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Cleaning of complex soil layers on vertical walls by fixed and moving impinging liquid jets

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ABSTRACT

Cleaning by a horizontal water jet, impinging onto a soiled Perspex vertical plate, is described. The plate, the *substrate*, was coated with PVA or petroleum jelly, the *soil*. The substrate was either.

(i) fixed, for batch tests in which the cleaned area, roughly circular, grew with time, or

(ii) the substrate moved vertically up or down in its own plane, the water jet remaining fixed; this reproduced the effect of a jet moving across a surface for cleaning, as found in real tank cleaning operations.

In the batch experiments, growth of the radius a of the cleaning area is well described, at early times t, by $a^5 - a_o^5 = K^5\,(t - t_o)$, a_o being the initial radius of the cleaned area at time t_o; K is a constant. At later times with petroleum jelly, the cleaning front reached a maximum value, when the outward momentum of the radially flowing water film balanced the strength of the soil. This maximum value is modelled as a ramp of viscoplastic soil inclined at angle χ to the substrate surface, where χ was found to vary from 7° to 25°.

In the tests of continuous cleaning of petroleum jelly, a lengthening cleaned area, of width w_c, was observed on the moving substrate. Near the jet was a stationary clean front, whose shape looked like half an ellipse. This shape, and the width w_c, are well described by theory (Wilson et al., 2015, **123,** 450–459) using parameters from the above-mentioned batch experiments. This establishes a good link between batch and continuous cleaning experiments.

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1. Introduction

Cleaning is an important step in any food manufacturing process, whether to clear away residual material from process equipment at product changeover or to remove fouling deposits which can affect process operability, product quality or hygienic operation (Fryer and Asteriadou, 2009). Automated plant makes increasing use of cleaning-in-place (CIP) operations, wherein material is removed by the action of recirculating rinse washes, cleaning solutions and disinfectants. Time spent cleaning represents a loss of production, affecting the financial sustainability of a plant. Cleaning affects the environmental sustainability in terms of energy consumption (cleaning solutions are frequently heated) and material (provision of cleaning chemicals and disposal of wastes, as well as neutralisation of acid and alkaline agents) (Köhler et al., 2015). There is thus a need to optimise the performance of cleaning operations.

Much of the research into CIP mechanisms to date has concentrated on enclosed units, *e.g.* pipes, heat exchangers, where the flow of cleaning solutions is well understood. The food industry makes extensive use of tanks and similar vessels for storage, mixing, reaction and heating, for which ‘fill and soak’ cleaning operations take long times and require large volumes of liquid. Some systems use moving[1] jets of liquid, created by nozzles or lances, to distribute cleaning solution across the walls of process vessels at higher velocities than in standard pipe flows so that cleaning is augmented by hydraulic action (Jensen, 2011). These can significantly reduce the time to clean a vessel.

There has, however, been relatively little work to date on cleaning of surface layers – which we refer to here as soiling layers – by impinging liquid jets. Meng et al. (1998) and Leu et al. (1998) studied the mechanisms of removing surface coatings by high

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[1] The terms ‘moving’ and ‘fixed’ in this paper refer to the relative motion of the nozzle. The liquid is in steady continuous flow.

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velocity waterjets (which formed sprays). Burfoot and co-workers (Burfoot and Middelton, 2009; Burfoot et al., 2009) quantified the effectiveness of high pressure jets in food cleaning applications. Yeckel and Middleman (1987) studied and modelled the removal of viscous (oil) films from horizontal surfaces by a vertical impinging water jet in the region bounded by the hydraulic jump; in this region the liquid flows outwards in a thin film and subjects the layer to significant shear forces. Lately, Walker and co-workers (Hsu et al., 2011; Walker et al., 2012) have extended this approach and considered the interaction of such jets on layers of non-Newtonian fluids.

The knowledge of cleaning mechanisms gained from the above studies is expected to apply to cases where the soiling material is attached uniformly to a wall, but the flow behaviour of the liquid changes noticeably as it moves over a vertical (or inclined) wall. When a liquid jet hits a flat surface, it spreads out radially as a thin, fast moving film (termed the *radial flow zone*, RFZ) until a point where the thickness of the film increases abruptly. When the liquid impinges downwards on a horizontal plate, this change in thickness is called a *hydraulic jump* and the flow pattern is symmetric. When a jet strikes a vertical wall a similar feature is formed above the point of impingement, which we call the *film jump*. Beyond the film jump the liquid flows downwards, moving around the film jump as a *rope* which increases in thickness. These features are shown in Fig. 1(*a*). Below the point of impingement the liquid flows downwards as a wide film, bounded by a rope on each side. The film can stay wide or narrow further downstream, depending on the wetting characteristics of the surface (Aouad et al., 2015). These flow patterns and quantitative models for predicting their dimensions and behaviour have been studied for jets impinging on stationary walls by Wilson and co-workers (Wilson et al., 2012; Wang et al. 2013a, 2013b; 2015). Cleaning of viscous drops on an inclined surface by a falling liquid film has recently been studied by Landel et al. (2015).

