# Numerical Simulation of Forced Convection Heat Transfer of Liquid Alcohol in Microchannel

Denpong Soodphakdee
Department of Mechanical Engineering, Faculty of Engineering
Khon Kaen University, Khon Kaen, 40002 THAILAND
Tel: 0-4324-4296 Ext.115, E-Mail: denpong@kku.ac.th

**Abstract**

Microchannel has been proved to be a high performance heat transfer device. However the design correlations for microchannel have not yet well established. Previous researches found such correlations to be inconsistency among them. The diversifying has made the design depend on the experimental data for each working fluid and microchannel geometry. Liquid alcohol is involved in many industrial products and sometimes required heating or cooling in the production process, the microchannel heat exchanger may be used as an effective compact heat exchanger. The heat transfer correlation is, however, essential for the design of microchannel. A series of CFD simulations of forced convection of liquid alcohol in microchannel is then performed. The heat transfer performance and, its penalty, pressure drop are presented in dimensionless forms. Heat transfer and flow correlations are produced statistically and presented.

**Introduction**

The advantage of microchannels was first introduced by Tuckerman and Pease [1] for microelectronic cooling devices. Applications have since been expanded to other micro- and nano-technologies such as bioengineering, mini heat exchangers, aerospace and micro-electromechanical systems (MEMS). Due to the ever-increasing needs for cooling of electronic components in the past decade, micro-fabrication has been one of the key research fields for heat transfer engineers. In spite of the rapid growth of the knowledge, the prediction of heat transfer in microchannel is not yet a well-established engineering practice. Various investigators proposed heat transfer correlations, but there is hardly any consistency among them [2]. Some investigators are attempting to interpret such discrepancies in terms of novel physical mechanisms which are claimed to be due to micro-scales encountered [3].

Tuckerman and Pease [1] proposed a high performance heat sink for cooling of electronic chips using low and high aspect ratio channels. They demonstrated that the heat transfer rate of liquid turbulent flow through microchannel might be higher than that of turbulent flow through normal sized channels. Since their work, a number of investigators motivated by the ever-increasing cooling requirements in electronic devices have studied various aspects of this research field. In fact, the differences between flow and heat transfer phenomena in microchannels and normal sized channels, encouraged researchers to try to understand such a complex phenomena [4, 5, 6].

Using the design approach of Tuckerman [7], Riddle *et al* [8] wrote a simple computer program to calculate the heat transfer coefficient based on the experimental results. They concluded that Tuckerman's design approach could only adequately be applied to laminar flow. Knight *et al.* [9] used the governing equations and combined conduction/ convection heat transfer to optimize microchannel heat sink analytically. They presented a set of equations for optimization of heat sinks. A series of experiments were conducted by Peng and Wang [10, 11] to study forced convection in microchannels. Their experimental results were inconsistent especially in transition and laminar regimes and indicated that the flow and heat transfer were quite different from those found in normal sized channels. They also pointed out that their adopted experimental apparatus was complicated and conducting the experimental measurements was very difficult.

Alternative energy resources have been studied seriously especially when the fossil fuel price is high. In order to reduce the damage of economic and environment, alcohol is one of the popular choices for the replacement of the synthetic octane increment of gasoline. The use and production process of alcohol are usually involve in heating or cooling of liquid alcohol which require heat exchanger. Enhancement of the overall heat transfer coefficient reduces the size of heat exchanger. Microchannel is selected to be the enhancement device and studied here. As discussed earlier, the design of such device requires the accurate heat transfer coefficient and pressure drop empirical equations, while the correlations studied earlier have yet well established. This study is aim to investigate the relation between flow and heat transfer of liquid alcohol in microchannel. Turbulent forced convection cases are systematically set up to investigated. However, for clarity, the causes of uncertainties in microchannel experiment should be noted as discuss following.

