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Condensation heat transfer coefficients in an inclined smooth tube at low mass fluxes

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The purpose of this study was to present the heat transfer coefficients and flow patterns during the condensation of R134a inside an inclined smooth tube at low mass fluxes and different temperature differences (the temperature differences were between the saturation temperature and wall temperature). Condensation experiments were conducted at different inclination angles ranging from −90° (vertically downwards) to +90° (vertically upwards), at low mass fluxes of 50, 75, and 100 kg/m^2·s, and temperature differences from 1 °C to 10 °C. Measurements were taken at different mean vapour qualities between 0.1 and 0.9 in a smooth tube test section with an internal diameter of 8.38 mm and length of 1.5 m. The average saturation temperature was kept constant at 40 °C. It was found that inclination significantly influenced the flow patterns and the heat transfer coefficients. Downwards flows accounted for an increase in heat transfer coefficient with the maximum heat transfer coefficient found at inclinations of −15° and −30° (downwards flow) at the corresponding minimum temperature difference was tested for in each case. The maximum inclination effect was approximately 60% and was obtained at the lowest mass flux of 50 kg/m^2·s. In general, it was concluded that the heat transfer coefficients were more sensitive to the temperature difference for downwards flows than for upwards flows. Furthermore, there was no significant effect of temperature difference on the heat transfer coefficients for upwards flows. It was also found that the downwards and upwards vertical orientations were almost independent of the temperature difference. With respect to the inclination effect, it was found that in general, it decreased with an increase in temperature difference but decreased with an increase in mass flux and vapour quality.

1. Introduction

1.1. Background

Inclination is an option when designing condenser tubes that cannot be oriented horizontally or vertically owing to space constraints, operating conditions, performance optimization, or environmental conditions [1–16]. Examples in which condensation occurs in inclined tubes include steam condensers used for air-cooling, certain rooftop industrial air-cooled refrigeration systems, and in the condensers of motor vehicles and trucks driving up and down hills. However, little work [1,12] has been published in the open literature which justifies the angles being used or which gives performance data at different inclination angles.

An example in which the environmental and space conditions are important factors is in dry regions of the world that lack large water resources for power-plant cooling. In such cases, large forced-convection, air-cooled power plant condensers are used. The condensers are normally constructed in an 'A' or 'V' frame configuration with the condensing steam in a downwards flow direction of approximately −60°. At least three countries (South Africa, Australia, and the U.S.) are currently increasingly using this technology. Some of the largest dry-cooling plants at present are found in South Africa, with an installed capacity of more than 10 GW. The typical water consumption of a dry-cooling plant is approximately 0.1 ℓ of water per kilowatt-hour of electricity produced. In comparison, a traditional wet-cooled plant requires nearly 2 l per kWh.

The cross-sectional geometry of the condensing channels of a dry-cooled power plant is finned on the outside. The channels are in many cases flat and rectangular and relatively large with dimensions of approximately 214 mm by 13 mm. The tube lengths are approximately 10 m in length with very low steam mass fluxes of lower than 10 kg/m^2·s [17–19]. The reasons for these choices of inclination angle and low mass fluxes have not been addressed in literature. There is thus a gap in the literature that addresses condensation at different inclination angles as well as condensation at low mass fluxes.

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Nomenclature

EB	energy balance, %
G	mass flux, kg/m^2·s
I	inclination effect
Q	heat transfer rate, W
T	temperature, °C
x	vapour quality
Greek symbols	
α	heat transfer coefficient, W/m^2·K
β	inclination angle (>0: upward, <0 downward) (rad)
Subscripts	
m	mean
max	maximum
min	minimum
sat	saturation
w	water

1.2. Inclination angles

Previous studies [1–4,6–16,20–38] on inclined tubes were at moderate to high mass fluxes. In those studies, it was found that varying the inclination angles altered the flow patterns with consequent effects on the heat transfer coefficients, pressure drops, and void fractions. It was also found that the effects of inclination became more pronounced as the mass flux decreased. For downwards inclinations, it was found that the effect of the gravity was dominant and caused a thinning of the liquid layer which led to a reduction in the thermal resistance within the tube surface, leading to higher heat transfer coefficients [1–5,9]. For upwards inclinations, no concrete trend was established. However, there are two main challenges. The first is that there is no study that has systematically coupled the effect of inclination and temperature difference on the heat transfer coefficients and flow patterns at low mass fluxes ($\leq$100 kg/m^2·s). The other challenge is that there are contradictory reports [1,4,7,8,11] on the recommended inclination angle for optimum heat transfer performance. This is further evidenced by the fact that there is no unifying correlation that can properly predict the heat transfer coefficients in inclined smooth tubes. This may be attributed to the fact that the available models are either limited by tube size, working fluid, saturation temperature, mass flux, or tube orientation. A review of the most relevant works on inclination is presented below.

