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AN EXPERIMENTAL AND NUMERICAL STUDY FOR ENERGY HARVESTING WITH PIEZOELECTRICITY IN RIVERS

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Abstract

This work is concerned with finding the optimal nozzle length for a piezoelectric harvester. Studies are carried out experimentally and numerically. First, the optimum Reynolds number is found. It was then numerically studied to find the optimum nozzle length. As a result, the most efficient design is produced and studied experimentally. The results found are compared. The "target function" is to find the best turbulent kinetic energy at the appropriate nozzle length.

Keywords: piezoelectric material, renewable energy, vortex generator, energy harvesting

1 Introduction

In recent years, existing and alternative energy sources have been used to meet the increasing energy needs. Many problems, especially air, water and environmental pollution, arise with the need for energy. With renewable and clean energy sources, solutions are sought without harming the nature. A large part of the increasing demand for energy needs is met by fossil fuels, which leads to greenhouse gases [1]. Fossil fuels such as natural gas, oil and coal are non-renewable natural energy sources. Non-renewable energy sources are used by burning to obtain heat energy. As a result, oxygen decreases and carbon dioxide ratio increases.

In order to meet the energy demand, we should prefer renewable energy sources instead of non-renewable energy sources. Natural processes are used to produce energy with renewable energy sources. The production time of renewable energy sources is faster than the exhaustion time. The use of renewable energy sources is more advantageous than the use of non-renewable energy sources. It is estimated that petroleum reserves, which are a non-renewable resource, will be depleted in about 2050 and coal reserves in 2250. It has become imperative to find new energy sources instead of these energy sources, which are calculated to be depleted in the near future [2]. We can list renewable energy sources as wind, solar, hydraulic, geothermal, biomass, hydrogen, tidal and wave energy.

The areas where renewable energy sources are used are increasing day by day. With the developing technology, the tendency to more ergonomic and micro-sized devices is increasing. Small size energy harvesters have many positive features such as portability and structural simplicity. These energy harvesting devices can make the wasted ambient energy useful [3]. Piezoelectric materials can be used for energy conversion in devices that can harvest energy in micro sizes.

Piezoelectric materials have the ability to convert kinetic energy, which occurs under the influence of pressure and vibration, into electrical energy. Piezoelectric components are ideal for all types of electromechanical transducers [4].

In this study, many literature reviews on electrical energy conversion with piezoelectric materials have been made.

Xie et al. (2015), aimed to convert the vibration caused by external factors such as wind into electrical energy in multi-storey buildings in a study they conducted. By using dampers on the roofs of high-rise buildings, they tried to both reduce the vibration felt in the buildings and produce electrical energy. They aimed to generate electrical energy by using piezoelectric materials from the vibration.

Xu et al. (2017) conducted a study to convert the vibration generated by vehicles traveling on the road into electrical energy. They placed piezoelectric material inside the boxes they designed for energy harvesting and then buried these boxes on the road. With the energy harvest they obtained, they aimed to meet the energy consumed by the traffic lights on the roads [6].

Wong et al. (2017) conducted a study to generate electrical energy from raindrops using rainwater. They designed a beam in which raindrops will fall on the piezoelectric material and create pressure. They worked to convert the energy generated by the impact force on the beams they designed into electrical energy with a piezoelectric material [7].

Cho et al. (2018) designed a battery-free remote control to generate electrical energy from piezoelectric materials via pressure. The remote control they designed includes a system that can provide self-power with piezoelectric material without the need for batteries [8].

Yayla et al. (2020) carried out different vortex generator plates designs from other studies in this field in order to obtain electrical energy with piezoelectric materials in streams in a study they have done. With their experimental studies, they determined the boundary conditions where the best efficiency was obtained by working with different Reynolds numbers, and then they carried out this study numerically in the ANSYS Fluent program. In their studies, they aimed to obtain electrical energy in low-energy regions such as streams and stream beds [9].

Tan et al (2021), in their study, designed a wind tunnel in order to obtain electrical energy from wind energy. They aimed to create a vortex by placing solid objects in three different geometries inside the wind tunnel. They examined the effect of the eddies on the piezoelectric material according to the ambient temperature and wind speed [10].

In this study, a solution to the energy problem is investigated. Hydraulic energy, which is a renewable energy source, was used. It is aimed to create turbulence with the nozzle plate in areas where the wavelength is not high, such as streams and lakes. This turbulence is aimed to both rotate the finned plate and create vibration on the piezoelectric material. The piezoelectric material is intended to generate electricity by the turbulence and rotating plate effect occurring in the current flow. Piezoelectric material is used to generate electricity. It was tried to find the appropriate nozzle length. The dimensions of the rotating plates remained constant in the study. In experimental and numerical studies, the position of the plates was taken as fixed. This value was not changed in other studies after the appropriate Reynolds number was found. Experimental and CFD software methods are used in the studies.

