PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

2D numerical analysis of energy harvesting in oscillating heat pipe using piezoelectric transducers

Sajiree Vaidya, Oliver Myers, Scott Thompson, Nima Shamsaei, John G. Monroe

2D Numerical Analysis of Energy Harvesting in Oscillating Heat Pipe Using Piezoelectric Transducers

Sajiree Vaidya*[a], Oliver Myers*[a], Scott Thompson*[b], Nima Shamsaei*[b], John G. Monroe*[c]
[a] Department of Mechanical Engineering, Clemson University, South Carolina, USA
[b] Department of Mechanical Engineering, Auburn University, Alabama, USA
[c] Department of Mechanical Engineering, Mississippi State University, Mississippi, USA

ABSTRACT

Energy Harvesting is a powerful process that deals with exploring different possible ways of converting energy dispersed in the environment into more useful form of energy, essentially electrical energy. Piezoelectric materials are known for their ability of transferring mechanical energy into electrical energy or vice versa. Our work takes advantage of piezoelectric material's properties to covert thermal energy into electrical energy in an oscillating heat pipe. Specific interest in an oscillating heat pipe has relevance to energy harvesting for low power generation suitable for remote electronics operation as well as low-power heat reclamation for electronic packaging. The aim of this paper is develop a 2D multi-physics design analysis model that aids in predicting electrical power generation inherent to an oscillating heat pipe. The experimental design shows a piezoelectric patch with fixed configuration, attached inside an oscillating heat pipe and its behavior when subjected to the oscillating fluid pressure was observed. Numerical analysis of the model depicting the similar behavior was done using a multiphysics FEA software. The numerical model consists of a three-way physics interaction that takes into account fluid flow, solid mechanics, and electrical response of the harvester circuit.

Keywords: Energy harvesting, piezoelectric transducer, oscillating heat pipe, fluid-structure interaction

1. INTRODUCTION

1.1 Use of oscillating heat pipe in energy harvesting

With ever increasing demand of energy, it has become extremely important to efficiently generate and store the energy. It is equally important to reuse the available waste energy by applying suitable energy harvesting techniques. Considerable amount of waste heat is generated within variety of working environment. Available waste heat can be essentially harvested and converted into useful electrical energy. Our work takes an advantage of the inherent properties of oscillating heat pipe to convert readily available and harvestable waste thermal energy to generate electrical energy. This work involving oscillating heat pipe is aimed at providing a means of generating low power suitable for remote electronics operations. It is also considered as a low-power heat reclamation method to eliminate and recover waste heat which is useful for the eventual reuse.

Oscillating heat pipes (OHP) are extensively investigated for their ability of serving as a power reclamation [1]. OHP is a two-phase heat transfer device that relies on the oscillatory flow of liquid slug and vapor plug in a long miniature tube bent into several turns [2]. Initially the OHP is evacuated and filled partially with the working fluid. During OHP operation, heat is added to the OHP evaporator region which vaporizes the liquid. As the liquid vaporizes, vapor plug starts expanding in size. Expanded vapor slug pushes liquid towards the condenser end. At condenser end, vapor pressure reduces and condensation of the vapor plugs occur [3]. This imbalance of pressure causes the fluid to oscillate/circulate through OHP at critical temperature difference. OHP fluid oscillations typically occur over a frequency spectrum less than 10 Hz. The specified oscillating frequency range fits perfectly for the use of piezoelectric transducers to convert thermal energy of the OHP into electrical energy. Our work explores the potential of using piezoelectric transducers for energy harvesting in OHP.

