INTERFACIAL WICKING FLOW THROUGH HIERARCHICAL STRUCTURE OF NATURAL CELLULOSE FIBERS FOR BIOMEDICAL MICROFLUIDIC DEVICES

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DEDICATION

To my father's soul for his words of inspiration and encouragement,

I wish he was here to see his dream comes true.

To my beloved mother, for her support and prayers to me,

To my lovely husband for his support and patience,

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ABSTRACT

Micro/Nanofluidics technology is a new research area focused on analyzing and controlling flow of fluids and bio-particles at nanometer and micrometer scales. In an attempt to achieve low cost fabrication and operation of microfluidic devices, the use of cotton fabric was proposed as a new platform for developing low-cost microfluidic devices. This thesis presents a novel wicking fluidic study through the hierarchical structures of textiles by multi-stage analysis of fluid flow at different structural scales, from the macro- (the three dimensional network structure of the cotton fabrics), via the micro- (the tiny segment of the textile structure, twisted multi fibers in a yarn) to the nanoscale (single fiber). The wicking flow within the cotton fabric structure and kapok fiber (as a hollow fiber and a simple model for the wicking flow) was experimentally analyzed using quantitative fluorescence microscopy data from the motion of fluorescent beads. Thereafter, in order to formulate the wicking flow through the hierarchical structure of the fibers network of the cotton fabrics and to predict how the wicking flow depends on the textile structure and basic material properties, experimental analyses based on fluorescent beads tracing with fluorescent and confocal microscopy as well as analytical analyses were carried out. The results of this study formed the foundation of new theories and novel ideas for interfacing microfluidics and nanofluidics. Additionally, the analyses prove that the wicking and the capillary action play important roles in selective mass transport in the textile structures. This phenomenon is potentially useful for biological and chemical detection in biosensors devices. The research targets application in novel passive size-based mechanical cell sorting using cotton fabric chip and fiber based enzyme-linked immunosorbent assay (ELISA).

ABSTRAK

Teknologi bendalir-mikro/nano adalah era baru penyelidikan yang fokus kepada penganalisisan dan pengawalan aliran cecair serta partikel-bio yang berskala nanometer dan mikrometer. Dalam usaha untuk mencapai kos fabrikasi dan operasi alat mikrobendalir yang rendah, penggunaan fabrik kapas telah dicadangkan sebagai satu platform baru. Tesis ini membincangkan satu kajian original berkenaan resapan bendalir melalui struktur hierarki kain menggunakan analisis pelbagai peringkat aliran bendalir untuk perbezaan skala struktur daripada makro (tiga dimensi rangkaian struktur fabrik kapas), mikro (bahagian kecil struktur tekstil, pelbagai benang yang dipintal) kepada nano (serat tunggal). Penyerapan bendalir dalam struktur fabrikc kapas dan serat kapok (sebagai satu serat berlubang dan model ringkas untuk kadar penyerapan) telah dianalisis secara eksperimen menggunakan data kuantitatif pendarfluor mikroskop daripada pergerakan manik pendarfluor. Oleh itu, untuk memformulasi kadar penyerapan melalui struktur hierarki rangkaian serat fabrik kapas dan meramalkan bagaimana kadar penyerapan bergantung kepada struktur tekstil dan sifat asas bahan, analisis secara eksperimen berasaskan manik pendarfluor dan mikroskop sefokus serta analisis secara analitikal telah dilakukan. Keputusan kajian telah menghasilkan teori asas baru dan idea original untuk interaksi antara mikrobendalir dengan nanobendalir. Selain itu, beberapa analisis membuktikan bahawa serapan dan tindakan kapilari memainkan peranan penting dalam pemilihan dalam struktur tekstil. Fenomene ini amat berguna untuk pengesanan biologi dan bahan kimia di dalam alat biopenderia. Aplikasi sasaran kajian ini ialah pengisihan sel mekanikal berasaskan saiz pasif menggunakan cip fabrik kapas dan serat berasaskan asai imunoserap terangkai ensim (ELISA).

