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A Comparative Analysis on the Velocity Profile and Vortex Shedding of Heated Foamed Cylinders

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Abstract

The flow pattern behind a circular cylinder is associated with various instabilities. These instabilities which are characterized by the Reynolds number (Re) and include the wake and vortices detached from it are well-studied in the past. However, the effect of heat transfer on these stabilities needs more attention. Moreover, depending on the physical application of the cylinder, increasing the level of turbulence on the surface of the cylinder could be a target for pressure drop reduction or heat transfer enhancement. Hence, hotwire anemometry has been carried out to investigate the velocity profile and vortex shedding from a heated foamed cylinder. The experiments are performed for a range of Reynolds numbers from 1000 to 10000 based on mean air velocity (0.5, 1 and 2 m/s) and the cylinder outer diameter (0.042, 0.062 and 0.072 m) at three different cylinder surface temperatures being ambient temperature, 50°C and 75°C.

Introduction

The flow over bluff bodies such as cylinders has been attracting considerable attention not only because of its interesting nature but also owing to a large number of engineering applications directly linked to that. Tubes inside the heat exchangers could be taken into account as a popular example of such bodies. There are two crucial factors that are considered in designing a heat exchanger; heat transfer augmentation and flow resistance reduction. One way to increase the thermal performance of a heat exchanger is area extension, e.g. through the use of fins attached to the bare cylinders. Studies show a relative enhancement in the heat transfer efficiency of the modified cylinders [1-8]. However, these extended surfaces cause a significant growth in pressure drop, consequently, the total efficiency of the heat exchanger could drop [9-12]. It should be noted that one reason for having higher pressure drop is the creation of a blockage in the main flow stream which leads to consuming more power by the fan to pump the air across the cylinders. Another source of pressure drop is the creation of a wake and vortex shedding downstream of the cylinders.

Currently, as an alternative to fins, metal foam is suggested to be used in the heat exchanger industry. Due to the existence of small pores within the foam, not only the heat transfer area per volume is increased [13-15], but also it affects the pressure drop by minimizing the blockage as the flow can be conducted through the pores. In addition, pressure drop in case of foam can be affected by existence of different turbulent structures [16-18].

It is well known that the turbulent structures downstream of the cylinder affect the flow field which is directly linked to the pressure drop. There has been broad and considerable published research in the field of the flow over the cylinder. In particular, the characteristics of the generated wake behind the cylinder, such as its size and the frequency of the structures detached from it, have been studied widely by a number of investigators. The size of the wake and the frequency of the vortex shedding from the wake are directly related to the Reynolds number. Extensive reviews about the effects of Reynolds number on the characteristics of the wake of a cylinder are presented by Roshko [19], Berger & Wille [20] and Zdravkovich [21]. Furthermore, it is thought that the attached fin or foam (to the cylinder) affects the flow structures [22-24]. However, very limited experimental researches have been conducted in this area.

There are two areas of interest regarding the structures of the flow over the cylinder; namely, the created wake and the structures detached from the wake. Regarding the former, Khashehchi et al. [25] and Ashtiani et al. [26] showed that the size of the wake behind the foam-covered cylinder is increased by increasing the Reynolds number. It was also showed that the turbulence kinetic energy inside the wake of foamed cylinder is significantly higher than that of a bare cylinder. Zdravkovich [21] indicated the role of the fins as vortex-spoilers as they disturb the shed vortices, making them less coherent and three-dimensional. Moreover, other studies on vortex shedding of finned-cylinders show that the vortex shedding frequency is well correlated with the cylinder effective diameter, which is based on the projected frontal area of the cylinder (Mair et al. [27], Hamakawa et al. [28]). Unlike the aforementioned studies on the detached structures from the wake of finned and bare cylinders, no specific investigation has been conducted in the literature regarding the foamed cylinder type. Indeed, several unresolved issues still need to be investigated in order to improve our understanding of the effect of the foam on the flow field behind the cylinder, since the flow structures past a porous-wrapped cylinder are different from those of bare and finned cylinders.

As such, we experimentally investigate the effects of aluminium foam on the velocity profile and vortex shedding.