Smart Materials and Nondestructive Evaluation for Energy Systems 2017,
edited by Norbert G. Meyendorf, Proc. of SPIE Vol. 10171, 1017107
 · doi: 10.1117/12.2259855

1.2 Use of piezoelectric transducers for energy harvesting

Piezoelectric materials possess the ability to generate electricity when stressed, which is called as a direct piezoelectric effect. This is due to their inherent ability of rearranging lattice dipoles. This effect can be reversed by applying an external charge on the piezoelectric material which results in inducing mechanical stress. Due to their ability of converting mechanical stress into electrical form, piezoelectric devices are a popular choice for the purpose of energy harvesting. Piezoelectric transducers are widely used to convert mechanical vibrations into electrical energy. However, their ability of coupling with fluid flows has also been explored to understand their potential use in harvesting energy from the fluid flows [4-6]. Our work takes an advantage of the piezoelectric transducer's energy generation capacity when coupled with fluid oscillations inside an OHP.

Our research aims at exploring the use of OHP to harvest waste thermal energy using piezoelectric transducers to essentially convert it into electrical form. The objective of this paper is to design and develop a multi-physics numerical model which aids in predicting the electrical power output based on the fluid oscillations observed in an OHP. Proposed model achieves similarity in the overall qualitative trend that is experimentally observed. Future work will look closely into achieving quantitative agreement with experimental results.

2. MATHEMATICAL MODEL

In our work, the piezoelectric patch is displaced under the pressure exerted by the fluid flow oscillating with a certain frequency range. Such a close interaction in between solid and fluid can be assumed to have a form of a fully coupled model. It is safe to consider that in a fully coupled fluid-solid interaction problem, velocity of the fluid is transferred to the solid at the surface of interaction. Navier-Stokes equation provides a solution for velocity field $u_{fluid.}$ The total force exerted on the solid boundary by the fluid is the negative of the reaction force on the fluid as given in Eq. 1,

$$f = n.\{-p + (\mu\left(\nabla u_{fluid} + \left(\nabla u_{fluid}\right)^{T}\right) - \frac{2}{3}\mu\left(\nabla . u_{fluid}\right))\} \quad (1)$$

In Eq.1 p denotes the pressure, μ is the dynamic viscosity for the fluid, and n is an outward normal to the boundary [7].

The coupling between solid mechanics and electric field can be expressed in the form of relation between material stress and its permittivity at constant strain. The stress charge form is written as given in Eq. (2) and (3)

$$T = c_E . S + e^T . E \quad (2)$$

$$D = e . S + \in^S . E \quad (3)$$

Material parameter $c_E, e^T, \in^S$ correspond to the material stiffness, coupling properties, and dielectric permittivity at constant strain. Piezoelectric constitutive equations summarized in Eq. (2) and (3) explain the mechanical stress to electrical energy conversion characteristic of a given piezoelectric material.

3. EXPERIMENTAL SETUP

A 4-turn OHP was filled with water as a working fluid to an 80% filling ratio. A section of brass tubing was used as a structure for the harvesting module. This harvesting module was placed in an adiabatic section of the OHP tube. A piezoelectric patch made up of macro fiber composite material was placed inside this harvesting module occupying almost entire width of the rectangular pipe. Piezoelectric patch was bent to form a bow like structure inside the harvester module to accommodate maximum patch length. Schematic representation of OHP under investigation is shown in Fig.1,

