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Experimental design of a system to investigate chaotic dripping

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Abstract. We report here the construction of a system designed to investigate chaotic dripping behaviour. The benchtop system has been designed for the purpose of measuring chaotic dripping in a microgravity test facility, although measurements under normal gravity only are reported here. The results confirm the main predictions of a simple 1-D mass-spring-damper theoretical model of the system, including the formation of point attractors and associated limit cycles, although there are significant departures from this model within specific flow rate regions resulting in the formation of what are termed here 'mid' drops (drops of a smaller size than normal). It is hypothesized that the origin of these mid drops arises from the development of a 'wetting' mass, namely a mass of liquid that is evacuated from the delivery tube from the previous drop excision.

1. Introduction and System Design

Three main types of behaviour of fluid flow from a nozzle can be identified: periodic dripping, chaotic dripping and jetting. The main parameters that affect the fluid flow are inertia, gravitational forces, surface tension and viscosity. Instabilities in jet flow were first studied by Rayleigh [1] and Plateau [2], and the effect of these instabilities was to create necking in the jet stream. Rayleigh's work assumed that the fluid was irrotational, non-viscous, incompressible and the effect of surface tension was ignored. Tomotika extended Rayleigh's work to include the effects of viscosity [3], and these studies collectively concluded that the jet stream would break up into drops of a similar size, driven by capillary instabilities. Leib and Goldstein demonstrated that these instabilities could be related to the Weber number [4].

Lin and Lian speculated that these jet instabilities could lead to dripping modes [5] when the Weber number was small. Clanet and Lasheras investigated this behaviour experimentally using a high speed camera [6], and determined a critical Weber number for the transition between jetting and dripping given by

$$\mathrm{We_c} = 4\frac{Bo_o}{Bo}\left[1 + KBo_oBo - ((1 + KBo_oBo)^2 - 1)^{\frac{1}{2}}\right]^2 \tag{1.1}$$

where: $\mathrm{Bo_o}$, Bo are Bond number for outside and within the nozzle respectively, and K is constant (equal to 0.37 for water in air). Their work identified the existence of two regions: regular periodic dripping; and chaotic dripping (referred to as the dripping faucet region). Later work identified a third, region between these two, consisting of quasi-period dripping [7,8]. To be clear, periodic dripping is the development of drops, which detach with the same period, quasi-periodic dripping is periodic dripping where detachment does vary but follows a sequence in the repetition of periods and chaotic dripping is where the time of detachment varies with no identifiable repetition pattern.

The dripping regime was modelled by Eggers and Dupont [9], using a modified Navier-Stokes equation and modified continuity equation in a 1-D cylindrical coordinate system, assuming viscous axisymmetric flow of an incompressible fluid. Their model predicted drop shape well, but was unable to deal with the singularities presented at the point of detachment, although later work by Eggers extended this model to deal adequately with detachment [10]. Zhang's work [11] also solved a Navier-Stokes equation and similarly was unable to deal with detachment, but, importantly, predicted the formation of a liquid 'thread' joining the main drop with the liquid cone formed at the nozzle.

In order to investigate dripping and jetting from a nozzle, a system was constructed at Kingston University. It was intended to carry out this investigation in microgravity conditions, and a microgravity facility was constructed for this purpose [12]. The system design is shown in Figure 1a and the constructed system in Figure 1b.

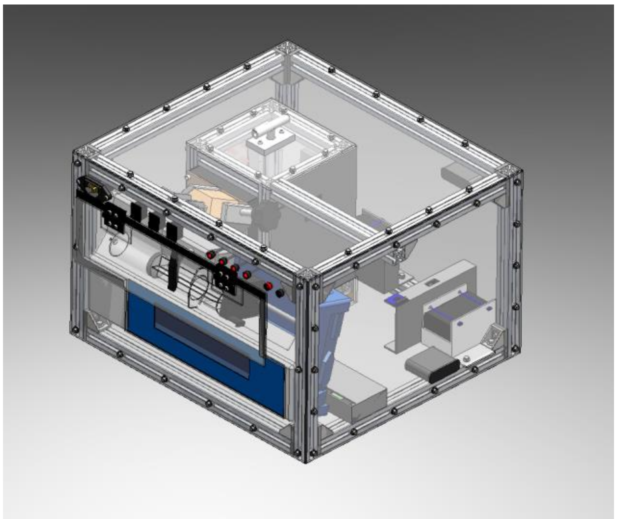

Figure 1a. Isometric view of the experimental module design

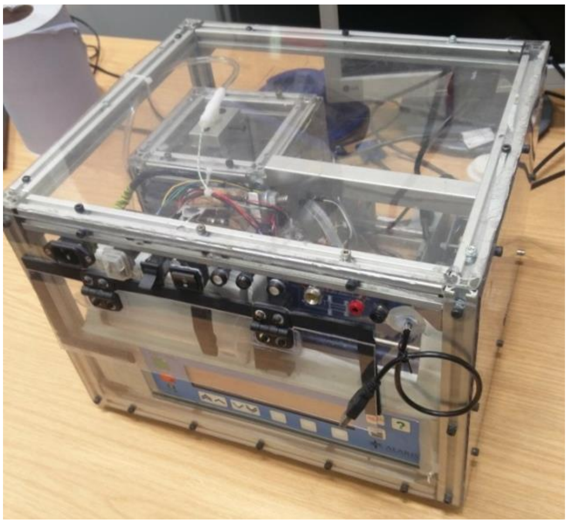

Figure 1b. Assembled experimental module

The built module dimensions are 394×252×354 ±0.5 mm (Width × Height × Depth), with a mass of 10.90±0.05 kg (dry mass when empty of fluid). The fluid system consists of (Figure2a): Pump; Syringe; Tubing and tee-connector; Test chamber (surrounding structure, water collection pot); Nozzle; Sensors (thermocouple and accelerometers)

