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Numerical investigation of a micro-heat exchanger with various channel geometries

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Abstract
The Micro-Electro-Mechanical System (MEMS) based heat exchangers had become popular recently in many practical applications. For example, MEMS heat exchangers can be used as a cooling system for micro-chips squeezed into smaller and smaller spaces, with very little place for heat to escape. Therefore, the improvement of their heat transfer characteristics is a key issue for the development of micro-scale integrated systems. In this paper, it was implemented a basic unit model for a micro-heat exchanger using commercial Finite Element Method (FEM) package Comsol Multiphysics (version 5.0). Thermal performance for this model having four different fluid channel geometries: circular, rhombic, square and octagonal was investigated in terms of temperature gradient, total internal energy and total enthalpy distributions along the hot and cold channels.

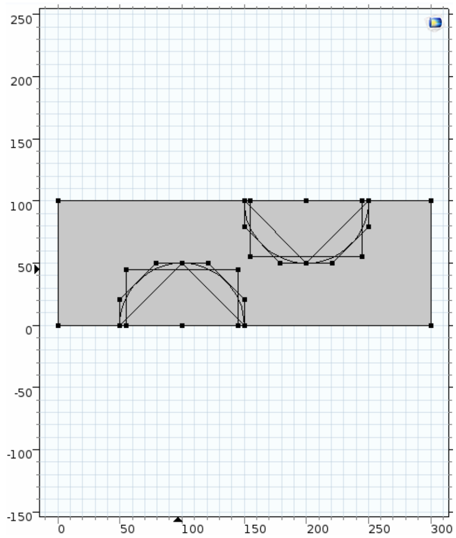
Keywords: Heat transfer; Internal energy; Temperature distribution.

1. Introduction
Heat exchangers can be used in some specific processes for the heat removing when convective cooling from fans and fins are not enough. Having the advantage of superior heat exchange properties, compact design at industrial throughput and low inner volume, the MEMS-based micro heat exchangers are becoming increasingly popular in the fields of medical, electronic and aerospace industries [1-3].
Okabe [4] built up the optimization flow for Micro heat exchanger with a commercial multi-physics solver and pointed out the necessary functionalities of commercial solvers to be used in the field of evolutionary computation. Qian [5] developed a three-dimensional micro-heat exchanger model based on the finite element software ANSYS in order to simulate the steady heat transfer process. Thermal dissipation depending upon very small amount of flow rate through the micro channels was investigated by Mistri and Mahapatra [6] for micro-machined MEMS heat exchangers using Coventor Ware, a finite element based numerical code.
Chhanda [7] conducted an analysis on the effects of different geometries of MEMS heat exchangers on heat transfer enhancement. Dang and Teng [8] showed that heat transfer rate can be increased by decreasing the size of channels in a heat exchanger.
In the following study of a heat exchanger model we developed and solved a conduction and convection heat transfer problem using *Heat Transfer in Solids* interface from Comsol Multiphysics software.

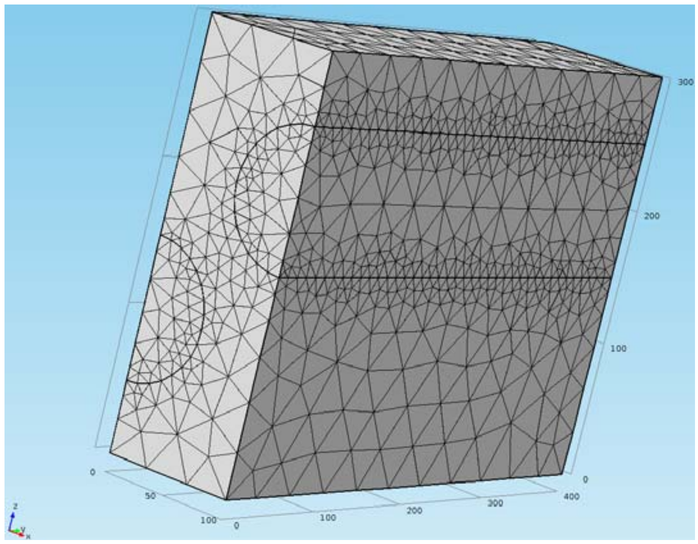
2. System modelling

Figure 1a shows a geometric diagram in XZ plane of all the MEMS-heat exchangers modeled in this study, with four different channel geometries: circular, rhombic, square and octagonal. The base model, having circular channels for fluid flow, is selected starting from a MEMS-heat exchanger with 14 circular micro-channels at a diameter of 100 µm [9]. Due to the symmetry of the channel, we modeled only half of the doubled channels, as we can see in Figure 1a.

