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Dynamics of a thin radial liquid flow

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ABSTRACT

The present work proposes an extension of the existing analytical development on the radial spread of a liquid jet over a horizontal surface to the case of a thin radial flow. When the gap, H, between the jet nozzle and the plate is reduced the discharging area may be smaller than the inlet area leading to an increase of the main flow velocity downstream of the thin cylindrical opening. This increase of velocity, defined here as $\frac{1}{\alpha}$, can be related to the relative gap of the nozzle $\frac{H}{R}$ with R the nozzle pipe radius. Numerical computations with a volume of fluid method were realised with for $\frac{H}{R}$ ranging from 0.2 to 3 and with flow rates Q of 3 and 6 l min^{-1}. The results of these computations allowed us to express α with respect to $\frac{H}{R}$. Taking in account the flow acceleration allowed us to extend the set of equation from the jet impacting flow to the thin cylindrical opening flow. The liquid layer thickness and the surface velocity differ with a maximum error of 4% between the flow predicted by the model and computations. Main discrepancies appear in the region close to the nozzle where the analytical model assumption of a constant velocity outside the boundary layer is not valid. However, further downstream the model and the computations are in good agreement.

1. Introduction

The radial spread of a liquid film created by a round jet impact on a surface (Fig. 1a) occurs in numerous applications including mass and heat transfer. Surface cooling using an impinging water jet has been studied [1,2,3]. Spray formation by fire sprinkler [4–6] or plate nozzle [7–9] involves a liquid film as the first step of a spray formation. The governing parameters of the spray formation process are the thickness and the velocity of the liquid layer. Ref. [5] proposed a sprinkler spray model which combines a film flow dynamic model based on analytical solution of [10] with an atomisation model. Since sprinkler are usually pressure based, one way to reduce the flow rate whilst keeping the same velocity is to constraint the liquid by bringing the nozzle closer to the plate (Fig. 1b). This way of working has the advantage that it does not require the modification of the orifice size.

The hydrodynamics of the impact of an axisymmetric liquid jet on a normal surface has been theoretically studied by Watson [10] who provided an analytical solution of the liquid layer thickness $h(r)$ and surface velocity $U(r)$ with respect to the radial distance from the jet centre r, the liquid kinematic viscosity ν, the jet volumetric flow rate Q and the jet radius R. His solution is realised using a self similarity solution and the momentum integral solutions. He distinguished three main regions in the flow. The first one begins at stagnation point where the boundary layer starts growing and it finishes at $r = r_0$ where the whole flow is within the boundary layer. In the second region, the boundary layer is fully developed. The liquid layer thickness is controlled by both radial dispersion and viscous wall effects. The liquid layer thickness is decreasing until $r = 1.43\, r_0$ and then it increases.

Measurements of the liquid layer thickness and the velocity profile realised by Azuma and Hoshino [11–13] using needle probe and laser Doppler velocimeter show a good agreement with the solution proposed by Watson for flows with a Reynolds number ranging from 2.2×10^4 [12] to 1.7×10^5 [13]. The laminar to turbulent transition defined by [11] as the presence of sandpaper-like waves in more than 50% of the peripheral direction. This transition occurs for a Re around 5×10^4.

When the nozzle is close to the plate (Fig. 1b), the water is discharging through a thin cylindrical opening creating a thin liquid layer spreading radially. At the inner corner of the constriction, the flow is separating leading to an actual discharging area smaller than $2\pi\, R\, H$. Ref. [14] performed 2D numerical computations using the free-streamline theory on right-angle elbows with geometrical ratio, upstream to downstream channel width, ranging from 0.01 to 1.2. They compute the contraction coefficient (C_c) defined as the ratio of the asymptotic stream width downstream of the corner to the upstream channel width. The C_c was decreasing

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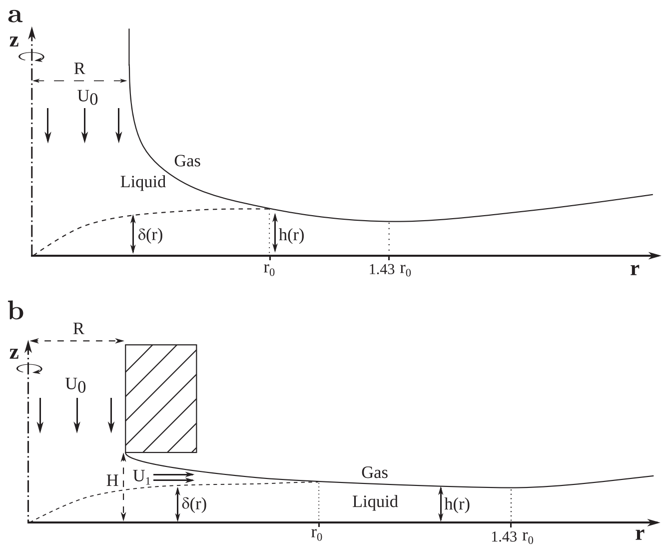

