

Numerical Simulation of Temperature Distribution Inside the Semiconductor Thermoelectric Generator under A Low Temperature

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Abstract: One-dimensional unsteady heat conduction equation inside the semiconductor thermoelectric generator was established and numerically calculated using Binder-Schmidt explicit method. The results showed that the semiconductor thermoelectric generator has a better dynamic response for the temperature and thermal equilibrium state can be reached within 6 to 10 seconds under a low temperature. Furthermore, the temperature change inside the semiconductor thermoelectric generator is linear from the hot side to the cold side.

Keywords: thermoelectric generator, temperature distribution, numerical simulation

1. INTRODUCTION

With more and more drastic environmental crisis and energy crisis, scientific and research workers in many countries are applied themselves to the development and utilization of new energy and energy-saving technology. And semiconductor thermoelectric generator technology provides us with a new branch of making use of low-temperature heat source like industrial remaining heat, underground heat, solar energy and so on ^[1]. Semiconductor thermoelectric generator has many excellent advantages such as small cubage, light weigh, no moving parts, long operating life, high reliability, no pollution and so on. Especially since the late 1980s, with rapid development of semiconductor thermoelectric materials, this new technology has been widely used in the military, medicine,

communication, navigation, dynamics, industrial production and other fields ^{[2][3][4][5][6]}.

Many researches on semiconductor thermoelectric generator have been made in recent years ^{[7][8][9]}. However, most of them are based on the analysis for final steady state. And the research on the dynamic procedure is seldom. In fact, studying dynamic procedure inside the semiconductor thermoelectric generator is very useful for us to understand the generation mechanism and improve the cycle performance. The purpose of this work is to develop and analyze dynamic change of temperature distribution inside the semiconductor thermoelectric generator from the angle of unsteady state and to provide some essential data for further research and application.

2. MATHEMATICAL MODEL AND NUMERICAL SIMULATION

The fundamental principle of a typical semiconductor thermoelectric generator can be shown and a cold source. By means of the transition of the electron and the cavity, the heat is absorbed on the hot side and is released on the cold side. At the same time, heat energy is converted into electric energy. In order to be convenient for our research, a simplified cycle model that consists of a P-type semiconductor and an N-type semiconductor is taken as an example. In the model, P-type semiconductor and N-type semiconductor are joined by three metal conductors like copper foils. The tiny resistance of copper foils can be neglected. Thus when the load is added, a generator cycle is formed.

According to the energy conservation law, detailed thermal equilibrium equation inside the semiconductor thermoelectric generator is expressed as follows:

$$-\lambda A \frac{\partial^2 T}{\partial x^2} + I^2 R = -\lambda A \frac{\partial T}{\partial x} + \frac{\partial}{\partial x} \left(-\lambda A \frac{\partial T}{\partial x} \right) dx + kI \frac{\partial T}{\partial x} + \rho c A \frac{\partial T}{\partial \tau} dx \quad (1)$$

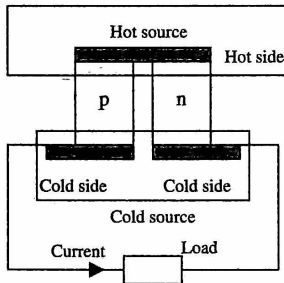


Fig1 Diagram of an ideal thermoelectric generator cycle

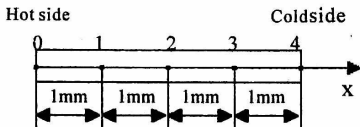


Fig 2 Diagram of the grid of nodes

If neglecting the heat lost due to Thomson Effect and Extrinsic Thomson Effect [10] under a low temperature, (the right third item of equation 1), then

$$\rho c \frac{\partial T}{\partial \tau} = \lambda \frac{\partial^2 T}{\partial x^2} + \frac{I^2 R}{A \rho c \Delta x} \quad (2)$$

as the Fig 1. Heat engine works between a hot source

Where ρ, c and λ are the density, specific heat and coefficient of thermal conductivity of thermoelectric modules respectively, A is sectional area of the couple, R is the resistance of thermoelectric modules and I is the current in the cycle.