**Uncertainty in Microchannel Experiments**

For a given Reynolds number, as the hydraulic diameter of channel decreases, the convection heat transfer coefficient, *h*, increases inversely. These phenomena drove the development of small opening channels for cooling of electronic equipment. The small rectangular passages are fabricated in silicon by precision sawing or by orientation etching. With the advent of wafer fabrication technology, recently, much smaller size passages have been fabricated than in the earlier experiments. Experiments for correlation development using single- and two-phase microchannel flow have been conducted over the years to allow heat transfer engineers readily predict heat transfer coefficients. However, when dealing with such a very small scale, experimental errors can easily occur and these are very difficult to control or avoid. Riehl *et al* [2] analyzed several correlations from past experiments and compare the heat transfer coefficients. They plotted the analyzed results of Nusselt number versus Reynolds number for three different working fluids using various experimental correlations. The graph of Nusselt number versus Reynolds number presented in their paper [2] showed a significant scatter. They noted that the slope of Nusselt number versus Reynolds number curves is different for all correlations compared. In addition, the Nusselt number values at a given Reynolds number could vary by as much as an order of magnitude.

The reason for the disagreement in those correlations could be the uncontrolled parameters or limitations of the experiments. These may include effects of thermophysical properties of fluid, variation of fluid properties for a varied range of temperatures and operation pressures used in different experiments which can all affect the value of heat transfer coefficient. As fluid moves along the microchannel, the fluid temperature is changed by heating/cooling of the surface. Consequently, the fluid properties vary from the entry to the end of microchannel. Impurities in the fluid such as very small dust particles can disturb the flow and affect heat transfer. These impurities may come from a dusty environment, dusty equipment surfaces, or leaking of the pump lubrication oil to the coolant fluid. Effect of entrance length, using different configurations for delivering fluid into the microchannel in each experiment can affect the heat transfer rate as well. Inclination of channel can also be the other possible source of correlation error. The effects of geometry, in such a small channel with high geometric aspect ratios, sub-micron misalignment of channel ceiling height causes a non-uniform flow passage area, which affects the flow. Flow acceleration/deceleration plays a major role in the development of flow and thermal boundary layers. Connectivity of experimental equipment and measurement instrument installation can also have an effect on the flow. Tolerance of the equipment miniaturization can amplify geometric imperfections in the channel. Channel surface roughness and surface material type might also have an effect on the flow and heat transfer rate. Etching a smooth surface to form the microchannels may lead to a relatively rough channel.

**Computational Fluid Dynamics Simulation and Validation**

CFD has been used as an effective tool for fluid flow and heat transfer for many years now. With its advantage of low cost and faster investigation of the heat transfer problem or design, CFD is widely used in many research and commercial areas. The governing equations are those of two- and three-dimensional continuity, Navier-Stokes and the energy equation in their incompressible turbulent form. The RNG-k-$\varepsilon$ model is used to solve the turbulent parameters in Reynolds-stress approach. These equations are well known and will not be repeated here. Even though the governing equations above are developed under the continuum fluid mechanics assumptions, for the case of microchannel, the minimum channel dimension is much higher than molecule size of liquid alcohol with many orders of magnitude. The solution method of continuity, Navier-Stokes and the energy equations used in CFD can then be applied in microchannel application and it has been validated as in literature.

In this study we have used the finite volume CFD package FLUENT Version 6. The code was validated using the available single phase microchannel data of Mizunuma *et al* [12]. Figure 1 shows a comparison of measured and simulated Nusselt number for various Reynolds numbers for the dielectric liquid PF5060 (from 3M$^{TM}$). Both two- and three-dimensional simulations were performed. A good agreement between the simulation and experiment is noted. As a result, it is reasonable