Fig. 1. Half radial cut of the radial flow created by an impact of a round jet on a horizontal plate (top) and thin cylindrical opening (bottom). With r the radial distance, R the jet radius, H the distance between the nozzle and the plate, U_0 jet mean velocity, U_1 the main stream velocity, $h(r)$ the liquid film thickness, $U(r)$ the interface velocity and $\delta(r)$ the boundary layer thickness.

with the geometrical ratio. Ref. [15] investigated the effect of the elbow angle on the contraction coefficient showing that C_c was decreasing with the elbow angle. Their computations of the C_c has been validated by [16] who solved the Euler equations of the flow at a corner using a Lagrangian model based on smoothed particle hydrodynamics method.

The goal of this paper is to provide an analytical description of the thickness and the velocity of a thin liquid layer generated by radial flow generated by a thin cylindrical opening. The solution combines the analytical solution given by Watson and a correlation expression the flow acceleration due to the flow separation with respect to the geometrical ratio. The paper is structured as follows: in Section 2.1 the theoretical development proposed by Watson for a round jet spreading radially is summarised. The full description of the theoretical developments can be found in Watson's paper [10]; Section 2.2 presents the theoretical extension to a radial flow of the Watson solution; Section 3 presents the numerical computations used to find the relationship between the geometrical ratio and the flow acceleration; finally, in Section 4 the validity and the quality of the proposed model is discussed.

2. Theoretical developments

2.1. Flow created by a round liquid jet impacting on a horizontal plate

2.1.1. Fully developed region: similarity solution

This axisymmetric flow can be described as a thin layer by the following equations:

$$\frac{\partial(ru)}{\partial r} + \frac{\partial(rw)}{\partial z} = 0 \tag{1}$$

$$u\left(\frac{\partial u}{\partial r}\right) + w\left(\frac{\partial u}{\partial z}\right) = \nu\left(\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

where r is the radial distance from the jet centre, z is the distance upward from the plate, u and w are the corresponding velocity components, ν is the kinematic viscosity.

The hypotheses are: a no slip condition at the plate (Eq. (3)), the shear stress at the free surface is negligible (Eq. (4)) and the flow rate along the radial axis is constant (Eq. (5)):

$$u = w = 0 \quad \text{at} \quad z = 0 \tag{3}$$

$$\frac{\partial u}{\partial z} = 0 \quad \text{on} \quad z = h(r) \tag{4}$$

$$Q = 2\pi r\int_0^{h(r)} u\,\mathrm{d}z \tag{5}$$

The velocity profile in the axial direction u can be rewritten as function of the velocity at the free surface $U(r)$ and a similarity solution $f(\eta)$:

$$u = U(r)f(\eta) \quad \text{with } \eta = \frac{z}{h(r)} \tag{6}$$

Then, the flow rate along the radial direction given by Eq. (5) can be rewritten as:

$$Q = 2\pi rUh\int_0^1 f(\eta)\,\mathrm{d}\eta \tag{7}$$

Watson used the integral method to retrieve the integral of the velocity profile over the liquid layer thickness equal to:

$$\int_0^1 f(\eta)\,\mathrm{d}\eta = \frac{2\pi}{3\sqrt{3}c^2} \tag{8}$$

where c is a constant of integration equal to 1.402. Finally, the constant flow Eq. (7) can be rewritten as:

$$rUh = \frac{3\sqrt{3}c^2Q}{4\pi^2} \tag{9}$$

Using Eqs. (2) and (9), $U(r)$ and $h(r)$ can be expressed as:

$$U(r) = \frac{27c^2Q^2}{8\pi^4\nu(r^3 + l^3)} \tag{10}$$

$$h(r) = \frac{2\pi^2\nu(r^3 + l^3)}{3\sqrt{3}Qr} \tag{11}$$

where l is a constant length arising from the integration of $\frac{\partial U}{\partial r}$ in Eq. (2). The value of l will be determined later using the boundary development region equations knowing that $h(r_0) = \delta$.

2.1.2. Boundary development region: general approximate solution

In the first region, the boundary layer is not fully developed thus the velocity outside the boundary layer is considered as equal to the velocity of the jet U_0 which is expressed as:

$$U_0 = \frac{Q}{\pi R^2} \tag{12}$$

Inside the boundary layer, the velocity profile is defined by the similarity function $f(\eta)$:

$$u = U_0 f\left(\frac{z}{\delta}\right) \quad \text{with } u = U_0 \quad \text{when} \quad z \geq \delta(r) \tag{13}$$

The momentum integral equation is equal to:

$$\left(\frac{d}{dr} + \frac{1}{r}\right)\int_0^{\delta}(U_0\,u - u^2)\,\mathrm{d}z = \nu\left(\frac{\partial u}{\partial z}\right)_{z=0} \tag{14}$$

Integration and rewriting of Eq. (14) gives: