

The Effects of Porosity and Inclination on the Pressure Drop across Porous Screens and Honeycombs Used for Heat Exchanger Simulations in Wind Tunnel Studies

Klementina Gerova, Stefan Velikov and Kevin P. Garry
Cranfield University

ABSTRACT

The simulation of heat exchanger air flow characteristics in a sub-scale wind tunnel test requires an accurate representation of the full-scale pressure drop across the element. In practice this is normally achieved using laminations of various porous materials and honeycombs on the basis of experience and ad hoc data. In view of this, a series of measurements of the pressure drop, in both the near and far field, across screens with porosity (β) in the range $0.41 < \beta < 0.76$ are reported. The aim being to establish a relationship between the porosity and the pressure drop characteristics of a given material at various angles of inclination to the free-stream flow. Furthermore, the effect of screen depth was investigated using honeycombs. This data will facilitate detailed design and accurate representation of the flow characteristics at sub scale.

The measurements were made in a simple open return blower wind tunnel within a range of Reynolds number (Re), based on screen thickness of $200 < Re < 2100$ and screen inclination to the free stream (α) in the range $0 < \alpha < 45$ deg.

At screen porosities of $\beta = 0.5$ the pressure drop coefficient ($\Delta p / q$) was found to be independent of Reynolds number above $Re = 500$. Pressure drop coefficients for screens orthogonal to the free stream ($\alpha = 0$) were found to agree well with existing experimental data and empirical predictions. The pressure drop coefficient is shown to reduce with increasing screen porosity and inclination to the free stream. The screen permeability was found to increase with increasing screen porosity and inclination. Empirical equations are developed giving the predicted pressure drop and permeability for screens with a given porosity and inclination.

CITATION: Gerova, K., Velikov, S. and Garry, K., "The Effects of Porosity and Inclination on the Pressure Drop across Porous Screens and Honeycombs Used for Heat Exchanger Simulations in Wind Tunnel Studies," *SAE Int. J. Passeng. Cars - Mech. Syst.* 6(2):2013, doi:10.4271/2012-01-2340.

INTRODUCTION

The flow of fluid through porous screens is of engineering interest due to the wide range of applications including membrane permeability in the biomedical industry [1], insect entry into greenhouses [2], and flow control in wind tunnels [3].

The specific application of interest in this paper is the use of laminations of porous sheets and honeycombs to facilitate a sub-scale simulation of the complex geometry of heat exchanger in wind tunnel studies. In such cases the primary requirement is to accurately reproduce the required pressure drop and flow deviation due to the heat exchanger element.

It is normal practice, particularly in race car applications and occasionally in conventional passenger cars, for the heat exchanger element to be inclined relative to the flow within an internal duct. This has the effect of increasing radiator size

without impacting on vehicle frontal area. There is clearly a compromise between heat exchanger size and the reduced aero-thermodynamic performance in terms of both effective local velocity component and the increased free stream pressure change (resulting in an aerodynamic drag).

Previous investigations of the flow through porous materials have been performed by experiments in wind tunnels as well as by numerical simulation. These have mainly involved the measurement of the pressure distribution and flow visualization around porous screens and gauzes. The first of such was carried out by Taylor [4] with the study of the theoretical relationship between gauze porosity and drag. Subsequently, Taylor and Davies [5] extended their study to the air resistance of perforated sheets, gauze and fabrics. Schubauer et al. [3] conducted a series of experiments dealing with the pressure drop and streamline deflection of damping screens for angles of inclination up to 45 deg. They showed

that the pressure drop is only a function of the solidity of the screen and the velocity component normal to it. They also found that the deflection of the streamlines depended solely on the resistance coefficient of the screen.

Baines et al. [6] conducted analytical and experimental studies on the relative pressure drop as a function of screen form and porosity, capacity of screens to modify velocity distribution and the characteristics of turbulence that the screens produce. Carrothers et al. [7] summarized all the available correlations for the pressure drop coefficients through wire mesh screens and textile nettings.

Further studies of flow in the wakes of perforated plates and gauze screens were carried out by Reynolds [9], who set up a mathematical model to predict the deflection of the flow passing through gauzes. Koo and James [10] proposed a mathematical model which replaces a screen with a distribution of sources. Their experimental and numerical data showed good agreement for the velocity profiles downstream of the gauze. O'Hern et al. [11] numerically studied flow downstream of fine-mesh screens. They found that the recirculating region behind the screen is found to grow almost linearly with Reynolds number.

Brundrett [12] formulated a new general correlation equation for pressure drop through woven wire and cloth screens for incompressible flows. He furthermore quantified the errors produced by screen porosity variation due to manufacturing tolerances, local screen damage or variable tension created during installation.

