Pore size effect on the wake shear layer of a metal foam covered cylinder at relatively high Reynolds number

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Abstract

In this paper, hot-wire anemometry is used to compare the energy spectra of stream-wise velocity fluctuations on the wake shear layer of two different metal foam-wrapped tubes (5PPI & 40PPI) at Reynolds number of 40000 based on outer diameter. The standard case of cross-flow over a bare tube, i.e. no surface extension, is also tested as a benchmark. Results show that using 5PPI foam delays the separation and increases the magnitude of fluctuations inside the wake. However, foams with smaller pores increase the energy of fluctuations both on and outside the shear layer compared to the one with larger pore size.

Introduction

The flow around a porous medium is a complex one. The rate at which flow goes through the pores is not easy to predict since this flow rate depends on different parameters. Studies show the flow behaviour around a foam-wrapped tube is significantly different from the one around a bare tube [1-6]. Nevertheless, being conductive, permeable and having high surface area, metal foams are appropriate for various thermal applications such as heat exchanger, heat sink and heat pipes [7, 8]. It is, therefore, of great interest to understand the flow behaviour around and through the foam. The flow field is linked to various instabilities that are identified by the Reynolds number, wake, separated shear layer and boundary layer. Specifically, in heat exchanger, having a good understanding of the cylinder's shear layer size and characteristics is of importance, since increase in its size is proportional to the whole system's pressure drop [9, 10]. Bonnet et al. [11] performed experiments on both liquid and gaseous flows to analyse their permeability into the metal foams. They correlated the permeability and inertia factor to the pore size. Bhattacharya et al. [12] formulated a theoretical model to represent metal foam structure also the results of experiments shows that the effective thermal conductivity of the foam is highly dependent on the porosity, however no systematic dependency on pore density was found. Phanikumar and Mahajan [13] also performed experiments on metal foams with different pore sizes to investigate pore size and porosity effect on natural convection in porous metal foams.

The present study, however, analyses the pore size effect on the shear layer formation and energy of turbulent fluctuations on and outside the shear layer by mean of a hot-wire anemometry.

Experimental setup

The experiments are performed in an open loop suction wind tunnel. The inlet velocity is controlled via a pitot tube. To decrease the turbulence intensity, a honeycomb containing 1700 cardboard tubes and removable flow smoothing screens are used at the inlet of the wind tunnel. The contraction is three-dimensional with a 5.5:1 area ratio. Test section is $0.46m \times 0.46m \times 2m$. The schematic of the experiment within the wind tunnel is shown in Figure 1. In the figure, the stream-wise and transverse directions are indicated by "X" and "Z" axis, respectively. The free stream turbulence level of empty test section is calculated to be 0.24% at $10ms^{-1}$. The experiment is done on 32mm diameter bare tube covered with 15mm aluminium foam layer of different pore sizes (5 and 40 PPI). Both foams have the same effective density of 5%. In addition, a bare cylinder with 62mm diameter is used as a benchmark case with the same frontal area as the foam-wrapped tubes. The length of all tubes is 600mm.

Dantec 55P15 single sensor hot-wire probe is used in this experiment. The probe has 1.25mm long platinum-plated tungsten wire sensing elements of 5μ diameter and is operated in constant temperature mode with an over-heat ratio set to 1.8. The probe is calibrated in the free stream using Dantec 54T29 reference velocity probe and is mounted to a computer controlled three-axis traverse system. Velocity fluctuations are acquired at logarithmic spaced points with a resolution of 50µm on straight lines normal to the cylinder surface as indicated by the red line in Figure 1. Measurements started 500µm (0.008D) from the surface all the way down to a point located 90.532mm (1.46D) far from the surface on the same normal line to the tube surface. Sufficient sampling frequency of 25 kHz is used to resolve the smallest scales and also the sampling lengths are sufficiently long (120 sec) for statistical convergence. The relatively uncertain maximum velocity at 95% confidence is calculated to be 0.8%

