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LAMINAR FILM CONDENSATION OF PURE VAPOURS IN TUBES

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Abstract—Laminar film condensation of pure vapours in tubes is studied on the basis of the integrated equations of change by the approximate integral method. The effects investigated in particular are the influences of the vapour velocity profile at the beginning of condensation, of some finite heat transfer from the tube to the surroundings and of the orientation of the tube with respect to gravity. While the vapour velocity profile at the beginning of condensation does not appear to be very significant, the two further effects can alter the condensing performance of a tube considerably in a way that is physically evident.

NOMENCLATURE

c_{pL}, specific heat capacity of condensate;
E, $= \dfrac{c_{pL}(T_i - T_a)}{P_{r_L}\Delta h_V}$ nondimensional temperature difference;
Fr, $= \dfrac{u_0^2}{gR}$ Froude number;
g, component of gravity in flow direction;
Δh, enthalpy of evaporation;
$\dot{m}_L$, mass flow density of condensate;
$\dot{m}_V$, mass flow density of vapour;
p, pressure;
P_{r_L}, Prandtl-number of condensate;
r, radial coordinate;
R, tube radius;
Re_0, $= \dfrac{u_0 R}{\nu}$ Reynolds number;
T_i, temperature of saturated vapour;
T_a, temperature of cooling medium;
u, local speed in vapour;
u_i, speed at the gas–liquid interface;
u_L, local speed in condensate;
x, $= \dfrac{\dot{m}_V}{\dot{m}_V + \dot{m}_L}$ vapour quality;
z, coordinate in flow direction;
z^*, $= \dfrac{z}{RRe_0}$ nondimensional coordinate in flow direction.

Greek symbols

α_a, external heat-transfer coefficient;
δ, thickness of vapour boundary layer;
δ_a, number characterizing external heat transfer;
δ_L, liquid film thickness;
λ_L, thermal conductivity of condensate;
μ, dynamic viscosity of vapour;
μ_L, dynamic viscosity of condensate;
ν, kinematic viscosity of vapour;
ν_L, kinematic viscosity of condensate;
ρ, density of vapour;
ρ_L, density of condensate.

INTRODUCTION

FILM condensation in tubes can occur under two different entrance conditions. In one case, the vapour is cooled directly at the inlet of the tube; its velocity distribution at the beginning of condensation may then be assumed to be uniform over the tube radius. In the other case, there is a dry inlet region which allows the vapour to develop its parabolic velocity profile before condensation starts.

The length of the dry inlet region has been studied by various investigators, e.g. [1]. The development of the velocity profile from the uniform distribution under the influence of condensation has been treated in [2]. In this work, we discuss the influence of the entrance condition on the performance of a condenser tube for laminar film condensation. For this purpose, we study the condensation process of pure vapours in tubes for uniform and developed vapour velocity distribution at the beginning of condensation. We further investigate the influence of some finite heat transfer from the tube to the surroundings and the effect of the orientation of the tube with respect to gravity. The effect of an non-condensing gas is studied elsewhere [3].

PHYSICAL AND ANALYTICAL MODEL

The physical and analytical model for laminar film condensation with uniform vapour velocity distribution at the beginning of condensation up to the location in the tube where the developing vapour boundary layer reaches the center line has been described in [2] and will not be repeated here. Contrary to that earlier work we will now assume a finite heat transfer from the tube wall to the surroundings, in order to get results of a more general nature. For the study of the processes

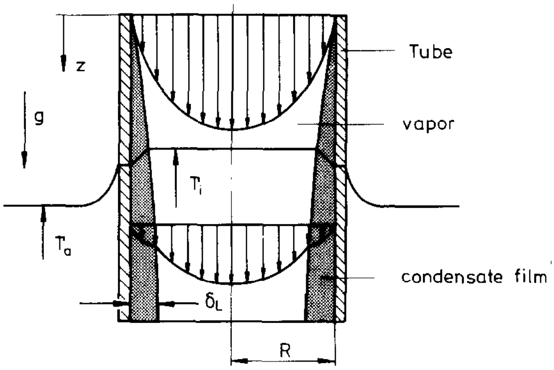

FIG. 1. Physical model and coordinates.

following this location as well as the case of a developed velocity distribution at the beginning of condensation, we use an analogous physical model, with some appropriate adaptions in the analytical representation.

