Measurement of a Round Jet: Prediction of Valvular Regurgitation and its Lesion Size

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Abstract: The velocity profiles of an axisymmetric circular jet with initially laminar boundary layer condition were measured extensively from the jet exit to about 45 diameters (d) downstream with a single hot wire probe to verify a new quantification method for valvular regurgitation and its lesion size. The flow visualization using smoke-wire at the near field of the jet indicates that the interaction of the mixing layer is rather smooth and gentle. As a result, the self-preservation of the centerline local mean velocity (U_0) and half radius (R_u) were established at a rather short distance from the jet exit. The onset of self-preservation of U_0 is found to be about 6d with initial laminar velocity condition and this distance may be used as a guide-line to predict the orifice of lesion (presumably circular in shape). Velocity measurements for valvular regurgitation jets for that for that matter, should be taken at a minimum distance of 6d.

Keywords: *Round jet, Valvular regurgitation, Lesion size*

INTRODUCTION

A regurgitant jet from an incompetent heart valve, in particular through the mitral or tricuspid valve can be considered in many, not all, cases as a free turbulent jet [1]. This valvular incompetence or insufficiency or regurgitation, refers to the condition in which a closed heart valve does not totally prohibit back flow, as in its fundamental purpose, but allows some leakage. This is usually due to either a leaflet lesion (tear) or improper closure of the leaflets. Both will hereafter be referred to as the lesion. The high pressure in the left ventricle make the mitral and aortic valves especially susceptible to this condition.

In the case of mitral regurgitation, the blood is driven through the lesion by a pressure difference of about 100 mm Hg (that is, the left ventricular pressure is about 120 mm Hg). As a result of the blood being forced through the small orifice by such a large pressure, a jet flow is formed distal to the lesion in the left atrium. The amount of blood lost through such a lesion during one heart beat is called the regurgitant volume. Since the heart pumps to a certain extent corresponding to the need of the body, the regurgitant volume is a quantity of interest in the assessment of this condition. From an engineering point of view, the energy wasted in pumping the regurgitant volume backwards instead of forward lowers the efficiency. Based on an estimation of regurgitant volume and/or lesion size, cardiologists can make decision on valve replacement.

The most common method to assess the severity of regurgitation has been angiography. But, the disadvantages of this method are its invasive and semi-quantitative nature. However, Doppler echocardiography is able to overcome these drawbacks since such ultrasound techniques have allowed visualization of regurgitant jets behind leaking heart valves, and have made velocity values available within the jet non-invasively [1, 2]. The equation, developed based on the conservation of momentum, can quantify regurgitant volume Q_O without requiring knowledge of the orifice size, may be written as:

$$Q_o = \frac{(U_o x)^2}{50.5 U_j} \tag{1}$$

where x is the axial distance from nozzle (see Figure 1 for the definition sketch) and U_j is the jet exit velocity. Note that both U_O and U_j are measurable with currently available Doppler ultrasound techniques, without the need for planimetering the jet area. U_j can be obtained by continuous wave Doppler and U_O by pulsed Doppler, while colour Doppler flow mapping can determine both U_O and U_j .

Based on the conservation of momentum and within the framework of self-preservation, the diameter d of the jet can be expressed as:

$$d = \frac{x U_o}{C U_j} \tag{2}$$

where C is a velocity constant. A semi-empirical value of 6.3 was recommended [3] for the constant C and the diameter d of the unknown hole size can therefore be predicted.

To validate Eq. (2), an experimental investigation [4] has been carried out to predict orifice size from the velocity measurements made within the issuing free jets from both circular and non-circular orifices. The non-circular orifices consist of ellipses, equilateral triangle, cross, square and rectangle. Although the predicted orifice size is satisfactory for the circular orifice, it under-predicted the equivalent diameter for the non-circular orifices by about 10 to 30 percent depending on the orifice shape. This under-estimation may be due to the measurements not being taken far enough downstream from the orifice exit, i.e., the self-preservations of the jet are not well established. In their study [4], since the sharp edge orifices were employed, the jet exit boundary layer were not established.

Recent study [5] has shown that there may be many self-preserving states, e.g., full, partial or local, and the attainment of any particular state is uniquely determined by the initial conditions.