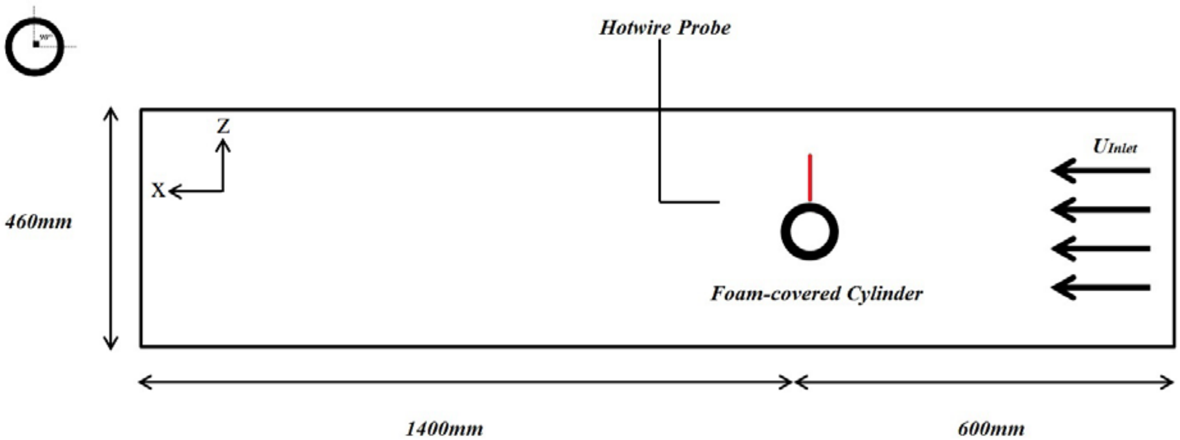

Figure 1 : Side view of the experimental setup – velocity profile is taken on the red line

Results and discussion

The effect of pore size density (PPI) on the shear layer of a foam covered tube is studied for inlet velocity of 10m/s. Figure 2 compares the velocity profiles of the three samples (5, 40 PPI and bare) at θ = 90°. It is clear that the wake size for the foam covered cylinders is considerably larger than that of the bare case at the same velocity similar to what reported by Khashehchi el al. [2]. Moreover, the figure shows the velocity profile inside the shear layer of the foam covered cylinders follows a different trend than the bare one. This could be due to the fouling in the media that blocks the inner pores and the ones near the downstream, which eventually lead the permeated flow to be redirected; then it exits from the pores near the surface. This affects the shear layer by pushing it back from the surface and changing the flow structures by mixing with the flow inside the inner layer. This effect is pronounced by decreasing the size of pores. This is because, the smaller pores size, compared to the bigger pores size, inject the redirected flow out by higher velocity, and also the surface of the foam for the case with smaller pore sizes could be considered as a rough surface that lets the flow to pass over it. Hence to analyse the shear layer for these cases we need to use some statistical tools like skewness and turbulence intensity.

Figure 3 and Figure 4 demonstrate the comparison for the same cases for skewness and turbulence intensity, consecutively. Both these tools can be used to identify where shear layer is forming. Skewness is a measure of the symmetry of the data around the sample mean. A large deviation from unity for skewness (>> 1 or <<1) shows a non-normal distribution that is happening near the position of maximum shear. Besides, turbulence intensity is a scale characterizing the turbulence. A large value of this number indicates large magnitude of fluctuations compare to the sample mean. The following equations are used to calculate skewness and turbulence intensity;

$$Skewness = \frac{\frac{1}{n}\sum_1^n (U_i - \bar{U})^3}{\sqrt{\frac{1}{n}\sum_1^n (U_i - \bar{U})^2}^{\,3}} \qquad (1)$$

$$Turbulence\ Intensity\ (\%) = \left(\frac{\sqrt{\frac{1}{n}\sum_1^n (U_i - \bar{U})^2}}{\bar{U}}\right) \times 100 \qquad (2)$$

Where U_i is the instantaneous velocity and $\bar{U}$ is the average velocity. By analysing both Figure 3 and Figure 4, it is possible to locate and characterize the shear layer. Surprisingly, in both figures the magnitude of skewness and turbulence intensity at the position of the maximum shear is significantly different from those for the bare cylinder. The maximum skewness in the compared profile for the bare cylinder is 8 times larger than the foam covered cylinder with 5PPI and 35 times larger than the one with 40PPI. However, the numerical value of turbulence intensity for both foam covered cylinders is within the same order of magnitude yet half of what has been obtained for the bare case. This is an interesting result indicating that mixing of the injected flow from the pores and the flow around the cylinder (foam covered) decreases the skewness of the obtained data which ends up with more normal distributed results. The pore size is proportional to the magnitude of skewness. Also, as can be seen in

Figure 4, this mixing decreases the magnitude of fluctuations in the shear layer although for turbulence intensity, the role of pore size is not significant. Moreover, comparisons show the maximum shear occurs at Z = 1.6, 3.6 and 5.1 mm away from the surface of bare tube, foam covered cylinder with 5PPI and 40PPI, respectively. We use these numbers to compare the energy of the stream-wise fluctuations on three different points on the velocity profile at θ = 90° for all three cases. The first point is where the shear is maximum, the second is where in the skewness peak starts forming and the last one is 5.7mm from the surface of the cylinder.

