Experimental study on the influence of wire diameter on the internal flow behaviour of woven metal screens

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Abstract. Sintered woven wire mesh structures are a classic porous medium. In this paper, we examined the internal flow behaviours of sintered metal wire mesh structures with 0.215mm diameter wires with different porosities. Following previous research results, the influence of woven mesh wire diameter on material penetrating quality was studied. The air that was applied by the gas source was used to investigate structure performance. The Reynolds numbers of the inlet changed from 8.2 to 66.1. The pressures and flow rate at the inlet and outlet were obtained to calculate the permeability and inertia coefficient of each specimen, as well as the friction factors. The experiment results showed that permeability increased and the inertia coefficient decreased as wire diameter increased. Moreover, structures with large wire diameters \( (d_s = 0.215 \text{mm}) \) showed better penetrating quality at the same porosity levels. Increases in pressure drop kept pace with increases in diameter. The friction factor decreased as the Reynolds number increased, and tended to be constant.

1. Introduction

As technological advances improve thrust levels for jet engines, these engines need correspondingly better cooling techniques. A key problem associated with jet engine cooling lies in decreasing coolant consumption. The current composite cooling method on turbine blade offer suboptimal cooling for modern jet engines. Aero-engine engineers seek new and improved cooling methods. Transpiration cooling is a new cooling method that uses porous media to achieve higher cooling efficiency than traditional methods. Porous media effectively transfer heat because of the large heat exchange area within the unit volume [1]. Porous materials are widely used for a variety of applications including heat exchanger, solar energy collection, etc. [2-5]. To apply porous media to aero-engine cooling, it is indispensable to investigate the friction characteristics of porous structure.

Most research on flow and heat transfer behaviours focus on powder metal structures [6-8], which has been widely used in heat exchange, electronic equipment cooling, and other applications. For high centrifugal force environments such as the turbine blade in an aero engine, woven wire mesh structures have more application potential [9]; additionally, they are made of strong materials and they are relatively cheap to produce. Generally, wire mesh structures are woven. In this study, the flow resistance of Dutch weave metal screens were investigated. The Dutch woven matrix consists of machine direction and orthogonal cross-direction wires in each layer. Figure 1 shows the weaving pattern and close-up of a Dutch weave.
In 1968, Armour [10] studied the hydraulic resistance of several types of woven screens through experiments with a single screen layer. An expression to calculate the pressure drop was obtained. Xiong and Jiang [11] studied the influence of fluid compressibility on air flow resistance characteristics in Dutch weave wire mesh structures. Liu et al. [12] designed an experimental procedure to investigate the flow behaviour and heat transfer characteristics of Dutch weave metal screens with different porosities. They developed an empirical equation of friction characteristic for Dutch weave metal screens. Ma and Luo [13] set up the experiment to investigate the forced convection heat transfer of air in woven mesh porous structure with two layered media of different porosity. The experimental results showed that different porosity combinations significantly affected the flow and heat transfer parameters.

Despite the numerous works done to determine the pressure drop through woven-screen matrices, there have not been studies on the influence of Dutch woven metal mesh structural parameters on flow performance. In this study, a series of experimental tests was conducted to determine the influence of metal wire diameter (\(d_s\)) on the internal flow friction characteristic of Dutch weave metal screens, based on the research in Liu et al. [12]. In the previous reference study [12], the penetrating quality of sintered woven mesh with small diameter wires (\(d_s = 0.14\) \(mm\)) were experimentally studied to acquire the relationship between friction factor and Re in different porosities. To investigate the effects of wire diameter on woven mesh structure flow performance, we selected a large wire diameter (\(d_s = 0.215\) \(mm\)) test sample to obtain the flow resistance characteristic curve at different porosities. The woven mesh porosity was kept as a constant with the reference experiment [12].

2. Experimental system

2.1. Woven matrix and test section

Dutch weave screens are made of SAE 316 stainless steel wires with wire diameter in 0.215mm. The melting temperature of this type of stainless steel ranges from 1370\(^{\circ}\)C~1398\(^{\circ}\)C, which far exceeds the working temperature range of the current experiment. Thus, we can ignore material changes caused by temperatures in this experiment. The woven stainless steel wires suitably comprised the single-layer structure. Table 1 and Table 2 shows the parameters of the test pieces in the current experiment and reference [12], respectively. The averaged pore diameter values were measured by the manufacturer with a 0.5% measuring accuracy.

