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Cleaning of toothpaste from vessel walls by impinging liquid jets and their falling films: quantitative modelling of soaking effects

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Abstract

The cleaning of thin toothpaste soiling layers from vertical glass surfaces by horizontal impinging water jets and the falling films created by the draining liquid were studied. The effect of soaking time on the rheological properties of the soil material, the force required to remove it, and the cleaning behaviour were determined. The adhesive removal model reported by Wilson *et al.* (2014, *Chem. Eng. Sci.*, Vol. 109, 183-195) and Bhagat *et al.* (2017, *Food Bioprod. Proc.*, Vol. 102, 31-54) gave a good description of the cleaning behaviour, including the shape of the cleaning front generated by jets from static and moving nozzles. This model was also applied to removal by the falling liquid film: when soaking kinetics are taken into consideration, it gives a good description of this process as well. This is the first study considering the effect of soil soaking on cleaning by water jets and falling films.

Keywords: Cleaning; Impinging jet; Falling film; Soaking; Toothpaste

1 Nomenclature

Roman

a	Cleaning distance, [m]
a_x	Distance to cleaning front on moving jet path, [m]
A	Lumped parameter, defined $A = 1 - 10\pi\mu r_0/3\dot{m}$, [-]
A_{blade}	Area of millimanipulation blade tip, [m ²]
B	Lumped parameter, defined $B = 10\pi\mu/3\dot{m}r_0^2$, [-]
C_1	Constant, defined $C_1 = \int_0^1 f(\eta)^2 d\eta$, [-]
C_2	Constant, defined $C_2 = \int_0^1 f(\eta) d\eta$, [-]
d	Jet diameter, [m]
f_c	Fraction of flow in core film, [-]
F_W	Force per unit width measured, [N m ⁻¹]
$F_{W,normal}$	Normal force per unit width, [N m ⁻¹]
$F_{W,shear}$	Shear force per unit width, [N m ⁻¹]
g	Gravitational acceleration, [m s ⁻²]
G'	Elastic modulus, [Pa]
G''	Viscous modulus, [Pa]
h	Film thickness, [m]
$h_{Kapitza}$	Mean film thickness, Kapitza's theory, [m]
$h_{Nusselt}$	Mean film thickness, Nusselt's theory, [m]
k_0	Lumped cleaning rate parameter, [m s kg ⁻¹]
k_1	Lumped cleaning rate parameter, [m kg ⁻¹]
k'	Lumped cleaning rate constant, [m s kg ⁻¹]
L_{blade}	Length of millimanipulation blade in contact with soil, [m]
$\dot{m}$	Mass flow rate, [kg s ⁻¹]
M	Momentum flow per unit width, [kg s ⁻²]
M_y	Yield momentum flow rate, [kg s ⁻²]
p	Radial distance to cleaning front, [m]

q	Volumetric flow rate per unit width, [$\text{m}^2 \text{s}^{-1}$]
Q	Volumetric flow rate, [$\text{m}^3 \text{s}^{-1}$]
r	Radial coordinate, [m]
r_0	Nozzle radius, [m]
r_b	Radius where boundary layer reaches the free surface, [m]
r_t	Transition radius from laminar to turbulent regime, [m]
R	Radius of impingement region, [m]
Re_f	Film Reynolds number defined by $Re_f = 4\rho q/\mu$, [-]
Re_j	Jet Reynolds number, [-]
t	Time, [s]
$t_{falling\ film}$	Cleaning time by falling film, [s]
t_{soak}	Soaking time, [s]
u	Flow velocity, [m s^{-1}]
U_0	Mean flow velocity from jet, [m s^{-1}]
U_{av}	Mean flow velocity, [m s^{-1}]
U_s	Surface velocity, [m s^{-1}]
v_{blade}	Millimanipulation blade velocity, [m s^{-1}]
v_{jet}	Nozzle traverse velocity, [m s^{-1}]
w_c	Width of cleaned region by moving jet, [m]
W	Falling film width, [m]
W_{blade}	Width of millimanipulation blade, [m]
W_c	Core film width, [m]
x, y, z	Cartesian co-ordinates, [m]

Greek

α	Lumped parameter, defined $\alpha = 9k'\dot{m}^3/50\pi^3\rho\mu$
β	Angle to direction of nozzle motion, [-]
γ	Surface tension (liquid/vapour), [N m ⁻¹]
$\dot{\gamma}$	Apparent shear rate, [s ⁻¹]
δ	Boundary layer thickness, [m]
δ_{soil}	Soil thickness, [m]
δ_{gap}	Gap between blade and substrate, [m]
η	Dimensionless distance normal to the wall, defined $\eta = y/\delta$, [-]
η_{app}	Apparent viscosity, [Pa s]
θ	Contact angle, [-]
μ	Dynamic viscosity, [Pa s]
ρ	Density, [kg m ⁻³]
σ	Lumped cleaning rate parameter, defined $\sigma = 3k'\dot{m}U_0/5\pi$, [m ² s ⁻¹]
τ_c	Critical stress, [Pa]
$\dot{\tau}$	Rate of increase of shear stress, [Pa min ⁻¹]
χ	Phase angle, [°]
Γ	Wetting rate, [kg m ⁻¹ s ⁻¹]
Γ_{core}	Wetting rate in core film, [kg m ⁻¹ s ⁻¹]
Γ_{rope}	Wetting rate in rope, [kg m ⁻¹ s ⁻¹]

Acronyms

BLFR	Boundary layer formation region
CTS	Confocal thickness sensor
RFZ	Radial flow zone

1

2

1. Introduction

Liquid jets are widely used in cleaning operations to remove soil layers from the internal surfaces of tanks and other vessels as well as exposed surfaces of process equipment. Devices commonly employed for tank cleaning operations by liquid jets include static spray balls and rotary jet heads. The selection of the device is determined by the shape and size of the unit as well as the nature of the soil on the surface to be cleaned.

There has been a noticeable increase in research activity on flow patterns and cleaning behaviour associated with a single coherent liquid jet. These studies can be categorised as either: (i) cleaning in the impingement area, where the jet hits the surface and flows radially outwards (Bhagat *et al.*, 2017; Chee *et al.*, 2019; Feldung Damkjær *et al.*, 2017; Gerhards *et al.*, 2019; Köhler *et al.*, 2016; Rodgers *et al.*, 2018; Wang *et al.*, 2013b); or (ii) cleaning by the falling film that exists below the impingement point, where the liquid flows down under gravity and wets a vertical or inclined wall (Morison and Thorpe, 2002; Wang *et al.*, 2013a).

Wilson *et al.* (2012) presented a simple model of the radial flow region to predict the hydraulic jump radius and the minimum width of the falling film based on momentum balances. In the radial flow region the flow was treated as a laminar film with a parabolic velocity profile, which was revised by Bhagat and Wilson (2016) to include the development of a laminar boundary layer and the transition to turbulent flow in the thin film. Wilson *et al.* (2014) used their flow result to develop a model for adhesive removal where the driving force for detachment is the momentum force applied at the cleaning front. They applied this to data obtained with a number of soft-solid soil layers. Glover *et al.* (2016) extended it to the case of viscoplastic soil layers. The removal model has also been extended to include nozzle motion (Wilson *et al.*, 2015) and the angle of inclination of the jet to the wall (Wang *et al.*, 2015). Liquid losses due to jet breakup at longer jet lengths observed in industrial tank cleaning were included via an effective flow rate term (Feldung Damkjær *et al.*, 2017).