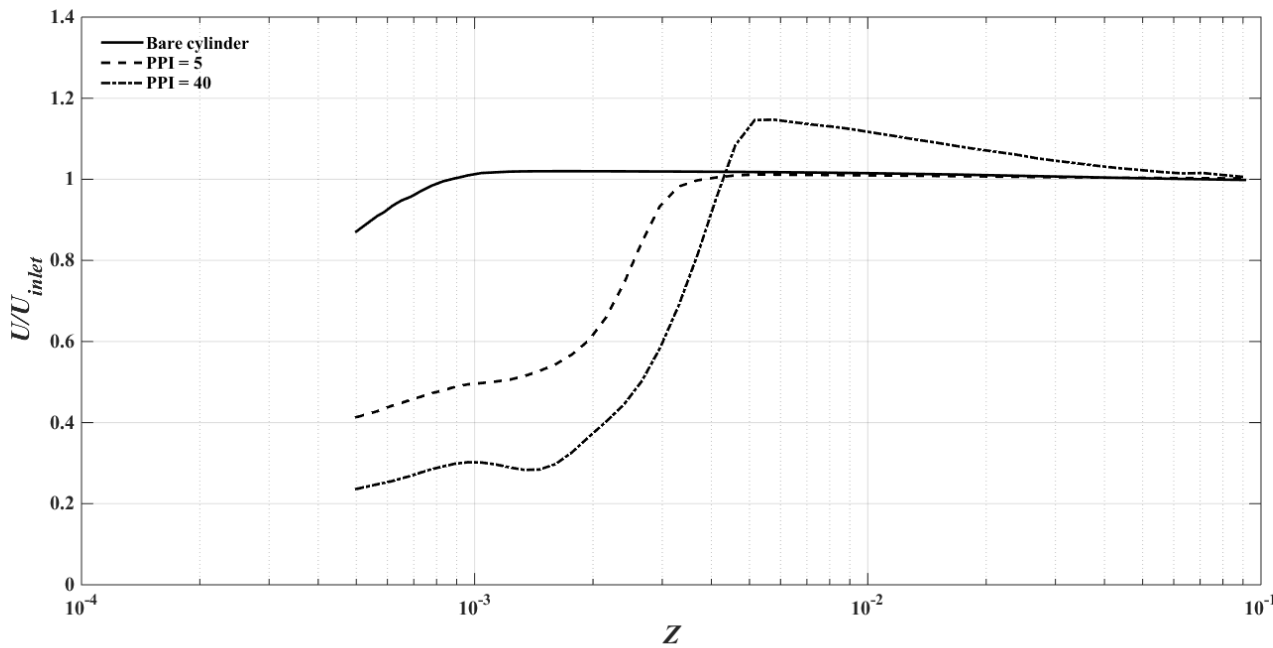

Figure 2 : Comparison of normalized velocity profile at θ = 90° at U_i = 10 m/s

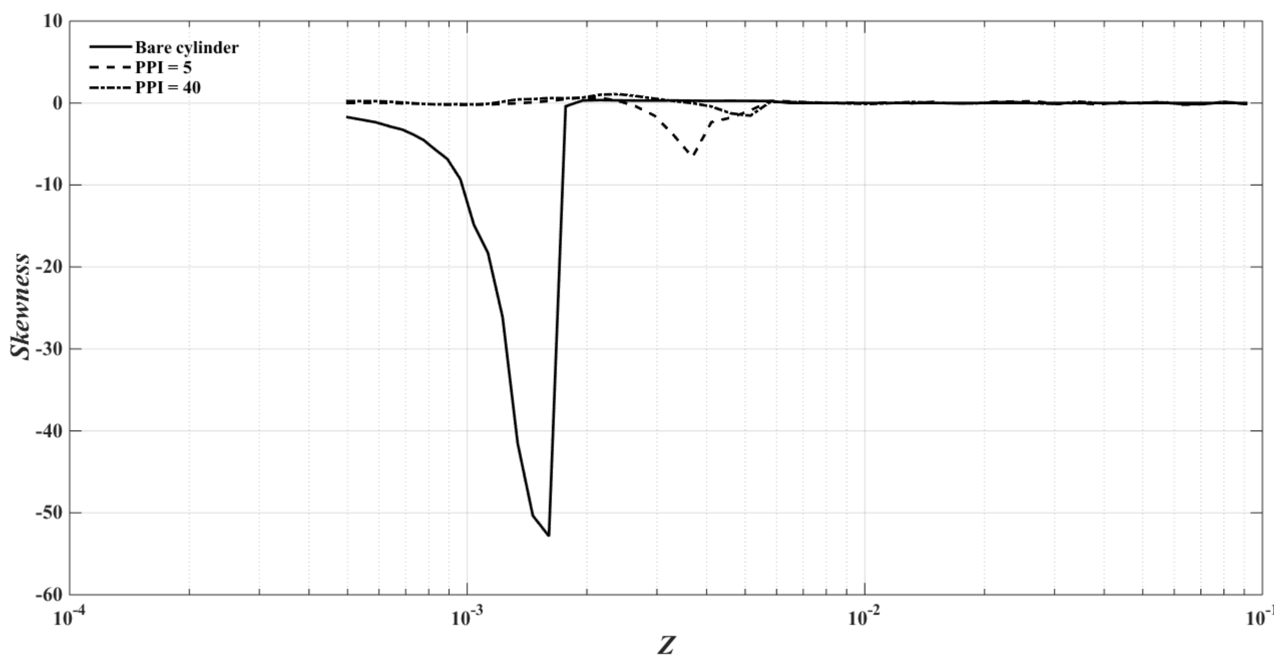

Figure 3 : Comparison of skewness profile at θ = 90° at U_i = 10m/s

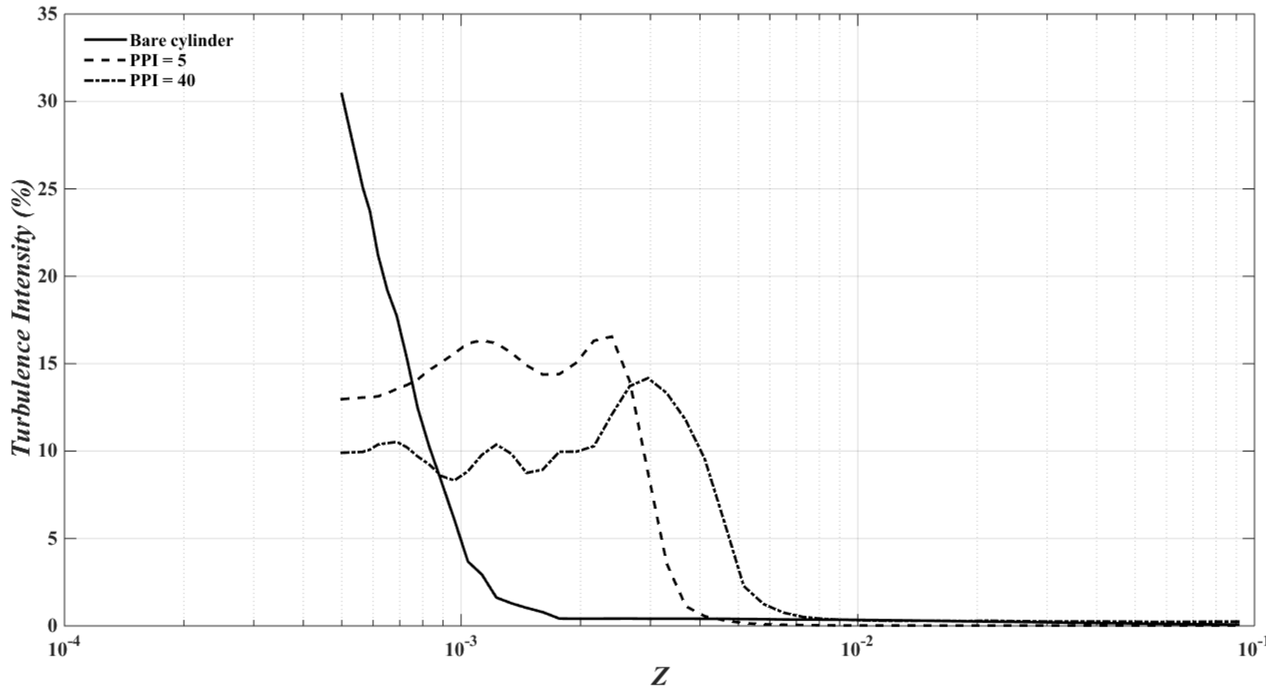

Figure 4 : Comparison of turbulence intensity profile at θ = 90° at U_i = 10m/s

Figure 5 and Figure 6 show the energy of stream-wise velocity fluctuation at the three mentioned points. The former pertains to the foam covered tube with 5PPI and the latter refers to the one with 40PPI. Besides, Figure 7, the spectra of stream-wise velocity fluctuations for the bare tube, is used as a benchmark. To calculate the power spectra, the velocity time series obtained from the hotwire is used. Each time series consists of 2^{21} points and is divided into 2^{10} segments. For each segment, the local mean velocity and fluctuation velocities are obtained. Afterward, Taylor's frozen-turbulence hypothesis is used and space-for-time substitution is carried out on the time series $u(t_i)$ to obtain the space series $u(x_i)$. The power spectra