2 Material and Method

Experimental and numerical methods are used in this study. Experimental studies are carried out in closed system flow channel and numerical studies are carried out using commercial code ANSYS Fluent 2021 R1.

2.1 Experimental Method

The experiments were carried out in a closed system flow channel shown in Figures 1 and 2.

Figure 1: Schematic representation of the experimental setup

Figure 2: The setup in which the experimental studies were carried out

The remote view of the canal where the experiments are made is given in figure 2 a), and the close view is given in figure 2 b). It is a closed system flow channel with a length of 5 meters and a height of 30 cm. The flow is driven by a single-phase hydraulic thrust pump. Mass flow is measured using a rotameter and the appropriate speed is set by the pump. Only the fluid is circulated in the channel. The fluid flows through a nozzle.

Figure 3: Position of the designed plates in the channel

The position of the designed plates in the channel is shown in Figure 3. The dimensions of the plates given in Figure 3 remained constant except for the nozzle plate. The nozzle length of the plate is 30 mm at first. Nozzle inlet diameter is 56 mm and outlet diameter is 20 mm. It has been studied to find the optimum value of the nozzle length. The rotating wheel has 14 blades. The angle between the two blades is 14.8 degrees. The distance between the blades and the nozzle exit is 10 mm. The distance between the rotating plate axis and the bottom wall is 100 mm. The distance between the rotating plate axis and the piezoelectric material is 60 mm. The distance between the piezoelectric material and the bottom wall is 110 mm.

The distances given in Figure 3 were found by trial-and-error method and were taken as constant. In this study, only the nozzle length of the plate was changed.

Figure 4: Devices used in the experimental study: a) Piezoelectric material used in experiments b) Oscilloscope used in experiments

The piezoelectric material shown in Figure 4 a) is used for energy harvesting. This material can generate electrical energy by vibration. This material is 28 μm thin, coated with PVDF polymer film. The operating temperature of this material is between 0°C - 85°C and it is a material with high impact resistance. The voltage value produced by the piezoelectric material used in the experimental studies is measured with the Oscilloscope shown in Figure 4 b).

2.2 Numerical Method

The designs of the nozzle plates are made in the SOLIDWORKS program. Numerical studies are carried out in the ANSYS Fluent program. First of all, independence of the solution on the mesh was checked. Influence of the mesh resolution on the resulting TKE was investigated. It was found that for mesh with 71702 cells and more, the value of TKE does not change (Table 1). Therefore mesh with 71702 cells was used for the investigation.

Table 1: Results of the TKE mesh independence study.

Mesh Structure	Number of element	TKE
Coarser	41207	0,003 J/kg
Coarse	58990	0,005 J/kg
Normal	64612	0,008 J/kg
Fine	71702	0,016 J/kg
Finer	74089	0,016 J/kg

Figure 5: Mesh applied in CFD software

Figure 5 shows the applied mesh. Problem was solved as two dimensional. Inlet boundary condition was set as velocity inlet with velocity of 1.172 m/s inclined by -28.06 degrees with respect to the x direction. Turbulence intensity at inlet was set at 5%. The gravitational acceleration of 9.81 m/s^2 was accounted for. Transient Time was chosen to solve the time-based analysis. Dynamic Mesh has been implemented. An interface is formed with the part separating the rotating plate inner flow and outer flow. Thus, the dynamic mesh method creates a deformable body separation. The flow portion where the turntable is located is defined as deformable. The boundary condition for the outflow section and the rotating plate is considered rigid. The $k-\epsilon$ turbulence model was chosen to model the turbulent flow. The $k-\epsilon$ model is a common method used in circulating turbulent flows, near-wall analysis, and low Reynolds number flows [11]. The $k-\epsilon$ model was chosen because the fluid is turbulent in the channel and the fluid circulates close to the wall.

Figure 6: The moment when the turbulent fluid and the rotating plate blade tip strike the Piezoelectric material

The moment when the turbulent fluid and the rotating plate blade tip hit the Piezoelectric material is shown in Figure 6. In order to evaluate the energy conversion, the Turbulent Kinetic Energy value on the piezoelectric material is examined. The main purpose of the study is to achieve energy conversion by creating turbulence in stationary flows. A nozzle plate is left in front of the stationary fluid and turbulence effect is tried to be created here. The turbulent fluid both strikes the finned plate and rotates the plate, and also causes vibration by striking the piezoelectric material. In this study, there are 2 major factors on the piezoelectric material. The first is the turbulence effect created by the fluid, and the second is the impact

effect created by the blades of the rotating plate. The purpose of both elements is to generate electrical energy by creating vibration in the piezoelectric material.

