REYNOLDS NUMBER EFFECTS IN DESIGNING A MICROMIXER FOR BIOMEMS APPLICATION

INTAN SUE LIANA BINTI ABDUL HAMID

A project report submitted as a partial fulfillment
of the requirement for the award of the
Master's Degree in Electrical Engineering

Faculty of Electrical and Electronics Engineering
Universiti Tun Hussein Onn Malaysia (UTHM)

NOVEMBER, 2008

ACKNOWLEDGEMENT

I wish to thank and acknowledge the assistance and contributions of several people without whom this project would not be possible.

First and foremost, I would like to express my sincere appreciations to my supervisor, Dr Muhammad Mahadi bin Abdul Jamil who provides his invaluable guidance for the work throughout my project. Many thanks to him for his frequent discussions with me about my general research directions and technical details which not only expanded my horizons but also stimulated my creativity and imagination. Thanks also due to my co-supervisor, Mr Alabqari bin Ma'Radzi, for his advice. Our meetings were a tremendous help and he provided assistance in every aspect of my work, above and beyond his duties. Thanks to the other postgraduates who are always there to listen to me when I needed someone to talk to or to help me with alternative views. Thank you very much for your friendship and I cherish the moments we shared together very much!

Finally I wish to thank my dear husband, Kusiar bin Wagimen, for his confidence in my capability, who pushes me to greater achievement, who so patiently supported me throughout the hard times of my work. Thanks to my children, Hurul Ain and Muhammad Mustaqiim for their faith and pride in their mom. Last but not least, I want to thank my mother for her love and dedications for raising me, supporting me and educating me.

ABSTRACT

Two-fluid mixing is an essential process in many microfluidic devices for Biomedical Micro-Electro-Mechanical Systems (BioMEMS) applications. For example, various biomedical and biochemical process involve the mixing of two fluids. The performance of such processes relies on effective and rapid mixing of samples and reagents. This project discussed the mixing characteristics of two fluids with different properties in term of Reynolds number (Re) with Y-Shape glass based micromixer. Blood flow properties was used to be mixed with a particular type of reagents which the difference in the properties of these two mixing fluids will be adjusted by varying the viscosity. The laminar mixing of the two fluids inside these micromixers was simulated at low (<<1) Re flow. The Reynolds number parameters consist of v_s, mean fluid velocity in m s^{-1}, L is the characteristic length in m, μ is the absolute dynamic fluid viscosity in $kgm^{-1}s^{-1}$, and ρ is the density of the fluid in kgm^{-3}. Simulation and visualizations results were obtained using CoventorWare2006. The mixing characterization will be based on the visualization results of the distribution field in term of viscosity. In this study it was found that higher Reynolds number will results in better mixing and smaller mixing channel width.

ABSTRAK

Percampuran dua jenis bendalir adalah satu proses penting dalam kebanyakan peranti bendalir mikro bagi aplikasi BioMEMS. Sebagai contoh, pelbagai proses bio-perubatan dan bio-kimia melibatkan percampuran antara dua bendalir. Prestasi bagi proses tersebut bergantung kepada kepantasan percampuran antara sample dan reagen. Projek ini akan membincangkan tentang ciri-ciri percampuran dua bendalir yang mempunyai perbezaan sifat; dari segi nombor Reynolds pada pencampur mikro berbentuk-Y berasaskan kaca. Sifat pengaliran darah digunakan untuk dicampur dengan beberapa jenis reagen dimana perbezaan sifat kedua-dua bendalir ini diubah dengan mengubah nilai kelikatannya. Percampuran laminar antara dua bendalir didalam pencampur mikro ini disimulasi pada pengaliran nombor Reynolds rendah (<<1). Parameter bagi nombor Reynolds terdiri daripada v_s, iaitu kelajuan bendalir dalam unit in m s^{-1}, L ialah panjang dalam unit m, μ ialah kelikatan dinamik bendalir dalam unit $kgm^{-1}s^{-1}$, dan ρ ialah ketumpatan bendalir dalam unit kgm^{-3}. Simulasi dan keputusan visual didapati menggunakan perisian *CoventorWare2006*. Ciri-ciri percampuran dibuat berdasarkan keputusan visual bagi kelikatan bendalir. Dalam kajian ini didapati nombor Reynolds yang tinggi akan memberi kesan percampuran yang lebih baik dan lebar mixing channel yang lebih kecil.

