Embedded Microfluidic/Thermoelectric Generation System for Self-Cooling of Electronic Devices

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ABSTRACT

A 3D electro-conjugate heat transfer model was made to study the an embedded microfluidic/TEG system (μF/TEG) system An innovative embedded microfluidic/TEG system (μF/TEG) system is proposed which enables a device to be able to provide power to its cooling system eliminating external power input and resulting in energy efficient and more reliable heat removal system. The research identifies important heat transfer, fluid flow and electrical parameters and optimization to enable the system to generate enough electricity to cool itself. COMSOL Multiphysics was utilized to analyze temperature and electrical characteristics of the embedded microfluidic/TEG system (μF/TEG) system

Keywords: Thermoelectric generator, Microfluidics, Self-cooling, Electronic devices

1. INTRODUCTION

There has been a demand for efficient and clean energy due to the rising cost of energy and increasing environmental awareness. Thermoelectric generation is a promising technology which converts waste heat into electricity in an efficient and clean way. Solid state thermoelectric devices don't have any moving parts or working fluid which results in high reliability of system and a compact design with noiseless operation. They have been applied in aerospace applications, waste heat recovery from industry or car exhaust system[1,2].There have been limited applications of thermoelectric generators due to low thermoelectric conversion efficiency, high manufacturing cost and system inefficiencies.

Thermoelectric application which utilizes the heat from a device to power a TEG to run a cooling system for the device has been demonstrate [3]. The system has been able to provide adequate power to run a fan reducing the temperature the device for low temperature applications. Kiflemariam et al [4] simulated and did a parametric study of thermoelectric generators based self-cooling of devices using fans.

For cooling devices where there is a constraint in space or device temperature could be more than 150 °C, microfluidic system integrated with TEG could be a better choice than fan based air cooled systems. Micro heat sink based on microfluidic system (μFS) for TEG applications could remove high heat fluxes as a result of both increased area and higher convection heat transfer coefficient (HTC). However μFS systems are associated with larger pressure losses and pumping power as compared to macro fluid systems [5]. Thus, they should be designed to operate at the lower flow rate possible and that reduced heat transfer resistance could be achieved [6].The application of μFS for TEG applications has been demonstrated which resulted in compact and effective cooling systems as compared to macro fluid systems.[7,8].

In this study, co-simulation of conjugate heat transfer, fluid flow and thermoelectric voltage and current production has been made to analyze the ability of TEG systems to provide power to μFS without the need from outside power input. This will contribute to the knowledge of designing a system which could generate its own power to run a cooling system.

2. MODEL DESCRIPTION

The computational model chosen for study is shown in Figure 1. An aluminum block is used to represent an uniform heat generation heat source. Microfluidic system consisting of micro channels grooved in aluminum plate with inlet and outlet plenum is used to circulate cooling water over the heated aluminum block. TEG module is assembled between microfluidic system and a spreader. The spreader conducts the heat to the bottom side of the TEG. A full scale modeling of μTEG is made and inside each module, the thermoelectric materials are assumed to be homogenously distributed. Due to the spatial variability of temperature on the surfaces of TEG module, a 3D full scale model would allow to accurately capture voltage and power generation from TEG modules. Some models assume constant temperature on the top and bottom side of the module which could lead to inaccuracies. To mitigate the computational complexity of 3D models, the use of symmetry and mesh optimization is made.

