

EXPERIMENTAL STUDY OF CONVECTIVE CONDENSATION OF R134A IN AN INCLINED TUBE

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ABSTRACT

Few studies are available in the literature on diabatic liquid-vapour flows in inclined tubes. The present paper is dedicated to an experimental study of convective condensation of R134a in an 8.38 mm inner diameter smooth tube in inclined orientations. Flow patterns, heat transfer coefficients and pressure drops are presented as function of the inclination angle for different mass fluxes and vapour qualities. Tilting influences the flow patterns and thus the heat transfer coefficients for low mass fluxes and low vapour qualities. An optimum inclination angle that leads to the highest heat transfer coefficient can be found for downward flow. The study of the pressure drops in inclined orientations requires the distinction between the frictional and the gravitational pressure drops. However, a void fraction sensor is necessary to measure the gravitational pressure drops.

INTRODUCTION

Convective condensation inside smooth and enhanced tubes in horizontal orientation has been widely studied during the last years [1]. Several accurate predictive tools have been developed, in order to determine the flow pattern map [2], the heat transfer coefficient [3,4] and the pressure drop [5] for this kind of flow. The models have been tested with a wide range of fluids and experimental conditions. However, no complete mechanistic model exists for the whole range of flow patterns, vapour qualities and mass fluxes and the results of existing models cannot be extrapolated to tilted orientations.

Some studies dealing with two-phase flows in inclined tubes are available in the literature. However, only a few of them considered the whole range of inclination angles, from vertical downward to vertical upward flow. Barnea [6] proposed a model of flow pattern maps for the whole range of inclination angles. Speddings et al. [7] performed an intensive study of two-phase pressure drops in inclined tubes and Beggs and Brill [8] proposed a correlation to predict the void fraction for all inclination angles. Hestroni et al. [9] conducted an

experimental study of air-water flow in an inclined tube: they visualized the flow patterns and measured the heat transfer coefficient as well as the film thickness distribution around the circumference of the tube. More recently, Ghajar and Tang [10] have published a review article on heat transfer correlations for liquid-gas flows in upward inclined tubes. All of these studies have been conducted with air as the vapour phase and most of the time water as the liquid phase. Thus, extrapolations of the results to application using refrigerant are uncertain. Moreover, heat transfer coefficient correlations developed for liquid-gas flows cannot be used for condensing flows.

Studies of condensation in inclined tubes are very rare [11-13] and are limited to very specific experimental conditions. In a comprehensive literature review, Lips and Meyer [14] highlighted the scarcity of experimental data of convective condensation in inclined tubes. They showed that more experimental studies are required in order to achieve a good understanding of the different phenomena involved and to develop predictive tools.

The present study is dedicated to an experimental investigation of convective condensation of R134a in an inclined tube. The first part of the article deals with the inclination effect on flow pattern and the second and third parts focus on the evolution of the heat transfer coefficient and pressure drop with the inclination angle respectively. This paper aims to get a first overview of the inclination effect on the flow properties as a preliminary study and work in progress for further experimental and theoretical studies.

NOMENCLATURE

G	[kg/m ² s]	Mass flux
x	[-]	Vapour quality
Special characters		
α	[rad]	Inclination angle

EXPERIMENTAL SET-UP

The experimental facility used in this study was adapted from the one already presented in previous works [15,16], and is therefore only briefly described. The set-up consisted of a vapour-compression cycle circulating the refrigerant R134a with two high-pressure condensation lines: the test line and the bypass line (Figure 1). Each line had its own electronic expansion valve (EEV). The bypass line was used to control the mass flow through the test line and the test pressure and temperature. The bypass line had one water-cooled heat exchanger whereas the test line was constituted by three water-cooled condensers: a pre-condenser, to control the inlet vapour quality, the test condenser, where the measurements were performed, and the post-condenser, to ensure that the fluid is fully liquid before the EEV. After the EEVs, the lines combined and entered a water-heated evaporator, followed by a suction accumulator and a scroll compressor.