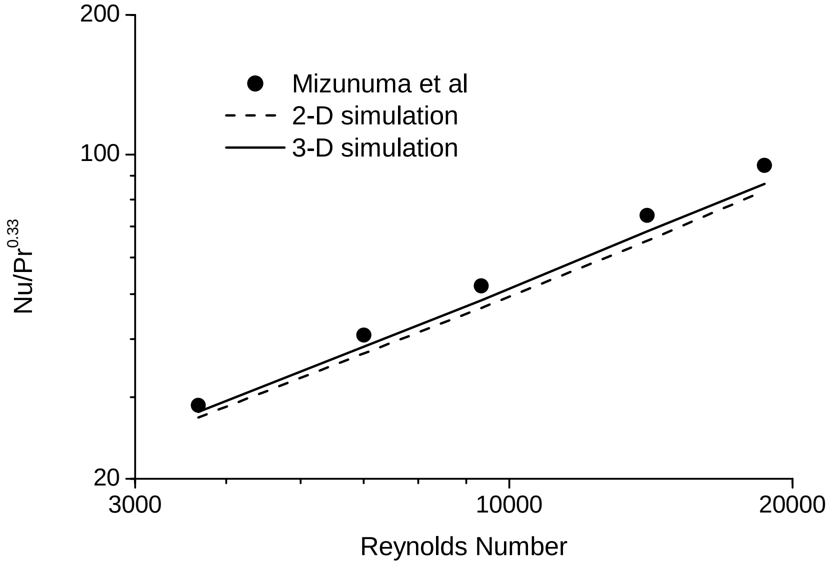


Figure 1: CFD validation using the flow of liquid PF5060 in microchannel

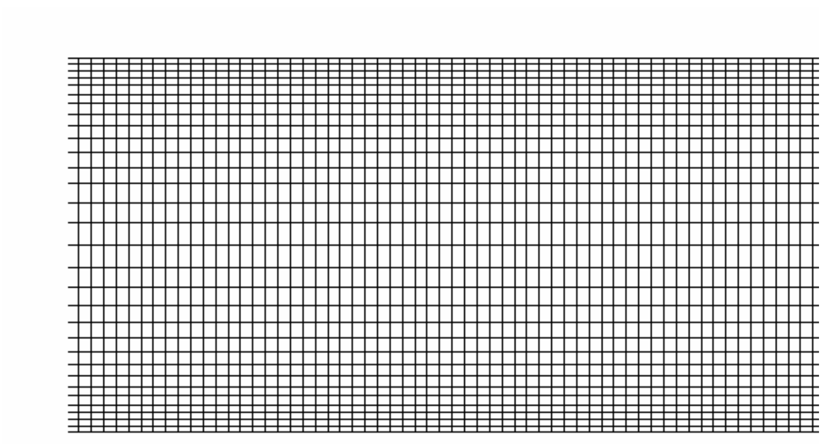

Figure 2: Computational mesh

to conclude that Fluent V.6 can be used to solve flow and heat transfer in microchannel.

**Problem Definition and Solving**

Two dimensional model of 1mm height and 20mm long channel is use as a base case for simulation. The mesh was gradually smooth to ensure boundary layer solving. Total of 180,000 cells are used to ensure good resolution. Figure 2 shows a part in the middle of channel. Physical properties of liquid ethyl-alcohol are shown in Table 1. Reynolds number is calculated base on channel hydraulic diameter which is twice channel height. Reynolds number of channel is varied from 1,200 to 8,000. As known for the flow in microchannel, the flow regime becomes fully turbulent where Reynolds number is higher than 300. Therefore the turbulent model must be used in this study. RNG k-$\varepsilon$ with standard wall function is used. SIMPLEC is implemented as discretization method for pressure-velocity coupling. And to ensure high accuracy solution the second-order upwind is used for momentum energy and turbulent discretizations.