Therefore, the temperature distribution inside the semiconductor thermoelectric generator can be expressed as one-dimensional homogeneous, unsteady, solid heat conduction equation with an internal hot source. The form of the equation is parabolic. Where the item of $I^2 R / (A \rho c \Delta x)$ is the internal hot source and its physical meaning is the heat created by Joule Effect per unit volume inside the thermoelectric module.

Initial conditions and boundary conditions of equation 2 are,

$$\text{When } \tau = 0, \quad T = T_0$$

$$\text{When } \tau > 0, \quad T_H = (T_0 + T_H) / 2; \quad T_C = (T_0 + T_C) / 2$$

Where T_0 is the initial temperature of thermoelectric modules before the heat transfer begins, T_H is the temperature of hot side when heat transfer begins, T_C is the temperature of cold side when heat transfer begins, T_H is the temperature of hot source and T_C is the temperature of cold source.

In order to decrease working amount of numerical calculation, Binder-Schmidt explicit method [11] is used to solve the above-mentioned partial differential equation. During the discretization of the equation, center difference is made for diffusion item and forward difference is made for unsteady item. Thus, we can obtain the following equation:

$$\frac{T_n^{(i+1)} - T_n^{(i)}}{\Delta \tau} = \frac{\lambda}{\rho c} \frac{T_{n+1}^{(i)} - 2T_n^{(i)} + T_{n-1}^{(i)}}{\Delta x^2} + \frac{I^2 R}{A \rho c \Delta x} \quad (3)$$

Furthermore, equation 3 can also be written as follows:

$$T_n^{(i+1)} = \frac{\lambda}{\rho c} \frac{\Delta \tau}{\Delta x^2} (T_{n+1}^{(i)} + T_{n-1}^{(i)}) + (1 - \frac{2\lambda}{\rho c} \frac{\Delta \tau}{\Delta x^2}) T_n^{(i)} + \frac{I^2 R}{A \rho c \Delta x} \Delta \tau \quad (4)$$

In order not to influence the partial equation's stability in the explicit method, Fourier number Fo is 0.5, namely:

$$\frac{\lambda}{\rho c} \frac{\Delta \tau}{\Delta x^2} = 0.5 \quad (5)$$

Thus, once the space step-length Δx is defined, the time step-length $\Delta \tau$ can be obtained. Then after the successive iteration, the relationship that internal nodes of thermoelectric modules vary with the time can be calculated.

3. RESULT ANALYSIS

In this paper, bismuth tellurium antimony solid alloy, a kind of popular semiconductor thermoelectric material, was taken as a example for numerical simulation. Physical properties of the material are as follows:

$\rho=10.3 \times 10^3 \text{ kg/m}^3$, $c=0.147 \text{ kJ/(kg} \cdot ^\circ\text{C)}$, $\lambda=1.6 \text{ W/(m} \cdot ^\circ\text{C)}$, $R=1.35 \times 10^{-5} \Omega \text{m}$, $A=10^{-4} \text{ m}^2$ and $L=4 \text{ mm}$. The maximum working temperature of thermoelectric modules is 125°C . During the practical calculation, space step-length Δx along the length direction of couple arm is 1 mm and five nodes are planned (Fig 2). Calculated time step-length $\Delta \tau$ is about 0.5 s . The results are shown in Fig 3 - 8.

