Numerical simulation of the transfer of high-frequency temperature fluctuations from hot air flow to the array of thin pyroelectric plates

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Abstract. Pyroelectric energy harvesting is an important option for powering autonomous electronic devices. For the technology to be efficient high-frequency thermal oscillations are needed. Here we suggest a method of creation of thermal oscillations in a pyroelectric plate, based on Karman instability. Vortices, shedding alternatively from the two sides of a heated body, accumulate heat in their cores and transfer it to a pyroelectric plate. The effect is demonstrated by means of numerical simulations. A number of geometries were considered, to optimize the parameters of operation and achieve maximal thermal oscillations in the plate. A prototypical device for waste heat harvesting is presented. It is able of achieving harvested power of 1 W/g for a thin (200 nm) plate of ferroelectric (BaTiO3).

1. Introduction
Thermal energy harvesting is attractive for many engineering and industrial processes where heat is wasted. Pyroelectric energy conversion is a direct way to convert heat to electricity. Unlike Seebeck effect, where temperature gradient is needed, pyroelectric harvesting is based on time-dependent temperature in a pyroelectric material. The harvester operates in a mode of thermodynamic cycles similar to that in a heat engine, and its efficiency is estimated to be up to 50% of the Carnot cycle [1]. The most attractive regimes of operation are high-frequency thermal cycles. The time necessary for heat exchange is an important factor limiting the highest operational frequency. Nanometres-thin pyroelectric films allow operation at hundreds-Hertz frequencies [2].

A widespread technological solution for a pyroelectric converter is a stack of pyroelectric plates which is subjected to a fluid flow with alternating temperature. The heat transfer between a turbulent fluid flow and the array of plates was studied in [3], where the effect of viscous suppression of vortices was present, particularly in narrow channels leading to decrease of thermal oscillations amplitude. However the issue of creation of the thermal oscillations in the fluid was out of the scope of the present paper.

A simple but yet unexplored idea to achieve thermal oscillations suitable for pyroelectric harvesting is to utilize a von Karman street-like behaviour of vortices shedding from a hot bluff body. The vortices may accumulate heat in their cores and transfer it in space, creating the necessary thermal oscillations on a solid surface, impinged by the flow. In the present paper we explore the possibility to employ the effect of Karman instability for the purposes of pyroelectric energy harvesting. A series of
Numerical simulations were conducted for a system consisting of a ferroelectric plate located at different distances from a bluff body in a two-dimensional configuration. As a result an optimal set of parameters (plate length, channel width, bluff-body dimensions) were found.

2. Computational details

The computational area consists of a channel with dimensions 10 x 1 cm. The wall of the heater was set isothermal with a temperature of 370 K. Two types of heated bluff body were used, of the rectangular and trapezoidal shapes with similar length of 1 cm and the width of the larger base of 0.4 cm. The size of the pyroelectric plate was chosen in accordance with the studies carried out earlier [2]. Physical properties of the pyroelectric material were taken from [6]. The fluid was air, with same parameters as in Ref. [2]. The computational grid consisted of 512x65 cells (figure 1). The flow velocity was set to 2.5 m/s (average velocity in the cross-section of the channel). This flow velocity ensured the frequency of vortex shedding to be 250 Hz which was previously shown to be optimal for pyroelectric plates 200 nm thick.

The temperature of the inflowing air and the initial temperatures of the plates were set to 270 K for both considered cases. This way, the temperature difference between the heater and the air was exactly 100 K.

The simulations were carried out with modified conjugate heat transfer solver from OpenFoam package, using the finite volume discretisation second order accurate in space and time in a two-dimensional formulation [3, 4]. The solver was operating in a laminar mode, without any explicit turbulence model. The applicability of the 2D model has been previously demonstrated in Ref. [3]. The proof of applicability is associated with the low Reynolds number of the flow (Re~1000, based on the height of computational domain). Mesh convergence was checked for all simulations.

