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Transient condensation of flowing vapor on a flat-plate: A scaling analysis

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ABSTRACT

We perform an analysis of condensation of pure vapor flowing over a cooled flat plate. We estimate the time taken to achieve steady-state condensation by a transient analysis where we use results from previous studies that show that the time-dependent behavior is governed by the propagation of a kinematic wave along the condensate film. The steady-state time at any streamwise location along the plate depends on the steady-state film thickness at that location. Classical theories of laminar steady-state condensation are reviewed, and a scaling analysis is performed to capture the scalings for relevant quantities such as the liquid film thickness, liquid velocity, and heat transfer coefficient. The results from the scaling analysis are entirely consistent with the classical theories. Finally, the scaling analysis is extended to take into account effects of turbulence in the liquid film.

1. Introduction

The Flow Boiling and Condensation Experiment (FBCE) is currently being developed by NASA as a flight experiment to be performed on the International Space Station. In the condensation part of the experiment, the vapor of a test fluid (currently planned to be normal pentafluorohexane (nPFH), which is the major pure component of the commercial fluid FC-72) will flow in a cylindrical tube that is cooled by a counterflow of chilled water flowing in an outer annulus. The temperature of the tube wall will be maintained below the saturation temperature of the test fluid so that the vapor condenses. The goal is to determine the heat transfer coefficient due to condensation, chiefly in the annular flow regime, for various flow rates of the vapor and cooling water.

As part of the development effort for the condensation experiment, there is a need to determine the transient response of the flowing vapor. The specific question is the time taken for the condensation process in the tube to attain a steady state following initiation of the vapor flow. The response time is necessary to know what experiments can be performed in the limited low gravity times available in earth-based facilities, and the ranges of experimental parameters for which long duration reduced gravity time on the International Space Station is required.

Both steady and transient condensation in laminar flow have been analyzed in several classical papers in the literature. The forced convection condensation of a flowing vapor over a cooled flat plate in the boundary layer regime has been analyzed by Koh [1]. This is a well-known analysis wherein a similarity solution to the condensation process is obtained. The salient features of the analysis are pointed out below. The analysis shows that the condensation process is influenced by three dimensionless parameters – (i) Pr_l, the Prandtl number of the liquid (ii) $\frac{k_l(T_\infty - T_w)}{\mu_l h_{fg}} = \frac{C_{p_l}(T_\infty - T_w)}{Pr_l h_{fg}} = \frac{Ja}{Pr_l}$ where Ja is the Jacob number and (iii) $R = \left(\frac{\rho_l \mu_l}{\rho_g \mu_g}\right)^{1/2}$. Sparrow, Minkowcyz and Saddy [2] simplified the treatment somewhat by neglecting inertial and convective effects in the condensate flow, and assumed the streamwise velocity component at the interface to be zero in calculating the vapor flow. Earlier, Cess [3] made the same assumptions, and obtained a solution by writing a series expansion for the flow and temperature fields in a boundary layer similarity coordinate, retaining only the first term. Shekriladze and Gomelauri [4] performed a different type of an analysis wherein the shear stress exerted by the flowing vapor on the liquid was approximated to be equal to the momentum transferred from the vapor to the liquid by the condensing mass.

Transient film condensation in laminar flow has been analyzed by Sparrow and Siegel [5], Wilson [6], and Flik and Tien [7] among others. These analyses show that transient film condensation is governed by the propagation of a kinematic wave along the film. At a fixed spatial position in the liquid film, the growth of the condensate film is a time-dependent process until the kinematic wave