The electronics, data collection and camera components consist of (Figure 2b): Onboard computers; Cameras; Batteries (for onboard computer and for light panels); Control panel (switches, identification Light Emitting Diodes; charging points); Video output cable adaptors

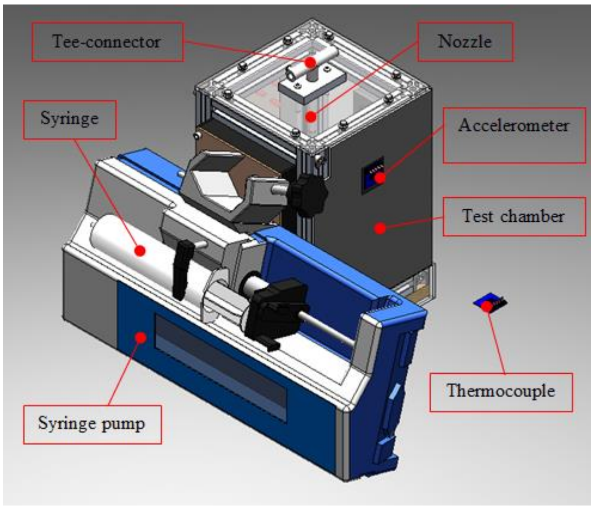

Figure 2a. Fluid system components

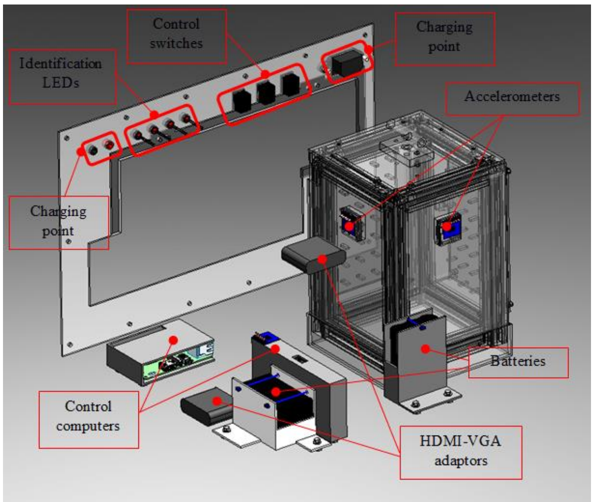

Figure 2b. Data processing, cameras and electronics components

The water jet is produced using the IVAC P6000 pump [13], which can provide a maximum purge rate of 500 ml/hr ($Re = 177.16$), and the pump provides ±2% volumetric flow rate error, with a flow rate step increase of 1 ml/hr (corresponding to a Reynolds number increase of 4.8×10^{-3} at 20 ^{o}C, 101 kPa). Two cameras were mounted at right angles to take simultaneous recordings of the drop formation, with backlit panels lit by LEDs (Figures 3a and 3b).

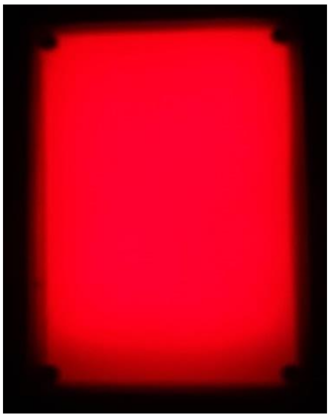

Figure 3a. Panel in operation in darkness

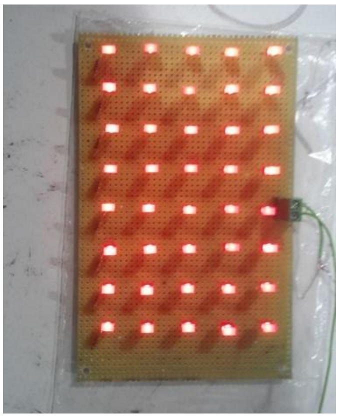

Figure 3b. LED distribution behind the panel

The video image underwent a series of enhancements in order to produce a sharper image from which centroid co-ordinates could be extracted in order to measure the movement of the drop, including determination of drop detachment.

2. Results

We present here indicative data on the development of ‘mid’ drops, a result not predicted by current models.

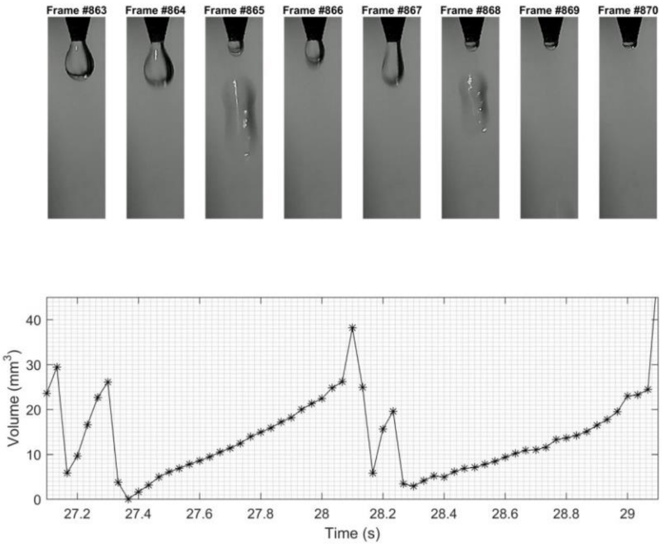

Figure 4. Mid drop development

3. Conclusion

A system was constructed to measure the development of liquid drops and results presented on the formation of a behaviour that is not predicted by current models of drop formation. The development of such a rig permits the study of drop development in greater detail, which can therefore provide results rendering the system more valuable for colleagues working in this field.

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