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**Bachelor Thesis** 

# Liquid-liquid two phase flow and solvent extraction in the squeezing regime with on-chip separation of phases

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### Abstract

The focus of this study is on mass transfer of segmented flow within a microfluidic device, in particular with on-chip separation of phases by capillary forces. The tested initial concentrations  $c_0$  were not of influence. The overall mass transfer coefficient increased with increasing flow rate. It is recommended to focus further efforts on separating the phases. Also recommended subsequent experiments are outlined.

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Nomenclature

$X_1, X_c, X_o$	subscript for continuous phase
$X_2, X_d, X_a$	subscript for dispersed phase
$X_M$	subscript for mixture properties using $\epsilon$
$\epsilon_i$	volumetric flow fraction
$Q_i$	Volumetric flow rate $[\mu l \min^{-1}]$
$Q_t$	Total volumetric flow rate $[\mu l \min^{-1}]$
$ ho_i$	density $[kg m^{-3}]$
$\mu_i$	dynamic viscosity $[\mathrm{kg}\mathrm{s}^{-1}\mathrm{m}^{-1}]$
$\gamma$	surface tension between continuous and dispersed phase
$\theta$	water/toluene contact angle
$\bar{ u}$	mean velocity $[m s^{-1}]$
$d_h$	characteristic length [m]
$k_L a$	overall volumetric mass transfer coefficient $[s^{-1}]$
$k_L$	mass transfer coefficient $[m s^{-1}]$
E	mass transfer efficiency [-]
K	partition coefficient between phase 1 and 2 $\left[ - \right]$
au	residence time [s]
w	width of channel [m]
h	heigh of channel [m]
l	length of mass transfer channel [m]
$w_c$	width of capillaries [m]
$d_c$	spacing of capillaries [m]
$l_c$	length of capillaries [m]
$N_c$	Number of capillaries [m]
$\Delta P_c$	capillary pressure on separation capillaries [Pa]
$R_{j}$	hydraulic resistance $[Pasm^{-3}]$
$\Delta P_o$	total organic phase outlet pressure drop [Pa]
$\Delta P_a$	total aqueous phase outlet pressure drop [Pa]

# Chapter 1

# Introduction

## **1.1** Miniaturization of devices and processes

The past two decades are characterized by an unprecedented technological advancement which is unlike earlier developments deeply entangled in everyday life. Obviously, earlier developments in physics, chemistry and medicine have had a high impact on society, but in particular the transistor (1947) and subsequently the semiconductor integrated circuit (1958) are nowadays unequalled regarding their indispensability and omnipresence. The rise of the computer chip or integrated circuit as found in many of our everyday devices, has been enabled by the advancement in photolithography. Now it is this photolithography which for two decades enabled us to further miniaturize a variety of existing devices and processes, resulting in microtechnology from the 1990s and even to nanotechnology from the 2000s [1].

As is the case with integrated circuits, micro- and nanotechnology offer a means to realize several process steps on a single integrated device, hence limiting the system's (dead) volume and the amount of required processing time. Also, the miniaturization of chemical analysis decreases the analytes sample consumption, increases the mixing rate and enhances the analysis speed, characteristics which rouse the quest for cheap portable analytical devices [2]. Integrated microfluidic systems are known as 'Lab-on-a-Chip' (LOC) or 'micro total chemical analysis system' ( $\mu$ TAS) [1].

And so microfluidics as the study and application of fluid flow on the microscale [3] offers numerous possibilities to both research and practical applications. The interest in microfluidics is reflected by the increasing number of published items on this topic,

as depicted by Figure 1.1. Still, in microfluidics care should be taken about simple scaling effects of quantities which can often be neglected in the equations for 'common' macroscopic flows. As Colin (2010) puts aptly, 'miniaturization gives a predominant role to surface effects, to the detriment of volume effects' [4]. It is these very surface effects which are the basis of both advantages of and the challenges to microfluidics.



**Figure 1.1:** Number of published items on topic 'microfluidics' in Web of Knowledge. After the example of Abgrall and Gué (2007)[5]

## **1.2** Introduction to microfluidics

Microfluidic systems are characterized by their characteristic length scale of less than a millimeter. A fundamental aspect of fluidics on this scale is the laminar flow regime: the flow is in parallel layers of constant motion with a parabolic velocity profile, which makes the fluidic behavior well-defined [6]. This in contrast to the more chaotic alternative regime of turbulent flow, in which eddy currents, vortices and other flow instabilities are common. The cause to this difference is that in laminar flow the viscous forces are dominant, while turbulent flow is dominated by the inertial forces.

A decrease in the length scale results in a decrease in the time scale for diffusive mass transport. 'This is the main reason for the enhanced selectivity and high yield of chemical reactions in microreactors', as Kockmann (2008) states [7]. It should be noted however, that the parabolic velocity profile results in an axial dispersion known as 'Taylor dispersion' [8]. This may be restricted by confining the sample with menisci as interfaces [4]: injecting two immiscible fluid streams into the microfluidic device creates a liquid-liquid two-phase flow with the possibility of segmented flow (Figure 1.2) [9]. Plugs in segmented flow moving in a straight channel generate internal circulation within two halves of the plug [9]. This is due to shear between the channel and the slug which in turn reduces the thickness of the interfacial boundary layer [10]. At higher flow rates, reaction within the plugs as micro-reaction vessels may even be further enhanced by adding an inert gas phase as third phase [11].



Figure 1.2: (a) segmented flow and laminar circulations. (b) parallel or stratified flow. From Dessimoz et al. (2008) [12]

### **1.2.1** Dimensionless quantities

It is necessary to develop insight in the order of magnitude of various effects in comparison to one another, like length and time scales, momentum, forces or energy scales. Dimensionless quantities can represent the different scales and ratios to provide a means to comparison of different systems, as it reduces the number of independent variables [13, 10].

#### **Reynolds** number

For example, a measure whether the flow regime is laminar or turbulent is given by the Reynolds number (Re). Transition from laminar to turbulent flow occurs at a Reynolds number of 2100 to 2500, both at macroscale and at microscale [14]. This quantity is

defined as the ratio of the inertial forces to the viscous forces:

$$Re = \frac{\rho \bar{\nu} d_h}{\mu} \tag{1.1}$$

in which  $\rho$  is the density of the fluid  $[\text{kg m}^{-3}]$ ,  $\bar{\nu}$  is the mean velocity  $[\text{m s}^{-1}]$ ,  $d_h$  is the characteristic length [m] or hydraulic diameter and  $\mu$  is the viscosity  $[\text{kg s}^{-1} \text{m}^{-1}]$ .

The hydraulic diameter  $d_h$  is an estimate of the equivalent diameter of a non-circular channel:

$$d_h = \frac{4A}{P} = \frac{2hw}{h+w} \tag{1.2}$$

where A is the cross sectional area and P is the wetted perimeter of the area. h and w are the channel height and width.

#### Capillary number

The ratio of the viscous forces to the interfacial forces is given by the Capillary number (Ca):

$$Ca = \frac{\mu\bar{\nu}}{\gamma} \tag{1.3}$$

in which  $\mu$  is the dynamic viscosity and  $\gamma$  is the surface or interfacial tension between the two fluid phases [15]. In microfluidics the Capillary number is small (Ca < 1), indicating the prevalence of the surface forces.

#### Mixture properties, arithmetic mean of average

The equations for Reynolds number and Capillary number encompass fluidic properties, such as density and viscosity, or a parameter as mean speed. The purpose of using dimensionless quantities is a comparison of the importance of the two forces in the numerator and denominator within certain conditions. This enables one to compare the numerous experimental studies on microfluidics [16]. To that matter, the dimensionless properties are defined with mixture properties, the arithmetic mean of the dimensionless quantities or an average of the liquid properties.

