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Study of surface roughness and its effect on the Nusselt number of circular microchannel

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Abstract

Miniaturization is playing an increasingly important role in ensuring the sustainability of energy systems and increasing their efficiency. In the current design environment, a high heat transfer rate with minimal pumping power is a key consideration. Microchannels are distinguished by flow and heat transfer in restricted microscopic geometries. The numerical simulation and analytical calculations were carried out in circular microchannels to evaluate roughness and its effect on the value of the Nusselt number. The dataset of available experimental investigations was cited, and the study was conducted using water as the working fluid and steel as the working medium, with Reynolds numbers ranging from 400 to 3200. Surface roughness is investigated as a result of homogeneous distribution at the microscale. This study focuses primarily on the Nusselt number, with simulated values of 4.0590 and 4.1347 for smooth channels and regular rough channels, respectively.

1. Introduction

The quest for alternative energy resources has become the major concern in the area of energy conservation in this era. This conservation has been important as the energy sources have been depleting day after another. Thus, to ensure sustainability of these energy system and increasing efficiency, miniaturization has been playing a major role. Miniaturization in manufacturing and electromechanical systems, according to studies, have the potential to become "economic drivers" in the near future [1]. Characterized by flow and heat transfer in confined tiny geometries, miniaturization has captured the heat exchanger technology also. As we know heat exchangers are inherently a crucial part of the systems involving heat and mass transfer, their efficiency contributes to overall system efficiency. With relation to that, Micro channel heat exchanger is a type of heat exchanger in which fluid flows in lateral confinements with dimension below 1mm [2].The fundamental benefit of adopting microchannel is that it has a high area to volume ratio, which results in a high convective heat transfer coefficient rate. Uneven flow distribution, pressure drop, and heat transfer rate are still some of the obstacles and limitations in increasing its performance. The pressure drop will increase as the channel diameters are reduced to micro-scale [3].

As the dimension is reduced, flow in microchannel differs from the macroscopic scale because the small scale makes molecular effects predominant and also amplifies the magnitudes of some ordinary continuum parameters to extreme levels. The thermal contact resistance at the interface of a heat-generating component and a heat sink can be minimized by integrating these micro channels directly within the heat-generating component. Our main target is to make pressure drop minimum and heat transfer rate maximum.

Surface roughness has a big impact on engineering issues and causes more turbulence near rough walls. Additionally, it has an effect on raising wall shear stress. The ability to accurately estimate near-wall flows is dependent on a number of factors. Hence, Surface roughness should be properly modeled. In CFD analysis, surface roughness can be considered using special parameter known as sand grain roughness that depend not only on roughness amplitude, but also on shape and frequency.

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Roughness components in the shape of plates, for example, are roughly the same height as sand grains. The Nusselt number for completely developed flow is only dependent on the cross-sectional form of the channel, according to the traditional theory of internal laminar heat transfer. However, with the current rapid development of microfluidic devices, the channel scale will continue to shrink, and the relative importance of channel surface roughness will become more of a concern and consequence. Recent research has focused on whether roughness has an effect on micro internal laminar heat transmission and whether the Nusselt number in rough micro channels is still solely determined by the cross-sectional form of the channel [4][5].

2. Literature review

Years ago, the first application of miniaturization for heat removal was presented in a paper titled "High Performance Heat Sinking for VLSI," which is considered as the first study on microchannel heat transfer. Many studies have followed in the footsteps of this pioneering study, and microchannel flow has been recognized as a high-performance heat removal method ever since [6].

The experiment on microtubes with diameters ranging from 50um to 254um have been performed and the results deviated from conventional theory of friction factor and other flow characteristics in laminar region. Also the laminar to turbulent flow was observed at Reynolds number between 300 and 900 [7].

The numerical simulation was carried out which concluded that the thermal conductivity ratio, hydraulic diameter and Reynolds number affect the behavior of axial heat conduction. Also, by employing porous fins, it improves heat transfer performance as well as the water in microchannels mechanism, lowering the pressure drop [8].

The pressure drop and heat transfer characteristics of air flow in microtubes was carried out where the surface roughness has also been considered with different value. The experimental results reveal that when the influence of gaseous flow compressibility is adequately taken into account, the frictional coefficient of gas flow in microtubes is the same as that in larger tubes [8].

An experiment in which the flow behaviors for air flow were investigated in microchannels with rectangular cross sections. Different roughness values were used, and the results showed that roughness with a higher value tends to have a higher Poiseuille number [9].

The influence of surface roughness on heat transfer in micro-channels was numerically investigated, and it was discovered that the Nusselt number grows with increasing relative surface roughness in laminar flow. The Nusselt number for turbulent flow increases as the relative surface roughness of the tubes increases [10].

A high relative roughness of the walls improves convective heat transfer because the thermal boundary layer regenerates. Surface roughness effects, on the other hand, were associated with a lower Nusselt number value when comparing experimental data to numerical results obtained by solving a conjugate heat transfer problem [11].

The effect of wall roughness on fluid flow and heat transmission in microchannels was investigated using a model. Roughness has a favorable impact on thermal performance and flow resistance, according to findings [12].

