18th Australasian Fluid Mechanics Conference
Launceston, Australia
3-7 December 2012

PIV Analysis of the Wake behind a Single Tube and a one-Row Tube Bundle: Foamed and Finned Tubes

I. Ashtiani Abdi[1,2], M. Khashehchi[1,2] and K. Hooman[1,2]

[1]Queensland Geothermal Energy Centre of Excellence
[2]School of Mechanical and Mining Engineering, The University of Queensland, QLD 4072, Australia

Abstract

The aim of this study is to investigate and compare the wake behind fin and foam covered circular cylinders by mean of Particle Image Velocimetry (PIV). Two different arrangements were examined namely single cylinder and a single-row bundle of three identical cylinders in cross flow. The experiments are conducted for a range of Reynolds numbers from 1500 to 8000 based on the inner cylinders diameter and the air velocity upstream of the bundle.

The two dimensional planar PIV results as well as POD analysis show the important effects of the inlet velocity, the foam and fin covers, as well as cylinder arrangement, being an isolated single cylinder or bundled, on the wake. The results show a considerable increase of the wake size by using the foam instead of fin in single tube. The results of this study can be used as an accurate boundary condition to model the flow field past such cylinders.

Introduction

The flow field over cylinder has been studied over past decades for wide industrial applications. Control of this flow helps to increases the heat transfer efficiency, and so decreases the waste of energy.

It is possible to categorize flow control techniques to active and passive. The active control technique is done by exerting external energy like inserting the time-dependent perturbations into the flow field. The control of the flow field is feasible in passive control technique by changing the shape of the body subjected to the flow. It is easier to control the flow by help of the passive control techniques since no complex mechanical devices are needed to exert energy to the flow [1].

Covering the Cylinders by metal foams or fins is a typical method of passive control of the flow field [2] which has many applications in heat transfer [3, 4]. In this method, the interaction of the cross flow and the foam or fin covered cylinder makes a complex flow field [5]. Many studies have been done recently on this area with the main focus on the flow past a porous cylinder like, Vanishtein et al. [6], Vanni [7], Nandakumar and Masliyah [8] and Masliyah and Polikar [9]. In addition, Iwaki et al [10], Hoyt et al [11] conducted a broad investigations on bundles. Furthermore, the application of proper orthogonal decomposition (POD) method in conjunction with field-measurement techniques like PIV in area of coherent structures has been increased significantly recently [12]. Shi et al [13] and Perrin et al [12] have done broad investigations on POD's applications on flow field characteristics around cylinder. Although still there are many unresolved problems needed to be studied in order to improve our knowledge of the effect of passive controlling on the flow characteristics. Moreover, the role of the foam on the structures behind the cylinder has not been studied in detail before.

In this paper, the flow over different sets of circular cylinders covered by foam or fin is studied in the near wake region, i.e. when $1.2<x/D<2.6$ (where D is the inner cylinder diameter and x is the distance downstream of the cylinder) using two dimensional planar PIV. Single foam and fin covered circular cylinders have been tested, one at a time, in order to investigate their wake structures. All these cylinders have the same inner diameter and the Reynolds number is calculated based on this diameter and the maximum (jet) velocity between cylinders.

The presented results here are part of a more detailed test program that involves more experimental studies in which the flow motion inside the foam pores is under investigation.

Experimental Setup

All the experiments have been conducted in a suction open circuit low-speed wind tunnel. The test section area is 460 x 460 mm^2 and the length of the test section is 1200 mm (figure 1).

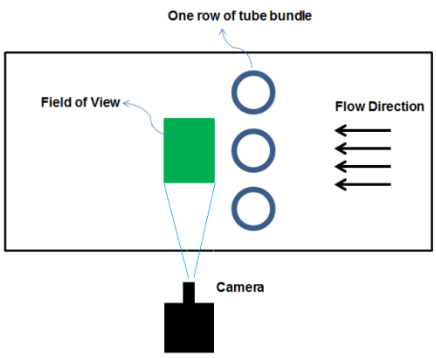

Figure 1. Experimental set up. The Nd:YAG laser is located above the Field of view on top of the wind tunnel, the camera faces the laser light sheet.

