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Submitted to

Chemical Engineering Science

© PA, KS, HK, MM, HS, J-PM, TW, JFD and DiW

January 2014

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Abstract

The cleaning action of stationary coherent liquid jets impinging (*a*) vertically downwards on horizontal plates, and (*b*) horizontally on vertical plates, was investigated using three soft-solid model soil layers: (*i*) PVA glue on glass and polymethylmethacrylate (Perspex) substrates; (*ii*) Xanthan gum on stainless steel; and (*iii*) petroleum jelly on glass. The liquid stream nozzle sizes, mass and volumetric flow rates and mean jet velocities investigated were: PVA, 2 mm, 17-50 g s⁻¹ (0.06-0.139 m³ h⁻¹), 5.3-15.9 m s⁻¹; Xanthan gum, 0.39-3.3 mm, 2.1-148 g s⁻¹ (0.008-0.53 m³ h⁻¹); 4.5-31.7 m s⁻¹; petroleum jelly, 2 mm, 7.8-50 g s⁻¹ (0.06-0.139 m³ h⁻¹); 2.5-15.9 m s⁻¹. For all three soils, rapid initial removal of soil from the jet footprint was followed by the growth of a nearly circular, clean region centred at the point of jet impingement. The rate of removal of soil decreased sharply when the cleaning front reached the hydraulic or film jump. The data for the radial growth removal stage were compared with a mathematical model describing removal of the adhesive soil layer, where the force on the cleaning front was evaluated using the result reported by Wilson *et al.* (2011): their theory gave the momentum of the liquid film; this momentum was balanced against the soil strength, giving a simple relation between the cleaned radius and time. All three soils showed reasonable agreement with the model, across the range of flow rates and temperatures studied. The kinetic constant in the model was sensitive to soil layer thickness and the nature of the soil. Cleaning tests on the petroleum jelly soils at different temperatures, and separate rheological measurements, showed that the kinetic time constant for coating removal was proportional to the (critical shear stress)^{-1.8}. There was good agreement between results obtained with vertical and horizontal plates for the PVA and Xanthan gum soil layers. The petroleum jelly results differed, which is partly attributed to differences in preparing the layers of this rheologically complex material.

Keywords: cleaning, hydraulic jump, impinging jet, PVA, petroleum jelly, Xanthan gum

1. Introduction

Liquid jets are widely used in cleaning operations to remove layers of deposited material ('soil') from the internal and external surfaces of process equipment (Jensen, 2011). The jets can be created by fixed or rotating nozzles, or computer-controlled lances. Spray balls also create liquid jets but the primary aim of these devices is to cover the surface with a draining liquid film. The liquid is usually water, but other solvents are also used. The effectiveness of the jets in cleaning depends strongly on the nature of the soil layer to be removed.

Cleaning challenges in the food sector have been discussed by Fryer and Asteriadou (2009). They characterised cleaning chiefly in terms of the type of cleaning fluid (in essence, chemical action) and soil complexity (the soil rheology, ranging from viscous liquids to cohesive materials). Both factors are influenced by the flow, if any, of the cleaning agent, via the rate of heat transfer, mass transfer of species, and hydraulic forces imposed by the flow.

For cleaning by liquid jets, it may be more appropriate to consider cleaning in terms of the mechanisms involved, which often occur in parallel:

- I. *Dissolution*, where the liquid is a solvent for the material in the layer. Flow of liquid promotes convective mass transfer into the solvent, as well as heat transfer.
- II. *Erosion*, where the force imposed on the layer by the impact and flow of the liquid promotes break-up and removal of the layer. Near the point where the jet strikes the surface, here termed the *impingement point*, impact forces and normal stress differences can be important, whilst further from the impingement point the shear stress generated by the moving liquid film is the major factor. Impact forces are limited to the jet footprint, *i.e.* the area subtended by the stream of liquid as it strikes the surface. The removal step can involve both *cohesive* breakdown, where the layer is broken down steadily, and *adhesive* removal, where the layer detaches itself from the substrate and is peeled off. The balance between cohesive or adhesive removal is determined by the nature of the layer ('soil complexity' according to Fryer and Asteriadou) and the substrate.
- III. *Soaking*, where prolonged contact with the solvent promotes changes in the microstructure of an insoluble layer, and/or leaches out soluble components, such that one of the above erosive mechanisms can occur. The importance of soaking is determined by the competition between the timescale for erosion of the original

layer and the time for the liquid to effect a change in the layer: where erosion is slow, soaking is more likely to be important if the solvent penetrates the layer.

Understanding and designing liquid jet cleaning systems therefore requires knowledge of the nature of the material, its response to being wetted by the solvent, and the flow behaviour of the liquid film. Two important cases are shown in Figure 1. When a steady vertical coherent liquid jet impinges downward on a horizontal surface (Figure 1(a)), the liquid flows radially outwards from the point of impingement until a hydraulic jump is formed, where the film depth increases strongly. The flow pattern is symmetric. Knowledge of the location of the hydraulic jump R_h is important as this is the boundary of the radial flow zone (RFZ) where the highest shear stresses are generated, promoting erosion. Beyond the hydraulic jump the shear stress on the wall is relatively low. For a horizontal jet striking a vertical wall, Figure 1(b), 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*.

Beyond the film jump the liquid falls downwards, forming a *rope* around the RFZ in the upper half and a falling film in the lower half. In these regions the deposit layer may undergo cleaning by a combination of the above mechanisms (as the falling liquid film will exert a shear stress on the layer). The shear stresses imposed on the soil in the falling film region are expected to be smaller than those in the RFZ, so the removal rate is likely to be slower and soaking phenomena are expected to be important in this region.

Liquid flow patterns in falling films have been studied for many years, partly due to their importance in evaporators (*e.g.* Nusselt, 1916; Patel and Jordan, 1970). Work on impinging jets has focussed mainly on the formation of *hydraulic jumps* (Figure 1(a)) generated by downward jets impinging on horizontal surfaces. Many workers have built on the early work by Watson (1964) to explain the influence of jet diameter, surface tension *etc.* on the formation and behaviour of these jumps (*e.g.* Liu and Leinhard, 1993). Inclined jets, impinging at non-vertical angles, have also been studied, *e.g.* Blyth and Pozrikidis (2005), Kate *et al.* (2007).

Until recently, there had been relatively little work on jets impinging on vertical walls, as encountered in vessel cleaning. Morison and Thorpe (2002) reported an experimental study of flow patterns generated by water jets from spray ball holes impinging on vertical walls, and presented an empirical correlation relating the size of the film jump region to the liquid flow

rate. Wilson *et al.* (2011) analysed Morison and Thorpe's data sets as well as new experimental data and presented a model which gave reasonable predictions of the size of the radial flow region, *i.e.* the location of the film jump at the mid-plane, R , as

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

where $\dot{m}$ is the mass flow rate, μ is the liquid dynamic viscosity, ρ its density, γ is the gas-liquid surface tension and β the contact angle. An empirical correlation relating the width of the falling film, W , to R was also presented. This model was developed for stationary, coherent jets with flow rates at the low end of the range employed by spray balls and industrial cleaning nozzles. The influence of surface nature, via the static contact angle β , was found to decrease at higher flow rates (Wang *et al.*, 2013a, b).