In Figure 1b was presented the discretization network based on the finite element method computed for the base model with circular channels. The mesh size is chosen from one of the predefined mesh sizes under general physics. The predefined sizes start from extremely coarse mesh size to extremely fine mesh size. The present model is meshed with normal size mesh, with triangular elements having minimum size of 7.2 µm and maximum size of 40 µm. Free triangular mesh elements with minimum size of 5 µm and maximum size of 10 µm were picked only for the channel walls (see Figure 1b). For the entire heat exchanger model, element growth rate and curvature factor were selected to be 1.5 and 0.6, respectively.



(a)



(b)

Figure 1. (a) Channel geometrical characteristics for all models and (b) triangular mesh elements with different dimensions for the heat exchanger unit cell having circular channels.

The basic component of a heat exchanger can be viewed as a tube with one fluid running through it and another fluid flowing by on the outside. One important heat transfer operation described in this paper is related to the conductive heat transfer through the tube wall.

The present model uses the *Heat Transfer in solids* interface, resolving the equation governing heat transfer through convection and conduction in terms of temperature T(considered here constant in time) for all the solid domains [10]:

$$\rho C_p u \nabla T = \nabla(k \nabla T) + Q \tag{1}$$

where C_p denotes the specific heat capacity (J/Kg·K), $u = 0.005\ m/s$ is the steam velocity (m/s), k is the thermal conductivity (W/m·K), ρ is the density (Kg/m^3) and Q is a source term representing the internally generated heat (W/m^3), which was set to zero because there is no production or consumption of heat in the device.

Heat transfer in fluids feature resolved an equation similar to (1) for water domain. An absolute pressure p_a = 1 atm and an initial temperature T = 293.15 K were considered in those two heat transfer features.

The governing equations are:

$$\nabla\left(\rho \bar{U}\right) = 0 \tag{2}$$

As *Continuity equation*, where $\bar{U}$ is the total internal energy vector, defined as:

$$\bar{U} = ui + vj + wk \tag{3}$$

with u, v and w the internal energy components on X, Y and Z directions.

Energy equation is defined as:

$$\nabla \cdot (\rho \bar{U} H) = \nabla \cdot (k \nabla T) + S \tag{4}$$

where volumetric heat source $S = 0$ and total enthalpy H is described by the equation:

$$H = h + \Delta H \tag{5}$$

The sensible enthalpy h is calculated using the following relation [10]:

$$h = h_{ref} + \int_{T_{ref}}^{T} c_p dT \tag{6}$$

The boundary conditions are insulating for all outer surfaces except for the inlet and outlet boundaries in the fluid channels. At the inlets, constant temperatures were specified for the cold and hot streams, T_{cold} = 300 K and T_{hot} = 330 K, respectively. At the outlets, convection dominates the transport of heat so we applied the convective flux boundary condition:

$$-k \nabla T \cdot n = 0 \tag{7}$$

were n is the normal vector of the boundary.

3. Results and discussions

All the FEM simulations were carried out considering water for the hot and cold stream through channels (fluid domains) and for the solid domain was selected a Steel AISI 4340 alloy with C_p =475 J/Kg·K, k = 44.5 W/m·K and ρ = 7850 Kg/m^3.

Figure 2 showed the temperature variation of cold and hot water versus channel length. The results indicated that using square channels increases the rate of temperature reduction of hot flow, with a difference of 1.9 K at the right end of the square channel by comparing with the circular channel (see Figure 2a).