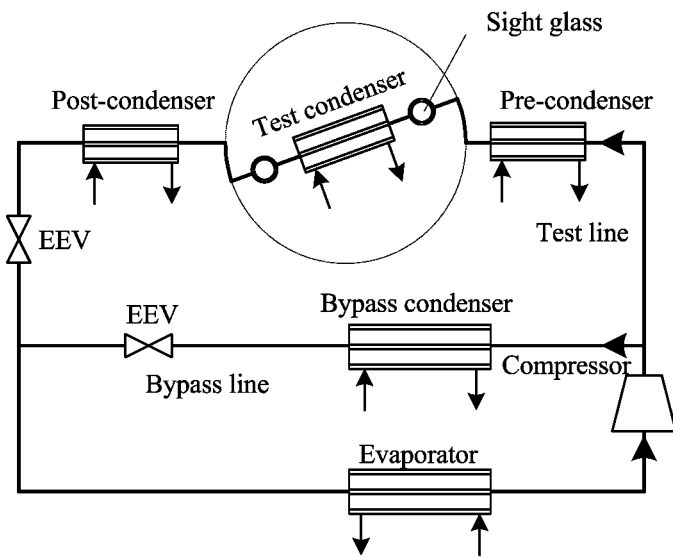


Figure 1 Experimental setup

The test condenser (Figure 2) consisted of a tube-in-tube counterflow heat exchanger, with water in the annulus and refrigerant on the inside. Its length was 1 488 mm and the inside channel was a copper tube with an inner diameter of 8.38 mm. Cylindrical sight glasses were positioned at the inlet and the outlet of the test condenser. It permitted flow visualisation and acted as insulators against axial heat conduction. A highspeed video camera (200 fps) was used to record the flow at the exit sight glass. Absolute pressures at the inlet and the outlet of the test condenser were measured by means of Gems Sensor pressure transducers and the pressure drop in the test condenser was measured by means of a FP2000 Sensotec differential pressure transducer. The length between the pressure taps for the differential pressure sensor was 1 702 mm. The pressure lines were heated by means of a heating wire and their temperature were controlled by means of four thermocouples and a labview program to ensure that the refrigerant remains always vapour in the lines.

Straight calming sections were positioned before and after the sight glasses. The test section could be inclined from 90° upwards to 90° downwards by using flexible hoses at the inlet and outlet of the test section. The outer wall temperature of the inner tube of the test section was measured at seven stations equally spaced. The refrigerant temperature was taken at four stations: inlet and outlet of the test section, inlet of pre-condenser and outlet of the post-condenser. These measurements were taken on the outside of the refrigerant tube. At each station thermocouple measurements were taken with four T-type thermocouples equally spaced and soldered onto the tube perimeter. On the water side, the water temperature was measured at six stations: the inlet and outlet of the pre-, test- (i.e. test section) and post-condenser. At each station thermocouple measurements were taken with three T-type thermocouples equally spaced and soldered onto the tube perimeter. All the thermocouples were calibrated together to an accuracy of 0.1°C. The refrigerant and water mass flows through the pre-, test- and post-condensers were measured with coriolis mass flow meters.

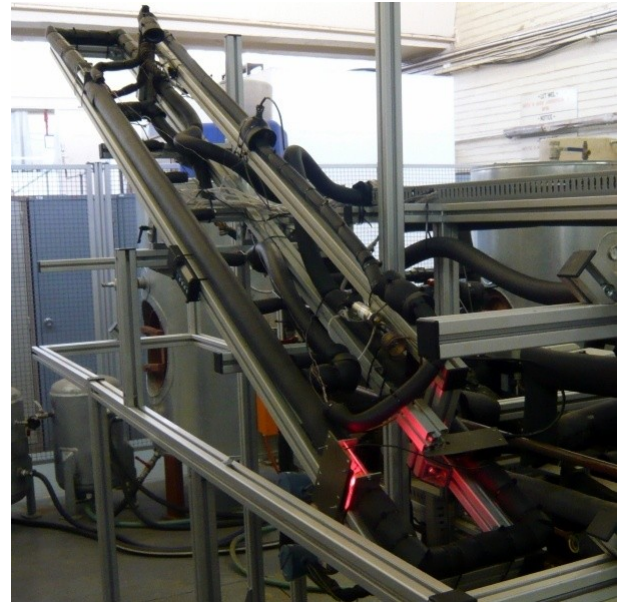


Figure 2 Picture of the test section in an inclined orientation

EXPERIMENTAL PROCEDURE

The instrumentation of the test-section allowed the calculation of the energy balance from the inlet of the pre-condenser, where the fluid is fully liquid, to the outlet of the post-condenser, where the fluid is fully vapour. The energy balance is defined as the percentage of heat that is lost, or gain, during the heat transfer between the water and the refrigerant in the three condensers. All the experiments have been performed with an energy balanced lower than 3%. A good energy balance permits to determine accurately the inlet and outlet vapour qualities, as well as the heat transfer coefficients, with the method presented in [15]. The experiments were conducted for different mass fluxes G , mean vapour qualities x and inclination angles α . The average saturation temperature was kept constant at 40°C and for all the experiments the heat transfer rate in the