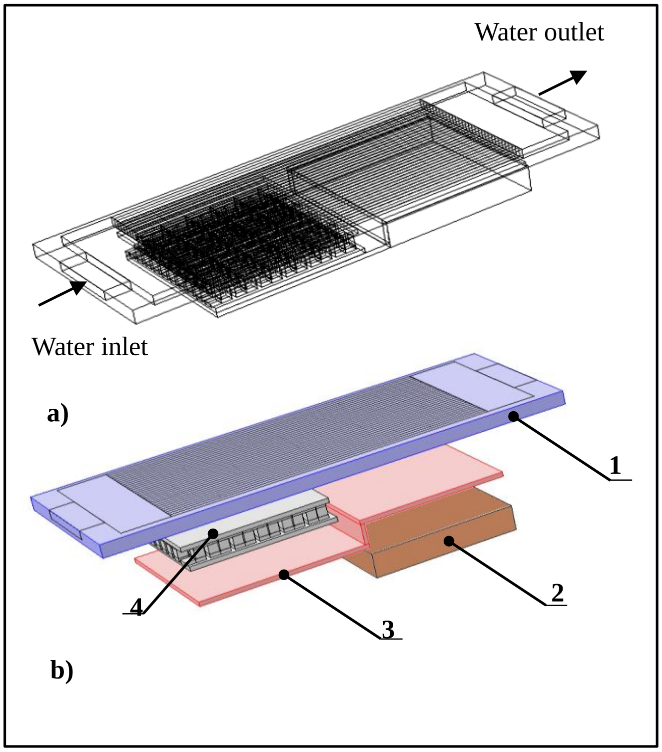

Figure 1. Embedded MicroTEG/microfludic system a) Wire frame rendering b) assembly diagram. (1- Microfluidic system; 2-Heated aluminum block; 3-Spreader; 4- TEG module)

3. GOVERING EQUATIONS

The electric potential in TEG module is proportional to the temperature difference between the hot side and cold side of TEG with proportionality constant termed as Seebeck coefficient (α). The voltage induced by Seebeck effect (V_{sb}) is given by Eq. 1 and Eq. 2 indicate the power produced by the module depends on the resistance inside the module and load resistance.

$$V_{sb} = 2N[(\Delta T_{PN}(\alpha_P - \alpha_N)] \tag{1}$$

$$P_{\mathrm{mod}} = \frac{V_{sb}^2 R_{ld}}{(R_{ld} + R_{\mathrm{mod}})^2} \tag{2}$$

Table 1.TEG module parameters

TEG module parts	Value
Ceramic layer (top and bottom)	
Height x Width x Length [mm]	0.1 x 3 x 3
Thermal conductivity (W/m.K)	31
Copper legs (top and bottom)	
Top: Height x Width x Length [mm]	0.08 x 0.48 x 0.2
Bottom: Height x Width x Length [mm]	0.08 x 0.21 x 0.2
Thermal conductivity (W/m.K)	400
P-N elements of TEG	
Seebeck coefficient(V/K)	1.41x 10^{-5}
Resistivity (Ω m)	1.44e-5
Height x Width x Length [mm]	0.2 x 0.2 x 0.2
Thermal conductivity (W/m.K)	1.6
Seebeck coefficient(V/K)	±205 x 10^{-6}
Resistivity (Ω m)	1 x 10-5

The power generated from TEG connected to an external electric resistor, R_{ld} can be simplified and expressed as Eq. 3:

$$P_{gen} = I^2 R_{ld} = [\frac{2N(\alpha_p - \alpha_n)(T_{hs} - T_{cs})}{R_{ld} + R_{\mathrm{mod}}}]^2 R_{ld} \tag{3}$$

The heat flow in the TEG as described in Eq. 4 is mainly due to the temperature difference between the hot side and cold side of the thermoelectric generator but the heat flow due to peltier effect (the first term on the left hand side of Eq. 4) and joule heating (the last term in Eq.4) also contribute to the total heat flow in the TEG.

$$\dot{Q}_{\mathrm{mod}} = 2NI\Delta T_{PN}(\alpha_p - \alpha_N) - K(T_{hs} - T_{cs}) - \frac{I^2 R}{2} \tag{4}$$

The steady state heat equation for the device and heater can be expressed as:

$$\nabla.(k\nabla T) + \dot{Q} = 0 \tag{5}$$

The steady heat conduction in the TEG and heat sink is given as:

$$\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}=0 \qquad (6)$$

4. USE OF COMSOL MULTIPHYSICS →

Numerical simulations were conducted using the commercial FEM solver COMSOL (Version 4.4). 3D simulation was implemented on half part of the model using the symmetric condition to reduce computational need. Mesh grid independence study were carried out and fine mesh with 616660 elements were used. The number of degrees of freedom solved was 67085. Segregated group solvers were used for solving Electric potential (V), Temperature field (T), Velocity field (U), and pressure. Steady state simulations were carried out with convergence criteria of 10^{-4}.

