MODULAR ARCHITECTURE IN MICROPUMP

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To my beloved family

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ABSTRACT

This research addresses the design of modular setup of micropump wherein the two basic components of micropump: actuation and flow rectification element are separated. Conventional approach with integrated actuator within the micropump shows less flexibility and discourages disposable usage. Furthermore, fabrication methods of these components need to be compromised to achieve pumping target. Hence, this research investigates and studies the flow behaviour of the modular micropump with a diffuser and a gourd-shape channel design in the flow rectification module. Numerical simulations were built in COMSOL Multiphysics to study and optimise parameters in module design. Based on the obtained parameters from the simulation results, the diffuser module was fabricated on poly (methylmethacrylate) (PMMA) polymer using a rapid hot embossing replication method, whereas the gourd-shape module was fabricated on poly (dimethylsiloxane) (PDMS) polymer with a photolithography and a replication moulding (REM) technique. The actuating gaps between the actuation module and the flow rectification module were studied. The diffuser module (100 µm membrane thickness) exhibited largest flow rate range of 0.06–5.78 mL/min with back pressure 1.35 kPa at 2.5 mm gap. The flow rate performance increased 16.43% with a thinner membrane, 70 µm. For multifunctional application, the gourd-shape chamber module poses bi-directional pumping and mixing characteristic. Experimental result shows the micropump with the flow rate range of 0.20–1.52 mL/min (forward direction) and 0.05–1.48 mL/min (reverse direction). The attributes of the mixing when using this module was further investigated in a forward flow configuration. The mixing performance was quantified by digitally counting each gray level of the captured image. Exclusively, the experimental findings of the proposed modular micropump indicate that the modular architecture is well adapted in micropump development with the advantageous of large flow rate range, flexible with multi-functionality and disposable features.

ABSTRAK

Kajian ini bertujuan untuk mereka bentuk modular mikropam di mana dua komponen asas mikropam: aktuator dan elemen penggarahan aliran dipisahkan. Kaedah konvensional integrasi aktuator di dalam mikropam mempunyai kelemahan daripada segi kekurangan kelenturan dan tidak boleh dibuang selepas digunakan. Tambahan pula, kaedah fabrikasi di antara dua komponen tersebut harus dikompromikan untuk mencapai tujuan mengepam. Justeru, penyelidikan ini mengkaji aliran mikropam dengan penggunaan peresap dan saluran yang berbentuk labu dalam modul penggarahan aliran dua hala. Simulasi telah dibina dengan menggunakan perisian COMSOL Multiphysics untuk mencari parameter yang optimum dalam proses mereka bentuk elemen peresap. Berdasarkan parameter-parameter yang diperolehi melalui keputusan simulasi, peranti tersebut direka dan difabrikasi daripada bahan *poly (methylmethacrylate)* (PMMA) dengan kaedah replikasi. Di samping itu, saluran berbentuk labu difabrikasikan dalam bahan *poly (dimethylsiloxane)* (PDMS) dengan penggunaan teknik fotolitografi dan teknik acuan replikasi. Sela pemisahan antara modul aktuator dan penggarahan telah dikaji. Modul peresap dengan membran (ketebalan 100 μm) menghasilkan kadar aliran dalam lingkungan julat yang besar di mana 0.06–5.78 mL/min pada tekanan balik 1.35 kPa dengan jurang pemisahan 2.5 mm. Pretasi aliran telah ditingkatkan sebanyak 16.43% dengan membran yang lebih nipis iaitu 70 μm. Untuk aplikasi lain, saluran berbentuk labu menunjukkan dua arah aliran dengan kadar 0.20–1.52 mL/min (aliran ke hadapan) and 0.05–1.48 mL/min (aliran terbalik). Selain itu, ciri-ciri campuran antara dua aliran turut disiasat. Pretasi campuran tersebut dikaji dengan membandingkan skala kelabu bagi setiap piksel dalam imej gambar yang ditangkap. Experimentasi mikropam telah menunjukkan seni bina modular adalah sesuai untuk diimplementasikan dalam modular mikropam dengan kelebihan julat kadar aliran yang besar, lentur dengan kepelbagaian fungsi dan mempunyai ciri-ciri pakai buang.

