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Cleaning of soft-solid soil layers on vertical and horizontal surfaces by stationary coherent impinging liquid jets

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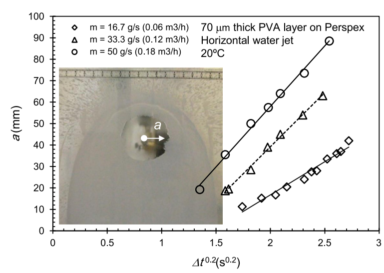
HIGHLIGHTS

- Removal of PVA and petroleum jelly from glass and Perspex monitored by photography.
- Removal of Xanthan gum from stainless steel monitored by luminescence method.
- All soils exhibit growth of circular region as liquid film detaches soil layer from substrate.
- Quantitative model gives good agreement with experimental data for all three soils.
- Lumped cleaning kinetic parameter depends on soil layer thickness and rheology.

GRAPHICAL ABSTRACT



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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 m^3 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 m^3 h^{-1}); 4.5–31.7 m s^{-1}; petroleum jelly, 2 mm, 7.8–50 g s^{-1} (0.06–0.139 m^3 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. (2012): 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

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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.

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:

(1) *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.
(2) *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 (2009)) and the substrate.
(3) *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 Fig. 1. When a steady vertical coherent liquid jet impinges downward on a horizontal surface (Fig. 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, Fig. 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* (Fig. 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 Lienhard, 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. (2012) 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, 2013b).

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