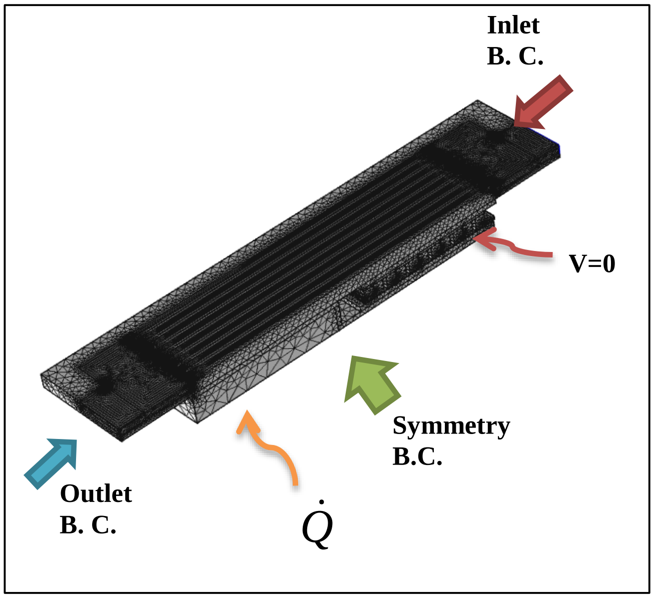

Figure 2. Boundary conditions (B.C.)

As shown in Figure 2, the computational model is half part of the full 3D domain. Thus, symmetrical boundary conditions were used on half side of the wall. Symmetrical fluid flow and heat transfer conditions were applied to the inlet/outlet, inlet and outlet plenums. Symmetrical heat transfer conditions were applied to the heated block, spreader and walls of the heat sink. At the inlet to the microchannel heat sink, boundary conditions of inlet fluid velocity and temperature of the fluid were applied. The boundary condition at the outlet of the microchannel was pressure outlet boundary condition. Uniform volumetric heat generation was applied at the heated block.

The inlet temperature of the fluid was assumed to be at room temperature. Adiabatic boundary conditions were applied to the microchannel wall, TEG wall and the heated block. A ground electric potential condition was used at the outermost n-leg of the TEG.

5. RESULTS AND DISCUSSION

5.1 Temperature field

The temperature distribution in the assembly was studied for the heat input of 50 W, 75 W, 100 W and 125 W to the aluminum block. The volume flow rate to the micro channel; is kept constant at 1.2×10^{-7} m^3/s. Figure 3 shows the temperature field associated with the heat input in the microchannel. In all the cases, the cold water temperature varies only slightly on the first half of section where it is in contact with the TEG module.

For heat input of 75 W, the temperature only increased by 5 °C at the region where the microchannel is in contact with the TEG while there was an increases by almost 25 °C to the outlet temperature of 50 °C downstream from the TEG region. If the heat input is tripled to 125 W, there was only a slight increase in the temperature field on the upstream region on the microchannel. The temperature of water in the microchannel increased by 8 °C while flowing over the TEG but by around 47 °C downstream to the outlet. The high thermal resistance of the TEG module ensures that there is slight temperature increase on the cold side of the TEG module from the hot side of the TEG which is being heated via a spreader form the heated block.

The temperature field along the section of the TEG and heating block is shown in Figure 4. Generally the temperature of both TEG and heated block decreases along the microchannel inlet to outlet direction. There is non-uniform temperature distribution on the cold side and hot side of the TEG. Ideally, the hot side of the TEG would have the highest temperature of the heated block for maximum temperature difference.

However, as could be observed in Figure 4, the highest temperature coming to the hot side of the TEG is only as high as the lowest temperature of the heated block and decreases along the spreader length. Figure 5 shows the temperature along the vertical distance H-H (cuts through the heated block and microchannel) and T-T (cuts through the TEG module and microchannel). For section H-H there is only slight temperature drop from heated block to the spreader. From the spreader to the microchannel, temperature drop could be as high as 42 °C for heating input of 125 W.

