Theoretical development and critical analysis of burst frequency equations for passive valves on centrifugal microfluidic platforms

Tzer Hwai Gilbert Thio · Salar Soroori · Fatimah Ibrahim · Wisam Al-Faqheri · Norhayati Soin · Lawrence Kulinsky · Marc Madou

Introduction

In recent years, there has been an increasing interest in the area of microfluidics for biochemical/biomedical applications. One particular area of microfluidics research is the development of microfluidic compact disc (CD) platforms that operate on the basis of centrifugal pumping. A microfluidic CD allows for the miniaturization of large and expensive equipment, reduction in reagent usage, faster heating and cooling, efficient chromatographic and electrophoretic separations, and low-cost fabrication [23, 32].

On a microfluidic CD, a wide range of processes such as valving, decanting, calibration, mixing, metering, heating, sample/volume splitting, separation, siphoning, flow rate control, droplet generation, etc. are possible [9, 23, 32]. Based on this wide variety and availability of processes, implementation of complex assays such as the enzyme-linkedimmunosorbent assay (ELISA) is possible on CDs. Some examples are the detection of rat IgG from a hybridoma cell culture by Lai et al. [17], the detection of Dengue nonstructural protein 1 (NS-1) by Yusoff et al. [29], the implementation of a 5-step ELISA through a simple 2-layer design by Ibrahim et al. [15], the detection of a cytokine interferongamma by He et al. [14], plasma separation and detection of Hepatitis B virus by Lee et al. [18], and allergen screening by Chen et al. [5]. Recent developments have also introduced

various enhancements to the basic CD valve design such as suction-enhanced siphon valve by Gorkin et al. [13], semi-circular valve by Lin et al. [21], ice valve by Amasia et al. [2], thermally actuated elastomer valve by Pitchaimani et al. [27], wax valves by Lee et al. [18] and Abi-Samra et al. [1], and dissolvable film valve by Gorkin et al. [12].

Madou et al. [23] and Zoval et al. [32] introduced several multi-step processes such as those involved in carrying out an ELISA on a CD through flow sequencing using ‘‘passive’’ valves. ‘‘Passive’’ valving is based on balancing of the capillary force (due to fluid interfacial tension) and the centrifugal force. When the centrifugal force exceeds the capillary force, liquid starts moving and is released, for example, from one reservoir to the next. Proper placement of reservoirs on a microfluidic CD, coupled with proper design of connecting channels, allows for controlled flowsequencing.The rotational frequency at which the centrifugal force overcomes the capillary force to ‘‘open’’ a valve and release a fluid is generally called the burst frequency. Precise control of the burst frequencies on a CD allows for a synchronized fluid release in complex assays. It should be noted that passive valving has some drawbacks. For example, these valves are not vapor-tight and thus have limited use where long-term reagent storage or heating (e.g., for polymerase chain reaction) is required [28].

Passive valves can be either hydrophobic or hydrophilic.A hydrophobic valve typically consists of a channel made of hydrophobic material or the application of hydrophobic material to a specific zone in a hydrophilic channel [23, 32]. An alternative method is to introduce air gaps within a channel to increase the hydrophobicity of that zone. Fishbone valves are structural gaps that serve such purpose [22, 25, 26]. A hydrophilic valve consists of a hydrophilic capillary that has a sudden expansion, for example, when a narrow channel opens into a wider reservoir. Figure 1 illustrates various designs of basic passive valves which are commonly used in various complex assays [5, 14, 15, 17, 18, 29].

Several mathematical models for describing passive

valves are summarized in Table 1. While the 1D model describes capillary pressure in both, hydrophobic and hydrophilic valves, more complex 2Dand 3D models address hydrophilic valves only [4, 16, 24]. Numerous variations of these 1D, 2D, and 3D models include modified 1D equations that consider the capillary pressure difference at the inlet and outlet of a channel [30, 32], modified 1D equations that take into account the heterogeneity of the channel surfaces [3, 8, 20, 22], and models that include the channel opening wedge angle b in the 1D equation [7, 11].

The present analysis will concentrate on the analysis of the models of hydrophilic passive valves. The meniscus propagation in hydrophilic (capillary) valve can be separated into four distinct phases: capillary flow is stopped at the channel opening (1), the fluid movement is resumed under the increased force (2), the concave meniscus becomes convex (3), and then it expands and finally bursts (4).

Methods

Burst frequency fundamentals

The underlying and common principle in all of the aforementioned models is the balancing between the centrifugal

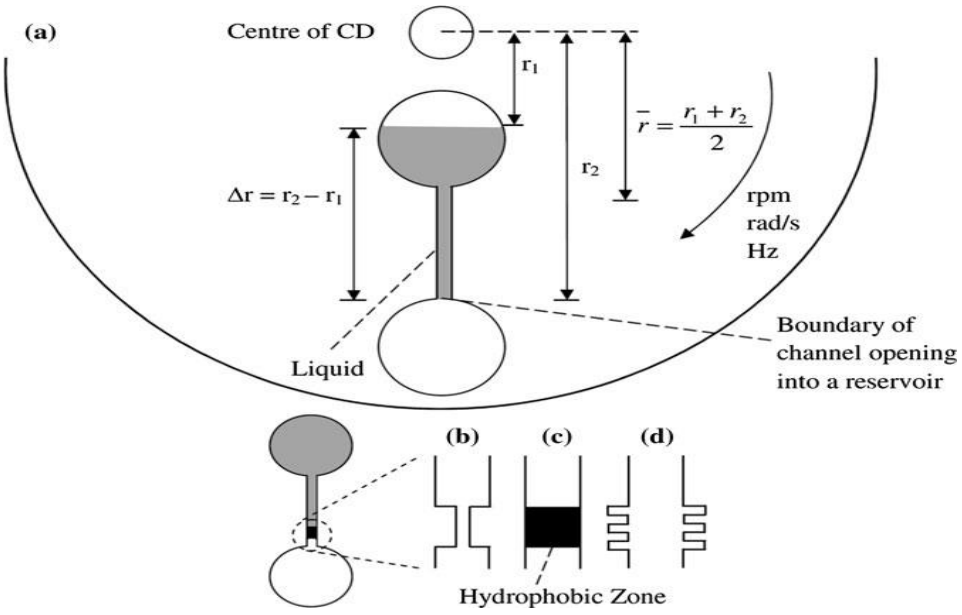

Fig. 1 a The microfluidic CD with hydrophilic capillary valve, b hydrophobic valve with constriction, c hydrophobic valve with hydrophobic zone in an otherwise hydrophilic channel, d fishbone valve

pressure and capillary pressure. The centrifugal pressure is due to the rotation of the CD and is given as