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Effect of inclination angle on the condensation of R134a inside an inclined smooth tube

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ABSTRACT

Almost all work on condensation in tubes were conducted for smooth tubes in a horizontal or vertical orientation, and little has been done at other inclination angles. Recent experimental works with condensation at different inclination angles showed that the pressure drops were a function of inclination angle. It was therefore the purpose of this paper to numerically investigate the pressure drop of condensation inside a smooth tube at different inclination angles, and to give additional perspectives and insight to previous experimental works. The case study investigated was a smooth tube with an inner diameter of 8.38 mm and a length of 1488 mm. The condensing fluid was R134a and the saturation temperature was 40 °C. Simulations were conducted at a heat flux of approximately 5 kW/m², at mass fluxes of 100–600 kg/m² s, and the inclination angles were varied from vertical downward to vertical upward. The Volume of Fluid (VOF) multiphase flow formulation was used and ANSYS FLUENT was used as solver of the governing equations. The predicted results showed a good agreement with experimental data. It was found that the effect of inclination angle on pressure drop and void fraction became negligible at high mass fluxes and vapour qualities. The pressure drop increased as the void fraction increased. The pressure drops also increased when the mass fluxes increased. These increases were more significant at high vapour qualities.

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1. Introduction

Many systems make use of vapour-compression cycles. The condenser in the vapour compression system needs to reject heat by condensing the working fluid from a gas to a liquid. Applications of vapour-compression cycles are found in the air-conditioning and refrigeration industries, oil refineries, petrochemical and chemical processing plants, and natural gas processing plants (Fair, 1960; Liebenberg and Meyer, 2008a,b). Other applications of condensation occur in nuclear, coal fired, and concentrated solar power generation plants where steam is condensed in air and water-cooled cooling towers. In the majority of these cases condensation occurs in tubes which are configured horizontally.

In recent studies by Lips and Meyer (2012a,b,c,d), an increase in heat transfer of up to 20% at an inclination of −15° (downward flow) was observed for combinations of low mass fluxes and vapour qual-

ities. The pressure drops at these inclination angles were also lower than at horizontal angles. In upward flow inclination angles the heat transfer decreased. At higher mass fluxes and vapour quality conditions in which the shear forces were dominant the flow patterns were mainly annular with the heat transfer coefficients independent of the tube inclination angle. In addition, the observed flow patterns did not correlate well with theoretical models.

Olivier et al. (2016) investigated the effect of the inclination angle on the pressure drop and void fraction inside a smooth tube. They found that the inclination angles did not affect the void fractions and heat transfer coefficients at high mass fluxes and vapour qualities. However, a significant increase in heat transfer coefficients occurred at low mass fluxes and low qualities.

It was also found that void fraction and flow pattern map predictions were found to be inadequate for inclined flow conditions and gravity effects must be taken into consideration (Lips and Meyer, 2011,

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Nomenclature

E	Internal energy, J
F	Source term in the momentum equation, N m^{-3}
g	Gravitational acceleration, m s^{-2}
h	Heat transfer coefficient, $\text{W m}^{-2} \text{K}$
G_b	Generation of turbulence kinetic energy due to buoyancy, $\text{m}^4 \text{s}^{-1}$
k	Thermal Conductivity, $\text{W m}^{-2} \text{K}$
p	Pressure, Pa
q''	Heat flux, W m^{-2}
R	Tuning coefficient, s^{-1}
Ma	Mach number
S_E	Energy source term, $\text{J m}^{-3} \text{s}$
S_l	Condensation mass source term, $\text{kg m}^{-3} \text{s}$
S_v	Evaporation mass source term, $\text{kg m}^{-3} \text{s}$
t	Time, s
T	Temperature, K
$\vec{u}$	Velocity, m s^{-1}
x	Vapour quality

Greek symbols

μ	Molecular viscosity, Pa s
ρ	Density, kg m^{-3}
k	Turbulent kinetic energy, $\text{m}^{-2} \text{s}^{-2}$
ε	Turbulent dissipation rate, $\text{m}^{-2} \text{s}^{-3}$
β	Inclination angle, degree
α	Volume fraction

Subscripts

ave	Average
eff	Effective
l	Liquid
L	Laminar
m	Mixture
sat	Saturation
t	Turbulent
v	Vapour
$wall$	Tube wall

2012a). Meyer et al. (2014) studied the effect of saturation temperature on the heat transfer coefficient inside an inclined tube. They considered the entire range of inclination angles from -90° downward, to $+90^\circ$ upward. Results showed that heat transfer coefficients increased with mass flux, and mean vapour quality. Also, that the effect of inclination was more pronounced at low mass flux, low mean vapour qualities, and at a high saturation temperature. Furthermore, they observed that the heat transfer coefficients reduced irrespective of the inclination angles and mass fluxes. It was due to the fact that at higher saturation temperatures, lower heat transfer coefficients corresponded to lower pressure drops.

