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Effect of geometrical parameters on flow-switching frequencies in 3D printed fluidic oscillators containing different liquids

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ABSTRACT

There is limited information available regarding fluidic oscillator design for liquid phase applications. In this paper, the results of a simple parametric study investigating the effects of seven geometrical parameters on the flow-switching frequencies produced in 3D printed single feedback loop bistable oscillators are reported for a variety of glycerol–water mixtures. The most consequential parameter was the splitter distance (distance between the power nozzle and two outlet streams). Reducing the splitter distance from 10 mm to 5 mm produced higher frequencies at the same flow rate. The angle between the outlet channels was also important, with wider angles (18–24°) producing slightly higher frequencies. Feedback loop widths of 4 mm and greater did not produce flow switching. Other factors that inhibited oscillations were reducing the inlet zone length from 32 mm to 22 mm and changing the feedback channel orientation from horizontal to vertical. Increasing the convergence length of the power nozzle (from 5 to 25 mm) and changing the feedback loop length (from 101 to 113 mm) did not greatly affect the frequencies obtained. Overall, frequencies of 2–22 Hz were produced for kinematic viscosities of 1.00–4.37 mm^2/s, in the range of Re = 600–12,000.

1. Introduction

Fluid oscillators of the bistable amplifier type are one example of fluidics that has found new interest in a wide range of applications. Example gas-phase applications include enhanced microbubble generation in gas spargers (Zimmerman et al., 2009a), flow control, flow separation (aeronautics) (Tesař et al., 2013), noise control (Raman and Raghu, 2004) and combustion (Guyot et al., 2009). Basic liquid-phase oscillator applications include sprinklers, shower heads, Jacuzzis and windscreen washers (Bobusch et al., 2013). Recently, improvements in liquid extraction mass transfer coefficients were also reported when using a microchannel oscillator (Xu and Chu, 2014; Xu and Chu, 2015).

A potential new application of liquid-based fluidic oscillators is their use in reactors. The Oscillatory Baffled Reactor for example operates through a vortex production and dissipation cycle by oscillating the fluid in the presence of baffles. When this mechanism is superimposed onto a net flow rate, plug flow can be realised due to the analogous behaviour of well mixed tanks-in-series. Oscillation has been achieved via two methods in the literature. Typically, the fluid is oscillated using some form of piston and bellows arrangement (Stonestreet and Van Der Veeken, 1999), or through the use of a syringe pump (Phan and Harvey, 2010). Alternatively, the baffle assembly itself has been oscillated to induce mixing (Ni et al., 1998). Both methods require moving parts, which although is non-problematic in laboratory settings, may limit their appeal for industrial applications. Fluidic oscillators offer the potential for realising mixing and plug flow (and heat/mass transfer improvements) without the need for moving parts.

Fluidic oscillators enable autonomous rapid flow switching between two outlets using internal feedback, leading to dual stream pulsations. Switching frequencies ranging from 10 Hz to 20 kHz (Gregory et al., 2007) are reported, although the highest frequencies are typically only obtainable in microchannels with high Reynolds numbers (Tesař, 2015). The two principle modes of operation are momentum transfer in double feedback designs, and pressure transfer in single feedback loop designs.

The single feedback loop design comprises of a supply port, two outlet channels and two control ports that are connected via a single feedback loop (Fig. 1). This design was originally patented by Warren (1960) and later applied by Tippetts et al. (1973) as a flowmeter. Operation is mainly governed by the Coandă effect, which describes the

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Nomenclature

b	Power nozzle width (m)
d	Feedback loop width (m)
De	Dean number ($=\sqrt{d/r}Re$)
f	Flow switching frequency (Hz)
l	Feedback loop length (m)
r	Radius of curvature of the feedback loop (m)
Re	Reynolds number ($=\rho v d/\mu$)
Sr	Strouhal number ($=fb/v$)
v	Liquid velocity emerging from the power nozzle (m/s)
v_a	Liquid velocity in the feedback loop (m/s)

Greek letters

ρ	Density (kg/m^3)
μ	Viscosity (m^2/s)

tendency of a fluid jet emerging from a nozzle to adhere to an adjacent surface. Wall attachment occurs because of the formation of a vortex near the wall as a result of fluid entrainment. This vortex creates a low-pressure zone leading to a pressure difference across the jet. Flow switching develops from instabilities provided by the feedback loop, whereby a pressure wave is transferred from the high-pressure side to low-pressure side (wall attachment side). The resulting feedback flow causes the vortex to grow large enough for the jet to detach and adhere to the other wall. The process is represented in Fig. 1. The concave wall between the two outlets shown in Fig. 1 also leads to the formation of a secondary stabilisation vortex in the oscillating chamber (Tesař and Bandalusena, 2011).