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LIST OF ABBREVIATION

µTAS	-	Micro total analysis system
LOC	-	Lab On a Chip
SMA	-	Shape memory alloy
PCB	-	Printed circuit board
IPMC	-	Ionic polymer metal composite
TiNi	-	Titanium–nickel
MEMS	-	Micro-electromechanical Systems
PDMS	-	Poly(dimethylsiloxane)
$Ni_{80}Fe_{20}$	-	Nickel Iron alloy
Cr-Cu	-	Chronium-copper
NdFeB	-	Neodymium magnet
UV	-	Ultraviolet
AC	-	Alternating current
DC	-	Direct current
rpm	-	Revolutions per minute
Re	-	Reynolds number
CR	-	Curvature ratio
PZT	-	Lead zirconate titanate
PIV	-	Particle image velocimetry
DRIE	-	Deep reactive ion etching
ICP	-	Inductive coupled plasma

PMMA	-	Poly(methyl methacrylate)
PC	-	Polycarbonatecoc
COC	-	Cyclic olefin copolymer
REM	-	Replica moulding
dpi	-	Dots per inch
PCR	-	Polymerase chain reaction
DNA	-	Deoxyribonucleic acid
V_{pp}	-	Peak to peak voltage
RL circuit	-	Resistor-inductor circuit
MOF	-	Maximum operating frequency
FSI	-	Fluid Structural interaction
FEM	-	Finite element modelling
Si	-	Silicon
CR	-	Curvature ratio
CVD	-	Chemical vapour deposition
IPA	-	Isopropanol alcohol
DI	-	De-ionized water
LC circuit	-	Inductor-capacitor circuit
ALE	-	Arbitary lagrangian-eulerian
PEB	-	Post exposure baking
USB	-	Universal serial bus
DMFC	-	Direct methanol fuel cells

LIST OF SYMBOLS

P	-	Pressure
V	-	Velocity
h	-	Height
ρ	-	Fluid density
g	-	Gravitational force
$\mu_{d.v}$	-	Dynamic viscosity
$\overline{\nabla}$	-	Velocity vector
$L_{channel}$	-	Length of a microchannel
$D_{channel}$	-	Diameter of a microchannel
Q_{volume}	-	Volumetric flow rate
F_L	-	Lorentz force
I	-	Current
B	-	Magnetic field
L_{wire}	-	Length of wire
Ø	-	Diameter
Z	-	Impedance
R	-	Resistor
f	-	Frequency
$L_{inductor}$	-	Inductor
d	-	Separation gap
$S_{pre\text{-}travel}$	-	Pre travel stroke volume

S_{work}	-	Working stroke volume
e	-	Entrance
o	-	Outlet
Pe	-	Pressure at entrance
Po	-	Pressure at outlet
θ	-	Opening angle
θ_{op}	-	Optimum half angle
ξ	-	Loss coefficient
ξ_d	-	Diffuser loss coefficient
ξ_n	-	Nozzle loss coefficient
V_{din}	-	Velocity at the inlet
η	-	Diffuser efficiency
L_{diff}	-	Length of diffuser
$v_{k.v}$	-	Kinematics viscosity
$L_{membrane}$	-	Membrane length
$t_{membrane}$	-	Membrane thickness
$L_{plunger}$	-	Plunger length
F_{load}	-	Loading force
$r_{membrane}$	-	Membrane radius
ω_{max}	-	Maximum deflection
$v_{p.r}$	-	Poisson’s ratio
$E_{e.m}$	-	Elastic modulus
$f_{resonant}$	-	Resonant frequency
f_{sp}	-	Self-pumping frequency
A	-	Actuation force
P_A	-	Pressure at end A
P_B	-	Pressure at end B

W_z	-	Z component of vortices
v	-	Velocity component in y direction
u	-	Velocity component in x direction
α	-	Inlet tube
β	-	Outlet tube
F_{off}	-	Offset frequency
η_{pump}	-	Pumping Efficiecny
Q_{max}	-	Maximum volumetric flow rate
P_{max}	-	Maximum back pressure
$P_{actuator}$	-	Power consumption of actuator
N_p	-	Total amount of pixels
$C(y_i)$	-	Concentration intensity at each point
σ	-	Mixing index

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CHAPTER 1

INTRODUCTION

1.1 Background

The Micro Total Analysis System (µTAS), commonly known as Lab-On-a-Chip (LOC) has emerged as a distinct subject with the potential to replace conventional laboratory procedures which are time-consuming and require repetitive fluid handling operations. LOC is considered as an integrated microfluidic platform which manipulates fluids on a microscale to incorporate the disciplines of chemical synthesis and biological analysis, ranging from sample preparation to electrical signal detection. The implementation of a LOC in these disciplines aims to reduce the sample volume, to have greater control of the assay with less manual intervention, allowing high throughput analysis, to shorten analysis time, and finally to reduce the cost of conventional analysis processes [1].

The basic procedure of a LOC comprises sample delivery, preparation before analysis, handling operations and lastly, signal acquisition and measurement. The operation of a LOC is presented as a functional block diagram in Figure 1.1.