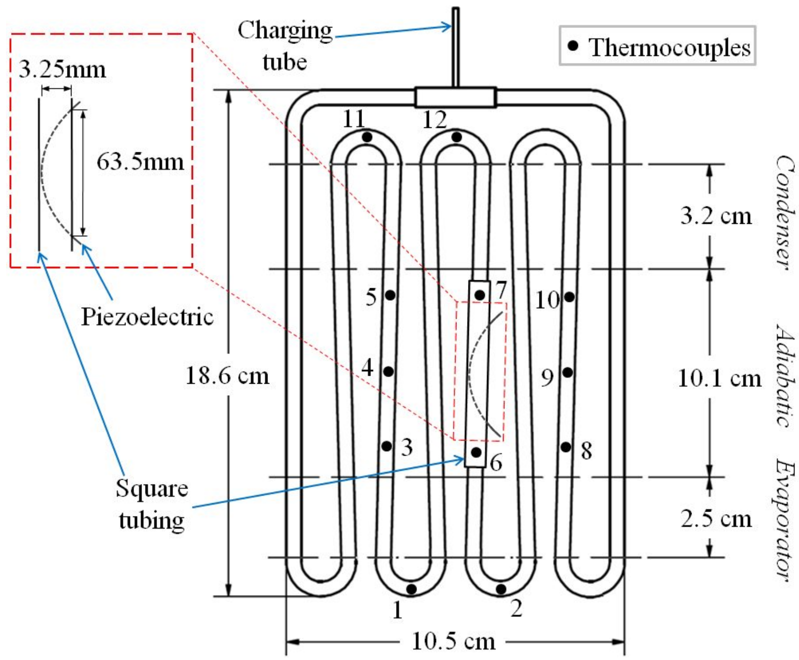

Fig 1: Schematic representation of OHP with piezoelectric patch

250W heat input was provided to the OHP. Experimentally measured fluid oscillations in an OHP were found to be in the range of 1-5 Hz. Fourier amplitude spectrum plot showed 3Hz to be the dominant frequency which was used in the numerical model. Pressure drop across piezoelectric was measured to be ~3.9kPa. This value was used to calculate pressure gradient across the harvester pipe. Average velocity of the fluid was recorded to be 628mm/s. An external DAQ system was used to collect temperature and open circuit voltage data. At the given power input, one minute of steady state temperature/voltage data was collected.

4. NUMERICAL MODEL

4.1 Assumptions

The proposed model is based on some assumptions to simplify the problem. It considers the flow to be laminar with 100% fill ratio of oscillating heat pipe due to consideration of mere fluid domain. However, in reality, the flow lies in the transition region and the oscillating heat pipe has a filling ratio of 80%. The model also ignores the pyroelectric effect of the piezoelectric due to unavailability of temperature data to include appropriate thermal effects.

4.2 Numerical model setup

A 2D multi-physics model consisting a laminar flow model, solid mechanics model and electrostatics model was built in FEA multiphysics software. The model aims at predicting the electric potential generated based on the input pressure condition. A major limitation of using a 2D model versus a 3D model, in this case, is the total separation of the fluid domain. Fluid domain present under the patch remains isolated from the upper fluid domain, as the patch completely touches the wall of the pipe. However, it was safe to assume that the lower domain doesn't contribute to the stress of on the piezoelectric patch, as the patch occupies the entire width of the pipe.

Fluid-structure interaction multiphysics node was selected to couple laminar flow physics with solid mechanics physics. A piezoelectric devices multiphysics node couples solid mechanics physics with electrostatics physics. A geometrical model of the cantilever attached inside the harvester was built, adhering to the actual dimensions of the piezoelectric patch. Length of the harvester pipe was limited to the entrance length of the laminar flow. Fig.2 shows the geometry of the assembly of harvester pipe and piezoelectric patch.