The aim of this work was to develop a cleaning rate model for toothpaste, based on the adhesive removal models of Wilson *et al.* (2014) and Bhagat *et al.* (2017). Toothpaste is a dense suspension of abrasive particles (with mean size between 10-20 μm) in a water soluble continuous phase, typically glycerine. This formulation introduces dissolution and dispersion mechanisms into the removal behaviour: it

represents a soil which interacts with the cleaning solution, weakening as a result of soaking time. As such it represents a model material for studying the interaction of cleaning timescales with weakening phenomena. This is important for industrial application as cleaning solutions often feature formulations which promote weakening by adjusting pH, solubility and wetting behaviour so there is a dynamic variation in removal behaviour (Yang *et al.*, 2019). This is particularly important for the soil layer below the point of jet impingement, which is subject to soaking by the falling film. Chee *et al.* (2019) demonstrated the importance of soaking for removal of layers of a viscoplastic soil layer (a Carbopol[®] gel).

This paper presents a systematic experimental investigation of the impact of soaking on jet removal in thin soil layers. The removal model is verified using cleaning tests employing static impinging jets, where the soil layer has been contacted with water for different times before removal. The time dependency of the model parameters is characterised. The model is then applied to cleaning by moving jets and falling films, and is shown to give good agreement with the experimental data.

2. Model description

2.1. Flow patterns induced by impinging jets

The flow pattern generated by a horizontal jet impinging on a vertical wall is illustrated in Fig. 1. A radial flow zone (RFZ) of radius R is formed around the impingement point, where the liquid moves rapidly outwards and terminates at a jump. In the RFZ, the effect of gravity is negligible, so the model also applies to a vertical jet impinging on a horizontal wall (Fig. 1(a)). Gravity determines what happens beyond the RFZ. Above the point of impingement a rope or corona with varying thickness and width forms around the RFZ, containing the liquid crossing the jump. Below the point of impingement, the jump height decreases rapidly and changes to a falling film driven by gravity. The falling film flow features two regions: (i) the outer bounding flow, which is the extension of the rope, and (ii) the inner section, here termed the core, of width W_c and film thickness noticeably smaller than the rope. The characteristics of the falling film in systems similar to that used here have been reported by Wang *et al.*, (2013b, 2013a) and Aouad *et al.* (2016).

In cases where the downward flow momentum is comparable or smaller than the force due to surface tension, the film width may narrow gradually to a thin tail, termed rivulet flow (Mertens *et al.*, 2005), or the film may split, creating a dry patch (Wang *et al.*, 2013a). The formation of different falling film types depends on the flow rate, losses due to jet breakup and rebound, liquid and surface characteristics. This study employed flat glass substrates which gave wide films that extended downwards for long distances (many R) before starting to narrow. A pseudo-stable gravity falling film of constant width W_c is formed with an assumed flow rate that is half the flow rate in the jet (the other half is in the ropes) (Wang *et al.*, 2013b).

2.2. Adhesive removal model

Glover *et al.* (2016) modelled removal of a viscoplastic soil layer in terms of adhesive failure, where the change in the size of the cleaned region is determined by the force acting on the soil at the soil-substrate-liquid contact line. The force is assumed to be proportional to the flow of momentum in the liquid film at the cleaning front, *viz*:

$$\frac{da}{dt} = k'(M - M_y) \quad \text{Equ. 1}$$

In the RFZ a is the radial distance from the point of impingement to the cleaning front at time t ; k' is a lumped cleaning rate constant; M and M_y are the momentum flow of liquid per unit width at a and the minimum momentum flow per unit width that needs to be overcome to yield the soil layer and promote cleaning, respectively. The value of k' is related to the soil layer thickness and the soil-substrate interactions. Since the same soil thickness was employed in the cleaning tests reported here, k' is expected to depend only on soaking time, t_{soak} . A linear dependency is assumed in the absence of supporting theory, giving

$$k' = k_0 + k_1 \cdot t_{\text{soak}} \quad \text{Equ. 2}$$

where k_0 and k_1 are positive constants, obtained by fitting experimental data. Soaking is therefore expected to increase the local rate of cleaning, reflecting a reduction in adhesive strength with time.

The flow of momentum of liquid per unit width, M , is calculated from:

$$M = \int_0^h \rho u^2 dy \quad \text{Equ. 3}$$

where h is the thickness of the liquid film; ρ the liquid density and u the velocity parallel to the wall at distance y from the wall. The model presented by Wilson *et al.* (2014) did not consider a contribution from yield momentum, M_y , when cleaning polyvinyl acetate, xanthan gum and petroleum jelly layers from polymethylmethacrylate (Perspex) and glass plates. Glover *et al.* (2016) observed asymptotic cleaning behaviour in their tests on viscoplastic layers (with a different petroleum jelly) and introduced the M_y term. Toothpastes have been reported to exhibit viscoplastic behaviour (Ahuja and Potanin, 2018; Palabiyik *et al.*, 2014) so the M_y term is retained. Since toothpaste contains water soluble components, M_y is also assumed to depend on t_{soak} .

2.3. Cleaning model, static nozzle

Fig. 1(a) illustrates the flow pattern around the impingement point on a flat surface. The flow is divided into four regions: (1) the stagnation region, (2) the boundary layer formation region (BLFR), (3) the laminar region, and (4) the turbulent region. The radial flow zone terminates at a hydraulic jump due to a balance between liquid momentum and surface tension (Bhagat and Wilson, 2016). Beyond the jump the liquid forms a rope or continues as a falling film.

In the stagnation region, the flow velocity is that in the jet, U_0 . In the BLFR, a boundary layer of thickness δ grows, where δ increases with r . The radial velocity increases across the boundary layer from 0 at the wall to U_0 at δ and beyond. The BLFR ends at radius r_b where the boundary layer reaches the film surface. Beyond r_b the liquid flows as a fully developed laminar film, which becomes turbulent at r_t . The turbulent flow region ceases at the jump radius R . It should be noted that R could be smaller than r_b or r_t . Expressions for δ , r_b , r_t and R are given by Equ. 4 - Equ. 7.

$$\delta = 2.12\sqrt{\mu r / \rho U_0} \quad \text{Equ. 4}$$

$$r_b/d = 0.24Re_j^{1/3} \quad \text{Equ. 5}$$

$$r_t/d = 0.2964Re_j^{1/3} \quad \text{Equ. 6}$$

$$R = 0.276 \left[\frac{\dot{m}^3}{\mu \rho \gamma (1 - \cos \theta)} \right]^{1/4} \quad \text{Equ. 7}$$

1 Here r is the radial coordinate, $\dot{m}$ is the mass flow rate in the jet, γ is the surface tension between the
 2 liquid and vapour, and θ is the contact angle. The jet Reynolds number is defined as $Re_j = \rho d U_0 / \mu$,
 3 with μ being the dynamic viscosity of the liquid. It should be noted that the expression for R in Equ. 7,
 4 from Wilson *et al.* (2012), is an approximate result: a more precise estimate requiring numerical solution
 5 was presented by Bhagat and Wilson (2016) and a detailed theoretical treatment which shows that the
 6 contact angle does not play a role in the formation of the jump is given by Bhagat *et al.* (2018). Assuming
 7 a contact angle of 90° produces essentially the same estimate for the films studied here.