Position of the piezoelectric material in the experimental setup is shown in Figure 3 and its position in the computational domain is highlighted in Figure 5. Mesh is applied to the piezoelectric material in this specified coordinate space. The length of the piezoelectric material suitable for the determined location coordinates is given in Figure 7.

Figure 7: Line drawn in CFD software

The data found in the experimental studies and the fixed parameters obtained by the literature review were kept constant in numerical studies. The length of the nozzle was examined at 6 different values. The aim here was to find the optimum nozzle length resulting in the highest achievable value of TKE at the position of the piezoelectric material.

2.2.1 The Use of Mathematical Modeling and Equations

The change in the velocity of the fluid used in this study affects the Reynolds number. The Reynolds number and the turbulent kinetic energy occurring in the flow were investigated with the following equation.

$$Re = \frac{\rho V D}{\mu} \quad (1)$$

ρ = Density of water (kg/m³)

V = Flow rate (m/s)

D = Hydraulic diameter of the tank (m)

μ = Dynamic viscosity of the fluid

The general continuity equation is as follows.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{V}) = 0 \quad (2)$$

In the experiments carried out, the flow of water flowing through the channel is a continuous and incompressible flow where the fluid density remains constant.

Continuity equation of incompressible flow:

$$\vec{\nabla} \cdot \vec{V} = 0 \quad (3)$$

The k- ϵ model was chosen because the fluid is turbulent in the channel and the fluid circulates in the region close to the wall. In this study, the turbulent kinetic energy value on the piezoelectric material is important.

k equation:

$$u \frac{\partial k}{\partial x} + \frac{\partial k}{\partial y} = \frac{1}{Re} \left(\frac{v_t}{\sigma_k} \right) \nabla^2 k + P - \epsilon \quad (4)$$

ϵ equation:

$$u \frac{\partial \epsilon}{\partial x} + \frac{\partial \epsilon}{\partial y} = \frac{1}{Re} \left(\frac{v_t}{\sigma_\epsilon} \right) \nabla^2 \epsilon - C_1 S_\epsilon - \rho C_2 \frac{\epsilon^2}{k} \quad (5)$$

In this study, the flow is assumed to be a Newtonian, continuous, single-phase, constant viscosity and incompressible flow.

The specified formulas are taken from the Fluid Mechanics and Applications book [12].

3 Findings and Discussion

First of all, the optimum Reynolds Number was determined. The flow rate of the fluid was changed and the total pressure of the fluid was measured with the Pitot tube. The velocity of the fluid was calculated with the measured pressure. Then, the velocity value found is used in equation 1 and the Reynolds number is calculated. Studies were done in the range of Reynolds number from 1.8×10^4 to 3.2×10^4 . The optimum Reynolds number was found to be 30805. Larger and smaller values than the specified Reynolds Number were tried. The value at which the best result was obtained was found to be 30825. Therefore, the optimum Reynolds Number of 30825 was used for specification of boundary conditions.

Three different values of the length of the nozzle were investigated. Distributions of TKE and velocity along the piezoelectric material were evaluated.

Figure 8: Distribution of TKE along the piezoelectric material for the three investigated nozzles.

In the system, 6 different nozzle lengths were used. A graph of 3 different nozzle lengths is given for easy comparison. In the graph given in Figure 8, TKE values in the position of the piezoelectric material at 3 different nozzle lengths were examined. First of all, the maximum TKE value at 35mm nozzle length was found to be 0.0086 J/kg. Maximum TKE value at 45mm nozzle length was found to be 0.012 J/kg. Thus, an increase in TKE value was observed. Later, the nozzle length was increased by 10 mm. The maximum TKE value at 55 mm nozzle length was found to be 0.0168 J/kg. It was noted that this value is the optimum TKE value.

Then, the velocity distributions on the piezoelectric material at 6 different nozzle lengths were found.

Figure 9: Distribution of fluid velocity along the piezoelectric material for the three investigated nozzles.

Distribution of fluid velocity along the piezoelectric material is shown in the graph in Figure 9. The optimum result was found to be 1.1m/s in case of the 55mm nozzle length. The TKE graph in Figure 8 and the Velocity graph in Figure 9 are compatible with each other. An increase in values was observed in both graphs and the best result was found at 55mm nozzle length.

