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Particle image velocimetry and modelling of horizontal coherent liquid jets impinging on and draining down a vertical wall

W. Aouad [a], J.R. Landel [b], S.B. Dalziel [b], J.F. Davidson [a], D.I. Wilson [a],*

[a] Department of Chemical Engineering and Biotechnology, University of Cambridge, New Museums Site, Pembroke Street, Cambridge CB2 3RA, UK
[b] Department of Applied Mathematics and Theoretical Physics, Centre for Mathematical Sciences, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK

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ABSTRACT

The flow patterns created by a coherent horizontal liquid jet impinging on a vertical wall at moderate flow rates (jet flowrates 0.5–4.0 L min^{-1}, jet velocities 2.6–21 m s^{-1}) are studied with water on glass, polypropylene and polymethylmethacrylate (acrylic, Perspex®) using a novel particle image velicometry (PIV) technique employing nearly opaque liquid doped with artificial pearlescence to track surface velocity. Flow patterns similar to those reported in previous studies are observed on each substrate: their dimensions differed owing to the influence of wall material on contact angle. The dimensions are compared with models for (i) the radial flow zone, reported by Wang et al. (2013) [1], and (ii) the part of the draining film below the jet impingement point where it narrows to a node. For (ii), the model presented by Mertens et al. (2005) [2], J. Liu et al. (1995) [3] is revised to include a simpler assumed draining film shape and an alternative boundary condition accounting for surface tension effects acting at the film edge. This revised model gives equally good or better fits to the experimental data as compared with the Mertens et al. model. The effective contact angle which gives good agreement with the data is found to lie between the measured quasi-static advancing and receding contact angles, at approximately half the advancing value. The PIV measurements confirmed the existence of a thin, fast moving film with radial flow surrounding the point of impingement, and a wide draining film bounded by ropes of liquid below the impingement point. While these measurements generally support the predictions of existing models, these models assume that the flow is steady. In contrast, surface waves were evident in both regions and this partly explains the difference between the measured surface velocity and the values estimated from the models.

1. Introduction

Impinging liquid jets are widely used in cleaning operations for removing soiling layers on process vessels [4], walls [5] and in dishwashers [6]. The liquid is usually water or an aqueous solution of surfactants and other detergent species. When a coherent jet impinges on a surface, liquid flows away from the point of impingement in a radial pattern until a point where the fast moving thin film changes to a deeper, slower moving state. When a vertical jet impinges downwards on a horizontal plate this gives rise to a circular hydraulic jump, which has been studied extensively since the initial work of Watson [7] (see, for example, [8–10]. When the jet impinges at an angle, the hydraulic jump is elliptical and this has been modelled successfully by Kate et al. [11] and Blyth and Pozrikidis [12].

When a jet impinges on a vertical wall the flow pattern is no longer cylindrically axisymmetric, owing to gravity, and the liquid falls downwards to give a range of wetting patterns determined by the flow rate, the fluid properties and the surface–liquid interaction manifested in the contact angle, β. Knowledge of this wetting behaviour is important for cleaning operations involving walls and inclined surfaces, as the removal of soiling layers or contaminants is determined by a combination of shear stress, material transport, and soaking (time spent in contact with cleaning solution) [13].

This paper follows on from a series of studies of the flow behaviour and cleaning performance associated with liquid jets impinging on vertical and inclined walls [1,14–17]. The series builds on a model presented in Wilson et al. [14] which uses a relatively simple momentum balance to describe the geometry and velocity field of the radial flow zone surrounding the impingement point (see below). In the present study, our aim is to study experimentally the geometry and, where possible, the velocity field of the different regions of the flow produced by a horizontal coherent jet impinging on a vertical surface.

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* Corresponding author. Tel.: +44 1223 334791; fax: +44 1223 334796.
E-mail address: diw11@cam.ac.uk (D.I. Wilson).

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Nomenclature

Roman	
a	constant in the height function, $h(x, y)$, Eq. (9) ($\mathrm{m^{-1}}$)
b	constant in the height function, $h(x, y)$, Eq. (9) ($\mathrm{m^{-3}}$)
D	rope width (m)
D_0	rope width, vertically above O, $\theta = 0$ (m)
d_N	nozzle diameter (mm)
F	capillary force acting on the half-braid ($\mathrm{N\,m^{-1}}$)
F^*	dimensionless form of the capillary force, $F^* = F/\gamma$ (–)
g	gravitational acceleration ($\mathrm{m\,s^{-2}}$)
h	height of the film (m)
h_R	height of the film at the film jump (m)
h_{rope}	height of film in rope (m)
l	characteristic length (m)
$\dot{m}$	mass flow rate ($\mathrm{kg\,s^{-1}}$)
Q	total flow rate ($\mathrm{m^3\,s^{-1}}$)
Q_F	flow rate in the central region of the falling film ($\mathrm{m^3\,s^{-1}}$)
Q_R	flow rate in the rope region of the falling film ($\mathrm{m^3\,s^{-1}}$)
R	radius of film jump at mid plane (m)
R_c	outer radius of flow at mid plane (m)
R_0	radius of film jump, vertically above O, $\theta = 0$ (m)
R_z	outer radius of film jump, vertically above O, $\theta = 0$ (m)
r_o	jet radius (m)
r	radial co-ordinate (m)
Re_c	critical film Reynolds number, defined $Re_c = uh/\nu$ (–)
Re_{jet}	jet Reynolds number, defined $Re_{\mathrm{jet}} = U_o r_o/\nu$ (–)
Re_{film}	falling film Reynolds number
U	mean velocity in RFZ film ($\mathrm{m\,s^{-1}}$)
U_o	initial mean velocity in RFZ film ($\mathrm{m\,s^{-1}}$)
U_R	film mean velocity at R ($\mathrm{m\,s^{-1}}$)
U_s	surface velocity in RFZ film ($\mathrm{m\,s^{-1}}$)
u	downwards velocity of the draining film ($\mathrm{m\,s^{-1}}$)
u_*	dimensionless form of u_x (–)
u_s	surface velocity of the draining film ($\mathrm{m\,s^{-1}}$)
V	characteristic velocity ($\mathrm{m\,s^{-1}}$)
w, w_0	local half width, half width at $x = 0$ (m)
w_*	dimensionless half width (–)
x	distance downstream from plane BB, in Zone IV (m)
x_*	dimensionless distance downstream from plane BB (–)
y	lateral distance from centreline, in Zone IV (m)
z	distance downstream from plane AA, in Zone III (m)