Wang *et al.* (2013a) extended the model to include effects of nozzle size. They showed that surfactants affected the falling film behaviour and width rather than R . The tendency of the falling film to narrow rather than remain wide depends on the flow rate and this was shown to be reasonably well described by the relationship originally developed by Hartley and Murgatroyd (1964) for evaporator films. Wang *et al.* (2013b) extended the Wilson *et al.* model to inclined jets impinging on vertical walls (where the jet is not horizontal) and the formation of dry patches in the falling film. These results mean that the behaviour of jets impinging on vertical walls can now be predicted with some certainty. This information can then be combined with models of soil behaviour to predict the cleaning performance of the jets and ultimately be used to optimise the cleaning process, as described by Köhler *et al.* (2013).

Yeckel and Middelmann (1987) presented the earliest quantitative study of this coupled flow problem. They considered vertical water jets impinging on horizontal substrates coated with a viscous oil layer (e.g. Figure 1(a)). [In this paper, 'vertical' refers to downward flows: the flow of upward jets striking the underside of a horizontal plate and forming features such as the 'water bell' are rarely used in cleaning and these flows have been studied by Jameson *et al.* (2010).] The oil layer thickness decreased with time as a result of the motion induced by the shear stress imposed on it by the radial outflow of cleaning liquid. This is an example of cohesive erosion, mechanism II, since the liquid phases were immiscible and the oil preferred to wet the substrate. They presented an analytical model which gave good agreement with experimental results. Recently, Fuller and co-workers (Hsu *et al.*, 2011; Walker *et al.*, 2012)

have investigated the cleaning behaviour of non-Newtonian coating layers in similar geometries to that studied by Yeckel and Middelma. The wide range of rheological behaviours exhibited by fouling layers, alluded to by Fryer and Asteriadou, means that this coupled flow problem exhibits a rich phenomenology requiring different approaches, particularly where the soaking step introduces a diffusion-related transition in soil properties.

This paper reports an investigation of the cleaning performance of stationary, coherent water jets impinging (a) downwards on horizontal plates, and (b) horizontally on vertical walls, where in both cases the soil layer is removed by adhesive breakdown, *i.e.* leaving the substrate almost clean. Three stages of cleaning are observed: (i) an initial stage where soil is rapidly removed from the jet footprint region, followed by (ii) steady growth of a circular cleaned region which eventually reaches the hydraulic or film jump, relevant to cases (a) and (b), and (iii) for the horizontal jet impinging on a vertical surface, removal of soil from the rope and draining film regions. An analytical model describing the steady growth stage of cleaning is presented and compared with experimental data obtained for three different soiling layers on different substrates, collected using two different techniques. The model does not consider removal beyond the RFZ, where the liquid flow pattern is complex, or after extended times when soaking may give rise to other removal mechanisms such as erosion of swollen soil.

2. Cleaning model

Consider a stationary, coherent liquid jet of radius r_0 and mean velocity U_0 impinging normal to the surface as shown in Figure 2. Gravitational effects are ignored, so the analysis applies to vertical jets impinging on horizontal surfaces and horizontal jets impinging on vertical walls. The liquid flows radially outwards. Beyond distance r_d (Figure 2(b)) the velocity profile in the liquid film is assumed to be fully developed with a parabolic velocity profile (see Watson, 1964). A hydraulic or film jump is located at distance R_h or R , respectively.

The soil layer is assumed to have a uniform and constant thickness, δ . Changes in the thickness or strength of the layer with time due to soaking, swelling *etc.* are not considered here. Adhesive failure causes the growth of a circular zone free of soil; the zone radius a increases with time. The rate of removal is determined by the force acting on the soil at the soil-substrate-water contact line, which takes the form of a circle of radius a mentioned above.

The force is assumed to be a fraction of the momentum in the liquid film at radius a . The rate is also related to the soil layer thickness, so that the removal rate is given by

$$\frac{da}{dt} = kMf(\delta) \quad [2]$$

where t is time, $f(\delta)$ represents the strength of the soil layer, M is the momentum in the liquid film per unit width at radius a , and k is the cleaning rate constant. The effect of differences in soil layer thickness on $f(\delta)$ is not investigated in this work so a lumped cleaning rate parameter, k' , is employed, giving

$$\frac{da}{dt} = kMf(\delta) = k'M \quad [3]$$

M can be estimated at $r_d < r < R$ (or R_h) from the following result in the Wilson *et al.* (2011) model, using their assumption of a parabolic velocity profile in the liquid film,

$$M = \frac{6}{5} \rho U^2 h \quad [4]$$

where ρ is the liquid density, U is the local mean film velocity and h is the local height of the liquid film. The flow behaviour in the film at $r > R$ is complex, particularly for vertical walls, and cleaning beyond $a \sim R$ is not considered here. The distance r_d is in practice small, of order a few r_o (see Section 4.1). Cleaning in this initial region is fast so the model is unlikely to give a reliable description of the initial cleaning events.

The total mass flow rate, $\dot{m}$, at $r = a$ is given by $\dot{m} = 2\pi ahU\rho$, so that Equation [4] can be written as

$$M = \frac{3\dot{m}}{5\pi} \frac{U}{a} \quad [5]$$

The local mean velocity in the liquid film at $r = a$ is given by (Wilson *et al.*, Eqn (10))

$$\frac{1}{U} = \frac{1}{U_o} + \frac{10\pi^2 \rho \mu}{3\dot{m}^2} (a^3 - r_o^3) \quad [6]$$

This expression also indicates that U decreases as a increases. If U_o^{-1} is small, this gives

$$\frac{1}{U} = \frac{10\pi^2 \rho \mu}{3\dot{m}^2} (a^3 - r_o^3) = \frac{c}{\dot{m}^2} (a^3 - r_o^3) \quad [7]$$

The validity of the assumption that $U_o^{-1} \sim 0$ is discussed by Wang *et al.* (2013a). Combining Equations [3], [5] and [7] gives

$$\frac{da}{dt} = k' \frac{3}{5\pi} \frac{\dot{m}^3}{c} \frac{1}{a(a^3 - r_o^3)} \quad [8]$$

This is integrated from the initial time, t_i , at which a cleared region of radius a_i is first observed to later time t to give

$$\left[\frac{a^5}{5} - r_o^3 \frac{a^2}{2} \right]_{a_i}^a = \frac{3k'}{5\pi c} \dot{m}^3 (t - t_i) \quad [9]$$

We observe in experiments that $a_i > r_o$, suggesting that $a^5 \gg r_o^3 a^2$, so that an approximate form of the result is

$$a \approx \sqrt[5]{\frac{3k'}{\pi c} \dot{m}^3} \times (t - t_i)^{1/5} = K \Delta t^{0.2} \quad [10]$$

Plots of a against $\Delta t^{0.2}$, termed ‘cleaning profiles’ in this paper, should be linear with gradient K . In equations [8-10], the properties of the liquid are captured in the parameter $c = 10\pi^2 \rho \mu / 3 = 38.90 \rho \mu$. The dependency on jet flow rate is captured in $\dot{m}^{0.6}$, while the strength of the layer or the adhesion mechanism is expressed in k' . Equation [3] indicates that k' will depend on the layer thickness: the effect of δ on k' is not investigated in this work and some variation in k' is expected as soil layer thickness could not be controlled precisely in the experiments.