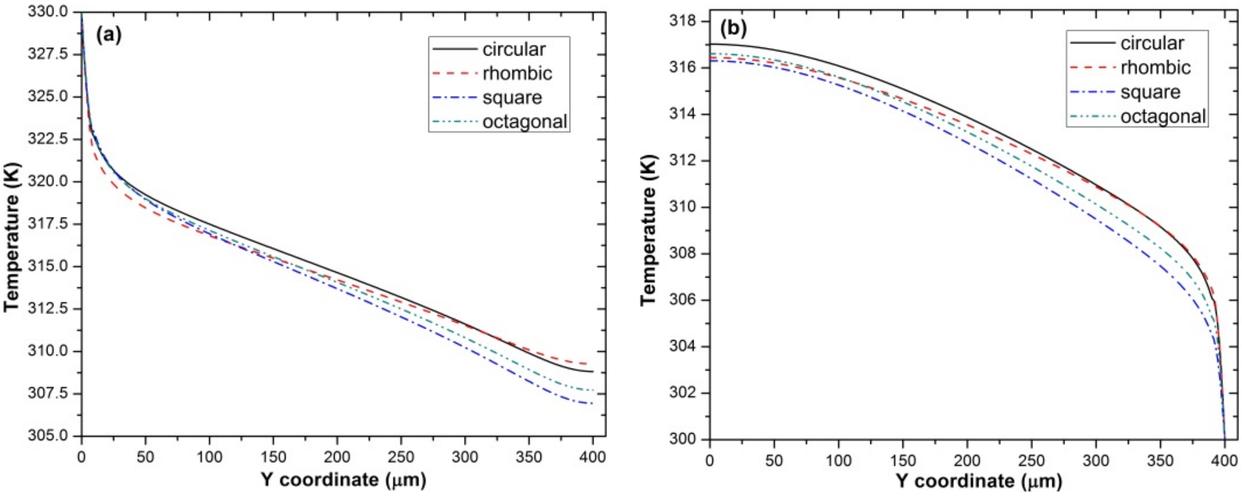


Figure 2. Temperature variation for the hot stream (a) and for the cold stream (b) along the length of the channel with four different geometries.

Moreover, this square channel configuration reduce the rate of temperature rise of cold flow (see Figure 2b), with a difference of 0.7 K at the beginning of the channel and 1.8 K at the right extremity of the channel (375 µm location), by comparing also with the temperature variation along the circular channel.
Total enthalpy variation along the upper boundary of the hot channel was presented in Figure 3. As we expected, the heat exchanger model with square channels presented also an increasing rate of the total enthalpy reduction for hot flow along the channel, with a difference of 4.4 KJ/Kg at the right end of the square channel (by comparing with the circular channel).
Total internal energy distribution along the hot and cold channels of the heat exchanger model is presented in Figure 4. For all the channel geometries investigated.