In the present work, a single hot wire probe was used to measure the mean and root mean square velocity profiles so as to establish the self-preserving region in the near and far fields of the circular jet which has an initially laminar boundary condition. Flow visualization by using smoke-wire is also carried out at the near field of the jet.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental facility used basically consists of a variable speed three-phase a.c. centrifugal blower which supplies air to a fibre-glass axisymmetric nozzle with a diameter contraction ratio of 10:1. The diameter of the nozzle is 25 mm. The measurements were made with velocity of jet U_j set at 26 m/s, that is for jet Reynolds number (Re = $U_j d/\nu$ where ν is the fluid kinematic viscosity) of 40900. The instantaneous velocity U was measured with single hot wire probe mounted onto a height gauge (with resolution of 0.01 mm) which was fixed to a traversing mechanism capable of traversing in three perpendicular directions (that is, x, y and z axes). The 5 μm diameter (Wollaston, Pt-10% Rh) wire was operated by a constant temperature anemometer at an overheat ratio of 1.5. The active length of the hot wire was approximately 1.2 mm. The hot wire was calibrated before and after each series of measurements at the potential core of the jet exit, by using a pitot static tube connected to a twin-wire resistance probe water manometer [6] with a resolution of 0.01 mm water. Signals from the constant temperature anemometer and the manometer were digitized by a 12-bit analog-to-digital converter. A sample of 100 was taken for each data used for processing (duration ≈ 7 sec).

For calibration of hot wire, the manometer and anemometer voltages were digitized and the wire calibration constants were determined by the method of least squares. The voltage fluctuation was digitized into a computer and a software converts the instantaneous voltages to velocities, the mean and root mean square velocities were then determined. The data gathered can be retrieved when required for further processing and analysis. At the centerline of the nozzle exit plane, the turbulent intensity of the flow u'/U_j is about 1.3%.

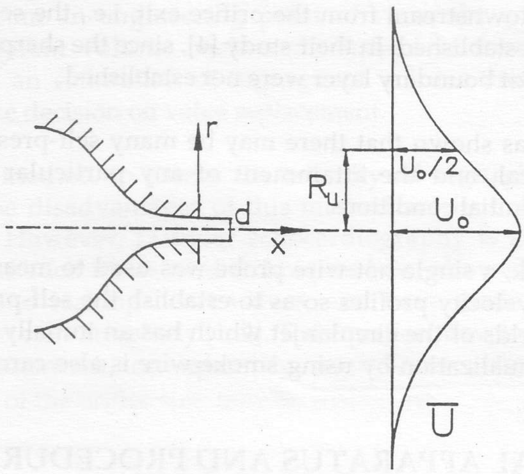

Fig. 1: Definition sketch

RESULTS AND DISCUSSION

The mean axial velocity across the nozzle was approximately top hat in shape and symmetrical about the jet centerline. The velocity profile at the jet boundary layer agrees closely with the Blasius solution for the flat plate as shown in figure 2. The normalizing length scale δm is the boundary layer momentum thickness which is equal to about 0.0067d, and y is the vertical distance measured from the wall of the nozzle.

Figure 3 shows a smoke visualization photograph taken in the near field of the jet so as to extend the documentation of its initial condition. In the photograph, the flow is from right to left and two vertical markers are placed at about 1.4d and 3.5d form the jet exit. The smoke is generated by heating an oil coated tungsten wire of 0.11 mm diameter, placed at about 2 mm away from the exit of the nozzle. The tungsten wire is stretched across the nozzle and fastened on the fringe of the nozzle by two screws (see figure 3) which are connected to a power supply with voltage varying from 20 to 30 volts and the heating time was set within 100-400 msec. The smoke is then illuminated by a vertical light sheet produced from a 1 W Argon laser using a cylindrical lens.

more prominent large-scale structure than those with an initially turbulent boundary layer[10].