Equation [10] can be compared with the dimensional, empirical result reported by Köhler *et al.* (2013) in their study of the removal of Xanthan gum layers by water jets impinging vertically on a horizontal substrate, *viz.*

$$a \propto r_o^{1.175} P^{0.38} t^{0.212} \quad [11]$$

where P is the gauge pressure in the liquid upstream of the nozzle. For a nozzle with discharge coefficient C_D , defined thus:

$$P = C_D \rho U_o^2 / 2 \quad [12]$$

the mass flow rate through the nozzle is given by

$$\dot{m} = \rho \pi r_o^2 U_o = \rho \pi r_o^2 \sqrt{\frac{2P}{\rho C_D}} = \pi r_o^2 \sqrt{\frac{2\rho P}{C_D}} \quad [13]$$

Substituting this result into Equation [10] gives the form

$$a \propto r_o^{1.2} P^{0.30} t^{0.20} \quad [14]$$

which compares favourably with the empirical result in Equation [11]. In this paper the Köhler *et al.* data sets, and new data sets generated for horizontal jets impinging on vertical walls, are compared with the model.

3. Materials and Methods

Three different soil layers were studied and cleaning was performed on three apparatuses.

3.1. Soils and substrates

Polyvinyl acetate (PVA) layers

Testing with vertical jets and horizontal PVA layers employed 25 cm diameter circular polymethylmethacrylate (Perspex) and float glass plates as substrates. 30 g PVA glue (Asda supermarket) was spread evenly across the surface using a rule and left to dry under ambient conditions for 24 h. The layer mass decreased to approximately 15% of its initial value after this time. Measurements of layer thickness using a Vernier micrometer indicated that the initial, dry layer thickness was approximately $120 \pm 30 \mu\text{m}$ (20 samples). Experiments with the glass plates indicated that these PVA layers were prone to penetration by the water such that blisters formed. The layer detached from the surface (adhesive failure) beneath the blisters but the remainder of the layer remained attached. Tests were therefore confined to PVA layers on Perspex substrates.

Testing with horizontal jets and vertical targets employed rectangular Perspex plates, dimensions 600 mm $\times$ 360 mm $\times$ 5 mm. Glue was spread across the surface with a rule using either (i) insulating tape or (ii) metal scale tape as a shim to control the layer thickness. After drying, the layer thicknesses were (i) $70 \pm 30 \mu\text{m}$ and (ii) $140 \pm 30 \mu\text{m}$. The horizontal and vertical tests were performed several months apart and the ambient temperatures experienced in drying differed by 5 K. The layer properties were expected to differ as a result.

Xanthan gum layers

Model food soil layers were prepared using 0.5 w/v% solutions of Xanthan gum (a natural polysaccharide, Kremer Pigmente GmbH & Co, Germany) containing 3 w/v% crystalline zinc sulphide (Lumilux® Effect Green N-FF, Honeywell, USA) as an optical tracer. The ZnS powder was sieved through an 80 μm sieve, giving a mean particle size of 20 μm . The gum was dissolved in distilled water at 23°C and stirred for 30 min at 600 rpm, before the ZnS powder was added to give a suspension. The AISI 304 steel plates (dimensions 500 $\times$ 500 $\times$ 1 mm, 2B finish) were prepared by cleaning in distilled water followed by absolute ethanol before drying at room temperature. The suspension was sprayed onto the metal sheets held vertical for application. Excess liquid flowed off the plate, leaving a uniform film which was dried at room

temperature for 24 h to give a mass coverage of $13 \pm 1 \text{ g m}^{-2}$. In the absence of ZnS crystals the Xanthan gum dried to a layer thickness of around $10 \text{ }\mu\text{m}$. The ZnS crystals adhered directly to the surface and the maximum layer thickness was therefore around $80 \text{ }\mu\text{m}$, the size of the larger particles.

Petroleum jelly

Layers of petroleum jelly were prepared by spreading petroleum jelly (Trilanco White Petroleum Jelly, Poulton-Le-Fylde, UK) at room temperature across the float glass or Perspex substrates using a rule travelling across $245 \text{ }\mu\text{m}$ thick metal spacers. This gave a rough layer of hydrophobic material which did not dissolve on contact with water. The thickness of the layers on the vertical plates was approximately $250 \text{ }\mu\text{m} \pm 30 \text{ }\mu\text{m}$. It proved more difficult to prepare the layers on the 25 cm diameter circular discs used in the tests with vertical jets and the average thickness was approximately $300 \text{ }\mu\text{m} \pm 30 \text{ }\mu\text{m}$.

The rheology of the petroleum jelly was studied separately using a Bohlin CV120 controlled stress rheometer fitted with 40 mm sandpaper-roughened parallel plates with a gap height of 0.7 mm . The steady shear viscosity was investigated in a series of shear stress sweeps from 20 - 1000 Pa and back, at temperatures of 20 - 60°C . Oscillatory tests were performed with the same tools, increasing the shear strain amplitude to 100% at a frequency of 1 Hz .

The thickness of the different soil layers and the temperatures at which cleaning was studied are summarised in Table 1.

3.2 Cleaning apparatuses

PVA and petroleum jelly layers

The majority of these tests were performed using the apparatus shown in Figure 3. The target plate is held above a collection basin which returns liquid to the 50 L holding tank. A thermostat can be used to control the liquid temperature. Tests on PVA layers were performed at 20°C , while tests with petroleum jelly were performed at 20°C , 24°C , 40°C or 60°C .