Del Col et al., (2014) studied the condensation phenomenon inside an inclined square cross-section mini channel with a hydraulic diameter of 1.32 mm. They used two refrigerants, R134a and R32, and the saturation temperature was 40°C during their experiments. They found that the orientation of the channel had a negligible effect on condensation for downward flow at high mass fluxes, and minor effects for flow in the upward direction. However, at lower mass fluxes the effects were significant, and specifically at qualities lower than 60%. The authors also developed a method to predict at which mass flux, critical mass flux, the channel inclination affected the condensation heat transfer by using the Buckingham theorem. In fact, at mass fluxes lower than the critical one, depending on the channel inclination angle and type of the refrigerant, the condensation heat transfer coefficient may dra-

matically decrease as compared to that in horizontal configuration. As an example, their proposed method confirmed that the effect of the inclination angle during downward flow of R32 in their test geometry started at the mass flux lower than $G = 200 \text{ kg/m}^2 \text{s}$.

Xing et al. (2015) investigated condensation heat transfer at different inclination angles of refrigerant R245fa in a smooth tube with a diameter of 14.8 mm and length of 1.2 m. The results showed that the maximum heat transfer coefficient and minimum pressure drop occurred at inclination angles of 30° and 15° , and the results were very sensitive to inclination angles near the horizontal position. They observed that the main flow patterns in the condenser tube were stratified-smooth flow, stratified-wavy flow, and intermittent flow. They also developed a new correlation of condensation heat transfer coefficients using a non-dimensional parameter analysis.

The effect of the inclination angle in the presence of non-condensable gases have also been investigated (Caruso et al., 2012, 2013a). Caruso and Maio (2014) investigated steam condensation in the presence of non-condensable gases within horizontal and inclined tubes theoretically and experimentally. The results showed that the presence of non-condensable gases adversely affected the heat transfer coefficients. They also presented a correlation based on dimensionless numbers which was compared with literature.

It can in general be concluded that little work had been done on condensation at different inclination angles as confirmed by a review article by Lips and Meyer (2011). Subsequent work on this topic mainly focused on the experimental (Caruso et al., 2013b; Chato, 1962; Beggs and Brill, 1973; Dziubinski, 1995) and analytical aspects (Lips and Meyer, 2012a; Szijártó et al., 2014; Lizarraga-Garcia et al., 2016) with many simplifying assumptions. Computational Fluid Dynamics (CFD) of the condensation phenomenon inside an inclined tube can explain the flow characteristics inside the tube cheaper and quicker than experimental work. Previous CFD works mainly focused on numerical simulations of condensation inside horizontal or vertical smooth tubes (Behafarid et al., 2015; Azizi and Ahmadloo, 2016; Fu et al., 2016; Li, 2013; Lin et al., 2013; Ratkovich et al., 2013; Ndinisa et al., 2005).

It was therefore the purpose of this study to numerically investigate the effect of inclination angles on pressure drops and void fractions. This work also supplements the previous experimental works (Lips and Meyer, 2011, 2012b,c) conducted by some of the authors of this paper.

2. Governing equations

2.1. Assumptions

The governing equations used were the equations of conservation of mass, momentum, and energy. The relevant assumptions made in supplementation to these governing equations for this study were:

1. The flow was unsteady, three-dimensional and turbulent.
2. The working fluid properties were constant at the saturation temperature considered.
3. The mass transfer between liquid and vapour phases took place at saturation temperature.
4. As the the Volume of Fluid (VOF) method was used for the simulation, the velocity difference between phases were neglected.
5. Both phases were incompressible Newtonian fluids, $Ma \ll 0.3$, (Städtke, 2006).
6. Three-dimensional CFD simulations were performed without any limiting assumption for the entrance effect.

2.2. Volume of Fluid model

In the VOF model (Hirt and Nichols, 1981), the volume fractions of each of the two phases in a computational cell sums to unity:

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