Experimental Setup

The experiments were performed in an open loop suction wind tunnel with a fan rotor driven by 17kW electric motor. The inlet velocity of the tunnel is controlled manually by means of a pitot tube. The flow conditioning consists of a fine mesh screen, followed by a honeycomb section containing 1700 cardboard tubes and removable flow-smoothing screens. The contraction is three-dimensional with a 5.5:1 area ratio. The test section is 0.46m wide, 0.46m high and 2m long. Figure 1 schematically shows the side view of the experimental setup. In this figure, the streamwise and transverse directions are indicated by “x” and “y” axes, respectively. The velocity range of air in an air-cooled heat exchanges is generally between 1 to 4 ms^{-1}, and the diameter of the tubes could be between 6 to 60 mm [29]. Hence, in this experiment outer tube diameters of 0.042, 0.062 and 0.072m and inlet velocities of 0.5, 1 and 2m/s have been selected. The free stream turbulence level of empty test section was calculated to be 0.5% at 1 to 4 ms^{-1}.

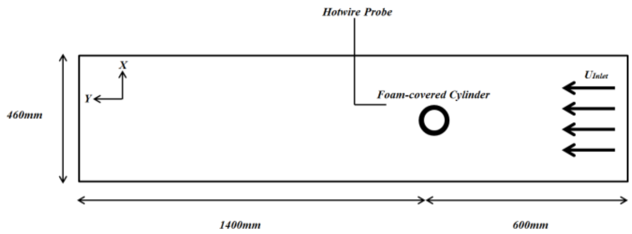

Figure 1. Side view of experimental setup

The experiments were conducted on 32mm diameter bare cylinders which are covered with aluminium foam of different thicknesses (10, 30 and 40mm). The length of all tubes was 600 mm. Moreover, an extra 120 mm of the tube length is used to support the tube and install it in the tunnel. Aluminium foam which was attached to the tube consists of ligaments forming a network of inter-connected cells. The samples with pore density of 10 PPI (pores per inch) with an effective density of about 5% of a solid of the same material are used.

The blockage ratio of the wind tunnel is between 9% to15% based on the total outer diameter of the tube and the height of the test section. Richter's studies [30] show for a circular tube with a blockage ratio of less than 25% blockage effect is insignificant. Hence, no correction for tunnel blockage is applied on the results of the present study. Nonetheless, it is expected that increasing the blockage, increases all the forces and also pressure coefficients [31] however, analysis of which is not covered in this paper.

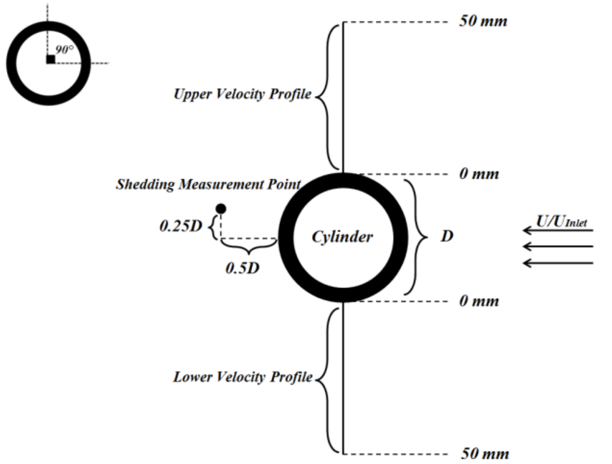

Figure 2. Schematic of hotwire measurements

We used a Dantec 55P15 single sensor hot-wire probe in our experiments. The probe has 1.25 mm long platinum-plated tungsten wire sensing elements of 5µm diameter and is operated in constant temperature mode with an over-heat ratio set to 1.8. The probe was calibrated in the free stream using Dantec 54T29 reference velocity probe. The probe was mounted to a computer controlled three-axis traverse system. To obtain shedding frequency, probe was fixed at 0.5D downstream of the cylinder as shown by a black dot in Figure 2, and velocity fluctuations along transverse direction at 90° and 270° were acquired at logarithmic spaced points with a resolution of 10 µm on straight lines normal to the cylinder surface as indicated by "Upper Velocity Profile" and "Lower Velocity Profile" in the same figure. Sufficient sampling frequency of 25 kHz to resolve the smallest scales and sufficiently long sample lengths (120 sec) for statistical convergence also have been used. The uncertainty relative to the maximum velocity at 95% confidence is calculated to be 1.3%.

