

# Contents

<b>Acknowledgements</b>	<b>iii</b>
<b>Abstract</b>	<b>iv</b>
<b>List of Figures</b>	<b>ix</b>
<b>List of Tables</b>	<b>xxx</b>
<b>1 The Impedance Pump</b>	<b>1</b>
1.1 Introduction . . . . .	1
1.1.1 Pump Background . . . . .	2
1.1.2 Impedance pump concept . . . . .	2
1.1.2.1 Principle and Basic physics . . . . .	2
1.2 A valveless microimpedance pump driven by electromagnetic actuation . . . . .	3
1.2.1 Introduction . . . . .	3
1.2.2 Principle of Operation . . . . .	5
1.2.3 Experimental setup . . . . .	5
1.2.3.1 Micro impedance pump actuation . . . . .	6
1.2.3.2 Closed Loop Flow . . . . .	7
1.2.3.3 Open Loop Flow . . . . .	9
1.2.3.4 Micro Open Loop . . . . .	10
1.2.4 Results . . . . .	11
1.2.4.1 Closed Loop . . . . .	11
1.2.4.2 Open Loop . . . . .	11
1.2.4.3 Micro Open Loop . . . . .	12
1.2.4.4 Description of the micro impedance pumping device . . . . .	12
1.2.5 Discussion . . . . .	13
1.2.6 Conclusion . . . . .	14
1.3 Characterizing the impedance pump . . . . .	15

1.3.1	Introduction . . . . .	15
1.3.2	Experimental Setup . . . . .	16
1.3.3	Results . . . . .	18
1.3.3.1	Pressure and Flow versus frequency . . . . .	18
1.3.3.2	Impedance pump flow response versus position . . . . .	18
1.3.3.3	The phase relationship between pressure and flow . . . . .	19
1.3.4	Discussion . . . . .	21
1.3.5	Conclusion . . . . .	21
1.4	Implementing the impedance pump on the microscale . . . . .	24
1.4.1	Introduction . . . . .	24
1.4.2	Design considerations . . . . .	24
1.4.3	The effect of fluid viscosity on pump performance . . . . .	25
1.4.4	Conclusion . . . . .	29
1.5	Microfluidic platforms and applications . . . . .	29
1.5.1	Impedance pumps in Lab-on-chip microfluidics . . . . .	29
1.5.2	Impedance pumps in rigid systems . . . . .	30
1.5.3	A case study: Optimization of microscale heat transfer . . . . .	32
1.5.3.1	Introduction . . . . .	32
1.5.3.2	Background . . . . .	32
1.5.3.3	Experimental apparatus . . . . .	33
1.5.3.4	Results and Discussion: System specific optimal points for heat transfer . . . . .	34
1.5.3.5	Conclusion . . . . .	34
1.6	Summary . . . . .	35
<b>2</b>	<b>Enhancing transport in microfluidic systems</b>	<b>37</b>
2.1	A systematic study of mixing and transport in microscale cavity flows . . . . .	37
2.1.1	Introduction . . . . .	37
2.1.2	Background . . . . .	38
2.1.3	Principles of microscale mixing . . . . .	38
2.1.4	Dimensionless parameters . . . . .	39
2.1.5	Micro mixers . . . . .	39
2.1.5.1	Passive mixers . . . . .	40
2.1.5.2	Active mixers . . . . .	40
2.1.6	Formulation of the cavity problem . . . . .	41
2.1.6.1	Large scale cavity studies . . . . .	41
2.1.6.2	Cavity flows at the microscale . . . . .	42