TABLE OF CONTENTS

LIST OF TABLE

LIST OF FIGURE

LIST OF SYMBOL

a	-	acceleration
d	-	diameter
dS	-	elemental surface area
F	-	force vector
$\vec{g}$	-	gravitational acceleration
L	-	characteristic length
m	-	mass of the body
μ	-	dynamic viscosity
$\vec{n}$	-	unit vector normal to the surface
p	-	pressure
ρ	-	mass density
Q	-	volume flow rate
$\vec{R}$	-	position vector
Re	-	Reynolds number
S	-	control surface
t	-	time
τ	-	shear stress
u_o	-	velocity
$u(y)$	-	velocity of the fluid at a distance y
V	-	fluid's velocity
υ	-	control volume
ν	-	kinematic viscosity
$\vec{v}$	-	flow velocity

θ	-	rate of the change of the induced shear strain
σ	-	standard deviation

LIST OF ABBREVIATIONS

Ab	-	Antibody
Ag	-	Antigen
BEM	-	Boundary Element Method
BioMEMS	-	Biomedical Micro Electro Mechanical Systems
CAD	-	Computer Aided Design
CE	-	Capillary Electrophoresis
CFD	-	Computational Fluid Dynamics
DNA	-	Deoxyribonucleic acid
DRIE	-	Deep reactive-ion etching
ELISA	-	Enzyme-linked immunosorbent assay
FDM	-	Finite Difference Method
FEM	-	Finite Element Method
FVM	-	Finite Volume Method
HPLC	-	High Performance Liquid Chromatography
IA	-	Immunoassays
LIGA	-	Lithographie Galvanoformung Abformung
LOC	-	Lab-on-a-chip
MAFIAS	-	Micro Ammonia Flow Injection Analysis System

MEMS	-	Micro-Electro-Mechanical Systems
MST	-	Microsystem Technology
μTAS	-	Micro-Total-Analysis Systems
ODE	-	Ordinary Differential Equations
PCR	-	Polymerase Chain Reaction
RNA	-	Ribonucleic acid
WBC	-	White blood cells

LIST OF APPENDICES

PUBLICATIONS

1. Intan Sue Liana Abdul Hamid, Ahmad Alabqari Ma'Radzi and Muhammad Mahadi Abdul Jamil (2008). "Low Reynolds Number Effect In Designing Y-Shape Micromixer For BioMEMS Application." 2nd International Conference on Science & Technology: Applications in Industry & Education 2008 (ICSTIE'08), Penang, Malaysia.

2. Intan Sue Liana Abdul Hamid, Ahmad Alabqari Ma'Radzi and Muhammad Mahadi Abdul Jamil (2008). "Viscosity Effect on Low Reynolds Number Mixing In Y-Micromixer." 6th Student Conference on Research and Development 2008 (SCOReD2008), UTM Skudai, Malaysia.

CHAPTER I

INTRODUCTION

1.1 Background

Micro-electro-mechanical systems (MEMS) technologies have been developed over the past 20 years for a diverse range of applications from automotive to medical devices. The development of miniature analytical devices with sophisticated functionality in the field of medical and life sciences is the result of recent advances of microsystem technology (MST) to biomedical applications (BioMEMS). Microsystems (so called lab-on-a-chip, biochips, microchips), which are based on integrating large parallel arrays of miniaturized fluidic components and sensors into the smallest possible space, provide a lot of advantages. In recent years, the demand for high-precision miniature devices and efficient processing technologies for micro-/nano-fabrication has been growing rapidly. The various fields of MST applications are listed in Table 1.1.

Table 1.1 Microsystems technology (MST) applications.

Application field	Devices
Chemical and medical	Gene-chips, hearing aids, drug delivery systems, bio-sensors, fuel cells.
Telecommunication and optical components	Diffraction gratings, miniature lens and mirrors.
Automotive	crash, acceleration and distance sensors
Mechanical	Printer heads, micro heat exchangers, camera and watch components.