All the measurements have been done 38.4 mm downstream from the cylinders to avoid the cylinders shadows in the PIV images.

The imaged region measured 40 mm in the streamwise direction and 54 mm in the cross stream direction.

Fin covered single cylinders, fin covered one row tube bundles, foam covered single tube cylinder and foam covered one row tube bundles have been tested. In tube bundle cases, the distance from the centres of two cylinders is 70 mm.

All the experiments have been conducted over a range of Reynolds numbers from 1500 to 8000 based on the inner cylinder D in all tubes (32 mm) and the air velocity upstream of the cylinder(s). Cylinders, foamed and finned, were 600 mm long and made out of aluminium. Fins are tapered with 0.4 mm thickness, 4.5 mm spacing and 16 mm height. The 6 mm thickness of aluminium foam which was attached to the inner cylinder consists of ligaments forming a network of inter-connected cells. The cells are randomly oriented and are mostly homogeneous in size and shape. Pore size varies from approximately 0.4 mm to 3 mm, and the effective density from 3% to 15% of a solid of the same material.

The PIV images were captured in a box, of size 1.4D in the streamwise direction and 1.6D in the cross stream direction, (40x54 mm^2) located 1.2D downstream the cylinder where the wake behind the obstacles can be captured without having their shadow effects in the images. The flow has been seeded by means of a pressure droplet generator with oil liquid. The particle illumination was conducted by a Nd:YAG PIV laser (Dantec-130 mJ). The images of the illuminated particles were captured by a CCD camera with a resolution of 1.3 Megapixel which was fitted with a 50 mm Nikon lens with f-stop set at 4.0, resulting in a magnification of 0.2. Synchronisation of the laser and camera was done by Dantec software included in the PIV package. For each experiment 1000 pairs of images were recorded. Background noises were estimated as the minimum of greyscale values in a time series and subtracted from each of the images in the ensemble. Each single image pairs were analysed using the multi-grid cross-correlation algorithm included in the PIV package software by Dantec, which has its origin in an iterative and adaptive cross-correlation algorithm. The analysis of each image pairs was conducted for a three-pass analysis. The first pass used an interrogation window of 128 pixels, while the second pass used an interrogation window of 64 pixels and the last pass used an interrogation window of 32 pixels with discrete interrogation window offset to minimize the measurement uncertainty. The sample spacing between the centres of the interrogation windows was 16 pixels.

The uncertainty relative to the maximum velocity in the velocity components at 95% for these measurements is 1.55%. In addition, the uncertainty in the sub-pixel displacement estimator of 0.1 pixels and the uncertainty in the laser sheet misalignment of 1% can be taken into account. Other uncertainties like timing, particle lag, seeding uniformity, and calibration grid accuracy have been neglected.

Results

The following figures demonstrate the time averaged mean flow velocities based on 1000 PIV image pairs for single tube and one row tube bundles covered by fin or foam. These figures have been superimposed by mean flow stream lines.

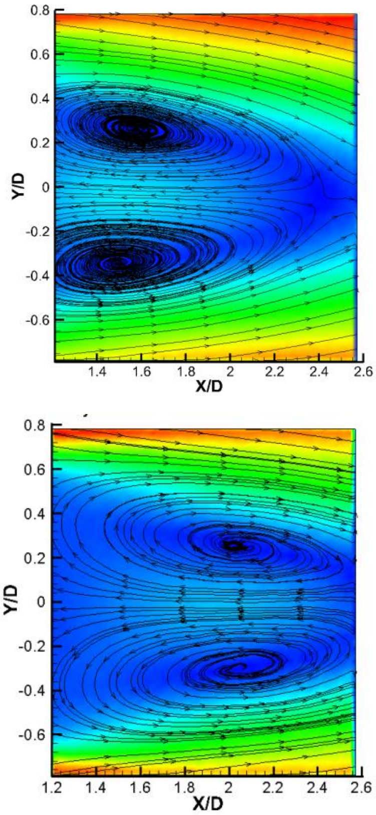

Figure 2. Mean velocity field for the flow over a single fin covered cylinder at Reynolds numbers of 2000 (Top) and 8000 (Bottom), colour bars are normalized with the maximum velocity at each graph (Blue indicates the minimum and orange the maximum velocity values)