Liquid is pumped from the tank through one of two control valve and rotameter spurs into a 40 cm long straightening section (internal diameter 4 mm) before discharge through the nozzle which gave a solid stream, *i.e.* no droplets. The nozzle was located approximately 80 mm from

the test plate. The flow rates ranged from $0.25\text{--}3\text{ L min}^{-1}$ ($0.015\text{--}0.18\text{ m}^3\text{ h}^{-1}$; $4.2\text{--}50\text{ g s}^{-1}$) and $3\text{--}10\text{ L min}^{-1}$ ($0.18\text{--}0.6\text{ m}^3\text{ h}^{-1}$; $50\text{--}167\text{ g s}^{-1}$), corresponding to jet Reynolds numbers (defined as $Re_{\text{jet}} = \rho U_0 d_N / \mu$) of $2700\text{--}108,500$. Watson (1964) reported a jet Reynolds number of 8185 for transition to turbulent behaviour. The nozzle used in these tests was fabricated from 304 stainless steel with internal angle of convergence 45° and throat diameter $d_N = 2\text{ mm}$. A pressure gauge was located on the straight section upstream of the nozzle. The discharge coefficient of the nozzle, C_D , was 0.93 ± 0.03 .

Cleaning experiments employing vertical jets were performed in the apparatus described by Wang *et al.* (2013b). This apparatus was designed for higher flow rates and differs from that in Figure 3 by the nozzle being located inside a waterproof cabinet with Perspex walls. The coated plate was mounted on a table and subjected to a vertical jet of tap water from a second solid stream nozzle of diameter, $d_N = 2\text{ mm}$, located approximately 80 mm above the plate. These vertical tests were performed with water at 20°C over the flow rate range $7.8\text{--}50\text{ g s}^{-1}$, corresponding to jet Reynolds numbers of $5,000\text{--}32,500$.

The size of the cleaned region in each case was monitored by a Nikon 12 megapixel digital camera mounted behind the vertical target plate or a GoPro Hero 3 Black Edition video camera located beneath the horizontal plate. The dry PVA layers were colourless but turned opaque shortly after contact with water. The layers were illuminated using oblique lighting to enhance the contrast on the photographs. The dimensions of the cleaned region were extracted manually.

Xanthan gum

The plates were cleaned using the jet system shown schematically in Figure 4. A detailed description is given in Köhler *et al.* (2013). The test plate was located in the horizontal or vertical plane and subjected to the flow of a coherent stationary jet created by a solid stream nozzle of circular cross section (Type 544, Lechler GmbH, $d_N = 0.39, 0.84, 1.69, 2.66$ and 3.30 mm). The distance from the nozzle exit to the plate was normally 100 mm. Some of the tests with the horizontal jet employed a separation varying from 50–150 mm, as described in Köhler *et al.* (2013). Tests normally lasted 10 min.

The jet and sheet were located within a light-tight enclosure and illuminated by two UV lamps. Under UV illumination the ZnS luminesces and the distribution of tracer was captured by a

CCD camera (Matrix Vision GmbH, mvBlueCOUGAR-X125aG, 5 Mpixel gray-sensor, 14 bit). Detailed descriptions of these luminescence techniques for cleaning studies are given in Mauermann (2012) and Schöler *et al.* (2009).

Each image was analysed by a Matlab® script. Cleaned areas appear dark, as shown in Figure 5(a). A radial band of length 240 mm and width 5.5 mm (1780×40 pixels) was identified and the intensity values at each radial pixel location (0.14 mm/pixel) analysed to give the mean and standard deviation at that value of r . These values were then divided by the measured mean dry intensity at that radial location to give the normalised intensity, as shown in Figure 5(b). The cleaned region exhibits a low intensity. There is a steep increase in intensity in Figure 5(b) at $r \sim 45$ mm and a plateau region with normalised intensity ~ 1 at larger r . Similar steps in the intensity profiles were observed at other times, confirming that cleaning involves a moving front, as postulated in the model. The co-ordinate of the cleaned radius was assigned to the point where the normalised intensity reaches 0.25, *i.e.* at $r = 44.6$ mm in Figure 5(b). This threshold level was determined by inspection of 9 cleaning tests, comparing both manual and automated analysis methods. At high r values, the intensity can exceed 1 due to reflection and accumulation of soil debris.

4 Results and Discussion

4.1 Flow behaviour

The size of the radial impingement zone depends on the flow rate and Figure 6 compares the location of the film and hydraulic jump on clean glass and Perspex plates. The data are plotted in dimensionless form, where $x^* = x/r_o$. For the horizontal jet impinging on a vertical surface, both the radius of the film jump at the mid-plane, R , and the height above the impingement point, Z , increase with mass flow rate and are insensitive to the nature of the substrate. Figure 6 shows that Equation [1] gives a reasonable estimate of R when a contact angle of $\pi/2$ is used, as reported by Wang *et al.* (2013b). The Z values lie consistently below the corresponding R values, which Wang *et al.* showed to be due to gravity. The agreement at higher flow rates is poorer, which is due to splattering reducing the flow rate of liquid in the film.

A circular hydraulic jump is formed on the horizontal plates; its location, R_h , differs noticeably between Perspex and glass. The glass is more strongly wetting than the Perspex (measured static

contact angles of 39° and 70° , respectively), but the fluid mechanics for the hydraulic jump are quite different from the fluid mechanics regulating the film jump. The hydraulic jump radius is determined by the flow conditions downstream of the jump: for example, if there was a vertical rim at the edge of the circular plate, R_h , would be reduced. It appears somewhat fortuitous that the measured values of R_h in Figure 6 are approximately predicted by Equation [1].

R_h , R and Z can be compared with r_d , the radial distance at which the velocity profile in the film is expected to be fully developed. The r_d values for these tests lie in the range 5-6 mm, which is small compared to R_h , R and Z in Figure 6 ($r_d/r_o = 2.5-3$) and also the size of the cleaned area in subsequent Figures. It follows that the majority of the removal process within the RFZ involves a fully developed velocity profile in the liquid film.

4.2 Cleaning of PVA layers

Figure 7(a) shows a photograph of a PVA layer ($\delta = 150 \mu\text{m}$) on a vertical Perspex plate during cleaning by a horizontal jet. The shape of the wetted area resembles Figure 1(b,i) and there is evidence of considerable splattering of water beyond the rope region. Some of this splattering is caused by interaction with the soil layer at the cleaning front. Splattering was even more marked on the petroleum jelly layers, as shown in Figure 7(b), where the hydrophobicity of the soil promoted droplet formation. The shape of the cleaned region in Figure 7(a) is not as circular as in Figure 7(b): many other PVA tests gave considerably more circular cleaned regions and this image is reported to illustrate the degree of variation observed.