The notation and the system of coordinates are evident from Fig. 1. We use integrated forms of the momentum equations in the vapour and condensate flow with assumed velocity profiles. Our analysis will therefore be only approximate which is considered appropriate for the somewhat qualitative purpose of the investigations. We assume the following velocity distributions:

$$\frac{u-u_i}{\bar{u}-u_i} = 2\left[1-\left(\frac{r}{R-\delta_L}\right)^2\right] \quad \delta_L < r < R, \tag{1}$$

where

$$\bar{u} = \frac{2}{(R-\delta_L)^2}\int_0^{R-\delta_L} ur\,\mathrm{d}r \tag{2}$$

is the average speed in the vapour.

$$u_L(r) = \left[4\frac{\mu}{\mu_L}\frac{\bar{u}-u_i}{\delta_L(R-\delta_L)} - \frac{u_i}{\delta_L^2}\right](R-r)^2 - \left[4\frac{\mu}{\mu_L}\frac{\bar{u}-u_i}{R-\delta_L} - 2\frac{u_i}{\delta_L}\right](R-r). \tag{3}$$

These velocity distributions satisfy obvious boundary conditions as well as coupling conditions between the two fluid phases.

The energy balance assumes pure heat conduction in the thin liquid film, a negligible heat-transfer resistance in the tube wall and a constant heat-transfer coefficient α_a from the tube wall to the surroundings. One then is faced with the following set of equations:

Energy balance

$$0 = k(T_i - T_a)\,\mathrm{d}A + \Delta h_V \frac{\mathrm{d}}{\mathrm{d}z}[\rho\bar{u}\pi(R-\delta_L)^2]\,\mathrm{d}z \tag{4}$$

where

$$\frac{1}{k\,\mathrm{d}A} = \frac{1}{\alpha_a 2\pi R\,\mathrm{d}z} + \frac{\delta_L}{\lambda_L\pi[R+(R-\delta_L)]\,\mathrm{d}z}. \tag{5}$$

Mass balance

$$0 = \frac{\mathrm{d}}{\mathrm{d}z}[\rho\bar{u}\pi(R-\delta_L)^2] + \frac{\mathrm{d}}{\mathrm{d}z}\left[\int_{R-\delta_L}^{R}\delta_L u_L 2\pi r\,\mathrm{d}r\right]. \tag{6}$$

Momentum equation in the vapour

$$0 = \frac{\mathrm{d}}{\mathrm{d}z}\int_0^{R-\delta_L} u^2 r\,\mathrm{d}r - \frac{u_i}{2}\frac{\mathrm{d}}{\mathrm{d}z}[\bar{u}(R-\delta_L)^2] - (R-\delta_L)\left[\nu\frac{\partial u}{\partial r}\bigg|_{R-\delta_L} - \frac{1}{2}\left(\frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}z} - g\right)\right]. \tag{7}$$

Momentum equation in the liquid

$$0 = \frac{\mathrm{d}}{\mathrm{d}z}\int_{R-\delta_L}^{R} u_L^2 r\,\mathrm{d}r + \frac{u_i}{2}\frac{\mathrm{d}}{\mathrm{d}z}[\bar{u}(R-\delta_L)^2] + (R-\delta_L)\nu_L\frac{\partial u_L}{\partial r}\bigg|_{R-\delta_L} - R\nu_L\frac{\partial u_L}{\partial r}\bigg|_R + \tfrac{1}{2}[R^2-(R-\delta_L)^2]\left[\frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}z} - g\right]. \tag{8}$$

Along with the assumed velocity profiles, equations (4) to (8) give the four unknowns $\bar{u}$, u_L, δ_L and p as a function of z. Starting values for $\bar{u}$, δ_L and u_i are found from polynomial functions for small z.

