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EXPERIMENTAL ANALYSIS OF R-134a FLOW CONDENSATION IN A SMOOTH TUBE

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ABSTRACT

Condensation processes inside tubes are widely used in air conditioning and refrigeration industry, since they promote an improvement of the heat transfer, reducing the equipment size. The distribution of the liquid and vapour phases inside the tubes is crucial in the heat transfer process. Several studies have been carried out for flow regime maps and flow regime prediction techniques, in order to predict which flow pattern is expected according to parameters such as the geometry of the tubes, the flow rate and refrigerant properties. In this work, an experimental research was conducted to obtain different condensation flow patterns inside an 8 mm inner diameter smooth copper tube. Experiments were carried out for mass fluxes of 100, 200, 300, 400 and 600 kg/m^{2}s, a saturation temperature of 40 ºC and varying the vapour quality from 0.20 to 0.80 at 0.15 intervals. Experimental photographs and videos are presented, discussed and compared against the results provided by some flow pattern maps and prediction techniques found in the literature.

INTRODUCTION

Heat exchangers using two phase flow processes inside tubes are widely used in air conditioning and refrigeration industry. These processes promote an improvement of the heat transfer, reducing the equipment size. Several tubes are used, with different geometries, materials and orientations, although the horizontal orientation of tubes is the most usual.

Heat transfer coefficients at both sides of tubes are needed for right-sizing the equipment. The distribution of the liquid and vapour phases inside the tubes is crucial in the heat transfer process, conditioning its behaviour. The different distributions and interrelations between the vapour and liquid phases are called flow patterns.

Most common two phase flow patterns in condensation processes inside horizontal tubes are shown in Figure 1. These flow patterns differ slightly from those found in evaporation, since the condensation process tends to wet the top of the tube wall.

Five flow patterns are observed: stratified flow, wavy flow, intermittent flow, annular flow and annular-mist flow. Some of these flow patterns can be subdivided into sub-regimes (e.g. plug flow, slug flow and wavy-annular flow inside intermittent flow). In many practical applications only two main categories are used: stratified flow and annular flow with a transition zone not-well established. From top to bottom each successive flow regime corresponds to an increase in the vapour velocity.

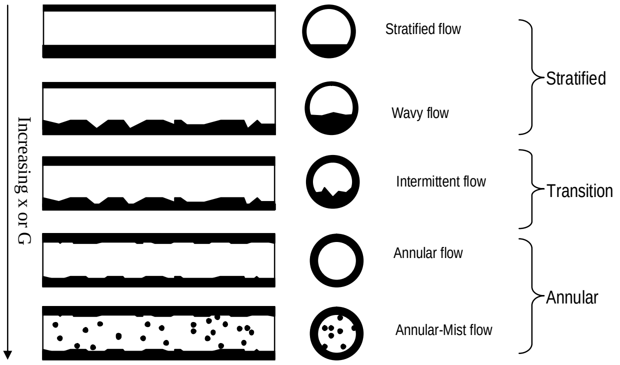

Figure 1 Most common flow patterns in condensation processes

At very low vapour velocities the stratified flow is observed. The condensate is formed in the upper wall of the tube falling by gravity and creating a liquid pool at the bottom of the tube. The liquid surface is smooth due to the low vapour velocities. As the vapour velocity is increased, the liquid surface becomes unstable, forming waves; this flow regime is referred to as wavy flow. As the vapour velocity is increased further, vapour shears are enough to cause the entrainment of droplets and the liquid phase tends to be uniformly distributed around all the periphery of the tube, leading to an annular flow. Between the annular flow and the stratified flow a transitional flow pattern is observed, usually called intermittent flow. Finally, at the highest vapour velocities, some of the droplets of the liquid film of annular flow are sheared off and entrained in the core of the tube. This is normally referred to as the annular-mist flow. However, due to high velocities this flow pattern is not very common.

Several studies have been carried out for flow regime maps and flow regime prediction techniques, in order to predict which flow pattern is expected according to parameters such as the geometry of the tubes, the flow rate and refrigerant properties. In this work, several flow regime maps and prediction techniques are reviewed; also experimental photographs and videos are presented. In these videos, flow patterns of R-134a condensation inside a copper tube of 8 mm inner diameter were obtained for different mass fluxes and vapour qualities, with a saturation temperature of 40 ºC.