Table 1: Physical Property of ethyl-alcohol

| Property | Value |
|---|---|
| Density, $\rho$ | 790 kg/m$^3$ |
| Viscosity, $\mu$ | 0.0012 kg/m-s |
| Specific heat, $C_p$ | 2470 J/kg-K |
| Thermal conductivity, k | 0.182 W/m-K |

**Results and Correlations Development**

In order to demonstrate microchannel performance, some important parameters have to be defined. Reynolds number, Nusselt number and friction coefficient are defined as shown in equation (1).

$$\text{Re}=\frac{\rho V D_h}{\mu},\quad \text{Nu}=\frac{hD_h}{k},\quad C_f=\frac{\Delta p}{\frac{1}{2}\rho V^2} \tag{1}$$

Figure 3 shows the relation between Reynolds number and Nusselt number. The square points represent the numerical simulation results and the line is produced from the best fit of numerical data. Figure 4 shows the relationship between friction coefficient and Reynolds number. The heat transfer and friction correlations are then developed using nonlinear multiple regression at the asymptotic of 95%. Those correlations are shown in equation (2) and (3), respectively. Both equations are fit with the graphs very well. The multiple coefficient of determination value, $R^2$, for Nusselt number and friction coefficient are 98.9% and 100%, respectively.

$$\text{Nu}=2.31\text{Re}^{0.491} \tag{2}$$

$$C_f=\frac{780.46}{\text{Re}^{0.514}} \tag{3}$$

Above correlations clearly demonstrate the different in both flow and heat transfer between microchannel and conventional channel flow.

