Assessment of stratification during horizontal two-phase flow of R-245fa: intermittent and annular flows

T. LAYSSAC*, S. LIPS, R. REVELLIN

Université de Lyon, CNRS ; INSA-Lyon, CETHIL, UMR5008, F-69621, Villeurbanne, France ;
*corresponding author: thibaut.layssac@insa-lyon.fr

Abstract:
An optical method has been developed for annular mini-channels in order to quantify stratification effects in R-245fa annular flow boiling. For each condition of temperature and mass velocity, the flow in the 2.95 mm inner diameter channel is recorded with a high speed camera during a total period of 2.7 s. The grayscale images are treated with an algorithm which determines liquid-vapor interface positions for annular flows. This method has then been modified to analyze intermittent flows. The tests are thus performed for a large range of vapor qualities, temperatures and mass velocities. The saturation temperatures tested are 60, 70, 80°C and the mass velocities are 100, 200 and 300 kg.m\(^{-2}\cdot s\)\(^{-1}\). The influence of these parameters and vapor quality is discussed through the consideration of Froude and Bond numbers. It appears eccentricity decreases with vapor quality and mass velocity and increases with saturation temperature.

Mots clefs : Stratification; Epaisseur de film; Méthode optique de mesure; Mini-canal; Ecoulement intermittent; Ecoulement annulaire

Keywords: Stratification; Film thickness; Optical measurement technique; Mini-channel; Intermittent flow; Annular flow
1 Introduction

Industrial processes, power plants and automotive fleet are the main carbon dioxide sources in the world. Thus, due to the environmental norms which are imposed to these sectors, their actors deal with a number of problems with energy effectiveness and environmental footprint reduction. Heat recovery systems, like Organic Rankine Cycles, appear to be possible solutions which are currently explored. Actually, these several sectors emit hot fumes (from 400°C to 900°C in the automotive fleet case) whose thermal energy can be recovered with Organic Rankine Cycles. Efficiency of these cycles depends largely on the choice of the heat transfer fluid and on the cycle architecture. Furthermore, fluid set conditions of use in hot cycles are not well-known since this kind of fluids is mainly used for air conditioning and refrigerating. Charnay et al. [1] pointed out the lack of data for high saturation conditions. Studies were led for reduced pressures up to 0.3 by Cioncolini and Thome [3] while Del Col [4] studied refrigerants flow boiling for reduced pressures up to 0.5. Several thermohydraulic aspects of R245fa in flow boiling with Organic Rankine Cycle conditions were also studied by Charnay et al. [1]. The test facility enables to study heat transfer coefficients, pressure drops and a flow patterns for horizontal flows. Thus, it qualitatively appeared that flow patterns had an influence on heat transfer. These observations led to the development of an optical method (Donniacuo et al. [2]) to observe stratification effects for annular flows for a set of temperatures between 40 and 100°C and a set of mass velocities from 300 and 400 kg.m$^{-2}$.s$^{-1}$. After these works, some tests were carried out to complete the database and to exploit intermittent flow frames. In the present communication, experimental data obtained for $G = 100$ to 300 kg.m$^{-2}$.s$^{-1}$ and $T_{sat}$ from 50 to 70°C are presented and discussed.

2 Material and methods

2.1 Experimental setup

The test bench, designed and previously described by Charnay et al. [1], enables to set the saturation temperature and pressure, the heat flux density, and the mass velocity conditions at the test section inlet. The liquid refrigerant, moved by a gear pump, passes through a filter, a flowmeter, a microvalve and arrives to the test section. Then, the fluid returns to the gear-pump after being cooled in a heat exchanger. The control of mass velocity can be ensured by setting the pump rotational velocity, bypass activation or by a micro-valve. The pressure is set thanks to a thermostatically controlled bath.

The test section consists in three parts which are a 2000 mm spirally shaped preheater, a 185 mm horizontal evaporator and a 200 mm glass visualization tube (Figure 1). The preheater ensures the vapor quality control at the test section inlet. The liquid refrigerant, moved by a gear pump, passes through a filter, a flowmeter, a microvalve and arrives to the test section. Then, the fluid returns to the gear-pump after being cooled in a heat exchanger. The control of mass velocity can be ensured by setting the pump rotational velocity, bypass activation or by a micro-valve. The pressure is set thanks to a thermostatically controlled bath.

