Temperature variations and cooling efficiency of forced convective heat transfer of nanofluids in microchannel laminar flow

†*V.K. Sin and K.K. Teng

[1]Department of Electromechanical Engineering, University of Macau, Macau SAR, China.
*Presenting author: vksin@umac.mo
†Corresponding author: vksin@umac.mo

Abstract

Numerical study of heat transfer of nanofluids has been conducted to investigate forced convective cooling in rectangular microchannel. A micro-electro-mechanical system is modelled by building with two heating resistors embedded in a silicon substrate. Microchannel made from polydimethylsiloxane is planted in the substrate with a length of 17.5mm. Two cross section areas with high and width of 100μm x 100μm and 100μm x 1000μm are being used for the study. TiO_2/water nanofluid with different volume fractions are used as the coolant. Because of the not well-insulated micro-electro-mechanical system, heat generated by the heating resistors will be lost to the surrounding as well as carried away by the nanofluids through the microchannel. Temperature variations along the microchannel is calculated based on the concept of conjugate convective heat transfer. Force convective heat transfer is analyzed at low Reynolds number for different nanofluid concentrations. Numerical results are compared with experimental data available in the literature.

Keywords: Nanofluid, convective heat transfer, microchannel

Introduction

Due to scientific and technological progress and innovations, traditional heat exchanger technology has become difficult to meet the cooling requirement. It is necessary to develop a better heat transfer technology. Some researchers began to explore the nanotechnology and cooling of micro-electro-mechanical system (MEMS). Nanofluid is proposed to improve the cooling effect by increasing heat transfer coefficient [1]. Nanofluid is a fluid which consists of nanometer-sized particles dispersed in liquids. Nanoparticles are typically made of metals, oxides, carbides, or carbon nanotubes and typically base fluids were water, ethylene glycol and oil. Nanoparticles sizes typically on the order of 1 to 100 nm. Moreover, nanoparticle shapes typically have sphere, cylinder, platelet, blade and brick. Nanofluid is primarily used as coolant in heat transfer equipment such as microelectronics, engine cooling, chiller and heat exchanger.

In order to improve heat transfer technology, one of the effective methods is to add high conductivity solid particles in fluid because thermal conductivity of solid is much larger than liquid. As shown in Table 1.1 of [2], the thermal conductivity of copper is larger than thermal conductivity of water almost by 650 times. Moreover, thermal conductivity of Alumina also is more than that of common nonmetallic liquid by a large amount. Adding solid particles in fluid can greatly increases thermal conductivity of fluid; however it may lead to an increase in friction and viscosity if micrometer scale particles are added to the fluid. Along with the progress of science and technology, adding nanometer scale particles to fluid is found that can effectively improve thermal conductivity of fluid without increasing friction and viscosity.

Numerous literatures began to study about the nanofluid for increasing the heat transfer coefficient. Although many results have indicated that nanofluids can increase the convective heat transfer coefficient [3]-[6], some other results show that adding nanoparticles do not improve the cooling effect or increase the friction factor [7][8]. The possible explanations for the anomalous reasons were Brownian motion of the particles, molecular-level layering of the liquid at the liquid/particle interface, the nature of heat transport in the nanoparticles and the effects of nanoparticle clustering.

Nanofluids experiments have many limits. For example, adiabatic wall condition, constant temperature wall condition and supply constant heat flux are difficult to achieve. The limited amounts of sensors and low precision sensors will also affect the result of the experiment. Computational investigation could meet the requirements more easily. Experimental data and conditions such as temperature field, velocity field and energy distribution can be realized through computational investigation.

In order to further analyze heat transfer enhancement of nanofluids in rectangular microchannels flow, this numerical study is based on the experiment of [7] for comparison. The objective of present study is to analyze the nanofluids for heat transfer enhancement in different conditions such as different channel size, Reynolds number, and volume fraction of the nanoparticles. Temperature variation along the channel and heat carried away by the nanofluid will be investigated and the results will be compared with experimental data available in the literature.

