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Turbulent characteristics of flow through open cell metal foam replica measured by time-resolved PIV

Chanhee Moon[1] and Kyung Chun Kim[1*]

[1]Pusan National University, School of Mechanical Engineering, Busan, Republic of Korea
*kckim@pusan.ac.kr

Abstract

Open-cell metal foam is a promising porous media for thermo-fluid systems. Flow characteristics inside a 10 PPI (Pores per inch) metal foam with a porosity of 0.92 are analyzed with a laminar inlet flow condition. The flow inside the metal foam structure is randomly furcated and interflowed by the interconnected pore network. Strong transverse motion is shown inside metal foam with about 23% of bulk velocity. This spanwise velocity is similar value to the result of Onstad et al. (2011) who investigated flow inside metal foam using magnetic resonance velocimetry in a turbulent inlet flow condition. It is evidence that the metal foam structure has a dominant influence on transverse motion. In addition, the evolution of spanwise vorticity was similar to the integral time and length scales of the streamwise center plane. The spanwise vorticity fluctuation inside metal foam structure is shown. Strong vorticity fluctuation was found. The results presented in this study are useful to understand turbulent characteristics of flow through metal foams.

1 Introduction

Open-cell metal foam is an irregular metallic porous media with open-cell topology. The skeletal portion of the metal foam, which is Plateau's border network, consists of many struts and nodes. The skeletal portion forms bone-like cell topology, this provides desirable geometrical characteristics to thermo-fluid applications such as high porosity, large specific surface area, tortuous flow path, good elastic moduli, and strength. Because of applicability to the various fields by these characteristics, the metal foam has been attracting attention.

Various experimental and numerical approaches have been used to understand metal foam flow. Experimental flow visualization is a promising approach to understand the underlying physics of metal foam flow. Lumped-parameter study inherently neglects the localized flow characteristics. The numerical simulation requires experimental validation data although they are a powerful tool to visualize the metal foam flow. Several experimental visualization studies have been performed.

Onstad et al. (2011) investigated characteristics of ensemble-averaged flow fields inside a 4x scale opaque metal foam replica using magnetic resonance velocimetry (MRV). A turbulent flow of bulk Reynolds number of 7900 passes through the metal foam replica that is filled in a duct. They found that the flow inside that replica has a strong transverse motion of 20-30% of the superficial velocity. MRV is the most advanced technology, which allows observing the flow inside an opaque material, but it has a drawback that cannot achieve time-resolved measurement of flow in complex and small structures like metal foam.

The characteristics of flow inside metal foams are still unclear. The flow features for non-turbulent inlet conditions, temporal characteristics, and the evolution of the flow inside metal foams should be examined further. Thus, this study conducted a time-resolved PIV measurement in a 3-D printed transparent metal foam replica. The turbulent characteristics of the flow in the metal foam were analyzed under incoming laminar flow condition.

2 Experimental setup

A 10 PPI aluminum foam was prepared for the metal foam sample. An X-ray computed tomography system was used to obtain a 3-D CAD (Computer-aided design) file. Under 200 kV, 200μA and 267ms condition, 743 x 740 x 459 voxels were generated with a spatial resolution of 0.032 mm. The voxels were converted to a 3-D CAD file. In CAD software, a part of the metal foam replica CAD file is cropped into a perfect hexagon that has a size of 10 mm x 10 mm x 25 mm. Because of the resolution of the 3-D printer, the size of the cropped model was doubled. Therefore, the final size of the metal foam replica file is 20 mm x 20 mm x 50 mm. The metal foam replica was printed by Polyjet type 3-D printer (Objet Eden260VS, Stratasys Ltd.). Vero Clear resin and water-soluble support material (SUP707) were selected as printing materials. Figure 1 shows the 3-D printed transparent metal foam replica after completion of every post-processing process.

