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General semi-empirical correlation for condensation of vapor on tubes at different orientations

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ABSTRACT

Analytical and experimental investigations for condensation of saturated vapor on smooth tube at different orientations are presented. An analytical model was developed starting from mass, momentum and energy equations. The model was solved analytically by the method of characteristics with the aid of a computer program. In the experimental work, heat transfer due to film wise condensation of saturated steam on smooth tube has been investigated for different tube inclinations. Seven series of experiments were conducted at tube inclination angles of 0°, 10°, 20°, 30°, 45°, 60° and 90° with the vertical. Variation of Nusselt number with temperature difference and inclination angles are investigated from the theoretical and experimental results. Both experimental and theoretical results showed the increase of the Nusselt number with the decrease of the temperature difference and the increase of the tube inclination angle from the vertical. Comparison between the experimental and theoretical results showed fair agreement for vertical and horizontal tubes. However, the deviation increased with tilting the tube from horizontal or vertical position. General semi-analytical correlation was deduced from the experimental and theoretical results to fairly predict the Nusselt number for any tube inclination.

1. Introduction

Tube-side condensation is used in a wide range of engineering applications such as refrigeration, air conditioning, space heating, food industry, automotive and process industries. Nowadays, higher energy efficiency and economic incentive requirements and material saving considerations have increased the need for highly efficient heat transfer surfaces. Heat transfer in tube condensation strongly depends on surface orientation and the enhancement of condensate drainage rate.

Literature review revealed that studies of condensation on vertical and inclined tubes are very limited. In contrast, numerous theoretical and experimental studies were carried out on condensation inside horizontal, vertical and inclined tubes. Many theoretical studies [1–9] were conducted to find the condensate film thickness and condensation heat transfer coefficient at any point in the tube surface in terms of the orientation of the surface and tube surface temperature. The analysis was performed under the same assumptions of Nusselt's classical theory of film condensation [1]. At the same time, numerous experimental studies were carried out to verify theoretical analysis and obtaining experimental correlations to avoid error in the theoretical analysis due to Nusselt's assumptions. Hassan and Jakob [2] compared their analytical results with the experimental results for the condensation heat transfer coefficient on inclined cylinder. The experimental results were found to be 28–100% higher than the analytical results. They attributed this deviation due to the rippling of the condensate film that was not taken into account in the theoretical study.

Hussein et al. [3,4] presented theoretical and experimental analysis for wickless heat pipes of different cross section geometries and deduced a correlation for laminar-film condensation heat transfer coefficient in the condenser section of inclined wickless heat pipes flat-plate solar collector. The comparison between theoretical relation and experimental results by other investigators showed a good agreement. Wang and Ma [5] carried out theoretical and experimental studies on condensation inside vertical and inclined thermosyphons tube. They pointed out that no final conclusion can be drawn on the optimum inclination angle at which the maximum heat transfer coefficient can occur. They presented semi-empirical correlations for reflux condensation inside inclined and vertical tubes. Fiedler and Auracher [6] experimentally investigated heat transfer during reflux condensation of

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Nomenclature

C_p	specific heat of cooling water, kJ/(kg K)
D	tube outside diameter, m
$d\dot{m}$	mass of element, kg
h	average heat transfer coefficient, W/(m^2 K)
h_{fg}	latent heat of vaporization, kJ/(kg K)
k	thermal conductivity of liquid film, W/(m K)
L	tube length, m
$\dot{m}$	mass flow rate, kg/s
Nu	average Nusselt number, dimensionless
q	heat transfer rate, W
R	tube inner radius, m
r	radial distance measured from tube outer surface, m
Re	Reynolds number, dimensionless
T	temperature, °C

Subscripts

c	condensate
cw	cooling water
L	liquid
i	inlet
o	outlet
x	x-direction
ϕ	ϕ-direction
s	saturated steam
v	vapor
w	tube wall