Model Setting in Simulation

The experiment of [7] is modelled by COMSOL-Multphysics and is given in Fig. 1. To complete this complex modelling, the following settings which are close to [7] as possible are applied in the modelling. A base silicon substrate with a size of 45mm x 45mm x 525μm is built first. Two heating resistors with size of 2mm width, 30mm long and 0.1mm high are then embedded on the substrate. Two reservoirs with diameter of 2mm are connected to the inlet and outlet of the microchannel separately. Microchannel with length of 17.5mm and two different rectangular cross section areas of 100μm x 100μm and 100μm x 1000μm are used for study. For analysis of the experiment and simulation data, the model is marked with seven points which are the locations of experiment thermocouples of [7] as shown in Fig. 2. Point A and point G represent inlet and outlet position of microchannel, respectively. Point B to point F are locations for temperature measurement which has distance of 0 (inlet), 4.4, 8.8, 13.2, and 17.5mm (outlet) from the inlet, respectively. The entire microchannel and reservoirs are sheltered with a polydimethylsiloxane (PDMS) channel cover. Property of silicon substrate and PDMS channel cover is given in Table 1.

The simulation model is solved with finite element method for the governing partial differential equations. The more the amounts of grids are meshed, the more precise the result should be. Because computer operational capability is limited, most of the grids are set at channel for analyzing fluids heat transfer. The model is mainly meshed to triangular prism grids and tetrahedral prism grids. Moreover the heat transfer analysis is mainly needed for the acquisition data of channel surface, for example calculating the convective heat transfer coefficient is required the surface temperature and surface heat flux. Boundary layer meshing way is used in this model to mesh grids at the channel boundary. The total number of grids consist of around one million elements as shown in Fig. 3. In order to find out the amount of heat that is lost to the ambient air which surrounds the MEMS, an appropriate convective heat transfer coefficient of air has to be determined. It is found in [9] that boundary condition with heat transfer coefficient, h=12 W/m^2/K, at room temperature of twenty-five degrees Celsius is accurate enough for present simulation. This value of heat transfer coefficient is in the range of natural convection coefficient between 2 and 25 W/ m^2/K [2].

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Table 1. Property of silicon substrate and PDMS cover

Material	Silicon substrate	PDMS cover
Density (kg/m^3)	2329	0.97
Thermal conductivity (W/m/K)	130	0.15
Specific heat (J/kg/K)	700	1460

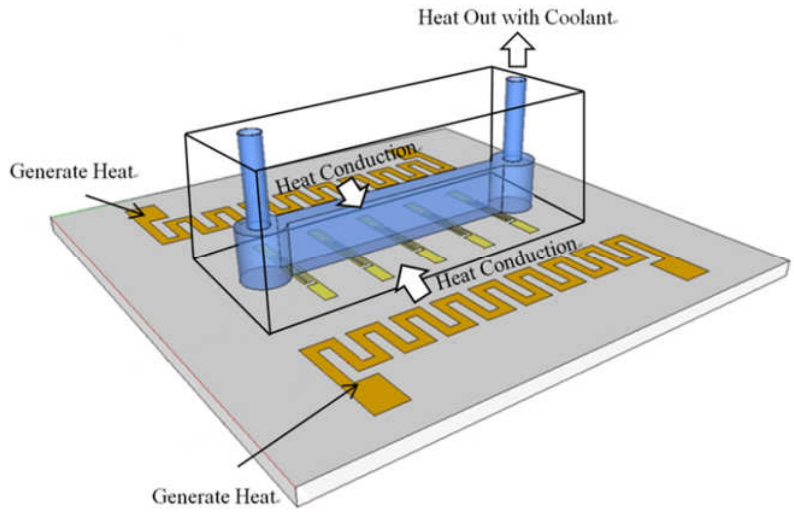


Figure 1. : Model setting of heat transfer in [7]

