FREQUENCY-CONTROLLED WIRELESS PASSIVE MICROFLUIDIC DEVICES

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I dedicate this thesis to my beloved family whose love, kindness, patience and prayer have brought me this far

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ABSTRACT

Microfluidics is a promising technology that is increasingly attracting the attention of researchers due to its high efficiency and low-cost features. Micropumps, micromixers, and microvalves have been widely applied in various biomedical applications due to their compact size and precise dosage controllability. Nevertheless, despite the vast amount of research reported in this research area, the ability to implement these devices in portable and implantable applications is still limited. To date, such devices are constricted to the use of wires, or on-board power supplies, such as batteries. This thesis presents novel techniques that allow wireless control of passive microfluidic devices using an external radiofrequency magnetic field utilizing thermopneumatic principle. Three microfluidic devices are designed and developed to perform within the range of implantable drug-delivery devices. To demonstrate the wireless control of microfluidic devices, a wireless implantable thermopneumatic micropump is presented. Thermopneumatic pumping with a maximum flow rate of 2.86 μL/min is realized using a planar wirelessly-controlled passive inductor-capacitor heater. Then, this principle was extended in order to demonstrate the selective wireless control of multiple passive heaters. A passive wirelessly-controlled thermopneumatic zigzag micromixer is developed as a mean of a multiple drug delivery device. A maximum mixing efficiency of 96.1% is achieved by selectively activating two passive wireless planar inductor-capacitor heaters that have different resonant frequency values. To eliminate the heat associated with aforementioned wireless devices, a wireless piezoelectric normally-closed microvalve for drug delivery applications is developed. A piezoelectric diaphragm is operated wirelessly using the wireless power that is transferred from an external magnetic field. Valving is achieved with a percentage error as low as 3.11% in a 3 days long-term functionality test. The developed devices present a promising implementation of the reported wireless actuation principles in various portable and implantable biomedical applications, such as drug delivery, analytical assays, and cell lysis devices.

ABSTRAK

Bendalir-mikro adalah teknologi yang berpotensi tinggi dan semakin menarik perhatian penyelidik kerana ciri-ciri kecekapan yang tinggi dan kos yang rendah. Pam, pencampur dan injap-mikro telah digunakan secara meluas dalam pelbagai aplikasi bioperubatan kerana saiz yang kecil dan kebolehkawalan dos yang tepat. Meskipun banyak penyelidikan dilaporkan dalam bidang ini, aplikasinya dalam peranti mudah alih dan boleh implan masih terhad. Sehingga kini, peranti sedemikian terbatas kepada penggunaan wayar, atau bekalan kuasa seperti bateri. Tesis ini melaporkan teknik novel yang membolehkan kawalan tanpa wayar bagi peranti bendalir-mikro pasif termopneumatik dengan menggunakan medan magnet. Tiga peranti bendalir-mikro direka bentuk dan dibangunkan untuk kegunaan dalam lingkungan peranti perembesan ubat boleh implan. Untuk mendemonstrasi kawalan tanpa wayar peranti bendalir-mikro, satu pam mikro thermopneumatik boleh implan dilaporkan. Pam termopneumatik dengan kadar perembesan maksimum 2.86 µL/min direalisasikan dengan menggunakan pemanasan induktor-kapasitor pasif satah yang dikendalikan tanpa wayar. Kemudian, prinsip ini dikembangkan untuk menunjukkan kawalan tanpa wayar bagi pengaktifan terpilih beberapa pemanas pasif. Sebuah pencampur-mikro thermopneumatik pasif berliku tanpa wayar dibangunkan sebagai satu alat peranti perembesan ubat implan berganda. Kadar pencampuran maksimum 96.1 % dicapai dengan mengaktifkan dua pemanas pasif tanpa wayar yang mempunyai nilai frekuensi resonan yang berbeza secara terpilih. Untuk menyingkirkan kesan haba yang berkaitan dengan peranti tanpa wayar tersebut, satu injap-mikro piezoelektrik biasa-tertutup dibina untuk aplikasi perembesan ubat implan. Penginjapan dicapai dengan kadar ralat serendah 3.11 % untuk pengujian jangka panjang selama tiga hari. Peranti yang dibangunkan menunjukkan potensi pengunaan prinsip-prinsip pergerakan tanpa wayar dalam pelbagai aplikasi bioperubatan mudah alih dan boleh implan seperti perembesan ubat, ujian analisis dan peranti sel lisis.

