

• Heat Transfer Community should quit proposing new “patternless” methods for flow boiling and flow condensation heat transfer!
• Significant progress in recent years with *flow pattern based heat transfer methods*;
• New condensation heat transfer model proposed for annular, intermittent, stratified-wavy, stratified and mist flow regimes (all except bubbly flow which occurs at very high mass velocities – no data available);
• Future: Need local h.t.c. as function of $\theta$ around tube perimeter for air-cooler condensers? (and evaporators)? Present 2-zone model can help.