test condenser was equal to 200 W. This heat transfer rate led to a vapour quality difference across the test condenser between 0.11 and 0.034 depending on the mass flux. Figure 3 summarises the experimental conditions on the Thome-El Hajal [2] flow pattern map. For a horizontal orientation, the experimental conditions mainly correspond to intermittent and annular flow patterns at the boundary of the stratified flow.

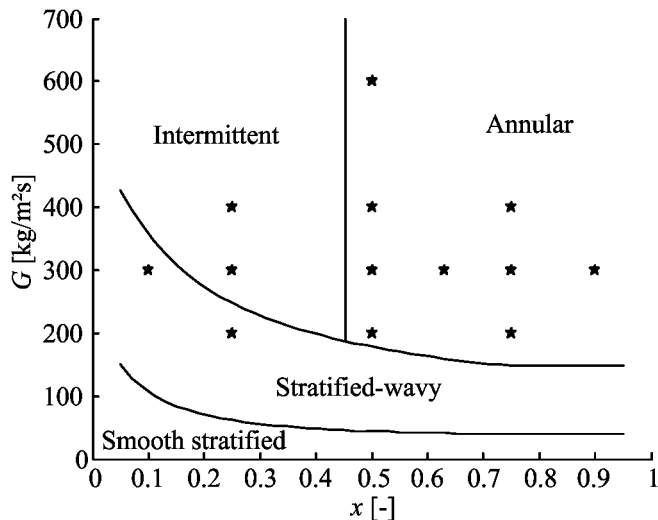


Figure 3 Experimental conditions plotted on the El-Hajal-Thome flow pattern map [2]

EXPERIMENTAL RESULTS

In this section, the experimental results are presented in terms of flow patterns maps, heat transfer coefficients and pressure drops.

Flow patterns

The flow pattern was determined visually using the recordings made by the high speed camera. Figure 4 summarises the different types of flow patterns considered in this study. It represents a concatenation of a small part of several pictures recorded in a short period of time. The flow is stratified-wavy (Figure 4a) when the liquid is mostly located at the bottom of the tube. The flow is annular-wavy (Figure 4b) when the thickness of the liquid film at the top of the tube increases. The slug flow (Figure 4c) occurs when the waves in the bottom part of the tube are big enough to reach the top of the tube. The flow is annular (Figure 4d) when the liquid is located uniformly at the perimeter of the tube. The churn flow (Figure 4e) is a highly turbulent flow where slugs of liquid regularly collapse in the central vapour core.

Figure 5 is a montage of pictures representing the flow visualisation for different inclination angles and different vapour qualities for a mass flux of 300 kg/m²s. For high vapour qualities, the flow remains annular whatever the inclination angle: in these conditions, the gravitational forces are negligible compared to the shear forces. For low vapour qualities, the shear forces decrease because of the decrease of the vapour velocity and the flow pattern becomes strongly dependent on the inclination angle. For horizontal and slightly downward orientation the flow is stratified. For upward flows, the flow is

intermittent because of the gravitational forces that lead to a decrease in the liquid velocity and thus an increase in the liquid height in the tube. In a general way, flows are more and more annular when the orientation is more and more vertical.

Figure 6 represents the experimental flow pattern maps for different inclination angles. For high mass fluxes and high vapour qualities, the flow remains annular whatever the inclination angle. However, the boundary between stratified-wavy and annular flows is affected by the inclination angle as well as the boundary between stratified-wavy and intermittent (slug or churn) flows. For vertical orientations, the flow is either annular or churn, depending on the vapour quality. It also seems that the transition between slug and churn flows is mainly led by the inclination angle. In conclusion, the flow pattern is strongly affected by the inclination angle as a result of a balance between gravitational, shear and capillary forces. A comprehensive experimental study has to be done to really understand the different phenomena leading this balance.