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LIST OF SYMBOLS

A	-	Area
ACS	-	Acute coronary syndromes
AFM	-	Atomic Force Microscopy
AMI	-	Acute myocardial infarction
ATR	-	Attenuated total reflectance
A_{welf}	-	Cross-sectional area of pore exposed to the welf way
A_{wrap}	-	Cross-sectional area of pore exposed to the wrap way
BSA	-	Bovine serum albumin
c_1, c_2	-	Wrap and welf crimp
CA	-	Cellulose acetate
CLSM	-	Confocal laser scanning microscopy
CRP	-	C-reactive protein
CSA	-	Camphorsulfonic acid
CVD	-	Cardiovascular disease
D	-	Diffusion coefficient
d	-	Diameter
DNS	-	Dinitrosalicylic acid

E	-	Interfacial energy
ECG	-	Electrocardiogram
EDA	-	Energy-dissipative electron spectroscopy
ELISA	-	Enzyme-linked immunosorbent assay
FESEM	-	Field-Emission Scanning Electron Microscopy
FTIR	-	Fourier transformation infrared roman spectroscopy
g	-	Gravity acceleration
HBSS	-	Hank's balanced salt solution
HF	-	Heart failure
h_{fab}	-	Wicking height in fabric
HFP	-	1,1,1,3,3,3-hexafluoro-2-propanol
J	-	Diffusion flux
K_n	-	Knudsen diffusion
L	-	Length
l_2	-	Modular length in transverse direction
LOD	-	Limit of detection
MI	-	Myocardial infarction
n_2	-	Number of weft threads
O.D.	-	Optical Density
p	-	Pressure
p_1, p_2	-	Wrap and welf spacing

PAD	-	Paper-based analytical device
PANI	-	Polyaniline
PBS	-	Phosphate Buffered Saline Solutions
PDMS	-	Polydimethylsiloxane
PLLA	-	polylactic acid
PMMA	-	Poly(methyl methacrylate)
POC	-	Point of care
PS	-	Polystyrene
Q	-	Volume fluid flow
R	-	Fluid resistance
Ra		Roughness
RBC	-	Red blood cell
Re	-	Reynolds
RMS	-	Root mean square
R_{μ}	-	Capillary radius
SAA	-	Salivary alpha amylase
SD	-	Standard deviation
SEM	-	Scanning Electron Microscopy
SWNT	-	Single-well carbon nano-tube
t	-	Time
TAD	-	Thread-based analytical device

TE	-	Thromboembolic
TGA	-	Thermal gravimetric analysis
TMB	-	Tetramethylbenzidine
TPI	-	Twisting per inch
u	-	Velocity
UV	-	Ultraviolet
WBC	-	White blood cell
WGA	-	White gern agglutinin
x	-	Particle travel distance
XPS	-	X-Ray Photoelectron Spectroscopy

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Recently, microfluidics technologists have developed different devices for the fast manipulation and characterization of fluid samples for biological and the chemical analyses. Microfluidic devices commonly consist of microscale fluidic channel with typical length of 1-100 μm. High throughput analysis, small sample volume, shortened analysis time, enabling new functionalities by integrating new micro components and application of novel physics phenomena; all these are reported benefits for microfluidics devices. In typical bio-diagnostic microfluidic systems, multiple different fluidic elements are connected into circuits to detect a specific analyte in a sample fluid.

Nanofluidics refers to the study of fluidics in nanochannels in the length scale of 1-100 nm. The unique physics phenomena behind the working of nanofluidics devices can be revealed by studying fluid flow in such devices. Since the channel sizes in nanofluidics are closed to biomolecule size, most of the time nanofluidics have been applied to carry out separation, to count or to characterize individual biomolecules such as protein or DNA molecules.

