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Flow patterns and cleaning behaviour of horizontal liquid jets impinging on angled walls

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ABSTRACT

Liquid jets are widely used in cleaning operations in the food sector. Morison and Thorpe (2002) reported an experimental investigation of the flow patterns and cleaning behaviour of horizontal jets impinging on vertical walls. The Wilson et al. (2012) model, which described Morison and Thorpe's flow pattern data well, is extended to describe the flow pattern generated by a liquid jet, approaching a surface at a given angle to the horizontal, impinging on a plate inclined at a known angle to the vertical. The results are compared with experimental data collected for horizontal water jets impinging on inclined Perspex and glass plates. Tests employed nozzle diameters of 1, 2 and 3 mm at room temperature, using flow rates of 0.78–2.23 g s^{-1}, 3.7–9.9 g s^{-1} and 7.1–17.3 g s^{-1} (0.025–0.062 m^3 h^{-1}) respectively. These are lower than industrial cleaning flow rates. The angle at which the horizontal jet impinged on the plate was varied from 30° to 120°. Two important dimensions are evaluated: (i) the width of the fast moving radial flow zone on the plate (the region bounded by the *film jump*, the feature similar to a hydraulic jump) at the plane of impingement; (ii) the distance on the plate to which the radial flow zone extends above the point of impingement. Both are described reasonably well by the model. Empirical relationships are reported for the width of the wetted region at the level of impingement, and the maximum width of the draining film. A short study of cleaning of layers of washable paint on glass, similar to the tests reported by Morison and Thorpe, show that the cleaning model recently developed by Wilson et al. (2014) gives a good description of the initial cleaning of such layers using an impinging stationary coherent water jet.

Keywords: Cleaning; Impinging jet; Model; Hydraulic jump; Draining film; Contact angle

1. Introduction

Liquid jets are widely used to remove surface soiling or fouling layers when cleaning process equipment. Their use for cleaning the internals of tanks and other vessels is increasing in the food, pharmaceutical and fine chemicals sectors as they offer several advantages over simple 'fill and soak' strategies in employing smaller volumes of liquid and generally requiring less time (Jensen, 2011). 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 pattern 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 distribution is required. Both instances require a working knowledge of the flow patterns created by the liquid jet when it impinges on the wall.

When a liquid jet impinges on the wall, it can rebound, giving splashback (*e.g.* Lienhard et al., 1992), or spread radially away from the point of impingement as a fast moving film. At some distance from the point of impingement the liquid slows down and a jump is formed, where the film depth increases and gravity dominates the flow pattern. Whereas the case of

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Nomenclature

Roman

c	group of parameters, Eq. (3) ($kg^2\,m^{-4}\,s^{-1}$)
d_N	nozzle diameter (m)
g	gravitational acceleration ($m\,s^{-2}$)
k'	cleaning rate constant ($s\,m\,kg^{-1}$)
K	lumped cleaning rate constant ($m\,s^{-0.2}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
PVA	polyvinylacetate
r	radial co-ordinate (m)
r_c	radius of cleaned area (m)
r_e	radius of impingement ellipse at angle θ (m)
r_o	radius of jet (m)
RFZ	radial flow zone
R	radius of RFZ at the midplane (m)
R^2	correlation coefficient (dimensionless)
R_c	outer radius of rope at the midplane (m)
R_{max}	maximum half-width of falling film (m)
R_θ	radius of RFZ at angle θ (m)
Re_{jet}	Reynolds number in jet, $= 2r_oU_o/\nu$ (dimensionless)
t	time (s)
t_i	time at which breakthrough is first seen (m)
U	mean velocity in film ($m\,s^{-1}$)
U_o	velocity of jet ($m\,s^{-1}$)
Z_r	height of RFZ at $\theta = 0$ (m)
Z_t	distance to top of rope at $\theta = 0$ (m)

Greek

α	angle of the jet to the horizontal (°)
β	contact angle (°)
δ	layer thickness (m)
γ	surface tension ($N\,m^{-1}$)
ρ	density ($kg\,m^{-3}$)
λ	angle of inclination of the plate to the horizontal (°)
θ	azimuthal angle of streamline along the plate (Fig. 1(b)) (°)
ϕ	angle at which the jet strikes the plate (°)
ν	kinematic viscosity ($m^2\,s^{-1}$)

a liquid jet impinging vertically downwards on a horizontal plate, giving a hydraulic jump, has been studied extensively in the fluid mechanics literature (*e.g.* Watson, 1964), the case of a liquid jet impinging on a vertical wall has received relatively little attention. Morison and Thorpe (2002) reported an experimental investigation of the flow pattern created by a horizontal jet from a spray ball impinging on vertical walls. Wilson et al. (2012) subsequently developed a model which predicted Morison and Thorpe's data sets well.

