Gas flow in a channel semi-obstructed by an array of wires

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Abstract. An experiment of a gas flow in a narrow channel partially obstructed by a regular array of wires is presented. The purpose of the study is to recreate ideal conditions of flow through easily penetrable media. The velocity profile along the channel was measured by means of a hot-wire anemometer, inside and outside the obstructed region. Flow instabilities were found in the free zone adjacent to the porous region, which were characterized by the standard deviation and the power spectrum of the signal of the anemometer.

1. Introduction

The study of flows passing complex obstructions is relevant in several engineering branches. In general this phenomenon involves a wide range of scales practically impossible to calculate numerically over the whole spectrum. For this reason, usually the analyses are based either on experimental measurements or on effective models that average the fluid behavior in space and time. A special case of interest of complex obstructions is the flow parallel to porous pervasive media. Natural examples are atmospheric currents over vegetation [1], flow in channels with aquatic plants [2], and flooding over cultivated lands [3]. This type of flows also occurs in technological applications, such as refrigerant flow over electronic components, fins, pin arrays and metallic sponges [4].

A common feature encountered in the boundary between the porous obstruction and the free flow area is an inflexion point of the velocity profile, similar to what happens in a planar mixing interface [5], [6] and compound channels [7]. This in turn produces local coherent structures of large scale, which enhance the momentum and scalar transversal diffusion [8], [9]. These structures can modify the concentration of scalars and the velocity profile not only at the interface where they are generated but also inside and outside the obstruction [10], [11].

The present study reports a controlled experiment at low Reynolds number of air flow in a narrow channel partially obstructed by an array of cylindrical wires. The small diameter of the wires is chosen to ensure that the local Reynolds number is sufficiently low to avoid the typical instabilities around obstacles such as vortex shedding. This experiment presents a 2D geometry that involves a porous medium homogeneous and isotropic in these two dimensions. The chosen geometry can be easily represented by a rectangular mesh and simple boundary conditions. Hence, the experimental results can be used to evaluate and validate CFD codes. In particular we are interested in developing a CFD code capable of simulating flows involving porous media under conditions where large scale
structures occur, *i.e.* fluid-dynamic structures with sizes larger than the elements of the porous medium.

2. **Experimental setup and method**

The design of the test section involves the compromise between attaining a low Reynolds and a good spatial resolution while keeping the flow velocity at measurable values. The test section consists of a rectangular channel as shown in figure 1, the total height being 56mm and the width 100mm. The lowest velocities are found in the porous region, which compromises the measurement accuracy in this region.

The channel walls are made of transparent acrylic 5 mm thick. The cross section is divided in two halves, one free and the other crossed by an array of cylindrical copper wires. The diameter of the wires is 0.25mm, and the gap between wires is $\Delta x = 5 \text{mm}$ in the horizontal direction and $\Delta y = 2.5 \text{mm}$ in the vertical direction (figure 1, “A”). The array is appropriate to simulate a pervasive porous media with low Reynolds number.

![Figure 1. Test section (all dimensions in mm).](image1)

![Figure 2. Measuring points P0, P1, P2 y P3 (all dimensions in mm).](image2)
The global Reynolds number is defined by:

\[ \text{Re} = \frac{\bar{U}_m h}{\nu} \]  

(1)

where \( \bar{U}_m \) is the mean inlet velocity, \( h \) is the channel width and \( \nu \) is the fluid viscosity. The maximum Reynolds studied is approximately 1300.

The diameter and gap between wires was chosen taking into account the manufacture feasibility and that penetration length of the velocity profile in the porous region should be longer than the distance between wires. The volumetric resistance of the media can be calculated by averaging the drag force per unit length [3]. Taking into account that the separation between wires is 10 and 20 diameters in each direction, the drag of a wire can be calculated from correlations for low Reynolds numbers flows through a single cylinder, using the local Reynolds number:

\[ \text{Re}_d = \frac{U d}{\nu} \]  

(2)

In our case, the maximum \( \text{Re}_d \) occurs at the front of the porous region, being smaller than 10, and it is substantially lower for most of the wires comprising the porous media. Under these conditions the drag force per unit length is given by \( D' = 4\pi \mu \varepsilon U \) Hunner and Hussey [12], where \( \mu \) is the dynamic viscosity and \( \varepsilon \) is a dimensionless coefficient. The volumetric resistance is then:

\[ D_w = \frac{D'}{\Delta x \Delta y} = f \mu U \]

where \( f \) is a volumetric drag coefficient. The resulting coefficient for the experimental condition is approximately \( f = 0.25 \text{ mm}^{-2} \).

The flow is forced in the channel by means of an extractor fan located at the exit of the test section, which is controlled with a variable voltage power supply. Three velocities were studied, as shown in Table 1. The corresponding Reynolds numbers are lower than the critical value for rectangular channels [13], [14]. A honeycomb and a fine metallic mesh are located at the inlet in order to homogenize the entrance flow. Another honeycomb is placed 2 cm before the fan to avoid the introduction of vorticity upstream.

### Table 1. Operating conditions.

| Flow | \( \bar{U}_m \) | Re |
|------|----------------|----|
| W1   | 0.11 m/s       | 410 |
| W2   | 0.24 m/s       | 900 |
| W3   | 0.34 m/s       | 1270 |

The average velocity profiles were obtained by means of a constant-temperature hot-wire anemometer (CTA) guided by a mechanical device. The measurements were taken at positions P0, P1, P2 and P3 as shown in figure 2, located at 27.2, 42.2, 57.2 and 72.2 (±0.1) cm downstream from the inlet mesh. In each of these positions 28 measurements were made placing the probe along the vertical coordinate. Each measurement recorded 100,000 samples (20s, 5 kHz).