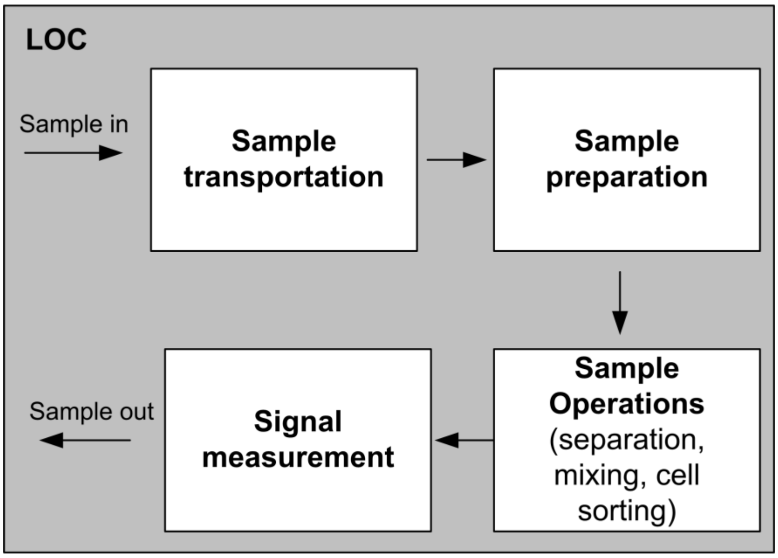

Figure 1.1 Basic operation of LOC (version adapted from *Shen et al.* [2])

From Figure 1.1, the sample transportation subsystem is central to the concept of a LOC to dispense and deliver a micro or nano amount of a material sample to other subsystems for subsequent operation. The physical properties of the sample in the microchannel, such as flow pattern, convection, flow rate and back pressure, will contribute to different levels of chemical reactions that will directly affect the result.

Conventional sample transportation is often established through manual pipetting, external regulated pressure source or by syringe pumps. This has limited the purpose of portability of LOC. Besides, the precision delivery of sample reagent in "micro" amount is difficult. The limited usage of "on chip pumping" mechanism might probably results from the lack of micropump availability with the combination of efficiency and cost [3]. Hence, for a LOC system to capitalize on the aforementioned advantageous, the development of on chip micropump is imperative to provide a better microscale fluid handling methods for microfluidic device.

The first development of a miniature pump can be traced back to 1975, when patented by Thomas *et al*. [4] for human body implantation applications. The device, actuated by a two opposing piezoelectric disc bender, is incorporated with a sequence control by an active solenoid valve to dispense small volumes of fluid. Subsequently, with the continued development of microfabrication technology, in 1990 Smits *et al.*

[5] demonstrated a peristaltic micropump with a silicon micromachining technique. Three piezoelectric operated active valves were used to control the insulin delivery.

For a single actuator operated micropump, van Lintel *et al*. [6] successfully demonstrated the feasibility of a passive silicon check valve integrated into a silicon based micropump to direct the flow. Since then, microfluidic systems with an integrated micropump have attracted much research attention. With this continued development, micropumps not only have a significant presence in academia, but have also begun to appear as commercial devices in biomedical applications.

A more practical instance can be related to the portable insulin delivery micropump (Omnipod^{TM}) developed by Insulet Corporation [7]. The insulin is filled into a syringe which is placed in the micropump and injected into human skin via a shape memory alloy (SMA) actuated linear motor. The portability and better insulin control benefit the diabetic patients compared with the conventional insulin injection system. Besides, a nebuliser which includes an ultrasonic working micropump is manufactured by Nektar [8]. The device is able to deliver an aerosolized antibiotic deep in the lungs of patients who require inhalation therapies. Further uses of micropumps in drug delivery and microneedle technologies are having a major influence in the biomedical field, where their impact will be as catalysts in miniaturised biomedical applications. Several excellent studies [1, 9, 10] have encapsulated the latest trend of micropump implementation as a biomedical device. In addition, the rapid growth of micropump devices has made their application as diverse as microelectronic cooling systems [11, 12] and the fuel cell industry [13].

1.2 Problem Statement

In view of the importance of the sample dispensing procedure in a self-contained LOC control system, a micropump with more flexibility and versatility is much needed. Most of the applications of the current micropumps have been limited to a single purpose device due to the monolithic approach to structure construction, where the actuator and microchannel are integrated into a single chip. This approach needs a common fabrication method for both actuator and microchannel, and their functionality might have to be compromised to achieve the pumping target. Additionally, slight modification to the particular functional component may require reconstruction of the whole device, which might incur a substantial cost and requires a longer development time [14].

In addition, the monolithic micropump structure is not well suited to the intention of being disposable. In a LOC design, disposability is a major aspect that should be highlighted to confirm that the sample is unpolluted. This feature is especially important when the LOC is meant for biomedical analysis applications. The device needs to be disposed of to eliminate the sterilizing procedure and to confirm the hygiene condition of the instrument. Nonetheless, this disposable feature is often constrained by the material used in their construction and the availability of fabrication facilities. For instance, the piezoelectric actuator involves expensive fabrication materials, a complicated fabrication procedure and high operating voltage, which require a specialised set-up which is hard to dispose of after one analytical use [15].