Sets of typical cleaning results observed with the thinner PVA layers on a vertical plate with a 2 mm diameter nozzle are presented in Figure 8(a). No removal is observed initially. A cleared region then appears: the time taken for breakthrough to the plate decreases with increasing flow rate. The cleared region grows steadily, at a falling rate, and after some time a can approach a plateau value which lies beyond the edge of the radial flow zone, R . The initial rate of removal and the final plateau value increase with flow rate. Where plateau behaviour was observed, this always lay within the rope region (see Figure 1(b))

Figure 8(b) shows good agreement between these data sets and the model (Equation 10). The time interval $\Delta t = t - t_i$ is taken from the time t_i at which a cleared zone was first observed, as the model does not describe the initial stage where the material is eroded near the impingement

point. Figures 8(b) and (c) show that the lines representing Equation [10] fit the data reasonably well. From the intercepts at $a = 0$, Figure 8 (b), t_i is in the range 1 – 8 s, a small proportion of the total time of erosion, 10 – 160 s. The intercepts at $a = 0$ in Fig. 8(c) show values of t_i less than 1 s. The fit between the data in Figures 8(b) & 8(c) and the lines representing Equation [10] show that the model, based on ‘rolling back’ the adhesive film, fits the data quite well. It is also evident that the rate of cleaning, for a given water flow rate, is slower in Figure 8(c) than in Figure 8(b) because of the thicker film for Figure 8(c). Similar trends were observed with vertical jets impinging on horizontal plates, where the dry film thickness was approximately 120 μm (data not reported).

The cleaning rate parameter k' can be obtained from the gradient, K , of the fitted trend lines. Equation [10] indicates that K should be proportional to $k'^{0.2} \times \dot{m}^{0.6}$. The K values obtained from the three series of tests are plotted against $\dot{m}^{0.6}$ in Figure 9. The data obtained with the horizontal jet and thicker PVA layers ($\delta = 140 \mu\text{m}$) are very similar to those obtained with the vertical jet and layers of similar thickness ($\delta = 120 \mu\text{m}$), while the values for the thinner PVA layer are noticeably larger. All three data sets exhibit the linearly proportional trend predicted by the model. The calculated k' values, obtained from the data in Figure 9, were (i) $\delta = 120 \mu\text{m}$, $k' = 4.5 \times 10^{-4} \text{ s m kg}^{-1}$; (ii) $\delta = 140 \mu\text{m}$, $k' = 1.0 \times 10^{-4} \text{ s m kg}^{-1}$; and (iii) $\delta = 70 \mu\text{m}$, $k' = 0.21 \text{ s m kg}^{-1}$. These values are compared with other soils in section 4.3.

Layer thickness has an evident effect on the rate of cleaning. The above soil layer thicknesses are comparable with the estimated liquid film thickness at r_d but the majority of the cleaning measurements are made at larger r , where the liquid film is deeper. The rheology of the layer is expected to be affected by the layer thickness as a result in differences during preparation such as drying, *etc.* A systematic investigation of layer thickness is required to elucidate the factors determining k' .

4.3 Xanthan gum layers

The data sets for vertical jets impinging on a horizontal plate reported by Köhler *et al.* (2013) were augmented by six further tests featuring a horizontal jet impinging on a vertical plate. The measurements of the hydraulic jump radius, R_h , in the former tests reported by Köhler *et al.* are compared with the predicted film jump radius from Equation [1] in Figure 10. Equation [1] again gave a reasonable estimate of the location of the hydraulic jump on the clean surfaces

when an effective contact angle of 90° is used for β . The static contact angle of 98° measured for soiled stainless steel plates gives less good agreement.

The stages in cleaning observed with a horizontal jet impinging on a vertical plate are illustrated by the photographs in Figure 11. Over the first 67 s, removal occurs in the radial flow zone and there is little change in luminescence in other regions. After 120 s (Figure 11(d)), the radial cleaning front has reached the film jump. There is a noticeable dark patch under the path of the rope, which is the fast moving band of liquid that falls down around the film jump and continues as a band at each edge of the falling film. By 170 s the rope region is clean and there is noticeable removal (darkening) in the rest of the falling film region. Removal is evident over the entire region wetted by the jet after 222 s. The change in behaviour after 60 s suggests that there is a weakening of the Xanthan gum layer after this time, so that the shear stresses or momentum generated by the rope and the falling film are sufficient to dislodge the material. The rheology of the layer is therefore changing and the cleaning model in its current form does not incorporate this behaviour. The Xanthan gum layer is not a model soil in terms of constant rheology, but it does reproduce the weakening behaviour observed with many real soils. Including soaking and weakening effects in the cleaning model requires further, detailed investigation.

The cleaning profiles for a series of horizontal jet tests are plotted in Figure 12. Elapsed time is used instead of $t-t_i$ because t_i was short and often lay between photographs. Open symbols are used where a was less than the estimated value of R measured in the absence of soil. The plots are quite linear in the interval of 5-90 s ($1.4 \text{ s}^{0.2} < t^{0.2} < 2.5 \text{ s}^{0.2}$), indicating that the model gave a reasonable description of the cleaning process. Non-linear behaviour is evident at longer times, and particularly for filled symbols when $a > R$. One of the reasons for this is that a is measured at the mid-plane of the jet, and removal by the rope flow in this region becomes important at longer times. This is more noticeable at the higher flow rates (larger d_N) as the flow rate in the rope is larger.

The gradients of the cleaning profiles for both horizontal and vertical jets were calculated from data for which $a < R$. Figure 13 summarises the results in the same form as Figure 9, and a linearly proportional relationship is again evident. The range of flow rates employed in the Xanthan gum tests is larger than that used in the PVA tests, and the K values are of similar

magnitude to the thinner PVA layers. The line of best fit, shown in Figure 13, gave a k' value of $2 \times 10^{-3} \text{ s m kg}^{-1}$, which lies between the values obtained for the different PVA layer thicknesses.

4.4 Petroleum jelly

The petroleum jelly layers are hydrophobic (see Figure 7(b)) and their properties are not expected to change over time. For tests using water at elevated temperature, there is an initial period for the layer to reach the temperature of the jet. The length of this warming period can be estimated by a transient heat transfer calculation, assuming that heat loss through the substrate is negligible, and external heat transfer is rapid. Assuming that the length of the warming period can be described by a Fourier number of 2 (from transient conduction through a symmetrical slab) gives an estimated heating time of $2h^2/\alpha$, where α is the thermal diffusivity. Taking $\alpha = 10^{-7} \text{ m}^2 \text{ s}^{-1}$ gives a heating time for a 250 μm thick soil layer of 1.3 s, which is negligible given the duration of these cleaning tests.

The effect of temperature on the rheology of the petroleum jelly is summarised in Figure 14. Both the apparent viscosity from steady state testing, and the viscous (G') and elastic (G'') moduli obtained from oscillatory testing, decrease strongly with increasing temperature. The steady state shear results in Figure 14(a) are plotted against shear stress rather than shear rate to highlight that the material is very strongly shear thinning above a critical shear stress which decreases at increasing temperature. Similar behaviour was reported for Vaseline™ (a formulated petroleum jelly) by Chang *et al.* (2003). The oscillatory test results in Figure 14(b) exhibit a transition from a gel state at lower shear stresses (where $G' \sim G''$) to viscous behaviour ($G'' > G'$) at higher shear stresses. The shear stress at which G' and G'' cross over, or G' decreases strongly, was taken as the critical shear stress, τ_c , at which the material weakened. The τ_c dependency on temperature fitted the Andrade equation, *viz.*

$$\ln \tau_c / \text{Pa} = \frac{11896}{T} - 35.697 \quad R^2 = 1.0 \quad [15]$$

where T is the absolute temperature and R^2 the correlation coefficient. These values are compared with the cleaning rate constant later.