NOMENCLATURE

Fr	[-]	Froude dimensionless number
G	[kg/m^{2}s]	Mass flux
T	[K]	Temperature
x	[-]	Vapour quality

Subscripts

So	Soliman

FLOW REGIME MAPS

One of the earliest flow regime maps was proposed by Baker [1] in 1954. As observed in Figure 2, in the Baker map, the coordinates are a function of fluid properties. Even though subsequent maps are more accurate, the Baker map still has great importance as far it is widely recognized as the first flow regime map.

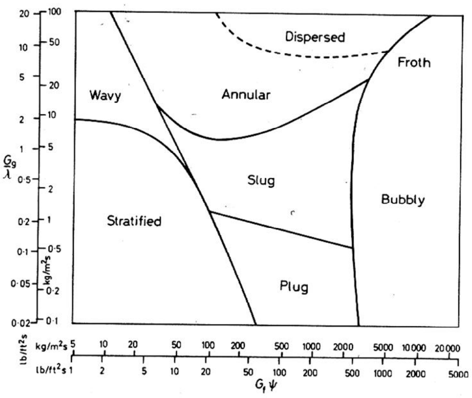

Figure 2 Baker [1] flow regime map

In 1974, Mandhane et al. [2] presented a flow regime map similar to Baker's, based on observations of a database. The flow regime map correctly predicted 68 percent of the available data. Comparisons with refrigerant data revealed systematic problems due to the fact that the map was built for air-water and the vapour density of the refrigerants is much higher than the air density.

Taitel and Dukler [3] developed a map based on theoretical analysis, so, each flow pattern and their transitions are associated to different physical mechanisms. Flow patterns in this map are a function of the existing forces and the predominant ones at each moment. The Taitel and Dukler map is shown in Figure 3.

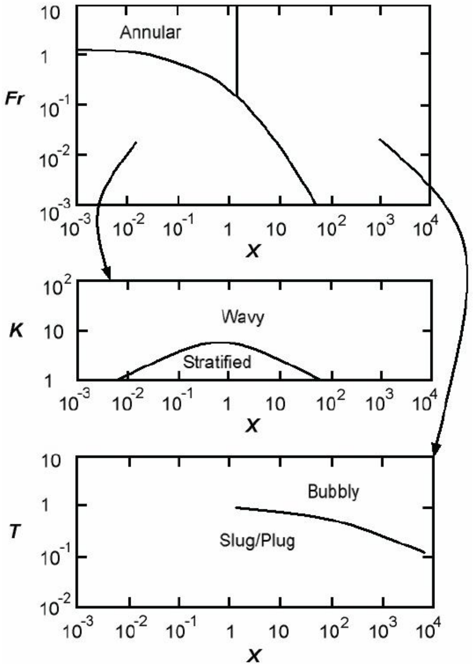

Figure 3 Taitel and Dukler [3] flow regime map

Other authors, like Soliman [4] in 1982, proposed flow regime transition criteria to predict the flow patterns. Soliman [4] distinguished between three flow regimes: wavy flow, annular flow and mist flow, so he developed 2 transition criteria. His proposed transition criteria between wavy and annular flow is based on a modification of the Froude dimensionless number. In this way, values of $Fr_{SO}<7$ represent wavy flow, while a value of $Fr_{SO}>7$ indicates annular flow. Later, Dobson and Chato [5] modified the Soliman transition criteria pointing out that $Fr_{SO}=7$ is a suitable transition value between wavy and intermittent flow. Moreover, they state that annular flow is not observed until $Fr_{SO}>18$.

In 2003, El Hajal, Thome and Cavallini [6] presented a map where the flow regime is a function of mass flux and vapour quality. In Figure 4, their flow regime map is shown for R-134a condensation inside smooth copper tubes. In 2009, Suliman et al. [7] proposed a map based on the previously mentioned [6] with some changes; amongst others, the flow regimes are slightly shifted to higher mass flux values, as shown in Figure 5.