1.3 Research Objectives and Scope of the Thesis

The primary objective of this thesis is to design a modular on-chip micropump to handle a microscale fluid transportation process. The specific goals can be further expressed as:

(1) To develop a micropump with a modular set-up and to study its pumping behaviour in a modular configuration.
(2) To explore the bi-directional pumping and mixing multifunctional features that contribute to the modular architecture.

To accomplish these objectives, two different micropump architectures were proposed and their pumping characteristics were studied. The setup of the first architecture is to demonstrate the feasibility of the on-chip pumping operation in an external separated actuation mechanism. The actuation mechanism will focus on a solenoid-based electromagnetic actuator. As the device is meant for *in vitro* LOC application, disposability will be highlighted in this thesis. The disposable feature of the device can be constructed by using widely available and cost-effective polymer and the utilisation of low cost rapid prototyping fabrication technology.

Structurally, the design of the chip which functions to regulate the flow is made in a planar configuration in order to fit within functional modules. To have a wider selectivity of the sample selection, such as particle-laden samples, no moving flap valve is involved in the construction of the structure, as such a moving valve might be susceptible to the risk of particle clogging. The focus on the chip design mainly concentrates on microchannel manipulation, where the fluid dynamics involved in flow regulation is examined. By altering the fluid dynamics in the microchannel, bi-directional flow and mixing functions can be established. This multifunctional behaviour is investigated in the second modular architecture.

1.4 Research Methodology

Basically, the micropump architecture consists of two basic modules: actuation module and flow rectification modules. The actuation module creates pressure difference within the pump chamber, whereas the flow rectification module directs the flow stream. In this thesis, the flow behaviour of the flow rectification module was studied with diffuser and gourd-shape elements. In addition, bi-directional and mixing performances of the gourd-shape elements were characterised.

To design the flow rectification module, finite element modelling (FEM) was employed to find the optimum parameters. The diffuser channel was evaluated based on minor loss theory with the investigation of the diffuser angle opening, curvature ratio and entrance length study. Besides, the membrane which creates stroke volume within the pump was judged on its shape geometry, material, thickness and surface interaction with plunger contact. After gaining the data, the flow rectification modules were fabricated with replication approach. The diffuser module was fabricated through rapid hot embossing technology with PCB mould in PMMA material. On the other hand, the gourd-shape module was constructed with PDMS material via photolithography technique in mould fabrication.

Experimental characterisation of the actuation module and flow rectification module include the pump flow rate performance at low operating frequency, nominal frequency, and at back pressure variation with the separation distance of 2.0 mm, 2.5 mm and 3.0 mm. Lastly, the flow rate and back pressure performance of the micropump was compared with its reported counter parts.

1.5 Significant Findings

This section describes the contributions of the research works to the body of knowledge in the field of micropumps. Experimental investigation of the modular micropump development is presented in this thesis. The major outcomes of this thesis can be summarised as follows:

(1) The pinch mechanism was introduced by using an electromagnetic solenoid for the modular setup. Experimental investigation was conducted on the behaviour of flow in the diffuser channel at the specified pinch mechanism.

(2) To address the low cost objective in pump construction, a low cost and more user-friendly prototyping protocol was developed in the module fabrication. Low cost equipments such as a printed circuit board (PCB) mould, laboratory oven, vice clamp and aluminium sheets were employed in the thermoplastic replication. 450 μm thick diffuser channels (replica) were successfully fabricated.

(3) To the best of the author's knowledge, no reports exist on flow regulation based on the dynamic rectification principle. The direction of flow depends on the flow dynamics induced by the pinch operation and the fixed geometrical structure of the chamber. This principle added extra credit in making the pump

more multifunctional such as for use in bi-directional pumping and particle mixing.

1.6 Thesis Outline

A review of the micropump development associated with the present study is given in Chapter 2, including the basic components of the mechanical micropump, the mixer and rapid prototyping technique. Then, in Chapter 3, the conceptual design of the modular setup is illustrated with the experimental investigation on the actuation module, in which an electromagnetic actuator will be utilised. In addition, a numerical simulation was performed to study the operating geometrical parameters of the diffuser flow module, and the results obtained will act as a guideline in device development. Subsequently, the development of the diffuser element in the flow rectification module is described in Chapter 4. In Chapter 4, the diffuser flow module is realised and experimental characterisation of the diffuser module is shown. Next, by changing the diffuser and chamber elements, a bi-directional flow can be established with the developed gourd-shaped chamber module in Chapter 5. In addition, the mixing characteristics contributed by the gourd-shaped module are investigated. Finally, the thesis concludes in Chapter 6 with an outlook on future project development.

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