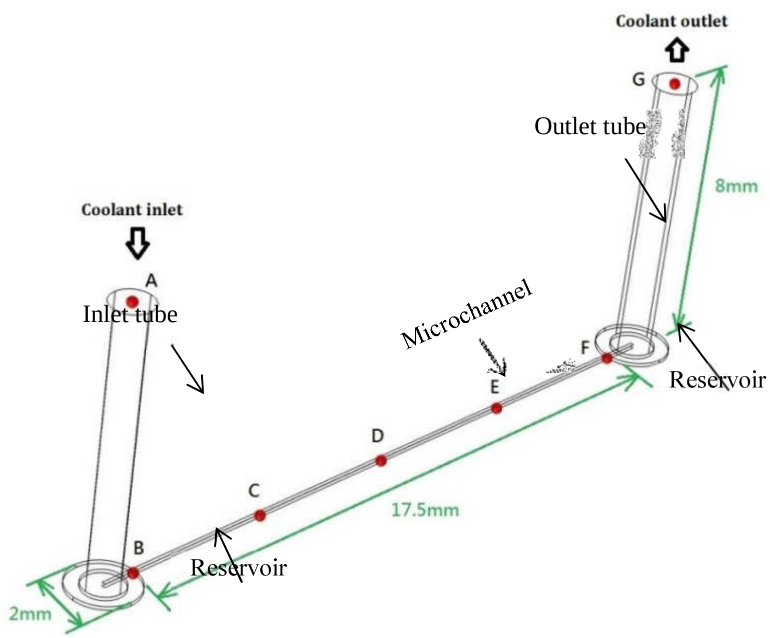


Figure 2. Locations of thermocouple and temperature simulation for comparison

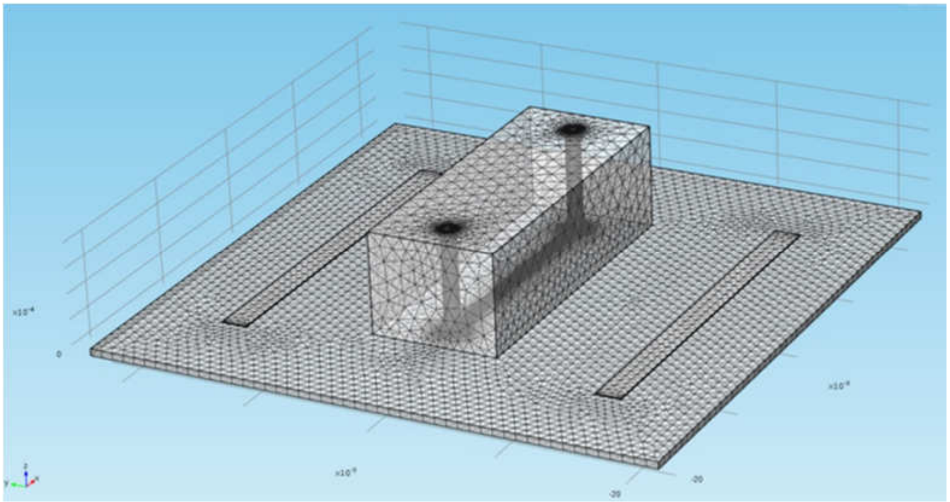


Figure 3. Typical mesh simulation model

Thermal and Transport properties of Nanofluids

Nanofluids in convective heat transfer has been researched only in past few decades, so nanofluid properties could not be explained by existing theories completely. In this study, nanofluid was assumed to be a new kind of fluid in the simulation. Effective thermal conductivity, specific heat capacity and dynamic viscosity of this new fluid were required in order to perform the simulation and analysis. Because there are many literatures indicated that the variation of dynamic viscosity can almost be ignored such as in [7], the dynamic viscosity was set the same as base fluid. Calculation of all these properties is given in [6] and the information is reproduced in Table 2.

Table 2. Properties of nanofluids

Volume fraction	0%	0.6%	1.2%	1.8%
Density (kg/m^3)	998.57	1017.96	1037.34	1056.73
Thermal conductivity (W/m/K)	0.6070	0.61644	0.62599	0.63564
Specific heat (J/kg/K)	4181.3	4094.24	4010.43	3929.70
Dynamic Viscosity (kg/m/s)	0.00084	0.00084	0.00084	0.00084

Results and Discussion

In order to analyze heat transfer enhancement of nanofluids flowing inside rectangular microchannels, the temperature of nanofluid along the microchannel is required for the analysis. The computational results and experimental results of [7] of nanofluid temperature along the channel with heating power 0.58Watt in different Reynolds numbers and different volume fractions for two cross section areas of 100μm×100μm and 100μm×1000μm are shown in Fig. 4 and Fig. 5, respectively. Reynolds number is defined as $Re = \frac{\rho u_m D_h}{\mu}$, where ρ is density of nanofluid, u_m is mean velocity of nanofluid in microchannel, D_h is hydraulic diameter, and μ is dynamic viscosity of nanofluid.