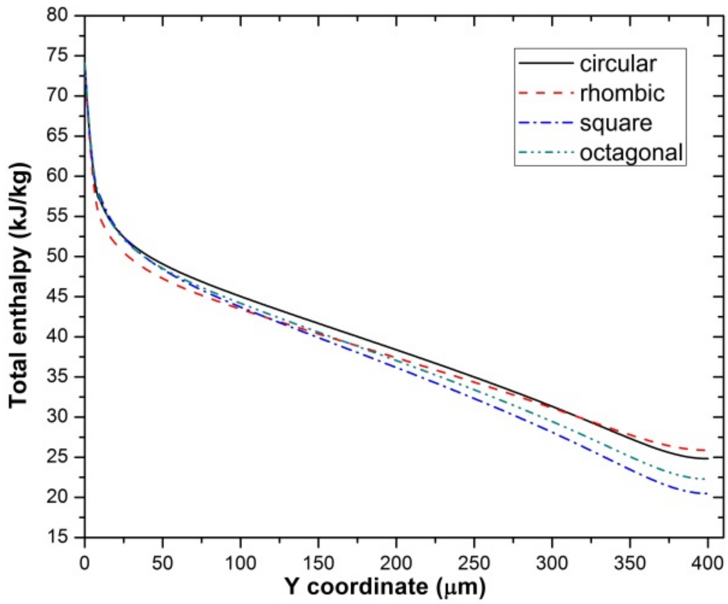
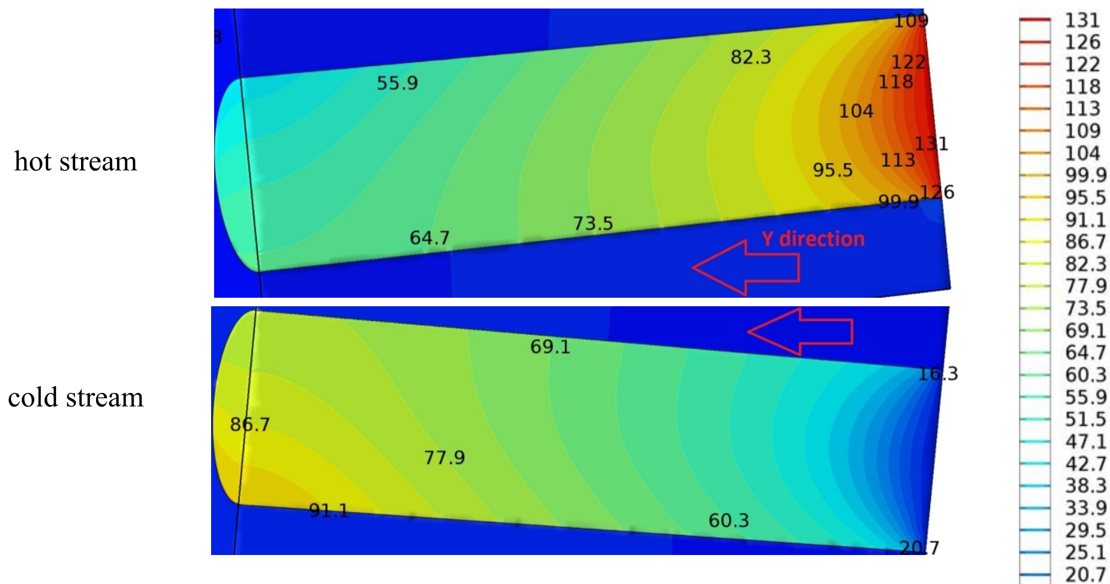
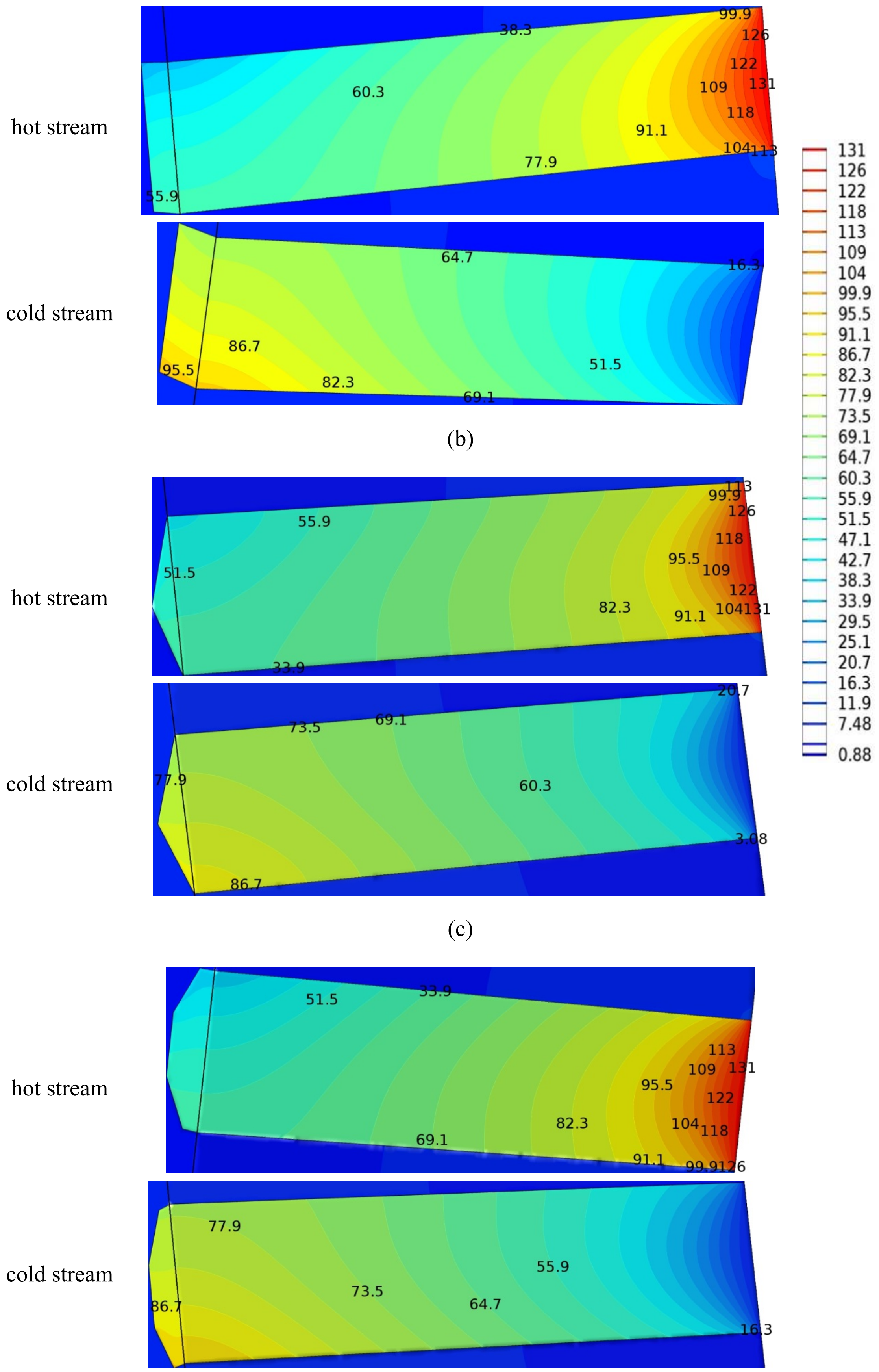


