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Untersuchungen zum Wärmeübergang in einem quadratischen Mikrokanal mit Al_2O_3-H_2O Nanofluid

Investigation of the heat transfer in a square microchannel with Al_2O_3-H_2O nanofluid

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Abstract

Nanofluids is a term for a fluid with suspended nanometer sized metallic or nonmetallic particles. The use of nanofluids to enhance heat transfer of fluidic cooling systems has gained strong interest in recent years. This is especially important in the field of microelectronics where heat loads of up to 200 W/cm^2 and more, at small temperature differences, are typical. On the other hand the convective heat transfer in microchannels is limited due to the laminar flow regime. Since the potential of the nanofluids is controversially discussed in the literature, experimental heat transfer investigations are necessary to understand the underlying phenomena. For this reason the aim of the current study was to design and test a reliable platform for the characterization of the fluid flow and the heat transfer in a microchannel. The microchannel has a cross section of 0.5×0.5 mm^2 and was made of copper. For first tests, pure water and water with 30-60 nm Al_2O_3 nanoparticles was used at two different volume fractions, 1% and 2.5%. The result implies that the experimental platform allows for reliable and reproducible measurements of heat transfer and its sensitivity to the nanofluid and flow properties. It could be shown that heat transfer coefficient could be enhanced by 5.9% by using 2.5% Al_2O_3-Water nanofluids compared to distilled water.

Schlagworte : Nanofluide, Wärmeübergangskoeffizient, Laminare Strömung, Mikrofluidik
Keywords : nanofluids, heat transfer coefficient, laminar flow, microfluidics

Introduction

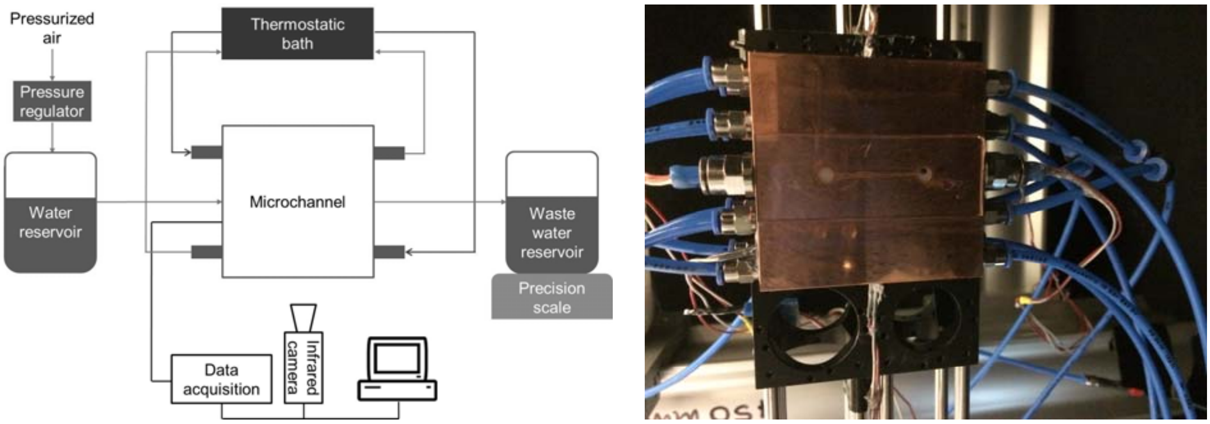
Microfluidic devices with typical characteristic length scales of less than a millimeter have a great potential in pharmaceutical and biological techniques and process engineering. The main benefits are the smaller size of the sample, allowing for faster reactions, better product quality, smaller amounts of costly reactants and easy parallelization of analytical processes. However, the flow in these devices is laminar, which limits mixing and thus heat transfer. In order to enhance the heat transfer, for example to utilize microchannels for the efficient cooling of microelectronics. Nanofluids are of recent interest for several reasons. The main reason for utilizing suspended nano-size particle (1-100 nm in diameter) within conventional fluids (e.g. distilled water, lubricant and glycol) is due to its higher thermal transport ability compared to the base fluid. This unique property of nanofluids makes them well suited for the needs of a higher heat removal application (e.g microelectronic components, high power LEDs).