1.1.1 BioMEMS

BioMEMS, or biomedical micro-electro-mechanical systems, has emerged as a subset of MEMS devices for applications in biomedical research and medical microdevices. The classes of BioMEMS devices commonly found including microsensing, microactuation, microassaying, micromoving and microdelivery. BioMEMS is a science that includes more than simply finding biomedical applications for MEMS devices. It represents an expansion into a host of new polymer materials, microfluidic physics, surface chemistries and modification, 'soft' fabrication techniques including polymers and biological components, biocompatibility, and cost-effective solutions to biomedical problems. BioMEMS devices are unique because they bring together the creative talents of electrical, mechanical, optical, and chemical engineers, materials specialists, clinical laboratory scientist, and physicians. Miniaturization is important in biomedical applications since we will include sample size from submicron to micron range, for instance the genes, protein and deoxyribonucleic acid (DNA).

BioMEMS devices can typically be considered as having at least one feature's dimension in the submicron to micron range (~100nm-200 μ m), and other dimensions of up to several millimeters. On one end of the application scale they may be the platform for nanotechnologies, while on the other end they may be the key component to a much larger device such as a medical imaging machine. They may be all encompassing devices, but more typically they are integrated with other component and perform one or more functions in a chain of operations connected by tubing or other conduits. Among the advantages of biochip miniaturization are lower manufacturing costs, reproducibility, small sample size, and reagent use. Improved signal-to-noise ratio, improved response time, precise control of mixing, reacting, and discarding of waste products, in-line or embedded detection methods, and high throughput are also advantages of miniaturization biochips (Steven, 2006). The acceleration of new biomedical instrumentation in recent years is due in part to demand for higher-quality medical care, especially in highly developed countries (Dario *et al.*, 2000). By improving current techniques for sample preparation and assay of blood, urine, cerebral spinal fluid, extracts, cells, cultures, and tissues; diagnostic systems can be improved.

1.1.2 Micro-Total Analysis Systems (M-TAS) and Lab-On-A-Chip (LOC)

Micro-total-analysis systems (μTAS), and the subset of devices referred to as lab-on-a-chip (LOC), derive from application of "hard" and "soft" fabrication techniques for the manufacture of miniaturized devices that perform all or part of a biochemical analysis. μTAS may be hybrids of multiple chips, integrated electronics, and external supports; while LOC refers more specifically to a microfluidic chip or other device that performs a well-defined analytical task. Lab-on-a-chip (LOC) is a term for devices that integrate (multiple) laboratory functions on a single chip of only millimeters to a few square centimeters in size and that are capable of handling

extremely small fluid volumes down to less than pico liters. The small size and portability of lab-on-a-chip systems are very advantageous. LOC greatly reduce reagent volume, sample contamination, and power consumption. It can also provide faster and more efficient compounding and separations in biomedical and analytical applications. The miniaturization also results in a significant improvement of lab safety. For example, spills, explosions, and other laboratory accidents that can occur during conventional sample preparation procedures are not a problem with the lab-on-a-chip devices due to the extremely small amount of sample used.

1.1.3 Microfluidics

Design and implementation of necessary microfluidic functions; integration of these functions with complete automation; and development of cost-effective manufacturing technology are the major technical challenges in making these microsystems. Microfluidics covers the science of fluidic behaviors on the micro/nanoscales and the design engineering, simulation, and fabrication of fluidic devices for transport, delivery, and handling of fluids on the order of microliters or smaller volumes. It is the backbone of biological or biomedical microelectromechanical systems (BioMEMS) and lab-on-chip concept, as most of biological analyses involve fluid transport and reaction.

Biological or chemical reactions on the micro/nanoscale are usually rapid since small amounts of samples and reagents are used, which offers quick and low-cost analysis. Major microfluidic components include sample introduction or loading (and in some cases, sample preparation); propulsion of fluids (such as samples to be analyzed, reagents, and wash and calibration fluids) through micron-sized channels;

valving; fluid mixing and isolation as desired; small volume sample metering; sample splitting and washing; and temperature control of the fluids. The main challenge in making miniaturized systems is the integration of different microfluidic components to perform certain functions at high speed and high throughput.

1.1.4 MEMS CAD Tools for Microfluidic Application

Due to the nature of MEMS devices, especially its size and manufacturing cost, it would be very difficult if not impossible to create without first designing and visualizing them. With a simulation tool, it is easier, faster and much less expensive to build a MEMS device. It is absolutely necessary to use a simulation tool so that the time it takes from designing to completion of the component is reduced significantly. It is less cost to modify, if there are mistakes in the design, before it is actually prototyped or manufactured. A simulation tool can be used to predict and improve device characteristics. The accurate analysis of these characteristics leads to an optimization of the device and hence improves system performance.