In this paper, the flow pattern and cleaning behaviour of impinging jets such as those generated by spray balls, albeit at flow rates below the lower end of the range employed in industry, was investigated by considering a single coherent jet impinging on clean, inclined plates. The flow rates (1 mm nozzle, 0.7–2.4 $g\,s^{-1}$; 2 mm nozzle, 3–11 $g\,s^{-1}$; 3 mm nozzle, 7–17 $g\,s^{-1}$) are similar to those employed by Wang et al. (2013a), who studied stationary jets impinging on vertical walls at different angles of inclination. Industrial static spray balls are typically operated at 2 barg, giving flow rates of 16 $g\,s^{-1}$ (0.056 $m^3\,h^{-1}$) and 141 $g\,s^{-1}$ (0.51 $m^3\,h^{-1}$) for 1 and 3 mm diameter holes, respectively. The purpose of this paper is to develop a model to describe the flow behaviour. Its application at industrial flow rates will require larger apparatuses, such as that described by Wilson et al. (2014), or even larger for surfaces inclined at acute angles to the flow.

The Wang et al. (2013a) model is extended to include the case where the jet impinges on inclined surfaces (*i.e.* the surface is not vertical). The model is written for the general case of jets inclined at an arbitrary angle but experiments were only performed using horizontal jets.

A short study of the cleaning performance of these water jets is presented for a stationary coherent jet impinging horizontally on a painted vertical glass wall, mimicking that reported by Morison and Thorpe. The removal of the paint layer by adhesive detachment, *i.e.* leaving the substrate almost clean, is successfully described by the Wilson et al. (2014) cleaning model.

2. Materials and methods

2.1. *Apparatus*

Experiments employed the apparatus reported in detail in Wang et al. (2013b). Water flowed under gravity from an elevated 20 L holding tank through a control valve and pressure gauge before discharging through the nozzle. The stainless steel piping had an i.d. of 4 mm, with removable nozzles of throat diameter $d_N = 1$ mm, 2 mm or 3 mm. The internal convergence angles, measured from the nozzle centre-line to the conical surface, were 45°, 56° and 71°, respectively. The angle of inclination of the nozzle to the horizontal was set by a pivot. The pressure drop across the nozzle was used to monitor the flow rate, using the coefficients of discharge reported in Wang et al. (2013a). The 0.5 m gravity head used in these tests gave mass flow rates, $\dot{m}$, of 0.78–2.23 $g\,s^{-1}$ for $d_N = 1$ mm; 3.7–9.9 $g\,s^{-1}$ for $d_N = 2$ mm and 7.1–17.3 $g\,s^{-1}$ for $d_N = 3$ mm. The jet Reynolds number, Re_{jet}, based on jet diameter, ranged from 500 to 3200 at 20 ± 2 °C.

The target plates were transparent, with dimensions 300 mm × 330 mm × 5 mm (thickness), made from Perspex (polymethylmethacrylate), and float glass (borosilicate glass). The plate was positioned approximately 30 mm away from the nozzle and could be rotated about a horizontal axis so that its plane lay at angle from 0° to ±60° to the vertical. The flow pattern created by the jet was photographed using a Nikon D5000 12 megapixel camera located behind the target. Transparent ruled tape was attached to the dry side of the target to allow distances to be extracted accurately from the photographs.

The tests reported here used local tap water at a temperature of 20 °C ± 2 °C. This water is hard, with composition 122 $mg\,L^{-1}$ as Ca^{2+} and 322 $mg\,L^{-1}$ as $CaCO_3$ (Cambridge Water Company, 2013). The advancing contact angle, β, for water was measured at room temperature using a Krüss DSA 100S drop shape analyser, starting with a 5 μL drop and increasing the volume to 20–50 μL until β was constant. This gave $\beta = 70° \pm 10°$ on the glass and $\beta = 90° \pm 10°$ on the Perspex.

The selection criteria proposed by Stenby et al. (2011) were used to select model fouling layers, namely: opaque when wet (no foaming); cheap; safe to dispose to drain; ease of application with approximately uniform thickness; and lack of cracking or peeling when dry. Blue washable liquid tempera paint (Reeves, UK) on glass was used for these tests. On