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LIST OF ABBREVIATIONS

°C	-	Degrees Celsius
3D	-	Three-dimensional
A	-	Ampere
AC	-	Alternating current
CAD	-	Computer-aided design
C	-	Capacitor
cm	-	Centimeter
cm^2	-	Squared centimeter
cm^3	-	Cubic centimeter
DI	-	Deionized
DNA	-	Deoxyribonucleic acid
Exp.	-	Experimental
F	-	Farad
FEA	-	Finite element analysis
g	-	Gram
H	-	Henry
h	-	Hour
Hz	-	Hertz
IR	-	Infrared
K	-	Kelvin
k	-	Kilo
kg	-	Kilogram
kHz	-	Kilohertz
kPa	-	Kilopascal
kΩ	-	Kiloohm
L	-	Inductor
LC	-	Inductor-capacitor

LOC	-	Lab-on-a-chip
m	-	Meter
mA	-	Milliampere
M	-	Mega
MEMS	-	Microelectromechanical systems
mH	-	Millihenry
MHz	-	Mega hertz
min	-	Minute
mm	-	Millimetre
mm^2	-	Squared millimeter
mm^3	-	Cubic millimeter
mW	-	Milliwatt
n	-	Nano
N	-	Newton
nH	-	Nanohenry
nL	-	Nanoliter
Pa	-	Pascal
PBS	-	Phosphate buffered saline
PC	-	Polycarbonate
PDMS	-	Polydimethylsiloxane
PEA	-	Piezoelectric actuator
pF	-	Picofarad
PI	-	Polyimide
PMMA	-	Poly(methyl methacrylate)
POC	-	Point-of-care
Ref.	-	Reference
RF	-	Radio frequency
rpm	-	Revolutions per minute
s	-	Second
Sim.	-	Simualtion
SMA	-	Shape memory alloy
V	-	Volt
W	-	Watt
WPT	-	Wireless power transfer

μL	-	Microliter
μm	-	Micrometre
μN	-	Micronewton
μTAS	-	Micro total analysis systems

LIST OF SYMBOLS

μ_f - Fluid viscosity

A_2 - Cross-sectional area of the device coil

A_C - Cross-sectional area of the microchannel

A_{Co} - cross-sectional area of the coil

A_{PDMS} - Cross sectional surface area between the LC wireless heater and the heating chamber

A_{Pl} - Area of the parallel plates of the capacitor

A_v - Polynomial of unknown vibration parameters

A_W - Area of the top wall of the chamber

b' - Damper coefficient of the piezoelectric actuator and coupled PDMS layers

B_v - Polynomial of output lag vibration parameters

c - Molar concentration

$\overline{c}$ - Mean molar concentration of a fully mixed solution

c_{ni} - Molar concentration at a point *ni*

C_P - Capacitance of the piezoelectric actuator

C_{par} - Parasitic capacitance

C_T - Tuning capacitor on the transmitter side

C_{th} - Effective heat capacity of the air chamber

C_{total} - Total capacitance of the planar heater

D - *D*iffusion coefficient

d - Piezoelectric material constant

$D_{2,j}$ - Distance between the centers of the *j*-th wire segments

d_{avg} - Average diameter of the planar coil

d_C - Separation gap between the plates of the capacitor

D_h - Hydraulic diameter of the microchannel

d_{in} - Inner diameter of the planar coil

d_{out} - Outer diameter of the planar coil

E - Young's modulus of the membrane of the reservoir

$\dot{E}$ - Thermal power supplied to the air chamber

f_m - Magnetic field frequency

f_o - Operating frequency

F_{P-} - Force generated by the piezoelectric actuator and the coupled parts during negative parts of the voltage signal

F_{P+} - Force generated by the piezoelectric actuator and the coupled parts during positive parts of the voltage signal