The cleaning profiles obtained at 20°C in Figure 15 show that the petroleum jelly deviated from the behaviour described by the model at larger values of a . The profiles are initially linear ($a \propto \Delta t^{0.2}$) but the rate decreases as more material is removed. Photographs showed that rather than being removed completely, the material tended to accumulate at the cleaning front increasing the effective thickness; this effect became more noticeable with time. In some cases (*e.g.* Figure 15, 3 kg min⁻¹ on Perspex; Figure 7(b)) a reached an asymptote when a berm of removed material deflected the flowing liquid film away from the surface. The removal process with this soil is therefore more complex than with PVA and Xanthan gum layers. The profiles for the horizontal jets show reasonably good reproducibility given the variability in layer thickness. There is a noticeable difference between the behaviour on Perspex compared to glass, and the influence of surface energy between the two substrates was not investigated further here.

Figure 16 shows that the cleaning rate increased with temperature. This is expected from the model as the momentum at fixed mass flow rate is insensitive to temperature (see Equation [5]) whereas the rheological tests (Equation [15]) indicated that the material softens considerably with increasing temperature. If removal was determined by the shear stress imposed by the flowing liquid film on the soil layer, as in Yeckel and Middelmann's model for removal of a viscous oil, the effect of temperature on the rate of cleaning would be determined by the ratio of water viscosity to oil/soil viscosity. The cleaning profiles all exhibit a linear region followed by a falling rate, with a sharp transition between the two at higher temperature.

The gradients of the initial, linear part of the cleaning profiles were calculated and are plotted in Figure 17 for comparison with the model (*cf.* Figure 9, Figure 13). There is reasonable agreement with the model at 40°C and 60°C, where the layer is primarily viscous, and poorer agreement at 20°C (*i.e.* the lines of best fit give a non-zero intercept). The critical shear stress obtained in the rheometry tests at the latter temperature is 130 Pa, which is large compared to the shear stress exerted by the film flow (data not reported), and the deformation of this soft solid is unlikely to be described well by the current, simple model. Fuller and co-workers (Hsu *et al.*, 2011; Walker *et al.*, 2012) have reported a range of complex liquid-soil behaviours for non-Newtonian soft solid layers contacted by vertical water jets in a similar configuration to the vertical jet tests in this study.

Another difference from the PVA and Xanthan gum results is that the K values obtained for vertical jets differ noticeably from those for horizontal jets. This is related to the soil layers proved harder to prepare and were less uniform, with average thicknesses around 300 μm .

The plot of K values in Figure 17 yields an estimate of k' at each temperature. These are reported in Table 1 alongside the values obtained for the PVA and Xanthan gum layers. k' decreases strongly with temperature, which is discussed below. There are evident differences between the three soils at the common test temperature of 20°C: the petroleum jelly value of $6.7 \times 10^{-6} \text{ s m kg}^{-1}$ is an order of magnitude smaller than the value obtained for the 140 μm thick PVA layers and two orders of magnitude smaller than the value for the 80 μm thick Xanthan gum layers. Soil layer thickness as well as soil rheology determine k' , and separating the contribution from the layer rheology and thickness requires further experimentation, employing materials that allow uniform coatings to be generated with known rheology over a range of layer thicknesses. The model presented here (Equations [9] and [10]) provides a useful framework for interpreting and comparing the results from such studies.

Figure 18 shows that the effect of temperature on the cleaning rate constant, k' , can be related directly to the effect of temperature on the critical shear stress, τ_c . At higher temperature, the material is less strong and is removed more rapidly. Any physically-based model for the soil strength factor in Equation [2], $f(\delta)$, should incorporate this result.

4.5 'Completing the circle'

This work on the flow and cleaning behaviour of impinging jets was inspired by the short paper on this topic by Morison and Thorpe (2002). They included a series of photographs of paint layers being cleaned by a water jet created by an industrial spray ball hole. Professor Morison kindly provided us with the original images from their paper and two measures were extracted: the radius of the cleaned zone on one side of the impingement point at the mid-plane (labelled a here), and the width of the cleaned zone (labelled b). The data obtained for $t < 180 \text{ s}$ are plotted in Figure 19 and follow the trend expected from the model for $a < R$ ($b < 2R$). All the paint was cleaned off the wetted region over time, indicating the existence of a soaking and weakening step which was observed in the Xanthan gum experiments and is not considered by the model presented here.

Conclusions

The removal of thin model soil layers by stationary liquid jets impinging on vertical and horizontal surfaces at flow rates at the low end of those used in industrial cleaning operations was investigated experimentally using water jets and two different imaging techniques. The removal of PVA and petroleum jelly layers from transparent glass and Perspex substrates was monitored by tracking the growth of the cleaned area by a camera located behind the substrate, while the removal of Xanthan gum layers from stainless steel sheets was monitored by quantifying the luminescence emitted by tracer particles in the gum.

The same cleaning pattern was observed with both techniques, namely rapid removal of material in the jet footprint, followed by the growth of a circular or near-circular cleared region until it reached the film jump or hydraulic jump feature associated with a transition in the liquid flow behaviour. After this point the removal behaviour depended on the nature of the soil. The PVA and Xanthan gum absorbed water and became weaker over time, so that the cleaned region extended beyond the film or hydraulic jump, while removal of the hydrophobic petroleum jelly could halt before the jump was reached owing to the force of the liquid film being insufficient to detach the soil layer.

A model describing the growth of the circular cleared region is presented based on the detachment of the soil by the force imposed by the flowing liquid film. Experimental data obtained using all three soil materials showed good agreement with the model, both for vertical jets impinging on horizontal surfaces and horizontal jets impinging on vertical surfaces. The kinetic parameter in the model was found to depend on the thickness and the nature of the soil layer. Experiments with petroleum jelly performed at different temperatures yielded a strong correlation between the kinetic parameter and the independently measured values of the critical stress for this material. The model explained the trends in the results presented by Köhler *et al.* (2013) for a large number of nozzles and flow conditions. These observations provide a basis for quantitative prediction of the efficiency of jet cleaning operations and optimisation of cleaning-in-place operations for tank internals, walls and other jetting applications.

Acknowledgements

Lee Pratt constructed the experimental apparatus. Dr Maria Dolores Torres Perez performed the rheological testing on petroleum jelly. We are grateful to Professor Ken Morison for providing us with the experimental data in Section 4.5. The work at TU Dresden was funded by the European Union and the Free State of Saxony as part of project SAB 080951793.