The mixture properties of the two phases are calculated using the volumetric flow

fraction  $\epsilon$  as :

$$\epsilon_1 = \left(\frac{Q_1}{Q_1 + Q_2}\right) \tag{1.4}$$

$$\rho_M = \epsilon_1 \rho_1 + (1 - \epsilon_1) \rho_2 \tag{1.5}$$

$$\mu_M = \epsilon_1 \mu_1 + (1 - \epsilon_1) \mu_2 \tag{1.6}$$

in which  $Q_i$  is the volumetric flow rate of said phase [10][15]. The mixture Reynolds number  $Re_M$  and Capillary number  $Ca_M$  are calculated accordingly.

The arithmetic mean  $Re_m$  and  $Ca_m$  is the arithmetic mean of the quantities of the two phases [12]:

The average is defined as [16]:

$$\bar{Re} = \frac{\rho\bar{\nu}d_h}{\mu}\frac{\mu_d}{\mu} \tag{1.7}$$

$$\bar{C}a = \frac{\mu\bar{\nu}}{\gamma}\frac{\mu}{\mu_d}$$
(1.8)

# **1.3** Description of the assignment

In the current assignment the flow regimes of an immiscible liquid-liquid two-phase flow in a microfluidic apparatus are characterized. The focus is on droplet based flow regimes, generated with toluene as continuous phase and water as the dispersed phase using a microfluidic device with a T-junction geometry. Subsequently the device's mass transfer performance is determined during liquid-liquid extraction within droplet based flow. To this end the two phases needed to be separated before photo spectroscopic analysis of one of the phases. This was achieved using capillary forces and based on a difference in wetting properties of the two phases by example of Kralj et al. [17]. The operation is schematically shown in Figure 1.3.



Figure 1.3: Segmented flow, mass transfer and subsequently phase separation in one microfluidic apparatus. NB in this image, the inlet channel of the organic phase is also perpendicular to the main channel, in contrast to the used experimental apparatus.

## 1.3.1 Review of flow regime and droplet generation

In a microfluidic device with a T-junction geometry, the continuous phase enters the main channel and the dispersed phase enters from a perpendicular channel as depicted in Figure 1.4. The current chips are chemically treated to hydrophobize the surfaces. In multiphase flow, the wetting phase is the continuous phase and the non-wetting phase is the dispersed phase. In this thesis the continuous phase is toluene, the dispersed phase is water with a solute.



**Figure 1.4:** Photo of the T-junction with an emerging droplet and two developed droplets. The dark centered line is a side effect of the fabrication.

#### Constant droplet size in the squeezing regime

Using a T-junction for droplet generation, De Menech et al. (2008) recognized three distinct regimes of droplet formation in order of increasing Capillary number: squeezing, dripping and jetting [18]. To keep the droplet size constant on account of characterizing the mass transfer, in this project the Capillary number will be low ( $Ca \ll 0.01$ ) and thereby corresponds to the squeezing regime. The interfacial force prevails and the dynamics of break-up is dominated by the pressure drop over the plug as it forms. More importantly, the sizes of the droplets are influenced only very weakly by the Capillary number and thus do not vary significantly with the various flow rates [19, 18].

#### Verification of squeezing regime

The results of both De Menech et al. and Xu et al. confirmed the scaling relationship of droplets, as proposed by Garstecki et al. (2006) for the squeezing regime [20, 19]. Gupta and Kumar (2010) confirmed these findings for low Ca number and thus also for the squeezing regime using 'Lattice Boltzmann Model' (LBM) computer simulations [21]. They also investigated the effect of geometry, i.e. the influence of widths of the two channels and the depth. Garstecki's scaling relation was in need for a constant of proportionality, which could be determined experimentally for a device in a certain range of parameters. Van Steijn (2010) expanded this scaling relation, by using geometric arguments for the modeling of those constants of proportionality. This made the experimental determination of this constant or fitting parameter superfluous, as has recently been confirmed with LBM by Yang et al. (2013) [2].

### **1.3.2** Review of phase separation

At the macroscale the phase separation is driven by the density difference between the phases and thus by the difference in gravitational forces. Günther and Jensen (2006) expound how for microfluidics the apparatus length scale is below the Laplace length scale (or capillary length,  $\sqrt{\gamma/(\rho g)}$ ). This explains that gravitational forces are negligible in microfluidics. Also it makes complete separation of two phases in a single step using surface forces possible [22]. The two phases are separated by incorporating multiple capillaries perpendicular to the microchannel and adjusting the two outlet pressures [17].

### 1.3.3 Review of mass transfer

#### Mass Transfer Efficiency

Mass transfer efficiency E in the device is quantified according to Equation (1.9). This describes the concentration difference achieved between the channel in- and outlet (numerator) compared to the maximum possible concentration difference defined by the equilibrium bulk concentration (denominator). Or, the amount transferred over the maximum amount transferable. The equilibrium bulk concentration is derived from the partition coefficient K as in Equation (1.10), which is defined as the ratio of equilibrium concentrations in the organic phase to the aqueous phase [23].

$$E = \frac{c_1^{out} - c_1^{in}}{c_1^{eq} - c_1^{in}} \tag{1.9}$$

$$K = \frac{c_1^{eq}}{c_2^{eq}}$$
(1.10)

In these equations, c is the concentration. The subscript 1 is for the continuous phase (organic) and the subscript 2 is for the dispersed phase (aqueous). The superscripts are for inlet, outlet or equilibrium bulk.

#### Mass Transfer Coefficient

It is common to benchmark continuous mass transfer devices using the volumetric mass transfer coefficient  $[s^{-1}]$ , which is a product of mass transfer coefficient  $(k_L)$  and specific interfacial area a. The specific interfacial area a is defined as the interfacial area per unit volume of the dispersed phase  $[m^2 m^{-3}][24]$ .

Generally, the following equation is used for  $k_L a$ :

$$k_L a = \frac{1}{\tau} \ln \left( \frac{c_1^{eq} - c_1^{in}}{c_1^{eq} - c_1^{out}} \right)$$
(1.11)

in which  $\tau$  is the residence time in the device. However, Equation (1.11) is only valid in the case that  $c_2 \gg c_1$  and so the driving force of the diffusion would only depend on the (lower) concentration in the organic phase. Rather, it is safe to assume that both concentrations will change with time, as this is the objective of the experiment. In this case, the mass transfer coefficient depends on the volume fraction of the phases. Therefore the equation will encompass the volume fraction and the equivalent resistance to mass transfer of the two phases [10]:

$$k_L a = \frac{1}{\tau \left[\frac{1}{K(1-\epsilon_1)} + \frac{1}{\epsilon_1}\right]} \ln \left(\frac{c_1^{eq} - c_1^{in}}{c_1^{eq} - c_1^{out}}\right)$$
(1.12)

in which K is the partition coefficient and  $\epsilon$  is the volumetric fraction of phase 1. A detailed derivation of Equation (1.11) and Equation (1.12) is given by Kashid et al. [25]. The residence time  $\tau$  is defined as the mean contact time of the two phases, from the T-junction to halfway the separating capillaries.

$$\tau = \frac{whl}{Q} \tag{1.13}$$

in which whl are the width, height and contact length of the channel [m<sup>3</sup>] and Q is the total volumetric flow rate [m<sup>3</sup>s<sup>-1</sup>]. An overview of similar work on mass transfer within segmented flow has been compiled in Table 1.1. It should be noted that there is a discrepancy in the used definition for  $k_L a$ .