A typical computer aided design (CAD) should have three basic components; a geometry builder where the geometry of the device could be drawn, a simulation module where the problem is solved using the relevant governing equations, and a visualization module where the simulation results can be displayed (Korsmeyer *et al.*, 2004). In order to create useful MEMS fluidic devices, the CAD tool must have as its underlying principle the models that definitively characterize the operation of the device. Such CADs must be able to handle fluids within the length scales that involve both noncontinuum fluid effects molecular models as well as continuum models (White, 2004).

CAD tools can be categorized as either field-solvers or network simulators. Field-solvers can solve complex partial differential equations, using finite element method (FEM) or boundary-element method (BEM). These equations are a detailed description of the physical design of the MEMS device. They are complex equations taking a lot of time to solve. Network simulators are required for system level modeling. These give a description of the system with a building-block orientation. Simpler ordinary differential equations are used to describe the system. For the design of MEMS, field-solvers are available and are widely used, such as *ANSYS / Multiphysics*. System-level tools are also available, such as *CoventorWare* and *Saber*. This project will be using the *CoventorWare2006* software; where once the behavior of the entire device is understood and promising design identified, detailed numerical modeling can then be carried out in order to confirm the system-level results and to optimize the design parameters.

1.2 Objective of Study

Objectives for this research are:

a) To find an optimum design of micromixer in term of Reynolds number by analysis and characterization of various lengths and width of Y-shape micromixer design.
b) To design and simulate micromixer for laminar fluid mixing of two fluids with various viscosity using *CoventorWare2006* software.
c) To characterize the diffusion properties in micromixer.

REFERENCES

Aubin, J., Fletcher, D.F. and Xuereb (2005). "Design of micromixer using CFD modeling." *Chemical Engineering Science.* **vol. 60.** 2503–2516.

Bharat Bhushan (2004). "Springer handbook of nanotechnology." 2nd. Ed. Springer Science and Business Media.

Burns M. A., Johson B. N., Brahmasandra S. N., Handique K., Webster J. R., Krishnan M., Sammarco T. S., Man P. M., Jones D., Heldsinger D., Mastrangelo C. H., Burke D. T (2001). "An integrated nanoliter DNA analysis device." *Science.* **vol 282**, 484-487.

C.Y. Lee, G.B. Lee, J.L. Lin, F.C. Huang, and C.S. Liao (2005). "Integrated Microfluidic Systems for Cell Lysis, Mixing/Pumping and DNA Amplification." *J. Micromech. Microeng.* **Vol. 15**, 1215-1223.

Chakrabarti R., Schutt C.E. (2001). "The enhancement of PCR amplification by low molecular-weight sulfones", *Gene.* **274(1-2).** 293–298

Cha'o-Kuang Chen, Ching-Chang Cho (2008). "A combined active/passive scheme for enhancing the mixing efficiency of microfluidic devices". *Chemical Engineering Science.* **Volume 63.** 3081-308.

Chiem N. and Harrison D. J. (1997). "Microchip-based capillary electrophoresis for immunoassays: analysis of monoclonal antibodies and tehophylline." *Analysis Chem.*, **Vol 69**, 373-379.

Chiem N., and Harrison D. J. (1998). "Microchip systems for immunoassay: an integrated immunoreactor with electrophoretic separation for serum theophylline determination." *Clinical Chemistry*, **Vol 44(3)**, 591-598.

Cohen c. B., Chin-Dixon E., Jeong S., and Nikiforov T. T. (1999). "A microchip-based enzyme assay for protein kinase." *Analytical Biochemistry*, **vol 273**, 89-97.

Dario, P. et al. (2000) "Micro-systems in biomedical applications." *J. Micromech. Microeng*. **Vol 10**. 235-244.

Dinan Wang, Jonathan L. Summers, Philip H. Gaskell. (2008). "Modelling of electrokinetically driven mixing flow in microchannels with patterned blocks." *Computers & Mathematics with Applications*, **Volume 55**, 1601-1610.

Guber, A.E. (2004) "Microfluidic lab-on-a-chip systems based on polymers-fabrication and application." *Chemical Engineering Journal.* **Vol 101**. 447-453.