8 For the water flow rates used in this study, the critical lengths for the different flow regions followed
 9 $r_b < r_t < R$. The value of M at a given r in each region was computed using the relationships presented
 10 in Table 1 (see Bhagat and Wilson, 2016).

1 Table 1. Summary of equations for calculating film thickness h , surface velocity U_s , velocity profile u and momentum per unit width M in the radial flow
2 zone when cleaning by static jets. The equations are reproduced from Bhagat and Wilson (2016).

Regions	h, U_s, u and η	Momentum per unit width M
BLFR $r < r_b$	$h = 0.125/r + 1.06(rd/Re_j)^{1/2}$	$M = \rho U_0^2 h - \rho U_0^2 \delta (C_1 - 1)$
	$U_s = U_0$	
	$u = \begin{cases} U_0 f(\eta), & y < \delta \\ U_0, & y \geq \delta \end{cases}$	
	$\eta = y/\delta$	
Laminar $r_b < r < r_t$	$h = d \left[\frac{3.792}{Re_j} \left(\frac{r}{d} \right)^2 + 0.1975 \left(\frac{d}{r} \right) \right]$	$M = C_1 \rho U_s^2 h$
	$U_s = \frac{U_0}{8C_2 hr/d^2}$	
	$u = U_s f(\eta)$	
	$\eta = y/h$	
Turbulent $r_t < r < R$	$h = \frac{0.0209d}{Re_j^{1/4}} \left(\frac{r}{d} \right)^{5/4} + (0.296 - 0.001356 Re_j^{1/2}) \left(\frac{d^2}{r} \right)$	$M = \frac{\rho \frac{64}{63} \frac{Q}{2\pi} u_0}{r \left[\frac{0.167}{Re_j^{0.125}} \left(\frac{r}{d} \right)^{9/4} + (2.37 - 0.0108 Re_j^{1/2}) \right]}$
	$U_s = \frac{4Q}{7\pi r h}$	
	$u = U_s \eta^{1/7}$	
	$\eta = y/h$	
The additional equations used for the calculations		
$f(\eta) = \eta - \frac{3}{2}\eta^2 + 4\eta^3 - \frac{5}{2}\eta^4$	$C_1 = \int_0^1 f(\eta)^2 d\eta \approx 0.352$	$C_2 = \int_0^1 f(\eta) d\eta = 0.5$

2.4. Cleaning model, moving nozzle

When a coherent jet impinges normally on a moving plate or the point of impingement moves across the plate, a roughly elliptical cleaning front is generated ahead of the impingement point. Wilson *et al.* (2015) modelled this scenario employing a moving frame of reference so that the point of impingement was static and the soiled surface moved toward it at relative velocity $-v_{jet}$, as shown in Fig. 2. Point X , located distance a_X ahead of the impingement point, is a stationary point where the cleaning rate equals the nozzle velocity, *i.e.* $da/dt = v_{jet}$. At point P , oriented at angle β to the direction of nozzle movement and at distance p from the origin, resolving the motion at steady state yields a non-linear differential equation (Bhagat *et al.*, 2017; Wilson *et al.*, 2015):

$$\frac{dp}{d\beta} = \left(\frac{da}{dt}\right)_P \frac{p}{v_{jet} \sin \beta} - \frac{p}{\tan \beta} \quad \text{Equ. 8}$$

Computing the solution to Equ. 8 requires knowledge of the variation of M with p . Using the expressions in Table 1 to calculate M requires numerical evaluation. In this work, the ‘intermediate strength soil’ model presented by Bhagat *et al.* (2017) is used to estimate $\left(\frac{da}{dt}\right)_P$, the local cleaning rate at the cleaning front, adding a yield term M_y to the original expression, *viz.*:

$$\left(\frac{da}{dt}\right)_P = \frac{\sigma}{p(A + Bp^3)} - k'M_y \quad \text{Equ. 9}$$

where σ , A and B are groups of parameters related to the cleaning rate: $\sigma = 3k'\dot{m}U_0/5\pi$, $A = 1 - 10\pi\mu r_0/3\dot{m}$, and $B = 10\pi\mu/3\dot{m}r_0^2$. At X , Equ. 9 yields:

$$\left(\frac{da}{dt}\right)_X = v_{jet} = \frac{\sigma}{a_X(A + Ba_X^3)} - k'M_y \quad \text{Equ. 10}$$

The distance to the cleaning front on jet path, a_X , can be solved analytically using Equ. 10. The shape of the cleaning front can be calculated by substituting Equ. 9 into Equ. 8 with initial condition $p = a_X$ at $\beta = 0$. A and B can be calculated from the jet properties so the parameters required to solve are k' and M_y , which can be obtained either from inspection of data generated by a static nozzle or by fitting the parameters to the experimental results of cleaning by moving nozzles.

The solution depends on the hydrodynamic model used. The shape of the cleaning front obtained using the Bhagat and Wilson (2016) model to evaluate M and $\left(\frac{da}{dt}\right)_p$ is compared to that obtained using Equ. 9 for a case representative of the experiments reported here, and the results are compared for a case in the Supplementary material, Figure S.1. The agreement is very good.

2.5. Cleaning model, falling film

Flow in the falling film is assumed to be laminar with a parabolic velocity profile:

$$u = \frac{\rho g}{2\mu}(2hy - y^2) \quad \text{Equ. 11}$$

where g is the gravitational acceleration and y is the distance from the wall. The average velocity in the film, U_{av} , is:

$$U_{av} = \frac{1}{h} \int_0^h u dy = \frac{\rho g h^2}{3\mu} \quad \text{Equ. 12}$$

Giving

$$M = \frac{6}{5} \rho U_{av}^2 h \quad \text{Equ. 13}$$

The water film thickness h is now evaluated. In Nusselt's theory, the film is purely viscous, and thus a flat surface is assumed (Nusselt, 1916). The mean film thickness is then:

$$h_{Nusselt} = \left(\frac{3\mu q}{\rho g}\right)^{1/3} \quad \text{Equ. 14}$$

where q is the volumetric flow rate per unit width. Waves were observed in the experiments: according to Kapitza's theory of wavy flow, the parabolic velocity profile also applies but the mean film thickness is given by (Portalski, 1963) :

$$h_{Kapitza} = \left(\frac{2.4\mu q}{\rho g}\right)^{1/3} \approx 0.928 h_{Nusselt} \quad \text{Equ. 15}$$

The Nusselt film thickness is therefore ca. 7% larger than the Kapitza value. Nusselt's and Kapitza's results are valid for water when the film Reynolds number ($Re_f = 4\rho q/\mu$) is less than 1 160 (Portalski, 1963). Since ropes exist on both edges of the falling film with a thickness much larger than the core film (see Fig. 1(c)), only the momentum per unit width in the core film region is calculated. q is estimated using $q = f_c \dot{m}/\rho W_c$, where the width of the core film, W_c , is determined experimentally. The fraction of the jet flow rate in the core film, f_c , is assumed to be 50%. Any losses due to splashing are ignored (Wang *et al.*, 2013b).