In Fig 4, solid lines are for computational results while solid symbols for experimental data of [7]. For low Reynold number such as Re=6 shown in Fig 4(a), both simulation results and experimental results cannot clearly indicate the increase of temperature with increase of volume fractions. But for Re=10 and 18 as indicated in Fig. 4(b) and 4(c), both simulation and experimental results of temperature increase with increasing the volume fraction of nanofluid. In Fig. 4(c) the simulation results with volume fraction of 1.2% and 1.8% have very close temperature variations, so these two results collapsed on a single line. Moreover It is noted that while the simulation results find the nanofluid temperature increases gradually along the channel from inlet to outlet, the experimental results of [7] show the other way, nanofluid temperature decreases along the channel. According to the report of [7], this temperature decreases along the channel may due to the fact that some titanium dioxide nanoparticles may have agglomeration inside the channel at lower Reynolds number with cross section area of 100μm×100μm. The simulation results seem more reasonable than the experimental results of [7] as simulation results truly predict the increase of temperature as the fluid flows along the channel, this is because the fluid absorbs heat from the walls and make the temperature rise.

Figure 5 gives temperature result for cross section area of 100μm×1000μm. Although the simulation nanofluid temperatures do not increase with increase in the volume fraction of nanofluid for all Reynolds numbers being considered, the nanofluid with 1.8% volume fraction has temperature higher than that of deionized water. Adding nanoparticles to fluid does not contribute any regular variations to the experimental temperatures. Both simulation and experiment results of temperature increase as the fluid flows from inlet to outlet. It is also found that simulation results of temperature decrease with increase of Reynolds number.

Cooling efficiency (E) of nanofluid in microchannel represents the ratio of heat carried out by coolant (Q_f) over heat generated by the heating electrodes (Q_{chip}), which can be expressed as:

$$E = \frac{Q_f}{Q_{chip}} \times 100\% \quad (1)$$

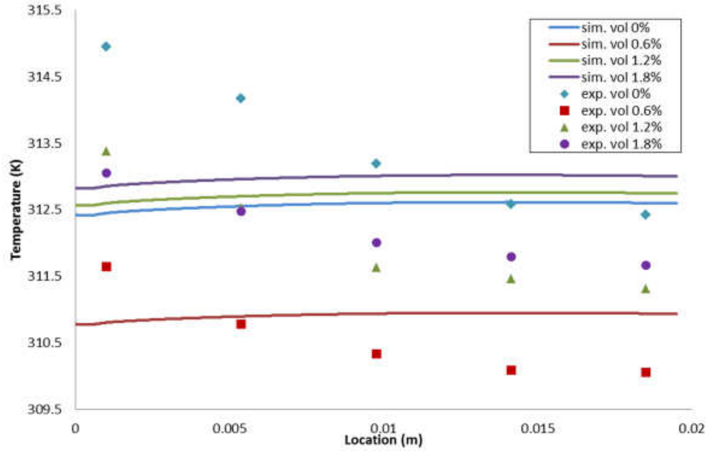
Where the heating power generated by electrodes is expressed as:

$$Q_{chip} = I * V$$

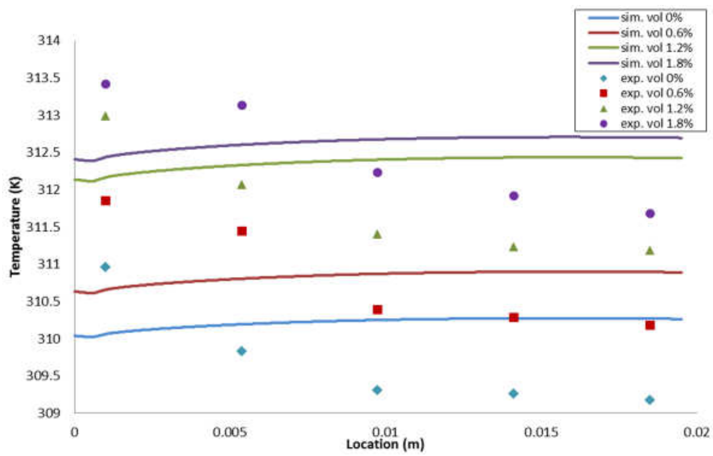
Where I is electric current and V is voltage. Heat carried out by the coolant can be expressed as

