Measurement of Fluid Dynamic Characteristics around Stenotic Obstruction in a Circular Channel

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Abstract : We measured experimentally the properties of fluid dynamics, velocity fields, and the pressure, around stenotic obstruction located inside a circular channel structure. Particle image velocimetry system was employed to obtain velocity fields at the central section of the circular channel in the streamwise direction. The stenosis model used was made of acrylic material with different stenotic aspect ratios. The working fluid was water and it was returned by a centrifugal pump system. Pressure measurements were carried out to validate the effect of a narrow passageway. Results showed that the acceleration of gap flow through stenotic obstruction and the pressure drop in the recirculation regime behind the stenosis model can be observed.

Key words : Stenotic Obstruction, Property, Particle Image Velocimetry, Aspect Ratio, Recirculation

1. Introduction

Cardiovascular-related diseases of the blood vessels are caused by various pathological factors. Stenosis, which is the drastic reduction in diameter of blood vessels, is one of these factors. Generally, the stenotic phenomenon has been observed to occur when LDL cholesterol contained in the blood sticks to the blood vessel wall and forms foam cells. The accumulation of sticky materials on a blood vessel wall generates arteriosclerosis.

It is also be one of the main causes of myocardial infarctions and heart failure, cardiovascular diseases with a global extent. From the fluid dynamics point of view, the investigation of the flow variables is very important in such tubular structure and can be helpful in the process of healing a severe

cardiovascular disease caused by stenosis.

In the fluid engineering research field, many experiments have been carried out for the measurement of the flow characteristics before and after a bluff body structure contained in a channel. These results can provide useful information to understand important properties of flow structure with considering the effect of geometry. Recently, more accurate measurements of flow field property are effectively performed by advanced measurement techniques [1].

To analyse a flow field completely, much more flow variables (velocity, temperature, density and pressure, etc.) are measured simultaneously and the flow field can be easily understood. In particular, for the case of internal flow, the flow field structure can

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be varied abruptly by the location of obstacle inside the channel [1,2]. Among these various physical quantities, pressure is known to suddenly drop when the flow passes around the structure [3,4].

Numerous numerical and experimental studies have been performed to discover fluid dynamic characteristic of stenotic structures [5]. In particular, numerical analyses [6,7] have been carried out to discover mechanisms that can avoid experimental limitations. A few experimental studies on the stenosis phenomenon have been performed [8,9] but the focus was mainly on the effect of pulsatile flow on the stenosis structure.

Therefore, in the present study, we focus on the flow structure around stenotic obstructions in a tubular structure by employing particle image velocimetry (PIV) velocity measurement technique with variations of stenotic aspect ratio (AR) and length. The pressure measurements are implemented by using dynamic pressure sensors placed at different locations before and after the stenotic obstruction. In addition to the experimental investigation on the pressure difference between front and back part of symmetric stenotic structure, we also validated pressure distributions by performing numerical analysis by using a commercial computational fluid dynamic code.

Figure 1: Experimental set up of a PIV measurement around the stenosis in a tubular structure.

(a)

(b)

Figure 2: Experimental model of tubular stenosis and coordinate system. (a) Stenotic structure and coordinate system, (b) Photograph of stenotic channel.

2. Experimental Apparatus and Method

Figure 1 shows the schematic of the experimental set-up used to measure velocity field around the stenotic structure in a transparent tubular channel. PIV measurement system consisted of a CCD camera with a resolution of $1K \times 1K$, delay generator, and pulse-type Nd:Yag laser system (30mJ, wavelength = 532 nm). A tubular structure channel made of acrylic material which contains a stenotic obstruction inside the channel wall region was used. A water tank with a centrifugal pump was employed to maintain constant inlet pressure at the entrance of the tubular channel.

Figure 2 shows the experimental model of tubular stenosis with coordinate systems used in the current study. The stenosis shape was modelled to accommodate variations of the inside obstruction rate, i.e., the stenotic aspect ratio (AR). The

stenotic AR is defined as the ratio of inner diameter (D_i) of stenotic section to the tube inside diameter (D_o) i.e., $AR = D_i/D_o$.

The stenotic aspect ratios tested were $AR = 0.25 \sim 0.5$. To observe the effect of stenotic length (L) on the wake structure behind the trailing edge of obstruction, the re-circulation regime was incorporated. The ratio of stenotic length to tube inside diameter used was $L/D_o = 1.75 \sim 2.0$.

To visualize flow structure qualitatively, the movement of seeded particle image is acquired with a high-resolution CCD camera. For a better understanding, the velocity field is overlapped with particle image and extracted velocity vectors.

To obtain the velocity field around a stenosis, the time interval between two image frames was set as approximately around 3~5 pixels/frame

movement ($\Delta T = 300 \mu s$). This allowed for a clear image acquisition. The resolution of the acquired image was 1008×1018 pixels and the physical observation area was approximately $950 \text{ mm} \times 960 \text{ mm}$. The interrogation window size was 64×64 pixels which overlapped by 50%.

To obtain the time-averaged mean flow structure, 300 instantaneous velocity fields were obtained for each stenotic shape. These instantaneous velocity fields were ensemble-averaged to obtain the spatial distributions of the mean velocity and turbulence statistics [10,11].

The measurement of the pressure at different sections of the tubular channel before and after the stenotic structure was made possible by inserting pressure sensor probes at five different locations along the length of the tube (i.e., $X/D_o = -3.0 \sim 3.0$,

Figure 3: Seeded particle image for PIV and overlapped velocity vectors according to stenotic aspect ratio and length variation. (a) $AR = 0.25$, $L/D_o = 2.0$, (b) $AR = 0.5$, $L/D_o = 2.0$, (c) $AR = 0.5$, $L/D_o = 1.75$.

where $D_o = 20$ mm). The highly accurate sensor used was the vented type with a range of 0~5 psi.