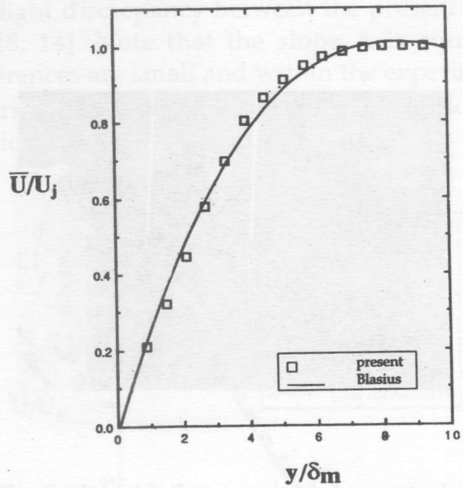

Fig. 2: Boundary layer velocity distribution at the nozzle exit

It can be seen in figure 3 that the streaklines from the smoke-wire at the exit of the nozzles are thin and straight, indicating that the initial flow condition is stable and laminar. At about 1.5d downstream the shear layers become unstable, and vortical structure, which is expected to be in the form of toroidal vortex ring, appears at about 2d downstream. As the flow proceeds, another pair of vortices is formed and the structures merge at the end of the potential core (about x/d = 4) and the flow becomes fully turbulent. Many features found in this photograph can be seen in smoke photographs [7], Schlieren photographs [8] and shadowgraphs [9]. It is evident from the photograph that the interaction between the structures is not strong when they merge at the end of the potential core. These may explain why the mean velocity is achieving self-preservation at a rather short distance from the jet exit.

Effort has been made to visualize the flow at higher Reynolds numbers and with transient (from laminar to turbulent) boundary layer, however due to early dispersion of the smoke at higher jet velocities, the results were not satisfactory, and hence not presented here. In general, it can be observed that, as the Reynolds number is increased, the size of the vortical structure is decreased and the structures appear earlier and at a closer distance from the jet exit. With a transitional boundary layer, the structure becomes less evident. This is consistent with the finding that the jet with initially laminar boundary layers has a much more prominent large-scale structure than those with an initially turbulent boundary layer [10].

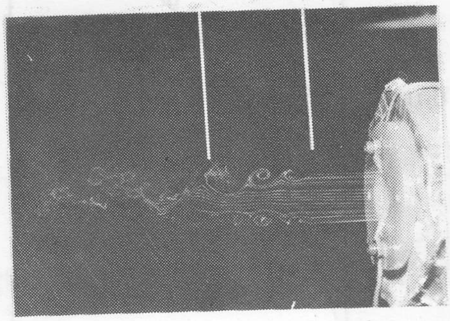

Fig. 3: Smoke-wire photograph in the near field of the jet (Re = 11,500 and U_j = 7.3 m/s). The 1st and 2nd markers are located at 1.4d and 3.5d respectively from the nozzle exit

The mean velocity profiles in the range of $4 \leq x/d \leq 45$ are presented in figure 4 using the centerline mean velocity U_o and the velocity half-radius R_u as the normalizing scales. The result complies reasonably well with self-preservation and bears a close resemblance with result obtained by Chua and Antonia [8]. The mean velocity profile indicated that similarity is achieved at very small x/d ($\approx$ 4). However, the shape of the normalized mean velocity is not a sensitive indicator of self-preservation [11, 12]. Within the frame work of self-preservation, the equations for the conservation of momentum is satisfied, on a local and integral basis, if $U_o \sim x^{-1}$ and $R_u \sim x^{1}$.

Figure 5 illustrates the variation U_o and R_u along the axial direction, also plotted in the graph are the results obtained by other investigators [8, 14]. It is indicated in figure 5 that the stream wise variation of U_o and R_u is approximately linear starting form 6 diameters downstream. The early attainment of self-preservation of U_o and R_u is consistent with the finding by Chua and Antonia [8] that the length of the interaction region, that is the region that extends approximately between the end of the potential core and the onset of self-preservation at the far field, of the circular jet is comparatively short. Further, the transition between the values corresponding to the potential core and those pertaining to the self-preserving far field appears to be quite smooth. A comparison of the slope A and B with those references with laminar boundary layer at the jet exit in Tables 1(a) and 1(b) show that there is only a slight discrepancy between the present result and that of the other investigators [8, 14]. Note that the slope A is equal to 1/C in Eq. (2). However, as the differences are small and within the experimental uncertainty (of ± 6%), the semi-empirical constant C of value 6.3 recommended [3] may be used in Eq. (2) for the prediction of nozzle size.

