The Study of the Enhancement of Micro-Vibration-Induced Harvester based on Vapor Impacting

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Abstract—With technology rapidly advance, the energy of demand is also with the greatly increased. Therefore, the development of new energy or energy harvesting attracts much attention. Our group has proposed an innovated micro heat pipe harvester based on the micro-piezoelectric vibration-induced power device. The deformation of the piezoelectric material by vapors impacting enables it to convert the vapor momentum to the power. In this paper, the purpose is to enhance the output of the micro heat pipe generator by the optimization of the vibration-induced device. A suitable cantilever beam combined with piezoelectric material is designed by multiphysics and genetic algorithm. The optimal geometry is found to approach its natural frequency. The experimental results show that the power improves about 293.38%. Through this study, the micro heat pipe generator will be practiced and approach the available usage.

Keywords—energy harvester; cantilever beam; resonance; natural frequency

I. INTRODUCTION

The power source of wireless sensors is the most important issue. The design of the energy harvester is a new and interesting topic in the field of wireless sensor. The generators are used vapor momentum to drive rotating of turbine, for instance, steam turbine and Organic Rankine Cycle (ORC). Generally, the turbine of generator for steam is bigger, larger and higher efficiency. For lower temperature, the smaller turbine is not suitable due to low thermal-electric converting efficiency. Specially, the temperature for thermal module of computer is lower. It is worth noted that how to collect thermal power of waste heat of computer and, then, convert it to useful of electric power. Some researchers designed the small turbine and placed in the adiabatic section of the heat pipe.

The heat pipe is a simple device that can transfer heat quickly. It divided into three sections were evaporator, adiabatic and condenser. When the heat pipe is heated, the working fluid will boil to vapor phase. The vapor travels along the heat pipe to the condenser section, then the condensate is returned to the evaporator section by gravity or capillary structure. In 1958, Hsu and Leo [1] were developed a simple device of energy harvesting. The low pressure of solar boiler driving the turbine enables it to generate power. After two years, they used distilled water in a device of vacuum and closed cycle [2]. Pryputniewicz and Haapala [3] proposed a new concept, they used the turbine in the heat pipe. Base on this concept, Akbarzadeh et al. [4] developed a thermosyphon rankine (TSR) engine on geothermal and solar, as show in Fig. 1 [4]. The temperature difference between evaporator and condenser section was approximately 30 °C, the input power at 100kW and TSR can harvest 3kW. The thermal-electric conversion efficiency is increased 3%, approximately.

However, the turbine is a mechanical system, the static friction must be overcome before driving. The static friction is relative larger in small scale turbine system resulted in low efficiency. To reduce friction effects, the turbine could be replaced by the piezoelectric material to generate electric power by vapor flow of working fluid in heat pipe.

Generally, the piezoelectric material is used to harvest the environment energy in the power source of wireless sensor. However, the energy power is insufficient. Objective of many researches still are focusing on how to increase output power or converting efficiency. Li et al. [5] proposed a novel mass of L-shaped combined with cantilever piezoelectric harvester. The piezoelectric harvester used in soles and test. At 3.0 mi/h, the average of power is 49μW. Koyama and Nakamura [6] found that the length of beryllium copper cantilever decreased from 18 to 4 mm resulted in the efficiency increased, approximately 0.233%. Li et al. [7] design a miniature generator with elastic base and compared without elastic base. Decreasing the natural frequency approach to the ambient vibration frequency, the experimental results show that the power for elastic base.

Fig. 1. The schematic diagram of TSR engine [4].
increases 376 times. Zhu et al. [8] used multi-layer structure to improve the output power of piezoelectric harvester. To increase efficiency, Ly et al. [9] used positive piezoelectric effect in first mode.

In this paper, a suitable cantilever beam combined with piezoelectric material is designed by multiphysics and genetic algorithm (GA) optimal method. The optimal geometry is found to approach its natural frequency at 60 Hz. The vapor-generator is build to examine performance of piezoelectric material with cantilever beam.