F_{P0} - Force exerted by the piezoelectric actuator and the coupled parts when no voltage is applied

F_R - Force exerted by the reservoir

f_r - Resonant frequency

f_{rP} - Resonant frequency of the unloaded piezoelectric actuator

f'_{rP} - Resonant frequency of the loaded piezoelectric actuator

g^{-1} - Time-shift operator

h_{air} - Effective heat transfer coefficient of the walls of the air chamber to the surroundings

h_{max} - Maximum height of the membrane of the reservoir

i - Number of the segments of the coil

i_1 - Total current of the device coil

i_2 - Total current of the external coil

j - Number of segments pairs of the coil

k - Thermal conductivity

k' - Stiffness of the piezoelectric actuator and coupled PDMS layers

K_1 - Layout dependent constant 1

K_2 - Layout dependent constant 2

k_B - Boltzmann constant

L - Inductor

l - Length of the coil

L_1 - Inductance of the external coil

L_2 - Inductance of the device coil

l_2 - Total length of the device coil

$l_{2,i}$ - Length of the *i*-th wire segment of the device coil

$L_{2,i}$ - Self-inductance value of each wire segment of the device coil

l_C - Length of the microchannel

L_{Co} - Inductance of the coil

L_{S1} - Self-inductance of the device coil

L_{S2} - Self-inductance of the external coil

L_T - Total inductance measured when the two coils are connected in series

m - Effective mass of the unloaded piezoelectric actuator

M - Mutual inductance between two coils

m' - Effective mass of the piezoelectric actuator and coupled PDMS layers

$M_{2,j}$ - Mutual inductance of between each pair of wire segments of the device coil

N - Number of air molecules enclosed in the air chamber.

n - Number of turns

ni - point inside the microchannel

n_p - Total number of sample points inside the cross-section of the microchannel

P - Power consumed in the heater

p - Pressure

Pe - Peclet number

Q - conduction of energy transfer

q - Flow rate

r - Radius of the microchannel

R - Resistance of the coil

r_1 - Bare radius of the wire of the external coil

R_1 - Resistance of the external coil

r_2 - Bare radius of the wire of the device coil

R_2 - Resistance of the device coil

r_C - Diagonal length of the microchannel.