Fluidic oscillators typically operate under constant Strouhal number (Sr) (Tesař et al., 2013), defined by Eq. (1). This is because the frequency response is proportional to the increase in velocity. Tesař et al. (2006) additionally proposed a modified Strouhal number that enables assessment of the velocity through the feedback loop. As shown in Eq. (2), the frequency is the reciprocal of the time taken to complete one full oscillation cycle, in which two propagations around the feedback loop occur. For Eq. (2) to provide a reliable estimate of the feedback channel velocity, the switching process must occur faster than the separation bubble growth process. In these equations, f is the switching frequency (Hz), b is the nozzle width (m), v is the velocity of the jet emerging from the nozzle (m/s), v_a is the velocity in the feedback channel (m/s) and l is the length of the feedback channel (m).

$$Sr = \frac{fb}{v} \tag{1}$$

$$Sr' = 2\left(\frac{l}{b}\right)\frac{fb}{v} = \frac{2fl}{v} = \frac{v_a}{v} \tag{2}$$

The advantages of fluidic oscillators over conventional oscillator designs (pistons etc.) as oscillators for OBRs are their simplicity and passive operation. Passive mixers are preferable because of their robustness. However, research into these oscillators typically focuses on gas phase applications, with only a small number of parametric studies available for air-based designs (Gregory et al., 2007; Tesař et al., 2006; Mack et al., 2011; Arwatz et al., 2008a).

There are fewer examples of liquid-phase design investigations. A single parametric study involving the design of a double feedback loop oscillator containing water is reported, where it was found that the jet nozzle width, feedback channel width, channel height and oscillator chamber shape did not influence the frequencies (Xu and Meng, 2013). However, this study did not investigate the effect of fluid property, and is only valid for single outlet channel applications. The internal flow mechanisms of feedback-free (Tomac and Gregory, 2014) and double feedback loop (Li et al., 2013) oscillators using water have also been studied via CFD and PIV. The aim of the current paper is to therefore investigate the effects of varying fluidic oscillator geometries on the frequency response using liquids of varying densities and viscosities. Here the focus was on the single feedback loop design containing two outlet channels, as shown in Fig. 1.

To accelerate the design, fabrication and characterisation of the fluidic oscillator geometries, 3D printing was used. 3D printing is being used increasingly frequently for such rapid prototyping, particularly when it allows development of geometries unobtainable using conventional means. Other advantages include: small batch production, economically viable prototypes, reduced waste, easy customisation and reduced costs.

2. Methodology

2.1. *Fluidic oscillator designs*

The base design of fluidic oscillator used here is shown in Fig. 2a, which is similar to the model used by Tesař et al. (2006). This design consists of a 1 mm nozzle constriction size and 25 mm nozzle convergence length, with a total inlet distance of 32 mm. After the nozzle, a splitter with 1 mm diameter concave wall was positioned at a distance of 7 mm. Also located adjacent to the nozzle were two control ports, connected by a 3 mm width, 101 mm length feedback loop. Due to the position of the feedback loop, the liquid was supplied via a 90° bend, converging from an 8 mm to 4 mm tube diameter. The two outlet channels were 65 mm in length and the diameters of the outlet ports were 4 mm. The external geometry was chosen to minimise the amount of resin required to print each

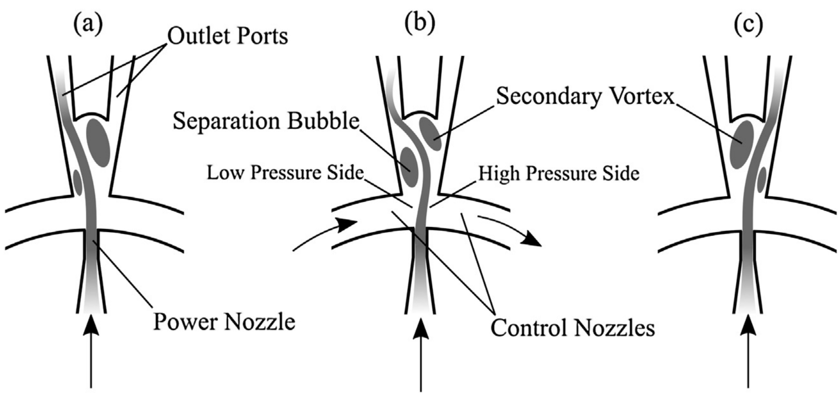

Fig. 1 – Flow switching mechanism in a single feedback loop bistable oscillator; (a) wall attachment and formation of separation bubble, (b) growth of the separation bubble via flow around the feedback channel, (c) switching of the main jet to the other outlet.