Miguel [13] investigated airflow characteristics of a number of screening materials. Based on the obtained results he concluded that the shape of the yard and mesh geometry have a negligible influence on the airflow characteristics of screening materials. Ito et al. [14] carried out a series of open-jet wind tunnel tests to obtain the static pressure near a 2D plane gauze for a range of angles of inclination. Additionally they visualized the flow pattern through the gauze using a smoke wind tunnel.

More recently, O'Neil [15], using the source panel method, investigated the different singularity flow models available to describe the time-mean flow field through and around finite screens. Dong et al. [16, 17] using scaled wind tunnel simulation studied the mean flow regime behind fences with different porosities and different wind velocities. They further extended their investigation to the turbulent fields behind such upright porous fences.

Valera et al. [18] evaluated the geometrical characteristics and airflow resistance of upright insect-proof screens. Based on obtained pressure drop coefficients, they proposed an overall governing equation for the relationship between the porosity of the screen and Reynolds number of the airflow. Teital et al. [2] investigated the effect of screen inclination on the flow parameters behind porous screens. They found that at 90 deg, the air velocity profile was constant with height, while upon inclination of the screen to 45 deg, the velocity increased with height. Conversely for 135 deg, the velocity decreased with height.

In the present study, porous materials are investigated specifically in relation to their applicability as model heat exchanger elements in sub-scale wind tunnel simulations. The aim being to establish a relationship between the porosity and the pressure drop characteristics of a given material at various angles of inclination to the free-stream flow. This data will facilitate detailed design and accurate representation of the flow characteristics at sub scale.

METHODOLOGY

The purpose of the experiment is to obtain pressure drop data across screens of various porosities and at different inclination relative to the free stream. This was achieved by adapting an existing blower wind tunnel such that a porous screen could be mounted in the blown duct covering its entire cross section area. A schematic of the blower wind tunnel arrangement is presented in [Fig. 1](#) (see [Appendix](#)). Sections 1 and 2 are fixed while 3 and 4 are varied, depending on the inclination of the mesh relative to the free stream. Variations of Section 3 and 4 are presented in [Fig. 2](#) (see [Appendix](#)).

A reference pressure is measured just upstream of the contraction, using the pneumatic average taken from a ring of static pressure tapings. Static pressure measurements are carried out at various positions both upstream and downstream of the screen. These tapings are aligned with the lateral centerline of the working section. For 0 deg inclination the readings are pneumatically averaged values from the wind tunnel top and bottom tapings, while at all other angles they are taken as individual readings.

The pressure tubes from the static, Pitot-static and reference ring pressure tapings were connected to OMEGA PX 139 pressure transducers. The relative measurement error specified by the manufacturer is $\pm 0.3\%$ of the full range of 0.3 psi (2.068 kPa), and thus giving an error of ± 0.0009 psi (± 6.2 Pa). The transducers were also connected to the input channels of a data acquisition (DAQ) hardware. The PC used for the data acquisition uses a National Instruments DAQ card and National Instruments LabVIEW software. A custom DAQ program was written for the tests.

The wind tunnel measurements were conducted with screens inclined at 0, 15, 30 and 45 deg to the free stream. The free-stream dynamic pressure was measured with a Pitot-static tube mounted on the working section centerline upstream of the screen, see [Fig. 1](#). The wind tunnel speed was varied between 3 and 31 m/s. Within this range the velocity profile of the empty working section (no screen mounted) was measured at the lateral centerline and was found to be uniform (within $\pm 1\%$ of the mean value) for 90% of the working section height.

Screen porosity (β) was defined as:

$$\beta = \frac{\text{Open screen area}}{\text{Complete screen area}} \quad (1)$$

Thus, values can be between 0 (solid flat plate) and 1 (no material present).

For this experiment, five different materials with porosity between 0.76 and 0.41 were tested. Most of the materials used had manufacturer data for their porosity. If this data was not available, the porosity was calculated either by measuring samples with a microscope or by taking photographic images of the meshes against a single-color background and using pixel-counting software, Pixcavator IA 4.2, to measure the ratio of mesh (material) pixels to background pixels. On these measured porosity values the tolerance was statistically estimated to be approx. ± 0.03 .