Table 1. Parameters in this experiment.

| Text# | Wire diameter (mm) | Number of layers | Averaged pore diameter(μm) | Porosity |
|-------|-------------------|------------------|---------------------------|----------|
| D1    | 0.215             | 15               | 154.7                     | 52%      |
| D2    | 0.215             | 18               | 126.6                     | 46%      |
| D3    | 0.215             | 22               | 76.4                      | 35%      |
Table 2. Parameters in the experiment of Liu et al. [12].

| Text# | Wire diameter (mm) | Number of layers | Averaged pore diameter(μm) | Porosity |
|-------|--------------------|------------------|-----------------------------|----------|
| S1    | 0.14               | 20               | 93.7                        | 55%      |
| S2    | 0.14               | 24               | 90.9                        | 47%      |
| S3    | 0.14               | 28               | 66.9                        | 37%      |

Figure 2. Schematic of the test sample.

As shown in Figure 2, the screen sample cross-section was 12mm × 5mm with 6mm thick in flow direction. The porosity in the present study is given by the following equation:

\[
\varepsilon = 1 - \frac{M}{\rho_f V}
\]

(1)

where \(M\), \(V\), and \(\rho_f\) are the mass, volume, and density of the test piece, respectively.

The porous sample itself is installed into a test bench as shown in Figure 3. It is observed that the sample was fixed in the middle of the flow channel which was tightly attached by two plexiglass cover plates. Two copper blocks can stop test sample from moving normal to the flow direction.

Figure 3. Test section.

2.2. Experimental apparatus

Originally constructed by Liu et al. [12], the experimental system used to investigate the flow and heat transfer performance of the sintered porous structure is shown in Figure 4. Compressed room temperature air was provided by an air compressor. The pressure and flow rate of the clean air which purified by filter were controlled through valve. Rosemount transducers (0.15% accuracy) were used for the pressure measurements which located before and after the test section. The K-type thermocouples with an accuracy of ±0.1 K were installed to measure the inlet and outlet gas temperatures. All the measurement instruments were connected to a data acquisition system with ADAM. The system was assumed to be at steady state when variations of the inlet and outlet fluid
temperatures were all within ±0.1K and the relative variations of the flow rate and pressure were all within ±2% for at least 10 min.

![Experimental setup diagram](image)

**Figure 4.** Experimental setup.

3. **Experimental results and discussion**

The modified Darcy equation [12] as shown in the following was used to calculate the pressure drop through a porous medium.

\[
\frac{\Delta P}{\delta} = \frac{\mu}{K} u + R_f \rho u^2 \tag{2}
\]

The value of permeability $K$ and inertia coefficient $R_f$ for each test sample should be evaluated in the experiment. $\delta$ is the test piece thickness, and $u$ is the average velocity calculated by the following equation:

\[
u = \frac{m}{\rho A_c} \tag{3}\]

where $m$ is the air mass flow rate, $A_c$ is the cross-section area of the channel.

In literature the pressure loss behaviour is commonly described with the dimensionless friction factor $f$.

In current study, the friction factor of the woven metal screen is defined as

\[
 f = \frac{\Delta P}{\frac{1}{2} \rho u^2} \cdot \frac{d_s}{\delta} \cdot \frac{\varepsilon^3}{1-\varepsilon} = \frac{2 \Delta P \rho A_c^2}{m^2} \cdot \frac{d_s}{\delta} \cdot \frac{\varepsilon^3}{1-\varepsilon} \tag{4}
\]

The characteristic length $d_s$ in this equation is the wire diameter of the screen, and $\varepsilon$ is the test piece porosity.

The Reynolds number is defined as

\[
\text{Re} = \frac{\rho ud_s}{\mu} \cdot (1-\varepsilon) = \frac{md_s}{A_c \mu} \cdot (1-\varepsilon) \tag{5}
\]

Following the uncertainty analysis in reference [12], the experimental uncertainty in the Reynolds number and friction factor are 6.1% and 9.3% of the presented data, respectively.