Guenat, O.T., D. Ghiglione, W.E. Morf, and N.F. de Rooij. (2001). "Partial Electroosmotic Pumping in complex capillary systems; Part 2: Fabrication and application of a micro total analysis system (μTAS) suited for continuous volumetric nanotitrations." *Sensors and Actuators B: Chemical.* **Vol. 72**. 273-282.

Guoqing Hu, Yali Gao, Dongqing Li. (2008). " Modeling micropatterned antigen–antibody binding kinetics in a microfluidic chip." *Biosensors and Bioelectronics*. **Volume 22.** *1403-1409.*

Hadd A. G., Raymond D. E., Halliwell J. W., Jacobson S. C., and Ramsey J. M. (1997). "Micorchip device for perfrorming enzyme assays," *Anal. Chem.* **vol 69**, 3407-3412.

Hassell, D.G., Zimmerman and W.B. (2006). "Investigation of the convective motion through a staggered herringbone micromixer at low Reynolds number flow." *Chemical Engineering Science.* **vol 61**. 2977–2985.

Hessel, V., Lowe, H., Schonfeld and F. (2005). "Micromixers—a review on passive and active mixing principles." *Chemical Engineering Science.* vol **60**. 2479–2501.

H M Xia, C Shu1, S Y M Wan and Y T Chew. (2005). "Influence of the Reynolds number on chaotic mixing in a spatially periodic micromixer and its characterization using dynamical system techniques." *Journal of Micromechanics and Microengineering.*

Joo-Sung MAENG, Kisoo YOO and Simon SONG. (2006). "Modeling for fluid Mixing in Passive Micromixers Using the Vortex Index." *Journal of the Korean Physical Society.* **Vol. 48**, 902-907.

Kang, T.G., Kwon and T.H. (2004). "Colored particle tracking method for mixing analysis of the chaotic micromixers." *Journal of Micromechanics and Microengineering.* **Vol 14**. 891–899.

Kim, J.H., K.H. Na, C.J. Kang and Y.S. Kim (2005). "A Disposable Thermopneumatic-actuated Micropump Stacked with PDMS Layers and ITO-coated Glass." *Sensors and Actuators A.* **vol 120**, 365-369.

Korsmeyer, T., J. Zeng, and K. Greiner. (2004). "Design Tools for BioMEMS." *Proceedings of the 41st annual Conference on Design Automation.* 622-627.

Koutny L. B., Schmalzing D., Taylor T. A., and Fuchs M. (1996). "Microchip electrophoretic immunoassay for serum cortisol." *Analysis. Chem.* **vol 68(1)**, 18-22.

Lagally E. T., Emrich C. A., and Mathies R. A. (2001). "Fully integrated PCR-capillary electrophoresis microsystem for DNA analysis," *Lab on a Chip, **Vol 1(1)***, 102-107.

Linnemann, R., P. Woias, C.D. Senfft and D.A. Ditterich. (1998). "A Self-priming and bubble-tolerant Piezoelectric Silicon Micropump for Liquids and Gases." *IEEE 11th International Workshop on Microelectromechanical Systems (MEMS 98)*. 532-537.

Liu, Y.Z., Kim, B.J., Sung and H.J. (2004). "Two fluid mixing in microchannel." *International Journal of Heat and Fluid Flow*. **Vol 25**. 986–995.

Manisah Aumerally (2004). "Analytic Model Derivation of Microfluidics Flow for MEMS Virtual-Reality CAD." Griffith University: Ph.D. Thesis

Manz A., Harrison D. J., Verpoorte E. M. J., Fettinger J. C., Paulus, A., Ludi H., Wilmer H. M. (1992). "Planar chips technology for miniaturization and integration of separation techniques into monitoring systems: capillary electrophoresis on a chip." *J. Chromatogr.* **Vol 593**, 253-258 (1992).

Mubashshir Ahmad Ansari, Kwang-Yong Kim. (2007). "Shape optimization of a micromixer with staggered herringbone groove." *Chemical Engineering Science*. vol 62. 6687 – 6695.

N. Kockmann, T. Kiefer, M. Engler, P. Woias. (2005). "Convective mixing and chemical reactions in microchannels with high flow rates." *The 13th International Conference on Solid-State Sensors, Actuators and Microsystems, Seoul, Korea.*

Nam-Trung Nguyen, Steven T. Wereley. (2006). "Fundamentals and applications of microfluidics." 2nd. Ed. Artech House integrated Microsystems series.

