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CFD Analysis of Microchannel Heat Exchanger with Slip Flow Heat Transfer

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Abstract—*This paper presents the numerical analysis of microchannel heat exchanger with slip flow heat transfer. The hydrodynamic and heat transfer characteristics in a rectangular, three-dimensional, laminar flow, incompressible, steady state, slip and counter flow is investigated. The momentum equations and energy equation are solved for cold and hot fluid with slip flow. The ANSYS FLUENT 15 code is used to solve the governing equations. The impact of slip flow is investigated numerically. The slip-flow region considered in this paper has Knudsen number in the range of 0.001 ≤ Kn ≤ 0.1. Effectiveness is the main parameter to design a better heat exchanger. From the results it was found that the factors affecting effectiveness are: Knudsen number Kn, Reynolds number Re and thermal conductivity ratio K_r. Increasing of Re andKnseparately lead to decrease the effectiveness. While the increasing of Re and Kn separately lead to increase pressure drop. The effectiveness increases with increasing $K_r$until it reach anoptimal valuewhich gives the maximum effectiveness atK_r =95. The nature of Nusselt number is also investigated with respect to slip flow.*

Keywords: *Microchannel, Slip flow, Knudsen number, Counter flow heat exchanger.*

1. INTRODUCTIONS

The concept of microchannel heat exchanger was explained by Tuckerman and Pease [1] in 1981.In last two decades microchannel heat transfer has become popular and interesting toresearchers. This is due to high heat transfer coefficients and low pressure drops with compared to conventional systems.

There are many newapplications ofthe microchannel flow in micro-pumps, micro-turbines, micro-heatexchangers and other micro-components. The advantages of compactstructure and high heat transfer performance make the microheat exchangers showing an efficient applicationin microelectronics,micro-devices fabrication, bio-engineering and micro-electromechanicalsystem (MEMS).

In this paper the heat transfer is investigated under the application of slip flow. The slip-flow region considered in this paper has Knudsen number in the range of 0.001≤ Kn ≤ 0.1. Knudsen number is defined as the ratio of mean free path to characteristic dimension i.e. $Kn=\lambda/L$, Where λis mean free path and L is characteristic dimension. Mean free path is defined as the average distance that a molecule travels between successive collisions. Values of Knudsen number is classified as following.

Small Knudsen number, $Kn\leq 0.001$ (Continuum approach valid)

Large values, $Kn\geq 10$ (Free molecular flow)

Slip flow region, $0.001 \leq Kn \leq 0.1$

Several studies have been performed in the field of microchannel. Many researchers described the criteria of microchannel. Mehendale et al. [2] described microchannel based on the hydraulic diameter (D_h) as:

Micro heat exchanger: 1 µm ≤ D_h ≤ 100 µm
Macro heat exchanger: 100 µm ≤ D_h ≤ 1 mm
Compact heat exchanger: 1 mm ≤ D_h ≤ 6 mm
Conventional heat exchanger: D_h ≥ 6 mm

Inefficiency of no-slip is investigated by many researchers. Errol B. Arkilc et al. [3] investigated the effect of the slip velocity in microchannel. It was found that the no-slip solution of Navier-Stokes equations fails to adequately model the momentum transferred from the fluid to the channel wall. However, by including a slip-flow boundary condition at the wall, which is derived from a momentum equation, we can accurately model the mass flow-pressure relationship.

Yu and Ameel [4] studied slip flow heat transfer in micro channel and found that heat transfer increases, decreases and remain unchanged compared to no slip flow condition depending upon two dimension variables that include effect of rarefaction and fluid wall interaction. Gad-el-Hak[5] investigated that the conventional no slip boundary conditions impose at a solid-fluid interface will begin to break before the linear stress -strain relationship becomes invalid.

Literature shows that the microchannel and microchannelheat exchangers were studied extensively but there are limited researchesrelated to the slip flow and performance of two fluids microchannelheat exchangers. Many researchers investigated the counter flowmicrochannelheat exchangers without considering the effects of velocity-slip at the walls. Therefore there is a need to study, analyze and investigatethe effects of velocity-slip at the wall.

From literature we can conclude that microchannel i.e. Small channel (D_h) has higher heat transfer coefficient. A large slip on the wall will increase the convection along the surface. From study of heat exchanger it is known that counter flow gives the best performance than other type of flow.