 Table 1.1: Overview of papers about mass transfer within segmented flow.

author	geometry	$d_h$	max. $k_L a$
		$\left[\mu m\right]$	$[s^{-1}]$
Ghaini et al. (2010) [26]	$\bigcirc$	1000	1.3
Kashid et al. (2011) [25]		400	0.3
Dessimoz et al. $(2008)$ [12]		400	0.5
Assmann et al. $(2011)$ [11]		220	12.0
Di Miceli Raimondi et al. $(2014)$ [27]		210	8.4
*		300	2.7
Kralj et al. (2007) [17]	$\Box$	157	0.3
Fries et al. (2008) [23]		191	5.3
Current work		29	4.5

## 1.4 Challenges

The main objective is to extract a solute from one phase to another and to separate said phases, within one microfluidic device. Fries et al. (2008) compare the mass transfer within segmented flow and stratified flow. They conclude segmented flow performs better on account of internal circulations [23]. Therefore in exploring the flow regimes in the microfluidic chip, emphasis is on segmented flow: in particular on segmented flow within the squeezing regime, for the constant droplet size.

In view of producing an efficient microfluidic device for liquid-liquid extraction, experimental parameters of interest are: initial solute concentration, droplet length and droplet velocity. The droplet length will be fixed. Relevant properties to the mass transfer performance and mechanism are: interfacial area, dynamic viscosity, volumetric ratio of phases, residence time.

The relevance of on-chip separation of phases to this project, is reflected by the need for in situ concentration measurements. Traditionally this would be achieved based on a difference in density of the two liquids. In this experiment it implicates the contact time of the two liquids increases, thus rendering the study of mass transfer within the device impracticable. In general, phase separation is of importance to a LOC or  $\mu$ TAS as it is a necessity to continue a succession of operations.

# Chapter 2

# Materials and Methods

## 2.1 Used chemicals and equipment

For this study 2 different chip layouts are adopted, designated 'chip 1' and 'chip 2'. Chip 1 was used for characterization of the flow regimes of a microfluidic device with a T-junction, whereas chip 2 was used for mass transfer experiments. The reason for the usage of two different chip layouts is the unavailability of chip 2 at the start of experiments.

Toluene was used as the continuous phase in the two-phase flow, water as the dispersed phase and phenol was used as solute during the mass transfer experiments. Octyltrichlorosilane ('OTS') was used for hydrophobizing chip 1, a polysiloxane was used for hydrophobizing chip 2. The OTS method is detailed in Appendix A.2 (i) . The polysiloxane method is described by Arayanarakool et al. [3].

The silicon/glass microfluidic chip was enclosed by a chip holder (Micronit). Liquids were injected with two syringe pumps (both Harvard Apparatus, PHD2000) and glass syringes (Hamilton Gastight 1700 Series) into flexible fused silica capillary tubing (Polymicro Technologies) of 50, 100, 200 and 250 µm (inner diameter). The tubing was cut with a diamond blade capillary column cutter (SGT Shortix). The syringes, capillary tubing and microfluidic devices were connected with ferrules and connectors (Upchurch Scientific, IDEX Health & Science). All chemicals and equipment are listed in detail in Appendix A.

### 2.1.1 Chips

Both chips have rectangular channels and contain a T-junction for generation of segmented flow. The T-junction is orthogonal with no curvature and the dimensions of the main channel and the channel of the dispersed phase are equal. It should be noted however that both the channel width and height of chip 1 and chip 2 differ. A detailed overview of the chips and dimensions is available in Table 2.1.

#### Chip 1

Chip 1 has two tapered channels (10 µm width) perpendicular to the main channel. The tapered channels were intended for measurement of the pressure drop along the channel, as previously conducted within the covering project and adopting the method of Gu et al. (2011) [28]. The channel length from the T-junction to the exit is 12 000 µm. Chip 1 is shown in Figure 2.1.

Chip 1 is used for characterizing the flow regimes, by varying the flow rates of both phases. The procedure is detailed in Appendix A.2 (ii) .

#### Chip 2

Chip 2 comprises 100 separation capillaries at the end of and perpendicular to the main channel. The length of the capillaries is  $2000 \,\mu\text{m}$  and the width is  $3 \,\mu\text{m}$  with a spacing of 50  $\mu\text{m}$ . The distance from the T-junction to the separation capillaries is  $7000 \,\mu\text{m}$ . The distance from the first to the last separation capillary is  $5250 \,\mu\text{m}$ . Chip 2 is shown in Figure 2.2.

	channel width	w	$100\mu{\rm m}$
ah in 1	channel height	h	$40\mu m$
cmp1	length	l	$12000\mu\mathrm{m}$
	tapered channel width	$w_t$	$10\mu{ m m}$
	width	W	50 µm
	height	h	$20\mu{ m m}$
	length	l	$7000\mu{ m m}$
chip2	width of capillaries	$w_c$	$3\mu{ m m}$
	spacing of capillaries	$d_c$	$50\mu{ m m}$
	length of capillaries	$l_c$	$2000\mu m$
_	number of capillaries	$N_c$	100

 Table 2.1: Dimensions of used microfluidic chips



Figure 2.1: Topology of chip 1. This diagram is not to scale.



Figure 2.2: Topology of chip 2, the microfluidic chip for mass transfer experiments. This diagram is not to scale.

# 2.2 Lab-on-a-Chip platform for mass transfer experiments

The experimental setup for mass transfer experiments is shown schematically in Figure 2.3. The lab-on-a-chip platform (chip 2) comprises a droplet generation section at the beginning and a phase separation section at the end.

### 2.2.1 Droplet generation section

From experiments on chip 1 it was learned that  $Q_d < Q_c$  established segmented flow. This was employed on chip 2, with low total flow rates to comply with the requirement of a low Capillary number in view of the squeezing regime. For a constant continuous phase flow rate  $Q_c = 5.0 \,\mu l \, min^{-1}$ , the dispersed phase flow rate  $Q_d$  was varied from  $Q_d = 0.5 \,\mu l \, min^{-1}$  to  $Q_d = 2.5 \,\mu l \, min^{-1}$  with increments of 0.5.



Figure 2.3: Complete setup for the mass transfer experiments

### 2.2.2 Phase separation section

Following the reasoning of Günther et al. (2005) and Kralj et al. (2007), separation of phases was achieved by setting a pressure difference over the two device outlets [29, 17]. A schematic is shown in Figure 2.4. The organic phase is the wetting phase and readily enters the separating capillaries, whereas the aqueous phase forms menisci. The capillary pressure of said menisci  $P_c$  is approximated as:

$$\Delta P_c \approx \frac{2\gamma \cos \theta}{w_c} \tag{2.1}$$

in which  $\gamma$  is the organic/aqueous surface tension,  $\theta$  is the measured water/toluene contact angle in chip 2 and  $w_c$  is the width of a separation capillary.

 $\Delta P_a$ ,  $\Delta P_1$  and  $\Delta P_2$  are experimental parameters and depend on the tubing length and internal diameter and therefore can be readily altered. As  $\Delta P_i = R_i Q_i$ , the hydraulic resistance  $R_i$  for a circular tubing according to the Hagen-Poiseuille equation is:

$$R_{i} = \frac{8\mu_{j}L_{i}}{\pi r_{i}^{4}}$$
$$= \frac{128\mu_{j}L_{i}}{\pi d_{i}^{4}}$$
(2.2)

in which  $\mu_j$  is the dynamic viscosity of the relevant phase,  $r_i$  is the inner radius and  $d_i$  is the corresponding inner diameter of the tubing. The hydraulic resistance  $R_s$  of flow through all  $N_c$  rectangular separation capillaries is:

$$R_s = \frac{12\mu_o}{w_c^3 h_c \left(1 - 0.63w_c/h_c\right) N_c} \tag{2.3}$$

which is valid for the case  $w_c < h_c$  [30].



