Chemical Engineering Science 102 (2013) 585–601

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Flow patterns and draining films created by horizontal and inclined coherent water jets impinging on vertical walls

T. Wang, D. Faria, L.J. Stevens, J.S.C. Tan, J.F. Davidson, D.I. Wilson*

Department of Chemical Engineering & Biotechnology, University of Cambridge, New Museums Site, Pembroke Street, Cambridge CB2 3RA, UK

HIGHLIGHTS

- Flow patterns created by liquid jets impinging at angles off horizontal are studied.
- Little effect of gravity and contact angle at flow rates studied.
- Width and height of radial impingement region are predicted by the model.
- Falling film width is correlated with film jump radius.
- Formation of dry patches in falling film is predicted by the model.

ARTICLE INFO

Article history:
Received 1 June 2013
Received in revised form
11 August 2013
Accepted 24 August 2013
Available online 4 September 2013

Keywords:
Cleaning
Contact angle
Fluid flow
Impinging jet
Surface tension

ABSTRACT

The flow patterns created by coherent water jets created by solid stream nozzles impinging on vertical polymethylmethacrylate (Perspex) and glass surfaces were studied for nozzles with diameters 2–4 mm at angles up to ±45° from the horizontal. The flow rates studied ranged from 7.1 to 133 g s^{-1} (26–480 L h^{-1}; jet velocities 2.6–10.6 m s^{-1}). The width and height of the film jump marking the limit of the radial flow zone were compared with models based on that developed by Wilson et al. (2011), modified to include the effect of gravity and the angle of inclination for non-horizontal jets (incorporating the flow distribution model reported by Kate et al. (2007. Journal of Fluid Mechanics 573, 247–263)). The location of the film jump and the flow pattern around the impingement point were sensitive to the nature of the substrate at low flow rates, but insensitive to substrate nature at higher flow rates. The models predicted the film jump location with reasonable accuracy, and the width of the wetted region at the mid-plane was found to follow a simple relationship to the film jump width there. A first-order model for the width of the rope of liquid draining around the film jump gave a lower bound estimate of this dimension. The falling film generated below the impingement point exhibited three forms of behaviour: a wide film, termed *gravity flow*; a narrowing film, termed *rivulet flow*, and a wide film which split into two with the formation of a *dry patch*. The transition to form a dry patch was found to obey the minimum wetting rate criterion reported by Hartley and Murgatroyd (1964), once loss of liquid due to splashback was accounted for. Dry patch formation within the falling film was only observed with upwardly impinging jets, and the tendency to form dry patches was predicted with some success by a simple two-stream model.

1. Introduction

Liquid jets are widely used to remove surface soiling (fouling) layers when cleaning process equipment (Jensen, 2011). Their use for cleaning the internals of tanks and other vessels is increasing as they offer several advantages over simple 'fill and soak' strategies in employing smaller volumes of liquid. Mechanical energy is required for pumping but this is usefully dissipated by the liquid, usually water-based, as it flows over the soil: the flow imposes a shear stress which enhances soil break-down and increases convective heat transfer as well as mass transfer of soluble species into the liquid.

The performance of jet cleaning systems such as spray balls, solid-stream nozzles, jet heads and rotating spray arms (*e.g.* in dishwashers) depends strongly on the wetting patterns of the liquid on the wall. For cases where cleaning arises primarily from the chemical or detergent action of the liquid, it is important to be able to predict whether the design will achieve complete coverage of the target area with liquid. For cases where cleaning also requires a high shear stress, knowledge of the shear stress

---

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

0009-2509/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ces.2013.08.054

distribution is required. Both instances require a working knowledge of the flow patterns created by the liquid jet. This paper investigates the flow patterns created by coherent liquid jets impinging on vertical surfaces, such as are created by solid stream nozzles and by spray balls before the jet breaks up (caused by Rayleigh instabilities). Studies of spray jets in cleaning have been presented by Leu et al. (1998) and Meng et al. (1998).

The flow patterns generated by coherent liquid jets impinging vertically downwards on horizontal surfaces, giving circular regions of rapid, radial flow terminating with an abrupt change in film height called the hydraulic jump, have been studied for over 50 years. The phenomenology, including the formation of surface waves and influence of surface tension, has been established and modelled by successive workers (*e.g.* Watson, 1964; Bush and Aristoff, 2003). The case of a non-vertical jet impinging on a horizontal plate and forming a non-circular hydraulic jump has been modelled by Blyth and Pozrikidis (2005), Kibar et al. (2010) and by Kate et al. (2007). Button et al. (2010) reported an elegant study and model of the less common case, where a liquid jet flowing vertically upwards impinges on a horizontal plate, spreads radially outwards and falls downwards to form a 'water bell'.

The behaviour of jets impinging on vertical or near-vertical surfaces has received less attention despite its importance in cleaning. Morison and Thorpe (2002) reported a study of the contact region, draining film and cleaning behaviour generated by individual spray ball jets operating at industrial flow rates. They studied jets created by spray ball holes with diameters 1.6–2.4 mm at pressures up to 3.6 barg at velocities ranging from 7 to 28 m s^{-1}. Atomisation was not observed in their tests. On a vertical wall, the liquid flows radially outwards from the point of impingement until a feature resembling a hydraulic jump occurs, which is here termed the *film jump*. Knowledge of the location of the film jump is important as this is the boundary of the *radial flow zone* (RFZ) where the highest shear stresses are generated. Wilson et al. (2011) analysed Morison and Thorpe's data sets as well as new experimental data and showed that the size of the RFZ could be predicted by a simplified model derived from the work by Button et al.; in this simplified model the film jump occurs when the radially outward flow of momentum is balanced by surface tension at radial location R (see Fig. 1), given by

$$R = 0.276\left[\frac{\dot{m}^3}{\mu\rho\gamma(1-\cos\beta)}\right]^{1/4} \tag{1}$$

where $\dot{m}$ is the mass flow rate, μ is the liquid kinematic viscosity, ρ its density, γ is the gas–liquid surface tension and β the contact angle.

