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Flow in the thin film created by a coherent turbulent water jet impinging on a vertical wall

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HIGHLIGHTS

- The development of boundary layers and transition to turbulence are modeled.
- Predicts transitions in film behaviour reasonably well.
- The model of Wilson et al. (2012) is extended to higher flow rates and oblique jets.
- Good agreement with new measurements of average velocity in the film.
- Insensitivity of the film jump location to contact angle at high flow rate is explained.

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ABSTRACT

When a liquid jet impinges on a vertical wall it forms a thin film which flows radially away from the point of impingement until a point where the outward momentum is balanced by surface tension and a film jump is formed. The model for the location for the film jump presented by Wilson et al. (Chem. Eng. Sci, 2012, vol. 68, pp 449–460) is revised to include the development of laminar and turbulent boundary layers in the thin film. The criterion for film jump formation is also revisited, and the analysis explains why the location is insensitive to the nature of the wall material at high flow rates. The model is compared with published data for velocity profiles in the thin film, the transition to turbulence, and new experimental data where the average velocity in the thin film was estimated from the initial growth of the radial flow pattern for flow rates of 1.95–4.01 $dm^3\,s^{-1}$, corresponding to jet Reynolds numbers of 15,500–32,000. Very good agreement with the published and measured data is obtained, with no adjustable parameters, for jets impinging perpendicularly as well as at an oblique angle. The model shows that the parabolic velocity profile assumed by Wilson et al. gives a reasonable estimate of the average velocity, but it is not able to predict phenomena such as the observed transition to turbulence.

1. Introduction

Liquid jets are widely used for cleaning, with applications ranging from the internal and external surfaces of processing and storage vessels (Burfoot and Middleton, 2009), to kitchenware in dishwashers (Pérez-Mohedano et al., 2015). Liquid jets impinging on solid surfaces are also employed in process intensification for enhancing local heat transfer rates (Lienhard, 1995). High speed jets can also be used for cutting (Leach and Walker, 1966). In cleaning applications, knowledge of the flow pattern created by the jet is important for determining local cleaning rates as well as predicting wetting and draining behaviour.

Following impingement, the liquid in the jet spreads radially away from the point of impingement in a thin film until the height of the film changes abruptly. When a coherent vertical jet impinges perpendicularly downwards on a horizontal surface the transition, termed the hydraulic jump, is circular (Watson, 1964). A vertical jet impinging *upwards* gives rise to a circular wetted region bounded by falling droplets or a liquid curtain known as the water bell (Button et al., 2010).

Many cleaning applications involve walls which are close to vertical and the influence of gravity gives rise to less symmetric flow patterns. When a coherent horizontal jet impinges on a vertical wall, as shown in Fig. 1, the liquid initially spreads out in a thin film in a region which is here labelled the radial flow zone (RFZ). At some radial position the outwards momentum in the film is countered by surface tension and a jump is observed: it is here termed the *film jump* to differentiate it from the hydraulic jump. Gravity causes the location of the film jump to vary with azimuthal position, θ. Beyond the film jump, the liquid drains under gravity

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Nomenclature

Roman

a_i coefficients in Eq. (16), dimensionless
C_1 constant ($\int_0^1 f^2(\eta)d\eta = C_1$), Eq. (9), dimensionless
C_2 constant ($f'(\eta)|_0 = C_2$), Eq. (9), dimensionless
C_3 constant ($\int_0^1 f(\eta)d\eta = C_3$), Eq. (13), dimensionless
d jet diameter, m
d_N nozzle diameter, m
E mechanical energy flux per unit width, kg m s^{-3}
g gravitational acceleration, m s^{-2}
h film thickness, m
H maximum height of the rope, at, $r = r_H$, m
$\dot{m}$ mass flow rate of liquid in the jet, kg s^{-1}
M momentum per unit width (Eq. 50), kg s^{-2}
Nu_d Nusselt number, dimensionless
P pressure, Pa
Q volumetric flow rate, m^3 s^{-1}
r radial co-ordinate, m
r_o jet radius ($r_o = d/2$), m
r_b radius where boundary layer reaches the surface, m
r_+ radius where boundary layer is fully developed, (Eq. (70)), m
r_t transition radius from laminar to turbulent flow, m
r_e radial distance from the focus to the boundary of the elliptical projection of a normal jet (Eq. (57)), m
R_j radius at film jump, m
r_H radius at the maximum height of the rope, m
Re_j jet Reynolds number based on nozzle diameter, dimensionless
t time, s
u radial velocity, m s^{-1}
U_o jet velocity, m s^{-1}
U_{av} average radial velocity in liquid film, m s^{-1}
U_t average radial velocity in liquid film at laminar to turbulent transition radius, m s^{-1}
U radial velocity at the liquid film surface, m s^{-1}
v velocity normal to the surface, m s^{-1}
v_θ velocity in azimuthal direction, m s^{-1}
z distance normal to the surface, m