Hot water, extracted from a hot bath, was pumped to flow through the cylinder and heats the walls internally. This process was controlled by a Julabo F33-ME refrigerated/heating circulator.

Results

The effect of aluminium foam on the velocity profile and shedding frequency of heated foamed cylinders mounted in the wind tunnel is studied for inlet velocities of 0.5, 1 and 2m/s.

Table 1 compares the Strouhal number (St) for different cases. As seen, the Strouhal number increases with the foam thickness and this more pronounced for higher temperatures and inlet velocities. More interestingly, Strouhal number decreases by increasing the velocity for a fixed foam thickness. With these two observations and knowing

$$Re = {U.D}/{\upsilon} \tag{1}$$

$$St = {f.D}/{U} \tag{2}$$

where U is the inlet velocity, D is the characteristic length, f is the shedding frequency and υ is the kinematic viscosity, one concludes that unlike the bare cylinder where Strouhal number linearly varies with the Reynolds number when Re $=10^2$ to 10^4, it is not easy to relate Strouhal number to Reynolds number in case of heated foam-covered cylinders. However, it is possible to choose another characteristic length instead of outer diameter for the case of foam. It might be useful to choose the average pore size as the characteristic length; however this is beyond the scope of this paper and is left for a future report.

By comparing the Storuhal numbers at different temperatures, it can be noted that increasing the temperature, increases the vortex shedding frequency. Unlike the effect of foam thickness, the effect of temperature is more pronounced at lower velocities.

Foam Thickness	U_{inlet}	Strouhal number for cylinder surface kept at:		
		Ambient temperature	50°C	75°C
10mm	0.5m/s	0.19	0.22	0.23
	1m/s	0.18	0.17	0.19
	2m/s	0.17	0.17	0.19
30mm	0.5m/s	0.19	0.22	0.24
	1m/s	0.18	0.19	0.20
	2m/s	0.17	0.17	0.21
40mm	0.5m/s	0.21	0.22	0.25
	1m/s	0.20	0.22	0.24
	2m/s	0.20	0.21	0.24

Table 1. Comparison of the Strouhal number between different cases

The following figures are demonstrating the upper and lower velocity profiles of heated foamed cylinders. Figure 3 and Figure 4 are comparing the velocity profiles of thick foam (40 mm thickness) where the former has been obtained at ambient temperature and latter at 75°C. Figure 5 and Figure 6 compare the same profiles for thin foam (10 mm thickness). It has to be mentioned that the measurements took place 10mm away from the surface of the foam to avoid errors induced by sharp temperature gradients.

Figure 3 and Figure 5 show that with surface kept at ambient temperature for both cases (thick and thin thicknesses), measured points are almost out of the shear layer which means increasing the foam thickness increases the size of the wake since the maximum velocity, indicating the boarder of the shear layer, is observed somewhere between 0mm to 10mm for the foam with 10mm thickness and around 12mm for the foam with 40mm thickness.

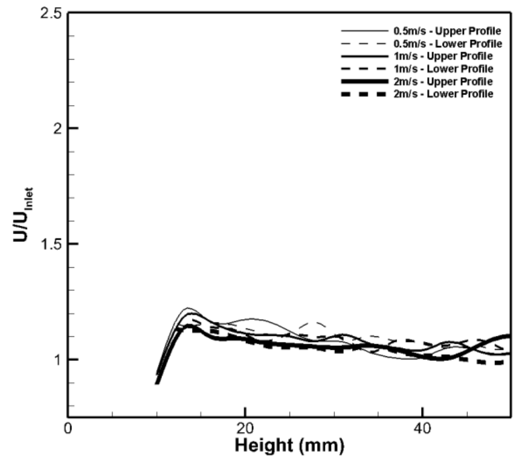

Figure 3. Comparison of the upper and lower velocity profiles between foamed cylinders with 40mm thickness at ambient temperature