R_C - Radial location in the microchannel

Re - Reynolds number

R_P - Resistance of the piezoelectric actuator

R_s - Internal resistance of the voltage source

R_T - Thermal resistance to the surroundings

s - Deformation of the walls

s_C - Separation gap of the planar coil

s_T - Total displacement of the piezoelectric actuator

T - Absolute temperature

t - Time

T_0 - Room temperature

T_1 - New temperature

T_{SS} - Steady state temperature generated in the heater

u - Flow velocity

u_z - z-component of the flow velocity

v - Electromotive force

V - Volume of the gas

V_0 - Volume of the air in the chamber at room temperature

V_1 - Volume of the air in the chamber at new temperature

V_D - Dispensed liquid volume

v_P - Voltage across the piezoelectric actuator

V_{PBS} - Volumes of the PBS solution

V_R - Volume of the reservoir

v_S - Voltage source

V_T - Total volume of the PBS and pH 4 buffer solutions

w_C - Width of the planar coil

Z_1 - Total impedance of the device coil

Z_2 - Total impedance of the external coil

α - Parameter that control the shape and the amplitude of the hysteresis loop

α_R - Temperature coefficient of the resistance of the circuit

β - Parameter that control the shape and the amplitude of the hysteresis loop

γ - Parameter that control the shape and the amplitude of the hysteresis loop

δ - Skin depth of the conductor

Δh - Change in the height of the membrane of the reservoir

Δp - Change in pressure inside the air chamber

ΔT - Temperature difference between the heater and the chamber

ΔV - Volume difference of the air in the chamber

Δx - Thickness of the membrane of the reservoir

Δxy - Gap separation distance

ε_0 - Vacuum permittivity

ε_r - Dielectric constant of the dielectric material

μ - Absolute magnetic permeability

μ_0 - Magnetivity of free space

ρ - Resistivity of the material

ρ_f - Fluid density

ρ_{fr} - Fill ratio

σ - Standard deviation of the molar concentration across the channel

σ_M - Standard deviation of the distance travelled by a molecule

σ_{max} - Maximum standard deviation at the inlet of the main microchannel

ω - Angular frequency of the AC current

Ω - Ohm

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Microelectromechanical systems (MEMS) is a promising technology that has enabled various sensors [1], actuators [2], electronics [3], and structures [4] to be realized. This consequently enabled manufacturing a wide range of miniaturized devices using microfabrication techniques [5]. Since the beginning of MEMS development, fluidic devices have captured the attention of researchers, which made them among the first devices to be fabricated in microscale [6]. The rapid development of MEMS-compatible technologies has provided means to continuously develop and miniaturize microfluidic devices, which allowed them to precisely manipulate small volumes of liquids within a short time. In addition, such devices require less human intervention and a lower cost, while maintaining a higher sensitivity and stability when compared to traditional fluidic platforms [7]. Since then, several types of microfluidic devices have been developed, such as micropumps [8], micromixers [9], microvalves [10], microneedles [11], microreservoirs [12], and microchannels [13]. However, the first three types form the majority of the reported microfluidic devices, due to their crucial functions in modern-day microfluidic applications [14-16].

In numerous microfluidic systems, a self-contained micropump is an essential component for precise samples/reagents transport, metering, and delivery [14]. Therefore, micropumping components are often integrated into such systems to achieve a reasonable flow rate and overcome the induced back pressure [16]. In addition to the micropump, the micromixer is another component that plays a core role in various microfluidic devices, where rapid homogeneous mixing is essential for biological assays and chemical reactions [17]. In such devices, mixing is dominated by a slow molecular diffusion, which is caused by the laminar flow that occurs at low Reynolds number (*Re*) values [18]. Thus, micromixers are utilized to overcome this challenge within microscale geometries, where traditional methods of stirring fluids are inapplicable [19]. The microvalve is another substantial component in microfluidic devices, which performs sealing, isolating regions, containing reagents, on/off switching, and regulating the fluids flow [20, 21].

Several types of micropumps, micromixers, and microvalves have been developed to achieve the aforementioned tasks using different approaches that suit the desired applications. These devices are often operated using different types of microactuators, such as electrostatic [22], electromagnetic [23], shape memory alloy (SMA) [24], thermal [25], piezoelectric [26], and thermopneumatic microactuators [27]. Electrostatic microactuators provide fast response and high efficiency. However, they have a short lifetime and require a high driving voltage while generating small stroke [28]. Despite the high efficiency possessed by electromagnetic microactuators, they suffer from limitations in terms of process and material compatibility, and the integration of the magnetic material into the overall fabrication process [29]. SMA microactuators offer a high force and a large actuation range. However, they are similar to thermal microactuators in terms of having low efficiency and slow cycle rates [30]. Piezoelectric actuators (PEAs) have the highest efficiency among the other types of microactuators. Furthermore, they have the advantages of high resolution in the nanometer range, fast response, and high stiffness [31]. Thermopneumatic microactuators are well-known for generating large pressure and deflection with a relatively low input voltage [5]. Thus, piezoelectric and thermopneumatic microactuators are favorable choices in various microfluidic applications.

The aforementioned attractive characteristics of microfluidic devices and their various actuation mechanisms promoted the integration of transport [32], mixing [33], separation [34], regulation [35], analyzing [36], and delivery [37] of biomedical samples into a single microfluidic device. The integration of some or all of the aforementioned operations led to the development of several biomedical applications, such as gene detection [38], cell culture [39], medical imaging [40], drug delivery [41], lab-on-a-chip (LOC) [42], point-of-care (POC) diagnostics [43], and micro total analysis systems (μTAS) [44]. Nevertheless, there are still opportunities for further enhancements in terms of the design, fabrication, and powering approaches of microfluidic devices in order to enhance their performance and implementation in portable and implantable applications.