Velocity distribution around the rotating plates and the piezoelectric material is provided in the graph in Figure 10. In the solution section, a line is drawn to represent the piezoelectric material whose coordinate area is determined in the Mesh section of the CFD software. The line has no effect on the contour drawing. The line drawing is drawn only to measure the Turbulent Kinetic Energy value in that region. Graphic and contour drawing area of Turbulent Kinetic Energy is obtained in coordinates on the line. It is very important to look at the TKE value here. Because in this study, the TKE value on the piezoelectric material is an important parameter for energy conversion. The increase between the blue color and the green color on the piezoelectric material in Figure 10 coincides with the increase in the graph in Figure 9. Contour area drawn in CFD software is important for determining the position of the piezoelectric material in future studies. As shown in Figure 10, the velocity value of the fluid increases as the color distribution approaches red. Since the speed and TKE value increase in connection with each other, it is possible to comment on the TKE value when examining the Speed Contour area in Figure 10.

Figure 10: Velocity distribution around the rotating plates and the piezoelectric material at the nozzle length 55mm.

Figure 11: Voltage measurement values

Then, the 55mm long nozzle plate was produced with a 3D printer. Experimental studies were carried out with two different plates with 35mm nozzle length and 55mm nozzle length.

Figure 11 shows the voltage data of 2 different nozzle lengths measured by Oscilloscope. The best Oscilloscope measurement made with a plate with a 35mm nozzle length was obtained as 0.016 Volts. Then, the best Oscilloscope measurement made with a 55mm nozzle length plate was recorded as 0.024 Volts.

When the data obtained are examined, it is seen that the numerical and experimental studies show similar trends concerning the nozzle length, performance of the piezoelectric material and magnitude of TKE.

	35mm nozzle length	40mm nozzle length	45mm nozzle length	50mm nozzle length	55mm nozzle length	60mm nozzle length
Turbulence	0,0086	0,01	0,012	0,0145	0,0168	0,0158
Kinetic Energy	J/kg	J/kg	J/kg	J/kg	J/kg	J/kg
Velocity	0,43 ms ⁻¹	0,55 ms ⁻¹	0,75 ms ⁻¹	0,9 ms ⁻¹	1,11 ms ⁻¹	1,09 ms ⁻¹
Voltage	0,016 Volt	-	-	-	0,024 Volt	-

Table 2: Table of data obtained

All obtained data are combined in Table 2. As seen in Table 2, the nozzle length with the best efficiency was found to be 55 mm. Voltage values could not be measured since other plates were not produced except for the plates with 55mm and 35mm nozzle lengths. All TKE and Velocity values obtained were obtained in CFD software. Since the TKE and Velocity values decreased after the 55mm nozzle length plate, the 55mm nozzle length plate was taken as the optimum.

4 Conclusion

The results obtained in this study are listed below;

- The design of the first plates was carried out with the solid modeling program. The dimensions were determined according to the dimensions of the closed system flow channel where the experiments were carried out and the literature review.
- In order to determine the Reynolds number of the fluid, the first plates were experimentally studied in the range of Reynolds numbers between 1.8×10^4 and 3.2×10^4 . The optimum Reynolds number was determined to be 30825.
- Boundary conditions were determined by experimental studies. With the Pitot tube, the inlet dynamic pressure of the fluid was determined as 686 Pa and the inlet velocity of the fluid was determined as 1.172 ms⁻¹.
- Numerical studies were carried out in CFD software with the determined boundary conditions. Sufficiently fine mesh consisting of 71702 cells was created. At this number of cells, the solution was found to be mesh independent. Dynamic mesh is applied in the system. The k- ϵ model was chosen because the fluid is turbulent in the channel and the fluid circulates in the region close to the wall.
- 6 different nozzle lengths were investigated using CFD. It was noted that the best turbulent kinetic energy was obtained in the 55mm nozzle length plate.
- The nozzle plate with the nozzle of 55 mm was produced by 3D printing method. Experimental studies were carried out with the new plate produced. In experimental studies, the voltage value produced by the piezoelectric material was measured with an oscilloscope.
- The graphs obtained from the CFD software and the graphs of the voltage values measured with the Oscilloscope were compared. Experimental and numerical studies show similar trends.
- As a result, the best energy harvesting efficiency was found when the Reynolds number of the fluid was 30825 and the plate nozzle length was 55mm. At this configuration, peak turbulent kinetic energy on the piezoelectric material was found to be 0.0168 J/kg and measured output voltage was 0.024 V.

The data obtained will be a reference for future studies.

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