Flow Pattern Map for In Tube Evaporation and Condensation

László Garbai Dr.*, **Róbert Sánta** **
* Budapest University of Technology and Economics, Hungary
**College of Applied Sciences – Subotica Tech, Serbia

Abstract - The aim of the article is the review of two phase flow pattern maps for horizontal tubes. The flow pattern in evaporation and condensation section in a small tube has been analyzed ín this article. The two-phase flow pattern map for evaporation is proposed by Wojtan et al. while the condensation section is proposed by Thome and El Hajal. The simulation was in MathCAD and the results are presented in diagrams. In the simulation refrigerant R134a was used.

Nomenclature

d	diameter (m)
x	vapor quality (-)
G	mass velocity (kg/sm^2)
$\dot{m}$	mass flow rate (kg/s^2)
p	pressure (Pa)
Q	heat flux (W/m^2)
T	temperature (K)
f	friction factor (-)
A	area of tube (m^2)

Greeks

α	heat transfer coefficient (W/m^{2}K)
λ	thermal conductivity (W/mK)
ε	void fraction (-)
η	dynamic viscosity (Ns/m^2)
σ	surface tension (-)
ρ	density (m^3/kg)

Index

l	liqued
v	vapor
tp	two phase

I. INTRODUCTION

For two-phase flows, the respective distribution of the liquid and vapor phases in the flow channel is an important aspect of their description. Their respective distributions take on some commonly observed flow structures, which are defined as two-phase flow patterns that have particular identifying characteristics. Heat transfer coefficients and pressure drops are closely related to the local two-phase flow structure of the fluid, and thus two-phase flow pattern prediction is an important aspect of modeling evaporation and condensation. In fact, recent heat transfer models for predicting in tube boiling and condensation are based on the local flow pattern and hence, by necessity, require reliable flow pattern map to identify what type of flow pattern exists at the local flow conditions.

Flow patterns have an important influence on prediction of flow boiling and convective condensation heat transfer coefficients, and two-phase pressure drops. For horizontal tubes, the methods of Taitel and Dukler [1] (1976) and Baker [2] (1954), Hashizume [3], Steiner [4], are widely used. The more recent flow pattern map of Kattan, Thome and Favrat (1998) and its more subsequent improvements, which was develop specifically for small diameter tubes typical of shell-and-tube heat exchangers for both adiabatic and evaporating flows. Another version of their map also been proposed by El.Hajal, Thome and Cavalinni [6] (2003) for in tube condensation.

II. FLOW REGIMES IN HORIZONTAL PIPES

When a vapor and a liquid are forced to flow together inside a pipe, there are at least seven different geometrical configurations, or flow regimes, that are observed to occur. The regime depends on the fluid properties, the size of the conduit and the flow rates of each of the phases.

Vapor and liquid phases flow in horizontal tubes according to several topological configurations, called flow patterns or flow regimes that are determined by the interfacial structure between the two phases.

Two-phase flow patterns in horizontal tubes are similar to those in vertical flows but the distribution of the liquid is influenced by gravity that acts to stratify the liquid to the bottom of the tube and the vapor to the top. Flow patterns for co-current flow of vapor and liquid in a horizontal tube are show in Figure 1. and are categorized as follows.