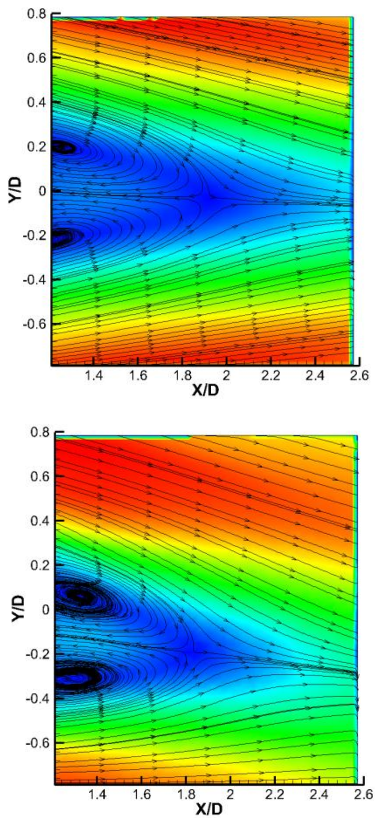

Figure 3. Mean velocity field for the flow over one row of fin covered cylinders at Reynolds numbers of 1500 (Top) and 6000 (Bottom), colour bars are normalized with the maximum velocity at each graph (Blue indicates the minimum and orange the maximum velocity values)

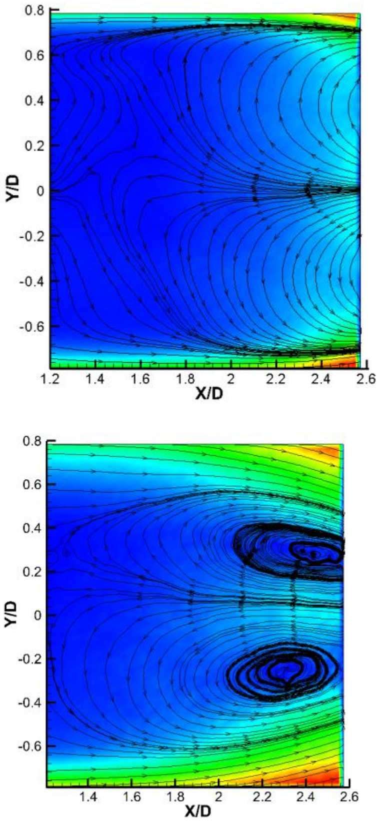

Figure 4. Mean velocity field for the flow over a single foam covered cylinder at Reynolds numbers of 2000 (Top) and 8000 (Bottom), colour bars are normalized with the maximum velocity at each graph (Blue indicates the minimum and orange the maximum velocity values)

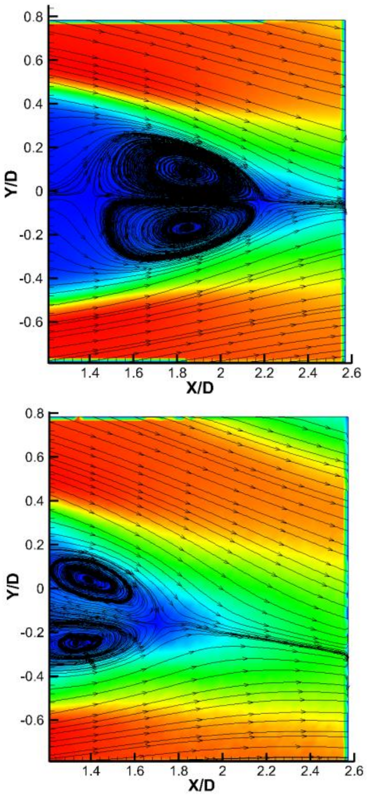

Figure 5. Mean velocity field for the flow over one row of fin covered cylinders at Reynolds numbers of 1500 (Top) and 6000 (Bottom), colour bars are normalized with the maximum velocity at each graph (Blue indicates the minimum and orange the maximum velocity values)

Comparing the mean streamwise velocity field of fin and foam covered cylinders in different arrangements and Reynolds numbers shows a dramatic difference in velocity field of these cases within the wake region.