1.2 Problem Statement

Despite the vast amount of research reported on micropumps, micromixers, and microvalves, the ability to miniaturize and implement these devices in portable and implantable applications is still limited. There are still many challenges with their actuation, powering, and integration methods. To date, such devices are restricted to the use of bulky magnetic cores [45], biofuel cells [46], nuclear cells [47], or on-board batteries [48]. These approaches are not suitable for long-term operation implants and require consideration of several practical issues, such as the device size and power stability, as well as the feasibility for biomedical applications and multiple-actuator control. Passively operated actuators offer the opportunity to minimize the size and cost of such systems while maintaining a higher robustness and longevity as compared to actively operated actuators. Additionally, passively operated systems are more favorable in the field of implantable biomedical devices, since they offer less potential risk and a longer interval between replacement surgeries, and require less complicated procedures when it comes to manufacturing and sealing with biocompatible materials [49]. Wireless actuation methods can potentially address the aforementioned issues in implantable microfluidic devices. One possible wireless actuation method can be achieved using wireless inductor-capacitor (LC) resonant circuits that are controlled by external magnetic fields. These LC circuits can be either designed to pass the transferred power to a microactuator or utilize that power to generate Joule heating and form passive heaters [50-54]. However, wireless actuation methods in microfluidic devices have not been well-explored. There still exist areas for continued development in terms of microactuation mechanisms and multiple-microactuator control. Addressing these issues will allow selective-activating of multiple microactuators to be realized, which will consequently allow multiple-drug delivery at different doses and concentrations for several clinical applications, such as treatments for Parkinson’s disease, diabetes, and glaucoma [50]. Furthermore, these abilities will also allow developing and testing multiple drugs in a single implantation using one animal [55].

Other issues associated with microfluidic devices are the fabrication process and microactuators integration in these devices, which usually consist of several steps that require high-cost fabrication methods [56]. Nonetheless, several alternative low-cost fabrication methods have been reported to address these issues [57-60]. However, this area has not been well-exploited to achieve a satisfactory advancement. There is still room for improvement in terms of the methods and materials used in molds and structures fabrication, as well as bonding and characterization techniques. These issues can be potentially solved using out-of-clean-room fabrication techniques, which offer cost-effective solutions for batch-fabrication processes.

Addressing the aforementioned challenges assosiated with microfluidic devices using wireless actuation methods and out-of-clean-room fabrication techniques will promote advances in several biomedical application areas.

1.3 Research Objectives

The main objectives of this research are to develop passive microfluidic devices for biomedical applications that involve a thermopneumatic micropump, a zigzag micromixer, and a piezo-actuated microvalve that are powered and controlled wirelessly using an external magnetic field. The specific objectives are:

1. To determine the parameters that govern the flow in microfluidic devices, as well as their actuation mechanisms and energy sources required.

2. To develop a passive wirelessly-controlled thermopneumatic micropump for drug delivery applications.

3. To develop a wirelessly-controlled passive thermopneumatic zigzag micromixer for variable concentration multi-drug delivery applications.

4. To develop a passive wirelessly-controlled normally-closed piezoelectric microvalve for drug dosage control.

5. To characterize the performance of the developed devices, including their wireless actuation and temporal responses.

1.4 Scope of Research

The scope of this research focuses on the development of three wirelessly-controlled microfluidic devices for biomedical applications, namely, a thermopneumatic micropump, a passive thermopneumatic zigzag micromixer, and a normally-closed piezoelectric microvalve. Furthermore, this research studies the wireless actuation approaches utilized in thermopneumatic and piezoelectric microactuators, as well as LC circuits design and *in vitro* characterization. In addition, using finite element analysis (FEA), the thermal responses of the LC heaters and thermomechanical behavior of the thermopneumatic microactuators were simulated. Furthermore, the wireless power transfer (WPT) process, piezoelectric microactuation, valving performance, back pressure, and flow and mixing rates were also simulated.