This paper included four terms; Microchannel, Heat transfer, Slip flow and Counter flow. Thus the paper title is **“CFD Analysis of Microchannel Heat Exchanger with Slip Flow Heat Transfer”**

2. ANALYSIS

The rectangular microchannel is shown in figure. The cold fluid, hot fluid and inlet of both fluids are specified in the model.
In the figure:
H = total height of the channel
H_{cold} = cold fluid channel height
H_{hot} = hot fluid channel height
W = width of the channel
t_{sep} = separating wall
$T_{c,inlet}$ = cold inlet temperature
$T_{h,inlet}$ = hot inlet temperature

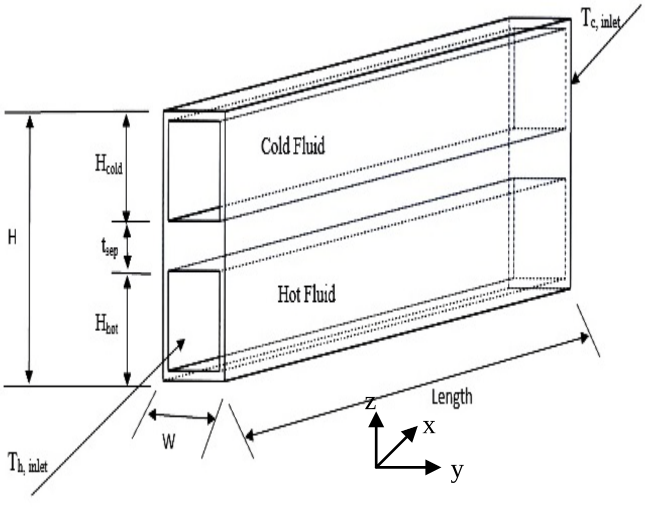

Fig. 1: A schematic model of rectangular channel

2.1 Assumptions

The physical and geometrical assumptions are following.
(1) The flow is 3-D,laminar, incompressible and steady state.
(2) Slip flow is applicable ($0.001 \leq Kn \leq 0.1$).
(3) Air is the working fluid (hot and cold).
(4) Thermo-physical properties are taken constant for both fluids.
(5) There is no heat transfer to/from the ambient medium.
(6) (6)There is no gravity effect.
(7) Viscous dissipation is zero.
(8) The pressure gradient is in axial (x-axis) direction only.

Based on the above assumptions, the governing equations are following

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{1}$$

Momentum equations
In x-axis:

$$\rho\left(u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}\right) = -\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

In y-axis:

$$\rho\left(u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}\right)=\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

In z-axis:

$$\rho\left(u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

Diffusion equation for channel

$$\frac{\partial^2 T_c}{\partial x^2}+\frac{\partial^2 T_c}{\partial y^2}+\frac{\partial^2 T_c}{\partial z^2}=0 \tag{5}$$

Energy equation for fluids (cold and hot)

$$\rho c_p\left(u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}\right)=k\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \tag{6}$$

Where u, v and w are velocity components in the $x, y$and z directions respectively.ρ, μ and k are the density, dynamic viscosity and thermal conductivity of fluid respectively.

T = temperature of fluid
c_p = specific heat at constant pressure
T_c= temperature of channel (solid)

2.2 Boundary Conditions

Fluid media = Air

Hot inlet temperature = 373 K

Cold inlet temperature = 293 K

Velocity inlet (hot and cold) = 0.038 m/s

The physicalproperties involved in these calculations suchas density and dynamicviscosity, were taken for air at average temperature$T_{average}$, where

$$T_{average} = \frac{(T_{h,in} + T_{c,in})}{2} = \frac{(373 + 293)}{2} = 333\ K$$

This means that the properties are equalfor both fluids.
Shear stress = 0
The outlet of the duct is kept open to the atmosphere.

By solving the governing equations using FLUENTR15 codethe temperature distribution and pressure distribution aredetermined in the solidand fluid domains, temperature outlet are followings.
Temperature Cold out = 334.16284 K
Temperature Hot out = 331.83713 K

From these outcomeswe can determine the following heat exchanger parameter.

