Generation of wake-induced thermal fluctuations past a heated bluff body

M Yu Hrebtov and A S Nebuchinov
Institute of Thermophysics of SB RAS, 630090, Ac. Lavrentiev ave. 1, Novosibirsk, Russia
E-mail: weexov@ya.ru

Abstract. We present the results of LES modelling and PIV experiment of heat exchange between a flow in a wake of a heated bluff body and an array of thin plates. The efficiency of thermal fluctuations generation was investigated with potential applications to waste heat storing by pyroelectric effect. The effect of periodic attachment of wake vortices to the plates was observed both numerically and experimentally. This effect intensifies local heat transfer from fluid to solid and can be used for the possible generation of coherent temperature fluctuations in the plates.

1. Introduction
Storing the electric energy from thermal fluctuations in solid bodies is one of the promising approaches to improve efficiency of industrial devices or create self-sustained microelectronics in remote locations. This storing can be done by using the pyroelectric effect. For a power generation to be effective the high frequencies of thermal oscillations are needed with nanoscale-thin ferroelectric films [1]. In such conditions very high specific power can be obtained [2].

The search for the simple and efficient way of creating thermal oscillations through the interaction between a solid body and the flow deserves thorough investigation. It was previously proposed that such oscillations can be generated by placing a heated bluff body into the flow [3]. In the wake behind the body a periodic vortex sequence (von-Karman vortex street) will be generated. Such vortices capture heat from the bluff body and transfer it in a coherent concentrated form. So the receiver plate placed in such a wake will experience thermal oscillations when the vortices collide with it.

The proposed setup is suitable for industrial application where the waste heat of the exhaust pipes might be utilized.

While our previous study [3] had shown promising results it did not consider the effects of turbulent diffusion which might affect negatively the transfer of thermal oscillations in the wake. The aim of current paper is to investigate the structure of wake behind the bluff body (a triangular prism) and its interaction with the flat plates array placed at some optimum distance by means of high-resolution Large Eddy Simulation (LES) complemented by a time-resolving Particle Image Velocimetry (PIV) experiment.
2. Experimental and computational details
The experimental aerodynamic channel consisted of a fan, honeycomb, confusor, working section and the outlet part. The working section of the aerodynamic channel had the cross-section dimensions of 125x125mm with the length of the working area of 1 m. The measured degree of flow turbulence in the inlet of working section was no more than 2%. The measurements were carried out using the method of time-resolving particle image velocimetry (PIV) with high temporal resolution. The used method made it possible to measure the spatial and temporal distribution of instantaneous velocity in a selected flow section. Tracer visualization was performed using the Photron FASTCAM SA5 camera. The frequency of recording images was 5 kHz. The statistics were averaged over the set of 2000 instantaneous velocity fields. The bluff body (prism) and the plates were made of Plexiglas.

The prism bluff-body had the dimensions of 90x30x125 mm in x, y, and z directions, respectively. The plate dimensions were 150x2x125 mm. The plates were placed apart from each other by the width of the bluff body (30 mm). The distance between the prism boundary and the plates was 150 mm. Such configuration was chosen based on previous 2D simulations, where a maximum efficiency in the generation of heat fluctuations in the plates had been shown.

The Reynolds number ($Re = \frac{hU_0}{\nu}$, where $h$ denotes the width of the bluff-body, 30 mm) was chosen to be 5000 in both experiment and simulation.

![Figure 1. The instantaneous distribution of transverse component of vorticity obtained in PIV experiment (top) and LES simulation (bottom).](image)

The simulations were conducted with an incompressible LES solver from OpenFoam (www.openfoam.org) package, with a finite-volume discretization of the second order accuracy in space and time.

We use the LES approach with DKSGS-model [4] with the following momentum-transport equations:

$$\frac{\partial \tilde{u}_i}{\partial t} + \frac{\partial \tilde{u}_i}{\partial x_j} (\tilde{u}_j u_i) = -\frac{\partial \tilde{p}}{\partial x_j} + \frac{1}{Re_s} \frac{\partial^2 \tilde{u}_i}{\partial x_j \partial x_j} - \frac{\partial}{\partial x_j} \left((\nu + \nu_{sgs}) \tilde{S}_j\right)$$

$$\nabla \cdot \vec{u} = 0$$

where the subgrid-viscosity $\nu_{sgs}$ is defined through the subgrid kinetic energy balance equation:
\[ V_{sgs} = c_s \sqrt{k_{sgs}} \frac{\alpha}{\sqrt{\alpha}} \]

\[ \frac{\partial k_{sgs}}{\partial t} + u_i \frac{\partial k_{sgs}}{\partial x_j} = -\tau_{ij} \frac{\partial u_j}{\partial x_i} - c_s \sqrt{k_{sgs}} \frac{\alpha}{\sqrt{\alpha}} + \frac{\partial}{\partial x_j} \left( \nu_{sgs} \frac{\partial k_{sgs}}{\partial x_j} \right) \]

The numerical grids consisted of \( 7 \times 10^6 \) nodes with the wall-adjacent gridcell width \((y^+)\) of about 10 in wall units.