II. THE MATHEMATICAL MODEL

A. The mathematical model of the vapor-generator

In this paper, the deformation of the piezoelectric material by vapors impacting enables it to convert the vapor momentum to the power. Therefore, it can understand the transitions between the liquid and the vapor in generator. Through the validation of theoretical, it would be beneficial to the experiment. The governing equations in this model included the Navier-Stokes equation and the equation of convection and conduction are as follows:

$$\rho_f \frac{\partial \vec{u}_f}{\partial t} + \rho_f (\vec{u}_f \cdot \nabla) \vec{u}_f = \nabla \cdot (2 \eta \nabla \cdot \vec{u}_f) + \rho_f \vec{g} = 0$$

(1)

where $\rho_f$ means the fluid density (kg/m$^3$), and $\vec{u}_f$ is the subdomain fluid velocity $\vec{u}_f$, and $f$ denotes liquid phase. For the vapor phase, the weakly compressible Navier-Stokes equations are solved:

$$\rho_v \frac{\partial \vec{u}_v}{\partial t} + \rho_v (\vec{u}_v \cdot \nabla) \vec{u}_v = \nabla \cdot (2 \eta \nabla \cdot \vec{u}_v) + \rho_v \vec{g}$$

(2)

where $\rho_v$ means the fluid density (kg/m$^3$), and $\vec{u}_v$ is the subdomain vapor velocity $\vec{u}_v$.

$$\frac{\partial \rho_v}{\partial t} + \nabla \cdot (\rho_v \vec{u}_v) = 0$$

(3)

The heat conduction equation of the vapor is listed as below:

$$\rho_v C_{p,v} \frac{\partial T_v}{\partial t} + \rho_v C_{p,v} (\vec{u}_v \cdot \nabla) T_v = \nabla \cdot (k_v \nabla T_v)$$

(4)

where $C_{p,v}$ (J/kg·K) means the specific of working fluid, and $k_v$ (W/m·K) is the thermal conductivity.

We used the phase field method, its governing equations by Cahn-Hilliard equation.

$$\frac{\partial \phi}{\partial t} + \vec{u} \cdot \nabla \phi - m \delta \left( \frac{\nabla \phi}{\epsilon} \cdot \vec{u} - \frac{\nabla \phi}{\epsilon} \right) = -\frac{\lambda}{\epsilon} \nabla \cdot \nabla \phi$$

(5)

where $\phi$ means the dimensionless phase field variable such $-1 \leq \phi \leq 1$, $\lambda(N)$ is the mixing energy density and $\epsilon(m)$ is the capillary width.

The moment equation includes surface tension effect as a volumetric body force:

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho \vec{u} \cdot \nabla \vec{u} = \nabla \left[ -\rho \vec{I} + \eta \left( \nabla \vec{u} + \left( \nabla \vec{u} \right)^T \right) \right] + \rho \vec{g} + G \nabla \phi$$

(6)

$G$ is the chemical potential (Pa). The equations of continuity is modified from liquid to vapor:

$$\nabla \cdot \vec{u} = \frac{1}{\rho} \frac{\partial p}{\partial \phi}$$

(7)

In this study, use the thermodynamic calculations and forecasts the thermal efficiency of vapor by Hsu and Leo [2] and Akbarzadeh et al. [4]. $Q$ is the input heat, and $Q_{fg}$ is the latent heat. The system is assumed stable.

$$Q = Q_{fg}$$

(8)

$$Q_{fg} = (P_f - P_g) \left( \frac{M}{2 \pi R T_f} \right)^{\gamma/2} \dot{m} T_{fg}$$

(9)

We assume the vapour generated is $T_{sat}$, and the condition is dry-saturated. The energy equation is listed as below:

$$H_v = h_v + \frac{1}{2} V^2 - \frac{1}{2} V^2 - g z$$

(10)

$$V = V_i A_i / A$$

(11)

The inlet and outlet enthalpy of the nozzle are $h_i$ and $h_e$. The inlet and outlet velocity of the nozzle are $V_i$ and $V_e$. And the inlet and outlet cross-sectional area of nozzle are $A_i$ and $A_e$.

The nozzle length is $L_{nozzle}$.

$$h_e = h_e - g z_{gap}$$

(12)

About the equation of the beam, $h_e$ is the enthalpy of vapor impinging jet, and between the piezoelectric material and the nozzle $Z_{gap}$ is the gap.

$$W = \dot{m} h_e$$

(13)

The efficiency of the generator in the heat pipe equation is

$$\eta = \frac{W}{Q}$$

(14)

B. The mathematical model of natural frequency

All the structure has the natural frequency which is belong to its own. When the natural frequency of the structure is close to the frequency of the environment, it will reach resonance and increase the amplitude of vibration. The natural frequency is estimated as follows [8]:

$$\omega_n = \sqrt{\frac{k}{m}}$$

(15)

where $k$ is the spring constant in static condition as below :

$$k = \frac{\beta \pi L^3}{E I}$$

(16)

where $\beta = 1.875, 4.694, 7.855, ..., \beta$ is the Young’s modulus, $I$ is the moment of inertia, $m$ is the mass and $L$ is the length of beam. Using Euler beam theory, the resonant frequency of beam in free vibration of environment as follows:

$$\omega_n = \sqrt{\frac{E I}{m L^3}} , \quad n = 1, 2, 3,$$

(17)