- Bubbly flow – the gas bubbles are dispersed in the liquid with a high concentration of bubbles in the upper half of the tube due to their buoyancy. When shear forces are dominant, the bubbles tend to disperse uniformly in the tube. In horizontal flows, the regime typically only occurs at high mass flow rates.
- Stratified flow – At low liquid and gas velocities, complete separation of the two phases occurs. The gas goes to the top and the liquid to the bottom of the tube, separated by an undisturbed horizontal interface. Hence the liquid and gas are fully stratified in this regime.
- Stratified-wavy flow – Increasing the gas velocity in a stratified flow, waves is formed on the interface and travel in the direction of flow. The waves climb up the sides of the tube, leaving thin films of liquid on the wall after the passage of the wave.
- Intermittent flow – Further increasing the gas velocity, these interfacial waves become large enough to wash the top of the tube. Large amplitude waves often contain entrained bubbles. The top wall is nearly continuously wetted by the large amplitude waves and the thin liquid films left behind. Intermittent flow is also a composite of the plug and slug flow regimes. These subcategories are characterized as follows:
    - Plug flow. This flow regime has liquid plugs that are separated by elongated gas bubbles. The diameters of the elongated bubbles are smaller than the tube such that the liquid phase is continuous along the bottom of the tube below the elongated bubbles. Plug flow is also sometimes referred to as elongated bubble flow.
    - Slug flow. At higher vapor velocities, the diameters of elongated bubbles become similar in size to channel height. The liquid slugs separating such elongated bubbles can also be described as large amplitude waves.

- Annular flow - At high gas flow rates, the liquid forms a continuous annular film around the perimeter of the tube, similar to that in vertical flow but the liquid film is thicker at the bottom than the top. The interface between the liquid annulus and the vapor core is disturbed by small amplitude waves and droplets may be dispersed in the gas core.
- Mist flow – Similar to vertical flow, at very high gas velocities, all the liquid may be stripped from the wall and entrained as small droplets in the now continuous vapor phase.

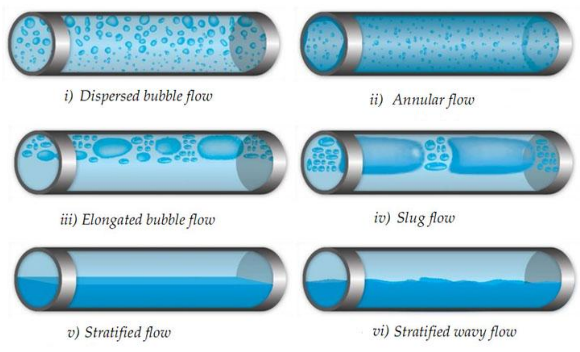

Figure 1. Flow regimes in horizontal pipes [11]

III. FLOW REGIME MAPS

To predict the local flow pattern in a tube, a flow pattern map is used. It is a diagram that displays the transitions boundaries between the flow patterns and is typically plotted on log-log axes using dimensionless parameters to represent the liquid and gas velocities.

Flow regime maps of the sort shown in figure 2. are useful when we want to gain insight into the mechanisms creating the flow regimes. Along the horizontal axis the superficial gas velocity has been plotted. Along the vertical axis we have plotted the superficial liquid velocity.

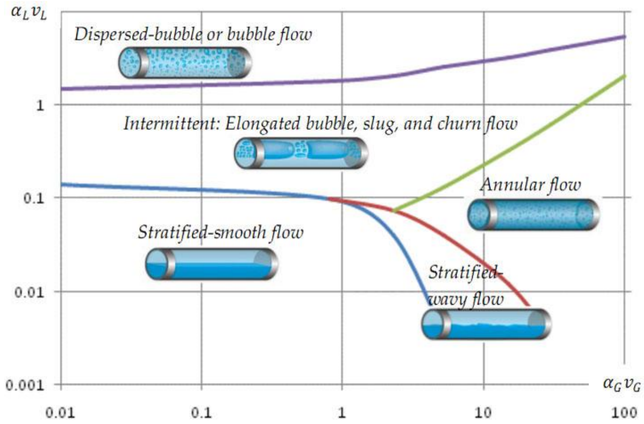

Figure 2. Example of steady-state flow regime map for a horizontal pipe

- If the superficial gas and liquid velocities is very low the flow is stratified.
- If increase the gas velocity, waves start forming on the liquid surface. Due to the friction between gas and liquid, increasing the gas flow will also affect the liquid by dragging it faster towards the outlet and thereby reducing the liquid level.
- If continue to increase the gas flow further, the gas turbulence intensifies until it rips liquid from the liquid surface so droplets become entrained in the gas stream, while the previously horizontal surface bends around the inside of the pipe until it covers the whole

circumference with a liquid film. The droplets are carried by the gas until they occasionally hit the pipe wall and are deposited back into the liquid film on the wall.