DISCUSSION OF RESULTS

We choose condensation conditions encountered practically for condensing steam of $T_i = 100°\mathrm{C}$ and $p = 1$ bar with $\mu/\mu_L = 0.043$ and $\nu/\nu_L = 70$. The non-dimensional temperature difference will be chosen as $E = 0.005$. In the horizontal case $Re_0/Fr_0 = 0$, in the vertical case we choose $Re_0/Fr_0 = 25$. The heat transfer to the surroundings is represented by $\delta_a = \lambda_L/\alpha_a R = 0.035$, which is typical for air-cooled finned tubes, or $\delta_a = 0$ as the limiting case of ideal heat transfer conditions outside the tube. Figure 2 shows the vapour quality over the nondimensional length coordinate z^* for $\delta_a = 0$. In the horizontal case, the decrease of the vapour quality is somewhat faster for a uniform velocity distribution at the beginning of the condensation. The horizontal distance of the two curves remains essentially constant after the developing vapour boundary layer has reached the center line. The effect, which is due to the flatter velocity profile during the development of the vapour boundary layer, is seen to be not very significant. It almost vanishes for the case of a vertical tube, where both curves are virtually identical. The phenomenon is then dominated by the action of gravity, the differences between the vapour flow characteristics in both starting conditions being irrelevant.

Figure 3 shows an analogous plot for the influence of the external heat transfer on the decrease of the vapour quality. Only the uniform velocity distribution at the beginning of condensation is studied here. A finite heat transfer to the surrounding air

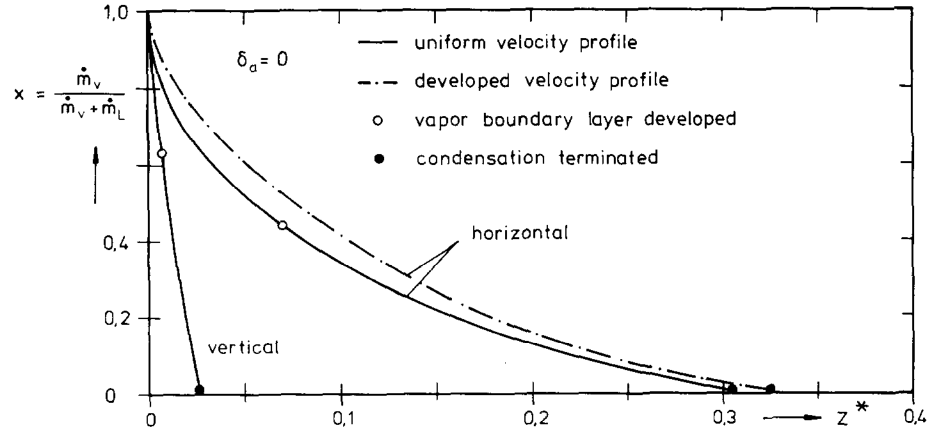

FIG. 2. Vapour quality over tube length.

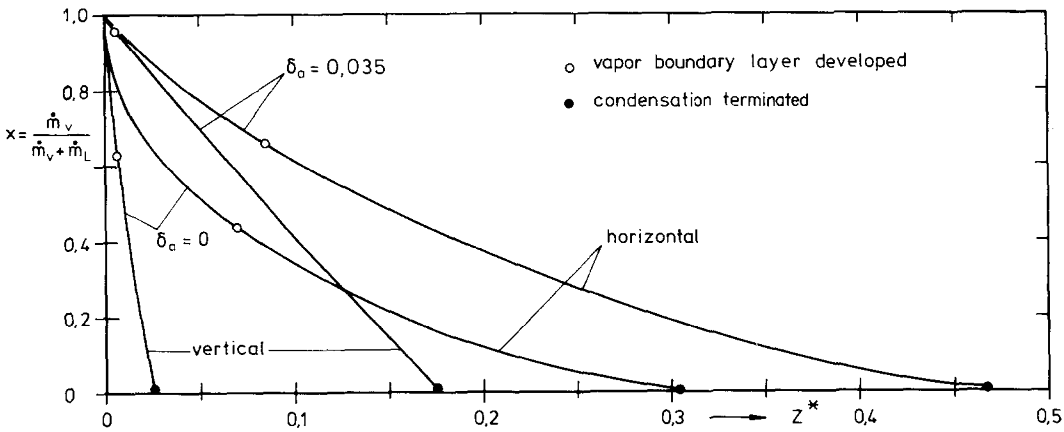

FIG. 3. Influence of external heat transfer.