3. Results and discussion

In order to check the validity of the simulation, the centerline profiles of mean longitudinal velocity and its second moments were compared with the experimental results (figure 2a, b). It can be seen that the profiles from the simulation converge quite well with the experimental results both for mean velocity and the second moments. The profiles show the appearance of the recirculation zone near the rear edge of the bluff body (figure 2a). The longitudinal velocity fluctuations have much smaller magnitude along the central axis as compared to the vertical velocity fluctuations (figure 2b). This is attributed to the checkerboard type vortices shedding from the edge of a bluff body.

These vortices are clearly seen in the distribution of transverse vorticity component (figure 1) both in the simulation and PIV results. The scale and structure of the vortices is similar in both the experiment and simulation. The vortex shedding frequency is close to \( Sh=\nu h/U_0=0.2 \) which is a theoretical prediction for the classical von Karman vortex street behind the cylinder [5].

In both the experiment and simulation a periodic reattachment of the wake vortices with interchangeable top and bottom plates is seen. This process was further investigated by means of the pressure field analysis.
In the pressure fields (figure 3) we may see that the effect of vortex reattachment event reduces the pressure in the channel between the plates where the reattachment occurs. So the process of reattachment reinforces oscillations of a vertical pressure gradient, which increases the coherent oscillations in the flow through the feedback effect.

The distribution of velocity fluctuations magnitude (figure 4) shows quite different pictures for the different velocity components. While the \( y \) and \( z \) components of the fluctuations have maximum values at the central axis of the flow, the longitudinal \( (x) \) component shows a dual-lobe structure with each lobe located at the height of each of the plates. This reflects the feedback effect from the plates on the main flow. The secondary maxima in fluctuations of \( x \) and \( y \) velocity components are clearly visible near the plates front edges. These are the traces of periodic vortex reattachment process described above.

This periodic reattachment may be quite useful for the pyroelectric generation if there would be a temperature difference between the flow and the plates. The coherent vortices rolling along the plates during this process increase locally the heat transfer between the plate and the fluid. So the local thermal oscillations will occur in the plate that may be used for a pyroelectric storing.

However, for the conversion of thermal energy the temperature difference between the flow and the plate is needed. To test this, a decoupled heat equation in the fluid was solved in LES simulation. The temperature of the inflowing fluid \( (T_0) \) was set to 300K while the temperature at the surface of the bluff body \( (T_v) \) was set to 400K. The efficiency of the thermal fluctuations transport in the shed vortices was investigated.
Figure 4 shows a mean temperature distribution together with the temperature fluctuation fields. It can be seen that the highest temperatures occur in the recirculation zone but further downstream the temperature becomes uniform quite rapidly.

The thermal fluctuation magnitude is quite significant (up to 20% of the \(T_s-T_t\)) in the flow region in front of the plates. However during interaction with the plates the mixing becomes more intensive thus increasing the diffusion of the temperature field. This is quite different from the 2D results [3] where high thermal fluctuations propagated into the space between the plates. The difference arises due to the effect of longitudinal vortices that are absent in the 2D simulation and due to 3D instability in the boundary of the mixing layers.

![Figure 4](image)

**Figure 5.** The distribution of mean temperature (left) and thermal fluctuations magnitude (right) in a longitudinal cross-section of the flow.

**Conclusion**

In the present work the setup for creating thermal fluctuations in the flow was tested both numerically experimentally. The results of numerical simulations agree well with the experimental ones. The formation of strong coherent flow oscillations near the receiving plates was observed. These oscillations occur because of the periodic alternating reattachment of the wake vortices to the different plates. While the simulated thermal fluctuations emerged from the heated bluff body appeared too small when they get to the plates because of turbulent mixing effect, there might be however different schemes that utilize the current setup to create the thermal oscillations in the plates. One of such setups might be the heating of plates without heating the bluff body. In that case the coherent vortices as they move along the heated plate will increase locally the heat transfer coefficient and induce thermal oscillations in the solid material through a local fast cooling.

**Acknowledgements**

The research was carried out within the state assignment of FASO of Russia for Kutateladze Thermophysics Institute SB RAS

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