The refractive index of Vero Clear material is 1.515 for 532 nm. Refractive index matched (RIM) solution based on NaI was prepared. As shown in Figure 2 (a), an acrylic square duct, which has size of 20 mm x 20 mm x 500 mm, was manufactured. Non-dimensional sizes and distances by duct diameter (D) are indicated. That duct has one inlet and one outlet, and they are positioned above the duct to observe the flow in the spanwise plane. 3-D printed metal foam replica is placed 15 D away from the inlet. A test loop has been configured to circulate the RIM solution through the test section. As shown in Figure 2 (b), it consists of a RIM solution container, a gear pump, a flowmeter, a bubble trap, a test section, and a traverse to move the test section. The RIM solution container is partially immersed in water bath. A constant temperature hot plate with 25°C was placed bottom of the water bath to maintain the temperature of RIM solution. The RIM solution is transported by the gear pump. Flowrate was measured by a turbine type flowmeter.

One CMOS high-speed camera (1k x 1k resolution) and one continuous wave laser (532 nm, 5 W) power were used to conduct time-resolved 2-D PIV experiment. Because equivalent diameter of struts is 0.8±0.06 mm, the thickness of laser sheets was set to 0.5 mm. Rhodamine B coated fluorescence polymer particle (1-20 μm) was used as tracer.

Calculated bulk velocity (U_b) from the flowrate was 0.82 m/s. Reynolds numbers based on channel hydraulic diameter and pore diameter are 511 and 100, respectively (Laminar).