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Nomenclature

Roman

a	radial location of cleaning front	m
a_i	radial location of cleaning front breakthrough	m
c	lumped parameter, Equation [7]	$\text{kg}^2 \text{m}^{-4} \text{s}^{-1}$
C_D	nozzle discharge coefficient	-
d_N	nozzle throat diameter	m
G'	viscous moduli	Pa s
G''	elastic moduli	Pa s
h	thickness of film	m
k	cleaning rate constant, Equation [2]	not defined
k'	lumped cleaning rate constant	m s kg^{-1}
K	gradient of cleaning profile plots	$\text{m s}^{-0.2}$
M	momentum flux per unit width	kg s^{-2}
$\dot{m}$	mass flow rate	kg s^{-1}
P	gauge pressure	Pa
R^2	correlation coefficient	-
r	radial co-ordinate	m
r_d	radius at which film velocity profile is fully developed	m
r_o	jet radius	m
R	radius of film jump at mid-plane	m
R_h	radius of hydraulic jump	m
Re_{jet}	jet Reynolds number, defined $Re_{\text{jet}} = \rho U_o r_o / \mu$	-
T	temperature	K
t	time	s
Δt	total time after cleaning front is first seen, $= t - t_i$	s
t_i	time at which cleaning front is first seen	s
U	mean velocity in film	m s^{-1}
U_o	jet and initial film mean velocity	m s^{-1}
W	draining film width	m
x^*	dimensionless length scale, $x^* = x/r_o$	-
x	hydraulic/film jump radius	-
Z	height of inner radial zone above the point of impingement	m

Greek

α	thermal diffusivity	$\text{m}^2 \text{s}^{-1}$
β	contact angle	$^\circ$
δ	thickness of layer	m
γ	surface tension (liquid/vapour)	N m^{-1}
μ	dynamic viscosity	Pa s
ρ	density	kg m^{-3}
τ_c	critical shear stress	Pa

Tables

Table 1: Summary of cleaning parameters

Layer material	δ μm	T $^{\circ}\text{C}$	k' s m kg^{-1}	Jet orientation
PVA	70 ± 30	20 ± 1	0.21	Horizontal
	140 ± 30	20 ± 1	1.0×10^{-4}	Horizontal
	120 ± 30	20 ± 1	4.5×10^{-4}	Vertical
Xanthan gum	$< 80 \mu\text{m}$	20 ± 1	2×10^{-3}	Horizontal
	$< 80 \mu\text{m}$	17 ± 4	2×10^{-3}	Vertical
Petroleum jelly	250 ± 30	20 ± 1	6.7×10^{-6}	Horizontal
	250 ± 30	24 ± 1	1.5×10^{-5}	Horizontal
	250 ± 30	30 ± 1	5.7×10^{-5}	Horizontal
	250 ± 30	40 ± 1	6.3×10^{-4}	Horizontal
	250 ± 30	60 ± 1	3.3×10^{-3}	Horizontal
	300 ± 40	20 ± 1	1.4×10^{-7}	Vertical

Figure captions

Figure 1 (i) Schematics and (ii) photographs of flow patterns created by coherent liquid jets impinging (a) vertically downwards on a horizontal plate, giving rise to a hydraulic jump of radius R_h , and (b) horizontally on a vertical plate, generating a film jump of radius R at the mid-plane and height Z , the rope, and falling film of width W . Below the mid-plane the film jump may not be evident. Dashed line indicates location of jump, grey lines flow path.

Figure 2 Schematic of impinging jet cleaning by adhesive removal: (a) elevation and (b) plan view for a vertical jet impinging on a horizontal surface. O is the point of impingement. The cleaning front is at radial location a ; r_d is where the velocity profile in the liquid film becomes fully developed, and R_h is the location of the hydraulic jump.

Figure 3 Apparatus used for PVA and some petroleum jelly tests. (a) schematic, (b) photograph. P – pressure gauge; F – flowmeter.

Figure 4 Schematic for apparatus for monitoring cleaning by luminescence method.

Figure 5 Example of data analysis for luminescent method for monitoring Xanthan gum cleaning. $\dot{m} = 38.8 \text{ g s}^{-1}$, $t = 200 \text{ s}$. (a) truncated image showing radial band (contrast adjusted manually for better visualization); (b) normalized intensity plot for the radial band in (a): error bars indicate $\pm$ one standard variation.

Figure 6 Effect of mass flow rate on size of (dimensionless) hydraulic jump, R_h^* , film jump, R^* , and height of impinging zone, Z^* . Water at 20°C, 4 mm nozzle. Solid symbols – Perspex; open symbols – glass. The hydraulic jump experiments employed a circular plate of diameter 25 cm.

Figure 7 Photographs of cleaning of (a) PVA layer on Perspex ($\delta = 150 \text{ }\mu\text{m}$), end view; (b) petroleum jelly on glass ($\delta = 250 \text{ }\mu\text{m}$), side view. Horizontal jet impinging on vertical plate, 20 °C.

Figure 8 Cleaning of PVA layers on vertical Perspex plates using horizontal water jets from a 2 mm diameter nozzle at 20°C. (a) Evolution of cleaned region width (at mid-plane), for 70 μm (dry thickness) layer; the horizontal lines indicate the radius of the film jump at the respective flow rate on a clean Perspex surface. (b) Data in (a) plotted in the form of Equation [10], where $\Delta t = t - t_i$ and t_i is the estimated breakthrough time; (c) results for 140 μm (dry) layer.

Figure 9 Effect of mass flow rate on gradient of PVA cleaning profiles in Figure 8. Open symbols - vertical plate ($\delta = 120 \text{ }\mu\text{m}$), V in legend, solid symbols – horizontal plate ($\delta = 70$ or 140 μm), H in legend. Loci show lines of best fit to the model trend (Equation [10]).

Figure 10 Comparison of hydraulic jump radius (vertical jet on horizontal, clean plate) measured on the apparatus used for Xanthan gum cleaning (Figure 4) with values predicted by Equation [1] with (i) solid line, $\beta = 90^\circ$; (ii) dashed line, $\beta = 98^\circ$: all nozzle sizes.

Figure 11 Progress of cleaning of Xanthan gum layer on a vertical plate by a horizontal water jet. $d_N = 2.66 \text{ mm}$, $\dot{m} = 4.7 \text{ L/min}$ (78.3 g s^{-1} , $U_o = 14.2 \text{ m s}^{-1}$).

Figure 12 Growth of cleaning front with Xanthan gum layers for horizontal jet and vertical surfaces. The front radius a was measured at the mid-plane of the jet. Data presented in the form of Equation [10] with t the time elapsed since cleaning started. Open symbols denote where a is smaller than R , the location of the film jump in the absence of the layer. Filled symbols are for $a > R$. The legend indicates the nozzle size and gauge pressure upstream of the nozzle. The grey symbols correspond to the test photographed in Figure 11.

