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Numerical study of steam condensation inside a long, inclined, smooth tube at different saturation temperatures

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ABSTRACT

In this study, the effects of the inclination angle on the heat transfer coefficients and on pressure drops were investigated numerically, during the process of development of heat condensation inside a long smooth tube, at different saturation temperatures. The simulation model included a smooth tube with a diameter of 18 mm and a length of 7.2 m. The imposed inclinations varied between −60° (downward flow) to +60° (upward flow). Moreover, the saturation temperatures varied between 40 °C and 70 °C. The flow field was assumed to be three-dimensional, unsteady, and turbulent. The Volume of Fluid (VOF) multiphase flow method was utilised to solve the governing equations comprising mass, momentum, energy, and turbulence equations, along with phase change rates. The simulation results were in good agreement with the experimental data. The results showed that the condensation heat transfer coefficient first increased and then decreased along the length of the tube. Furthermore, it was noted that the condensation heat transfer coefficient and pressure drop decreased when the steam saturation temperature increased.

1. Introduction

Condensation inside tubes can be found in the air-conditioning, refrigeration, automotive, and processing industries. For designs applicable to these industries, an accurate and in-depth understanding of the flow patterns and the heat transfer phenomenon is of major importance [1–5]. Many applications involve condensation inside inclined tubes such as, in A-frame steam condensers used in air-cooled, power generation plants, some rooftop air-cooled refrigeration systems, and also in the low temperature multi-effect evaporation in desalination industry [6]. However, a literature review by Lips and Meyer [7], showed that very limited work was conducted on condensation inside inclined tubes.

Mohseni et al. [8] conducted an experimental investigation to study the heat transfer and flow patterns inside an inclined smooth tube during condensation. They found that the inclination angle had a significant effect on the heat transfer coefficients and on flow patterns, particularly at low vapour qualities and mass fluxes. They also captured eight different flow regimes during condensation inside the tube at different tube inclination angles.

Nada and Hussein [9] presented a semi-empirical correlation to predict the heat transfer coefficient inside an inclined smooth tube during condensation. They found that the Nusselt number increased as the temperature difference decreased, while the tube inclination angle increased. Their analytical results showed a good agreement with experimental data for vertical and horizontal tubes, but the deviation increased as the inclination angle increased. This result shows a lack of understanding of the effects of the inclination angle on condensation.

Lips and Meyer [10–13] experimentally studied the effect of the inclination angle on the condensation inside a smooth tube. The inclination angles varied from the vertical downward, to the horizontal, and to the vertical upward directions. They studied the effect of tube inclination angles on the pressure drop, void fraction, and heat transfer coefficient, and also captured the flow regime at the tube outlet. Their most important result was that the optimum heat transfer coefficients occurred at a downward inclination angle in the range of 15°–30°, and specifically at mass fluxes lower than approximately 200 kg/m^2 s.

Xu et al. [14] studied gas–liquid, two-phase flows inside an inclined tube. They focussed on the influence of the liquid phase properties on flow patterns, void fractions, and pressure drops. They used both Newtonian and non-Newtonian fluids for the liquid phase. They concluded that the properties of non-Newtonian fluids had no significant effect on the flow patterns in horizontal and

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Nomenclature

E	internal energy
F	source term in the momentum equation
g	gravitational acceleration
G	mass flux
G_b	generation of turbulence kinetic energy due to buoyancy
h	heat transfer coefficient
h_{lv}	latent heat
k	thermal conductivity
k_l, k_v	curvatures of liquid and vapour phases
L	tube length
P	pressure
ΔP	pressure drop
q''	heat flux
r	tuning coefficient for condensation rate
S_l	condensation source term
S_v	evaporation source term
S_E	energy source term
t	time
T	temperature
T_{sat}	saturation temperature
u	velocity

Greek symbols

α	volume fraction
μ	molecular viscosity
τ	shear tension
ρ	density
κ	turbulent kinetic energy
ε	turbulent dissipation rate
β	inclination angle
r	tuning coefficient in condensation source term
σ	surface tension
φ	rotation angle
ω	angular velocity
$\bar{\Omega}_{ij}$	mean rate of rotation tensor

Subscripts

ave	average
eff	effective
l	liquid
L	laminar
m	mixture
sat	saturation
t	turbulent
v	vapour
wall	tube wall

near-horizontal flows. They also found that the non-Newtonian features of the liquid phase had a considerable effect on the void fraction. Furthermore, they presented predictive models for the calculation of void fractions and pressure drops for the stratified flow of gas and non-Newtonian liquids.

Shah [15] conducted a literature review on heat transfer during condensation in an inclined tube. He proposed a method for the calculation of heat transfer coefficients inside inclined tubes during condensation. The method elicited a mean absolute deviation of 15.7% with the use of the available database.

In addition to various prior publications on the condensation of refrigerants, many researchers considered steam as the working fluid in their investigations. Caruso et al. [16] experimentally studied condensation of steam–air mixed with gas inside inclined tubes at four inclination angles. They found that the heat transfer coefficients at inclination angles of 15° and 30° were higher than those at 7° and 45°. They also developed a correlation that predicted the heat transfer coefficients as a function of the inclination angle.

Wang et al. [17] investigated the steam condensation inside a long, 8 m, horizontal smooth tube. They studied the effects of saturation temperature, steam mass flow rate, and temperature differences, between steam and cooling water on the condensation heat transfer coefficient. They found that the condensation heat transfer coefficient increased first and then decreased along the flow direction. Moreover, their results showed that the heat transfer coefficient also increased with saturation temperature, and decreased with condensation temperature differences.

Wang and Du [18] studied steam condensation in long smooth tubes experimentally and analytically. They considered different parameters in their investigation, such as steam mass flow rate, tube diameter, and inclination angle. Their results showed that gravity decreased the condensation heat transfer coefficient in small/mini tubes. It was also found that the inclination angle affected the condensation heat transfer mainly by stratifying the fluids, and by thinning the liquid film.

In addition to prior publications on the condensation of pure steam, some researchers worked on the condensation of steam inside a smooth tube by considering the effect of non-condensable gases [19–22].

Vyskocil et al. [23] developed a CFD model to study the effect of non-condensable gas on the heat transfer coefficient during steam condensation inside a vessel. They used the FLUENT commercial package solver and claimed that their proposed code is applicable for both compressible and incompressible flows of air–steam mixtures with additional non-condensable gases. Their condensation model was also examined on CONAN experiments with air–steam flow in a vertical channel with one cooled wall. Satisfactory results were elicited. However, the model suffered from various parameters that were over-simplified.

Ren et al. [24] studied the effect of air as a non-condensable gas on the condensation heat transfer coefficient and the flow regime inside a smooth horizontal tube. They considered the effects of various parameters in their experiments, such as the inlet non-condensable gas mass fraction, inlet gas mixture mass flux, and inlet pressure. They found that the heat transfer coefficient decreased as the non-condensable gas fraction increased. Their results also showed that the increase in the inlet mass flux would increase the heat transfer coefficient. They also proposed two correlations for the condensation heat transfer coefficient for stratified flow and annular flow regimes, based on the modified Froude number.

Although there are several experimental and numerical works on the condensation of the refrigerant and steam inside vertical and horizontal tubes [25–28], to the best of our knowledge, there has been no prior published numerical work in which the effects of saturation temperature and tube inclination angle on the condensation of steam inside tubes have been investigated. Furthermore in this study we aimed to consider very low mass fluxes in which a complete condensation happened. This type of condensing flows are widely seen in many applications particularly in A-frame