The value of permeability and the inertia coefficient for all the samples were determined from the experimental data are listed in Table 3. In this study, the experiments were repeated several times for ensuring the results reliable. For comparison, Table 4 shows the reference results [12].
Table 3. Properties of the investigated samples.

| Text# | Wire diameter (mm) | Porosity | Permeability ($\times 10^{-10} m^2$) | Inertia coefficient ($\times 10^{-5} m^{-1}$) |
|-------|-------------------|----------|---------------------------------------|------------------------------------------|
| D1    | 0.215             | 52%      | 1.45                                  | 0.181                                    |
| D2    | 0.215             | 46%      | 1.19                                  | 0.261                                    |
| D3    | 0.215             | 35%      | 0.29                                  | 1.377                                    |

Table 4. Properties of the investigated samples in Liu et al. [12].

| Text# | Wire diameter (mm) | Porosity | Permeability ($\times 10^{-10} m^2$) | Inertia coefficient ($\times 10^{-5} m^{-1}$) |
|-------|-------------------|----------|---------------------------------------|------------------------------------------|
| S1    | 0.14              | 55%      | 1.26                                  | 0.401                                    |
| S2    | 0.14              | 47%      | 1.06                                  | 0.883                                    |
| S3    | 0.14              | 37%      | 0.36                                  | 2.166                                    |

As shown in Tables 3 and 4, the variation trend of the permeability and inertia coefficient were similar on large and small diameters wires when the porosity changed. Permeability increased as porosity increased, while the inertia coefficient showed the opposite trend. Using these results, the relationship between pressure gradient and air velocity values could be obtained. Figure 5 shows the pressure gradient sharply increased with respect to the entrance velocity. The pressure gradient dropped with the porosity increase.

![Figure 5](image)

Figure 5. Penetrating quality curves for test pieces.

Test sample D1, D2, D3 $d_s = 0.215 mm$;
Test sample S1, S2, S3 $d_s = 0.14 mm$ from Liu et al. [12].

It can also be seen from Figure 5 that a larger wire diameter ($d_s = 0.215 mm$) led to lower flow resistance and higher penetrating quality at the same porosity.

Figure 6 shows the pressure drop variations for small and large wire diameter samples. The pressure loss of each piece increased following the air flow rate increase. When under constant flow rate, decreasing wire diameter led to the fall of pressure. Note that the parameters from Tables 1 and 2 revealed that test pieces with large diameter ($d_s = 0.215 mm$) had higher averaged pore diameter when compared at the same porosity. The wire diameter decrease resulted in smaller averaged pore diameter. It means that more channels were formed in the unit area of flow section which generated larger area of fluid-solid interface. Thus the higher frictional dissipation was created by much greater
contact area between air and inner wall of porous structure. This rule showed that a large diameter resulted in less effective contact area, thus decreasing the flow resistance.

![Figure 6. Pressure drop for samples in different diameters. Test sample D1, D2, D3 $d_s = 0.215\, mm$; Test sample S1, S2, S3 $d_s = 0.14\, mm$ from Xiong et al. [11].](image)

Figures 7 and 8 plot the friction factor variations at different Reynolds numbers for small and large diameter wires. With increasing Reynolds number Re, the friction factor $f$ decreases significantly in the beginning and then the variety reduction. It is important to note that for small wire diameter samples as showed in Figure 7, the data for the test pieces showed a single curve within an error band. This indicates that an empirical equation about the friction factor in different porosities could be provided in small diameter wires.

![Figure 7. The friction factor for various Reynolds numbers at various porosities (55%, 47%, 37%). Small wire diameter of test samples: $d_s = 0.14\, mm$.](image)

However, there is a clear difference between the friction factor curves with large diameter wires, which mean the results cannot be represented by one empirical equation. Moreover, it can be seen from Figure 8 that the friction factor curves for 52% and 46% porosity were very close. The trend can also be seen in the pressure gradient curve from Figures 5 and 6. This phenomenon may be caused by comprehensive factors such as parameter definition and mesh geometry structure. Thus, it is necessary to further study this problem.
Conclusions

In this work, an experimental setup was established to measure the internal flow resistance performances of woven metal porous structure with the same 0.215mm in wire diameter. The influence of woven mesh wire diameter on the penetrating quality of the material was studied and compared with the research results in Liu et al. [12].

The permeability and inertia coefficient change tendency of woven mesh structures along with porosity in different wire diameters were similar. However, large wire diameter ($d_s = 0.215\text{mm}$) structures showed better penetrating quality at the same level of porosity. For the conditions studied here, the pressure drop increase with respect to the diameter. The friction factor decreased as the Reynolds number increased, and tended to be constant.

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