- If the liquid flow is very high, the turbulence will be strong, and any gas tends to be mixed into the liquid as fine bubbles. For somewhat lower liquid flows, the bubbles float towards the top-side of the pipe. The appropriate mix of gas and liquid can then form Taylor-bubbles, which is the name we sometimes use for the large gas bubbles separating liquid slugs.
- If the gas flow is constantly kept high enough, slugs will not form because the gas transports the liquid out so rapidly the liquid fraction stays low throughout the entire pipe.

IV. FLOW PATTERN MAP FOR EVAPORATION IN HORIZONTAL TUBES

The two-phase flow pattern map and heat transfer model for evaporation proposed Wojtan et al.[7] (2005), is a slightly modified version of Kattan, Thome and Favrat [5] map for evaporation flows in small diameter horizontal tubes.

The six principal flow patterns encountered during evaporation inside horizontal tubes are:

- Stratified flow(**S**),
- Stratified-wavy flow (**SW**),
    - Slug flow zone,
    - Slug/Stratified-Wavy zone
    - Stratified-Wavy zone.
- Intermittent flow (**I**),
- Annular flow (**A**),
- Dryout (**D**),
- Mist flow (**MF**)

A. *FLOW PATTERN MAP OF WOJTAN ET AL. (2005)*

- The transition boundary curve between stratified flows to stratified-wavy flow is:

$$G_{strat}=\left(\frac{226.2\cdot A^2_{ld}\cdot A^2_{vd}\cdot \rho_v\cdot(\rho_l-\rho_v)\cdot\mu_l\cdot g\cdot\cos\varphi}{x^2\cdot(1-x)\cdot\pi^3}\right)^{1/3} \tag{1}$$

- The transition boundary curve between annular and intermittent flows to stratified-wavy flow is:

$$G_{wavy}=\left(\frac{16\cdot A^3_{vd}\cdot g\cdot D\cdot\rho_l\cdot\rho_v}{x^2\cdot\pi^2\cdot\left(1-(2\cdot\alpha_{ld}-1)^2\right)^{0.5}}\cdot\left[\frac{\pi^2}{25\cdot\alpha^2_{ld}}\cdot(1-x)^{-F_1}\cdot\left(\frac{We}{Fr}\right)^{-F_2}+1\right]\right)^{0.5}+50 \tag{2}$$

- Threshold line of the intermittent to annular flow transition at X_{IA} is:

$$X_{IA}=\left[\left(0.34^{1/0.875}\cdot\left(\frac{\rho_v}{\rho_l}\right)^{-1/1.75}\cdot\left(\frac{\mu_v}{\mu_l}\right)^{-1/7}\right)+1\right]^{-1} \tag{3}$$

- The stratified-wavy region is then subdivided into three zones as follows:
    - $G \rangle G_{wavy}(X_{IA})$ gives the slug flow zone,
    - $G_{strat} \langle G \langle G_{wavy}(X_{IA})$ and $0 \langle x \langle X_{IA}$ give the Slug/Stratified-Wavy zone
    - $1 \rangle x \rangle X_{IA}$ gives the Stratified-Wavy zone.

- The transition boundary curve between annular flows to dryout flow is:

$$G_{dryout}=\left[\frac{1}{0.235}\cdot\left(\ln\left(\frac{0.58}{x}\right)+0.52\right)\cdot\left(\frac{d_i}{\rho_g\cdot\sigma}\right)^{-0.17}\cdot\left(\frac{1}{\rho_g\cdot(\rho_l-\rho_v)\cdot g\cdot d_i}\right)^{-0.37}\cdot\left(\frac{\rho_g}{\rho_l}\right)^{-0.25}\cdot\left(\frac{q}{q_{DNB}}\right)^{-0.7}\right]^{0.926} \tag{4}$$

