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Technical Note

Flow pattern visualization and heat transfer characteristics of R-134a during condensation inside a smooth tube with different tube inclinations

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ABSTRACT

Experimental investigations are conducted herein to study the heat transfer and observe the condensation flow patterns of refrigerant R-134a inside a single smooth tube. The test apparatus makes the tube capable of having different inclination angles, 'α'. The experiments are performed for seven different tube inclinations in the range of $-90°$ to $+90°$ and six refrigerant mass velocities between 53 and 212 kg/m^2 s for each tube inclination angle. It is observed that the tube inclination noticeably influences the vapor and condensed liquid distribution, and also the condensation heat transfer coefficient. Eight different flow regimes have been observed during condensation inside a smooth tube with different tube inclinations. In the case of condensation heat transfer, the best performance is achieved by the tube with inclination angle of $+30°$ (for all refrigerant mass velocities). The effect of inclination angle on heat transfer coefficient, h, is more prominent at low vapor quality and mass flux. Finally, an empirical correlation has also been developed to predict the heat transfer coefficient during condensation inside a smooth tube with different tube inclinations.

1. Introduction

Condensation flows are commonly found in many industrial processes, such as air-conditioning and refrigeration. For economical design and optimized operation, knowledge of heat transfer and patterns of these flows is of key importance in the mentioned industrial applications. However, due to the complex nature of the condensation two-phase flow, the accessible heat transfer data and applicable correlations for condensation flow in inclined tubes covering various flow patterns are limited in the literature.

A review of tilting effects on the flow patterns, heat transfer and pressure drop during condensation inside smooth tubes has been presented by Lips and Meyer [1]. However, few studies are available for two-phase flows inside adiabatic inclined tubes.

More recently, Lips and Meyer [2] published an experimental study of convective condensation of R134a in an 8.38 mm inner diameter smooth tube at inclined orientations. They presented flow patterns and heat transfer coefficients during condensation for different mass fluxes and vapor qualities for the whole range of inclination angles (from vertical downwards to vertical upwards). They found that for low mass fluxes and/or low vapor qualities, the flow pattern is strongly dependent on the inclination angle, whereas it remains annular for high mass fluxes and high vapor qualities regardless of the tube inclination. Their experimental results also showed that there is an optimum inclination angle that leads to the highest heat transfer coefficient for downward flow.

Akhavan-Behabadi et al. [3], studied the condensation heat transfer of R-134a inside inclined microfin tubes. The experimental results indicated that the tube inclination affected the condensation heat transfer in a significant manner. Meanwhile, the highest heat transfer coefficient was attained at inclination angle of $+30°$.

Furthermore, Mohseni and Akhavan-Behabadi [4], carried out a visual study of flow patterns during condensation of R-134a in a microfin tube for the whole range of inclination angles. From analysis of acquired data, eight different flow regimes were observed. The experimental results also revealed that for all the tube inclinations annular flow is commonly observed at high vapor qualities and in this region, the effect of gravitational force is negligible.

As mentioned before, gravitational force, vapor–liquid interfacial shear stress and surface tension are dominant factors to control the vapor and liquid distribution inside the tube. Thus, it is essential to obtain information about how the gravitational force affects the two-phase flow patterns as well as heat transfer for condensation in a smooth tube. Therefore, an experimental investigation has been carried out to determine the flow patterns and heat transfer coefficient for condensation of R-134a inside a smooth tube with different inclinations.

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Nomenclature

C	empirical parameter in Eq. (1)
Cp	specific heat, J/kg K
D	internal diameter of test-section, m
G	mass flux, refrigerant mass flow rate per unit cross sectional area, kg/m^2 s
H	condensation heat transfer coefficient, W/m^2 K
K	thermal conductivity, W/m K
L	length of test-section, m
N	empirical parameter in Eq. (1)
Nu	Nusselt number
Pr	Prandtl number
We	Weber number
X	vapor quality or dryness fraction of vapor

Greek symbols

α	test-section tube inclination angle with respect to horizon, degree
P	density, kg/m^3
M	dynamic viscosity, N s/m^2
Δx	variation of vapor quality along the test section

Subscripts

L	liquid phase
M	mixture of liquid and vapor
V	vapor phase

2. Results and discussion

Experimental apparatus applied in the present study is the same as our prior works [3,4]. The test-condenser was a 1.04 m long double pipe counter-flow heat exchanger. Cooling water passed through the annulus and the refrigerant was condensed in the internal smooth copper tube with an inner diameter of 8.38 mm. Likewise, data collection and data reduction were employed as in our previous investigations [3,4]. First of all, the flow pattern maps during condensation inside the smooth tube were studied for seven different tube inclinations from $\alpha = -90°$ to $\alpha = +90°$ (with intervals of 30°) and at selected values of mass flux of 53, 85, 117,148, 180 and 212 kg/m^2 s. Experiments were also conducted at an average saturation temperature of 35 °C. Furthermore, in order to determine the condensation heat transfer coefficient, three different refrigerant mass velocities of 53, 107 and 180 kg/m^2 s in seven different tube inclinations are presented in this work. Moreover, the uncertainty analysis of the experimental results was carried out by the method proposed by Schultz and Cole [5], and it was found that the highest uncertainty in determination of heat transfer coefficient was about 9%.