3. Materials and methods

3.1. Rheology

The rheology of the toothpaste (Advanced White, Colgate) was measured on a rotational rheometer (Kinexus lab+, Malvern Panalytical, UK) using roughened parallel plates at 20 °C with 1 mm gap. The solids content of the toothpaste sample was 62.1 ± 4.5 w/w %. The measurements included undiluted or diluted (10 – 50 % extra water) samples without pre-shear, as well as undiluted toothpaste with pre-shear at 5 Pa for 3 min (see Table 3). Pre-shear at 5 Pa was based on the estimated wall shear stress imposed by the falling film under the jet flow rates considered (around 3 Pa).

First, an oscillatory time sweep was applied with a stress amplitude of 0.1 Pa at a frequency of 1 Hz for 3 min to identify the viscous and elastic characteristics of the sample. A stress ramp was then applied, increasing the shear stress at a rate of $\dot{\tau} = 10 \text{ Pa} \cdot \text{min}^{-1}$ from 0.25 Pa until the material yielded. Hysteresis tests were also performed, imposing an increasing and then decreasing ramp for a shear rate between 0.01 and 100 s^{-1} , to test the macro- or micro-structural rearrangement of the material over time.

3.2. Millimanipulation

The millimanipulation device reported by Magens *et al.* (2017) offers a method for determining the forces required to remove the soiling layer. Fig. 3 is a schematic of the device operation. The sample was spread on a glass plate (dimensions $5 \times 5 \text{ cm}$) with a known thickness of the soil, and a blade moved relative to

the plate at constant velocity v_{blade} with a defined gap between the blade base and the substrate. The millimanipulation device used here featured a static blade and the sample moved towards it. The force imposed on the blade was measured by a force transducer (HBM S2M, Germany). The width of the blade tip W_{blade} was 0.140 ± 0.017 mm, determined by a confocal thickness sensor (CTS, IFS 2405-3, Micro-Epsilon, Germany).

Millimanipulation was performed to investigate the effect of soil thickness, gap distance and soil type (soaked or not) on the removal force. Measurements were made at blade velocities of 0.1, 1, 5 and 10 mm·s⁻¹. To prepare the soaked samples, the plate was mounted in the millimanipulation chamber and the chamber was filled with deionized water then emptied after 3 min using a syringe.

The soil deformed and accumulated in front of the blade, as shown in Fig. 3. The force measured by the sensor included three components: (i) the force to deform material ahead of the blade, (ii) the force to displace the deformed material, and (iii) the force to overcome the shear resistance under the tip of the blade. The shear force per unit width (region III in Fig. 3), $F_{W, shear}$, could be determined from:

$$F_{W, shear} = \frac{\tau A_{blade}}{L_{blade}} = \frac{\eta_{app} \dot{\gamma} L_{blade} W_{blade}}{L_{blade}} = \eta_{app} \dot{\gamma} W_{blade} \quad \text{Equ. 16}$$

Here, A_{blade} and L_{blade} are the area and length of the blade tip, respectively. τ is the shear stress under the tip of the blade. The apparent viscosity, η_{app} , was taken from the rheological data at apparent shear rate $\dot{\gamma} = v_{blade} / \delta_{gap}$. The combined force of deforming and displacing the soil ahead of the blade (regions I and II in Fig. 3) was labelled the normal force and determined using:

$$F_{W, normal} = F_W - F_{W, shear} \quad \text{Equ. 17}$$

The parameters studied in millimanipulation testing are summarised in Table 2.

Table 2. Millimanipulation test conditions. Tests were conducted using blade velocities ranging from 0.1 to 10 mm·s⁻¹.

Investigated parameters	Fixed parameters	Varied parameters
Soil thickness	Soil: original toothpaste $\delta_{gap} = 100 \mu\text{m}$	$\delta_{soil} = 200, 500, 700 \mu\text{m}$
Gap distance	Soil: original toothpaste $\delta_{soil} = 500 \mu\text{m}$	$\delta_{gap} = 50, 100, 200, 400 \mu\text{m}$
Soil type	$\delta_{gap} = 50 \mu\text{m}$ $\delta_{soil} = 500 \mu\text{m}$	Soil: original toothpaste and toothpaste soaked for 3 min

3.3. Impinging jet apparatus and experimental design

The pilot-scale apparatus has been described previously by Glover *et al.* (2016). The test plates were made from transparent float glass. The dimensions of the vertical test plates were 360 × 600 mm, while horizontal plates measured 150 × 150 mm. The plates were coated with toothpaste before being mounted prior to cleaning. Even soil layers were prepared by dragging a blade over the plate with fixed and known clearance between the blade and the plate. The resulting soil layers were approximately 500 μm thick, giving a mass coverage of 0.59 ± 0.04 kg·m⁻².

Cleaning experiments were performed soon after soiling (within 3 min of preparation) in order to reduce drying effects. Cleaning was performed with water jets generated by a brass nozzle with diameter, d , 2 mm. The nozzle position could be adjusted to be horizontal or vertical. Normally impinging jets and single-pass deionized water at room temperature (22 ± 2 °C) were used in all tests. The nozzle was located approximately 10 cm from the test plate and generated a coherent, turbulent jet: break-up was not observed. An interrupter plate was initially located between the nozzle and the soiled plate while the flow was set and stabilized. The interrupter was then removed, and timing of the experiment was started simultaneously.

Video recordings of jet impingement and cleaning were made with a digital camera (Nikon D3300 D-SLR, Japan) located on the reverse side of the vertical plate or above the horizontal plate. Images were processed using the image analysis toolbox in Matlab[®] (MathWorks, US).

Three cleaning configurations were studied and described in sections 3.5 - 3.7: cleaning by jets from static nozzles, cleaning by jets from moving nozzles, and cleaning by falling films.

3.4. Falling film thickness measurement

Aouad *et al.* (2016) reported particle image velocimetry measurements of surface velocities in the falling film region. Measuring the film thickness was complicated by the presence of gravity waves. In this study, a confocal thickness sensor was used to determine the thickness of the falling film directly for comparison with the Nusselt and Kapitza models. The sensor projects a polychromatic white light spot on the transparent target surface, focusing each wavelength at a specific distance with controlled chromatic aberration (see Fig. 4). The sensor receives the light that is reflected from each interface and transfers this information to the controller (ConfocalDT controller 2461, Micro-Epsilon, Ortenburg, Germany). Spectral analysis is then conducted to calculate the distance between the interfaces and therewith the thickness of the liquid film (Micro-Epsilon, 2016).

Fig. 4 shows the arrangement for measuring the thickness of the film generated on a vertical transparent Perspex plate (thickness ca. 5 mm) by a coherent 2 L·min⁻¹ water jet generated by a 2 mm diameter nozzle. The sensor was located on the dry side of the plate and was traversed horizontally across the film at a distance 15 cm below the impingement point. Under these conditions R was ca. 8 cm (Wang *et al.*, 2013a), so the film was fully developed. Measurements were made at ca. 2 mm intervals at a sample frequency of 10 Hz: h was determined as the average value over a 20 s period.