As it can be seen in both foam and fin covered cylinders, by increasing the Reynolds number, an asymmetric wake forms behind the cylinders. Khashehchi et al [14] reported same observation which can be due to the limited number of images. Also, the size of the wake behind the single fin covered tube is significantly larger compare to Khashehchi et al [14] results for the same Reynolds number. This is because in current experiments the laser sheet illuminated the particles in front of the fin itself but in the other experiments by Khashehchi et al the laser sheet illuminated the particles in front of the cylinder between two fins lobes.

By comparing the figures, one note that using the foam increases the wake size behind the cylinder but this is less pronounced for the bundled cylinders. It can be attributed to increased blockage induced by the foams compared to finned tube bundle. It is expected that, compared to a fins, the foam layer on the cylinder surface show more resistance to fluid flow and pushing the air through the gap between the cylinders. As a result, the foamed bundle acts as a bundle of thicker tubes leading to larger wakes behind the foamed bundle. As expected, a single cylinder in cross flow does not show the same behaviour when considerably wider bypass area is available as opposed to the densely set bundle.

Table 1 shows the comparison of maximum velocity magnitude in the field of view. Comparing the single tube and one row tube bundle demonstrates that with the former, the velocity near the cylinder is lower for the foam, but for the latter case higher velocities are expected as a result of smaller flow areas due to foam blockage

In addition, two more observations can be made from this table. First, the jet effects decrease the wake size of one row foam covered tube bundles compared to single row finned bundles. Furthermore, the wake size considerably shrinks down compared to a single fin (or foam) covered cylinder in cross flow.

		Re #	**Max. Field Velocity**
Fin Covered	Single Tube	2000	0.86 m/s
		8000	3.96 m/s
	One Row Tube	1500	1.76 m/s
		6000	6.95 m/s
Foam Covered	Single Tube	2000	0.40 m/s
		8000	3.39 m/s
	One Row Tube	1500	1.90 m/s
		6000	7.43 m/s

Table 1. Comparison of maximum velocity magnitude in the field of view

Figures 6 and 7 demonstrate the comparison of POD modes of the fin and foam covered cylinders. POD is a method which extracts and sorts out the structures of the flow based on their energy. Sirovich [15] proved mathematically that these extractions of structures by means of their energy are optimal in terms of kinetic energy of the flow compared to other decompositions. The decomposition of the flow structures by means of POD can be done by snapshots method developed by Sirovich [15]. To obtain these results, Dantec software included in the PIV package has been used.

An interesting feature of these graphs is in the one row foam covered tube where the first mode has higher contribution in formation of the structures compared to single foam covered tube. Things are, however, another way around in the finned case.

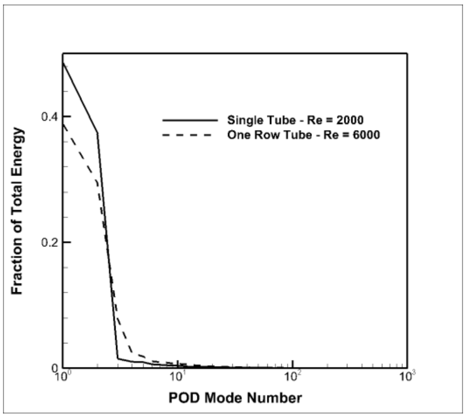

Figure 6. Comparison of POD modes of single and one row fin covered cylinders at Reynolds number of 2000 and 6000

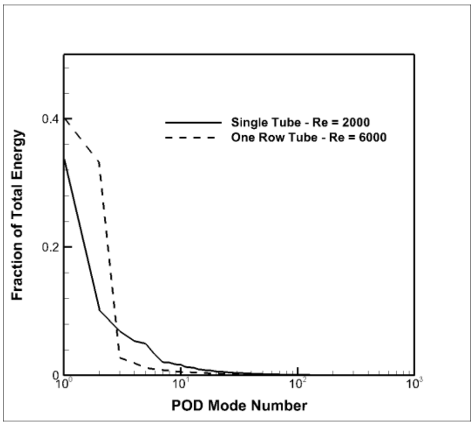

Figure 7. Comparison of POD modes of single and one row foam covered cylinders at Reynolds number of 2000 and 6000

This observation, once again, shows that the foam covered cylinder is following the bare cylinder pattern. This is an interesting argument which asks for a more rigorous analysis of the problem. One way to achieve this is to obtain more details about the flow structure within the bundle. That is the flow between two adjacent fins as well as that through the gap between the nearby tubes has to be investigated. With foam-wrapped tube bundles, however, it is more difficult to obtain such information as the flow through foams has to be investigated. To complete the picture, flow behaviour between two adjacent foamed tubes has to be better understood. These are left for a future report.