The findings of experimental research on microchannel heat transfer and fluid flow characteristics are varying and one can come to a conclusion that the results are highly scattered. This is particularly problematic in the case of heat transfer effects. In the so-called microchannel heat sink, for example, there is an optimum channel size, and the optimization result is highly influenced by the heat transfer characteristics of microchannels. As a result, the study of single-phase microtube heat transfer was initiated [13].

Because of small hydraulic diameters, microchannels have extremely high heat transfer coefficients. An alternate method for forecasting average Nusselt Number in circular microchannels when the flow is fully developed has been used and the results of this research are derived as equations for the average Nusselt Number under the different condition of flow [14].

3. Methodology

The data has been referenced through experimental research paper which is then followed by analytical calculations where the parameters and equations are applied in order to calculate and validate the results from the simulation. The geometry has been prepared either on software Solidworks or Ansys Design Modeler as per the case. As the research is based on a CFD flow analysis, followed by geometry setup, mesh generation, physics setup and post processing, the simulation is carried out in Ansys where every cases has been evaluated (Figure 1). Finally, the results have been verified from the numerical simulations.

3.1. Data set description

This study is conducted by undertaking the experimental research performed on topic “ Heat transfer character-

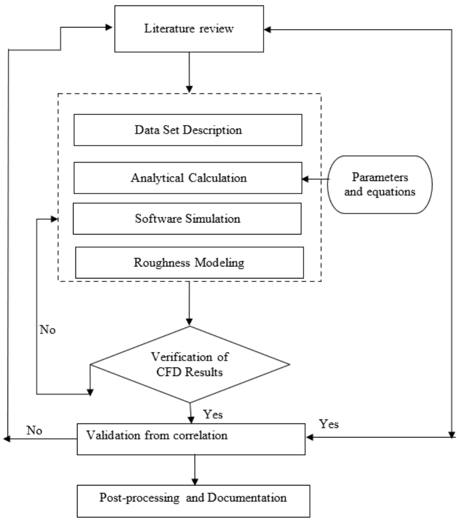

Figure 1: Flowchart of methodology

istics of water flow in microtubes" [15] , an efficient model where the findings of the tests demonstrate that conventional correlations for laminar and turbulent flow may be used to accurately predict fully developed heat transfer performance in microtubes. Due to the difficulty and unavailability of MEMS fabrication technology, no experimental analysis has been done for now for this research. Therefore this work incorporates modeling of roughness by constructing the rough microchannel geometry to observe the effects of roughness particularly focused on Nusselt number.

Table 1: Data details of the circular microchannel [15]

S.N.	Particulars	Values
1	Inner diameter of microchannel	123 μm
2	Outer diameter of microchannel	282 μm
3	Length of microchannel	140 mm
4	Heating length	120 mm
5	Fully developed length	75 mm
6	Average roughness	1.4 μm
7	Standard deviation	1 μm
8	Number of tubes measured	15
9	Transition Reynolds number	2300–3000

3.2. Analytical calculation

The convective heat transfer characteristics in circular micro channel can be derived from following equations.

Heat transfer area is given by

$$A = \pi D_i L \tag{1}$$

where D_i is the internal diameter and L is the length of the tube.

The tube cross-sectional area is given by

$$A_c = \frac{\pi D_i^2}{4} \tag{2}$$

The mass flow rate is given by

$$\dot{m} = A_c V \rho \tag{3}$$

Further, the fluid temperature T_x at a position x from the heating entrance can be estimated as

$$\frac{q_x}{L} = \dot{m} c_p \left(T_x - T_i\right) \tag{4}$$

From the law of convection,

$$\dot{q} = \frac{q}{A} = h \left(T_{wx} - T_x\right) \tag{5}$$

Shah and Bhatti presented a set of correlations to calculate the value of local Nusselt number of thermally developing laminar flow in a circular tube across a wide range of Graetz numbers (Gz).

The flow regime shifts to turbulent about Reynolds numbers of 2300–3000. Thus the turbulent Nusselt numbers has been calculated for 3000<Re<5*106 by the Gnielinski correlation [16].

3.3. Software simulation

The CFD analysis, conducted through the use of CFD software namely: ANSYS Fluent which has been utilized to run simulations. The research has been based on a CFD flow analysis, followed by geometry setup, mesh generation, physics setup and post processing.

3.3.1. Case 1: Smooth microchannel

The circular microchannel of mentioned values (Table 1 was constructed with the sliced solid section as heated and unheated section and the fluid domain throughout the geometry. The fluid characteristics and type of turbulence model are selected during setup. In the ANSYS Meshing itself, the cell conditions are adjusted to fluid (Figure 2). After that, the setup has been initialized.