Figure 2.4: Phase separation section

The capillary pressure  $\Delta P_c$  should be higher than the pressure difference between the outlets of the organic phase and of the aqueous phase:

$$\Delta P_c > \Delta P_m \tag{2.4}$$

This is to prevent the aqueous phase from entering the capillaries. Also, the pressure drop  $\Delta P_{\chi}$  from the organic phase wrongly flowing through the aqueous outlet tubing, should be higher than the pressure drop over the entire organic phase outlet  $P_o$ :

$$\Delta P_{\chi} = \frac{128\mu_o Q_1 L_a}{\pi d_a^4} \tag{2.5}$$

$$\Delta P_{\chi} \gg \Delta P_o \tag{2.6}$$

The total organic phase outlet pressure  $\Delta P_o$  is the sum of:

- 1.  $\Delta P_s = (\text{the flow resistance of all separating capillaries}) \cdot Q_2$
- 2.  $\Delta P_1 = (\text{the tubing from the organic outlet to the flow cell}) \cdot Q_2$
- 3.  $\Delta P_f = (\text{the flow resistance of the flow cell}) \cdot Q_2$
- 4.  $\Delta P_2 = (\text{the tubing from the flow cell to the waste container}) \cdot Q_2$

$$\Delta P_o = \Delta P_s + \Delta P_1 + \Delta P_f + \Delta P_2 \tag{2.7}$$

 $\Delta P_f$  has been approximated in Table 2.2 by estimating the flow cell diameter. Both requirements in (2.4) and (2.6) are met by solving for tubing length  $L_i$  with available capillary tubing inner diameter  $d_i$  under the condition that both outlets are at atmospheric pressure:

$$\Delta P_a = \Delta P_o \tag{2.8}$$

and the total flow is conserved:

$$Q_t = Q_1 + Q_2 \tag{2.9}$$

A worst case design criterion has been taken into account in Equation (2.11), of both phases going through the aqueous outlet [17]. To ease solving the equations,  $\Delta P_2$  is set rather low, so  $\Delta P_1$  and  $\Delta P_a$  are the remaining experimental parameters.

$$P_1 = \frac{128\mu_1 Q_1 L_1}{\pi D_1^4} \tag{2.10}$$

$$P_a = \frac{128\mu_M Q_t L_a}{\pi D_a^4}$$
(2.11)

Table 2.2:	Experimental	parameters
------------	--------------	------------

Properties of phases	
$\mu_o = 5.753 \times 10^{-4} \mathrm{Pas}$	organic phase dynamic viscosity [31]
$\mu_a=8.9\times 10^{-4}\mathrm{Pas}$	aqueous phase dynamic viscosity
$\gamma = 37.1 \times 10^{-3}{\rm Nm^{-1}}$	organic/aqueous surface tension [32]
$\theta = (156.4 \pm 6.1)^{\circ}$	water/toluene contact angle
Flow cell	
$V_f = 2.4 \times 10^{-9} \mathrm{m}^3$	specified volume of flow cell
$L_{\hbar} = 10 \times 10^{-3} \mathrm{m}$	specified optical path length
$\frac{V_f}{L_h} = \frac{1}{4}\pi d_f^2 \to d_f = 553 \times 10^{-6} \mathrm{m}$	estimate of flow cell diameter
Experimental parameters	
$Q_1 = 5.0 \mu \mathrm{l}  \mathrm{min}^{-1}$	constant flow rate
$Q_2 = 0.5 - 2.5 \ \mu l \ min^{-1}$	initial flow rate
$Q_t = Q_1 + Q_2$	total flow rate

#### Phase separation efficiency

The phase separation efficiency  $E_{\phi}$  has been defined as:

$$E_{\phi} = \frac{V_{c,1} - V_{c,2}}{V_{c,1}} \tag{2.12}$$

in which  $V_{c,1}$  and  $V_{c,2}$  are the volume of the continuous phase slug before and after phase separation, respectively. The volume has been defined in Equation (2.13) in the next section.

# 2.3 Visualization

### 2.3.1 Reflection Microscopy

An inverted microscope for bright-field imaging (Leica Microsystems DMI5000M) with digital camera (Leica Microsystems DFC300FX) was used for monitoring the chip and recording of the flow regimes. Leica Application Suite 4.2 was used for realtime monitoring and capturing the images. Image analysis for determination of plug length was conducted using the open source software ImageJ 1.47k.

### 2.3.2 Image analysis

#### ImageJ

A known calibration microscope photo of a circle of 600 µm diameter was loaded and used to set a global scale calibration. Microscope photos of segmented flow were and the global scale calibration was verified with the known channel width. Next, the image type was changed to '32 bit' (grayscale), the stack was sharpened once and the threshold was adjusted to intensify the contrast between the two liquid phases. This resulted in nearly binary images of water droplets within the continuous phase.

Next, the extremes of the menisci of subsequent droplets were selected with the segmented line tool. This way, the length and distances of droplets were captured with a minimum of operations to decrease the error of measurement. ImageJ was programmed with a custom macro script<sup>1</sup> to readily measure the subsequent distances. Care was taken if a specific image was from before, during or after the phase separation. Subsequent calculations were conducted using Matlab R2012b.

#### Volume of droplets

By employing the geometric assumptions (Figure 2.5) of a spherical front cap and end cap and starting with a situation in which the wetting film is neglected, the following is deduced:

$$r = \frac{w}{2}$$

$$k = L - 2r$$

$$= L - w$$

$$A = \frac{\pi w^2}{4} + (L - w) w$$

in which A is the top view area, L is the measured plug length, w is the channel width an r is the radius of the cap. Following reasoning of Van Steijn et al. (2010), the top

<sup>&</sup>lt;sup>1</sup>http://dx.doi.org/10.6084/m9.figshare.1133868



Figure 2.5: Simplified top view of a plug in a channel

view area A is protruded to a volume V [33]:

$$\beta = 2\pi r + 2 \left( L - w \right)$$
$$= 2 \left( \pi r + L - w \right)$$
$$V = hA \pm 2 \left( \frac{h}{2} \right)^2 \left( 1 - \frac{\pi}{4} \right) \beta$$
(2.13)

in which  $\beta$  is the top view circumference. The right term of Equation (2.13) accounts for the amount of continuous phase in the corners, so it should be subtracted in calculating the volume of a dispersed plug or added in calculating the volume of a continuous phase slug. This is shown in Figure 2.6.

### 2.3.3 Integrated spectroscopy

Mass transfer was measured using in situ absorption photo spectroscopy via a flow cell incorporated in the setup, as shown in Figure 2.3. Absorption spectra were obtained using a deuterium light source (Ocean Optics DH-2000) and an UV-Vis spectrometer (Ocean Optics USB2000+UV-VIS). The flow cell (WPI, MicroLWCC-10, 2.4 µl, 10 mm) was connected to the microfluidic chip using silica capillary tubing. It was optically connected with patch cord optical fiber to the light source and detector. Calibration measurements to known concentrations were conducted by directly connecting a syringe with phenol in toluene solutions to the flow cell. Analysis of the acquired spectra is done using Matlab.



**Figure 2.6:** Geometric considerations to deduce specific interfacial area. From Van Steijn et al. (2010) [33]

# Chapter 3

# Results

## 3.1 Flow regime

The flow regimes for two phase flow at low flow rates have been determined in chip 1. Three distinct flow regimes were observed, in general: plug flow if the toluene flow rate was higher and stratified flow if the water flow rate was higher. Furthermore a transient regime was observed in which no equilibrium was obtained, i.e. no stable flow regime. A flow map as in the figure is specific to a certain device and it's dimensions. Using dimensionless numbers helps in generalizing the data. In Figure 3.1 the mean Capillary number has been plotted against the mean Reynolds number. The same data has been plotted in Figure 3.2, yet in a more practically sensible manner of volumetric flow rates. Figure 3.3 shows the droplet lengths in chip 2, during mass transfer measurements.