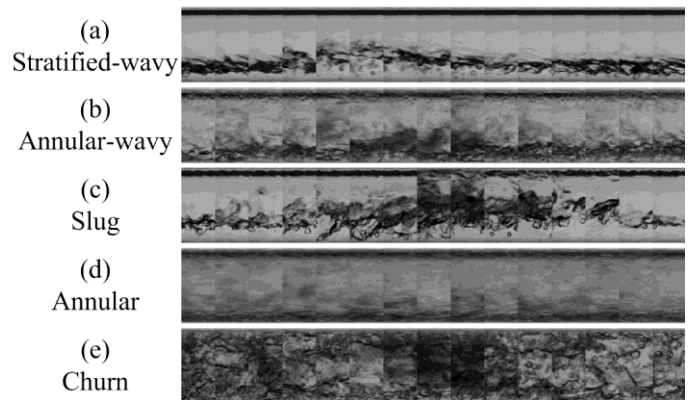


Figure 4 Flow pattern considered in the study

Heat transfer coefficients

Heat transfer coefficients during convective condensation are strongly dependent on the liquid and vapour distribution in the tube. Flow patterns being affected by the gravitational forces, the heat transfer coefficient must also be dependent on the inclination angle. Figure 7 represents the heat transfer coefficient as function of the inclination angle for a mass flux of 300 kg/m²s and for different vapour qualities. The experimental uncertainties were calculated with the theory of the propagation of errors. They are mainly due to the temperature measurement uncertainties. An inclination effect is noticeable for low vapour qualities: a maximum of heat transfer coefficient is observed for an inclination angle of -15° (downward flow) and a local minimum is observed for 15° (upward flow). The inclination angle leading to high heat transfer coefficients corresponds to stratified flows whereas the low heat transfer coefficients correspond to slug flows. The difference between the maximum and the minimum heat transfer coefficient can reach 40% of the heat transfer coefficient for the horizontal orientation for $G = 300 \text{ kg/m}^2\text{s}$ and $x = 0.1$, which highlights the necessity to understand the inclination effect on the heat transfer for the design of condensers in inclined orientation.

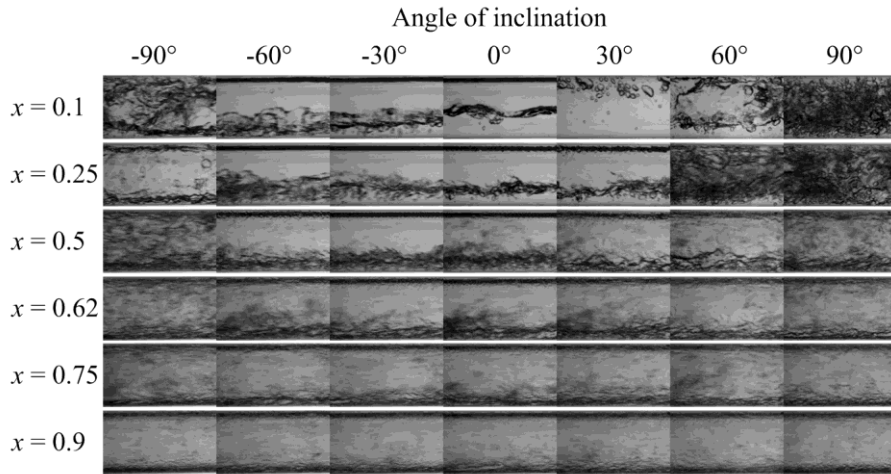


Figure 1 Flow visualisation for different experimental conditions ($G = 300 \text{ kg/m}^2\text{s}$)