Greek symbol

β	tube inclination angle with reference to the vertical, °
δ	film thickness, m
μ	dynamic viscosity, kg/m s
ρ	density, kg/m^3
ϕ	perimeter angle of the tube, °
ΔT	temperature difference between condensing steam and tube surface, °C

refrigerant R134a in an inclined small diameter tube. They found that the inclination angle has a significant effect on the heat transfer coefficient. Shah [7] presented general modified correlations for condensation inside vertical, inclined and horizontal tubes which can be applied for a wide range of fluid and geometric parameters. Meyer et al. [8] conducted experimental investigation on the effects of the saturation temperature and inclination angle on condensation of R134a flowing inside inclined tubes. The results showed (i) the increase of the heat transfer with the decrease of saturation temperature, and (ii) the existence of optimum inclination angle at which heat transfer is maximum. Wang and Du [9] presented a theoretical study for laminar film-wise condensation inside small diameters tubes. Lips and Meyer [10] reviewed condensation two phase flow inside horizontal and inclined tubes. The review showed that the inclination angle strongly affects the flow regime and the heat transfer.

Recently, a lot of theoretical and experimental works were conducted to study the effects of the presence of non-condensable gases on the condensation inside vertical, inclined and horizontal tubes [11,12]. Experimental correlations were presented to show the effect of the presence of non-condensable gases on the condensation rate. The studies showed that the presence of non-condensable gases adversely affect the condensation efficiency and heat transfer.

Condensation inside vertical and inclined tubes in case of upward vapor flow (Reflux condensation) is limited by flooding phenomenon where at a certain upward vapor velocity part of the condensate will be carried upward by the vapor and the other part is draining downward. Nada et al. [13,14] and English et al. [15] proposed correlations that are widely used in industry to predict the flooding point. Fiedler and Auracher [6] and Fiedler et al. [16] showed experimentally that the flooding point during reflux condensation in small diameter tubes is affected by the inclination angle. They showed that the optimum inclination angle at which the highest flooding vapor velocity can be reached is between 45° and 60°.

In spite of the several theoretical and experimental works and correlations for condensation inside horizontal, vertical and inclined tubes, the results of these works and correlations cannot be applied for condensation outside tubes where the phenomena and condensate film motion and drainage mechanism are totally different. Some theoretical and experimental studies have been reported on condensation heat transfer performance on vertical and horizontal tubes. However, a relatively small number of studies have been published on the performance of inclined tubes, where the flow of condensate film becomes two dimensional flow. Thomas [17] studied the effect of the presence of longitudinal rectangular fins on condensation heat transfer of saturated steam outside the tube. The study showed an increase of the heat transfer due to the presence of such fins. It was found that the film condensation enhancement coefficient increases with the decrease of heat flux and the increase of the number of fins. Domingo and Michel [18] studied condensation of Ammonia on smooth tube at various tilt angle. The results showed that the heat transfer coefficient increases as the tilt angle decreases from the vertical to horizontal position. Amin [19] presented an experimental investigation of heat transfer augmentation during condensation on vertical tubes using drainage caps. Experimental results showed that using drainage caps dramatically improve heat transfer rates.

In the present paper, comprehensive theoretical and experimental investigations of saturated vapor condensing outside tube at different orientations (vertical, horizontal and inclined at different angles of inclination) are presented. The effects of temperature difference, tube inclination angle and tube geometrical parameters are studied. Comparisons between theoretical and experimental results are quantified and investigated. General semi-empirical correlation is suggested for accurate estimation of Nusselt number during condensation on tubes at different orientations.

2. Theoretical analysis

To simplify the mathematical model, some assumptions are considered during the present theoretical analysis. The assumptions are the same of Nusselt [1] assumptions for condensation on vertical surface taking in consideration the effect of the buoyancy force. These assumptions are summarized as follows:

- The flow of the condensate film is laminar, uniform and steady.
- The vapor is considered dry, saturated, pure and free from non-condensable gases.
- The vapor velocity is very small, thus the shear stress at the vapor–liquid interface can be neglected.