3.5. Cleaning by jets from static nozzles

Soiled glass plates with dimensions 150 × 150 mm were used in these tests. The plate was prepared as described above and then placed flat in a basin, raised 2 cm from the base by aluminium blocks. Both unsoaked and soaked layers were studied. Soaking was achieved by carefully adding deionized water to the basin to submerge the soil layer, then removing the water after the required soaking time.

Cleaning employed a vertical, coherent jet at a flow rate of $2 \text{ L} \cdot \text{min}^{-1}$ ($Re_j = 21\,200$) which impinged normally at the centre of the plate. Cleaning was recorded on a digital camera located above the nozzle. The cleaned region in the RFZ was found to be circular when the jet was vertical as well as horizontal. The radius of the cleaned region was extracted from the video recordings.

3.6. Cleaning by jets from moving nozzles

The rectangular glass plate was soiled and mounted on an aluminium frame with its longer side vertical. The nozzle was horizontal and stationary while the plate was moved vertically upwards (at $1.25 \text{ cm} \cdot \text{s}^{-1}$) or downwards (at $1.5 \text{ cm} \cdot \text{s}^{-1}$) by a motor.

The jet could impinge initially either directly on the soil layer, or above/below the soil region, as illustrated in Fig. 5. When the plate moved downwards (replicating the jet moving upwards) the liquid film encountered unsoaked soil. When the plate moved upwards cleaning involved both unsoaked and soaked regions of soil.

In tests investigating the effect of pre-soaking, a falling film was generated by impinging the jet above the soiled region for 1 or 2 minutes, as illustrated in Fig. 5(a). No soil was observed to be removed during the pre-soaking period, and the full width of the soil layer was covered by a water film. Following soaking, the upward movement of the plate was started. The width of the cleared path and the shape of the cleaning front were recorded.

3.7. Cleaning by falling films

The large glass plate was mounted vertically on an aluminium frame, with a soiled region located 15 - 30 cm below the impingement point, as in Fig. 5(a). The flow rates investigated ranged from $0.6 - 2.5 \text{ L} \cdot \text{min}^{-1}$, corresponding to $Re_j = 6\,300 - 26\,500$. Only the removal of soil layers by the core falling film (width W_c in Figure 1(c)) was analysed. The soiled area was divided into bands of 1 cm high and the time taken for the whole band to be cleared (no soil visible) was denoted the cleaning time, $t_{\text{falling film}}$.

1 The regions over which the ropes flowed were cleaned more quickly, which is consistent with the local
2 wetting rate in these areas being higher than in the core film.

3 4. Results and Discussion

4 4.1. Rheology

5 The rheological behaviour of the toothpaste and the effect of dilution are presented in Fig. 6. In the
6 oscillatory time sweep measurement, the elastic modulus (G') and viscous modulus (G'') gave steady G'
7 and G'' values over the test periods. The data in Fig. 6(a) show $G' > G''$, indicating that the toothpaste
8 can be regarded as mainly elastic at low shear stress. Both moduli decrease strongly on dilution. Pre-
9 shearing can reduce both shear moduli, but the effect is less significant than dilution.

10 The apparent viscosity data in Fig. 6(b) show shear-thinning behaviour similar to that reported by Ahuja
11 *et al.* (2018). The dependency of apparent viscosity on shear rate could be fitted by a Cross or Carreau
12 model. Pre-shearing of the undiluted toothpaste at 5 Pa for 3 min did not affect the trend noticeably,
13 whereas shearing at 100 Pa (the limit of the ramp) did: the hysteresis on the return sweep indicates a time
14 dependent behaviour of the material. Dilution also significantly decreases the apparent viscosity.

15 The shear stress at which the apparent viscosity starts to decline sharply was labelled the critical stress.
16 These values and the phase angle, $\chi = \tan^{-1}(G''/G')$, at small stresses are presented in Table 3. Diluting
17 the toothpaste reduced the critical stress noticeably and increased the phase angle. These results indicated
18 that the deposit is easier to remove after soaking.

19 Table 3. Rheological characteristics of toothpaste materials. The presented data are averages and standard
20 deviations of at least two experiment repetitions.

Samples	Phase angle χ , [°]	Critical stress τ_c , [Pa]
Without pre-shear, undiluted	13.7 ± 0.8	179 ± 1
With pre-shear, undiluted	15.2 ± 1.6	160 ± 6
Without pre-shear, 10% dilution	19.4 ± 0.2	66.5 ± 7.5
Without pre-shear, 30% dilution	24.9 ± 0.3	15.3 ± 0.7
Without pre-shear, 50% dilution	32.8 ± 0.2	1.65 ± 0.05

21

4.2. Millimanipulation testing

The millimanipulation results in Fig. 7(a) show that the shear force under the blade is a minor contribution to the force required to move the blade through the toothpaste layer. Deformation and displacement of the soil dominate. Fig. 7(b) shows that the measured removal force is proportional to the volumetric removal rate of soil displaced by the blade, calculated from $(\delta_{soil} - \delta_{gap})v_{blade}L_{blade}$. This force is expected to be dominated by the cohesive interactions in the toothpaste layer, which have to be overcome in order to deform the material as the blade passes through the layer and moves the deformed material up the blade.

Fig. 8 shows that the force required to remove an unsoaked layer and a layer pre-soaked for 3 min increases linearly with v_{blade} in both cases, indicating that the cohesive forces in the toothpaste decrease significantly on soaking (as observed in the G' values in Fig. 6). This will be shown to be reflected in the effect of soaking on the M_y term in the adhesive cleaning model (Equ. 1).

There were noticeable amounts of residual material on the test plates after the blade had passed (see insets in Fig. 8), indicating that the adhesive interactions between the soil and substrate were weaker than the cohesion within the soil matrix. If they were comparable or stronger, a uniform film of toothpaste would be left by the blade. The amount of toothpaste remaining on the substrate decreased after soaking, indicating that both the adhesive and cohesive interactions had decreased. The results are consistent with the findings of Cuckston *et al.* (2019), who reported reduced removal forces after immersing a carbohydrate-fat food soil in a detergent solution for some time. These residues are not observed in the impinging jet experiments as the soil layer (and any residue) is subjected to continual hydraulic force by the liquid film: the toothpaste contained a water soluble mobile phase (glycerine) so any residue was readily dispersed by the flow of water. It is acknowledged that visual cleanliness does not equate to complete removal of all residues, as material may be present in the form of very thin layers or patches. The absence of visual residue was used here as a measure of cleaning, reflecting what is often used in industrial practice.

4.3. Cleaning behaviour – static jet

Fig. 9(a) summarises the cleaning behaviour for toothpaste layers ($\delta_{soil} = 500 \text{ } \mu\text{m}$) on a horizontal plate contacted by a vertical coherent water jet at a flow rate of $2 \text{ L} \cdot \text{min}^{-1}$ ($Re_j = 21\,200$). The momentum per unit width (M) on the abscissa was calculated using the equations in Table 1. The results obtained for layers subject to different soaking times all exhibit the linear dependency of Equ. 1, confirming that the adhesive removal model gives a satisfactory description of this system.