In terms of the fabrication process, this study follows the standard and unconventional of MEMS fabrication techniques, including photolithography, etching, electroplating, three-dimensional (3D) printing, and xurography. The software used in the design were AutoCAD and SolidWorks, while COMSOL Multiphysics® was used in the finite element simulation. In addition, the image processing and portions of the simulation were carried out using MATLAB®. For the characterization purposes, several instruments, such as a network/spectrum/impedance analyzer, an infrared (IR) thermal camera, a laser displacement sensor, a force sensor, a pH meter, and a microscope were used for the circuits components measurements, thermal analysis, displacement sensing, force measurement, dispensed liquid volume, and microscopic imaging and flow and mixing rates, respectively.

1.5 Research Contributions

The research proposes three significant contributions by utilizing out-of-clean-room fabrication methods to develop three different wirelessly-controlled microfluidic devices that utilize two actuation methods. These contributions can be highlighted as follows:

1. Development of three novel designs with self-contained fluids reservoirs for three microfluidic devices, namely, a thermopneumatic micropump, a thermopneumatic micromixer, and a piezoelectric microvalve.

2. Development of a novel wirelessly-controlled thermopneumatic micropump that is operated using a passive frequency-sensitive wireless planar LC heater enabled by an external magnetic field. The device can pump the liquid stored in its reservoir using single or multiple strokes without requiring moving parts.

3. Development of a novel wirelessly-controlled passive zigzag thermopneumatic micromixer by selectively activating two passive wireless planar LC heaters enabled by an external magnetic field. The micromixer provides mixing-ratio controllability in a relatively short mixing length.

4. Development of a novel wirelessly-controlled normally-closed piezoelectric microvalve that is operated by activating a wireless LC resonant circuit using an external magnetic field. The LC circuit was formed by connecting a multilayer coil to a piezoelectric microactuator that behaves as a capacitor and a resistor in parallel. The device efficiently controls the flow of the fluid that is stored in a pressurized balloon reservoir during short and long-term tests.

1.6 Potential Impact of the Research

The applications of MEMS microfluidic implantable medical devices are very limited, due to the limitation of mobility of these devices when using wires and conventional powering methods. To date, the alternative solutions of this problem are using on-board batteries, magnets, biofuel cells, or nuclear cells, which increase the size of these devices and limit their application range and operation time [47]. The use of the proposed wirelessly-controlled micropump, micromixer, and microvalve can uniquely address these limitations and allows developing their implementation in a variety of potential applications. One of these promising applications is implantable drug delivery devices, where the powering method, biocompatibility, and overall size are very crucial factors to ensure achieving minimal invasiveness and long-term operation [49]. In addition, the ability to wirelessly-control multiple microactuators that are integrated into a single device in a selective manner will play an important role in microfluidic devices for multiple-drug delivery [55] and multifunctional systems [25]. Furthermore, the ability to utilize a piezoelectric microactuator to serve as a capacitor and a microactuator simultaneously will eliminate the need for an additional capacitor to form the LC circuit. This can greatly reduce the size, cost and fabrication complexity of wireless devices that contain piezoelectric microactuators or other types of microactuators, such as dielectric elastomers [61]. Moreover, the out-of-clean-room fabrication methods utilized in this thesis offer promising alternative fast, reliable, and cost-effective solutions microfluidic devices fabrication, which opens doors to new batch-fabrication processes. The proposed study contributes to multidisciplinary fields and can be utilized in several essential research areas. The successful outcomes of this research are expected to promote advances in these device technologies in biomedical fields and beyond.

1.7 Methodology

In order to achieve the objectives of this research and according to the aforementioned review, the methodology that followed in this work involved multiple steps that were taken to develop three wirelessly-controlled microfluidic devices, namely, a thermopneumatic micropump, a passive zigzag thermopneumatic micromixer, and a normally-closed piezo-actuated microvalve. The development process of these devices involves the design, simulation, fabrication, and characterization. The dimensions, materials, operating frequencies, and fabrication methods of the developed devices were selected to be within the range of the reported implantable and portable microfluidic devices [6, 20, 30, 31, 51, 62-73]. It is worth mentioning that miniaturizing certain parts of the developed devices, such as the microchannels and the LC circuits was constrained by limitation of the utilized fabrication methods. The aforementioned steps are further explained in the following subsections.