For 50 W, the temperature drop from spreader to the microchannel decreased by 150% to 17 °C as compared to 125 W (heating input) around 46.7 °C for 125 W to about 19 °C for 50 W heat input.

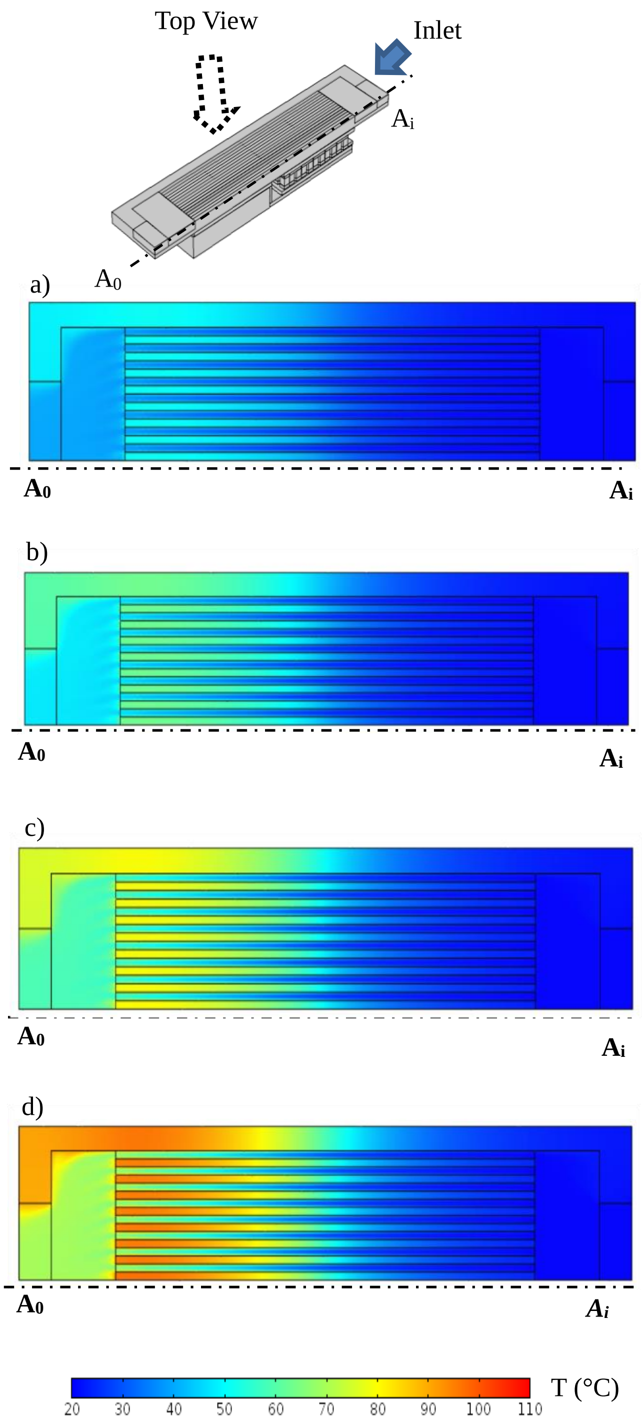

Figure 3. Temperature distribution (Top View) for heating power input a) 50 W b) 75 W c) 100 W d) 125 W

The temperature drop along section T-T ranges from The The temperature drop for heat input of 100 W and 75 W was 36.7 °C and 26.5 °C respectively. The major drop along the T-T is on the P-N legs.