Figure 1: 3-D printed transparent metal foam replica

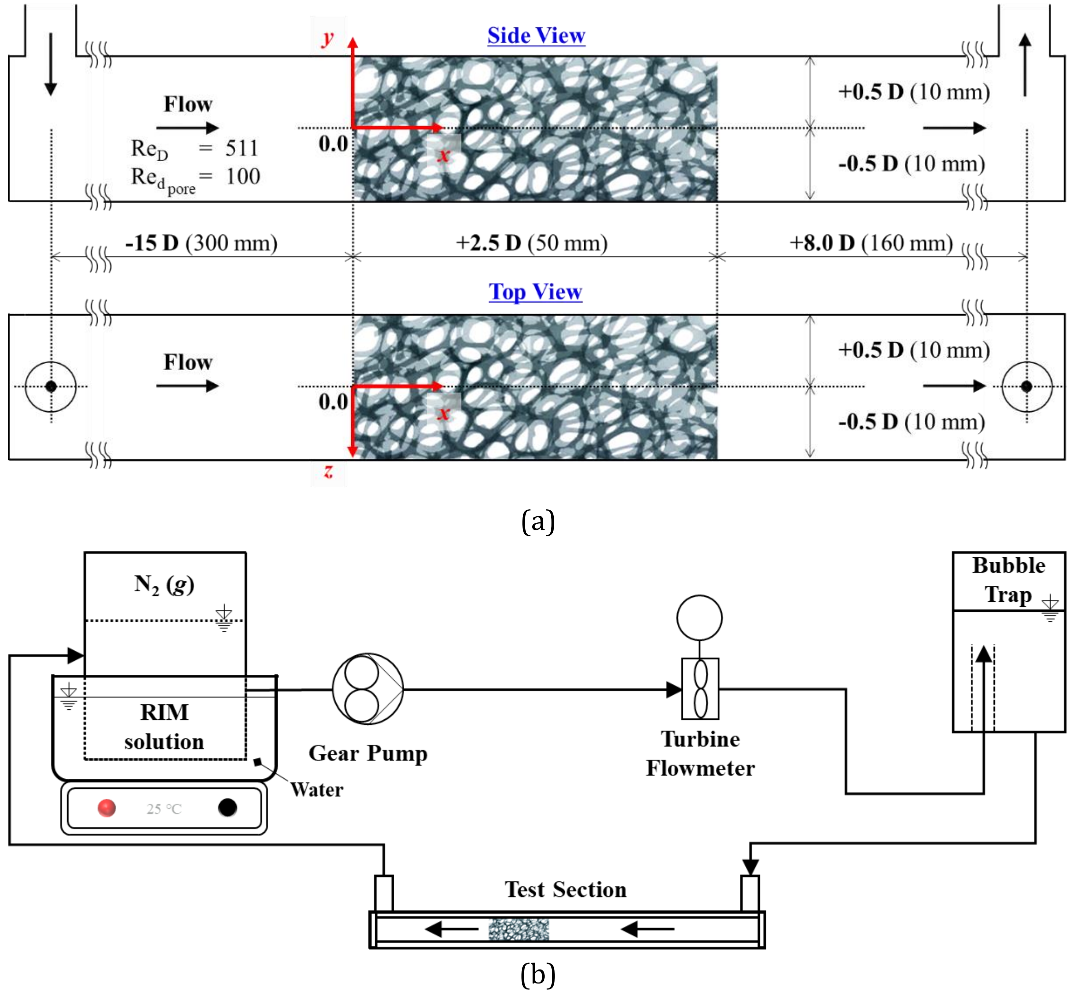

Figure 2: PIV setup and validated velocity vector field

3 Results and discussion

Figure 3 shows a contour of mean velocity magnitude of u (x-direction) and v (y-direction) components on the plane at z = 0 D. Mean velocity vector field is superimposed on the contour. Fluid flows to the right side. The distance of x-direction is non-dimensionalized by the channel diameter and pore diameter, respectively. The former is shown on the downside of the figure and the latter is shown on the upper side of the figure. The distance of y-direction is non-dimensionalized by the channel diameter. Mean velocity is non-dimensionalized by bulk velocity.

The unidirectional upstream flow of the channel is furcated into two or three by the pore network as soon as they encounter the metal foam structure. Four jets are formed at the entrance of metal foam structure (x = 0 to 0.25 D). The jets are decelerated after passing through one or two cells, but new jets are simultaneously formed through other pores. The new jet interflows into another jet. This furcating and interflowing process occurs throughout the metal foam and leads mixing of fluid inside metal foam structure. Considering this is just a two-dimensional plane, the number of furcating or interflowing jets could be larger than two or three.

The separation area behind struts should be noted due to its influence on pressure drop. Although Figure 3 does not show out-of-plane velocity component, the flow separation behavior is similar to

MRV data of Onstad et al. (2011). The size of the separation region is believed that depends on strut shape of metal foam. The shape of the metal foam strut is circular or triangular, and it depends on the porosity according to Plateau's law. The higher porosity, the shape of strut becomes triangular from circular. The strut shape of the present metal foam is triangular. The variations in heat transfer and pressure drop due to the strut shape change of Kelvin cells were studied by Moon et al. (2018), but the effects of strut shape in irregular metal foams should be investigated.

When $< \mathrm{v} >/\mathrm{U}_b$ is averaged over the inside of the metal foam, $\overline{< \mathrm{v} >/\mathrm{U}_b}$ is about 23%; <·> and $\bar{\cdot}$ indicates time and spatial average, respectively. This is similar to the result of Onstad et al. (2011): 20-30%. This similar result is important because the Reynolds number of present study is much lower than that of Onstad et al. (2011). This represents that the advection flow inside the metal foam is dominantly affected by the metal foam structure itself, and is consistent well with the prediction of Onstad et al. (2011) that large transverse motion may occur in laminar flow condition.

Figure 4 shows the root mean squared fluctuation velocity generated inside the metal foam.

Root mean squared fluctuation velocity can be defined as:

$$u'_{rms} = \sqrt{\frac{u_1'^2 + u_2'^2 + \cdots + u_l'^2}{l}} \tag{1}$$

where u'_{rms} is root mean squared fluctuation value of streamwise velocity, l is the number of vector frames. 10000 frames were used to obtain u'_{rms}. Root mean squared fluctuation value of transverse velocity (v'_{rms}) can be defined as in the same manner.

At the entrance of metal foam, u'_{rms}/U_b and v'_{rms}/U_b are near zero, but it increases to 0.1-0.4 inside the metal foam structure. After passing the exit of the metal foam, they approach to zero again. Velocity fluctuation occurs at the outlet region of the pores, at the junction of the jets, and behind the strut. This represents that the fluctuation might be caused by transverse motions generated by metal foam structure or unstable shear layer by the interaction of jets. However, these phenomena are extremely complex, so it seems that an extensive investigation of the cause of this fluctuation is considered necessary.