The gradient and intercept of the fitted linear trend lines in Fig. 9(a) yield the cleaning rate constant, k' , and the product $k'M_y$, respectively, which allows M_y to be calculated. These calculation results are presented in Fig. 9

Fig. 9(b) and (c). k' increases initially linearly on soaking, and fitting Equ. 2 to the data yielded parameters $k_0 = 0.0051 \text{ m} \cdot \text{s} \cdot \text{kg}^{-1}$ and $k_1 = 0.000094 \text{ m} \cdot \text{kg}^{-1}$. The product $k'M_y$ passes through a minimum as t_{soak} increases: the estimated value of M_y decreases steadily with t_{soak} and this was modelled as an exponential decay:

$$M_y = 1.03 \cdot \exp\left(-\frac{t_{soak}}{40.6}\right) + 0.0291 \quad \text{Equ. 18}$$

The uncertainties in k' and $k'M_y$ combine to give large uncertainties in M_y , as displayed in Fig. 9(c).

Separate tests employing vertical walls yielded similar k' values (data not reported) so the above soaking dynamics are employed for vertical walls in subsequent sections.

It is interesting to compare the liquid film momentum (M) with the force measured by millimanipulation (F_W), as both terms have the same unit $\text{kg} \cdot \text{s}^{-2}$ ($= \text{N} \cdot \text{m}^{-1}$). The comparison is shown in Fig. 8, taking $da/dt = v_{blade}$, for cleaning by an impinging jet of an unsoaked and a soaked toothpaste layer of similar thickness to those in the millimanipulation tests. Both groups of data exhibit the linear dependency of Equ. (1) and show order of magnitude agreement. At a given blade velocity or cleaning rate, the force measured by millimanipulation is larger than the liquid film momentum calculated via Equ. 3. This is because the measured F_W mainly quantifies the cohesive bonds within the soil matrix and the work required to move the dislodged soil over the face of the blade. The proposed adhesive removal model describing the cleaning tests assumes adhesive failure between the soil layer and the substrate. When the soil layer is dislodged as shown in Fig. 1(a), the force to be overcome by the liquid film includes the adhesive interaction and a contribution arising from cohesive failure at the cleaning front. Despite the

1 difference in forces between millimanipulation and cleaning tests, the former technique is still a useful
2 tool to investigate the removal force and soaking effect. It also provides a lower bound on k' .

3
4 In some tests, after some time, cleaning was observed to involve fingering. Fig. 10(a) shows an example.
5 For most cases documented in Fig. 9 (with the exception of $t_{soak} = 10$ min), the cleaned region grew as
6 a circle, then formed unstable fingers before a maximum cleaning radius was reached. The radius where
7 fingers started to appear and the associated value of M are plotted in Fig. 10(b). When a finger formed,
8 the water film was seen to penetrate beneath the soil layer and peel the soil off.

9 The radius at which fingering appeared was always smaller than R and increased linearly with t_{soak} . The
10 appearance of fingers is related to the stability of the liquid-liquid interface (Hsu *et al.*, 2012) and the
11 yield momentum of the soil material. This represents an area for further investigation. Fingering is
12 undesirable in the context of cleaning as it leads to non-uniformity of removal as a result of liquid being
13 channelled into the finger regions.

14 15 4.4. Cleaning behaviour – moving nozzle

16 The cleaning of unsoaked toothpaste by a water jet generated by a moving nozzle was observed to occur
17 by means of two mechanisms:

18 I Pure adhesive failure (Peeling)

19 When the water jet initially impinged outside the soiled region and moved towards unsoaked soil
20 so that the film jump contacted the contact line between the soil and the substrate (Fig. 5(a) and
21 (b)), the thin film of water in the RFZ was observed to flow along the interface between the soil
22 and substrate, detaching the soil layer via peeling, as shown in Fig. 11(a). Peeling was also
23 observed in some cases after fingering was observed.

24 II Contact line erosion

When the water jet initially impinged on the soil layer (Fig. 5(c)), the thin liquid film did not penetrate along the soil-substrate interface. Cleaning involved the continuous removal of the soil at the contact line (Fig. 11(b)). The rate of removal was smaller than by peeling. This mechanism is similar to that reported in other studies (Glover *et al.*, 2016; Wilson *et al.*, 2015; Wilson *et al.*, 2014).

The difference in behaviour is related to the cohesive strength of the soil. In tests where a jet from a static nozzle impinged above the soiled region for 1 to 2 minutes so that the soil layer was soaked by the falling film before the nozzle started to move (Fig. 5(a)), no soil was removed during the initial wetting phase. When the nozzle subsequently moved over the soil, only removal by contact line erosion (Mechanism II) was observed. This change was attributed to a decrease of the cohesive strength of the soil layer as a result of soaking to the point where the layer could not be stripped off as a coherent film. This is discussed further in section 4.5.

Fig. 12 compares the experimental results for the shape of the region cleaned by a moving nozzle with the model prediction, where the model parameters were obtained from tests conducted with a static nozzle. Peeling (Mechanism I) gives a noticeably larger cleared area. Fig. 12(a) shows results for the case where the soil being cleaned was not contacted by liquid in the falling film. The ratio of the cleared width, w_c as indicated in Fig. 2, to a_x in Fig. 12(a) differs between the two cases: for case I, $w_c/a_x = 76 \text{ mm}/31 \text{ mm} = 2.45$ while for case II, $w_c/a_x = 38 \text{ mm}/12 \text{ mm} = 3.17$. The latter is close to the value of 3.04 reported by Bhagat *et al.* (2017), where the adhesive removal model was applied for cleaning ‘weak’ soils with $M_y = 0$.

For the case II, experimental data and the profile predicted by the model (Equ. 8, with parameters from Fig. 9) show good agreement. The model results were generated by integrating Equ. 8 using Matlab®.

When the jet moves downwards (Fig. 12(b)), the falling film wets the soil in advance of the RFZ and this soaking is expected to increase the rate of removal. This is very evident in the data for tests showing case II behaviour, where the width of the cleared region did not reach a steady value. The profile for the case I test with no soaking period is similar in shape to that in Fig. 12(a), but with $w_c/a_x = 104 \text{ mm}/34 \text{ mm} = 3.06$. The prediction fits the case II experimental data reasonably well.

These results indicate that the case II cleaning performance of a jet moving across an unsoaked or soaked soil layer can be estimated with some confidence, using parameters obtained from static nozzle tests. The next stage of development would be to incorporate this prediction with a simulation that traces the path of the jet and also records the region of the wall that receives the falling film.

4.5. Falling film behaviour and cleaning

Falling film thickness

Fig. 13 shows the film thickness measured using the CTS for a falling film generated by a $2 \text{ L} \cdot \text{min}^{-1}$ jet on a Perspex plate. The presence of the ropes is evident on both sides of the film. The mean thickness of the core film is nearly constant and agrees well with the values predicted by the Kapitza model (Equ. 15). The Nusselt model (Equ. 14) over-predicts the film thickness by ca. 17%, confirming that the surface waves need to be considered when computing the film thickness. Regular wavy flow was observed during all the cleaning experiments. This is represented by the percentiles of film thickness in Fig. 13. In the core film, most thickness measurements (75th/25th percentiles) lay within 8% of the average thickness measured by the CTS. The intensity of the waves is expressed as the difference between the 99th and 1st percentiles, and is about 160% of the average film thickness.