Fluid evolution was simulated according to the incompressible Navier-Stokes equations (1-2). Heat transfer in the fluid and solid media was resolved according to (3-4).

\[
\text{div}\vec{U} = 0 \quad (1)
\]

\[
\frac{d\vec{U}}{dt} + \left(\vec{U}\nabla\right)\vec{U} = -\frac{1}{\rho_f}\nabla P + \nu\Delta\vec{U} \quad (2)
\]

\[
\frac{dT}{dt} + (\vec{U} \nabla)T = \frac{\nu}{Pr}\Delta T \quad (3)
\]

\[
\frac{dT}{dt} = k \frac{\Delta T}{\rho_s c_p} \quad (4)
\]

where \(\rho_s\) is the density of solid, \(c_p\) is the heat capacity of a solid, and \(K\) is the coefficient of thermal conductivity. The temperature dependence of the viscosity and thermal diffusivity of the fluid and the

**Figure 1.** Computational grid
buoyancy effects were neglected for current simulations, as they did not show significant impact on the results in a series of preliminary computations for the current setup.

3. Results and discussion

Using the numerical method described above, a series of numerical simulations were run to explore the possibility of creation of thermal oscillations in a pyroelectric body, placed in a flow after a heated bluff body.

A series of preliminary simulations were conducted with different configurations of the plates. The best results in terms of the amount of heat fluctuations absorbed in the plates were achieved for parallel plates configuration with the spacing between the plates equal to the width of the bluff body. The consequent vortices were interacting with upper or lower plates interchangeably thus the effective wavelength of the fluctuations was increased by the factor of 2, allowing using longer plates for the same bluff body (as the effective length of the plate should not exceed the wavelength of the heat fluctuations).

The parameters for final simulations were chosen in accordance of Refs. [2,3]. Specifically, here we consider 200 nm thick plates with 3.3 mm channels around them. The optimal frequency calculated for this configuration based on equations from Ref. [2] is 250 Hz. This operation frequency was provided with the parameters indicated in section “computational details”, as controlled with the Karman street natural Strouhal number $Sh = f L/V = 0.2$ (here $V$ is velocity, $L$ is the width of the bluff body, and $f$ is the frequency) [7]. Figure 2 presents the results for trapezoidal (a,c) and rectangular (b,d) shapes of the bluff body. In the instantaneous temperature distribution (a), (b) it is seen that heat is accumulated in the vortex cores. The analysis of the temperature fields, where in the cores of the vortexes $T \sim 300$K, reveals that the vortex “accumulates” about 30% of the initial temperature difference. This excess temperature is transmitted, almost without loss, to the pyroelectric plate. Temperature variance chart (c,d) illustrates trails of vortexes. In the configuration with rectangular heater the vortexes pass into two outer channels. Configuration with trapezoidal heater directs the vortex cores to the edges of the pyroelectric plates. This illustrates, that the spread of the vortical traces can be controlled by the geometry of the heater.

Figure 3 illustrates temperature oscillations in the pyroelectric plate. In the two cases the leading-edge of the plates is heated to nearly same extent. However in the case of trapezoidal heater, the thermal oscillation keeps at a higher level throughout the plate length, compared to the case of rectangular heater, where the temperature difference drops down rapidly (figure 3b). The highest temperature amplitude is about 4 K. It indicates that about 15% of the temperature difference, available in vortex cores, is transmitted into the plate. Mean temperature amplitude throughout the
length of the plate is about 1 K for the trapezoidal heater and 0.5 K for the rectangular heater. Our estimates, based on the results of Ref. [2] indicate that the achieved thermal oscillations in the pyroelectric material, under optimal voltage management, will be converted to electric power, of the order of 1 W/g.

4. Conclusion

In this work, we demonstrate a method to achieve thermal oscillations in a pyroelectric plate, when it is placed into a flow behind a heated body. The oscillations are automatically generated by the fluid flow, as controlled by the Karman instability. The frequency of the vortex generation is determined by the Strouhal number $\text{Sh} = 0.2$. Our numerical simulations demonstrate that the transversal spread of the vortexes with different polarities may be controlled by the shape of the heater. This can be profitably used to direct the vortices towards functional pyroelectric plates which convert thermal oscillations into electric power. In configuration with trapezoidal heater the temperature oscillation amplitude at the leading edge of a ferroelectric plate (200 nm thick barium titanate) reached 4 K, while average temperature oscillations along the plate were up to 1 K. The vortices were formed with the frequency of 250 Hz. According to the results of Ref. [2], the demonstrated thermal regime can be exploited to achieve electric power of the order of 1 W per g. of the pyroelectric material.

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