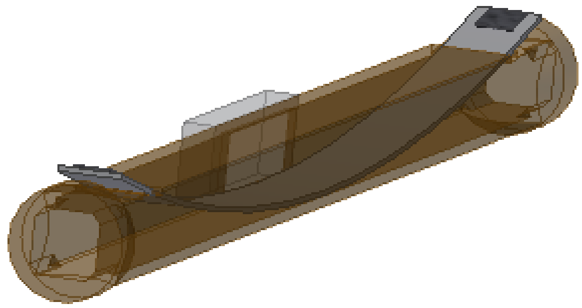

Fig. 2: 3D geometric representation of the assembly

In order to solve Eq. (2) and (3), it is required to compute coefficient of matrices for $c_E, e^T, \in^S$ along with values of density, young's modulus and Poisson's ratio specific to MFC. A new material was built in FEA model with MFC material properties. Laminar flow physics is solved using Navier stokes equation along with continuity equation. A pressure boundary condition at the inlet and outlet of the pipe was used in the laminar flow. Pressure at the inlet of the pipe consisted of the summation of mean pressure component and oscillating pressure component. Mean pressure component ensures the steady state flow through the rectangular duct. A sinusoidal oscillating pressure component was superimposed on the flow after the flow reaches steady state condition. A fixed constraint was assigned on both ends of the piezoelectric patch in the solid mechanics physics. Mechanical damping and dielectric loss factor were assigned to the piezoelectric material. Electrical boundary conditions were specified in electrostatics physics. Output variable of electrostatics physics is designed to give an open circuit voltage inherent to the stress generated in the piezoelectric material.

4.3 Mesh

Meshing of the geometry is one of the critical parameter in numerical analysis. In a multiphysics problem, it is important to create a sound mesh adhering to the involved physics. In a problem involving fluid flow, it is necessary to generate boundary layers in the mesh to get satisfactory results. However, due to limitations in availability of computational resources, a comparatively coarse mesh was formed. A comprehensive mesh structure will be used in the 3D model of the problem.

5. RESULTS AND DISCUSSION

An oscillating pressure boundary condition having a fluid oscillation frequency of 3Hz was provided as an input condition to the laminar flow physics model. Pressure difference was scaled down to the order of 100 Pa to reduce computational time. Pressure trend observed in the numerical model is shown in Fig.3

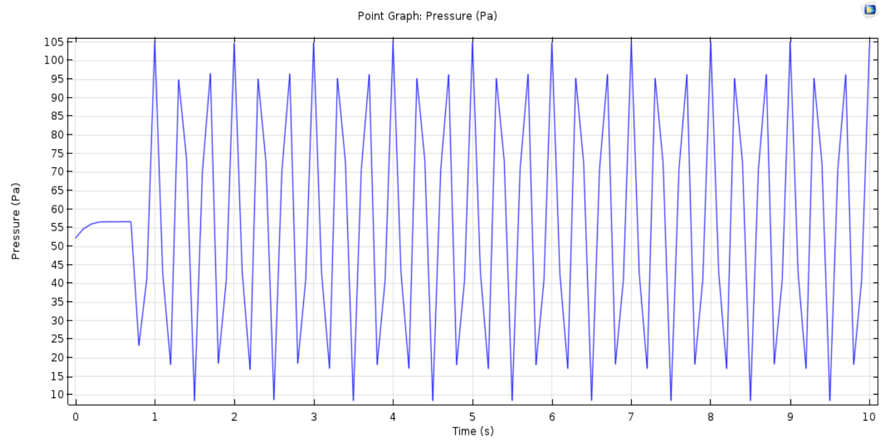

Fig. 3: Oscillating pressure at inlet

Oscillating pressure difference maintained at inlet and outlet of the pipe forces the fluid to flow in forward direction with fluid oscillation frequency. The oscillating flow exerts pressure on the piezoelectric patch surface inducing stress in the patch. Flow rate observed in the numerical model was found to be in agreement with the value calculated using an analytical expression. The velocity field was observed to have a dominating forward direction. Fig. 4 shows stress and velocity field as generated by application of pressure difference.

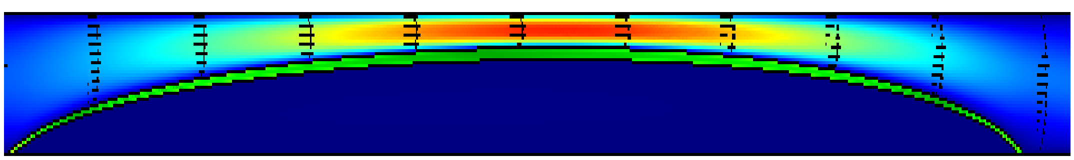

Fig. 4: Stress filed marked with fluid velocity direction

Due to the induced stress, electric potential is generated across the piezoelectric patch. Open circuit voltage can be measured by applying suitable electrical boundary conditions. Maximum electric potential was observed to be of the range of 10-15mV. Fig. 5 shows the overall trend observed by the AC voltage measured against the time. Voltage oscillations have ~3Hz oscillation frequency which is relatable to the input frequency of fluid oscillation.