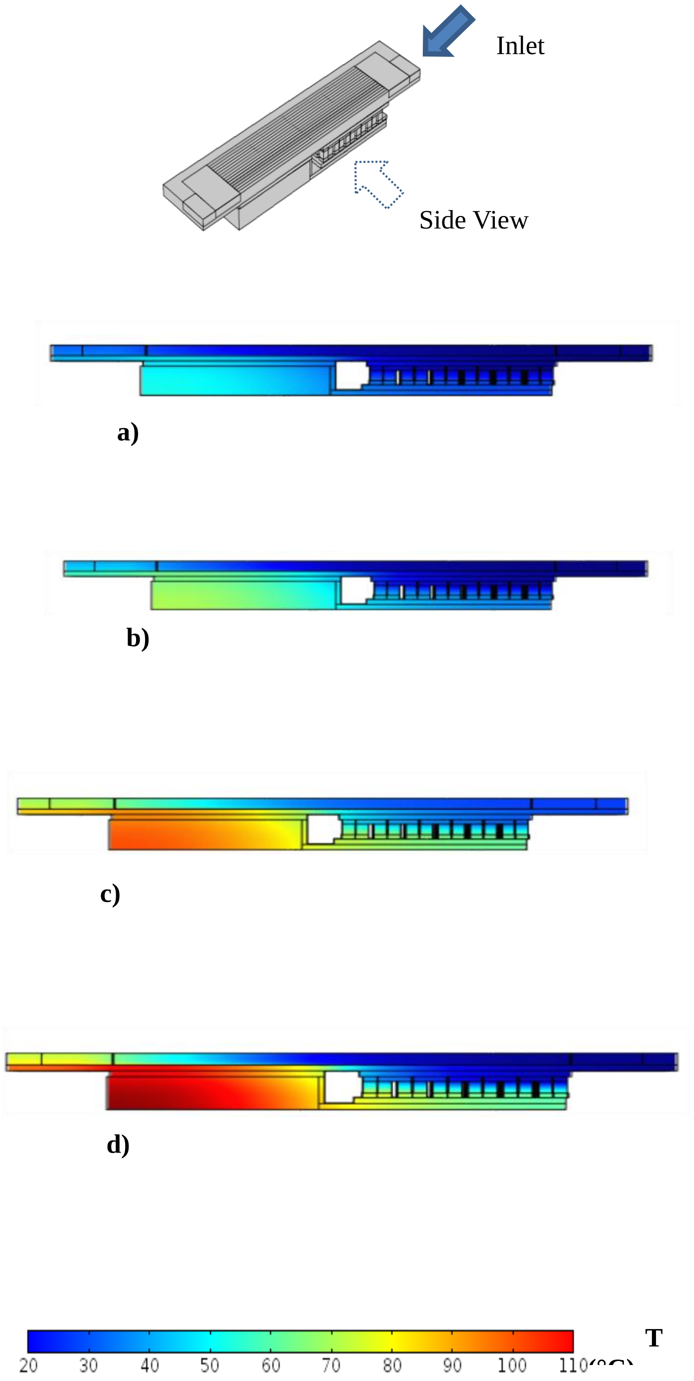

Figure 4. Temperature distribution (Side View) for heating power input a) 50 W b) 75 W c) 100 W d) 125 W