Integral time and length scales can be calculated for better understanding. Temporal auto-correlation function ($\rho_{u'}$) for streamwise velocity component u' is defined as:

$$\rho_{u'}(x, y, z, \tau) = \frac{u'(x,y,z,t)u'(x,y,z,t+\tau)}{\langle u'(x,y,z,t)u'(x,y,z,t)\rangle} \tag{2}$$

where τ is time lag. Integral time scale ($\mathrm{T}_{u'}$) of streamwise velocity component u' are defined as:

$$\mathrm{T}_{u'}(x, y, z) = \int_0^n \rho_{u'}(\tau)dt \tag{3}$$

where n is the time that $\rho_{u'}$ reaches the first zero. In this study, n is set to point that $\rho_{u'}$ reaches sufficiently low value (0.05) for a practical purpose. If the Considering Taylor hypothesis, the integral length scale ($\mathrm{L}_{u'}$) can be defined as:

$$\mathrm{L}_{u'}(x, y, z) = \mathrm{T}_{u'}(x, y, z)\langle u(x, y, z)\rangle \tag{4}$$

Figure 5 shows calculated integral time and length scales of $u'(t)$ on the plane at z = 0 D. The scales were normalized by the maximum their value, respectively. Overbar indicates line average for the y-axis. The integral scales rapidly decrease at the early stage. It logarithmically decreases from 0.5 D to 2.25 D. The integral scales slightly increase from the outlet region of the metal foam x = 2.0 D-2.25 D. These results represent that the flow is gradually complicated as it passes through metal foam structure. This may be effect of evolving transverse motion in the metal foam structure.

The evolution of spanwise vorticity through metal foam structures should be investigated. Spatially averaged vorticity magnitude ($\overline{\sqrt{< \omega_x >^2}}$) and root mean squared vorticity fluctuation ($\overline{\omega'_{x,rms}}$) of spanwise planes are shown in Figure 6. The $\sqrt{<\omega_x>^2}$ value increases inside the metal foam and dissipates to the original state at the downstream of the metal foam. Variation of $\overline{\omega'_{x,rms}}$ is interesting. This is also one of the evidence that the metal foam causes considerable flow disturbances even at a relatively low Reynolds number. The $\overline{\omega'_{x,rms}}$ value increases sharply in the entrance region of metal foam. After the entrance region, the $\overline{\omega'_{x,rms}}$ value is maintained at a similar level inside metal foam structure. From x = 2.0 D, the $\overline{\omega'_{x,rms}}$ value rapidly decreases. After then, it gradually decreases in the section of x = 2.75-4 D which is downstream of the metal foam structure. The reason the $\overline{\omega'_{x,rms}}$ value rapidly decreases at x = 2.0-2.5 may be the effect of outlet flow of metal foam. On the downstream side of the metal foam, a flow separation area larger than the inside is formed, thereby lowering the static pressure. This flow separation influences the upstream flow.