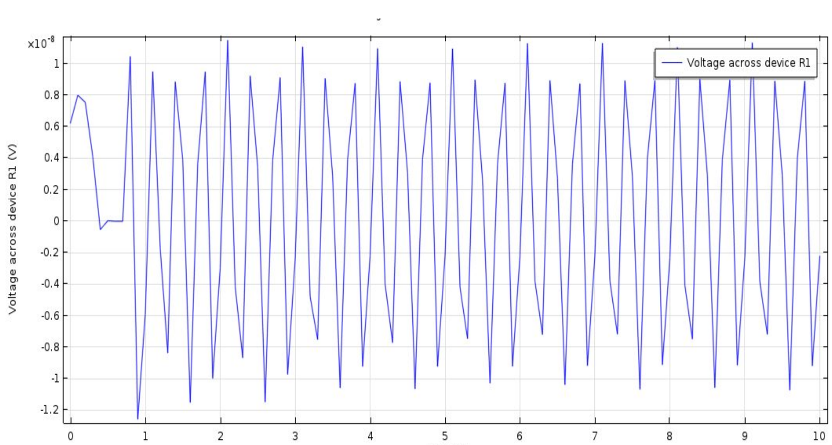

Fig. 5: Electric potential across the piezoelectric patch

6. CONCLUSIONS AND FUTURE WORK

Use of oscillating heat pipe to harvest thermal energy using a piezoelectric transducer is a proof of concept work. The proposed model was built to achieve a multi-physics coupling of the involved physics to achieve similarity in qualitative trend as observed experimentally. A 2D fully coupled scaled down model consisting fluid domain, structural mechanics and electrostatics was successfully built to predict generated electric potential. According to the numerical model's results, an electric potential of 1e-8 V was recorded on the application of pressure difference of 100 Pa in the adiabatic region. Due to computational requirements, a scaled down version of the actual experimental model was built in 2D, due to which it was not possible to compare experimental voltage results with the numerical model. Future work will look into building a more comprehensive and up to the scale 3D model which will aid in predicting electrical output with lesser error. Future work will also look into analyzing the relationship between heat input and pressure difference created inside the OHP. This will enable the use of heat input as an input condition to the model.

REFERENCES

[1] Zhang, Yuwen, and Amir Faghri. "Advances and unsolved issues in pulsating heat pipes." Heat Transfer Engineering 29.1 (2008): 20-44.

[2] Ma, H. B., et al. "Heat transport capability in an oscillating heat pipe." Journal of Heat Transfer 130.8 (2008): 081501.

[3] Fasula, C. H. R. I. S. T. O. P. H. E. R. "Oscillating Heat Pipes (OHP)." Masters of Science in Mechanical Engineering and Applied Mechanics, University of Rhode Island (2009).

[4] Xia, Yifan, Sébastien Michelin, and Olivier Doaré. "Fluid-solid-electric lock-in of energy-harvesting piezoelectric flags." Physical Review Applied 3.1 (2015): 014009.

[5] Doaré, Olivier, and Sébastien Michelin. "Piezoelectric coupling in energy-harvesting fluttering flexible plates: linear stability analysis and conversion efficiency." Journal of Fluids and Structures 27.8 (2011): 1357-1375.

[6] Cunefare, Kenneth A., et al. "Energy harvesting from hydraulic pressure fluctuations." Smart Materials and Structures 22.2 (2013): 025036.

[7] Multiphysics, Comsol. "Structural Mechanics Module User's Guide, November 2008 Comsol 3.5 a." (2008): 386-390.