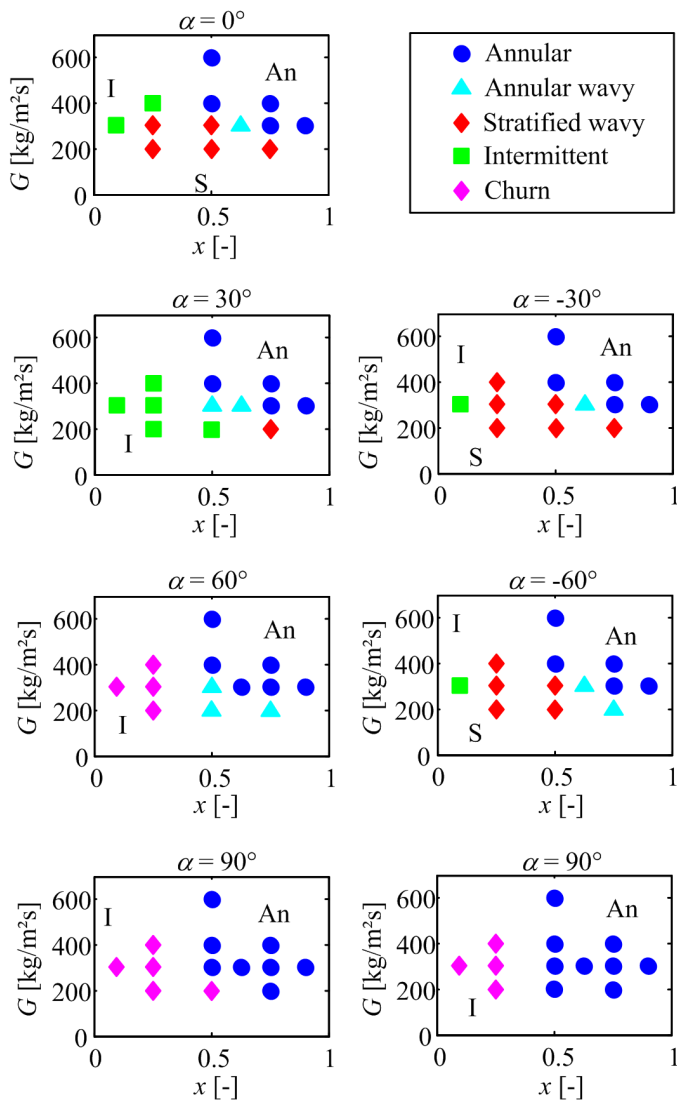


Figure 6 Experimental flow pattern maps for different inclination angles.

Figure 8 represents the heat transfer coefficient as function of the inclination angle for a vapour quality of 0.5 and for different mass fluxes. An inclination effect is noticeable for low mass fluxes only, which correspond to stratified flow in a horizontal orientation.

In conclusion, two zones can be defined: for low mass fluxes and low vapour qualities, the heat transfer coefficient is strongly dependent on the inclination angle whereas for high vapour qualities and high mass fluxes, the heat transfer coefficient remains constant whatever the tube orientation. It can directly be linked to the dependence of the flow pattern on the tube orientation shown in the previous section. No predictive model exists in terms of heat transfer coefficient during convective condensation in inclined tubes and more experimental studies are required to have a good overview of the physical phenomena involved in the heat transfer.

Pressure drops

The pressure drops across the test condenser were measured for the different experimental conditions by means of a FP2000 Sensotec differential pressure transducer with accuracy of 50 Pa. The measured pressure drops is the sum of three different terms: the gravitational, the momentum and the frictional pressure drops. The momentum pressure drop depends on the kinetic energy at the inlet and the outlet of the tube and requires an estimation of the void fraction that can be calculated using the Steiner [17] version of the Rouhani and Axelsson [18] drift flux model. In the present study, the momentum pressure drops were always less than 10% of the measured pressure drops. The gravitational pressure drop depends on the void fraction and on the inclination angle of the test section. However, it is not possible to separate experimentally the frictional and the gravitational pressure drop without measuring the void fraction in the flow. In the rest of the article, the pressure drops correspond to the measured pressure drops minus the momentum pressure drops, i.e. the sum of the frictional and gravitational pressure drops.

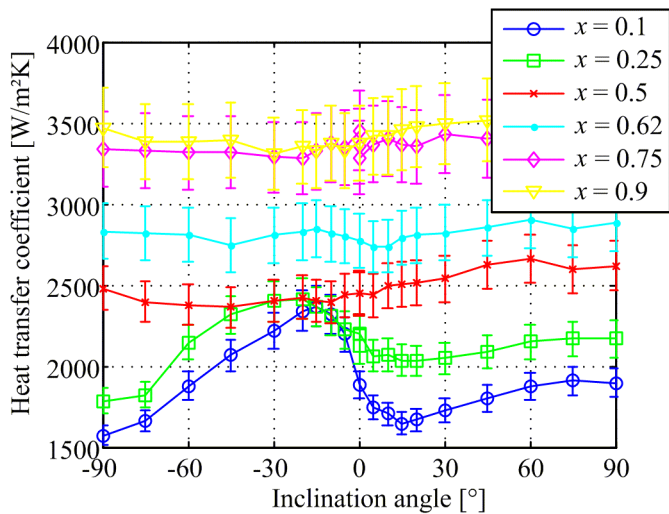


Figure 7 Inclination effect on the heat transfer coefficient ($G = 300 \text{ kg/m}^2\text{s}$)