The term of nanofluids was first introduced by Choi 1995 who theoretically found an enhancement in thermal conductivity by factor of 1.5 over that of the base fluid with 5% volume concentration. Since then, there has been a growing interest for nanofluids research. The heat transfer characterization of water-based Al_2O_3 nanofluids in fully developed laminar flow regime was examined by Hwang et al. 2009. With 0.3% volume loading of Al_2O_3, a constant 5% enhancement of heat transfer coefficients under the variation of Reynolds numbers ranging from 550 to 750 was observed. Kahyani et al. 2012 found a maximum 17% enhancement of the turbulent heat transfer coefficient to that of distilled water when using H_2O-TiO_2 nanofluids with 2% volume concentration and a particle size of 15 nm. The measurements were done by using a circular copper tube with 5 mm inner diameter and 2 m length. An enhancement of 47% in heat transfer coefficient was found by Wen and Ding 2004. This enhancement was achieved at a Reynolds number of 1600 and 1.6% volume concentration of γ-Al_2O_3 nanoparticles. A copper tube with 4.5 mm inner diameter and 970 mm of length was used in this measurement. Jung et al. 2009 also found a 32% increase in heat transfer coefficient when using 1.8% Water-Al_2O_3 with 170 nm particle diameter. Three different sizes of microchannels were used for these experiments: 50 x 50 μm^2, 50 x 100 μm^2 and 100 x 100 μm^2. Albadr et al. 2013 found an enhancement of 75% in the heat transfer coefficient with 2% volume fraction of Water-Al_2O_3 nanofluids. Xuan and Roetzel 2000 found that the enhancements of heat transfer rate of nanofluids are due to the increase of the thermal conductivity of the nanofluids.

Since the flow condition and the range of heat transfer enhancement (and even reduction was reported) differs among different studies, the purpose of the current work is to establish a stable and reliable platform to characterize the flow and the heat transfer simultaneously for constant wall temperatures. As a first step, the temperature stability and homogeneity of the setup was verified. Later the heat transfer coefficient of Water-Al_2O_3 nanofluids with 1% and 2.5% volume concentration was measured.

Experimental setup

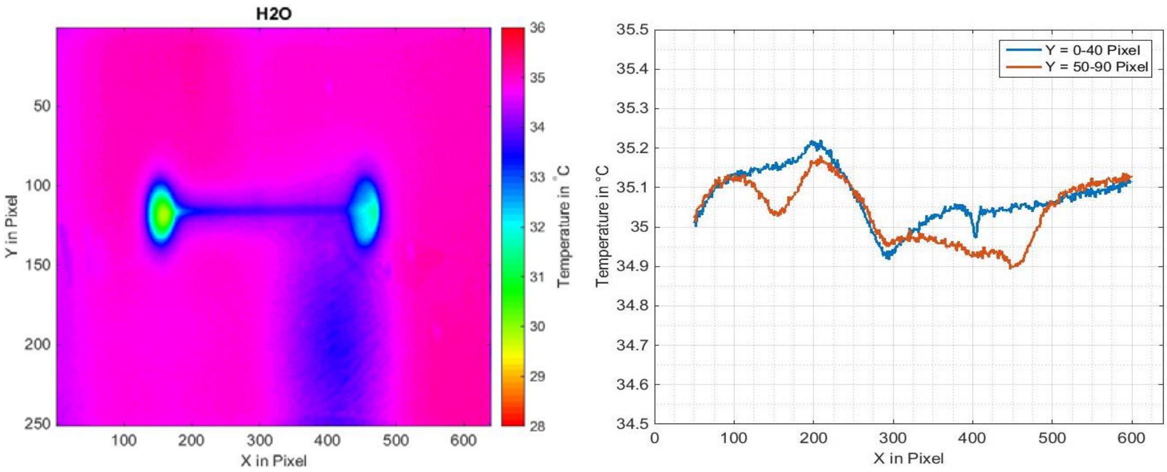
The constructed experimental setup for this work is schematically shown in Fig. 1. To maintain the wall temperature, a circulating water flow, fed by a thermostatic bath from Julabo (D-7633) was used. The measurement was started when the wall temperature of the microchannel remained within a range of ± 0.3 K from the temperature of the thermostatic bath. Data acquisition system DEWE-50-PCI-16 from Dewetron GmbH was connected to eight PT-100 temperature sensors from Conrad GmbH. The temperature sensors have an uncertainty of ± 0.3 K and were placed at different positions: the inlet, the outlet of the microchannel, four different positions at the copper block of the microchannel to check for homogeneity and stability of the wall, one sensor in the reservoir to monitor if the temperature is changing due to the waste heat from the thermostatic bath and another in the surrounding of the microchannel. A SC7000 infrared camera from FLIR was included into the setup to measure the uniformity of the microchannel surface temperature. The pressure driven flow was generated and a pressure regulator was used to control the pressure at the reservoir. A precision scale AX623 from Sartorius with 0.1 mg accuracy was used to measure the mass flowing through the channel during a certain time to calculate the mass flow rate. The microchannel in this measurement has a square cross section with 0.5 mm height, 30 mm length and was made of copper. The upper part of the microchannel was sealed with a glass slide to provide an optical access to the infrared camera as presented in fig 1 (b).