Figure 3. Total enthalpy variation at the upper extremity of the hot stream along the length of the channel for all the models investigated.



(a)

Figure 4. Continued.



(d)

Figure 4. Total internal energy distribution (kJ/kg) along the hot and cold channel length for the following channel geometries: (a) circular, (b) square, (c) rhombic and (d) octagonal.

After comparing the internal energy gradients located in the last quarter of the cold and hot channels (from right to left in Figure 4) for all the model geometries, we conclude that the highest distribution of the total internal energy, at values of 82.3–95.5 kJ/kg, was obtained for the model with a square geometry of channels (see Figure 4b). The lowest values for the internal energy gradients (at values of 38.7-32.3 kJ/kg) were observed in the left upper region of the channel with square geometry.

4. Conclusions

MEMS-heat exchanger model with square type channel geometry presented the highest distribution values for total internal energy in the last quarter of the cold channel along the y direction.

An improvement of 0.7-1.9 K for the temperature rate reduction/increasing in the cold/hot channel was obtained for the heat exchanger model having square channel geometry. This model presented also the highest variation of total enthalpy between the channel extremities.

Using Finite Element Method modelling, with the help of the present study it was demonstrated that the channel geometry represents an important factor for the thermal performance enhancement of the MEMS-heat exchanger.

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Viorel Ionescu was born in Constanta, Romania on 17th September 1977. He has received B.Sc. on 2001 in Physics and Chemistry, with specialization in Physics from Ovidius University of Constanta and M.Sc. on 2015 in Advanced Electrical Systems from Maritime University of Constanta. He obtained his Ph.D. degree in Physics in 2010 from the University of Bucharest. As a PhD student he has studied different type of nanostructured materials with special electrical, magnetic and mechanical properties. Currently Dr. Viorel an Assistant Professor at the Faculty of Applied Science and Engineering, being a member in the Department of Physics at Ovidius University of Constanta. His research activities focus on the finite element method modelling of various types of sensors, actuators and micro-heat exchangers, and also on the modelling of some alternative sources of energy, like Proton Exchange Membrane Fuel Cells(PEMFC) and Solid Oxide Fuel Cells(SOFC). He is a member of the European Society of Cardiology, performing in the last years some research activities in the biomedical signal processingarea, by using Matlab and Labview software tools. He is the author of 23 scientific articles, 14 of them being published in ISI(Web of Science)Journals: https://www.researchgate.net/profile/Ionescu_Viorel/contributions
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