2.2	Problem statement . . . . .	43
2.2.1	Approach . . . . .	44
2.3	Description of the experimental setup . . . . .	44
2.3.1	Optical setup . . . . .	46
2.3.2	Microfluidic chip design . . . . .	46
2.3.3	Micro Particle Image Velocimetry . . . . .	46
2.3.4	Analysis of microscale transport . . . . .	47
2.3.4.1	Definition of Particle Residence time . . . . .	47
2.3.4.2	Lagrangian Coherent Structures . . . . .	48
2.4	Experimental results . . . . .	48
2.4.1	Steady flow in microscale cavities . . . . .	48
2.4.1.1	Separation and reattachment versus Re and geometry . . . . .	49
2.4.1.2	Shear layer penetration depth and the affect of freestream Reynolds number . . . . .	50
2.4.1.3	Tangential circulation velocity and freestream Reynolds number . . . . .	52
2.4.1.4	The influence of Reynolds number and geometry on shear stress across the top of the cavity . . . . .	53
2.4.1.5	Residence times of steady cavity flows . . . . .	53
2.4.1.6	Lagrangian Coherent Structures in steady cavity flows . . . . .	56
2.4.1.7	Dimensionality of microscale flows - affect of out-of-plane dimension 30 $\mu\text{m}$ and 100 $\mu\text{m}$ . . . . .	59
2.4.1.8	Dimensionality of microscale flows - affect of out-of-plane dimension 30 $\mu\text{m}$ and 100 $\mu\text{m}$ . . . . .	59
2.4.1.9	Shape of z-profile . . . . .	59
2.4.2	Enhancing transport through pulsatile flow . . . . .	60
2.4.2.1	Influence of Wo and amplitude on pulsatile transport with Re = 1 . . . . .	61
2.4.2.2	Time averaged shear stress versus Wo . . . . .	62
2.4.2.3	Residence times under pulsatile conditions . . . . .	64
2.4.2.4	Lagrangian coherent structures in pulsatile cavity flows . . . . .	64
2.5	Conclusion . . . . .	66
	<b>A Summary of characterization system metrics</b>	<b>69</b>
	<b>B Design of the voltage to current amplifier to drive inductive micro-actuators</b>	<b>70</b>
	<b>C Impedance pump characterization system dynamic response and control system</b>	<b>71</b>
	<b>D Derivation of the Finite Time Lyapunov Exponent</b>	<b>72</b>

<b>E</b>	<b>Supplementary data for Chapter 2 - Steady cavity flow</b>	<b>74</b>
E.1	Data for the AR = 2 cavity . . . . .	74
E.2	Data for the AR = 1 cavity . . . . .	94
E.3	Data for the AR = 0.5 cavity . . . . .	110
<b>F</b>	<b>Supplementary data for Chapter 2 - Pulsatile cavity flow</b>	<b>139</b>
F.1	13 Hz . . . . .	139
F.1.1	Velocity field data at 13 Hz . . . . .	139
F.1.2	Streamline images at 13 Hz . . . . .	180
F.1.3	Residence time of particles in the cavity at 13 Hz . . . . .	219
F.1.4	Lagrangian coherent structures at 13 Hz . . . . .	220
F.2	80 Hz . . . . .	240
F.2.1	Velocity field data at 80 Hz . . . . .	240
F.2.2	Streamline images at 80 Hz . . . . .	281
F.2.3	Residence time of particles in the cavity at 80 Hz . . . . .	320
F.2.4	Lagrangian coherent structures at 80 Hz . . . . .	321
F.3	113.14 Hz . . . . .	341
F.3.1	Velocity field data at 113.14 Hz . . . . .	341
F.3.2	Streamline images at 113.14 Hz . . . . .	382
F.3.3	Residence time of particles in the cavity at 113.14 Hz . . . . .	421
F.3.4	Lagrangian coherent structures at 113.14 Hz . . . . .	422
F.4	113.14 Hz with an amplitude of 0.2 mm . . . . .	442
F.4.1	Velocity field data at 113.14 Hz with an amplitude of 0.2 mm . . . . .	442
F.4.2	Streamline images at 113.14 Hz with an amplitude of 0.2 mm . . . . .	483
F.4.3	Residence time of particles in the cavity at 113.14 Hz with an amplitude of 0.2 mm . . . . .	522
F.4.4	Lagrangian coherent structures at 113.14 Hz with an amplitude of 0.2 mm . .	523
	<b>References</b>	<b>543</b>