- The transition boundary curve between dryout flows to mist flow is:

$$G_{mist}=\left[\frac{1}{0.0058}\cdot\left(\ln\left(\frac{0.61}{x}\right)+0.57\right)\cdot\left(\frac{d_i}{\rho_g\cdot\sigma}\right)^{-0.38}\cdot\left(\frac{1}{\rho_g\cdot(\rho_l-\rho_v)\cdot g\cdot d_i}\right)^{-0.15}\cdot\left(\frac{\rho_g}{\rho_l}\right)^{0.09}\cdot\left(\frac{q}{q_{DNB}}\right)^{-0.27}\right]^{0.943} \tag{5}$$

V. FLOW PATTERN MAP FOR CONDENSATION IN HORIZONTAL TUBES

The two-phase flow pattern map for condensation proposed by El Hajal, Thome and Cavallini [6] is a slightly modified version of Kattan, Thome and Favrat [5] map for evaporation and adiabatic flows in small diameter horizontal tubes. Thome and El Hajal have simplified implementation of that map by bringing a void fraction equation into the method to eliminate its iterative solution scheme.

The five principal flow patterns encountered during condensation inside horizontal tubes are:

- Annular flow (often referred to as sheared-controlled regime) (**A**),
- Intermittent flow (heat transfer modeled like annular flow), (**I**),
- Mist flow (annular flow heat transfer model assumed for this regime) (**MF**)
- Stratified-wavy flow (**SW**),
- Stratified flow(**S**),

Intermittent flow refers to both the plug and slug flow regimes (it is essentially a stratified-wavy flow pattern with large amplitude waves that wash the top of the tube). Also, stratified-wavy flow is often referred to in the literature as simply wavy flow.

A. FLOW PATTERN MAP OF THOME AND EL HAJAL (2003)

This model can be easily applied and gives the void fraction as a function of total mass flux. Hence it makes sense to use the same void fraction model in both the flow pattern map and the flow boiling heat transfer model for which the Rouhani-Axelson [8] model is a better choice as a general method.

The sectional area of the tube **A** and after calculating **ε**, the values and are directly determined by:

$$A_{ld} = \frac{A\cdot(1-\varepsilon)}{D^2}, \qquad A_{vd} = \frac{A\cdot\varepsilon}{D^2} \tag{6}$$

The stratified angle can be calculated from an expression evaluated in terms of void fraction proposed by Biberg [9] $P_D = \sin\left(\frac{2\pi-\theta_{strat}}{2}\right)$

- The transition boundary curve between Stratified flows to Stratified-wavy flow is:

$$G_{strat} = \left(\frac{226.2\cdot A^2{}_{vd}\cdot A^2{}_{vd}\cdot\rho_v\cdot(\rho_l-\rho_v)\cdot\mu_l\cdot g\cdot\cos\varphi}{x^2\cdot(1-x)\cdot\pi^3}\right)^{1/3} \tag{7}$$

- The transition boundary curve between Stratified flows to Intermittent/Annular flow is:

$$G_{wavy} = \left(\frac{16\cdot A^3{}_{vd}\cdot g\cdot D\cdot\rho_l\cdot\rho_v}{x^2\cdot\pi^2\cdot\left(1-(2\cdot\alpha_{ld}-1)^2\right)^{0.5}}\cdot \cdot\left[\frac{\pi^2}{25\cdot\alpha^2{}_{ld}}\cdot(1-x)^{-F_1}\cdot\left(\frac{We}{Fr}\right)^{-F_2}+\frac{1}{\cos\varphi}\right]\right)^{0.5}+50 \tag{8}$$

- The transition boundary curve between Annular flows to Mist flow is:

$$G_{mist} = \left(\frac{7680\cdot A^2{}_{vd}\cdot g\cdot D\cdot\rho_v\cdot\rho_l}{x^2\cdot\zeta_{ph}\cdot\pi^2}\cdot\left(\frac{We}{Fr}\right)_l\right)^{0.5} \tag{9}$$