## 3.2 Mass Transfer

During the mass transfer experimentsm,  $Re_M = 3.9$  to 4.9 and  $Ca_M = 1.5 \times 10^{-3}$  to  $2.3 \times 10^{-3}$ . The mass transfer ( $k_L a$ , Equation (1.12)) of two initial phenol concentrations  $c_0$  (dataset 1 and dataset 2) has been plotted in Figure 3.4 and Figure 3.5. An increase in  $c_0$  is not of influence within the applied concentration ranges. In Figure 3.4 the overall volumetric mass transfer coefficient  $k_L a$  increases with increasing flow rate Q. In Figure 3.5 it is shown how  $k_L a$  decreases with residence time  $\tau$ . In Figure 3.7, the phenol extraction efficiency (E, Equation (1.9)) has been plotted, defined as the amount extracted over the maximum possible amount.



**Figure 3.1:** Mean Capillary number vs mean Reynolds number for water-toluene two-phase flow in chip 1. The diagonals indicate the mean transition between plug flow and stratified flow. After example of Dessimoz et al. (2008)



Figure 3.2: Flow regimes for water-toluene two-phase flow in chip 1.



Figure 3.3: Plug lengths during mass transfer measurements.



**Figure 3.4:** Mass Transfer  $k_L a$  vs. total volumetric flow rate



**Figure 3.5:** Mass Transfer  $k_L a$  vs. residence time  $\tau$ 



**Figure 3.6:** Mass Transfer  $k_L a$  vs. reciprocal residence time  $1/\tau$ 



Figure 3.7: Extraction efficiency vs. residence time



Figure 3.8: Plug lengths during mass transfer measurements, compared to literature

# 3.3 Phase Separation

The continuous and dispersed phases where successfully separated. Figure 3.9 shows the phase separation efficiency during the mass transfer experiments. In Figure 3.10 two photos of the segmented flow are shown. The first photo is taken before the phase separation, the last photo is taken after the phase separation. In the last photo, eight of the separation capillaries are visible. The flow rates during the photos were  $Q_c =$  $5 \,\mu l \, min^{-1}$  and  $Q_d = 2.5 \,\mu l \, min^{-1}$ , corresponding to the last datapoint in Figure 3.9.



**Figure 3.9:** Phase separation efficiency  $E_{\phi}$  during the mass transfer experiments



Figure 3.10: Plug flow recording before and after the phase separation

# Chapter 4

# Discussion

## 4.1 Mass transfer

The mass transfer coefficient  $k_L$  can be regarded as 'the rate constant for moving one species from the boundary into the bulk of the phase', as Cussler remarks [34]. According to Kashid, 'it depends mainly on the diffusivity of solute, characteristic diffusion length and interfacial hydrodynamics.' [10]. The latter refers in this case to the existence of circulating lamellae due to the aqueous-organic interface. The specific interfacial area *a* depends on the flow regime and on microchannel dimensions. To that extent a proper benchmark of a device's performance is the overall volumetric mass transfer coefficient  $k_L a$ , as it implicates the device's geometry and flow conditions.

Precise measurement of the specific interfacial area a is no requisite, as it is 'lumped' into Equation (1.12) according to the so-called 'lumped-parameter model' [34]. Knowledge of area a would however give more insight in the mechanism, as it can be used to accordingly calculate  $k_L$ . Nonetheless the quality of the microscope photos have shown to be insufficient for area measurements. In this particular case of droplet flow, the length of the droplets is constant (Figure 3.3) over the applied range of flow rates so one could assume a constant area a. Not only is this beneficial in characterizing the mass transfer performance, as it makes the experiments more systematic since it eliminates one variable. It also causes  $k_L$  to be directly proportional to the measured  $k_L a$ .

### 4.1.1 Droplet geometry and mass transfer

In section 2.3.2 the droplet was simplified as having a cross-section equal to the channel's width and height. This is not accurate, as the continuous phase is the wetting phase and forms a layer  $\delta$  between the non-wetting droplet and the channel. This would implicate mass transfer not only occurs at the front and back caps of the droplet, but also with the wetting film. Regarding the mass transfer between the droplet and the continuous phase depicted in Figure 4.1, the following can be considered:

- a) diffusion across the boundary, from the droplet into the wetting film
- b) diffusion across the boundary, from the droplet into the continuous phase bulk
- c) diffusion from the continuous phase bulk into the wetting film

There are also internal convections within the droplets and within the continuous phase bulk, which enhance mixing in both phases. These convections intensify with the droplet velocity, so mixing increases with flow rate.

The wetting film thickness  $\delta$  changes with flow conditions. There are various empirical scaling models, similar to Bretherton's relation for the case of gas-liquid flow [26]. Within this study's limited range of flow rates, the wetting film thickness is assumed to be constant. Also would a low Capillary number be indicative for a more constant  $\delta$ , as viscous forces are of less influence.



Figure 4.1: Mass transfer zones in segmented flow. The circulations depict the convection within the droplet and within the continuous phase

### 4.1.2 Mass transfer at the T-junction

The contribution of mass transfer during droplet formation at the T-junction is ignored. The formation of a droplet is regarded as two steps:

- 1. growing of the droplet, the continuous phase is able to pass
- 2. squeezing of the droplet, continuous phase is essentially blocked until the droplet is pinched of

During the first step, all continuous phase from this droplet to the droplet downstream, has been in contact with the emerging interface. Possibly the entering dispersed phase can be considered as a very long droplet in which internal circulation occurs. During the second step, the continuous phase which is in contact with the droplet, is the same unit of continuous phase as in step 1. With this reasoning, at the beginning of the droplet flow the concentrations in the dispersed phase and the continuous phase are lower and higher, respectively.

## 4.2 Phase separation

In Figure 3.9 and Figure 3.10 it is shown to what extent the phases were separated. Complete separation has not been achieved. Focus was not on complete separation, but on realizing a single phase flow into the spectroscopic flow cell. Tiny amounts of aqueous phase within the feed for the spectroscopic flow cell would be problematic for the measurements, as it erects an interface in the stream which scatters the spectroscope's light. Scattering would cause less light to reach the spectroscope's detector, resulting in a higher measured absorbance. As refraction is dependent on the wavelength, this higher absorbance would be experienced as a non-uniform baseline shift. Despite visual confirmation of no aqueous phase after the separating capillaries, the baseline of the adsorption measurement shifted as shown in the top part of Figure 4.2. One possible explanation is leaking capillary connectors from the chip to the flow cell, so tiny amounts of air enter. Another possibility may be cavitation due to dissolved gases and pressure changes from separating capillaries to the flow cell. Feasibility of the latter has not been studied.

The baseline shift has been estimated and corrected by applying a 'mixture model for baseline estimation', as described by De Rooi and Eilers (2012) [35].



Figure 4.2: Estimate (top) and correction (bottom) of the baseline shift in an absorbance measurement

## 4.3 Recommendations

Establishing a stable segmented flow using a T-junction geometry is fairly easy and has received a lot of attention in the last decade. On the other hand, on chip separation of phases is being neglected.

First, focus should be on this separation and on subsequently adding a next step to the setup, as in this study is embodied by the spectroscopic flow cell. Possibly adding an inert gas as third phase helps in separation [11]. Yet it is advicable to focus on the separation dynamics without adding a third phase, because of possible influence of said phase on the mass transfer performance.