$$Q_f = \dot{m} * C_p * (T_{out} - T_{in})$$

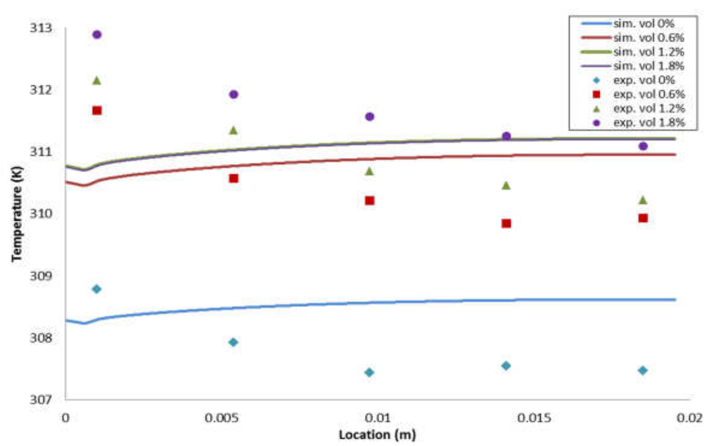
Where T_{out} and T_{in} are the outlet and inlet temperature of nanofluid respectively, $\dot{m}$ is the mass flow rate of nanofluid, and C_p is the specific heat capacity of nanofluid.