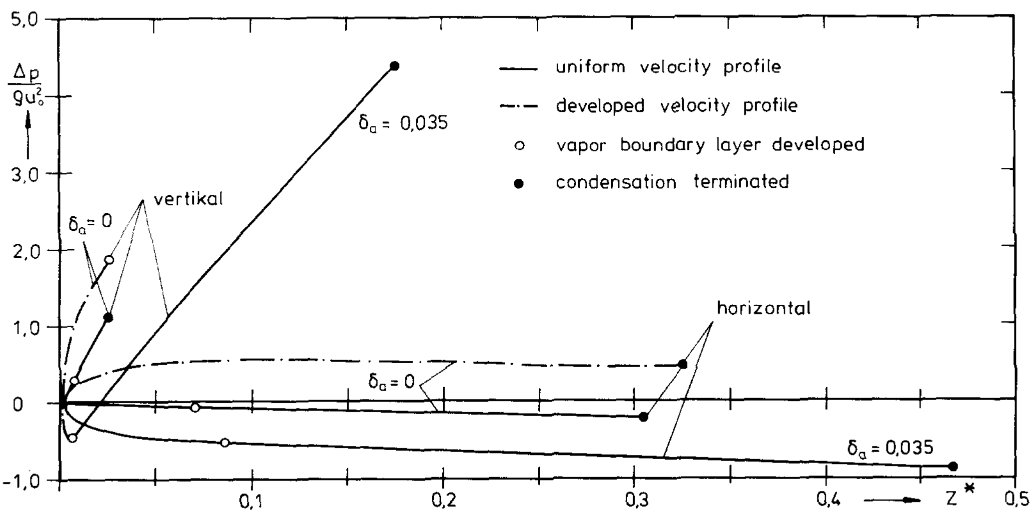

FIG. 4. Pressure variation in the tube.

evidently reduces the condensation performance of the tube, since it essentially diminishes the temperature difference across the film. In the vertical case, the decrease is almost linear. It would be rigorously linear, if the film heat transfer resistance were entirely negligible with respect to the external heat transfer resistance, the condensation length then being $z^* = 0.151$ for the studied conditions.

In Fig. 4 we give our results for the non-dimensional pressure variation in the tube. The general tendency is a small effect due to the velocity profile condition and the magnitude of the external heat-transfer coefficient, while the effect of the orientation with respect to gravity is considerable. In more detail, the development of the vapour boundary layer leads to a pressure drop, which cannot be