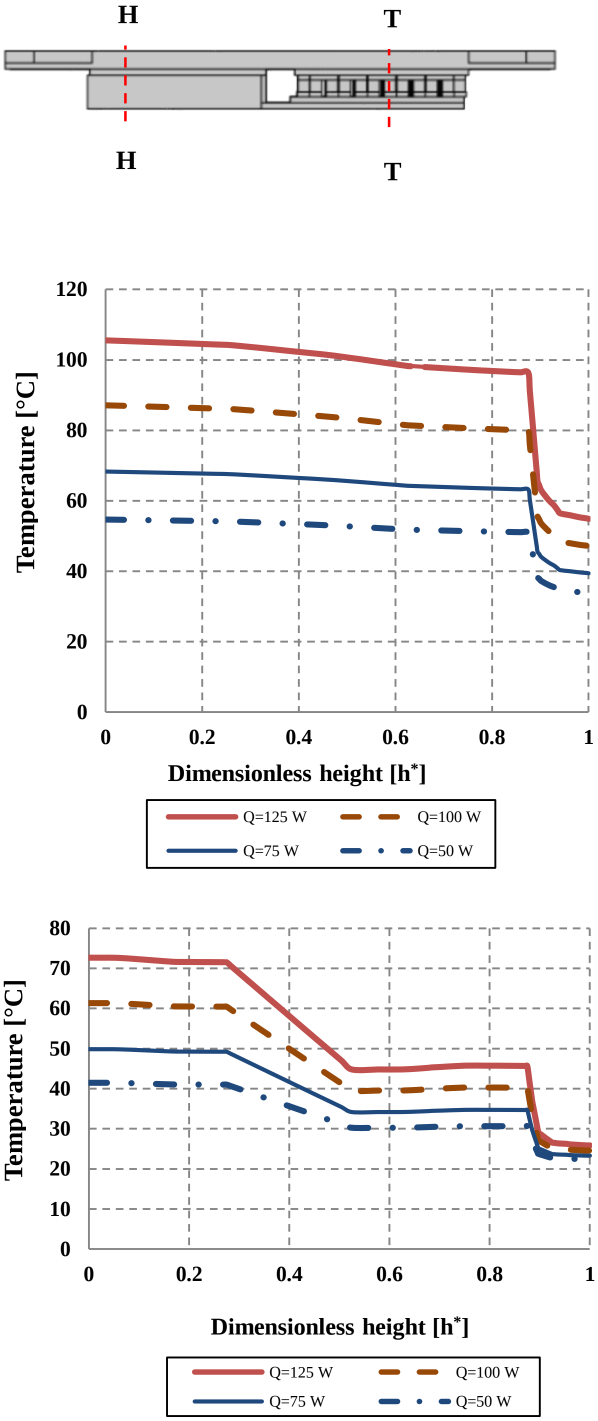

Figure 5. Temperature distribution along a) line H-H b) line T-T

5.2 Voltage and power characteristics

As observed from Figure 6, the TEG module produces more power as the heat input to the heated block increases. The power produced by TEG increased from 2.3 mW to 14 mW corresponding to heating power of 50 W to 125 W respectively. There is a 50% increase in power production for 25 W increases from 50 W to 75 W and 75 W to 100 W of heating power. This is in line with the increase in temperature difference along the TEG with an increase in heat input. The open circuit voltage also increased by 145% for a 75 W increment in heat input from 50 W. The temperature difference along the TEG also increased by similar margin of 145% for increment of heat input from 50 W to 125 W.This is due to the linear relationship of voltage in TEG with temperature difference between the hot side and cold side of the module.

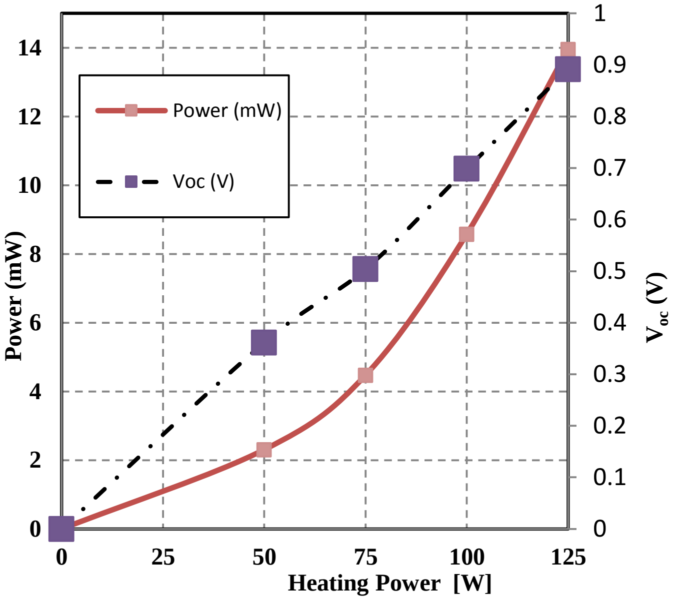

Figure 6. Voltage and power as a function of heating power to the block

6. CONCLUSION

An electro-conjugate heat transfer model was made to study the an embedded microfluidic/TEG system (μF/TEG) The system aims to minimize or eliminate external power input enabling a self-cooling by providing self-sustaining cooling power resulting in energy efficient and more reliable heat removal system. COMSOL was utilized to analyze temperature and electrical characteristics of the embedded microfluidic/TEG system (μF/TEG) system The system has been able to maintain the temperature of the electronic device below 80 °C while producing up to 14 mW of power.

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