- The transition boundary curve between Annular flows to Intermittent flow is:

$$X_{IA} = \left[\left(0.34^{1/0.875}\cdot\left(\frac{\rho_v}{\rho_l}\right)^{-1/1.75}\cdot\left(\frac{\mu_v}{\mu_l}\right)^{-1/7}\right)+1\right]^{-1} \tag{10}$$

V. SIMULATION OF MATHEMATICAL MODEL

Mathematical models are simulated by the use of the software tool MathCAD. The solution of the deterministic mathematical models of the flow pattern and heat transfer coefficients is complex. The applied numerical simulation model for each variable is discretized. The input data and initial conditions in the deterministic mathematical model clearly define the value of flow pattern and heat transfer coefficient i.e. is the output of the model.

The initial condition and values for the simulation:

- Refrigerant: R134a
- Mass velocity: $G = 100$ $\left[\frac{kg}{m^2 s}\right]$
- Vapor quality ranged: x = 0 – 1 [-]

- Tube diameter: $d = 6$ $[\text{mm}]$
- Heat flux: $q = 3000$ $\left[\frac{\text{W}}{\text{m}^2}\right]$
- Temperature of evaporation: $t_o = 5$ [°C]
- Temperature of condensation: $t_c = 40$ [°C]

Graphs are drawn for the considered evaporation and condensation heat transfer coefficients and flow pattern in function of different quality.

VI. RESULTS AND DISCUSES

The motivation for the composition of this article was to investigate the flow pattern map and heat transfer coefficients in the horizontal tube of the condenser and the evaporator.

The flow pattern is of crucial definition. With the change of flow pattern, the change of mass velocity of refrigerant occurs. The value of the two-phase heat transfer coefficient is determined by the mass velocity.

The discrete value of the two-phase heat transfer coefficient is a function of the refrigerant mass velocity, the vapor quality, the refrigerant condensing or evaporation temperature and the inner diameter of tube.

$$\alpha = f\left(\dot{m}, x, T, d\right)$$

Besides the heat transfer coefficients, accuracy of the pressure drop and the void fraction value is determined by the heat pump system of the accurate mathematical model.

The flow pattern map for boiling and flow boiling heat transfer model for refrigerant R134a on the inside of horizontal tubes are proposed of Wojtan et al. (2005).

The flow pattern for condensation of refrigerant R134a on the inside of horizontal tubes are suggested by Thome and El Hajal (2003). The condensation heat transfer model was used of Shah [10] correlation (1979).

The existence of a particular flow regime depends on a variety of parameters, including the thermo physical properties of the fluid, the tube diameter, orientation and geometry, force field, mass flux, heat flux and vapor quality.

On the flow pattern maps, the value change of the heat transfer coefficients of evaporation and condensation can be seen. It can be seen that the added input values, the annular flow is predominantly formed in the evaporating section. (Figure 3.) On the contrary, in the condensing section of the annular flow pattern the image did not even appear. In the condensing sections the flow regime is stratified wavy. (Figure 4.) In practice, however, this is not completely the case. If the cross section of wall is considered, the condenser tube wall is the coldest, hence the vapor of the two-phase refrigerant is condensed in the wall, so there a degree of annular flow develops.