Conclusions

Investigations on the wakes behind foam and fin covered cylinders in single tube and one row tube bundle have been done by means of POD analysis and a two dimensional Planar Dantec Dynamic PIV system in the low speed wind tunnel at the School of Mechanical and Mining Engineering at the University of Queensland. Measurements have been conducted for different Reynolds number from 1500 to 8000.

The results show that in the single cylinder, adding foam will increase the wake size. This can be due to the effect of foam's body structure which represents an obstacle to the incident flow in single cylinder but the jet effect in one row tube neutralizes this effect.

In addition, this study shows that PIV can be a reliable facility in case of measuring the characteristics of complex flow structures thus these results can be used for validating numerical models of such cases. However, still more efforts are needed to improve the accuracy and efficiency of these results.

References

1. Bhattacharyya, S. and A.K. Singh, *Reduction in drag and vortex shedding frequency through porous sheath around a circular cylinder.* International Journal for Numerical Methods in Fluids, 2011. 65(6): p. 683-698.
2. Bruneau, C.H. and L. Mortazavi, *Control of vortex shedding around a pipe section using a porous sheath.* International Journal Of Offshore And Polar Engineering, 2006. 16(2): p. 90-96.
3. Lu, T.J., *Ultralight porous metals: From fundamentals to applications.* Acta Mechanica Sinica, 2002. 18(5): p. 457-479.
4. Phanikumar, M.S. and R.L. Mahajan, *Non-Darcy natural convection in high porosity metal foams.* International Journal of Heat and Mass Transfer, 2002. 45(18): p. 3781-3793.
5. Bhattacharyya, S., S. Dhinakaran, and A. Khalili, *Fluid motion around and through a porous cylinder.* Chemical Engineering Science, 2006. 61(13): p. 4451-4461.
6. Vainshtein, P., M. Shapiro, and C. Gutfinger, *Mobility of permeable aggregates: effects of shape and porosity.* Journal of Aerosol Science, 2004. 35(3): p. 383-404.
7. Vanni, M., *Creeping flow over spherical permeable aggregates.* Chemical Engineering Science, 2000. 55(3): p. 685-698.
8. Nandakumar, K. and J.H. Masliyah, *Laminar flow past a permeable sphere.* The Canadian Journal of Chemical Engineering, 1982. 60(2): p. 202-211.
9. Masliyah, J.H. and M. Polikar, *Terminal velocity of porous spheres.* The Canadian Journal of Chemical Engineering, 1980. 58(3): p. 299-302.
10. Iwaki, C., et al., *PIV measurement of the vertical cross-flow structure over tube bundles.* Experiments in Fluids, 2004. 37(3): p. 350-363.
11. Hoyt, J.W. and R.H.J. Sellin, *Flow over tube banks - A visualization study.* Journal Of Fluids Engineering-Transactions Of The ASME, 1997. 119(2): p. 480-483.
12. Perrin, R., et al., *Obtaining phase averaged turbulence properties in the near wake of a circular cylinder at high Reynolds number using POD.* Experiments in Fluids, 2007. 43(2): p. 341-355.
13. Shi, L.L., Y.Z. Liu, and J.J. Wan, *Influence of wall proximity on characteristics of wake behind a square cylinder: PIV measurements and POD analysis.* Experimental Thermal and Fluid Science, 2010. 34(1): p. 28-36.
14. Khashehchi, M., et al., *A comparison between the wake behind finned and foamed circular cylinders in cross-flow*, in 15th International Symposium on Flow Visualization. 2012: Minsk.

15 Sirovich, L., *Turbulence and the dynamics of coherent structures*, Parts I, II and III. Q Appl Math, 1987. XLV(3):561–582