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Nomenclature

B	constant in Eq. (9)
C_{p_l}	liquid specific heat
F	function defined in Eq. (7)
h	heat transfer coefficient
h_{fg}	latent heat
Ja	Jacob number; $Ja = \frac{C_{p_l}(T_\infty - T_w)}{h_{fg}}$
k_l	liquid thermal conductivity
$L(t)$	length of steady state region for transient condensation
L	length of flat plate
$\dot{m}''$	condensation mass flux
Nu	Nusselt number; $Nu = \frac{hL}{k_l}$
Pr_l	liquid Prandtl number
Pr_t	turbulent Prandtl number
R	Property ratio; $R = \left(\frac{\rho_l \mu_l}{\rho_g \mu_g}\right)^{1/2}$
Re	Reynolds number; $Re = \frac{U_\infty L}{\nu}$
Re_f	film Reynolds number; $Re_f = \frac{U_l \delta_l}{\nu_l}$
T	Temperature
T_{sat}	saturation temperature
T_w	wall temperature
T_∞	vapor free-stream temperature
t	Time
t_{ss}	time to achieve steady state
U_c	scale for interfacial correction velocity $U_\infty - u_i$
U_l	scale for liquid velocity in x direction
U_o	free stream velocity
U_∞	vapor free stream velocity
u	velocity component along flat plate (x direction)
u_i	interfacial velocity in x direction
V_g	scale for vapor velocity in y direction
v	velocity component perpendicular to the flat plate (y direction)
x	coordinate along flat plate
y	coordinate perpendicular to flat plate

Greek

α_l	liquid thermal diffusivity
δ	layer thickness
δ_g	vapor boundary layer thickness
δ_l	liquid film thickness
δ_{ss}	liquid film thickness at steady state
ΔT	temperature difference; $\Delta T = T_\infty - T_w$
ΔT^*	turbulent temperature scale in laminar sublayer (wall unit)
η	similarity coordinate; $\eta = \frac{y}{\sqrt{\alpha_l t}}$
μ	viscosity
ν	kinematic viscosity
τ	shear stress

Subscript

g	vapor
i	interface
l	liquid
n	normal direction
sat	saturation
ss	steady state
w	wall
∞	free stream

Prime

$'$	turbulent fluctuating quantity

Overbar

$\overline{U_l}$	turbulent mean flow quantity

reaches it. After this time, the film thickness and the condensation process achieves a steady state at this location. For condensation on a flat plate which is initially dry, the kinematic wave propagates downstream from the flat plate's leading edge. Thus the plate can be divided into two regions (see Fig. 1) – a steady region $0 \leqslant x \leqslant L(t)$, and a transient region $x \geqslant L(t)$ where $L(t)$ is the distance measured from the leading edge that demarcates the two regions. At the boundary $x = L(t)$ between these regions, the condensate film thickness is the same. As time progresses, $L(t)$ increases, and a greater portion of the flat plate will be covered by a condensate film that is steady.

In this report we perform a scaling analysis of condensation of vapor flowing over a cooled flat plate. The sole driving force for the liquid flow is the shear stress exerted by the flowing vapor. No gravitational effects are included. The goal is to determine the time scale for the condensed liquid film to be established, as well as scales for the liquid film thickness, liquid velocity, and the heat transfer coefficient. In what follows we analyze the steady and transient regions on the flat plate separately. We will first consider laminar flow, and then extend the analysis to address the effects of turbulence.

2. Condensation boundary layer features

2.1. Steady state region

As mentioned before, the steady-state condensation boundary layer for flow over a cooled flat plate has been analyzed by several people. In what follows, we summarize the salient features of the liquid and vapor flow, primarily from Koh's theory, and will then perform a scaling analysis that captures the essential features of the previous studies.

2.1.1. Liquid boundary layer

It is assumed that in the condensate liquid boundary layer the flow is incompressible and fluid properties are constant. The effects of inertia and convection of energy are included but are typically negligible. Thus typically the liquid flow is controlled by viscous forces and energy transfer by conduction. At the liquid–vapor interface the latent heat energy released by condensation of the vapor is carried away from the interface by conduction in the liquid.

2.1.2. Vapor boundary layer: Energy considerations

In Koh's theory, the gas stream temperature is uniform and corresponds to saturation temperature of the vapor. Thus in this theory, energy transfer in the gas phase is not considered.

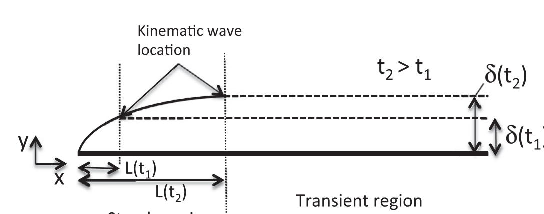

Fig. 1. Steady and transient regions for condensation on a flat plate.