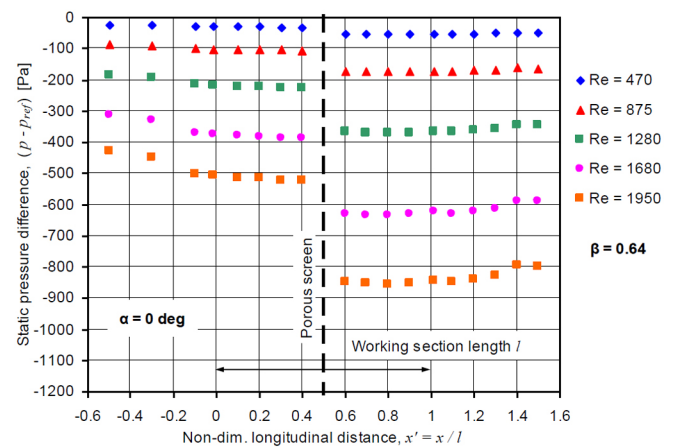
RESULTS AND DISCUSSION

Effects of Screen Porosity and Inclination on Pressure Drop

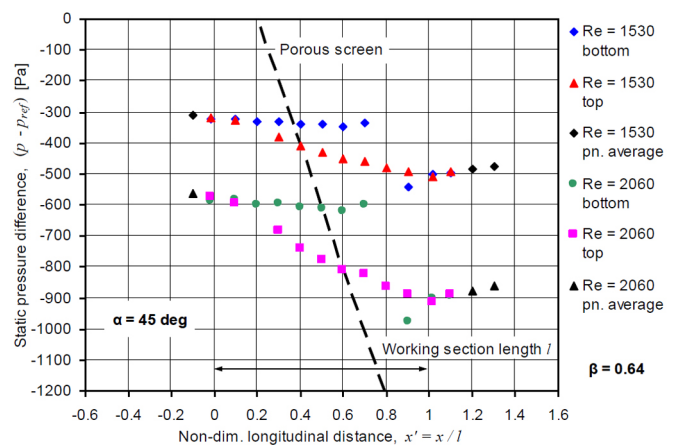
The results for the longitudinal pressure distribution along the duct show a consistent trend which is qualitatively similar for all screens tested. An example for a mesh of porosity $\beta = 0.64$ at 0 deg and 45 deg is shown in Fig. 3a and 3b respectively, where the non-dimensional coordinate (x') is used to describe the longitudinal distance from the start of the working section (x) relative to its total length (l). Generally, the pressure drop occurs in close proximity to the screen and its magnitude increases with wind tunnel velocity (shown as variation with Reynolds number in Fig. 3). The newly established lower static pressure remains approx. constant downstream of the screen for the remainder of the working section up to its end at $x' = 1$ and then slowly increases with distance. The same trend is observed upstream of the mesh. These changes in static pressure away from the mesh are due to variable cross section of the duct parts 1 and 2 which have corner fillets of longitudinally decreasing (with distance from the working section) cross section area.

As a result of the duct-type working section arrangement, when the mesh is inclined, differences in top and bottom pressure distribution occur in close proximity to the screen. These differences are of greater magnitude with increasing speed and angle of inclination. This occurs possibly due to a difference in the effective mesh inclination angle relative to the incoming flow (streamlines are aligned with the duct walls) between top and bottom of the working section. For example, as shown in Fig. 3b for an inclination of 45 deg, the mesh at the ceiling is inclined with the flow direction and at the floor it is inclined against the flow direction.

This results in a noticeably greater pressure drop across the mesh at the floor ($x' = 0.8$) compared to the one at the ceiling ($x' = 0.2$). Sufficiently far away from the mesh (upstream of $x' = 0.1$ and downstream of approx. $x' = 1$) the pressures on top and bottom even out as the flow symmetry in vertical direction within the duct is restored.



(a)



(b)

Figure 3. Longitudinal static pressure distribution across the 0.64 porous screen at 0 and 45 deg inclination x -axis: longitudinal distance along the wind tunnel centre line non-dimensionalized by the working section length, working section starts at $x' = 0$ and ends at $x' = 1$; y -axis: pressure difference between the local static pressures (upstream and downstream of the screens) and the reference ring static pressure in the contraction.

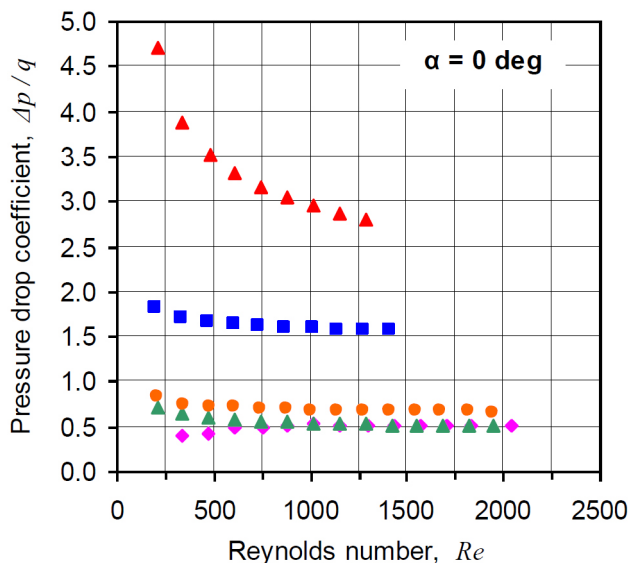
Note: the screen angle as shown in Fig. 3b is not indicative of the actual angle due to axis scale distortion.