Heat Transfer Rate (q) It is the amount of heat exchange between two fluids.

$$q = \dot{m}_c c_{p_c}(T_{c,out} - T_{c,in}) = \dot{m}_h c_{p_h}(T_{h,in} - T_{h,out})(7)$$

Effectiveness (Ɛ) Heat transfer effectiveness is the ratio of actual heat transfer to the maximum possible heat that can be transferred.

$$\varepsilon = \frac{q_{actual}}{q_{max\ .possible}} \qquad (8)$$

Where

$$q_{act} = \dot{m}_c c_{p_c}(T_{c,out} - T_{c,in}) = \dot{m}_h c_{p_h}(T_{h,in} - T_{h,out}) \qquad (9)$$

And

$$q_{max\ .possible} = C_{min}(T_{h,in} - T_{c,in})$$

Where

$C_c = \dot{m}_c c_{p_c}$and $C_h = \dot{m}_h c_{p_h}$

Then the effectiveness is

$$\varepsilon = \frac{C_c(T_{c,out} - T_{c,in})}{C_{min}(T_{h,in} - T_{c,in})} = \frac{C_h(T_{h,in} - T_{h,out})}{C_{min}(T_{h,in} - T_{c,in})} \qquad (10)$$

Pressure Drop The total pressure drop is defined as:

$$\Delta P_t = \Delta P_h + \Delta P_c = (P_{hi} - P_{ho}) + (P_{ci} - P_{co}) \qquad (11)$$

3. NUMERICAL SOLUTION

The whole analysis is carried out with the help of software “ANSYS Fluent 15”. ANSYS Fluent 15 is computational fluid dynamics (CFD) software package to stimulate fluid flow problems. It uses the finite volume method to solve the governing equations for a fluid Geometry and grid generation.Pressure-based coupled algorithm is used to solve a coupled system of equations comprising the momentum equations and the pressure-based continuity equation.

4. RESULTS AND DISCUSSIONS

Results of different parameter and its discussion are done in this section. All the results are based on the slip flow heat transfer. Point wise discussion is below.

4.1 Effectiveness comparison between Slip and No-Slip Flow

The effectiveness comparison made on the basis of slip flow and no-slip flow. The inlet temperatures for both cases are same. Other geometrical and physical parameters are same.

Table 1: Effectiveness for slip and no-slip flow

Parameter	No-slip flow	Slip flow
Temp. Hot inlet (K)	373	373
Temp. Cold inlet (K)	293	293
Temp. Hot outlet (K)	352	331
Temp. Cold outlet (K)	312	334
Velocity inlet (m/s)	0.038	0.038
Mass flow rate (kg/s)	3.24.e-10	3.24.e-10
Specific heat (J/kg-K)	1007	1007
Effectiveness	0.26	0.52

From this comparison we can say that the slip flow has more effectiveness.

4.2 Variation of effectiveness with aspect ratio

Fig. 2 illustrate the variation of effectiveness with aspect ratio for different values of Reynolds number. Aspect ratio is the ratio of height of the channel to width of the channel. From this Fig. it is well known that, the effectiveness increase with decreasing of the aspect ratio. It happens due to the increase of the heat transfer area and consequently increases the heat transfer rate between two fluids.

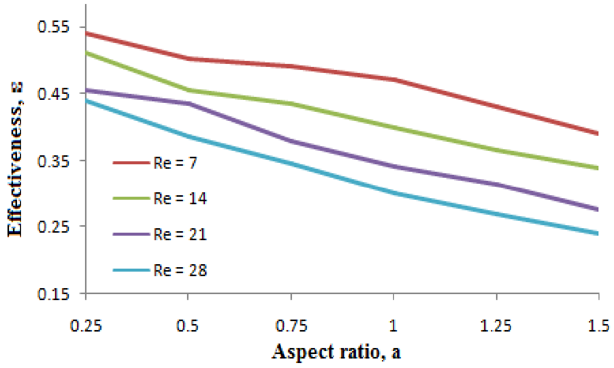

Fig. 2 Variation of effectiveness with aspect ratio

The analytical results are same for all ranges of the Reynolds number.

4.3 Variation of fully developed velocity with channel height

Fig. 3 shows the velocity variation for slip flow and no-slip flow. For no-slip flow the fluid velocity at the channel wall is zero. But in case of slip flow the velocity is not zero at the channel wall.