Many different fabrication techniques are reported to develop microfluidics, nanofluidics and interfacing them together. However, all of these methods require considerable cost and specialized equipment to reduce the high development cost for the fabrication and operation of modern microfluidic and nanofluidic devices that are

made up of materials such as, silicon [1], glass [2], and polymers i.e. PMMA [3], SU-8 [4] and PDMS [5, 6]. Microfluidic systems that are intended to be low cost and portable for home-use diagnostic applications have been proposed by many researchers. These microfluidic systems are made from hydrophilic materials such as paper [7, 8], threads [9, 10] and cloth like silk [11] and cotton [12]. Since capillary force wicks and drives liquids in their hydrophilic microchanels, no pumping system and advanced control system is necessary in such microfluidic systems.

Capillary effect is also known as wicking and has been widely used as a pumping force in microfluidic systems in recent years. Capillary pumping is surface-directed and has no external power input. It exhibits a small pressure drop in the micro channel. Hydrophilic surface is essential for capillary pumping. Relevant capillary effect issues in microfluidic chips have been studied in terms of the theory, channel geometry, patterned structure and applications [13-17].

1.2 Background of the study

Intensive demand to have sensitive, simple and portable biodiagnostic devices especially in developing countries has received much attention. Such devices exploit low-cost, disposable and hydrophilic materials (such as paper, thread and fabric) to create a hydrophilic pattern to form a microfluidics device platform for medical diagnostics test.

Microfluidics paper-based analytical devices (µPADs) have been developed for point of care diagnostics and environmental monitoring at resource-poor regions. The concept of paper based microfluidics was first proposed by the Whiteside research group at Harvard University [7]. Most of the µPADs have been fabricated by patterning hydrophobic barriers on Whatman filter paper. Wax [18, 19] , polystyrene [20], polydimethylsiloxane [5], alkyl ketene dimer [21] and flourochemicals [22] have been used as the materials for patterning hydrophobic barriers on the paper. Different patterning methods have also been applied for patterning the hydrophilic channels on paper such as photolithography [7], printing

[18] plasma [23], laser [24] and chemical etching method [25]. Due to simplicity and compatibility with aqueous solutions, the Whiteside's wax printing has become one of the popular techniques for μPADs fabrication. The limitations of paper based microfluidic devices mostly are related to the material properties of paper. Some of the limitations are as follows:

- Low wetting strength of paper [26].
- Low efficiency of sample delivery due to sample retention and evaporation through the hydrophilic channels on the surface of paper [27].
- Low strength of the patterned hydrophobic barrier on paper [27].

Thread [9, 10] and fabric [11, 12] have been applied as low-cost platforms for developing inexpensive microfluidic devices. The gaps between the fibers on the thread and between the yarns in textiles are considered as capillary channels to move liquid without external forces or pumping effect. This capillary force and driven liquid in the hydrophilic multi-filaments microchannels define the wicking properties of these structures. Researchers proved that coated waxes on the natural fibers decrease or even stop fluid wicking within the threads of cotton fabric [28]. To overcome the aforementioned problem, various surface modification methods were reported to remove natural wax from the fiber's surface to improve their wettability of the fibers and consequently also the wicking capillary action occurred in the porous fiber structure of threads and cotton fabric [12].

Several microfluidic thread-based analytical devices (μTADs) have been reported as a colorimetric assay device to detect glucose and protein in urine or blood [10, 29]. Thread was also used for blood typing [30]. The advantages of thread compared to paper are its flexibility and wet strength. The fabrication of thread-based microfluidic devices is simpler and relatively low cost, because it requires only sewing needles or household sewing machines.

Designing and developing microfluidics devices based on the multiplex and multiple-dimensional thread is relatively difficult, since one-dimension is assumed for thread. On the other hand, a publication by our research group reported an innovative two- and three-dimensional cotton fabric-based microfluidic devices which was developed based on the two-dimensional fabric [12]. We have proved their potential as unconventional assay for glucose, nitrate and protein detection, and as quick colorimetric enzyme-linked immunosorbent assay (ELISA) to determine human chorionic gonadotropin [31]. In another recent paper, cotton fabric was used for developing a microfluidic device to electrochemically detect lactate level in saliva [32]. Several advantages of thread and cotton fabric versus papers to develop microfluidic systems are listed below;

- High flexibility due to great tensile strength; wicking and reaction still happen despite bending, twisting, stretching and compression [28].