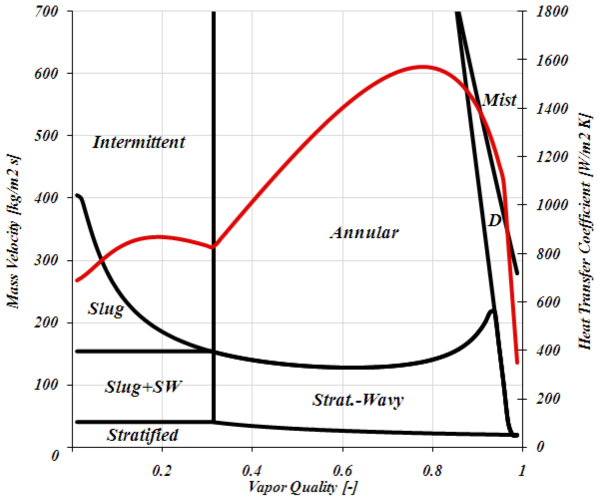

Figure 3. Flow Pattern map and Heat Transfer model for in tube boiling

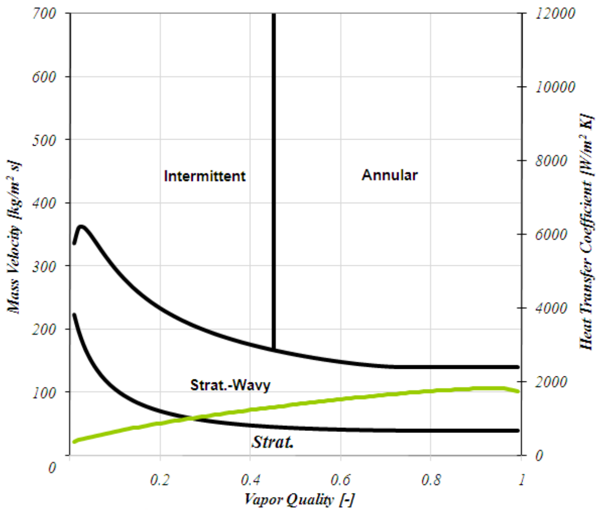

Figure 4. Flow Pattern map and Heat Transfer model for in tube Condensation

Flow patterns that occur during condensation inside horizontal tubes are similar to those for evaporation, with the following exceptions:

- The process begins without any entrainment of liquid.
- There is no dryout.

- During condensation, the condensate formed coats the tube perimeter with a liquid film.
- During condensation in stratified flow regimes, the top of the tube is wetted by the condensate film while in evaporating flows the top perimeter is dry.

REFERENCES

[1] Y.Taitel and A.E. Dukler, A model for predicting low regime transitions in horizontal and near horizontal gas-liquid flow, AICHE Journal 13. no.2, 43-69

[2] O. Baker, Design of pipe lines for simultaneous flow of oil and gas, Oil and gas journal (1954), 185-190

[3] K. Hashizume, Flow pattern and void fraction of refrigerant two-phase flow in a horizontal pipe, Bulletin of JSME26, no.219, 1597-1602

[4] Verein Deutscher Ingenieure VDI-Warmeatlas (VDI Heat Atlas), Chapter HBB, VDI-Gessellschaft Verfahrenstechnik und Chemieingenieurwsen (GVC), Düsseldorf, 1993

[5] Kattan, N., Thome, J. R., and Favrat, D. (1998). Flow Boiling in Horizontal Tubes. Part 1: Development of a Diabatic Two-Phase Flow Pattern Map, *J. Heat Transfer*, 120, 140-147.

[6] El Hajal, J., Thome, J.R., and Cavallini, A. (2003). Condensation in Horizontal Tubes, Part 1: Two-Phase Flow Pattern Map, *Int. J. Heat Mass Transfer*, vol. 46, 3349-3363.

[7] L Wojtan, T Ursenbacher, J Thome, Investigation of flow boiling in horizontal tubes: Part I: A new diabatic two-phase flow pattern map, International Journal of Heat and Mass Transfer (2005)

[8] Rouhani, S. Z., and Axelsson, E., Calculation of Void Volume Fraction in the Subcooled and Quality Boiling Regions. *International Journal of Heat and Mass Transfer*, vol. 13, no. 2, pp. 383–393, 1970.

[9] D. Biberg, An explicit approximation for the wetted angle in two-phase stratified pipe flow, Canadian J. Chemical Engineering (1999), 1221-1224

[10] Shah MM. A general correlation for heat transfer during film condensation inside pipes. Int. J Heat & Mass Transfer 1979; 22: 547–56

[11] Dr. Ove Bratland: The Flow Assurance, Bergen Area, Norway, Oil & Energy