Fouling layers and residues in the food sector are often complex soft solids (Fryer and Asteriadou, 2009). Knowledge of cleaning mechanisms has been driven by the need to understand and optimise CIP systems, particularly duct flows (*e.g.* Gillham et al., 1999; Fryer et al. 2006). The removal of soil layers by impinging jets can involve *adhesive* and/or *cohesive* mechanisms. In the former, the forces imposed by the liquid are sufficient to overcome the strength of attachment of the layer to the substrate and the layer is peeled off: it may fragment as part of this process, depending on its strength (*i.e.* the interactions between elements of the soil). With cohesive removal, the forces imposed by the liquid are sufficient to fragment the soil, *i.e.* by erosion or delamination. The soil is worn away until the substrate is reached. Dissolution, enhanced by convective mass transfer, may also occur. Wilson et al. (2014) studied the adhesive removal of soils by fixed impinging jets, where a circular, cleaned region grows outwards from the point of impingement. They presented a quantitative model, using results from the hydrodynamic model of Wilson et al. (2012), which gave a good description of data obtained for layers of polyvinyl acetate (PVA), Xanthan gum, and petroleum jelly. They subsequently extended this model (Wilson et al., 2015) to describe the cleaning action of a liquid jet moving across a soiled plate and were able to predict the shape of the cleaned front and the trends observed for Xanthan gum layers reported by Köhler et al. (2015).

This ability to predict the liquid contacting pattern and the shape of the cleaned front (see Wilson et al., 2015) is critical for detailed simulation of cleaning by impinging jets. Knowledge of the liquid contacting pattern allows the regions wetted by the cleaning solution to be identified, as well as the time that the layer is in contact with solution: soaking time and reaction with a cleaning agent are important factors in the removal of complex soils (Wilson, 2005; Fryer and Asteriadou, 2009). Knowledge of the shape of the cleaned front allows the area cleaned by a moving jet to be calculated for different trajectories, so that these can be optimised.

This paper presents an extension of the above experimental and modelling studies in two aspects. The first is the use of a new experimental configuration which allows the shape of the cleaned front and the flow patterns to be determined in real time. In previous studies (Köhler et al., 2015; Wilson et al., 2015) the jet had to be interrupted in order to determine the shape of the cleaned front. In the current work, the jet is stationary but the soiled plate is moved upwards (or downwards) past the jet while being videoed.

Moving surfaces and stationary nozzles have been employed by workers such as Gradek et al. (2006) to study hydraulic jump behaviour but have not, to the authors' knowledge, been used to study cleaning, particularly for vertical surfaces. The second aspect is the study of more complex soils, specifically layers of non-crosslinked PVA and a petroleum jelly. The influence of layer thickness is here investigated for both materials. The adhesive removal model of Wilson et al. (2015) is adapted to describe the removal of the petroleum jelly, which is a viscoplastic material (Ali et al., 2015).

2. Models

2.1. Radial flow zone hydrodynamics

In these experiments cleaning is observed within the radial flow zone, where the liquid flows as a thin fast moving film. Wilson et al. (2012) modelled the flow in the RFZ as a Nusselt film, with the average velocity, U, at radius r given by

$$\frac{1}{U}-\frac{1}{U_o}=\frac{10\pi^2\mu}{3\rho Q^2}\left[r^3-r_o^3\right] \qquad [1]$$

Here U_o is the velocity in the impinging jet of radius r_o, Q is the jet volumetric flow rate, ρ is the liquid density and μ its dynamic viscosity. The momentum in the liquid film per unit circumferential width, M, at radius r is

$$M=\frac{3\rho Q}{5\pi}\frac{U}{r} \qquad [2]$$

They calculated the location of the film jump, R, from a force balance in which the outward flow of momentum was balanced by surface tension, γ, acting along the surface and at the liquid-substrate contact line (with contact angle β). Assuming that $U_o \gg U(R)$ and $R \gg r_o$ gave

$$R=0.276\left[\frac{\rho^2Q^3}{\mu\gamma(1-\cos\beta)}\right]^{1/4} \qquad [3]$$

This result is compared with the experimental data for jets impinging on moving substrates.

2.2. Cleaning – static jets

Wilson et al. (2014) presented a model to describe the removal, by adhesive failure, of soil within the RFZ by a static jet. Material is removed to leave a circular clean region of radius a, as shown in Fig. 1(*b*). The rate of growth of the cleaned region is postulated to be proportional to the force imposed by the fluid, which is a fraction of the momentum per unit width, M, at a:

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