The flow pattern maps for different tube inclinations are illustrated in Figs. 1–4. In these maps the Weber number for the liquid phase is taken along abscissa, while the Weber number for the vapor phase is extracted along the ordinate. The corresponding Weber numbers were defined in our prior study [4]. The border lines in flow pattern maps have been obtained by curve-fitting the experimental data (which are transition locations between different flow patterns), so that the transition conditions between different flow patterns can be correlated as follows:

$$We_V = CWe_L^n \quad (1)$$

In this regard, Table 1 presents the values of C and n for the various tube inclinations as determined from the experimental data for the transitions between the different flow patterns.

For downward flow inside smooth and microfin [4] vertical tube, −90°, the dominant flow pattern is the annular flow and hence, no flow pattern map is drawn for this case. At this tube inclination, the gravitational force and the interfacial shear stress are both acting at flow direction and regardless of vapor quality and flow rate, the flow pattern is annular.

For the −60° inclined tube, the behavior of flow pattern is analogous to that of vertical downward flow. Fig. 1 shows the flow pattern map inside the smooth tube with −60° inclination angle. As this figure shows, for a wide range of vapor quality and flow rate, the dominant flow pattern is annular or semi annular. In this case, for the flows with low vapor qualities, the stratified flow pattern is observed at all mass flow rates. However, for the −60° inclined microfin tube [4] the stratified flow pattern is observed at mass flow rate less than 148 kg/m^{2}s. Observation of the two phase flow inside the tube with −60° inclination angle indicates that flow pat-

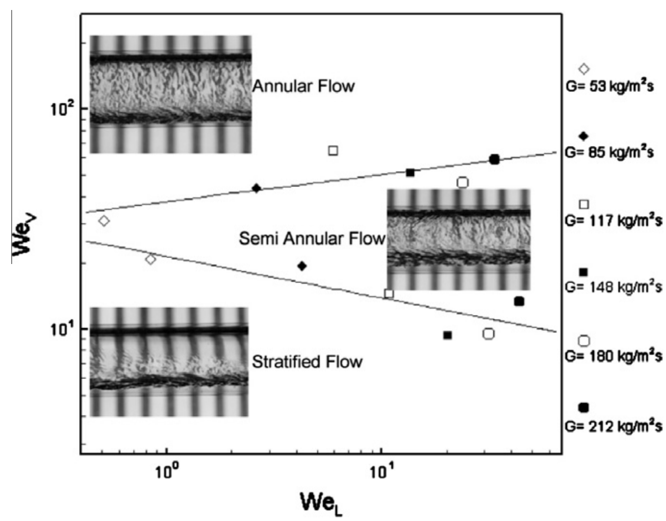

Fig. 1. Flow pattern map for condensation inside the smooth tube with inclination angle of −60°.

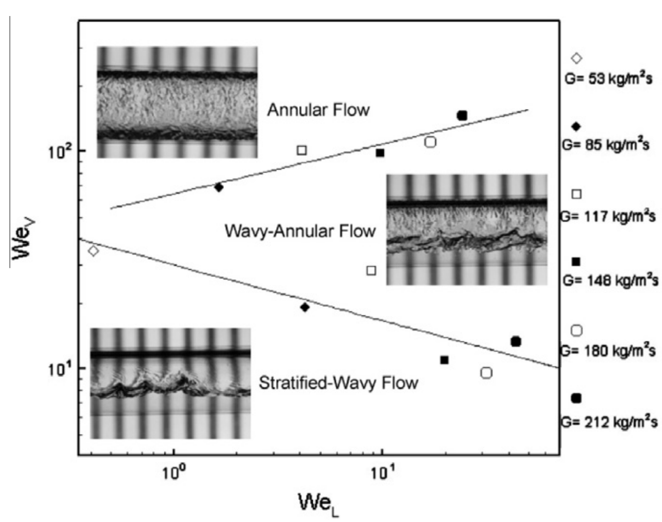

Fig. 2. Flow pattern map for condensation inside the horizontal smooth tube.