(a) (b)

Fig. 1: Schematic of experimental setup; (a) the complete experimental setup (b) the microchannel during the measurement process

The temperature measurements with the data acquisition and the infrared camera were done simultaneously. The infrared camera images were used to verify the uniformity of the microchannel surface temperature and the temperature reading of the data acquisition was done to calculate the heat transfer coefficient. The measurement result of temperature homogenity with the infrared camera can be seen in fig. 2. The thermal image is depicted in fig. 2 (a), the measurement was done with distilled water as working fluid at a Reynolds number of 140. The temperature reading of the infrared camera is plotted in fig. 2 (b). The temperature is an average of 40 positions along the X-axis (50-600 pixel). The maximum temperature difference along the line was 0.31 K. With a small temperature difference along the microchannel surface, it can be concluded that the experimental setup has a stable and uniform temperature.



(a) (b)

Fig. 2 The thermal image of the microchannel surface; (a) The temperature reading of infrared camera, (b) the average temperature along the X axis

To observe the effect of Reynolds number and particle concentration on the heat transfer coefficient, the experiments were done with different Reynolds numbers and nanoparticle concentrations. The Al_2O_3 particles were purchased from Sigma Aldrich (642991) and have a size distribution between 30-60 nm. Three different Reynolds numbers were used with three different nanoparticle concentrations for every Reynolds number. To avoid agglomeration and sedimentation, the nanofluids were stirred with a magnetic stirrer for 30 minutes right before the experiment. During the experiments, no sedimentation was observed. The Reynolds number and the type of the working fluid are listed in table 1. To clean the channel pressurized air was first injected into the microchannel and then followed by ethanol to ensure that there was no nanofluids attached to the channel walls. This rinsing procedure was repeated for each experiment.

Table.1: The experimental variations

No	Reynolds number	Working fluid
1	140	Distilled water
		Water-Al_2O_3 1%
		Water-Al_2O_3 2.5%
2	210	Distilled water
		Water-Al_2O_3 1%
		Water-Al_2O_3 2.5%
3	260	Distilled water
		Water-Al_2O_3 1%
		Water-Al_2O_3 2.5%

Thermal properties of nanofluids

To calculate the heat transfer coefficient of the nanofluids, the thermal properties of the nanofluids are required. The following correlations, which are well accepted in the literature, were used to calculate the thermal properties of the nanofluids.

The density (*p*) of the nanofluids is given by the Pak and Cho 1998 correlation:

$$\rho_{nf} = \left(1-\alpha\right)\rho_{bf} + \alpha\rho_{np} \tag{1}$$

The heat capacity (*Cp*) of the nanofluids was calculated by using the correlation from Xuan and Roetzel 2000:

$$\left(\rho Cp\right)_{nf} = \left(1-\alpha\right)\left(\rho Cp\right)_{bf} + \alpha\left(\rho Cp\right)_{np} \tag{2}$$

The thermal conductivity (*k*) of the nanofluids was calculated with the Maxwell's model of a homogenous suspension of solid-liquid mixtures Maxwell 1873:

$$k_{nf} = \frac{k_{np} + k_{bf} + 2\left(k_{np} - k_{bf}\right)\alpha}{k_{np} + 2k_{bf} - \left(k_{np} - k_{bf}\right)\alpha} k_{bf} \tag{3}$$

The viscosity (μ) of nanofluids with less than 5% volume concentration could be calculated by the correlation introduced by Drew and Passman 1999:

$$\mu_{nf} = \mu_{bf}\left(1+2.5\alpha\right) \tag{4}$$

Where the subscript *nf* refers to nanofluid, *bf* to base fluid, *np* to nanoparticle and *α* indicates the particle volume fraction. The thermal properties were calculated with the bulk temperature of the fluid which is an average between inlet and outlet temperature of the microchannel. The thermal properties of the Al_2O_3 nanoparticle at 293 K are listed in table 2 from Mohammed et al. 2010, the properties of Al_2O_3-Water nanofluids were calculated with equations (1), (2) and (3).