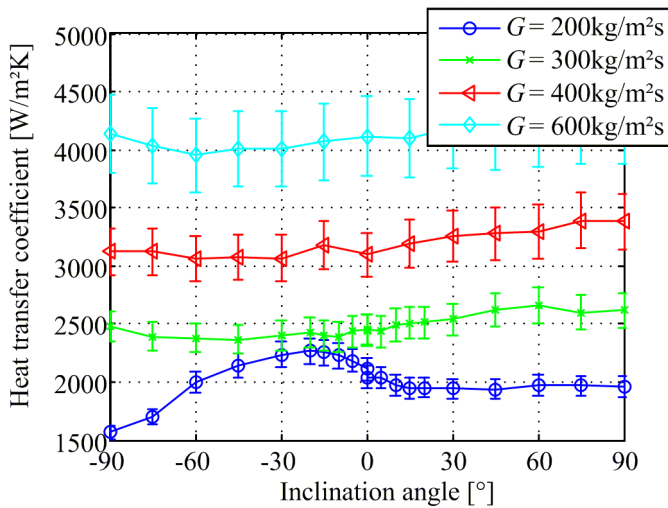


Figure 8 Inclination effect on the heat transfer coefficient ($x = 0.5$)

The pressure drop as function of the inclination is presented on Figure 9 for a mass flux of $300 \text{ kg/m}^2\text{s}$ and different vapour qualities. For horizontal orientation ($\alpha = 0^\circ$), the pressure drops increase when the vapour quality increase because of the increase of the vapour velocity. For inclined inclinations, the gravitational pressures drops increase when the inclination increase and the less the vapour quality, the more is the increase of gravitational pressure drops. This is due to the equivalent density of the mixture that increases when the vapour quality decreases. As a result, for vertical upward orientation ($\alpha = 90^\circ$), the total pressure drop decreases when the vapour quality increases.

Figure 10 represents the pressure drops as function of the inclination angle for a vapour quality of 0.5 and for different mass fluxes. Whatever the inclination angle, the pressure drops increases when the mass flux increases. The evolution of the pressure drop with the inclination angle is very similar for all the mass fluxes, especially for upward flows. It tends to show that the inclination effect on the pressure drops is almost

independent of the mass flux. This is highlighted by the Figure 11 that represents the apparent gravitational pressure drop as function of the inclination angle for different mass fluxes and different vapour qualities. The apparent gravitational pressure drop is defined as the difference between the measured pressure drop and the pressure drop obtained for the horizontal orientation. Figure 11 shows that the inclination effect on the apparent gravitational pressure drop is strongly dependent on the vapour quality and is almost independent of the mass flux. It is due to the dependence of the gravitational pressure drop on the void fraction, which is also mainly independent of the mass flux.

In conclusion, the experiments highlight the need for a void fraction sensor in the test-section in order to study separately the gravitational and the frictional pressure drops and to develop predictive tools for the determination of the pressure drops in inclined tubes.

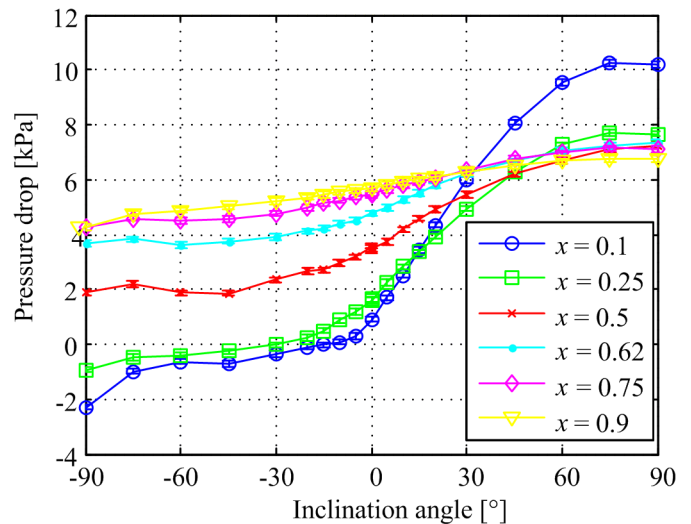


Figure 9 Inclination effect on the pressure drop ($G = 300 \text{ kg/m}^2\text{s}$)