Olsson A. (1998). "Valveless Diffuser Micropumps." Royal Institute of Technology, Sweden: Ph.D. Thesis.

Paul C. H. Li. (2006) "Microfluidic Lab-on-a-Chip for Chemical and Biological Analysis and Discovery." CRC Press.

Rafael Vargas-Bernal. (2006). "Selection of Micromixers for Biochemical Detection of Pesticides." *Proceeding of the Electronics, Robotics and Automative Mechanics Conference* (CERMA'06).

Rossier J. S., Girault H. H., "Enzyme linked immunosorbent assay on a microchip with electrochemical detection," Lab on a Chip, 1(2), pp. 153-157 (2001).

S. H. Wong, P. Bryant, M. Ward, C. Wharton. "Investigation of mixing in a cross-shaped micromixer with static mixing elements for reaction kinetics studies." *Sensors and Actuators B*. **vol 95**. 414–424.

Sato K., Tokeshi M., Kimura H., and Kitamori T. (2001). "Determination of carcinoembryonic antigen in human sera by integrated bead-bed immunoassay in a microchip for cancer diagnosis." *Analysis Chem*. Vol **73(6)**, 213-1218.

Siyi Lai (2003). "Design and Fabrication of Polymer-based Microfluidic Platform for BioMEMS Applications." The Ohio State University: Ph.D. Thesis

Schneegab I., Brautigam R., and Kohler J. M. (2001). "Miniaturized flow-through PCR with different template types in a silicon chip thermocycler." *Lab on a Chip*, **Vol 1(1)**, 42-49.

Steven S.Saliterman. (2006). "Fundamentals of bioMEMS and medical microdevices." SPIE Press.

Stroock, A.D., Dertinger, S.K., Ajdari, A., Mezic, I., Stone, H.A., Whitesides and G.M. (2002). "Chaotic mixer for microchannels." *Chemical Engineering Science*. **vol 295**. 647–651.

Tai-Ran Hsu. (2002). "MEMS and Microsystems: Design and Manufacture." International Ed., Mc-Graw Hill.

Tamal Mukherjee, Yong Zhou and Gary K. Fedder. (1999). "Automated Optimal Synthesis of Microaccelerometers."

Tang, Y., Wu, J., Czyzewska, E. Stanley and K. (2004). "An optimized micromixer with patterned grooves." *In: Proceedings International Conference on MEMS, NANO and smart systems* (ICMENS'04).

Vanderplaats, G.N., (1984). "Numerical optimization techniques for engineering design with applications." McGraw-Hill, New York.

Wang, H., Ioveitti, P., Harvey, E., Masood and S. (2002). "Optimizing layout of obstacles for enhanced mixing in microchannels." *Journal of Micromechanics and Microengineering.* **Vol 11**. 662–667.

Wang, H., Ioveitti, P., Harvey, E.,and Masood. (2003). "Numerical investigation of mixing in microchannels with patterned grooves." *Journal of Micromechanics and Microengineering*. **Vol 13**. 801–808.

Waters L. C., Jacobson S. C., Kroutchinina N., Khandaurina J., Foote R. S., and Ramsey J. M. (1998). "Multiple sample PCR amplification and electrophoretic analysis on a microchip." *Analysis Chem*. **Vol 70(24)**, 5172-5176.

White, J. (2004). "CAD Challenges in BioMEMS Design." *Proceedings of the 41st annual Conference on Design Automation*. 629-632.

Woias, P., C.H. Mastrangelo and H. Becker (2001). "Summarising the First Two Decaes, Microfluidics and BioMEMS." *Proceeding of SPIE*, **vol. 4560**, 39-52.

Zeng J., Banerjee D., Deshpande M., Gilbert J., Duffy D.C., and Kollog G.J. (2000). "Design Analyses of Capillary Burst Valves in Centrifugal Microfluidics." *Micro Total Analysis Systems*, 579-582.

Zengler, Z., S. Kluge, M. Richter and A. Richter (1995). "A Bidirectional Silicon Micropump." *Proceeding of IEEE Conference on MEMS*. 19-24.

www.coventor.com (2008), Analyzer: Microfluidic Solvers. Updated: Not Available [cited 19 February 2008]. Available from http://www.coventor.com/mems/analyzer/microfluidic.html