i. Design and Simulation of the Wireless Thermopneumatic Micropump

In this stage, a literature review on micropumps and their actuation mechanisms has been performed, where thermopneumatic micropumps and the parameters that affect their design, actuation, and performance were the main focus. In addition, this review involved the methods and challenges related to the wireless control of passive heaters. COMSOL Multiphysics® software was utilized to perform the FEA on the wireless thermopneumatic micropump. The design of the device, thickness of the PDMS walls, and the pumping performance were analyzed at this stage.

ii. Fabrication and Characterization of the Wireless Thermopneumatic Micropump

Based on the FEA results, the passive wireless heater of the device was fabricated by following MEMS fabrication process, which includes photolithography and wet etching, while the structure of the micropump was fabricated using PDMS replication with 3D printed molds. The experimental temporal thermomechanical and pumping results were compared with the simulation results.

iii. Design and Simulation of the Wireless Passive Zigzag Thermopneumatic Micromixer

A literature review on micromixers and their mixing mechanisms has been carried out, where passive zigzag micromixers and their design parameters were the main concern. Integration and selective activation of multiple passive heaters with different f_r were necessary to realize this micromixer. COMSOL Multiphysics® software was utilized to perform the FEA on the wireless thermopneumatic passive zigzag micromixer to analyze the design of the device, thickness of the PDMS walls, and the mixing and pumping performances.

iv. Fabrication and Characterization of the Wireless Passive Zigzag Thermopneumatic Micromixer

Two passive wireless heaters were fabricated according to the simulation results and by following the same steps used to fabricate the passive heater of the thermopneumatic micropump, while the structure of the micromixer was fabricated using photolithography process. In addition, the temporal thermomechanical, pumping and mixing performances were characterized and compared with the simulation results.

v. Design and Simulation of the Wireless Normally-Closed Piezo-Actuated Microvalve

In this step, a literature review on microvalves and their actuation mechanisms has been performed, where piezo-actuated normally closed microvalves and the parameters that affect their design, actuation, and performance were the main topic. In addition, this review also involved the methods and challenges of achieving the wireless control of piezoelectric actuators, as well as the design factors of pressurized microreservoirs. COMSOL Multiphysics® software was utilized to perform the FEA on the device to analyze the design, thickness of the PDMS microreservoirs and walls, and the valving performance.

vi. Fabrication and Characterization of Wireless Normally-Closed Piezo-Actuated Microvalve

The structure of the device was fabricated according to the FEA results using xurography fabrication process while encapsulating a piezoelectric microactuator within the structure of the device. Furthermore, the experimental temporal pressure of the microreservoirs, piezoelectric actuation, and valving performance were compared with the simulation results.

vii. Optimization and Application

The optimization process of the developed devices focuses mainly on the improvement of the temporal response, design, characterization, and fabrication related issues. The improvement of the temporal response includes using optimal f_r values, and LC circuits and microchannels designs to achieve optimal pumping, mixing, and valving performances. Potential applications of the developed devices were presented and detailed analysis were performed.

The aforementioned steps are summarized in Figure 1.1, which shows a flowchart of the general methodology steps followed in this thesis.