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2.2 Optical measurement technique

An optical measurement technique has been developed by Donniacuo et al. [2] to measure the two-phase flow liquid film thickness in the glass tube. A high-speed camera system (Photron Fastcam SA3 120K M3) and an adjustable light system behind the tube enable the visualization of the flow by recording frame sequences. The camera is located near the glass tube inlet to get the local liquid film thickness with a precision of 160 pixels.mm$^{-1}$.
Maximum flow velocity is 400 kg.m$^{-2}$.s$^{-1}$, which corresponds to a vapor velocity of 5.6 m.s$^{-1}$ for a temperature of 100°C. With a recording speed of 2000 frames.s$^{-1}$, slug sizes are superior to 50 frames, which allows getting all of them and the large majority of bubbles. In each condition of temperature and mass velocity, 4 series of 1363 frames are taken, corresponding to a total time of 2.7 s. The frame size is of 1024 X 1024 pixels and each pixel has a grayscale value ranging from 0 to 255.

To measure the liquid film thickness, a MATLAB program has been conceived by Donniacuo et al. [2]. It detects the high transitions of pixel values along a line situated at 50 pixels of the left limit, allowing getting the majority of liquid-gas interfaces. The image for liquid single-phase flow provides scale conversion in pixels/mm and R245fa – glass and glass – air boundaries, which correspond to local extrema of grayscale function on the line (Figure 2). Additionally, the presence of glass on optical path generates refraction effects, which deform the recorded frames. This deformation has to be corrected by a factor previously calculated and checked with a target.

However, the previous method based on grayscale analysis along the line needs an improvement to be applied to intermittent flows. Indeed, the analysis on local extrema of the line allows detecting interfaces on an annular flow but is not able to detect zones which correspond to liquid single-phase during intermittent flows. Thus, a method based on the comparison between the grayscale profiles of single-phase and two-phase flows has been developed to provide position of liquid-only zones. This method also permits to sensibly reduce the uncertainty on interface detection for annular parts.
Since the direct measurement suffers of the refraction effects through the glass of the tube, a correction factor was introduced. Concerning two-phase flows in micro-tubes, Fu et al. [5] performed both a theoretical and experimental approach for the quantification of the image deformation. They developed a simple optical model. According to this model, the image enlargement compared to the real situation depends on two factors: the different refractive indexes of the glass tube and the fluid and the geometrical configuration of the test section. This model was used to evaluate the distortion of the top and bottom liquid film thickness in our configuration. Therefore, the refractive index of liquid R-245fa is needed, that is a function of the temperature. Here an averaged value is considered. Applying the formulas of the model, for each point inside the horizontal tube, the apparent position viewed by the camera is known. The linear approximation of these points shows a low mean square error. For this reason, a uniform enlargement in the vertical direction was assumed. The slope of the regression line is the enlargement factor, the value of which is 1.24.

The next step was to perform some experimental tests to validate the optical model. A metallic target was placed inside the glass tube. This target has a height equal to the internal diameter of the pipe and a negligible width compared to its height. There are five grooves every 0.5 mm in the direction of the tube diameter. The distances between adjacent grooves were measured with a scanning electron microscope. Only liquid phase flowed inside the view section, because the purpose was to evaluate refraction effects for the liquid R-245fa. Through the image processing, the distance in pixels between two adjacent grooves was calculated. The apparent distance (mm) was evaluated through the scale conversion factor (Sc (pixel/mm)). Hence, by knowing the real distance values, the enlargement for each distance was known. The comparison with the model provides good results. Therefore, a uniform enlargement factor, EF, was assumed, which value is 1.240 ± 0.047.

Consequently, the real value of the liquid film thickness for each picture was calculated as follows:

\[
\text{Real film thickness (mm)} = \frac{\text{Apparent film thickness (pixel)}}{EF \cdot Sc (\text{pixel/mm})}
\]

The uncertainty on the apparent film thickness is ± 2 pixels. At each operating condition, the top and bottom liquid film thickness were calculated as the average value from 5452 recorded frames.

For each measurement was also calculated the error bar, taking into account several sources of uncertainty: inner and outer diameter dimensions; variation of liquid R-245fa refractive index with the temperature; limitations of image resolution, due to finite pixel dimensions. The combined uncertainty for film thickness measurement was evaluated as following:

\[
\delta_{\text{Real film thickness}} = \sqrt{\left(\frac{1}{EF \cdot Sc} \cdot \delta_{\text{Apparent film thickness}}\right)^2 + \left(\frac{\text{Apparent film thickness}}{-Sc \cdot EF^2} \cdot \delta_{EF}\right)^2}
\]

\[
\quad + \left(\frac{\text{Apparent Film thickness}}{-EF \cdot Sc^2} \cdot \delta_{Sc}\right)^2
\]

For the operating conditions presented in this paper, the mean uncertainty of film measurement is about 20%.