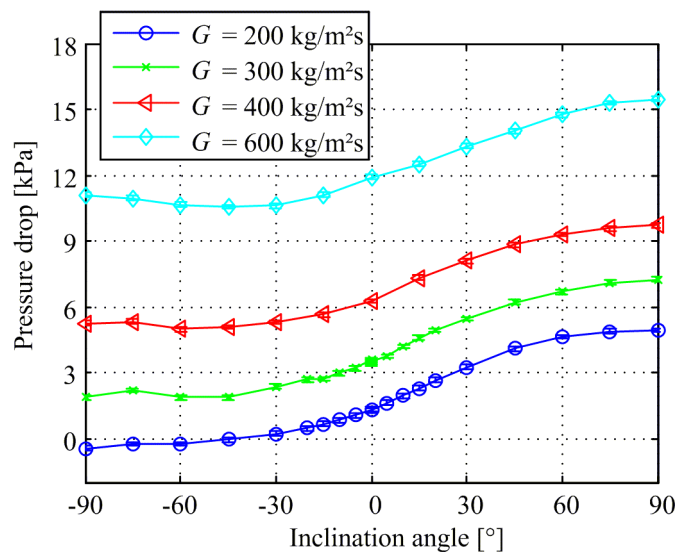


Figure 10 Inclination effect on the pressure drops ($x = 0.5$)

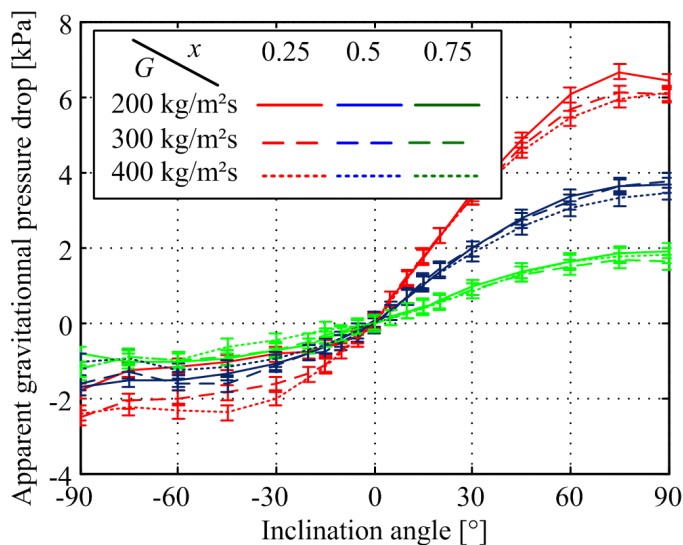


Figure 11 Inclination effect on the apparent gravitational pressure drops

CONCLUSION

Convective condensation of refrigerant R134a in an inclined tube was studied experimentally in terms of flow pattern maps, heat transfer coefficients and pressure drops. The flow pattern is strongly affected by the inclination angle for low mass fluxes and low vapour qualities: The flow can be stratified or annular-wavy in a horizontal orientation and becomes more and more annular when the orientation becomes closer to the vertical orientation. For high mass fluxes and high vapour qualities, the flow remains annular, whatever the inclination angle. The influence of the inclination angle on the flow pattern also affects the heat transfer coefficient, as it is strongly dependent on the liquid-vapour configuration inside the tube. For low mass fluxes and low vapour qualities, there is a specific inclination angle that leads to the highest heat transfer coefficient.

The pressure drops during convective condensation in inclined tubes are strongly dependent on the inclination angle as the gravitational pressure drops are not negligible in the experimental conditions of this study. However, a void fraction sensor is required to study the inclination effect on the frictional pressure drop.

This study is the first step to understand the inclination effect on the different flow properties in order to achieve the development of predictive tools to help in the design of condensers with inclined tubes.

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