(a) Re = 6

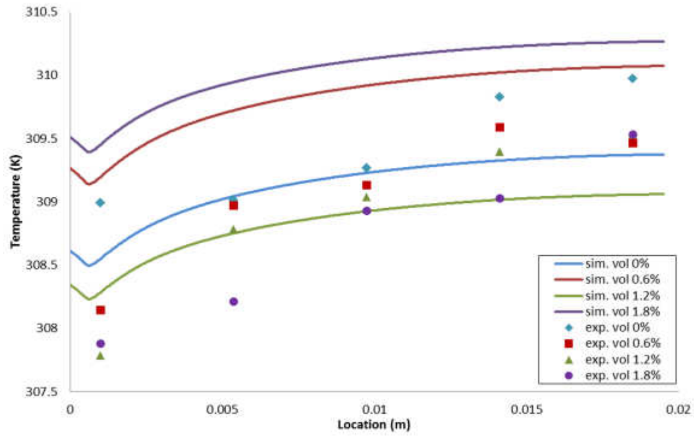


(b) Re=10

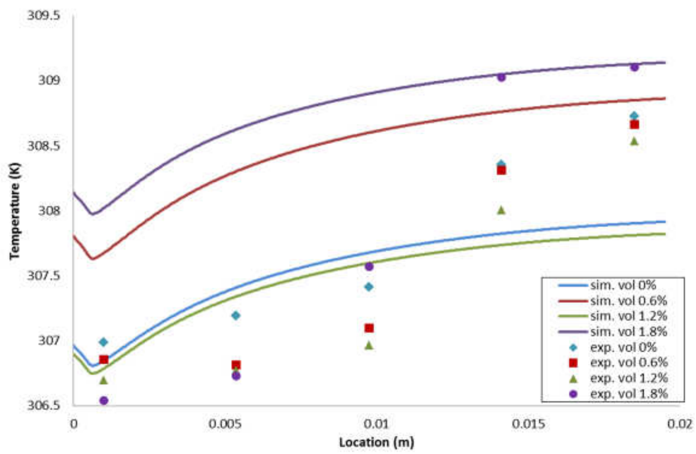


(c) Re = 18

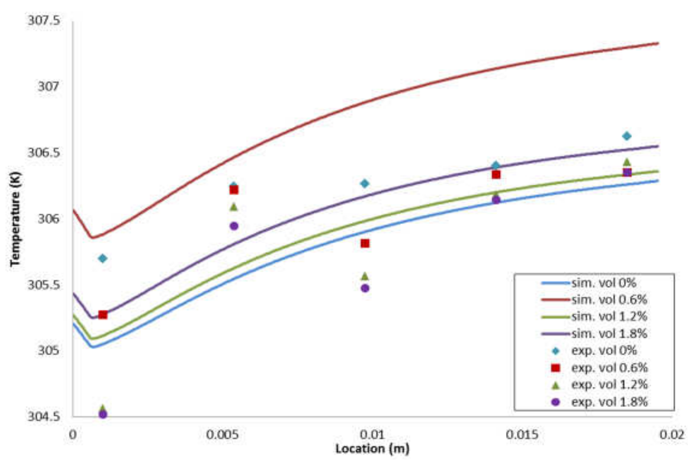
Figure 4. Temperature variations of nanofluid along the microchannel for different Reynolds Numbers (cross section=100μm×100μm, heating power=0.58Watt).



(a) Re = 6



(b) Re = 10



(c) Re = 18

Figure 5. Temperature variations of nanofluid along the microchannel for different Reynolds Numbers (cross section=100μm×1000μm, heating power=0.58Watt).

Figure 6 shows the numerical results of cooling efficiency versus Reynold number based on Eq. (1) for different combinations of cross section areas and heating powers. Also shown in the figure are the experimental results of [7] for comparison. Hollow symbols and solid symbols represent computational findings and experimental data respectively. In Figs. 5 (a) and 5(b) it is shown that simulation results of cooling efficiency is always lower than the experimental results for heating power = 0.58Watt, but in Fig. 5 (c) simulation results of cooling efficiency gradually become higher than experimental results, especially for higher Reynolds number. Moreover the cooling efficiency increases with increasing Reynolds number for all combinations of cross section areas and heating powers considered in this study. When comparing with Figs 5 (a) and 5(b) which different only in cross section area, it is clearly indicated that increase of cross section area of the microchannel always leads to increase of cooling efficiency.

Conclusions

Simulation of nanofluid heat transfer with software COMSOL Multiphysics was performed based on an existing experiment [7]. Simulation results show that nanofluid temperature increases along the microchannel. This finding is different from the experimental data for small cross section area of $100\mu m \times 100\mu m$. It is also displayed that cooling efficiency increases with increasing cross sections area of microchannel.

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References

[1] Choi, S. U. S. and Eastman, J. A. (1995) Enhancing thermal conductivity of fluids with nanoparticles, *ASME International Mechanical Engineering Congress & Exposition*, 12-17.

[2] Cengel, Y. A. and Ghajar, A. J. (2015) *Heat and Mass Transfer Fundamentals and Applications*, 5th edn, McGraw Hill, USA

[3] Lie, J. and Kleinstreuer, C. (2008) Thermal performance of nanofluid flow in microchannels, *International Journal of Heat and Fluid Flow* **29**, 1221-1232.

[4] Choi, E. S., Brooks, J. S., Eaton, D. L., Al-Haik, M.S., Hussaini, M.Y., Garmestani, H., Li, D. and Dahmen, K. (2003) Enhancement of thermal and Electrical properties of carbon nanotubepolymer composites by magnetic field processing, *Journal of Applied Physics* **9**4, 6034-6039.

[5] Heris, S. Z., Etemad, S. G. and Esfahany M. N. (2006) Experimental investigation of oxide nanofluids laminar flow convective heat transfer, *International Communications in Heat and Mass Transfer* **33**, 529–535.

[6] Dalkilic, A. S., Kayaci, N., Celen, A., Tabatabaei, M., Yildiz, O., Daungthongsuk, W. and Wongwises, S. (2012) Forced Convective Heat Transfer of Nanofluids – A Review of the Recent Literature, *Current Nanoscience* **8**, 949-969.

[7] Chen, Y. M., Experiment on Forced Convection of Nanofluids in Micro Channel, Master Thesis, National Taiwan University, Taiwan, 2013.

[8] Ho, C. J., Wei, L. C. and Li, Z. W., (2010) An experimental investigation of forced convective cooling performance of a microchannel heat sink with AL2O3/water nanofluid, *Applied Thermal Engineering* **30**, 96-103.