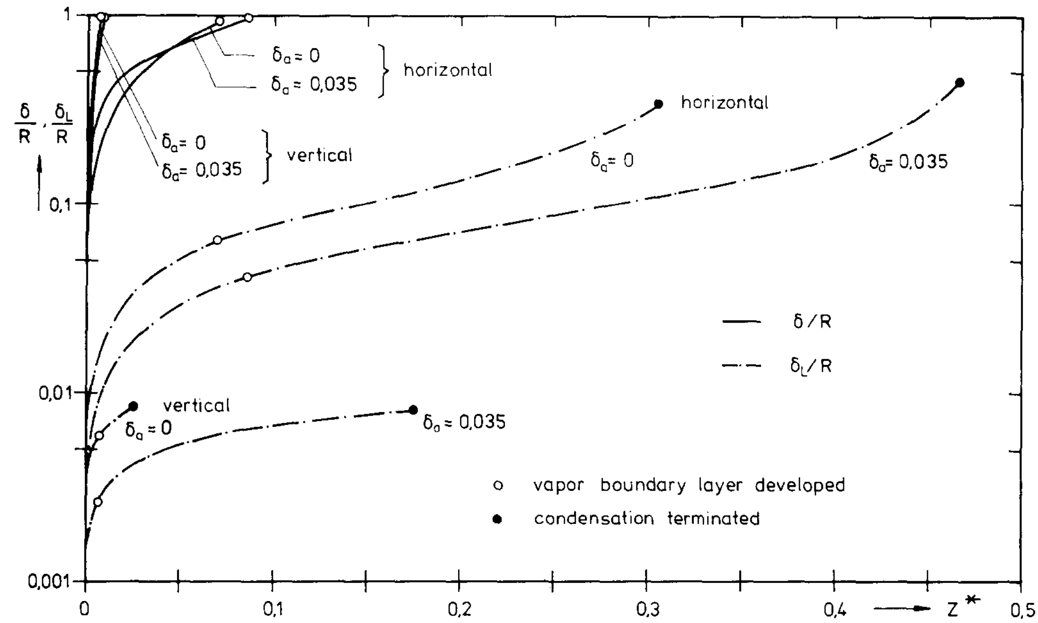

FIG. 5. Liquid film thickness and vapour boundary-layer thickness.

compensated by the tendency of increasing pressure due to a stronger condensation rate. The relative rise of pressure due to high external heat transfer and a vertical position is a consequence of the increased condensation rate at such conditions. Even an absolute pressure rise in the tube can be found for the investigated conditions.

Finally, Fig. 5 gives some detailed information on the magnitude of the liquid film thickness and the vapour boundary thickness during its development. In the vertical case, the liquid film thickness is always very much smaller than the tube radius. In the horizontal case, it may become considerable, and the assumption of pure annular flow and negligible heat convection effects in the film may be seriously in error.

CONCLUSIONS

The above results demonstrate that the assumed velocity profile at the beginning of condensation is not very significant for the calculated condensation performance in the tube. The findings of this paper are expected to hold for other condensation conditions as well. The effects of the heat transfer to the surroundings and the orientation of the tube can be quite considerable. Increasing the external heat transfer and putting the tube in a vertical position improves the performance of the condensation tube.

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CONDENSATION DE VAPEURS PURES EN FILM LAMINAIRE DANS DES TUBES

Résumé—La condensation de vapeurs pures en film laminaire dans des tubes est étudiée à partir des équations de bilan intégrées par la méthode intégrale approchée. Les effets particulièrement étudiés sont l'influence du profil de vitesse de la vapeur au début de la condensation, celle du transfert thermique fini entre le tube et son environnement, celle de l'orientation du tube par rapport à la verticale. Alors que l'influence du profil de vitesse ne semble pas être très visible, les deux autres paramètres peuvent altérer considérablement la condensation d'une façon physiquement évidente.

LAMINARE FILMKONDENSATION REINER DÄMPFE IN ROHREN

Zusammenfassung—Die laminare Filmkondensation in Rohren wird auf der Grundlage der integrierten Bilanzgleichungen mit Hilfe eines Integralverfahrens untersucht. Insbesondere werden der Einfluß des Geschwindigkeitsprofils zu Beginn der Kondensation, die Auswirkung eines endlichen äußeren Wärmeübergangs sowie die Orientierung des Rohres in bezug auf die Richtung der Schwerkraft studiert. Während das Geschwindigkeitsprofil im Dampf zu Beginn der Kondensation nicht sehr Effekte die Kondensationsleistung eines Rohres in physikalisch einleuchtender Weise beträchtlich verändern.

ЛАМИНАРНАЯ ПЛЁНОЧНАЯ КОНДЕНСАЦИЯ ЧИСТЫХ ПАРОВ В ТРУБАХ

Аннотация — Исследуется ламинарная плёночная конденсация чистых паров в трубах путём решения уравнений переноса интегральным методом. В частности, исследуется влияние на процесс конденсации профиля скорости пара в начале конденсации, внешнего теплообмена и ориентации трубы по отношению к силе тяжести. В то время как профиль скорости пара не играет большого значения, два других фактора могут существенно влиять на процесс конденсации пара в трубе.