The quality of the microscope photos should be improved. Doing so helps accomodating proper image analysis, for example for interfacial area measurements. This method, described as the 'physical method' by Ghaini et al. (2010), may be complemented by a 'chemical method' [26].

Droplet size within the squeezing regime can be adjusted by varying the width of the dispersed phase inlet channel. This way the droplet can be adjusted within the same sets of volumetric flow rates. Also it would be interesting to gather data on mass transfer for certain volumetric ratios of phases. Finally, mass transfer measurements of the limiting case of a spherical drop could shed light on the mass transfer with the continuous phase bulk and with the wetting film.

# Bibliography

- A. Manz, N. Graber, and H. M. Widmer, "Miniaturized total chemical analysis systems: A novel concept for chemical sensing," *Sensors and Actuators B: Chemical*, vol. 1, pp. 244–248, Jan. 1990.
- [2] H. Yang, Q. Zhou, and L.-S. Fan, "Three-dimensional numerical study on droplet formation and cell encapsulation process in a micro T-junction," *Chemical Engineering Science*, vol. 87, pp. 100–110, Jan. 2013.
- [3] R. Arayanarakool, L. Shui, A. van den Berg, and J. C. T. Eijkel, "A new method of UV-patternable hydrophobization of micro- and nanofluidic networks," *Lab on a Chip*, vol. 11, no. 24, p. 4260, 2011.
- [4] S. Colin, Microfluidics. Wiley-ISTE, London, UK; Hoboken, NJ: ISTE ; Wiley, 1 ed., 2010.
- [5] P. Abgrall and A.-M. Gué, "Lab-on-chip technologies: making a microfluidic network and coupling it into a complete microsystem—a review," *Journal of Micromechanics and Microengineering*, vol. 17, pp. R15–R49, May 2007.
- [6] H. Stone, A. Stroock, and A. Ajdari, "Engineering Flows in Small Devices," Annual Review of Fluid Mechanics, vol. 36, no. 1, pp. 381–411, 2004.
- [7] N. Kockmann, Transport phenomena in micro process engineering: with 17 tables. Berlin, Heidelberg: Springer, 2008.
- [8] D. Joshua, H. Song, A. D. Lyon, and R. F. Ismagilov, "Formation of droplets and mixing in multiphase microfluidics at low values of the Reynolds and the capillary numbers," *Langmuir*, vol. 19, no. 22, p. 9127–9133, 2003.
- [9] H. Song, J. D. Tice, and R. F. Ismagilov, "A Microfluidic System for Controlling Reaction Networks in Time," Angewandte Chemie International Edition, vol. 42, no. 7, p. 768–772, 2003.
- [10] M. N. Kashid, A. Renken, and L. Kiwi-Minsker, "Gas-liquid and liquid-liquid mass transfer in microstructured reactors," *Chemical Engineering Science*, vol. 66, pp. 3876–3897, Sept. 2011.
- [11] N. Assmann and P. R. von Rohr, "Extraction in microreactors: Intensification by adding an inert gas phase," *Chemical Engineering and Processing: Process Intensification*, vol. 50, pp. 822–827, Aug. 2011.
- [12] A.-L. Dessimoz, L. Cavin, A. Renken, and L. Kiwi-Minsker, "Liquid-liquid two-phase flow patterns and mass transfer characteristics in rectangular glass microreactors," *Chemical Engineering Science*, vol. 63, pp. 4035–4044, Aug. 2008.

- [13] D. Mark, S. Haeberle, G. Roth, F. v. Stetten, and R. Zengerle, "Microfluidic lab-on-a-chip platforms: requirements, characteristics and applications," *Chemical Society Reviews*, vol. 39, pp. 1153–1182, Feb. 2010.
- [14] C. Rands, B. W. Webb, and D. Maynes, "Characterization of transition to turbulence in microchannels," *International Journal of Heat and Mass Transfer*, vol. 49, pp. 2924–2930, Aug. 2006.
- [15] Y. Zhao, Y. Su, G. Chen, and Q. Yuan, "Effect of surface properties on the flow characteristics and mass transfer performance in microchannels," *Chemical Engineering Science*, vol. 65, pp. 1563–1570, Mar. 2010.
- [16] A. Günther and M. T. Kreutzer, "Multiphase Flow," in *Micro Process Engineering*, pp. 1–40, Wiley-VCH Verlag GmbH Co. KGaA, 2009.
- [17] J. G. Kralj, H. R. Sahoo, and K. F. Jensen, "Integrated continuous microfluidic liquid-liquid extraction," Lab on a Chip, vol. 7, pp. 256–263, Jan. 2007.
- [18] M. De Menech, P. Garstecki, F. Jousse, and H. A. Stone, "Transition from squeezing to dripping in a microfluidic T-shaped junction," *Journal of Fluid Mechanics*, vol. 595, pp. 141–161, 2008.
- [19] P. Garstecki, M. J. Fuerstman, H. A. Stone, and G. M. Whitesides, "Formation of droplets and bubbles in a microfluidic T-junction—scaling and mechanism of break-up," *Lab on a Chip*, vol. 6, pp. 437–446, Feb. 2006.
- [20] J. Xu, S. Li, J. Tan, and G. Luo, "Correlations of droplet formation in T-junction microfluidic devices: from squeezing to dripping," *Microfluidics and Nanofluidics*, vol. 5, no. 6, pp. 711–717, 2008.
- [21] A. Gupta and R. Kumar, "Effect of geometry on droplet formation in the squeezing regime in a microfluidic T-junction," *Microfluidics and Nanofluidics*, vol. 8, no. 6, pp. 799–812, 2010.
- [22] A. Günther and K. F. Jensen, "Multiphase microfluidics: from flow characteristics to chemical and materials synthesis," *Lab on a Chip*, vol. 6, pp. 1487–1503, Nov. 2006.
- [23] D. M. Fries, T. Voitl, and P. R. von Rohr, "Liquid Extraction of Vanillin in Rectangular Microreactors," *Chemical Engineering & Technology*, vol. 31, no. 8, p. 1182–1187, 2008.
- [24] M. Kashid, A. Renken, and L. Kiwi-Minsker, "Effects of Microfluidics on Preparative Chemistry Processes," in *Microreactors in Preparative Chemistry*, p. 13–54, Wiley-VCH Verlag GmbH & Co. KGaA, 2013.
- [25] M. Kashid, A. Renken, and L. Kiwi-Minsker, "Influence of Flow Regime on Mass Transfer in Different Types of Microchannels," *Industrial & Engineering Chemistry Research*, vol. 50, pp. 6906– 6914, June 2011.
- [26] A. Ghaini, M. Kashid, and D. Agar, "Effective interfacial area for mass transfer in the liquid–liquid slug flow capillary microreactors," *Chemical Engineering and Processing: Process Intensification*, vol. 49, pp. 358–366, Apr. 2010.