Greek

β contact angle, deg
γ surface tension, N m^{-1}
δ boundary layer thickness, m
η dimensionless distance normal to the wall, dimensionless
θ azimuthal angle, deg
μ dynamic viscosity, Pa s
ρ density, kg m^{-3}
ϕ angle of inclination of the jet to the vertical, deg
τ_w wall shear stress, Pa

Acronyms

BLFZ boundary layer flow zone
LZ laminar zone
TZ turbulent zone
RFZ radial flow zone

and flows circumferentially around the perimeter of the RFZ in the *rope*. Below the level of impingement (marked AA′ on Fig. 1), the rope and radial flow spread out further to generate a falling film which may narrow further downstream.

The hydrodynamics of the symmetric, circular hydraulic jump have been studied in detail. The transition from a fast moving film with a developing boundary layer to a laminar film and subsequently a turbulent film has been analysed mathematically and investigated experimentally (*e.g.* Watson, 1964; Bohr et al., 1993; Bush and Aristoff, 2003; Arakeri and Rao, 2013). Similar analyses have also been applied to inclined jets (Blyth and Pozrikidis, 2005; Kate et al., 2007).

Morison and Thorpe (2002) reported the first systematic study of jets impinging on vertical walls. Wilson et al. (2012) presented a

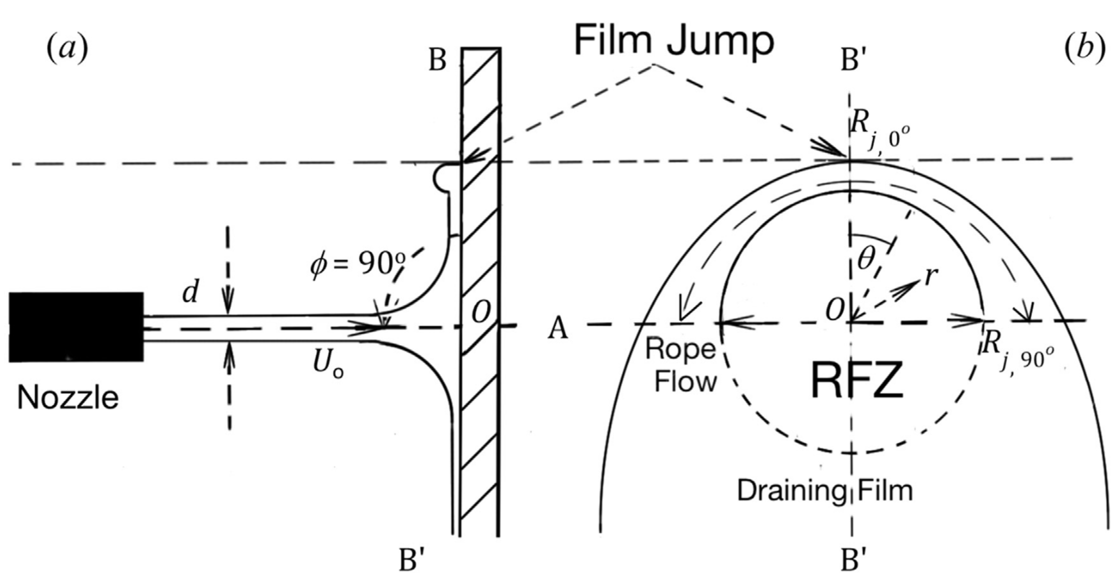

Fig. 1. Schematic of flow pattern formed by a jet impinging normally on a vertical wall. (a) Side view through section BB′ and (b) front view. O is the point of impingement, U_o is the jet velocity and d is the jet diameter.