3 Experimental results

The experiments are performed during intermittent and annular flows for mass velocities equal to 100, 200 and 300 kg.m\(^{-2}\).s\(^{-1}\), and for saturation temperatures of 60, 70 and 80°C. In each case, vapor quality range includes intermittent – annular transition. In the present study, four flow patterns are considered, which are bubbly, transition, slug and annular (Figures 4).
The asymmetry parameter used in the present study, enabling the characterization of the stratification effect is the eccentricity of the vapor core. This parameter is defined by the ratio of the difference between position of vapor core center and the internal radius to the internal radius. Practically, it is calculated with the strictly equivalent formula:

\[ Ecc = \frac{\delta_{\text{bottom}} - \delta_{\text{top}}}{d} \]  

where \( Ecc \) is the eccentricity, \( d \) the internal diameter, \( \delta_{\text{bottom}} \) and \( \delta_{\text{top}} \) respectively the bottom and top film thicknesses. Due to this definition, the eccentricity is 0 if the vapor core center is centered in the two-phase flow. On contrary, the eccentricity limit is 1 when all the liquid is at the bottom and the bottom film thickness tends to the internal diameter.

Figure 5 shows the vapor eccentricity for a mass velocity of 100 kg.m\(^{-2}\).s\(^{-1}\) and for temperatures of 60, 70 and 80°C. Each curve is divided in different parts which correspond to the different flow regimes. Independently of mass velocity, stratification effects decrease with vapor quality and increase with the saturation temperature. Figure 6 deals with the evolution of eccentricity with mass velocities of 100, 200 and 300 kg.m\(^{-2}\).s\(^{-1}\) and for a temperature of 70°C. It is observed that vapor core center tends to be more centered in the tube when the mass flux increases. With mass velocity increasing, the vapor core eccentricity decreases faster with vapor quality. Indeed, contrarily to the temperature which mainly translates curves, the mass velocity tends to deform them. Furthermore, for \( G = 200 \) and 300 kg.m\(^{-2}\).s\(^{-1}\), the eccentricity can be measured slightly negative, which can be explained by potential perturbation in the flow. This perturbation could be due to the temperature range in the flow boiling study. Glass dilatation can potentially create a space in the junction between steel and glass. This kind of singularity, if present in the flow could make it oscillate. This point requires more analysis.

The evolution of the eccentricity is mainly due to three forces which are inertia, weight and surface tension forces. The ratios of power between these forces lead to considerate two dimensionless numbers, the Bond number and the Froude number as defined:

\[ Bd = \frac{\text{gravity forces}}{\text{surface tension forces}} = \frac{g(\rho_{\text{liq}} - \rho_{\text{vap}})d^2}{\sigma} \]  

where \( \rho_{\text{liq}} \) is the liquid density, \( \rho_{\text{vap}} \) is the vapor density, \( g \) the gravity acceleration, \( d \) the internal diameter, and \( \sigma \) the surface tension coefficient.
This Froude number definition has been suggested by Cioncolini and Thome [6]. It represents the ratio of the vapor core inertia forces to buoyancy forces. When the Bond number increases, the stratification tends to decrease. On the contrary, when the Froude number increases, the stratification tends to decrease which means that inertia tends to center the flow.

When the vapor quality increases, the Froude number increases which means inertia forces are more and more important compared with gravity. Consequently, the flow will be more centered, which corresponds to the general form of all the curves.

When the saturation temperature increases, the gravitational term decreases, but the surface tension decreases faster. Thus, the Bond number increases with the saturation temperature and the Froude number decreases with the saturation temperature. Thus, when the saturation temperature increases, eccentricity increases.

When the mass velocity increases, the inertia term increases, which makes Froude number to increase and does not affect Bond number. In consequence, the flow is more centered.

As a conclusion, the stratification effects during R-245fa flow boiling can be characterized with the introduction of eccentricity parameter. Its definition enables to get the evolution of stratification with condition parameters which are mass velocity, vapor quality and temperature. These pieces of information on flow-patterns are relevant to develop heat transfer models for Organic Rankine Cycles.

4 Conclusion

A new method has been developed to analyze intermittent horizontal flows. This method enables to analyze a large range of vapor qualities. Eccentricity can be calculated for all types of flows which are bubbly, transition, slug and annular flows. Graphs show eccentricity decreases with vapor quality and mass velocity; it increases with temperature, which corresponds to the dimensionless analysis. These stratification phenomena depend on the orientation of the mini-channel. Consequently, a larger study should be considered to analyze inclined flows and to directly visualize flow boiling with the use of ITO coating. This new configuration would enable to get the influence of the orientation on stratification. Additionally, the results on eccentricity evolution in new configurations can be used for the development of heat transfer models and can be applied to better predict efficiency of evaporators in Organic Rankine Cycles.

References