3.3.2. Case 2: Single regular rough microchannel

The total number of tubes undertaken is fifteen, and the average among them has been used as the primary data for construction (Figure 3 and 4). As a result, taking into account the standard deviation and average roughness, data was generated for internal, external, and roughness

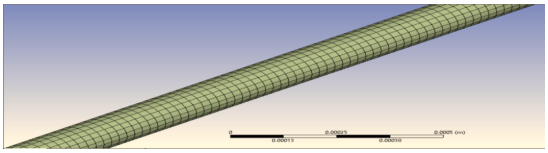

Figure 2: Structured mesh (Isometric view)

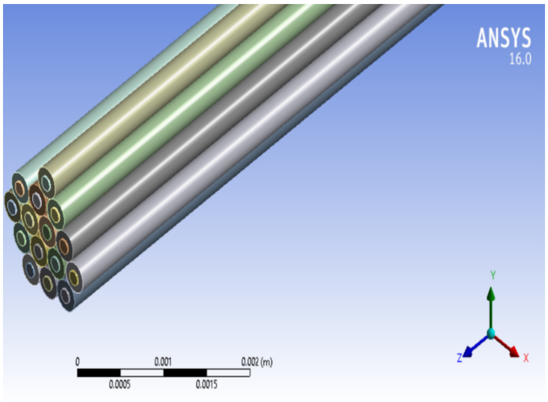

Figure 3: Construction of fifteen microchannel

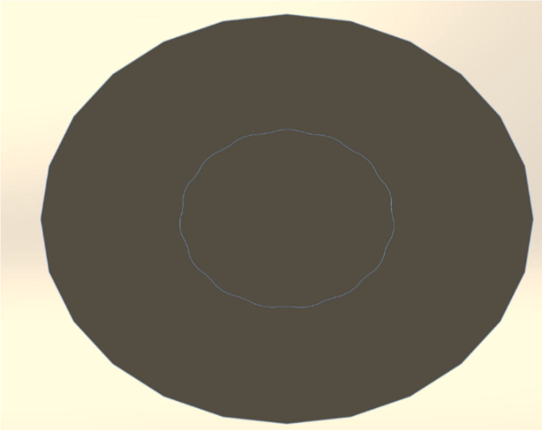

Figure 4: Regular rough tube

and one of the values was chosen for generating geometry and running the simulation in ANSYS.

This study utilized k-α turbulence modeling with the usual wall function. Most commercial CFD programs use the conventional k-turbulence model, which consists of two equations. This model employs two transport equations to account for the turbulent properties of the flow, providing a comprehensive description of turbulence. When there are no large adverse pressure gradients or severe local pressure shifts, this model works properly. In re-attachment zones, turbulent kinetic energy might be overestimated, leading in inaccurate predictions of the evolution of the boundary layer around bluff bodies and when separation occurs.

4. Results and discussion

The simulation was carried out in ANSYS Fluent. One of the most critical needs is to complete a sufficient number of iterations in order to achieve the desired result. Parameters were monitored during the procedure's execution. In this situation, the solution converged after 1000 iterations. Following a successful iteration, post-processing is performed to calculate and validate the numbers received from numerical calculations. The performance parameters of several types of microchannels are shown below, along with a comparison to values obtained from analytical calculations and software simulations (Table 2).

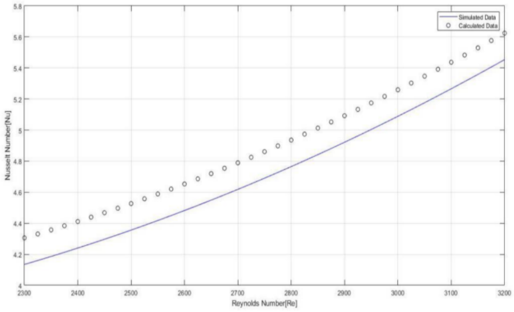

Figure 5: Graph showing Nu vs Re with simulation data and polynomial model

The simulated data has been plotted (Figure 5) against the fitted polynomial model, representing the simulated data. The order of the polynomial has been varied, and the polynomial of order 2 is observed to be enough to represent the simulated data.

From above all, it can be justified that the microchannel created with the randomly generated profile holds better value than the other case. This justifies the real case scenario in the construction of microchannel by various micromachining techniques where are surface deviation can be seen.

5. Conclusion and recommendation

The study indicates that using a higher roughness percentage produces a more realistic representation of actual manufacturing conditions compared to assuming a smooth surface. Among the two roughness modeling approaches considered, random roughness was found to better reflect practical manufacturing realities than regular roughness patterns. Across all investigated cases, the Nusselt numbers obtained from numerical simulations closely matched the analytical results, with an average deviation of about 7.5% for the three cases examined, confirming the reliability of the numerical approach. To further enhance microchannel design methodologies,

Table 2: Summary of values

S.N.	Micro channel type	Value from simulation	Value from analytical calculation	Percentage Error
1	Smooth channel	4.059	4.3641	7.50%
2	Regular rough channel	5.0886	5.4355	6.82%

future research should focus on comprehensive experimental investigations involving well-designed fabrication and precise instrumentation to reduce result inconsistencies. In addition to heat transfer characteristics, other performance parameters should be analyzed to better understand the broader influence of surface roughness. Moreover, with advancements in micro-machining technologies, experimental validation is strongly recommended to improve the robustness and applicability of the findings.

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