Only two data points are reported for the rope on the left side compared to five for the right side. This is because the CTS measurement sensor has a limited range, of ca 3 mm, and the distance from the sensor to the plate, the depth of the plate, and the rope thickness exceeded this value.

The good agreement between the measured and predicted film thicknesses indicates that the f_c value of 0.5 used to calculate the volumetric flow rate in the core film gives reliable estimates of the flow and hence the value of M to use in the cleaning model.

Cleaning behaviour

The evolution of the cleaning of a band of soil below the point of impingement by the falling film (see Fig. 5(a)) is reported in Fig. 14. Cleaning starts at $t = 0$. The soil beneath the ropes is cleared more quickly than that in the core region, which is consistent with the local flow rate being higher in the ropes. A vertical finger is evident after $t = 60$ s, which was caused by flow channelling. These channels were observed in all cleaning tests, resulting in faster cleaning in the channel areas. The location and width of the channels were found to be random when experiments were repeated. By $t = 180$ s, more channels had appeared and a cleaning front can be seen to have started to move downwards from the top of the soiled band. Over time further channels appear, existing channels widen, and the cleaning front descends more quickly as the soil weakens as a result of soaking. The regions beyond the ropes are not cleaned.

The progress of the cleaning front was quantified by sectioning the core region into 1 cm high horizontal bands: the cleaning time, $t_{\text{falling film}}$, was the length of time taken for no soil to be visible above each band boundary.

Fig. 15 shows a typical example of the observed cleaning profiles. There is an initial delay of nearly 3 min before the cleaning front starts to move. This is attributed to time taken for soaking to reduce the yield momentum, M_y , to a value comparable with M imposed by the film. The rheology measurements have confirmed that pre-shearing the soil material at the shear stress imposed by the falling film for 3 min did not reduce the critical stress of the toothpaste significantly (Table 3), so pre-shearing effects can be neglected.

The cleaning model, Equ. 1, with t_{soak} dependent parameters given by Equ. 2 and Equ. 18, was applied to cleaning by the falling film where M is calculated using Equ. 13, at approximately $0.02 - 0.05 \text{ kg}\cdot\text{s}^{-2}$ for the range of flow rates investigated. The observation of channelling suggests that the flow rate across the core film may not be uniform. Two flow rate scenarios were considered:

(i) Continuous soaking (see Fig. 16(a))

This is associated with a high flow rate in the falling film. Channelling is assumed not to affect the flow rate distribution significantly. The values of k' and M_y are given by Equ. 2 and Equ. 18, respectively, with the former increasing and the latter decreasing with extended soaking.

(ii) Discontinuous soaking (see Fig 16(b))

In this scenario, the soil layer is assumed to be covered by the falling film until some channels appear. Liquid is assumed to flow preferentially along the channels so that there is no further effect of soaking: k' and M_y do not change after a certain period. The value of M should also change to reflect the change in local flow rate. Detailed knowledge of the flow pattern would be needed to implement this scenario, and it would require a reliable model for channel formation. In the absence of such information, the calculations use M for the uniform film.

The time when the yield momentum M_y becomes lower than the film momentum, M , is labelled t_i , after which the cleaning front moves down. t_i and M_y can be calculated via Equ. 18 by either (i) setting $M_y = M$ to solve for t_i or, (ii) using the observed value of t_i to calculate M_y . The challenge in applying Equ. 18 is the significant uncertainty in M_y evident in Fig. 9(c), originating from the combined uncertainties in k' and $k'M_y$. The lowest value of M_y estimated by this method for low flow rates was higher than the film momentum calculated using Equ. 13, indicating that t_i was infinite. This was not observed in practice, so t_i was based on observations, and M_y is determined by fitting experimental results. This represents an area for further work, where the influence of surface waves should be considered.

Fig. 15 shows the fits for the two scenarios alongside the experimental data for a jet flow rate of $2 \text{ L} \cdot \text{min}^{-1}$. The cleaning times based on the Nusselt film thickness result are longer than the Kapitza film because the former predicts a thicker film, smaller mean flow velocity and lower M . The continuous soaking scenario gives rise to an increase in cleaning rate with time, whereas the discontinuous case gives a linear trend. The behaviour evidently lies somewhere between the two scenarios, and at higher flow rates (up to $2.5 \text{ L} \cdot \text{min}^{-1}$, Fig. 17) the continuous soaking scenario gives better agreement.

The mechanism of cleaning the toothpaste soil from vertical surfaces by the falling film can be described as involving the following steps:

- 1) The initial yield momentum of the soil is larger than M for the falling film, so the soil is soaked but is not removed. The liquid flows over the soil layer and soaks the soil layer.
- 2) At t_i , M_y for the soaked soil is smaller than M for the film and soil starts to be removed by adhesive failure. Channelled flow appears at this time or earlier: its occurrence is determined by the heterogeneity of the soil layer and the flow pattern.

- 3) At low flow rates, liquid tends to flow along channels, so only the cleaning front and channel boundaries are in contact with liquid. The rest of the soil layer is not soaked further and the cleaning front moves downwards at a constant rate. The channels widen progressively with time.
- 4) At high flow rates, a fraction of the liquid flows through the channels and the remainder flows over the soil layer. The liquid continues to soak the soil and the cleaning rate increases with time.

Fig. 17 suggests that the transition between continuous soaking and discontinuous soaking occurs at a flow rate of 2 - 2.5 L·min⁻¹. This value can be compared with guidelines for wetting rates (*i.e.* mass flow rate per unit width of film) for cleaning process equipment. In these experiments, the wetting rate for the core film is 0.097 - 0.112 kg·m⁻¹·s⁻¹. This is lower than the ASME BPE standard of 0.517 - 0.617 kg·m⁻¹·s⁻¹ for cleaning vertical cylindrical vessels using static spray devices (American Society of Mechanical Engineers, 2016), indicating that a device sized to the industrial standard would not encounter problems associated with channelling when cleaning a soil with properties similar to the toothpaste. Indeed, the rate of cleaning would accelerate with soaking time.

Critique – cleaning by falling film

The momentum flow rate in the water film differs significantly between the impingement area ($M > 0.1$ kg·s⁻²) and the falling film ($M < 0.05$ kg·s⁻²). It has been shown above that the adhesive removal model developed by Wilson *et al.* (2014) and Bhagat *et al.* (2017) for cleaning near the point of jet impingement also applies to the cleaning by the falling film. However, there are two challenges in using the model to describe the cleaning of toothpaste by falling films, both related to soaking. Firstly, soaking determines the initial delay before the cleaning front starts to move downwards. The duration of this soaking step is related to the flow conditions, and the mechanism behind this is not yet completely understood. Secondly, the value of the yield momentum of toothpaste after soaking, $M_y(t_{\text{soak}})$ is subject to large uncertainty, and a more accurate method for determining this quantity is required. The millimanipulation method gives an indication of the trends involved but does not allow the cleaning rate to be estimated reliably.

5. Conclusions

The cleaning of toothpaste soils from glass surfaces by impinging water jets and falling films was studied experimentally. The adhesive removal model presented by Wilson *et al.* (2014) and Bhagat *et al.* (2017) gave a good description of the cleaning behaviour in the RFZ and was extended to incorporate the effect of soaking and applied to removal in the falling film region below the RFZ.