Therefore, the resonant frequency is solved:

$$f_n = \frac{1}{2 \pi} \omega_n = \frac{1}{2 \pi} \sqrt{\frac{k}{m}}$$

(18)
III. EXPERIMENTAL METHODS AND MODELING

A. Experimental apparatus

The performances of PVDF and cantilever beam are examined by experiment apparatus. The vapor-generator experimental system consists of heater, data logger, power supply, tank and holder. The schematic of experimental system is shown in Fig. 2. In the present study, water is used as working fluid to impact sample as vaporization of working fluid. The power supply can provide stable output power to heater. The heated power is adjusted by voltage or current. The temperature of heater and tank is measured by four thermocouples and logged by Data logger. The output voltage and frequency of PVDF are measured by GWINSTEK GDS-2062 during experiment.

B. Simulated Model and Optimization

This research demonstrates how the application of numerical optimal simulation techniques can be used to search for an effective and higher output voltage of PVDF design. The optimal design of a hybrid PVDF structure for obtaining resonant frequency between hybrid PVDF structure and vapor-generator is achieved in the present study. The numerical design was developed by combining a direct finite element solver with an optimal method a genetic algorithm, GA [10, 11]. A finite element analysis model, COMSOL, is used as the subroutine to solve the natural frequency profile associated with the variation in the geometry of hybrid PVDF structure during an iterative optimal process. GA is the numerical optimal method based on natural selection, through reproduction, crossover, and mutation to evolve. The high adaptation individual surviving chances more than the lower adapt adaptation individual. According repeated iterations to obtain the optimal solution.

C. The sample of energy harvester

The PVDF of piezoelectric material is used as energy harvester device in this study. The PVDF material has large deformation due to “soft” effect. To adjust its resonant frequency matching with vapor-generator system, the PVDF is adhesive with the cantilever beam of aluminum. The cantilever beam dimension is optimized by COMSOL multiphysics and GA. The objective function is frequency at 60 Hz. The 60 Hz is measured from vapor-generator system as vaporization of working fluid to impact cantilever beam. The dimensions of PVDF and cantilever beam before optimal process are shown in Fig. 4.

IV. RESULTS AND DISCUSSIONS

The natural frequency with 127.44 Hz for PVDF was estimated by COMSAL. Furthermore, output voltage of PVDF induced by vapor-generator system is 272mV at frequency 60Hz. The natural frequency for PVDF simulated results is shown in Fig. 5. To understand effect of dimension for cantilever beam on natural frequency, the natural frequency and output voltage for PVDF with and without cantilever beam are measured, as shown in Table 1.

In the present study, frequency of the vapor-generator system is 60 Hz as impacting of vapor of working fluid on energy harvester. The PVDF with cantilever beam is changed its length to adjust natural frequency. It is worth noted that the output voltage is increased as natural frequency of PVDF with cantilever beam is approximately 60 Hz. The output voltage is increased 20% at natural frequency increased from 54.58 Hz to 57.36 Hz. Furthermore, the results show the resonance frequency for PVDF with cantilever beam was encountered at 60 Hz.
<table>
<thead>
<tr>
<th>NO</th>
<th>Cantilever beam</th>
<th>Length (mm)</th>
<th>Natural frequency (Hz)</th>
<th>Max. Output Voltage (mV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>W/O</td>
<td>25.00</td>
<td>127.44 ±136</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>W/I</td>
<td>60.00</td>
<td>54.58 ±400</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>W/I</td>
<td>58.80</td>
<td>57.36 ±480</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>W/I</td>
<td>57.77</td>
<td>60.00 ±535</td>
<td></td>
</tr>
</tbody>
</table>

To reach resonance of system, the genetic algorithm is used to search optimal geometry for hybrid PVDF structure. In this study, the objective function is set at 60 Hz. The length of cantilever beam is 57.77 mm at natural frequency 60 Hz after optimal process. The simulated result of PVDF with cantilever beam in resonance is shown in Fig. 6. The photo and dimension for PVDF with cantilever beam are shown in Fig. 7.

In conclusion, we had designed geometry of the cantilever beam combined with piezoelectric material through commercial software and genetic algorithm. In the present study, the dimension of cantilever beam is optimized and verified by experiment. The resonance of energy harvester device can improve output efficiency as natural frequency for hybrid PVDF structure equal to vapor-generator system.

V. CONCLUSION

REFERENCES