Acronyms	
PIV	particle image velocimetry (–)
RFZ	radial flow zone (–)

Greek	
β	contact angle (°)
β_a	advancing contact angle (°)
β_{fit}	contact angle derived from data fitting, Fig. 11 (°)
β_r	receding contact angle (°)
δ	thickness of the falling film (m)
θ	angle from vertical (°)
γ	surface tension ($\mathrm{N\,m^{-1}}$)
Γ	wetting rate ($\mathrm{m^2\,s^{-1}}$)
Π_I	dimensionless group in Eq. (12), defined in (16) (–)
Π_{II}	dimensionless group in Eq. (13), defined in (17) (–)
μ	dynamic viscosity (Pa s)
ν	kinematic viscosity ($\mathrm{m^2\,s^{-1}}$)
ρ	liquid density ($\mathrm{kg\,m^{-3}}$)

This is the first time that detailed experimental measurements of the velocity field of a thin falling film produced by an impinging jet are presented. The novel particle imaging velocimetry technique of Landel et al. [18] can capture, at high time and space resolutions, the two-dimensional velocity field at the surface of a thin film that is not constrained in a channel. In our experiments, it is essential that the film remains unconstrained at the edges, and flows freely on a planar surface. Indeed, the force due to surface tension, acting at the edges of the film, is key to understand the physics of the flow produced by an impinging jet. As modelled by Wilson et al. [14], the size of the radial flow zone is controlled primarily by surface tension acting at the film boundary. In the model of Mertens et al. [2], the narrowing and subsequent braiding pattern observed in the draining flow downstream of the radial flow zone is also controlled by surface tension forces acting at the edges.

1.1. Anatomy of the impingement pattern

Fig. 1 shows photographs and a schematic identifying the characteristic features of a horizontal jet impinging at point O on an otherwise dry vertical wall. The terminology which follows is that employed in our previous studies [14,15]. Short videos of the impingement region and the draining film are provided as Supplementary material V1 and V2, respectively.

AA is the horizontal line passing through O. At and above AA, the liquid flows radially outwards from O until the change in depth, which we term the *film jump* in order to distinguish it from the hydraulic jump on horizontal surfaces. This *radial flow zone* (RFZ) is labelled Zone I and has radial dimension R along AA (where $\theta = 90°$), and extends to height R_0 directly above O. Beyond this radius R, the liquid flows circumferentially downwards in a rope, in Zone II, with outer radial dimension R_c along plane AA (Fig. 1b). The rope is typically much thicker than the film in the RFZ. Symmetry suggests that the volumetric flow rate in each rope crossing AA between R and R_c, if there is no splashing (i.e. loss as droplets of spray), is close to $Q/4$, where Q is the flow rate in the jet. As the flow in the RFZ will be influenced by gravity, the flow will be slightly less than $Q/4$. Above AA we employ cylindrical co-ordinates based on point O.

Below AA, liquid still flows radially away from O within the RFZ but the film jump is less pronounced and is not evident in much of this region. In these experiments the additional sideways momentum provided by the remaining liquid from the jet causes the wetted region to expand until it reaches a maximum at plane BB, of width $2w_0$. The zone between the horizontal lines AA and BB is labelled Zone III. The photographs (Fig. 1b and c) indicate that ropes of similar width still exist in this region and there are many surface waves forming a circular pattern. Wang et al. [15] found that the vertical extent of Zone III (from AA to BB) is greater than or equal to R. In Zone III, the flow out from the impingement point still provides a source of horizontal momentum, acting against the surface tension trying to narrow the film. The net result is a slight increase in the width of the film. Below Zone III there is no longer significant addition of horizontal momentum and surface tension causes the film to narrow, giving Zone IV. (If low flow rates are used, surface tension will cause the wetted region to contract below AA, see Wilson et al. [14].) Between AA and BB we employ Cartesian co-ordinates; z is the distance downstream from AA.

Zone IV is marked by a number of features: the continuation of the rope on each boundary, of significant width and with a thickness much larger than in the interior of the flow (see darker edges in Fig. 1c); the interior region bounded by the ropes in which almost horizontal crests of surface waves of varying wavelength