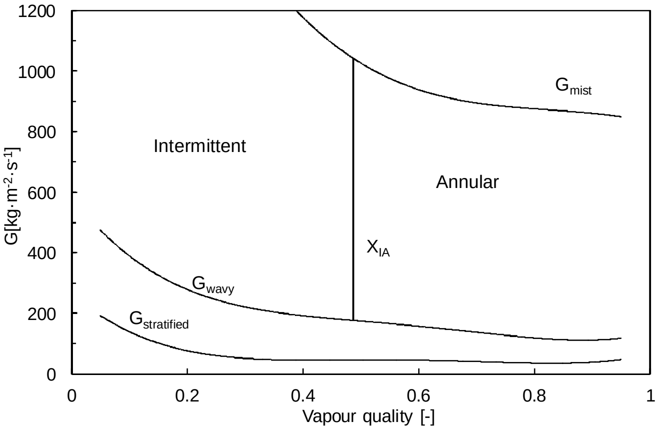

Figure 4 Flow regime map proposed by El Hajal, Thome and Cavallini for R-134a condensation inside a smooth copper tube

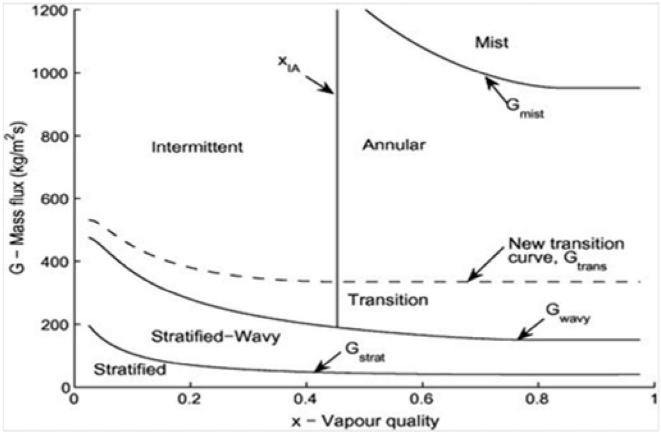

Figure 5 Suliman et al. [7] flow regime map for R-134a condensation inside a smooth copper tube

EXPERIMENTAL FACILITY

The layout of the experimental facility is shown in Figure 6. Main components are presented, as well as several measuring devices of the data acquisition system. The facility is composed of two closed loops, the refrigerant loop and the cooling water loop.

A vane pump forces the refrigerant from a reservoir tank through the pre-heater coil, the test section and a plate heat exchanger (Post-condenser in Figure 6) to return to the reservoir tank slightly sub-cooled. The pre-heater coil allows the control of the heating power delivered by the electric resistances, thus controlling the vapour quality at the test section inlet.

The test section consists of a twin tube heat exchanger with an effective condensation length of 1000 mm. Outer tube is made of stainless steel and the inner tube is exchangeable to place the different tubes tested. The refrigerant is conducted through the inner tube, where it is partially condensed by circulating cooling water through the annulus section.

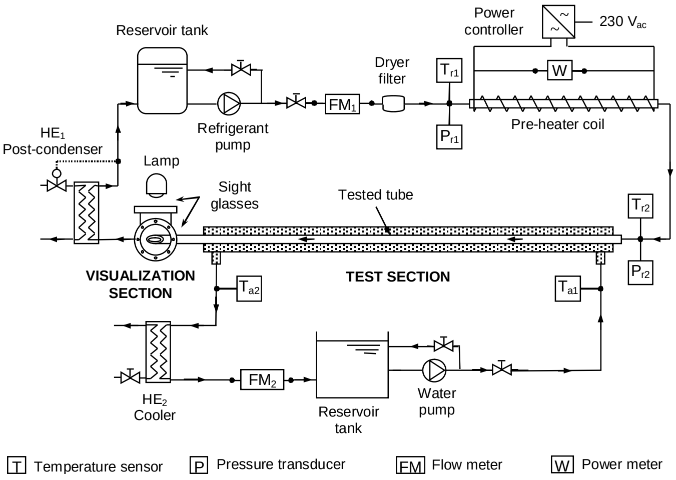

Figure 6 Layout of the experimental facility

Between the test section and the post-condenser (Figure 6), the facility is equipped with a visualization section for visual observation and the procurement of photographs and videos of the condensation processes. This section consists of a stainless steel bottle with two sight glasses. The tested tube is bevel cut and introduced into the bottle, Figure 7. The experimental setup was equipped with a data acquisition system and carefully insulated to avoid any heat transfer to the ambient.

