Condensation inside smooth and inclined smooth tubes at low mass fluxes: A quick review

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Abstract: The focus of this research article is to provide a state of the art review on smooth and inclined tubes condensation with particular emphasis on low mass fluxes. The most relevant experimental investigations are explained with a view to identifying the gaps in the literature. Overall, it could be deduced that at low mass fluxes, there needs to be a fundamental understanding between the relationship between difference in temperature and inclination on transfer of heat and pressure drops to enable designers optimize heat exchangers.

1.0. Introduction

The importance of condensation cannot be over emphasized because of its usefulness in air conditioning, refrigeration, automotive, power plants and chemical process industries to mention but these. It literally means change of state from vapour to liquid, which naturally takes place in a condenser. Adequate knowledge of the 2-phase process that occurs in there is vital to proper design and construction of condensers. Condensation in tube is a complex 2-phase phenomenon which is very difficult to analyse and this further corroborated by the limited solutions analytical and numerical treatment. Hence, there is a need for further experimental research and the development of new experimental rigs to research the two phase flow processes.

In this work, a quick review is presented on condensation inside smooth tubes with a particular emphasis on low mass fluxes to establish gaps in previous work for further studies. A number of studies on condensation are focused on vertical and horizontal configurations at mass fluxes ranging between 200 kg/m²s and 1000 kg/m²s [1]. But studies are lacking for the case of condensation in tubes at low mass fluxes.

2.0 Condensation heat transfer
Analyses of transfer of heat by condensation inside tubes are very complicated due to the effect of velocity of vapour and the rate at which the liquid accumulates on the enclosures of the tubes as presented in Figure 1.

![Condensate flow in a horizontal tube with high and low vapour velocities](image)

**Figure 1** Condensate flow in a horizontal tube with high and low vapour velocities [2].

Pioneering research work on condensation heat transfer was carried out by Nusselt [3]. For a vertical plate, he reduced the complexity of the real condensation phenomenon to an elementary model by assuming that the only resistance for heat removal during condensation occurred in the condensate film. He assumed that the viscous shear of the vapour on the film was insignificant and solved the continuity, momentum and energy equations using some assumptions to simplify the complex process. The assumptions were that there was a uniform vapour temperature and vapour is saturated. He also assumed constant fluid properties; the only force from the outside acting on the film is gravity (static force balance because momentum is ignored); the adjoining vapour is static and exerts zero drag on the film; and the latent heat is much greater than the sensible extraction of heat from the film. For a horizontal tube, he used a numerical integration approach to derive the laminar film condensation outside of the horizontal tubes obtaining the relation: In arriving at this, he assumed a laminar condensate flow round the tube and that the coefficient of heat transfer was highest at the centre of the tube decreasing around the surface as the intrinsic thermal resistance in the film grew with its thickness and finally resulting to nil at the bottom of the tube. A major shortcoming of Nusselt was that he neglected the surface tension forces that help up the condensate at the bottom of the tube until been overcome by the force of gravity resulting in the formation of condensate droplets instead of a continuous sheet. The Nusselt [3] equation can be applied to estimate condensation in the horizontal tubes to calculate the falling film heat transfer coefficient when considering stratified flows.

### 3.0 Condensation in Horizontal Tubes
Most condensation processes encountered in refrigeration and air-conditioning applications, etc. involve condensation on the inner surfaces of horizontal or vertical tubes. Aprea et al. [1], Suliman et al. [4], El-Hajal et al. [5]. Lee and Son [6] and Azzolin et al. [7] designed a system to investigate the influence of gravity with Hydrofluoroether (HFE-7000) as the refrigerant. They found that when gravity acted perpendicularly to the channel flow, there was an increase in the coefficient of transfer of heat by acting on the liquid distribution penalization factor which increased along the tube.

4.0 Condensation in Inclined Tubes

Most previous studies seen in [8-27] on inclined tubes were carried out at medium to high mass fluxes. In these studies, variation in the angles of inclination changed the patterns of flow with resultant effects on the coefficients of transfer of heat, void fractions and pressure drops. It was only recently that the first comprehensive study by [28, 29] at low mass fluxes was carried out. This section, exhibited the works on inclination that were relevant.

Tepe and Mueller [30] were undoubtedly the pioneers to publish their results on the impact of inclination while condensation is on-going inside the smooth tubes.

5.0 Low mass fluxes (inclined tubes)

In spite of its wide applications, the available information on the transfer of heat performance of condensers inclined at low mass fluxes. The review of the previous study in this area according to [1, 5, 9, 13, 14, 20, 25, 26, 31-38] showed that most investigations on condensation within smooth tubes focused on both vertical and horizontal configurations at mass fluxes typically higher than 200 kg/m²s and less than or equal to 1000 kg/m²s. Other findings of [4, 33, 39-45] noted that at low mass fluxes, the coefficient of transfer of heat was dependent on the difference in temperature.

6.0 Conclusion

A brief overview of previous work done on condensation in smooth and inclined tubes with particular reference to low mass fluxes was presented. It has been found that even though extensive research has been done in condensation inside the tube, studies were limited to condensation at high mass fluxes in smooth horizontal and vertical tubes. It was also found that there are gaps in the literature on low mass fluxes, the temperature difference effect and inclination. Overall, there needs to be a fundamental understanding between the relationship between difference in temperature and inclination on transfer of heat and pressure drops to enable designers optimize heat exchangers.

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