Tepe and Mueller [29] were arguably the first to publish their findings on the effect of inclination during condensation inside smooth tubes. They performed experiments during the condensation of benzene inside a smooth tube 18 mm in diameter at a single inclination angle of 15°. They observed that there existed an effect of inclination on their measured heat transfer coefficients. They also found that their measured heat transfer coefficients were approximately 50% higher than the predicted values when compared to the Nusselt [39] classical theory. Following closely were Hassan and Jakob [32], who performed numerical and empirical studies on the effect of inclination on the heat transfer coefficients during condensation outside horizontal tubes. They noticed an effect of inclination on the measured heat transfer coefficients. Furthermore, they applied the Nusselt [39] classical theory and compared the results of their experiments to that of their numerical analysis. They found that the heat transfer coefficients of their numerical study were between 28% and 100% lower than the results of their experiments. They attributed this to the rippling effect of the condensate film, which was not accounted for in their theoretical model. Later, Chato [31] also observed an inclination effect during condensation of R113, wherein he observed that slightly downwards inclinations led to an increase in heat transfer rates.

Chato [23] studied and developed analytical solutions for stratified laminar condensation in horizontal and inclined tubes. It was assumed that the condensate depth decreased along the tube length. Hence, he neglected the heat transfer in the liquid pool at the bottom of the tube and assumed that the void fraction did not change significantly with respect to vapour quality. These assumptions led to large errors at high mass fluxes and low vapour qualities, because convective heat transfer prevailed in those conditions. He further developed a Nusselt-type equation for the condensation of refrigerants at low vapour velocities inside horizontal and inclined tubes based on Chen's [36] analysis of falling film condensation outside a horizontal cylinder.

Nitheanandan and Soliman [28,40] obtained flow regime data during the condensation of steam inside a 13.4 mm diameter tube at upwards and downwards inclinations within ±10°. In all their experiments, they achieved complete condensation inside the condenser. They found that the zones occupied by the wavy and slug regimes experienced significant shifts, whereas the effect on the annular flow boundary appeared to be insignificant at the present small inclination angles. They also compared their data with adiabatic gas–liquid flow regime maps developed analytically and experimentally for horizontal and inclined tubes.

Lips and Meyer [3–6] studied the heat transfer and pressure drops during the condensation of R134a inside a smooth inclined tube. They carried out experiments at different inclination angles for upwards and downwards flows. With the aid of a high-speed camera installed at the exit of their test section, they captured and studied the flow patterns by varying the mass fluxes, vapour qualities, and inclination angles. They found that at high mass fluxes and vapour qualities; the flow was independent of the angle of inclination and always remained annular. However, at high mass fluxes and low vapour qualities, the flow regime was largely intermittent and dependent on the inclination angle. They defined the impact of gravity on the heat transfer coefficients as the 'Inclination effect' (I_α) and presented an expression for it. They also found that the highest heat transfer coefficients were achieved at an inclination angle of between $-15°$ and $-30°$ (downwards flow). The gap in their work was that they did not investigate the combined effect of the temperature difference and inclination on the heat transfer coefficients.

Mohseni and Akhavan-Behabadi, Mohseni et al. [7,10] conducted experiments for seven different tube inclinations between $-90°$ and +90° and six (6) refrigerant mass fluxes between 53 and 212 kg/m^2·s to measure the heat transfer coefficients and observe the flow patterns of R134a condensing inside smooth and microfin inclined tubes. They found that the tube inclination noticeably influenced the heat transfer coefficients. In terms of the flow regimes, they found an effect of inclination on the vapour and condensed liquid flow distribution leading to eight distinct flow regimes with respect to the different tube inclinations. They also found that the best heat transfer performance was achieved at an inclination angle of +30° (for all refrigerant mass fluxes). Their findings were in sharp contrast with the findings of Lips and Meyer [3–5,9]. A holistic look at both studies showed that