Rheological studies confirmed that the toothpaste exhibited viscoplastic behaviour. The critical yield stress decreases sharply when the sample is diluted with water, reflecting the effect of soaking on removal. The effect of soaking was also evident in millimanipulation testing: this technique gave a measure of the cohesive forces within the soil matrix, and confirmed that these were stronger than the adhesive interaction between the soil and the plate surface.

Soaking was found to affect the cleaning rate constant and the yield momentum parameters in the cleaning model. The values of these parameters, and their dependency on soaking time, were identified with tests using jets generated by stationary nozzles. Employing these results in existing models for predicting the shape of the region cleaned by a moving nozzle gave good agreement with the experimental data for cases where peeling did not occur. Peeling and fingering were both observed under certain conditions with the toothpaste used, indicating that cleaning of these complex fluids is subject to a range of phenomena.

The model was then extended to cleaning by the falling film, where the occurrence of channelling was found to affect the results. Two scenarios were presented to represent the influence of channelling – effectively no effect (soaking continues unabated) and no further soaking. The former gave a more reliable description at the higher flow rates tested, which did not reach the wetting rates recommended for industrial practice: this indicates that a continual weakening scenario is expected to apply for such cases.

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Open Data

A statement providing a link to the data reported in this paper on the University of Cambridge Apollo data repository will be included here if the manuscript is accepted for publication.

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3 Fig. 1. Schematic of the flow patterns formed by a horizontal jet impinging on a vertical wall: (a) side view of radial flow zone
 4 with (right) and without (left) soil, (b) side view of the radial flow zone and the falling film, (c) front view of the radial flow zone
 5 and the falling film. O marks the jet impingement point.

Fig. 2. Schematic of a jet from a moving nozzle impinging on a vertical plate. (a) is flow pattern when the nozzle moves upwards. (b) is flow pattern when the nozzle moves downwards. The frame of reference is the point of impingement so the soiled plate moves downwards or upwards. Figure based on Glover *et al.* (2016).

Fig. 3. Schematic of the millimanipulation device. In the experiments, the blade is static and the soiled plate moves towards the blade. Three regions denote the three components of the measured force: (I) to deform the material, (II) to displace the deformed material, (III) to overcome the shear resistance in the gap.

Fig. 4. Plan view of the configuration for measuring falling film thickness on a vertical wall by the CTS. Measurements were made 15 cm below the point of jet impingement.

Fig. 5. Schematic showing soiled regions and impingement points in experiments investigating cleaning by moving jets and falling films. (a) Impinging above the soiled region, nozzle moving downwards (plate moves upwards); cleaning only by falling films (both nozzle and plate are static, the liquid drains down). (b) Impinging below the soiled region, nozzle moving upwards (plate moves downwards). (c) Impinging on the soiled region, nozzle moving either downwards or upwards (plate moves either upwards or downwards).

Fig. 6. Effect of dilution on (a) shear and elastic moduli of toothpaste measured by oscillatory time sweep at a constant oscillation stress of 0.1 Pa and frequency of 1 Hz, and (b) apparent viscosity. An increasing shear rate ramp was applied in all cases apart from that labelled descend.

Fig. 7. Millimanipulation measurement results. (a) Shear force and normal force as a fraction of the measured force. (b) Measured force required to dislodge volume of soil. Error bars indicate the standard deviation of at least three measurements.

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2 Fig. 8. Effect of soaking on the force measured by millimanipulation (solid symbols). Inset photographs
 3 show the soiled glass plates after testing: white colour indicates the presence of toothpaste. Initial soil
 4 layer thickness 500 μm , gap beneath blade 50 μm . The error bar (the error bars for some points are too
 5 small to see) indicates the standard deviation of at least three measurements. The millimanipulation
 6 results are compared with the cleaning of soils by static jets (open symbols) from

7 Fig. 9 (a), taking $da/dt = v_{blade}$ and $M = F_W$.

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Fig. 9. Cleaning of toothpaste by water jet ($Re_j = 21\,200$) from static nozzle. (a) Effect of M on cleaning rate. The values of M for different flow regions are computed by the equations in Table 1. The gradient of the fitted linear trend lines gives the lumped cleaning rate constant k' ; the intercept is $k'M_y$. (b) Effect of soaking time on k' . (c) Effect of soaking time on $k'M_y$, and the yield momentum required to clean the soil material, calculated using $M_y = k'M_y/k'$. The continuous grey line in (c) represents Eq. (18).

(a)

Fig. 10. (a) Example of the formation of fingers around the impingement point. The soil is unsoaked toothpaste, and the cleaning time is 3.5 s. (b) Effect of soaking time on the radius where the fingers start to form, and the momentum calculated at the radius of the onset of fingering.

Fig. 11. Two mechanisms of cleaning unsoaked toothpaste by jets from moving nozzles: (a) peeling when the jet initially impacts outside the soiled region (as in Fig. 5(a)); (b) contact line erosion when the jet initially impacts within the soiled region (Fig. 5(c)). (i) Photographs from experiments; (ii) schematics.

Fig. 12. Shape of the cleaning front obtained by experiments and predictions: (a) plate moves downwards at $1.5 \text{ cm} \cdot \text{s}^{-1}$ (jet moves upwards); (b) plate moves upwards at $1.25 \text{ cm} \cdot \text{s}^{-1}$ (jet moves downwards). The symbols and lines are experimental observations and model predictions, respectively. The shaded areas indicate prediction uncertainties caused by the uncertainties in k' and M_y .

Fig. 13. Film thickness measurements across a falling film, 15 cm below the impingement point. Conditions: Perspex plate, jet flow rate $2 \text{ L} \cdot \text{min}^{-1}$. The estimated Reynolds number in the core film is $Re_f = 70$. The 75th/25th percentile band represents the measurement range of most samples. The 99th/1st percentile band represents the maximum and minimum film thickness, respectively.

Fig. 14. Cleaning in the falling film region: soiled region located 15-30 cm below the point of impingement (see Fig. 5(a)). No pre-soaking, jet flow rate $2 \text{ L} \cdot \text{min}^{-1}$. Black indicates all toothpaste has been removed. t is the time since jet impingement started. Salient features marked.

Fig. 15. An example of cleaning times and the fitting of the adhesive removal model based on Nusselt and Kapitza film theories and continuous or discontinuous soaking mechanisms. The flow rate is $2 \text{ L} \cdot \text{min}^{-1}$. $t_i = 155 \text{ s}$ based on the experiment.

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3 Fig. 16. Two cleaning scenarios by core falling films: (a) continuous soaking, (b) discontinuous soaking.

Fig. 17. Line-based cleaning times at different flow rates as well as the adhesive removal model. At $0.6 \text{ L} \cdot \text{min}^{-1}$, only discontinuous soaking applies with $t_i = 145 \text{ s}$ and $M_y = 0.7M$. At $2.5 \text{ L} \cdot \text{min}^{-1}$, continuous soaking applies with $t_i = 128 \text{ s}$ and $M_y = 0.7M$. The film thickness is determined using Kapitza's theory.