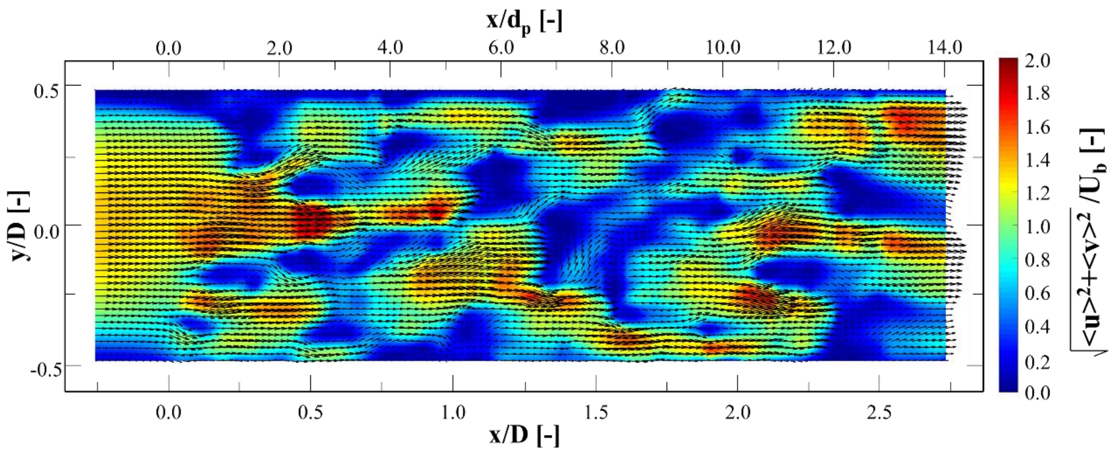

Figure 3: Mean velocity field at z=0 D

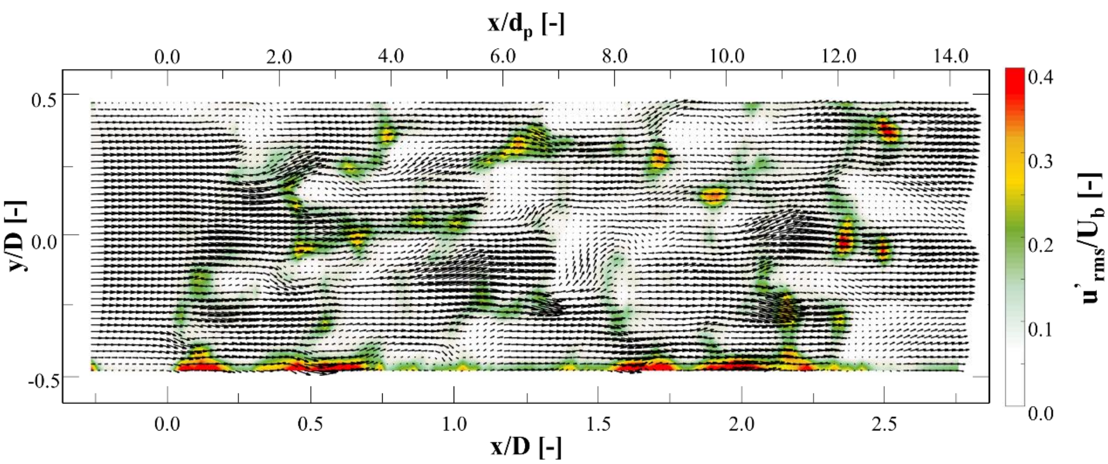

Figure 4: Root mean squared fluctuation velocity field at z=0 D

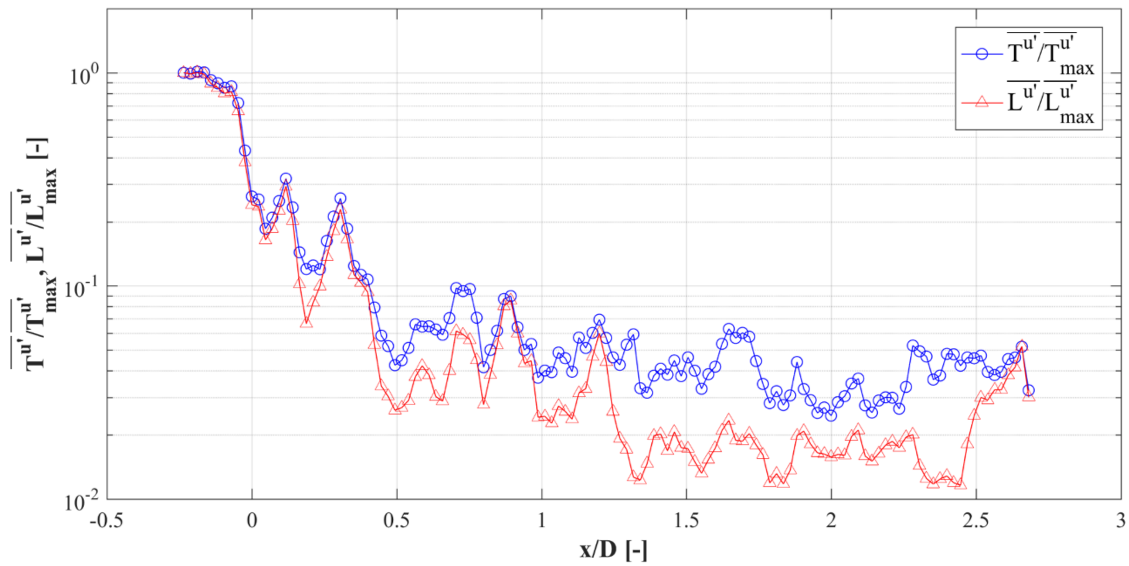

Figure 5: Integral time and length scales

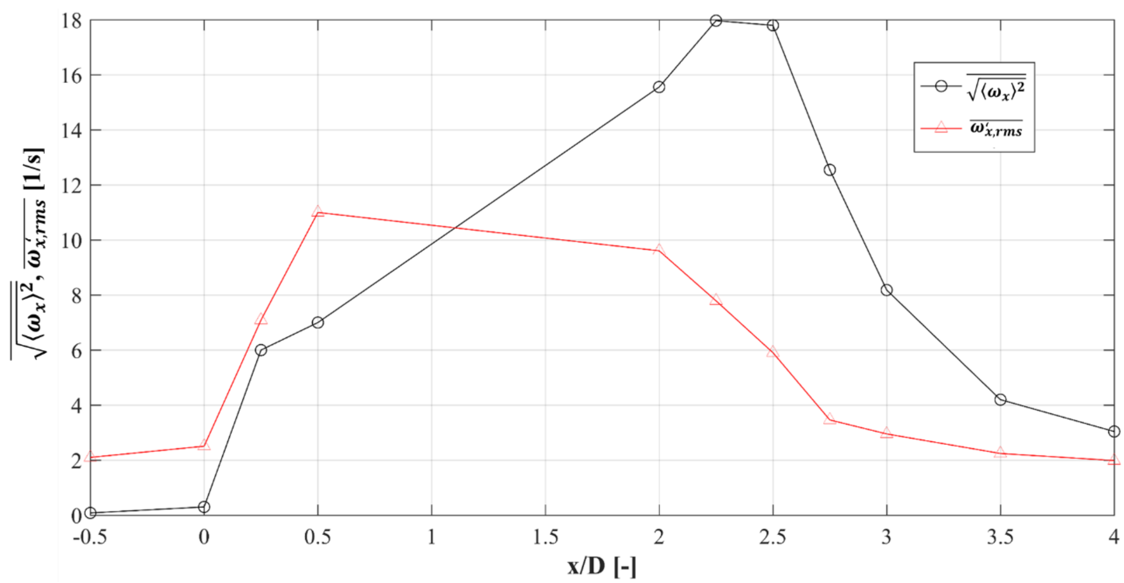

Figure 6: Spatially averaged vorticity magnitude and vorticity fluctuation along x-axis

4 Conclusion

Fluid flow entering the metal foam structure shows turbulent features. Jet-like flows are generated by the pore network, and the flow is furcated and interflowed successively. Shear layers generated by a jet are disturbed by interflowing jets. Strong transverse velocity was generated by 23% of U_b, and this was consistent with Onstad et al. (2011)'s prediction that the strong transverse motion in a metal foam may occur even in laminar flow condition. Evolution of the spanwise vorticity in the metal foam structure was presented. The spanwise vorticity inside metal foam is predicted to increase linearly along streamwise and this evolution shows a similar tendency of variation of integral time and length scales on the streamwise plane at z = 0 D. Spanwise vorticity shows considerable fluctuation due to the complexity of flow motion in the metal foam structure. It is expected that this fluctuation enhances heat and mass transfer inside the metal foam. However, in this study, the investigation was conducted only for a single Reynolds number and single metal foam geometry. Present channel size is also not large enough to avoid wall effect. It is necessary to study the flow characteristics under the various Reynolds number and metal foam structures.

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