Table.2: Thermal properties of nanoparticle Al_2O_3 at 293 K (Mohammed et al. 2010)

Properties	**Al_2O_3**	**Water-Al_2O_3 1%**	**Water-Al_2O_3 2.5%**
ρ (kg/m^3)	3970	1027.92	1072.5
Cp (J/kg K)	765	4050.03	3865.79
K (W/m K)	40	0.631	0.658

Results and discussions

Since the thermal entry length of the flow is longer than the physical length of the microchannel, the flow is still in the region of developing flow. For the developing laminar flow and constant wall temperature conditions, combining equation (5) and (6) leads to the heat transfer coefficient. The Nusselt number is given by the equation from Cengel 2002.

$$Nu = 3.66 + \frac{0.065(D/L)\,\mathrm{Re}\,\mathrm{Pr}}{1+0.04\left[(D/L)\,\mathrm{Re}\,\mathrm{Pr}\right]^{2/3}} \tag{5}$$

$$Nu = \frac{hD}{k} \tag{6}$$

Where:

Nu	: Nusselt number
Re	: Reynolds number
Pr	: Prandtl number
D	: hydraulic diameter of the channel (m)
L	: channel length (m)
k	: thermal conductivity (W/m K)
h	: heat transfer coefficient (W/m^2 K)

To find the uncertainty effect of the measured variables on the heat transfer coefficient, the sensitivity analysis of the measurement result was done. All of the maximum uncertainties from the sensors were added to estimate the maximum error of the measurement. The uncertainty of the mass flow rate and the temperature sensors are ±2% and ±0.3 K, respectively. Distilled water was used for this study under Reynolds number ranging from 140 to 280. The result from this analysis can be seen in fig. 3, the maximum uncertainty of the PT-100 and mass flow rate were added to the measurement result and shows a maximum 0.25 of standard deviation to the measured heat transfer coefficient with a maximum uncertainty of 3.18%. This study shows that there is a very small effect from the uncertainty of the temperature sensors and mass flow rate to the calculated heat transfer coefficient.

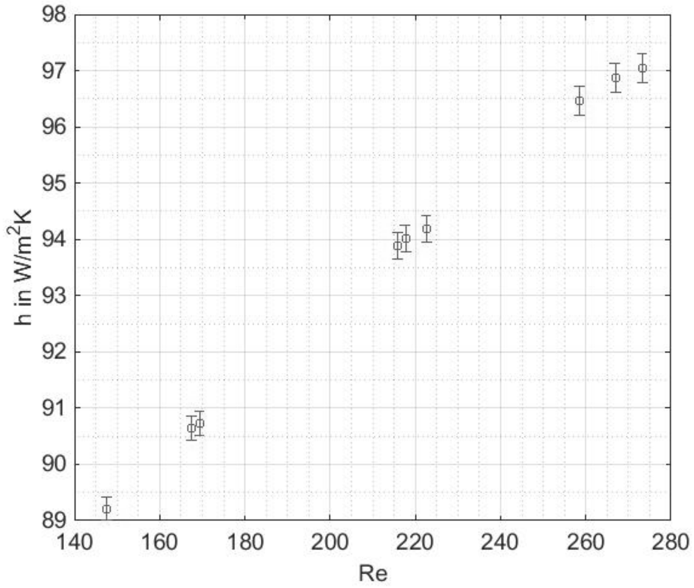


Fig. 3 The effect of temperature and mass flow rate sensitivity on the heat transfer coefficient

The comparison of the heat transfer coefficient of the nanofluids on the Reynolds number is depicted in fig. 4. It can be clearly seen that the heat transfer coefficient increases with increasing the nanoparticle concentration in nanofluids as well as the Reynolds number. According to Xuan and Roetzel 2000, the enhancement of the heat transfer coefficient is mainly due to the increase in the thermal conductivity of the nanofluids, though other factors also include the particle type, particle size, base fluid and flow regime.