for each of the segments, is the square of the magnitude of the discrete Fourier transfer of the$u(x_i)$. Following [14], the stream-wise power spectra is obtained by averaging the power spectra over all the segments. It is worth to note that no filter has been applied to the spectra.

The first observation that can be made is that the bare tube has the highest magnitude of energy on all the three points on which the power spectra is calculated. Just ahead of the maximum shear point the power spectra magnitude for 5PPI foam is 2 orders and 40PPI 3 orders lower than the bare one. This number is in the same order for both pore sizes where the maximum shear exists and is 4 order smaller than the benchmark case. However, in 5.7mm away from the surface, this magnitude is ~ 10^{-7} for 5PPI, ~10^{-6} for 40PPI and ~ 10^{-4} for the bare tube – 5.7mm distance for the bare case is far away from the shear layer but the same distance for both foam cases is near the shear layer as seen in Figure 2. This is an interesting observation, since changing the pore size doesn't change the order of magnitude of the fluctuation's power on or beyond the shear layer. Moreover, as expected, this energy starts decreasing by setting back from the surface of cylinder. Besides, when comparing foams and bare, in foams the larger frequency range in which the power of fluctuations remain almost constant (up to almost 1 kHz) is seen. Moreover, for all the cases there is a large peak at about 8.5 kHz. However, in 40 PPI case a smaller peak at about 1.5 kHz is also recognizable. The strange trend inside the boundary layer (the yellow colour) of the both foam covered tubes is another remarkable note which could be due to the flow mixing described earlier.

Further notable observation is that, using foam decreases the range of fluctuations. As Figure 7 shows for a bare tube, the range of fluctuation specifically inside the shear layer is significant, which is not the case for 5 or 40PPI foams. In foam cases, the plots seems smooth with insignificant fluctuations over the mean line.

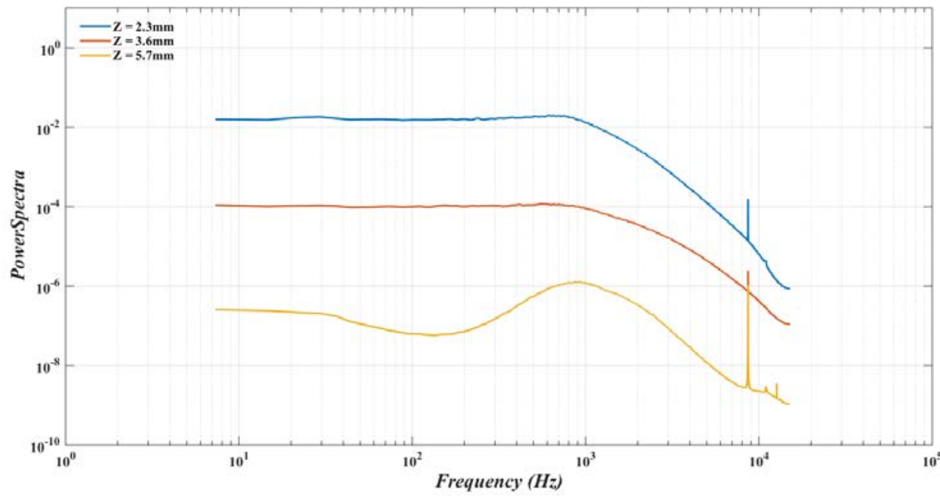

Figure 5 : Spectra of the stream-wise velocity fluctuations at θ = 90° for the 5PPI foam at U_i = 10m/s