Beyond the film jump the flow pattern is complex. Fig. 1 shows schematics of three types of behaviour observed in this work. The pattern above the plane of impingement is common to all, where beyond the film jump the liquid falls circumferentially in a rope until it reaches the plane of impingement, beyond which it falls downwards. The width of the rope and RFZ at the impingement plane (labelled X–X) is $2R_c$. An *a priori* prediction for R_c is currently not available. Wilson et al. (2011) and Wang et al. (2013) observed that $R_c \approx 2R$ at lower flow rates and approached $R_c \approx 4R/3$ at higher flow rates (above 11 g s^{-1} for a 3 mm nozzle). The flow rate at which the transition in R_c/R behaviour occurred depended on the substrate and thus the contact angle.

In the case where downward momentum dominates surface tension (Fig. 1(a)), the flow forms a stable falling film of width W, which is here termed *gravity flow*. The film width may change gradually. In cases where surface tension is significant, two behaviours can arise: *rivulet flow*, Fig. 1(b), where the liquid forms a narrow tail, and *dry patch* formation, Fig. 1(c), where the falling film splits. Both rivulet flow and dry patch formation are undesirable for cleaning applications.

Wilson et al. studied water flow rates which were low compared to those used in industrial cleaning jets, up to 2.0 g s^{-1}, and observed either gravity or rivulet flow. They found that the occurrence of stable wide films, of width W, could be predicted by the criterion for the minimum wetting rate, $\Gamma_{\min}$, for stable falling films developed for evaporators by Hartley and Murgatroyd (1964) *viz.*

$$\Gamma = \dot{m}/W \geq 1.69(\mu\rho/g)^{0.2}[\gamma(1-\cos\beta)]^{0.6} = \Gamma_{\min} \tag{2}$$

where g is the gravitational acceleration. The reliability of this criterion for higher flow rates is explored here.

Wang et al. (2013) studied the effect of a surfactant, Tween 20, for similar flow rates and found the presence of surfactant to have little influence on the size of the film jump, but strongly affected falling film behaviour. This was attributed to dynamic contact angle effects: in the falling film there was sufficient time for the surfactant to accumulate at the wetting line and influence the contact angle.

The contact angle is also determined by the nature of the substrate. Wang et al. (2013) reported results for jets impinging on vertical glass and Perspex (polymethylmethacrylate) substrates, which have different water contact angles. At lower flow rates (<11 g s^{-1} at 20 °C), the location of the film jump was sensitive to substrate nature but at higher flow rates, obtained by Wang et al. using larger nozzles, the film jump location was insensitive to substrate nature. Draining film behaviour continued to be sensitive to the substrate and static contact angle.

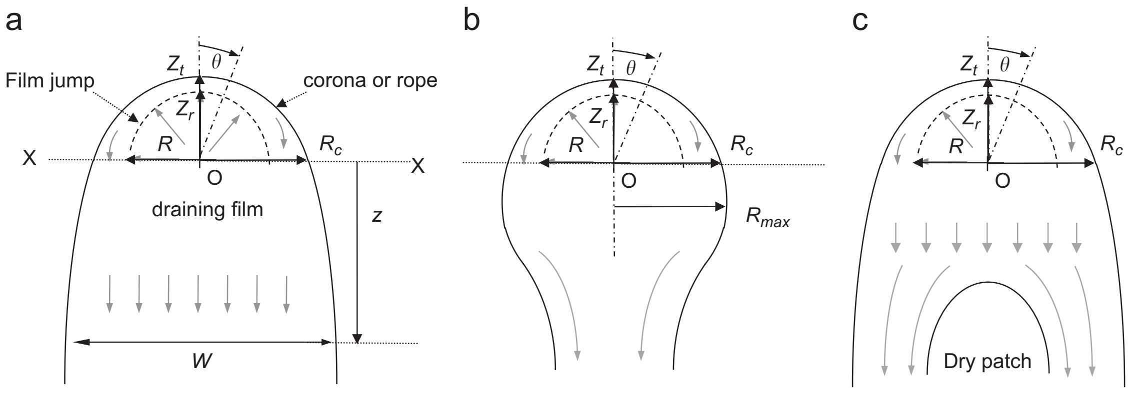

Fig. 1. Schematics of flow patterns, viewed from behind target in Fig. 2, generated by a jet impinging on a vertical plate. O is the jet impingement point, R is the radius of the film jump, R_c is the radius of the corona or rope at the impingement level (X–X). Z_r is the height of inner radial zone above O; Z_t is the maximum height of the film above O. The grey arrows show the flow pattern: radial from O to the jump; tangential around the rim. The polar coordinate is θ. Flow regimes below X–X are (a) Gravity flow, with a draining film of width W at z, where z is the distance measured downwards from O. (b) Rivulet flow. (c) Gravity flow, with dry patch formation.