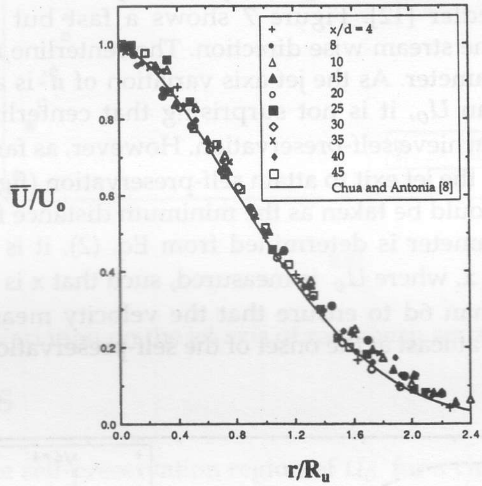

Fig. 4: Mean velocity distributions using self-preserving scales

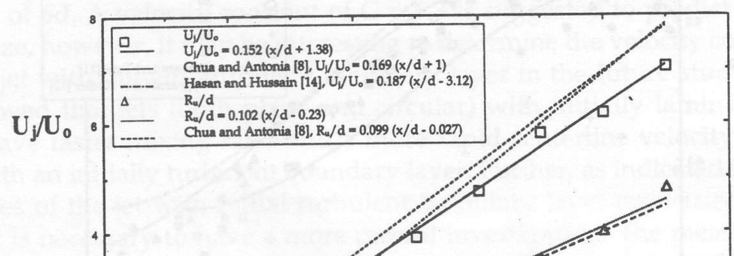

Fig. 5: Streamwise variation of the mean velocity U_0 and the half-radius R_u

Bevilaqua and Lykoudis[16] introduced a concept of a hierarchy of self-preservation, that is self-preservation of order one, the state when the mean velocity profiles are self-preservation, of order two, when in addition of the Reynolds normal stress profiles are self-preserving and so on through the higher order moments. The normalized root mean square longitudinal velocity u' profiles in figure 6 indicate that the self-preservation is achieved at x/d=10. the present self-preserved u'/U_0 profiles agree reasonably well with Chua and Antonia [8] and Chevray and Tutu [11] although comparatively lower than those obtained by Wygnanski and Fiedler [12]. Figure 7 shows a fast but linear increment of centerline u' along the stream wise direction. The centerline u' reaches a constant value at about 15 diameter. As the jet axis variation of u' is a stricter indicator of self-preservation than U_0, it is not surprising that centerline u' take a longer distance than U_0 to achieve self-preservation. However, as far as U_0 is concerned, it takes only 6d form the jet exit to attain self-preservation (figure 5). It is therefore suggested that 6d should be taken as the minimum distance for the measurement of U_0. When the diameter is determined from Eq. (2), it is worth checking the stream wise distance x, where U_0 is measured, such that x is at least equal to and preferably greater than 6d to ensure that the velocity measured is behind the potential core, and is at least at the onset of the self-preservation region.