- [27] N. Di Miceli Raimondi, L. Prat, C. Gourdon, and J. Tasselli, "Experiments of mass transfer with liquid–liquid slug flow in square microchannels," *Chemical Engineering Science*, vol. 105, pp. 169– 178, Feb. 2014.
- [28] H. Gu, M. H. Duits, and F. Mugele, "Interfacial tension measurements with microfluidic tapered channels," *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, vol. 389, pp. 38–42, Sept. 2011.
- [29] A. Günther, M. Jhunjhunwala, M. Thalmann, M. A. Schmidt, and K. F. Jensen, "Micromixing of Miscible Liquids in Segmented Gas-Liquid Flow," *Langmuir*, vol. 21, pp. 1547–1555, Feb. 2005.
- [30] H. Bruus, "Ch. 3: Basic flow solutions," in *Theoretical microfluidics*, Oxford: Oxford University Press, 2008.
- [31] F. J. V. Santos, "Standard Reference Data for the Viscosity of Toluene," Journal of Physical and Chemical Reference Data, vol. 35, no. 1, p. 1, 2006.
- [32] J. Saien and S. Akbari, "Interfacial Tension of Toluene + Water + Sodium Dodecyl Sulfate from (20 to 50) °C and pH between 4 and 9," *Journal of Chemical & Engineering Data*, vol. 51, pp. 1832–1835, Sept. 2006.
- [33] V. van Steijn, C. R. Kleijn, and M. T. Kreutzer, "Predictive model for the size of bubbles and droplets created in microfluidic T-junctions," *Lab on a Chip*, vol. 10, no. 19, p. 2513, 2010.
- [34] E. Cussler, "Ch. 8: Fundamentals of Mass Transfer," in Diffusion Mass Transfer in Fluid Systems, University of Minnesota: Cambridge University Press, 3 ed., 2009.
- [35] J. J. de Rooi and P. H. Eilers, "Mixture models for baseline estimation," Chemometrics and Intelligent Laboratory Systems, vol. 117, pp. 56–60, Aug. 2012.
- [36] R. Maboudian, W. Ashurst, and C. Carraro, "Self-assembled monolayers as anti-stiction coatings for MEMS: characteristics and recent developments," *Sensors and Actuators A: Physical*, vol. 82, pp. 219–223, May 2000.
- [37] B. J. Adzima and S. S. Velankar, "Pressure drops for droplet flows in microfluidic channels," *Journal of Micromechanics and Microengineering*, vol. 16, pp. 1504–1510, Aug. 2006.

Appendices

# Appendix A

# Appendices to materials and methods

# A.1 Chemicals

All used chemicals with the exception of OTS and the polysiloxane were filtered with a syringe filter (Whatman,  $0.2 \mu m$  PTFE membrane). Filtering was carried out both before preparation of solutions as before injection into a microfluidic device. Water was obtained from a water purification system (Millipore,  $0.22 \mu m$  filter, TOC setting of 3 ppb). A balance (Denver Instrument, max 100 g, d=0.1 mg) and various micropipettes with an adjustable volume (Eppendorf Research) were used for preparing the solutions, as well as standard glassware.

Table A.1

continuous phase	Toluene (C_6H_5CH_3, Sigma-Aldrich, assay $\geq\!99.9\%)$
solute	Phenol $(\mathrm{C_6H_6O},\mathrm{Alfa}$ Aesar, $>\!99\%)$
SAM	Octyl trichlorosilane ('OTS', $\rm CH_3(\rm CH_2)_7SiCl_3,$ Sigma-Aldrich, 97%)
SAM	Polysiloxane ('silicone oil', 20 cSt, $(-{\rm Si}({\rm CH}_3)_2{\rm O}-)_n,$ Sigma-Aldrich)
syringe filter	Whatman Rezist Syringe Filter 30 mm (PP housing, PTFE membrane,
	$0.2\mu\mathrm{m})$
water purification	Millipore Milli-Q Advantage A10 Ultrapure Water Purification System
	with Millipak Express 40 Filter Unit $(0.22\mu\mathrm{m})$ and a Total Organic Car-
	bon (TOC) quality setting of 3 ppb.
scale	Denver Instrument APX-100 scale (max $100\mathrm{g};\mathrm{d}{=}0.1\mathrm{mg}$ )
micropipette	Eppendorf Research micropipette with adjustable volume and Eppendorf
	epT.I.P.S. pipette tips (polypropylene)
	1. $0.5 \mu$ l to $10 \mu$ l with $20 \mu$ l pipette tips
	2. $10 \mu$ l to $100 \mu$ l with $200 \mu$ l pipette tips
	3. $20 \mu$ l to $200 \mu$ l with $300 \mu$ l pipette tips
	4. $100 \mu$ l to $1000 \mu$ l with $1000 \mu$ l pipette tips
syringes	Hamilton Gastight 1700 Series
syringes syringe pumps	Hamilton Gastight 1700 Series Two separate Harvard Apparatus PHD2000 Infusion
syringes syringe pumps capillary tubing	Hamilton Gastight 1700 Series Two separate Harvard Apparatus PHD2000 Infusion Polymicro Technologies Flexible Fused Silica Capillary Tubing
syringes syringe pumps capillary tubing	Hamilton Gastight 1700 Series Two separate Harvard Apparatus PHD2000 Infusion Polymicro Technologies Flexible Fused Silica Capillary Tubing 1. TSP050375 50 um
syringes syringe pumps capillary tubing	Hamilton Gastight 1700 Series Two separate Harvard Apparatus PHD2000 Infusion Polymicro Technologies Flexible Fused Silica Capillary Tubing 1. TSP050375 50 µm 2. TSP100375 100 µm
syringes syringe pumps capillary tubing	<ul> <li>Hamilton Gastight 1700 Series</li> <li>Two separate Harvard Apparatus PHD2000 Infusion</li> <li>Polymicro Technologies Flexible Fused Silica Capillary Tubing</li> <li>1. TSP050375 50 µm</li> <li>2. TSP100375 100 µm</li> <li>3. TSP200350 200 µm</li> </ul>
syringes syringe pumps capillary tubing	<ul> <li>Hamilton Gastight 1700 Series</li> <li>Two separate Harvard Apparatus PHD2000 Infusion</li> <li>Polymicro Technologies Flexible Fused Silica Capillary Tubing</li> <li>1. TSP050375 50 µm</li> <li>2. TSP100375 100 µm</li> <li>3. TSP200350 200 µm</li> </ul>
syringes syringe pumps capillary tubing	Hamilton Gastight 1700 Series Two separate Harvard Apparatus PHD2000 Infusion Polymicro Technologies Flexible Fused Silica Capillary Tubing 1. TSP050375 50 µm 2. TSP100375 100 µm 3. TSP200350 200 µm 4. TSP250350 250 µm
syringes syringe pumps capillary tubing connections	<ul> <li>Hamilton Gastight 1700 Series</li> <li>Two separate Harvard Apparatus PHD2000 Infusion</li> <li>Polymicro Technologies Flexible Fused Silica Capillary Tubing</li> <li>1. TSP050375 50 µm</li> <li>2. TSP100375 100 µm</li> <li>3. TSP200350 200 µm</li> <li>4. TSP250350 250 µm</li> <li>Ferrules, NanoTight Fittings, NanoPort Connectors (Upchurch Scientific,</li> </ul>
syringes syringe pumps capillary tubing connections	<ul> <li>Hamilton Gastight 1700 Series</li> <li>Two separate Harvard Apparatus PHD2000 Infusion</li> <li>Polymicro Technologies Flexible Fused Silica Capillary Tubing</li> <li>1. TSP050375 50 µm</li> <li>2. TSP100375 100 µm</li> <li>3. TSP200350 200 µm</li> <li>4. TSP250350 250 µm</li> <li>Ferrules, NanoTight Fittings, NanoPort Connectors (Upchurch Scientific, IDEX Health &amp; Science)</li> </ul>
syringes syringe pumps capillary tubing connections cutter	<ul> <li>Hamilton Gastight 1700 Series</li> <li>Two separate Harvard Apparatus PHD2000 Infusion</li> <li>Polymicro Technologies Flexible Fused Silica Capillary Tubing</li> <li>1. TSP050375 50 µm</li> <li>2. TSP100375 100 µm</li> <li>3. TSP200350 200 µm</li> <li>4. TSP250350 250 µm</li> <li>Ferrules, NanoTight Fittings, NanoPort Connectors (Upchurch Scientific, IDEX Health &amp; Science)</li> <li>SGT Shortix Fused Silica Tubing Cutter</li> </ul>
syringes syringe pumps capillary tubing connections cutter microscope	<ul> <li>Hamilton Gastight 1700 Series</li> <li>Two separate Harvard Apparatus PHD2000 Infusion</li> <li>Polymicro Technologies Flexible Fused Silica Capillary Tubing</li> <li>1. TSP050375 50 µm</li> <li>2. TSP100375 100 µm</li> <li>3. TSP200350 200 µm</li> <li>4. TSP250350 250 µm</li> <li>Ferrules, NanoTight Fittings, NanoPort Connectors (Upchurch Scientific, IDEX Health &amp; Science)</li> <li>SGT Shortix Fused Silica Tubing Cutter</li> <li>Leica DMI5000M with CTR6000 controller</li> </ul>
syringes syringe pumps capillary tubing connections cutter microscope camera	<ul> <li>Hamilton Gastight 1700 Series</li> <li>Two separate Harvard Apparatus PHD2000 Infusion</li> <li>Polymicro Technologies Flexible Fused Silica Capillary Tubing</li> <li>1. TSP050375 50 µm</li> <li>2. TSP100375 100 µm</li> <li>3. TSP200350 200 µm</li> <li>4. TSP250350 250 µm</li> <li>Ferrules, NanoTight Fittings, NanoPort Connectors (Upchurch Scientific, IDEX Health &amp; Science)</li> <li>SGT Shortix Fused Silica Tubing Cutter</li> <li>Leica DMI5000M with CTR6000 controller</li> <li>Leica DFC300FX</li> </ul>
syringes syringe pumps capillary tubing connections cutter microscope camera UV-Vis flow cell	<ul> <li>Hamilton Gastight 1700 Series</li> <li>Two separate Harvard Apparatus PHD2000 Infusion</li> <li>Polymicro Technologies Flexible Fused Silica Capillary Tubing</li> <li>1. TSP050375 50 µm</li> <li>2. TSP100375 100 µm</li> <li>3. TSP200350 200 µm</li> <li>4. TSP250350 250 µm</li> <li>Ferrules, NanoTight Fittings, NanoPort Connectors (Upchurch Scientific, IDEX Health &amp; Science)</li> <li>SGT Shortix Fused Silica Tubing Cutter</li> <li>Leica DMI5000M with CTR6000 controller</li> <li>Leica DFC300FX</li> <li>WPI MicroLWCC-10 Flow Cell (2.4 µl volume, 10 mm optical path)</li> </ul>
syringes syringe pumps capillary tubing connections cutter microscope camera UV-Vis flow cell Spectrometer	<ul> <li>Hamilton Gastight 1700 Series</li> <li>Two separate Harvard Apparatus PHD2000 Infusion</li> <li>Polymicro Technologies Flexible Fused Silica Capillary Tubing</li> <li>1. TSP050375 50 µm</li> <li>2. TSP100375 100 µm</li> <li>3. TSP200350 200 µm</li> <li>4. TSP250350 250 µm</li> <li>Ferrules, NanoTight Fittings, NanoPort Connectors (Upchurch Scientific, IDEX Health &amp; Science)</li> <li>SGT Shortix Fused Silica Tubing Cutter</li> <li>Leica DMI5000M with CTR6000 controller</li> <li>Leica DFC300FX</li> <li>WPI MicroLWCC-10 Flow Cell (2.4 µl volume, 10 mm optical path)</li> <li>Ocean Optics USB2000+UV-VIS</li> </ul>
syringes syringe pumps capillary tubing connections cutter microscope camera UV-Vis flow cell Spectrometer light source	<ul> <li>Hamilton Gastight 1700 Series</li> <li>Two separate Harvard Apparatus PHD2000 Infusion</li> <li>Polymicro Technologies Flexible Fused Silica Capillary Tubing</li> <li>1. TSP050375 50 µm</li> <li>2. TSP100375 100 µm</li> <li>3. TSP200350 200 µm</li> <li>4. TSP250350 250 µm</li> <li>Ferrules, NanoTight Fittings, NanoPort Connectors (Upchurch Scientific, IDEX Health &amp; Science)</li> <li>SGT Shortix Fused Silica Tubing Cutter</li> <li>Leica DMI5000M with CTR6000 controller</li> <li>Leica DFC300FX</li> <li>WPI MicroLWCC-10 Flow Cell (2.4 µl volume, 10 mm optical path)</li> <li>Ocean Optics USB2000+UV-VIS</li> <li>Ocean Optics DH-2000 deuterium-halogen light source</li> </ul>