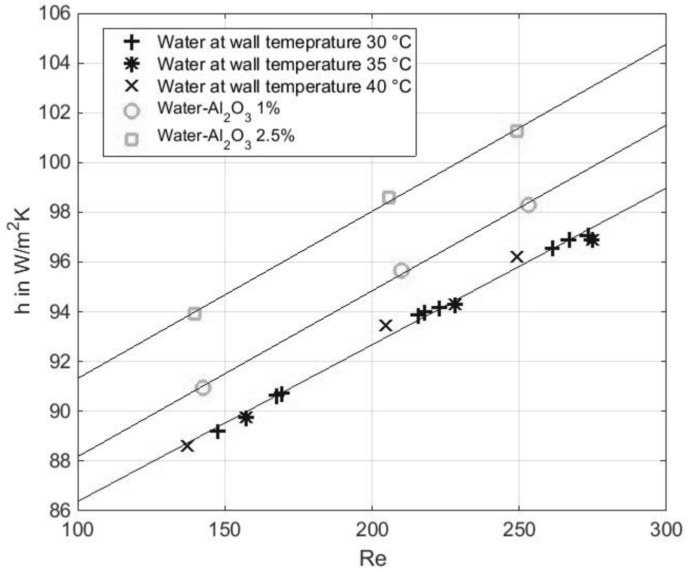
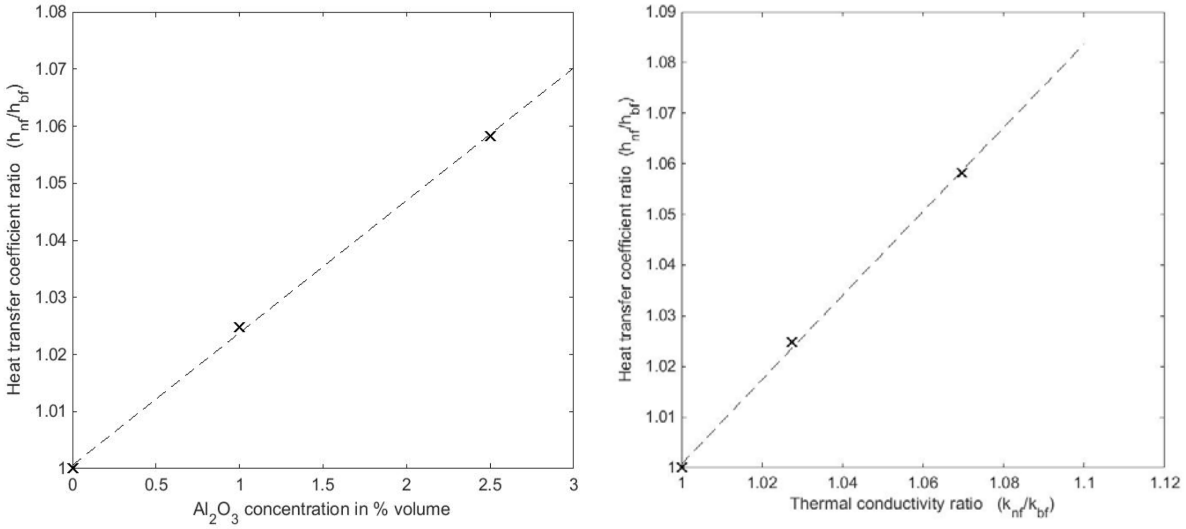


Fig. 4 Heat transfer coefficient vs Reynolds number under different Water-Al_2O_3 volume concentrations

Figure 5 shows the heat transfer coefficient ratio of the nanofluids compared to distilled water for different concentrations of nanoparticles at a Reynolds number of 260. The figures show that the ratio increases with volume concentration and thermal conductivity. Fig. 5 (a) shows the addition of 2.5% Al_2O_3 to the distilled water increases 7% of the thermal conductivity and fig. 5 (b) shows an enhancement of 5.9% to the heat transfer coefficient. This result shows that the increase in the volume concentration leads into the enhancement of the thermal conductivity of the working fluids. The addition of nanoparticles to the distilled water changes the thermal properties of the base fluids, in this term the thermal conductivity. Zeinali Heris et al. 2007 explained that increasing the volume fraction causing the interaction and collision of nanoparticles and also the near wall movement of the nanoparticles leads to the enhancement in the heat transfer process from the wall to the nanofluid.



(a) (b)

Fig. 5 Heat transfer coefficient ratio; (a) Heat transfer coefficient ratio vs Water-Al2O3 volume concentration and (b) Heat transfer coefficient ratio vs thermal conductivity ratio

Conclusion

The experimental setup for reliable heat transfer measurements of nanofluids in a square microchannel was constructed and validated. The temperature stability experiment shows that the temperature distribution is uniform on the microchannel surface. A pressure driven flow system provides a stable flow condition at a predefined Reynolds number. Two different volume concentrations of water-Al_2O_3 nanofluids were tested and compared to the base fluid. The thermal properties of the nanofluids were calculated in the bulk temperature of the fluids according to the correlations from the literature. To compare the heat transfer performance of nanofluids to the base fluid, the heat transfer coefficient was calculated. The measurements show a promising 5.9% enhancement in heat transfer coefficient when 2.5% (volume concentration) of Al_2O_3 was added to the distilled water. The increase in volume concentration of the nanofluids also shows an increase of the heat transfer coefficient. The non-intrusive temperature and velocity measurement method by implementing the Thermo Liquid Crystals (TLCs) to the microchannel will be used or the future work. The reasons to use this method are to observe the temperature and velocity profile of the flow and also to find the different temperature distribution due to the increase of thermal conductivity. Furthermore, particle manipulation techniques will be tested to enhance the heat transfer even further.

Acknowledgements

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