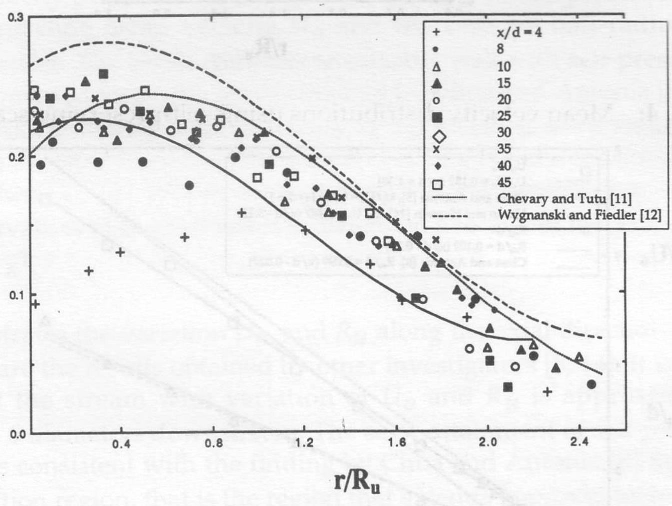

Fig. 6: Distribution of longitudinal Reynolds stress

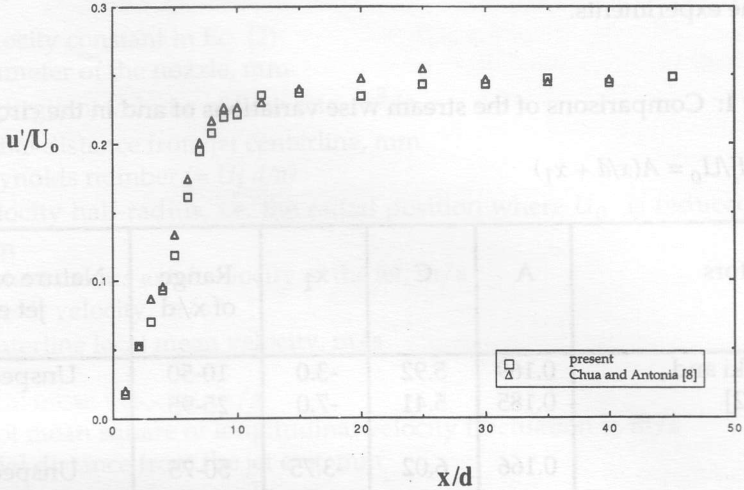

Fig. 7: Variation on the jet axis of root mean square velocity

CONCLUSIONS

The beginning of the self-preservation region of U_0 for a circular jet with initially laminar condition is found to be about 6d downstream from the jet exit. Velocity measurements for predicting orifice size therefore should be taken at a minimum distance of 6d. A velocity constant of C = 6.3 is suggested to predict the circular orifice size, however, it may be interesting to determine the velocity constant C for circular jet with initially turbulent boundary layer in the future study. Hill, et al [10] showed that jets (both plane and circular) with initially laminar boundary layers have faster mixing rates and a more rapid centerline velocity decay than those with an initially turbulent boundary layer. Further, as indicated in Table 1(a) the slopes of the jet with initial turbulent boundary layer are varied in a wider range, it is necessary to have a more careful investigation. The measurements of jets with other configuration such as square, triangle, rectangle and ellipse with known initial boundary layers may be worth pursuing in the future investigation in order to obtain an acceptable universal constant C in predicting the size of the heart valvular lesion and regurgitation volume.

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Table 1: Comparisons of the stream wise variations of and in the circular jet

(a) $Uj/U_0 = A(x/d + x_1)$

Investigators	A	C	x_1	Range of x/d	Nature of flow at jet exit
Wygnanski and Fiedler [12]	0.169 0.185	5.92 5.41	-3.0 -7.0	10-50 25-95	Unspecified
Rodi [13]	0.166	6.02	-3.75	50-75	Unspecified
Hasan and Hussain [14]	0.187 0.247	5.35 4.04	-3.12 -6.20	10-45 10-45	Laminar Turbulent
Saetran [15]	0.203	4.93	-4.02	20-55	Turbulent
Chua and Antonia [8]	0.169	5.92	1.00	6-45	Laminar
Winoto, et al [4]	0.167	6.0	N. A.	4-20	Sharp edge nozzle
Present	0.152	6.58	1.38	6-45	Laminar

(b) $R_u/d = B(x/d + x_2)$

Investigator	B	x_2	Range of x/d	Nature of flow at jet exit
Saetran [15]	0.099	-6.0	20-55	Turbulent
Chua and Antonia [8]	0.099	-0.027	6-45	Laminar
Present	0.102	-0.23	6-45	Laminar

NOMENCLATURE

C	velocity constant in Eq. (2)
d	diameter of the nozzle, mm
Q_o	regurgitant volume of flow rate, m^3/s
r	radial distance from jet centerline, mm
Re	Reynolds number (= $U_j\ d/n$)
R_u	velocity half-radius, i.e. the radial position where U_0 is reduced to half, mm
U	instantaneous axial velocity of the jet, m/s
U_j	jet exit velocity, m/s
U_o	centerline local mean velocity, m/s
$\bar{U}$	axial mean velocity, m/s
u'	root mean square of longitudinal velocity fluctuation u, m/s
x	axial distance from the jet exit, mm
n	kinematics viscosity, m^2/s

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