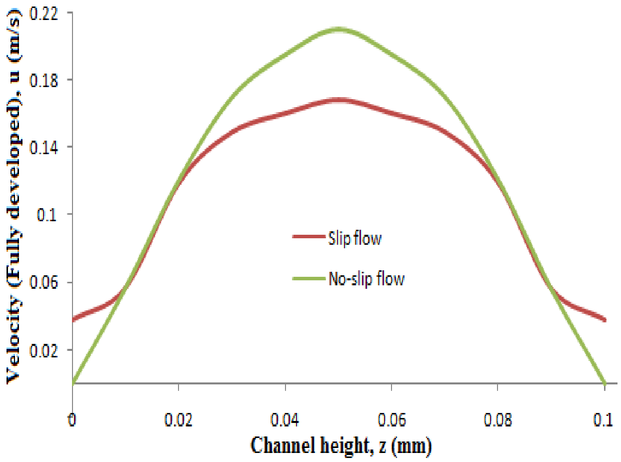

Fig. 3 Variation of velocity with channel height

Also the peak value of the velocity at the centre of the channel is less with respect to no-slip flow. For less velocity lead to decrease the Reynolds number and consequently increase the effectiveness.

4.4 Variation of pressure drop with axial distance

Table 2shows the variation of pressure drop with dimensionlessaxial distance for different Reynolds numbers. The table data clarifies that pressure drop increases with Reynoldsnumber of higher values. If the Reynolds number is higher, the inlet velocity will also higher. And this will lead to increase the shear stress and consequently increase the pressure drop. The higher pressure drop means higher the power required. And ultimately the cost of the operation is higher.

Table 2 variation of pressure drop with axial distance

Dimensionless axial distance, x* (x/Dh)	**Pressure drop (Pa)**			
	Re = 7	**Re = 14**	**Re = 21**	**Re = 28**
0	0	0	0	0
0.5	800	1200	1550	2000
1.0	1200	2100	3000	3900
1.5	1600	3100	4500	6000
2.0	2000	4000	6000	7000
2.5	2500	4900	7300	10000
3.0	2900	5800	8800	11800

4.4 Variation of effectiveness with thermal conductivity

Fig. 4 shows the variation of effectiveness with thermal conductivity ratio fordifferent values of Reynolds number. The thermal conductivity ratio is the ratio of thermal conductivity of solid wall (channel) to fluid. Fromthis Fig. it can be observed that, the effectiveness increased withincrease of $K_r$until the optimum value. And after this optimum value the effectiveness decreases. The optimum value of $K_r$in case of counter flow is 95.

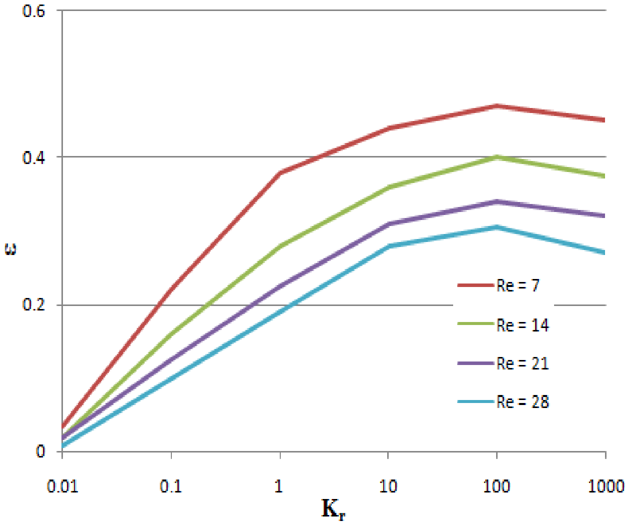

Fig. 4: Variation of effectiveness with conductivity ratio

This is due toincrease of axial conduction at higher thermal conductivity. And theoptimal value of K_r remains constant for all values of Reynolds number. It meansthat Reynolds number will not affect the trend of effectiveness.

4.5 Effect on Nusselt number

The Nusselt number decreases in case of slip flow in comparison with no-slip flow. This is due to the higher Knudsen number. For high value of Knudsen number, the temperature jump will be high and ultimately the Nusselt number decreases. Hence, neglecting the temperature jump will result in overestimation of the heat transfer coefficient.

5. CONCLUSIONS

In this paper heat transfer and pressure drop in the rectangular microchannel heat exchanger with slip flow have been investigated by CFD FLUENT R15 code.From the present work following results are concluded.

1- Effectiveness increases with slip flow in comparison with

no-slip flow.
2- Verification of velocity profile with theoretical approach. And velocity profile is parabolic nature.
3- Large slip will increase the convection along the surface and large temperature jump will decrease the heat transfer by reducing the temperature gradient at wall.
4- Increasing the value of Reynolds number will decrease theeffectiveness.
5- Increasing the value of Reynolds number willincrease the pressure drop.
6- The optimum value of K_r (thermal conductivity ratio between solid and fluid) in case of counter flow microchannel is 95. And effectiveness trend does not depend on the Reynolds number.

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