Figure 7 Process of procurement of photographs and videos

EXPERIMENTAL PROCEDURE

Before each experiment, special attention was paid to guarantee an effective removal of any non-condensable (air). Experiments were conducted by varying the vapour quality while keeping constant the refrigerant temperature and mass flux in the test section. The vapour quality was fixed by regulating the heat flow supplied by the electric heaters by means of an electric power regulator. The refrigerant temperature was controlled by means of the heat flux exchanged with the cooling water loop. Finally, the mass flux was fixed by a recirculation loop from the outlet pump to the reservoir tank (Figure 6).

Once the system was stabilized with the desired vapour quality, refrigerant temperature and mass flux, the experimental data were recorded. Experiments were carried out for mass fluxes of 100, 200, 300, 400 and 600 kg/m^{2}s, with a refrigerant temperature at the test section of 40 ºC and varying the average vapour qualities from 0.20 to 0.80 at 0.15 intervals.

RESULTS

Experimental condensation process visualization

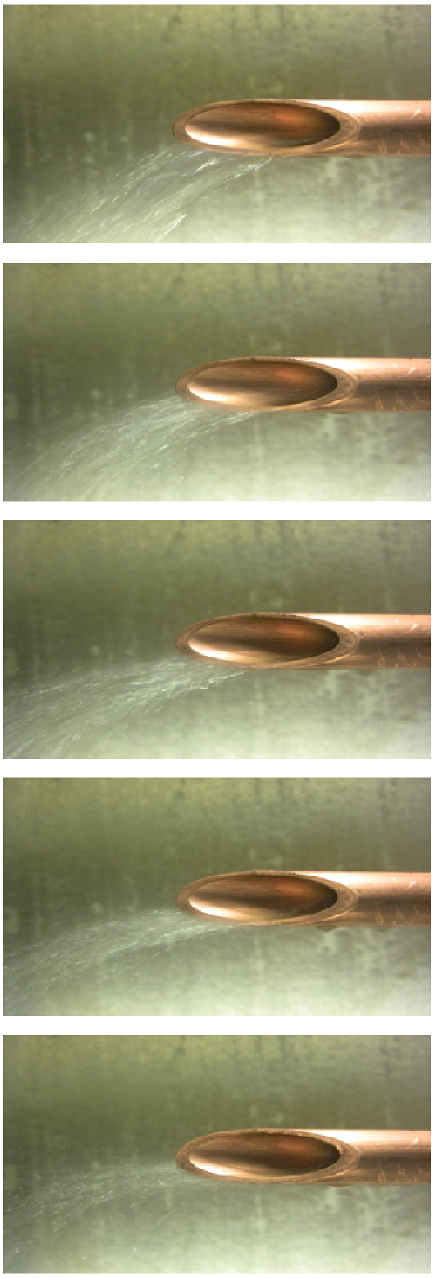

Figure 8 Condensation process at 40 ºC with 200 kg/m^{2}s

In Figure 8 several photographs of the condensation process at 40 ºC, with a mass flux of 200 kg/m^{2}s and varying the vapour quality from 0.20 to 0.80 at 0.15 intervals, are shown. With these conditions, the condensate formed in the upper wall of the tube falls by gravity, corresponding to stratified flow.

In Figure 9 photographs of condensation process at 40 ºC, with a mass flux of 600 kg/m^{2}s and varying the vapour quality from 0.20 to 0.80 at 0.15 intervals, are shown. In these conditions, with vapour quality higher than 0.5, annular flow appears. In this flow pattern, the liquid phase is uniformly distributed around all the periphery of the tube