- Long term mechanical durability; despite the platform being bent, stretched, comprised or twisted [33].

- Long term continuous flexible sampling; it can endure liquid wicking without damaging the structure, under various mechanical disturbances [32].

- Additional porous structure due to the wide variety of pores: higher surface area to volume ratio which guarantee higher sensitivity of thread and fabric-based assays [31].

Both thread and fabric have a wide-ranging diversity of pores and gaps such as nanopores and gaps between the cellulose microfibrils in a single fiber, microscale interfiber gaps and inertial void spaces between the twisting and weaving fibers in the thread and the yarns in the cotton fabric. Therefore, the wicking flow characterization inside this hierarchical structure is difficult to carry out and requires further study. In this study, capillary and wicking flow through the complex and porous structure of natural fibers and hierarchical structures of cotton fabric are investigated. The aim of this study is to develop inexpensive and simple

micro/nanofluidic devices from the multi filaments of natural fibers including fibers, thread and fabric for biological and chemical applications.

1.3 Problem statement

In this study, we aim to characterize and develop models of liquid wicking on cotton fibers, thread and fabrics to meet emerging technical and performance needs in micro/nanofluidics applications, e.g. biomedical devices and chemical/biological devices. In this manner, understanding how liquids wet, permeate and flow in multiscale porous fibrous structures is important.

Characterizing the physical and mechanical properties of the complicated and hierarchical structures of cotton fabric is no a small task. Wicking flow and Fluid interactions through these structures of cotton fabric, especially considering their pore size diversity, further adds the complexity. Wetting and wicking of fluids through fibrous structures is dynamic and stochastic, often involving changing physical nature due to surface adsorption, fiber shifting and fiber swelling. Characterizations of fluid wicking phenomena in the fibrous structures of fibers to fabric is extremely required to precise by control fluid flow in microfluidics system which are fabricated from fibers, thread or fabric.

1.4 Objectives of the study

1. Study on the morphology and the hierarchical structure of the textile, from fiber to fabric, single fiber (cotton and kapok fiber), cotton thread and fabric.

2. Experimental measurements of the wetting properties and the wicking rate of single fiber to fabrics and correlating them to analytical and mathematical modelling.

3. Study on fluidic wicking through the hierarchical fibrous structure of cotton fabric by multi-stage analysis of the fluid flow at different scales from the micro- (through three-dimensional network structure of the cotton fabric, tiny segment of textile structure or twisted multifibers in thread) to the nanoscale (in a single fiber).

4. Designing and developing cotton thread and fabric-based microfluidics devices for a passive size-based mechanical cell sorting by characterization the wickability and sortability of multiple sizes of beads and cells through the fibrous structure of the devices.

5. To design a fiber-based assay and an enzyme linked immunosorbent assay (ELISA) with high sensitivity by utilizing the high surface area to volume ratio property.

1.5 Scopes

1. Chemical modification is conducted to modify the surface chemical composition and surface morphology of the fiber.

2. Prior to the further studies of multiscale fluid flow, the hierarchical structures and morphology of the textile should be carried out based on the microscopy studies.

3. In the next stage of the study, the wicking movement of fluid along a single fiber, spun fibers and thread with different twistings per inch (TPI) and a strip of cotton fabric is examined experimentally through “image analysis of liquid rising”. Additionally, the analysis of wicking in a single cotton fiber is done using an optical macroscopic method. Thereafter, a mathematical model for wicking in textile is developed based on textile structure and capillarity properties in macro- and microscales.

4. Wicking characterization of the liquid on or in the cellulosic fibers is carried out using confocal laser scanning microscopy. Fluorescent beads having various sizes in the micro- and nano range are flown along the fibers to investigate channel size at different scales. Time-lapse imaging is carried out to measure wicking rate, while z-stacking imaging is conducted to know the exact wicking position in the fiber.