3. Results and Discussion

Figure 3 shows the qualitative image of seeded particle with the overlapped mean velocity vector

field around the stenotic obstruction structure at the central section of a channel. The laser light sheet illuminates the XR-plane passing through the tube centerline.

In the mean velocity field inside the stenotic structure, the oncoming flow accelerates as it goes

Figure 4: Mean velocity vector field and contour of streamwise velocity component with variations of stenotic aspect ratio and length ($AR = 0.25$, $L/D_o = 2.0$)

Figure 5: Mean velocity vector field and contour of streamwise velocity component with variations of stenotic aspect ratio and length ($AR = 0.5$, $L/D_o = 2.0$)

Figure 6: Mean velocity vector field and contour of streamwise velocity component with variations of stenotic aspect ratio and length ($AR = 0.5$, $L/D_0 = 1.75$)

downstream and passes the stenotic regime. Since we considered a 2-dimensional image, the stenotic structure is shown as a gap, and thus it exhibits a jet-like gap flow structure.

With regard the case of stenotic aspect ratio of $AR = 0.25$, the flow passes the gap region at a relatively low speed, and moves downward after passing through the trailing edge of stenotic structure hill due to rapid momentum loss. Since the flow momentum is relatively small, the size of re-circulation bubble decreases and rotational movement is slight.

In contrast, as the stenotic aspect ratio increases to that of $AR = 0.5$, the flow speed increases due to decreased gap area. The flow velocity increment causes a relative increase of re-circulation bubble size, which is directly related to the momentum increase of wake at the downstream regime [12,13]. This is shown in Figures 4 and 5.

When the stenotic aspect ratio is small, the maximum velocity level is relatively decreased with widely spread low speed flows at the gap regime as shown in Figure 4. In addition, the streamwise mean velocity component variations are relatively

dominant due to momentum decreases than those of larger aspect ratio cases. As the aspect ratio of stenosis increases, however, the maximum gap flow velocity increases and fluctuations decrease with the relative momentum recovery (Figure 6).

The two counter-rotating re-circulation zones behind the trailing edge of stenotic obstruction are observed. However, the entire wake structure behind a stenotic obstruction is relatively similar according to the changes of the stenotic length variations in the ranges between $L/D_0 = 1.75$ and 2.0.

It means that the momentum loss difference during passing through the gap region of stenotic channel is relatively slight in the range tested in this study. The re-attachment region is almost same at both cases. Therefore, we can conjecture that the effect of aspect ratio variation on the re-circulation length variation is more significant than that of the stenosis length.

Figure 7 shows the pressure variations in the tubular structure containing the stenosis at the wall region. In both cases, the pressure starts to decrease from the inlet of the tube. Pressure achieves a minimum value in the middle of the structure and subsequently increases again.

Figure 7: Pressure variations in the tubular structure before and after the stenosis. (a) Effect of AR variation ($L/D_o = 2.0$), (b) Effect of stenosis length variation ($AR = 0.5$)

This increase is not enough to avoid the formation of the recirculation zones after the trailing edge of the stenosis because the pressure remains negative except for the case of $AR = 0.25$, where the pressure nearly reaches the value of the inlet pressure. This accounts for the undefined recirculation zones for this particular velocity measurement.

In order to validate the pressure distribution around stenotic obstruction, we carried out numerical simulation based on computational fluid dynamics. The channel containing the stenotic

Figure 8: Pressure distribution around stenosis based on numerical analysis ($L/D_o = 2.0$). (a) Effect of AR variations, (b) Contour plot of pressure distribution ($AR=0.5$).

structure was modeled under the same conditions as that of experiment case. A commercial code CFX (ANSYS, USA) was employed for the analysis of the problem.

The model is divided using unstructured mesh method with the maximum face and tetrahedron size. The walls and the boundaries are inflated in smooth transition and the maximum inflation layers used were 5. Total numbers of the elements solved are 112,961.

The inlet condition is subsonic range with an

average static pressure of 490 Pa. The outlet of the channel is assigned as an atmospheric pressure boundary condition and no slip boundary condition is assumed at the walls. Steady state, incompressible and inviscid flow conditions with 5% turbulence intensity are assumed. Navier-Stokes equations are solved using $k-\varepsilon$ turbulence model. The finite element method based program is running for 87 iterations and it takes approximately 12 minutes to converge with a convergence criterion of 1.0×10^{-4} .

Figure 8 shows the pressure variation along the axial direction of the channel. In front of the stenosis entrance region, the pressure is increased due to accumulation converging flow. While passing the stenosis, the pressure drops subsequently with decrease of cross-sectional area of the stenotic channel part [14]. These results are in good agreement with the experimental data and previous results [15].

4. Conclusion

In the present study, the flow and wake structures around the stenosis located inside a tubular structure were investigated experimentally by using PIV velocity field measurement technique with variations of stenotic aspect ratio and length. In the near wake regime, we observed a weak recirculation flow structure. In addition, the gap flow momentum increased relative to the increase of stenotic aspect ratio.

When the stenotic obstruction length increased, the size of recirculation length likewise increased. However, the flow structure inside the gap regime of stenotic structure showed nearly similar flow patterns under these experimental conditions. The results from the pressure measurement in the whole tubular structure support the velocity field distributions and the formations in the recirculation region, especially those measured after the trailing

edge of the stenosis.

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