Figure 13 Effect of mass flow rate on cleaning profile gradient, K , for Xanthan gum layers. Solid symbols, horizontal jet; open symbols, vertical jet. Dashed line shows line of best fit.

Figure 14 Rheological characterisation of petroleum jelly. (a) steady flow curve, with shear stress as the manipulated variable; (b) oscillatory testing, 1 Hz; open symbols – G' , solid symbols – G'' .

Figure 15 Effect of mass flow rate on cleaning profiles for petroleum jelly at 20°C. Horizontal jet impinging on vertical substrates, $\delta = 250 \mu\text{m}$. Legend labels a,b refer to repeat experiments; G – glass; P – Perspex.

Figure 16 Effect of temperature on petroleum jelly cleaning. Horizontal jets impinging on vertical glass plates at 33.3 g s^{-1} (or 2 L min^{-1}), $\delta = 250 \mu\text{m}$.

Figure 17 Effect of temperature on gradient of petroleum jelly cleaning profiles. Horizontal jet, vertical glass substrate unless otherwise noted. Soil layer thickness: horizontal plate, $\delta = 250 \mu\text{m}$; vertical plate $\delta = 300 \mu\text{m}$.

Figure 18 Effect of critical shear stress on cleaning rate constant for $250 \mu\text{m}$ thick petroleum jelly layers. Horizontal water jets impinging on vertical glass surfaces. Locus shows trend line obtained by linear regression, $k' = 0.0336 \tau_c^{-1.7}$.

Figure 19 Analysis of cleaning of paint from an acrylic sheet reported by Morison and Thorpe (2002). The horizontal water jet was generated by a $d_N = 1.6 \text{ mm}$ hole in a 50 mm diameter industrial spray ball operating at 1.3 barg. $\dot{m} = 18 \text{ g s}^{-1}$, 20°C. Solid symbols indicate that the cleaned region lies within the radial flow zone. Dimension b is the total width of the cleaned zone; a is the width to the right of the impingement point as the cleaned region was not symmetric.

Figure 1 (i) Schematics and (ii) photographs of flow patterns created by coherent liquid jets impinging (a) vertically downwards on a horizontal plate, giving rise to a hydraulic jump of radius R_h , and (b) horizontally on a vertical plate, generating a film jump of radius R at the mid-plane and height Z , the rope, and falling film of width W . Below the mid-plane the film jump may not be evident. Dashed line indicates location of jump, grey lines flow path.

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(a)

(b)

Figure 7 Photographs of cleaning of (a) PVA layer on Perspex ($\delta = 150 \mu\text{m}$), end view; (b) petroleum jelly on glass ($\delta = 250 \mu\text{m}$), side view. Horizontal jet impinging on vertical plate, 20°C .

(a)

(b)

Figure 8 Cleaning of PVA layers on vertical Perspex plates using horizontal water jets from a 2 mm diameter nozzle at 20°C. (a) Evolution of cleaned region width (at mid-plane), for 70 μm (dry thickness) layer; the horizontal lines indicate the radius of the film jump at the respective flow rate on a clean Perspex surface. (b) Data in (a) plotted in the form of Equation [10], where $\Delta t = t - t_i$ and t_i is the estimated breakthrough time; (c) results for 140 μm (dry) layer.

(c)

Figure 8 Cleaning of PVA layers on vertical Perspex plates using horizontal water jets from a 2 mm diameter nozzle at 20°C. (a) Evolution of cleaned region width (at mid-plane), for 70 μm (dry thickness) layer; the horizontal lines indicate the radius of the film jump at the respective flow rate on a clean Perspex surface. (b) Data in (a) plotted in the form of Equation [10], where $\Delta t = t - t_i$ and t_i is the estimated breakthrough time; (c) results for 140 μm (dry) layer.

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Figure 10 Comparison of hydraulic jump radius (vertical jet on horizontal, clean plate) measured on the apparatus used for Xanthan gum cleaning (Figure 4) with values predicted by Equation [1] with (i) solid line, $\beta = 90^\circ$; (ii) dashed line, $\beta = 98^\circ$: all nozzle sizes.

(a) 5 s

(b) 25 s

(c) 67 s

(d) 120 s

(e) 170 s

(f) 222 s

Figure 11 Progress of cleaning of Xanthan gum layer on a vertical plate by a horizontal water jet. $d_N = 2.66$ mm, $\dot{m} = 4.7$ L/min (78.3 g s⁻¹, $U_o = 14.2$ m s⁻¹).

Figure 12 Growth of cleaning front with Xanthan gum layers for horizontal jet and vertical surfaces. The front radius a was measured at the mid-plane of the jet. Data presented in the form of Equation [10] with t the time elapsed since cleaning started. Open symbols denote where a is smaller than R , the location of the film jump in the absence of the layer. Filled symbols are for $a > R$. The legend indicates the nozzle size and gauge pressure upstream of the nozzle. The grey symbols correspond to the test photographed in Figure 11.

Figure 13 Effect of mass flow rate on cleaning profile gradient, K , for Xanthan gum layers. Solid symbols, horizontal jet; open symbols, vertical jet. Dashed line shows line of best fit.

(a)

(b)

Figure 14 Rheological characterisation of petroleum jelly. (a) steady flow curve, with shear stress as the manipulated variable; (b) oscillatory testing, 1 Hz; open symbols – G' , solid symbols - G'' .

Figure 15 Effect of mass flow rate on cleaning profiles for petroleum jelly at 20°C. Horizontal jet impinging on vertical substrates, $\delta = 250 \mu\text{m}$. Legend labels a,b refer to repeat experiments; G – glass; P – Perspex.

Figure 16 Effect of temperature on petroleum jelly cleaning. Horizontal jets impinging on vertical glass plates at 33.3 g s^{-1} (or 2 L min^{-1}), $\delta = 250 \text{ }\mu\text{m}$.

Figure 17 Effect of temperature on gradient of petroleum jelly cleaning profiles. Horizontal jet, vertical glass substrate unless otherwise noted. Soil layer thickness: horizontal plate, $\delta = 250 \mu\text{m}$; vertical plate $\delta = 300 \mu\text{m}$.

Figure 18 Effect of critical shear stress on cleaning rate constant for 250 μm thick petroleum jelly layers. Horizontal water jets impinging on vertical glass surfaces. Locus shows trend line obtained by linear regression, $k' = 0.0336\tau_c^{-1.7}$.

Figure 19 Analysis of cleaning of paint from an acrylic sheet reported by Morison and Thorpe (2002). The horizontal water jet was generated by a $d_N = 1.6$ mm hole in a 50 mm diameter industrial spray ball operating at 1.3 barg. $\dot{m} = 18 \text{ g s}^{-1}$, 20°C . Solid symbols indicate that the cleaned region lies within the radial flow zone. Dimension b is the total width of the cleaned zone; a is the width to the right of the impingement point as the cleaned region was not symmetric.