## A.2 Experimental procedures

## A.2 (i) Hydrophobizing the chips

Chip 1 was hydrophobized with OTS, a self assembled monolayer (SAM). To this end, the following internal protocol based on work of Maboudian et al. was followed [36]. A similar procedure is described by Adzima and Velankar (2006) [37]. The chip was filled with and submerged by nitrous acid and thereupon placed in a vacuum chamber (4 hours), respectively flushed with water (5 minutes), isopropanol (30 minutes) and hexane (30 minutes). A 5 mM solution of OTS in hexane was prepared and carefully flushed through the channels (30 minutes), whereupon the channels were respectively flushed for 10 minutes with hexane, isopropanol and water. The channels of the device were dried using nitrogen gas and placed in an oven at 120 °C (2 hours).

Referring to Figure 2.1, during this procedure the left ports were used as inlet and the right port was used as outlet. With every step, the top left port was switched with the top middle port for some time, to treat the tapered channels as well. The majority of the time, the fluids were inserted in the two left connections with a syringe pump at a flow rate of 50  $\mu$ l min<sup>-1</sup>. An important notion about this procedure is the filtering of all the fluids prior insertion. The channels were monitored with a microscope to detect possible interfering clots.

Chip 2 was hydrophobized in a similar manner, adopting the procedure described by Arayanarakool et al. (2011) [3].

### A.2 (ii) Characterization of flow regime in chip 1

The flow regime in chip 1 was investigated by varying the flow rate of the aqueous phase at a certain continuous phase flow rate. After changing the flow rates and waiting approximately 5 minutes, the flow regime had settled. Within a period of approximately 5 minutes images at the T-junction and downstream were captured for further analysis. The analysis of these recordings was two-fold. First, the resulting flow regimes at the specified flow rates were classified to be either 'segmented flow', 'stratified flow' or a 'transition regime'. The flow rates were tabulated in one of these three corresponding classes and plotted with Matlab.

### A.2 (iii) Finding segmented flow regime in chip 2

In a similar yet less extensive way, the segmented flow regime was located in chip 2, by varying the aqueous phase flow rate at a certain constant continuous phase flow and waiting until the flow regime had settled. Images of the T-junction and downstream were captured for further analysis using ImageJ and Matlab.

## A.2 (iv) Distribution coefficient

Two experiments with different initial concentrations have been conducted to measure the distribution of phenol between the aqueous and organic phase. A known solution of 5 ml phenol in water was added to a separation flask with 5 ml of toluene. The contents were stirred and after a waiting time of approximately 30 minutes for the two layers to settle, the solutions were separated. The absorbance of the resulting organic phase and the resulting aqueous phase was measured. The reason for measurement of the absorbance of both phases, is to check the total amount of measured phenol with the initial amount of phenol, within the measurement error.

### A.2 (v) Measurement of mass transfer performance

The outlet of organic phase was connected to the flow cell, the outlet of the aqueous phase was connected to a closed waste bin. A total of two sets of experiments were conducted, both with a different starting concentration of phenol in water. In the experiments, the flow rates of the continuous phase was kept constant at 5  $\mu$ l min<sup>-1</sup>, while the flow rate of the aqueous phase was changed from 0.5  $\mu$ l min<sup>-1</sup> to 2.5  $\mu$ l min<sup>-1</sup> with increments of 0.5.