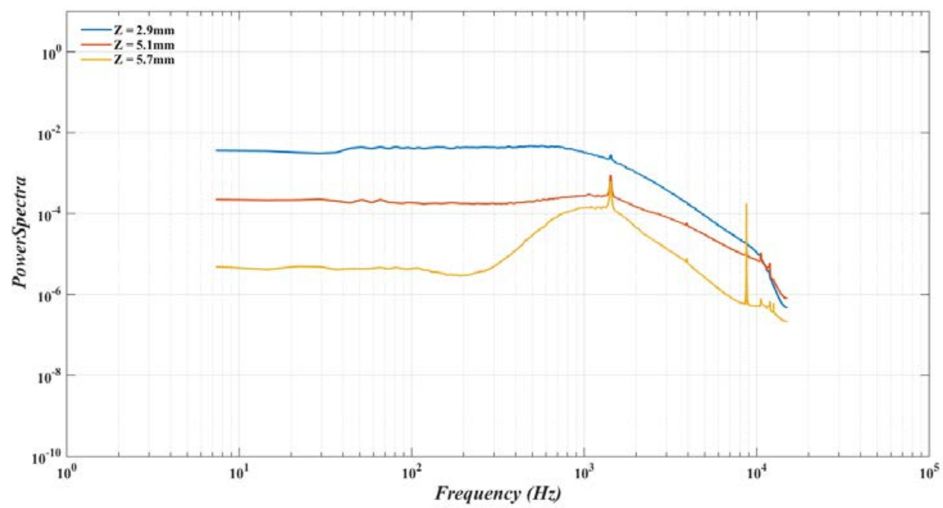

Figure 6 : Spectra of the stream-wise velocity fluctuations at θ = 90° for the 40PPI foam at U_i = 10m/s

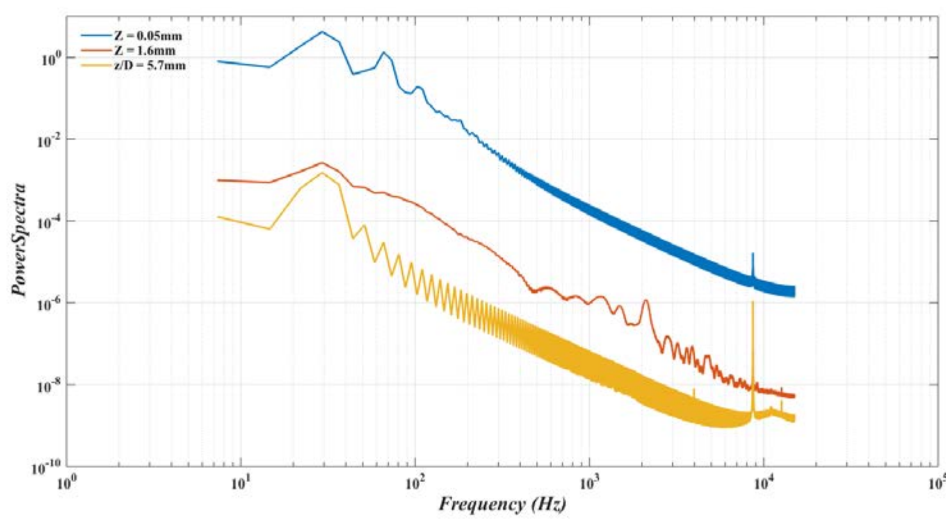

Figure 7 : Spectra of the stream-wise velocity fluctuations at θ = 90° for the bare cylinder at U_i = 10m/s

Conclusion

A Dantec 55P15 single sensor hot-wire probe is utilized in a low speed wind tunnel to study the effect of the pore size on the wake shear layer of a metal foam covered tube at relatively high Reynolds number. Turbulence intensity and skewness as statistical measures are used to compare the shear layer characteristics on top of power spectra to measure and analyse the energy of fluctuations inside and outside the shear layer. Experiments are conducted on three different cases, a bare tube as a benchmark and two foam covered tubes with 5 and 40 PPI pore densities, with the same frontal area as the bare tube. Experiments are conducted at 10m/s (Re = 40000).

Analysis shows that using the foam with larger pore sizes delays the separation and increases the magnitude of fluctuations inside the wake. This is while using the 40PPI foam increases the energy of fluctuations on and outside the shear layer considerably. This could be due to the fouling in the media that blocks the inner pores and the ones near the downstream, which makes the permeated flow to exit from the pores near the surface. This pushes the shear layer back from the surface and changes the flow structures by mixing with the flow inside the shear layer.

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