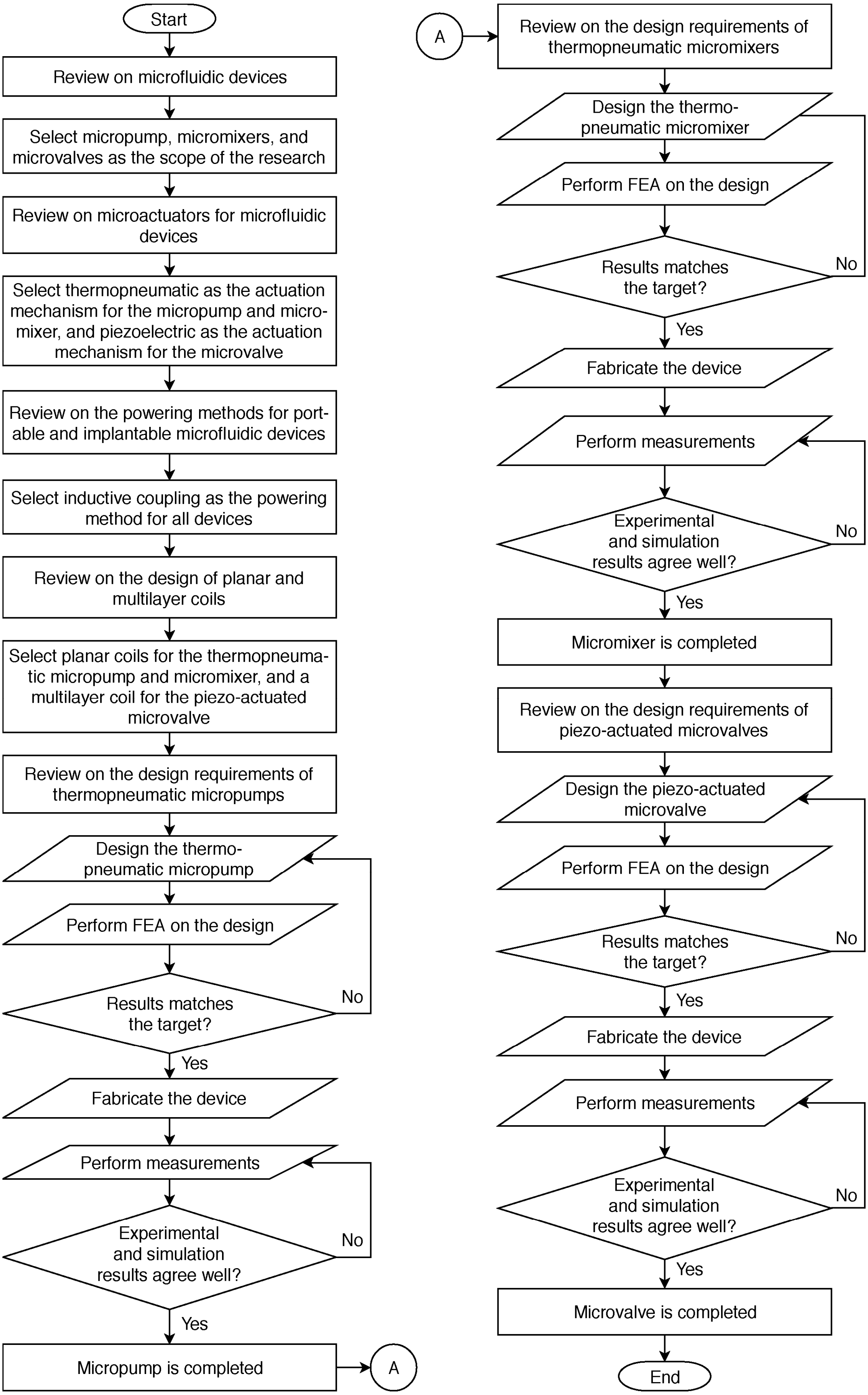

Figure 1.1: General methodology steps followed in this thesis

1.8 Thesis Outline

This thesis is divided into six chapters. Chapter 1 is a general overview of MEMS microfluidic devices and their main types and applications, followed by the problem statement, objectives, scope, and methodology of the research. Chapter 2 presents the literature review of this research, which covers an overview of the categories of MEMS micropumps, micromixers, and microvalves, followed by their actuation mechanisms, including thermopneumatic and piezoelectric actuations, as well as their powering methods, including wireless WPT. Chapter 3 presents a novel thermopneumatic micropump and studies the wireless control of a single passive planar LC heater that drives a thermopneumatic actuator, and the thermomechanical behavior and pumping performance of the device. Chapter 4 proposes a novel wireless passive zigzag thermopneumatic micromixer that is operated wirelessly using two passive planar LC heaters, and demonstrates the ability of selective activation of each actuator, as well as the thermomechanical, pumping, and mixing behaviors. Chapter 5 presents a novel wireless normally-closed piezoelectric microvalve and demonstrates the ability to form an LC circuit by connecting a multilayer coil to the piezoelectric microactuator, as well as the wireless valving performance during short and long-term operations. The thesis concludes with Chapter 6, where the key results and directions for future work are discussed, followed by a list of publications arising from the thesis.

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