5. Several low-cost health care devices based on natural cellulosic fibers are developed by inspiration from the wicking and wetting properties of natural cellulose fibers.

1.6 Thesis outline

Remaining chapters of thesis are organized as follows (Figure 1.1);

Chapter 2 presents the main concept of microfluidics in order to introduce the physical aspect behind microfluidics. It introduces to explain the chemical and the physical properties of single natural cellulose fiber such as cotton and kapok fibers. In the final section of this chapter, research on analytical analysis of liquid transport through fabric structures will be reviewed.

Chapter 3 conveys details for investigation of the physical properties of natural cellulose fibers to achieve appropriate understandings of the wicking flow through the hierarchical structures of natural cellulose fibers and cotton fabric.

Chapter 4, 5 and 6 explain several implementations of the wicking study to develop fiber-based biodiagnostic devices for point of care applications. The steps and procedures for the fabrication and development of fabric and thread based microfluidic for the cells sorting will be explained in chapters 4 and 5, respectively. Chapter 6 will present the development of fiber-based CRP-ELISA to detect the

salivary C-reactive protein (CRP) level as a predictor for cardiovascular disease (CVD).

Chapter 7 concludes the whole research approach and give some suggestions for further study.

It should be noted that chapters 3 to 6 have been written as separate journal papers, which have been submitted to or are already accepted for scientific journal publications. A list of publication is given in Appendix A.

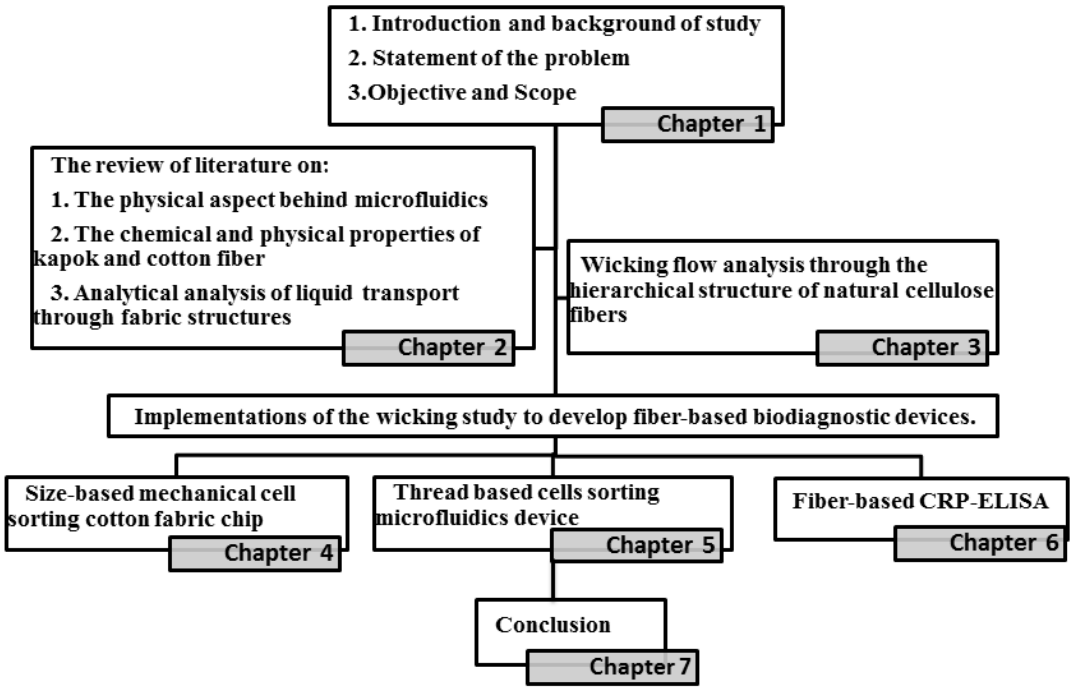

Figure 1.1; Flowchart representation of the thesis structure

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