[9] Sin, V.K., Teng, K.K. and Deng, W.Y., Computational investigation of heat transfer of nanofluids in microchannel with improper insulation, *Lecture Notes in Computer Science 9786, The 16th International Conference on Computational Science and Its Applications (ICCSA 2016),* Beijing, China, July 4–7, 2016, Proceedings, Part I, O. Gervasi et al. (Eds.): ICCSA 2016, Part I, LNCS 9786, 505–513, 2016**, ISBN:** 978-3-319-42084-4, Springer Publisher
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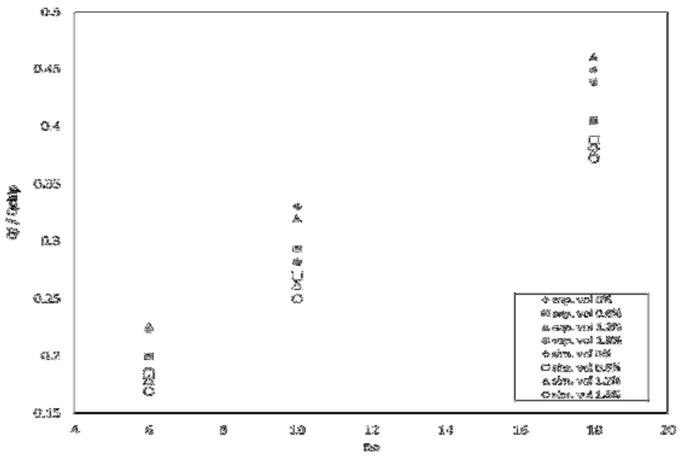
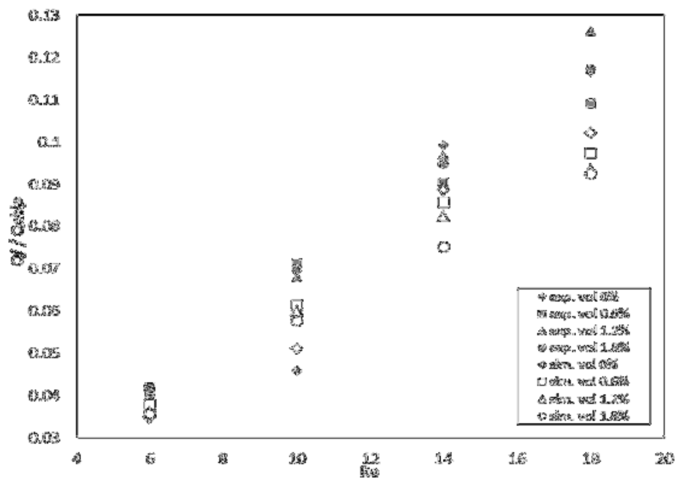
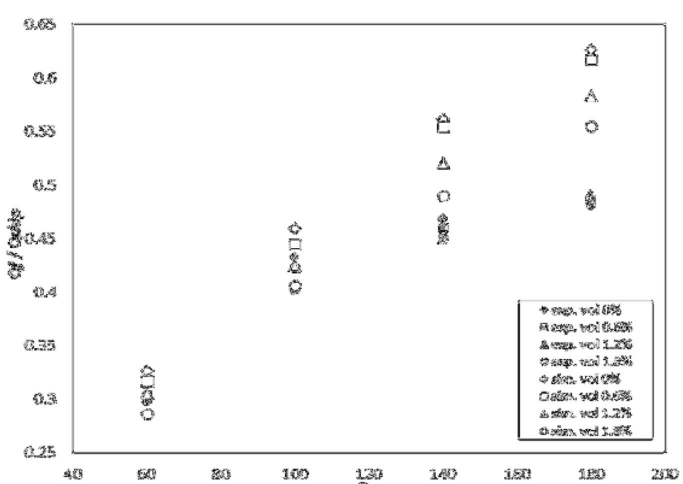


(a) Cross section=100μm×1000μm, Heating power= 0.58Watt



(b) Cross section=100μm×100μm, Heating power= 0.58Watt



(c) Cross section=100μm×100μm, Heating power= 1.9Watt

Figure 6. Cooling Efficiency for different Reynolds numbers