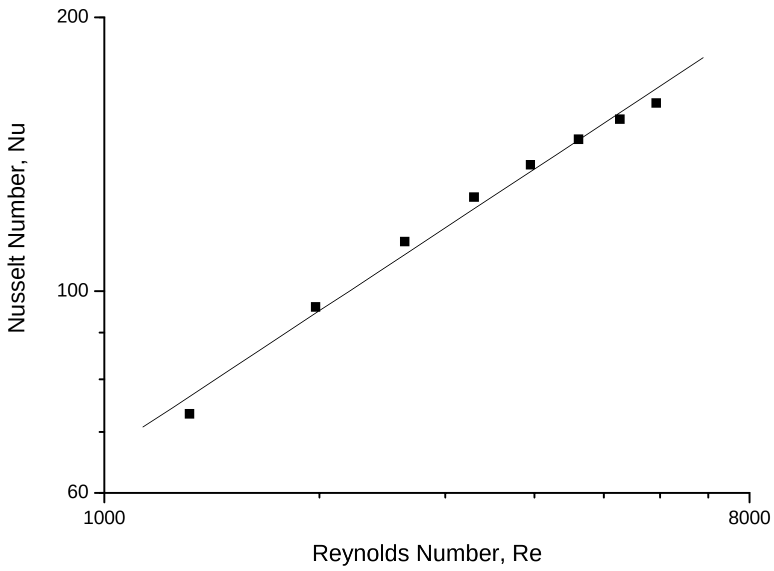


Figure 3: Reynolds number versus Nusselt number

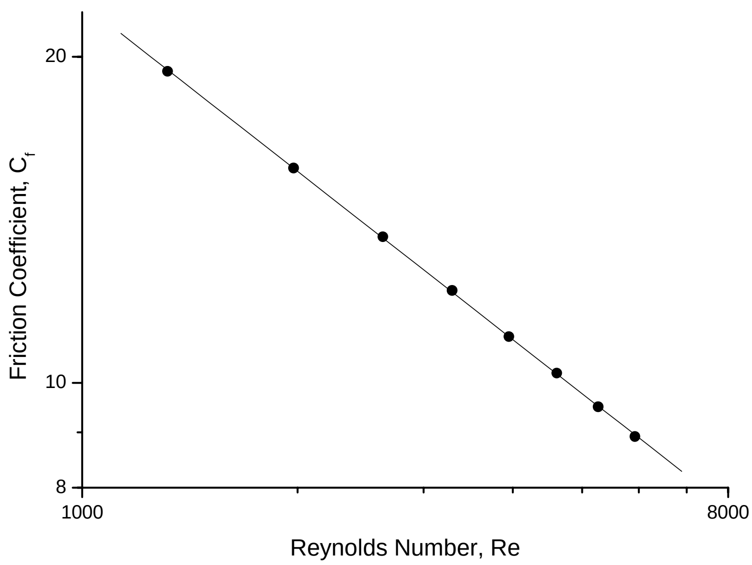


Figure 4: Reynolds number versus friction coefficient

## Concluding Remarks

The promising heat transfer performance of microchannel has pushed the requirement of trustable flow and heat transfer correlations for the design of devices that implement microchannel. However, diversifying of the experimental results drives the need of more accurate way to investigate the flow and heat transfer characteristic in microchannel. Since the knowledge of flow and heat transfer phenomena in microchannel have yet to be established, individual study cannot be avoided. Liquid alcohol has no exception; this study conducts the CFD simulation with a very high resolution of grid to ensure accuracy. A series of simulation cases are setup and simulated. The results are presented in a proper way. Dimensionless parameters are used to present the performance as well as the penalty. Flow and heat transfer correlations are statistically produced and presented.

## References


[1] D. B. Tuckerman and R. F. W. Pease. High-Performance Heat Sinking for VLSI, *IEEE Electron Device Letters*, EDL-2(5):126-129, 1981

[2] R. R. Riehl, P. Seleghim Jr., and J. M. Ochterbeck. Comparison of Heat Transfer Correlations for Single- and Two-Phase Microchannel Flows for Microelectronics Cooling, In *The Sixth InterSociety Conference on Thermal Phenomena*, pages 409-416, Washington, USA, May 1998

[3] X. F. Peng and B. X. Wang. Forced Convection and Flow Boiling Heat Transfer for Liquid Flowing Through Microchannels, *International Journal of Heat and Mass Transfer*, 36(14):3421-3427, 1993

[4] P. Y. Wu and W. A. Little. Measurement of Friction Factor for Flow of Gases in Very Fine Channels Used for Microminiature Joule-Thomson Refrigerators, *Cryogenics*, 23:273-277, 1983

[5] J. Pfahler, J. Harley, H. H. Bau, and J. Zemel. Liquid Transport in Micron and Submicron Channels, *Journal of Sensors Actuators*, A21-23:431-434, 1990

[6] S. B. Choi, R. F. Barron, and R. O. Warrington. Liquid Flow and Heat Transfer in Microtubes, *Micromechanical Sensors, Actuators and Systems*, ASME DSC, 32:123, 1991

[7] D. B. Tuckerman. Heat Transfer Microstructures for Integrated Circuit, *Lawrence Livermore National Laboratory UCRL-53515*, February 1984

[8] R. A. Riddle, R. J. Contolini, and A. F. Bernhardt. Design Calculation for The Microchannel Heatsink, *NEPCON West*, pages 161-171, 1991

[9] R. W. Knight, D. J. Hall, J. S. Goodling, and R. C. Jaeger. Heat Sink Optimization with Application to Microchannels, *IEEE Transactions on Components, Hybrids, and Manufacturing Technology*, 15(5):832-842, 1992

[10] B. X. Wang and X. F. Peng. Experimental Investigation of Liquid Forced-Convection Heat Transfer Through Microchannels, *International Journal of Heat and Mass Transfer*, 37(1):73-82, 1994

[11] X. F. Peng, B. X. Wang, G. P. Peterson, and H. B. Ma, Experimental Investigation of Heat Transfer in Flat Plates with Rectangular Microchannels, *International Journal of Heat and Mass Transfer*, 38(1):127-137, 1995

[12] H. Mizunuma, M. Behnia, and W. Nakayama. Heat Transfer from Micro-Finned Surfaces to Flow of Fluorinert Coolant in Reduced-Size Channels, *IEEE Transactions on Components, Packaging, and Manufacturing Technology-Part A*, 20(2):138-145, 1997