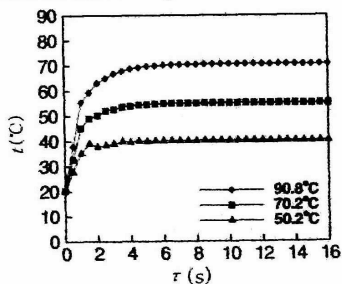


Fig 3 Transient temperature of node 1

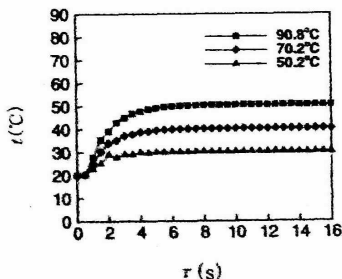


Fig 4 Transient temperature of node 2

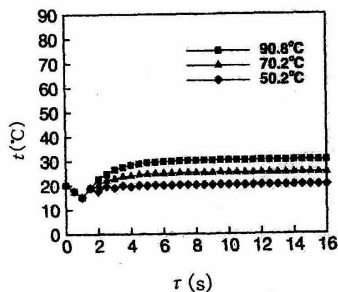


Fig 5 Transient temperature of node 3

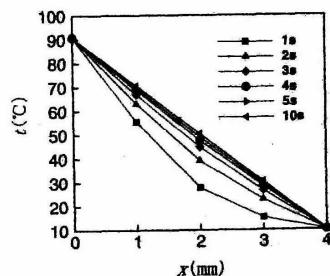


Fig 6 Temperature distribution when $t_f=90.8^\circ\text{C}$ and $t_c=10.2^\circ\text{C}$

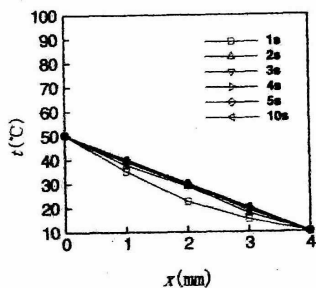


Fig 7 Temperature distribution when $t_f=70.2^\circ\text{C}$ and $t_c=10.2^\circ\text{C}$

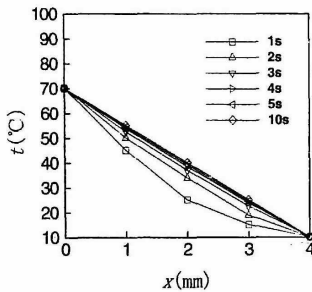


Fig 8 Temperature distribution when $t_h=50.2^{\circ}\text{C}$ and $t_c=10.2^{\circ}\text{C}$

If the temperature of cold source is kept a constant 10.2°C , transient change curves that the node temperature varies with the time when the temperature of hot source is 90.8°C , 70.2°C and 50.2°C are shown in Fig3, Fig4 and Fig5, respectively. It can be seen that, under a low working temperature ($<125^{\circ}\text{C}$), temperature distribution inside the semiconductor thermoelectric generator can reach thermal equilibrium state within 6 to 10 seconds. Furthermore, the influence of the difference of the hot source temperature on the time that the nodes reach the equilibrium state is not very clear, which is different from common solid materials. And two reasons can be used to explain this phenomenon. One is that because the longitudinal length of semiconductor thermoelectric generator is rather short (4-10 mm), any temperature fluctuation inside the semiconductor thermoelectric generator can be transmitted to other adjacent nodes in a short time. Another is that Joule heat effect and Thomson effect of thermoelectric materials have a certain regulating function on the temperature. After the regulation, the temperature of nodes can reach the steady state in a short time. Especially, for some nodes like node 3, which are adjacent with the cold source, the regulating effect is more obvious.

When the temperature of hot source is 90.8°C , 70.2°C and 50.2°C , internal temperature distributions of

all nodes are shown in Fig6, Fig7 and Fig8, respectively. It can be seen that when τ is 6-10s, the temperature inside the semiconductor thermoelectric generator has been steady. Furthermore, the temperature change inside the semiconductor thermoelectric generator is linear from the hot side to the cold side when thermal equilibrium state is reached. And this result can coincide with experimental results very well^[6].

4. SUGGESTIONS

One-dimensional unsteady heat conduction equation inside the semiconductor thermoelectric generator has been established and numerically calculated using Binder-Schmidt explicit method. The results showed that the semiconductor thermoelectric generator has a better dynamic response for the temperature and thermal equilibrium state can be reached within 6 to 10 seconds under a low temperature. Furthermore, the temperature change inside the semiconductor thermoelectric generator is linear from the hot side to the cold side. Besides, because of working under a low temperature ($<125^{\circ}\text{C}$), some heat effects of semiconductor thermoelectric materials, such as Thomson Effect, Extrinsic Thomson Effect and so on, are neglected during the numerical calculation. However, for high-temperature semiconductor thermoelectric generator (working temperature is $200-500^{\circ}\text{C}$), the influences of these effects on the temperature distribution must be taken into full account. And this needs our further research in future.

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