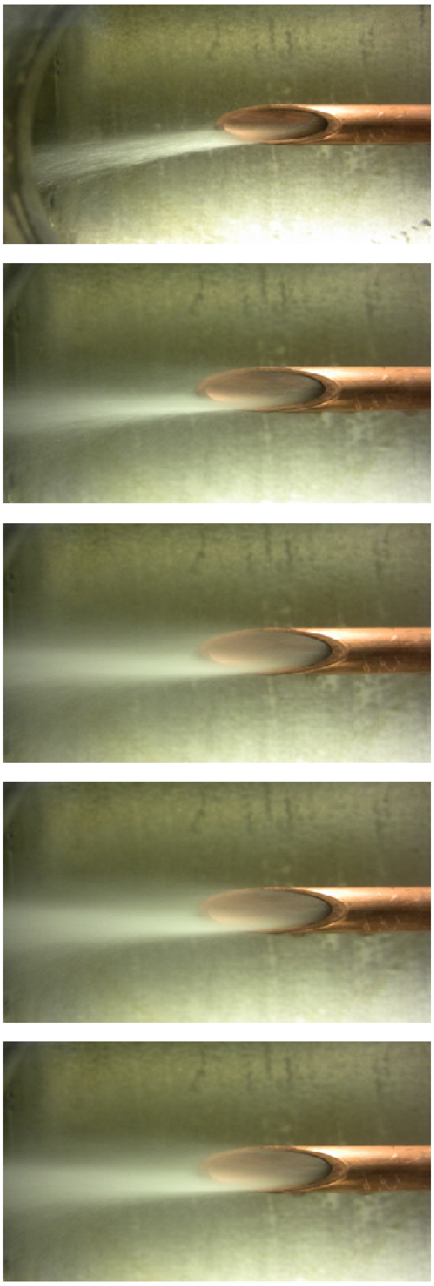

Figure 9 Condensation process at 40 ºC with 600 kg/m^{2}s

Flow regime maps and transition criteria

In Figure 10, experimental data of R-134a condensation inside a smooth copper tube of 8 mm inner diameter are presented. Fr_{SO} dimensionless values are represented for different mass fluxes and vapour qualities at 40 ºC. Soliman [4] and Dobson and Chato [5] transition criteria are also shown in the figure.

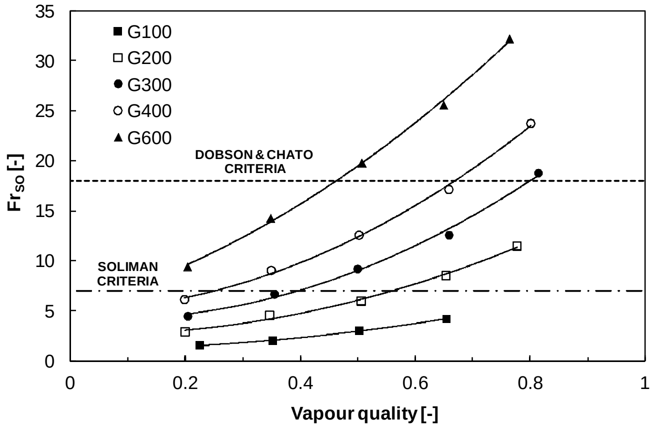

Figure 10 Soliman and Dobson & Chato criteria with experimental data process at 40 ºC with 600 kg/m^{2}s

Taking into account the Soliman criteria, Figure 10 depicts that a large percentage of the data should be annular flow. However, the analysis of the experimental videos and photographs did not agree with this prediction, especially with the lowest values of vapour quality. In contrast, the prediction done by the Dobson and Chato transition criteria agrees with the experimental data. The highest values of mass flux (300, 400 and 600 kg/m^{2}s) with the corresponding highest values of vapour quality are included in annular flow. In detail, vapour quality values higher than 0.5 with 600 kg/m^{2}s and values of 0.8 with 300 and 400 kg/m^{2}s would be included in annular flow. Moreover, values of vapour quality of 0.65 with 400 kg/m^{2}s are also very close to annular flow.

In a similar way, the above mentioned map proposed by Suliman et al. [7], is quite consistent with the videos and photographs obtained.

CONCLUSIONS

In this work, several flow regime maps and flow regime prediction techniques are reviewed. An experimental analysis was carried out to obtain photographs and videos of different flow patterns in condensation process. Based upon this work the following conclusions were drawn:

- Main flow patterns in condensation inside tubes are described and different flow regime maps and transition criteria existing in the literature are briefly analyzed.
- Photographs and videos of R-134a condensation inside a smooth copper tube of 8 mm inner diameter have been obtained. Experiments were carried out for 40 ºC and varying the mass fluxes from 100 to 600 kg/m^{2}s and vapour quality from 0.2 to 0.8.
- Experimental data are specially consistent with predictions done by Suliman et al. map [7] and Dobson and Chato transition criteria [5].

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