To evaluate its variation with porosity and screen inclination, the pressure drop (Δp) is calculated with static pressure (p) values measured at both ends of the working section, see Eq. 2. This is sufficiently far enough to eliminate the previously described effects on the pressure distribution at the top and bottom of the wind tunnel caused by inclining the screen. For the purpose of non-dimensionalizing the data obtained, a pressure drop coefficient was introduced as follows:

$$\frac{\Delta p}{q} = \frac{(p-p_{ref})_{x \approx 0} - (p-p_{ref})_{x \approx 1}}{q} \quad (2)$$

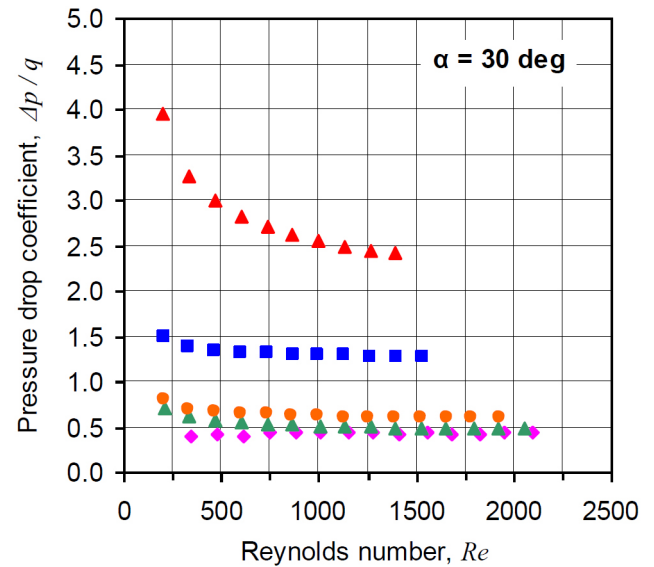
Idelchik [19] describes the pressure drop coefficient of barriers distributed uniformly over tube or duct cross sections to be dependent on their porosity, shape (holes arrangement) and flow Reynolds number. Data included in [19] for screens of various shape and porosity, suggests that $\Delta p / q$ becomes independent of Reynolds number (based on free-stream velocity and screen thickness) for $Re > 500$. Taking an average thickness of 1 mm for the meshes tested in the current experiments, the Reynolds number range is between approx. 200 and 2100.

The variation of $\Delta p / q$ with Reynolds number for 0 and 45 deg screen inclination is shown in Fig. 4. It is evident that for materials with porosity greater than 0.50, $\Delta p / q$ becomes virtually independent of Reynolds number for $Re \geq 500$ ($V \approx 8$ m/s) regardless of the mesh inclination, which is in good agreement with Idelchik [19]. The pressure drop coefficient variation for $\beta = 0.41$ shows tendency to become constant at higher speeds outside the tested range. For a given porosity, $\Delta p / q$ reduces with angle of inclination, thus inclining the screen would reduce its aerodynamic loading. As evident from Fig. 4, this effect increases with increased angle of inclination. For example, at $Re \approx 1280$ ($V = 19$ m/s) the pressure drop coefficient for $\beta = 0.41$ is reduced only by 1.6% between 0 and 15 deg, whereas between 0 and 45 deg the reduction is 39%.

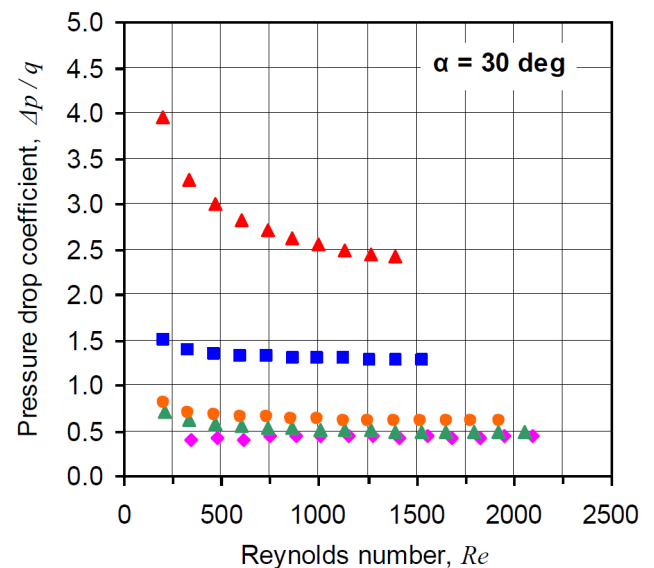


(a)

Figure 4.



(b)



(c)

Porosity:
 ◆ 0.76 ▲ 0.70 ● 0.64 ■ 0.50 ▲ 0.41

Figure 4. Pressure drop coefficient variation with Reynolds number and screen inclination