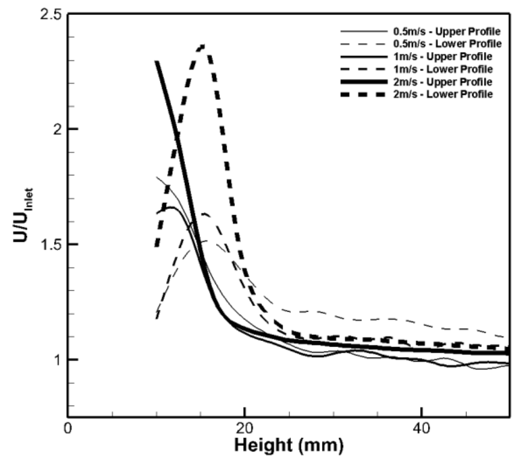

Figure 4. Comparison of the upper and lower velocity profiles between foamed cylinders with 40mm thickness at 75°C

Comparing Figure 3 with Figure 4 and also Figure 5 with Figure 6 show that temperature has a significant effect on the wake size. Profiles with higher velocity reach $U/U_{inlet} = 1$ later than those with lower velocities at 75°C. However, the converse is true for the case when the cylinder wall is not heated, i.e. when it is at ambient temperature. This rather peculiar behaviour can be attributed to the rapid change of the local temperature and accordingly local viscosity and density changes where high velocity flow is drifted abruptly from the high temperature region near the surface. Here, low velocity flow has enough time to respond to the upstream flow field changes. More interestingly, comparing the upper and lower profiles demonstrate that shape of the wake in heated foamed cylinder is not symmetrical and the wake region is further extended in lower side of the cylinder compared with the upper side. This effect is more pronounced with thicker foam. This can be attributed to the buoyancy effects. By increasing the surface temperature, buoyancy causes an increase in the magnitude of the transverse component of the velocity and, thus, distorts the shape of wake.

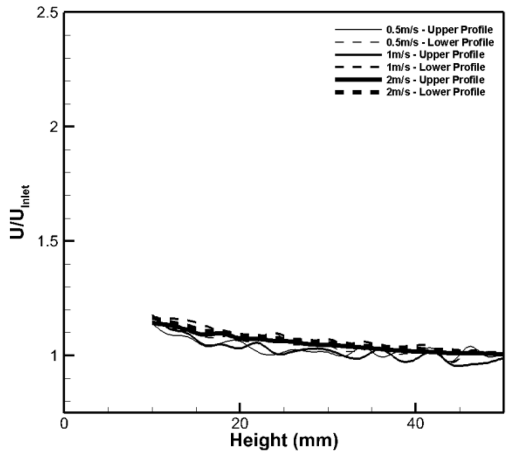

Figure 5. Comparison of the upper and lower velocity profiles between foamed cylinders with 10mm thickness at ambient temperature

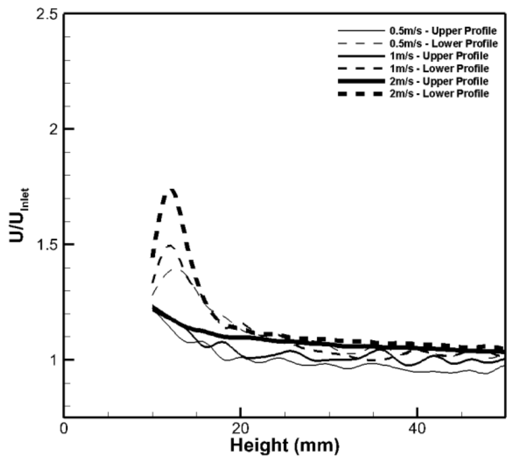

Figure 6. Comparison of the upper and lower velocity profiles between foamed cylinders with 10mm thickness at 75°C

Conclusion

Hotwire have been used in a low speed wind tunnel to perform velocity measurements downstream of heated foam-covered cylinders. A range of Reynolds number from 1000 to 10000 was covered in this study. The results show that adding foam to a bare cylinder decreases the vortex shedding frequency and heating strengthens this effect. Moreover, heating the foamed cylinder makes an asymmetric wake downstream of the cylinder where its lower part is further extended than the upper part as a result of buoyancy forces.

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