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Pendant drops shed from a liquid lens formed by liquid draining down the inner wall of a wide vertical tube

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ABSTRACT

When a viscous liquid empties from an initially full, wide vertical tube, the drainage behaviour changes from a filament to a regime in which individual drops are shed by a lens formed at the end of the tube: liquid drains down the wall and the lens grows until it becomes unstable. This drop shedding regime was investigated for four Newtonian liquids (rapeseed oil, glycerol, honey and golden syrup) in three tube sizes and two tube materials (Bond number based on tube i.d. > 1 in all cases). The drop mass increased modestly with flow rate and the equivalent sphere diameter, *d*, was strongly related to the capillary length $L_c \equiv (\gamma/\rho g)^{1/2}$ rather than the tube diameter. The results were fitted to a correlation of the form $d/L_c = f$(Bond, Reynolds, Morton, sine of the contact angle) derived from dimensional analysis. The data were compared with existing models for drop formation from filled narrow capillaries and a new, simple model based on a quasi-static model of the lens. Agreement with these models was poor, particularly for larger tubes, indicating the need for more detailed analysis. Insights into the dynamics, generated by video analysis of the lens shape, are presented.

1. Introduction

The formation of drops by a liquid as it drains out of a vertical tube has been studied for some time [11] and is widely used for the determination of surface tension, either by measuring the weight of successive drops [7] (see review [8]); or by analysing the shape of a pendant drop (reviewed by Berry et al. [4]). The evolution of the shape of the liquid as it approaches pinch-off to create a drop and the relationship between the drop volume and the tube diameter was first considered for Newtonian fluids by Rayleigh: the Rayleigh instability has since been considered for other types of fluid (*e.g.* Balmforth et al. [2], Balmforth et al. [3]).

Drop weight tests employ relatively narrow tubes or capillaries. Periodic drop formation is also observed when a viscous liquid drains from a wide upright tube which is open to the atmosphere at both ends. This behaviour was reported by Ali et al. [1] in their experimental study of the self-drainage of viscous food-related liquids in process pipework: their aim was to establish how much liquid (*i.e.* product) could thereby be removed from a tube before introducing a flow of cleaning agent to flush it out. As the liquid drains from the base of the tube as a long filament, air enters from the top of the tube in the form of a long slug (see Fig. 1(a)). When the slug nose approaches the base of the tube, it does not break through but halts and the filament breaks, creating a liquid lens (Fig. 1(b)) [See Supplementary Videos A and B]. As liquid is steadily added to the lens from the draining annular film, the lens increases in size (Fig. 1(c)) until it becomes unstable, shedding a drop and reforming the lens (Fig. 1(d)). The cycle repeats itself.

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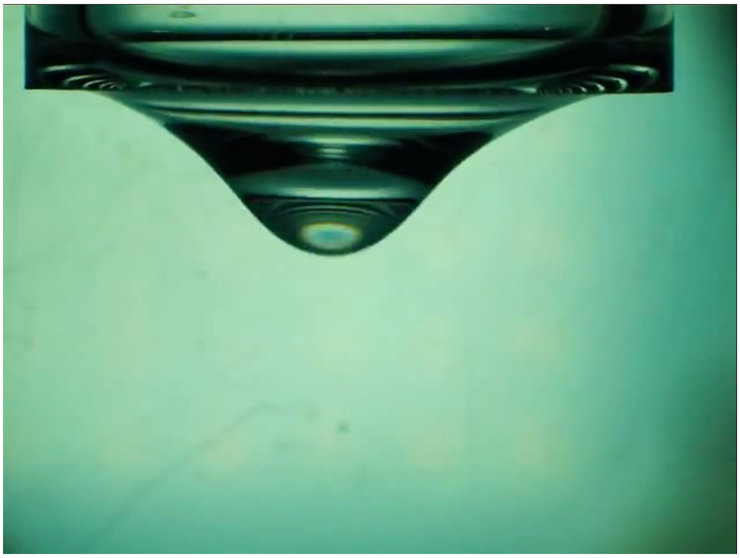
Nomenclature

Roman

a_1	constant, Eqs. (27) and (28)
a_2	constant, Eqs. (27) and (28)
a_3	constant, Eq. (27)
Bo	Bond number
d	drop equivalent sphere diameter
D	tube inner diameter
f	Eq. (2)
f_1	Eq. (3)
f_2	Eq. (4)
F	filament diameter
Fr	Froude number
Fr_c	Froude number (characteristic velocity is associated with flow in a capillary)
g	acceleration due to gravity
Ga	Galilei number
h	minimum meniscus thickness
L_c	capillary length
m	drop mass
m_{lens}	lens mass at critical point
m_{total}	total mass on scale
M	mass flow rate in draining annular film
M_c	mass flow rate in draining annular film of thickness L_c
M^*	dimensionless mass flow rate, $M^* = M/M_c$
Mo	Morton number
P_{atm}	atmospheric pressure
P_b	liquid pressure at the tube outlet ($z = 0$)
$P_{L,int}$	local hydrostatic pressure on the liquid side of the lens interface
Q	volumetric flow rate
Q_A	volumetric flow rate in annular film
Q_0	volumetric flow rate in filled tube
r	radial co-ordinate
r^*	dimensionless radial co-ordinate
r_i	radial position of annular film interface
R	tube inner radius
Re	Reynolds number
S	shape function, Eqs. (23) and (24)
t	time
t_d^*	scaled time, Eq. (1)
u	mean velocity in draining annular film
U	mean velocity in filled capillary
U_s	velocity of slug front
V_{lens}	lens volume
$V_{YY'}$	lens volume (hemispherical meniscus), Fig. 4(b)
x_c	dimensionless radial position of annular film interface (annular film of thickness L_c)
x_i	dimensionless radial position of annular film interface, $x_i = r_i/R$
z	axial co-ordinate
z^*	dimensionless axial co-ordinate
z_b	lens distance below the tube exit plane at $r = 0$
z_b^*	dimensionless lens distance below the tube exit plane at $r = 0$, $z_b^* = z_b/R$

Greek

γ	surface tension
Γ	wetting rate
κ	curvature
μ	dynamic viscosity
θ	contact angle
ρ	density



Video 1. Glycerol, $D = 21.6$ mm