The CTA is basically a feedback resistive bridge that maintains the resistance (and hence the temperature) of the wire sensor constant. The probe consists of a Pt-Ir wire 15 \( \mu \text{m} \) thick 2 mm long.
placed vertically, supported by two stainless steel prongs (figure 3). The vertical orientation of the sensible filament allows filtering the vertical component of the velocity. Since the horizontal velocity component normal the flow is negligible, as observed from smoke line visualizations, the signal carries information essentially of the axial velocity component $U_x$. The CTA was operated with 50% overheating. All measurements were performed with ambient temperatures between 19.9 and 20.8 °C.

![Figure 3. Hot wire sensor.](image3)

Figure 3. Hot wire sensor.

![Figure 4. Photograph of a smoke line in the test section. The fluid flows from left to right.](image4)

Figure 4. Photograph of a smoke line in the test section. The fluid flows from left to right.

The data was acquired by means of a PC with a National Instruments card PCI-6070E. Details of the electronics can be found in Osorio et al (2010). The CTA was calibrated, establishing the following correlation between the velocity and voltage:

$$ U_x = 0.91(E - E_0)^{1.35} $$

where $U_x$ is the axial velocity in m/s, E is the signal output from the CTA, and $E_0$ is the stagnation voltage.

3. Results

The global operation of the test section was visualized injecting smoke at the inlet to track the stream lines. An image of the visualization is shown in figure 4. The curvature of the smoke lines at the inlet can be appreciated as well as the growth of undulation instabilities in the downstream region. No other type of instabilities was observed. It was also observed that, after the flow contraction brought about by the porous region, the stream lines rapidly become parallel to the channel walls. No significant deformation of the flow lines were observed in the lateral direction. The flow rate $W_2$ corresponds to the visual observation of the onset of instabilities.
Figure 5. Velocity profiles at positions P0 (■), P1 (○), P2 (▲) and P3 (◊) for flow rate W2.

Figure 5 shows the mean velocity profile at positions P0, P1, P2 and P3 obtained when the flow rate W2 is imposed. The porous area spans from the channel wall at y = 0 to y = 28mm, while the free flow area spans from y = 28mm to y = 56mm, which is the location of the opposite channel wall. It can be observed that the maximum development is reached at position P3, showing very low velocities in the porous region and a skewed parabolic profile in the free zone. The maximum velocity is found in the free area closer to the wall. An inflexion point can be distinguished in the transition between these two regions. The precise location of the inflection point is difficult to determine from the measurements due to the relatively large experimental error but lies between y = 30 mm and y = 40 mm for all cases.

Figure 6 shows the mean velocity and the standard deviation measured at P3 for each flow rate. As we have mentioned the lowest velocities exhibit relatively large errors. These errors are due to limitations of the thermal anemometry technique such as natural circulation, thermal perturbations from nearby objects (wires, walls, etc.), thermal drifts, etc., which are particularly important at low flow velocities. The maximum velocities are measured at the vertical positions y = 48 mm and 50 mm. The standard deviation shows for all the cases two clear peaks at y ~ 38 mm and y ~ 54mm. These positions are the locations of the highest derivative of the velocity profile. The latter is consistent with eddy diffusion brought about by instabilities. Furthermore, even though in the porous zone the errors are comparable with the measured values, for the highest flow rate W3 the fluctuations are relevant even in the porous zone, indicating that eddies penetrate into this area. It can be seen that even though the general aspect of $\sigma_x$ profile is similar in all the flow rates, only for W2 and W3 there is a clear unstable behavior with strong velocity fluctuations. This is an indication that the critical flow rate is between W1 and W2.

In order to analyze the instabilities, the signals of the anemometer were processed to obtain the corresponding power spectrum densities. Figure 7 shows the power spectra at y = 38 mm for flow rate W2. A remarkable feature is the local minima appearing in the power spectra at P1, which coincide with local maxima at P2 and P3. The calculation was checked carefully to ensure that these features are not artifacts produced by the signal processing procedure. A possible cause of this singularity is turbulence reduction found in the contraction of stream lines, in this case at the beginning of the porous media [15].
4. Conclusions

An experimental study of the gas flow though a channel partially obstructed by a regular array of wires was presented. The velocity profiles, measured with a hot-wire anemometer at different positions along the channel, showed that the gas velocity decreases substantially in the porous region as a consequence of the resistance of the wires.

Flow instabilities were found in the free region adjacent to the wired region, which were quantified by means of the standard deviation and the power spectra of the signal provided by a hot-wire anemometer. It was found that the standard deviation presents two maxima in the free region, one adjacent to the porous media and the other to the wall. Both coincide with the maxima of $\partial U / \partial y$.

For this geometry, the flow fluctuations quantified by the axial velocity standard deviation, shown in figure 6, are negligible for Reynolds number 400 and become significant for Reynolds numbers 900 and 1270. It was observed in figure 6 that the power spectrum of the measurements at $y = 38$ mm show a distinctive peak at a Strouhal value of approximately 0.6 for the positions P2 and P3, i.e. the fluctuations present in the flow have a characteristic frequency. Moreover, the low value of the
Strouhal number, smaller than 1, suggests that the fluctuations are originated by large scale structures. This is a relevant feature of the flow that might be used in the evaluation of numerical solutions to this kind of problems.

Figure 7. Power spectra at \( y = 38\text{mm} \) for the flow rate \( W_2 \).

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