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WALL-PRESSURE FLUCTUATIONS OF SUBSONIC AND SUPERSONIC ORIFICE-PLATE FLOWS

M.K. BULL and W.T. JOHNSON

Department of Mechanical Engineering,
University of Adelaide, SA 5001
AUSTRALIA

ABSTRACT

Measurements of the internal wall-pressure fluctuations in the separated and reattaching flow downstream of an orifice plate in a turbulent pipe-flow show that, in the separated flow region, the ratio of rms wall-pressure to dynamic pressure in the jet issuing from the orifice does not change significantly from subsonic to supersonic flow. However, at a given streamwise position in the region just downstream of flow reattachment dramatic differences can occur owing to differing rates of decay of orifice-generated turbulence. Tests of an orifice and a simple valve-model, both with supersonic flows, show that even if flow-disturbing devices have different geometries, they will produce similar wall-pressure fields if they cause similar flow separations.

1. INTRODUCTION

As part of a general study of the internal turbulence and acoustic pressure field generated when a fully-developed turbulent pipe-flow is disturbed by pipe fittings, the effects produced by various orifice plates and a simple valve-model have been investigated. The general character of the orifice flow (figure 1a) involves flow separation from the pipe walls and subsequent reattachment. Earlier work, by Norton (1979), Bull & Norton (1983), Bull & Agarwal (1984) and Agarwal (1985), was confined to flows in which the velocity in the free jet issuing from the orifice was subsonic or, at most, just sonic. When the jet velocity becomes supersonic, an under-expanded jet forms in the region of separated flow downstream of the orifice plate. Some results for the internal fluctuating wall-pressure field of supersonic flows have been given previously by Bull and Johnson (1986). Here additional subsonic and supersonic data are presented in an attempt to highlight further the similarities and differences between the wall-pressure fluctuations of supersonic and subsonic orifice-flows, and to explain some previous, apparently anomalous, results. A comparison is also made between a supersonic orifice-flow and an axi-symmetric flow through a simple model of a drilled-hole-cage valve (figure 1(b)), with almost identical mean-flow parameters.

2. EXPERIMENTAL DETAILS

The rig in which the tests were made consists of an 11 m run of steel pipe, of internal diameter $d_p = 72.54$ mm, through which an air flow can be induced. Atmospheric air enters through a bell-mouth and discharges, through a nozzle of throat diameter d_c, to vacuum tanks. Orifice plates of diameter d were installed about 44 pipe-diameters downstream of the inlet, at a point where the undisturbed flow would be fully-developed. Steady conditions, determined by the combination of D_o and D_c (written as D_o/D_c, where $D_o = d_o/d_p$ and $D_c = d_c/d_p$) prevail in the pipe while the exit nozzle remains choked.

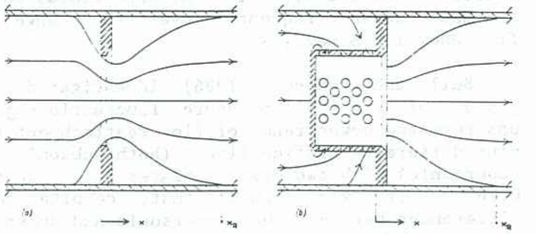

Figure 1 Flow through a) orifice plate & b) valve-model.

Two orifice plates, with $d_o = 36.27$ mm ($D_o = 0.50$) and $d_o = 55.0$ mm ($D_o = 0.76$) respectively, were tested with a wide range of chokes, $D_c = 0.39$ to 1.00. Another orifice-plate, with $D_o = 0.62$, and a model of an axial-flow drilled-hole-cage valve with an equivalent diameter based on open hole area of 42.7 mm (equivalent $D_o = 0.59$) and an internal cage-diameter $d_v = 47.00$ mm, giving $D_v = d_v/d_p = 0.65$, were tested with only one choke, $D_c = 0.80$. The valve model has five rows of eighteen 4.5 mm holes equally spaced around its circumference.

In terms of the streamwise coordinate x measured from the upstream face of the orifice plate, flow reattachment occurs at $x = x_R \simeq 10h$, where $h = (d_p - d_o)/2$ is the orifice height. Measurements were made of the internal wall-pressure fluctuations, by means of a flush-mounted 6.3 mm Bruel and Kjaer condenser microphone, at various positions in the range of $X = x/d_p$ from -3.31 to 51.2, although spectral data are presented here for only two positions on either side of flow reattachment ($x/h = 8.3$ and 25.0), for $X = 51.2$ far downstream, and for $X = -3.31$ just upstream of the orifice.

3. PREVIOUS WORK

Agarwal (1985) investigated the streamwise variation of wall-pressure fluctuations for four orifice-plates ranging from $D_o = 0.62$ to 0.83. To describe the streamwise variation of overall rms wall-pressure fluctuation p', he suggested a scaling of p'/q_j as a function of x/x_R (where $q_j = \frac{1}{2}\rho U_j^2$ is the dynamic pressure in the jet flow from the orifice) for the range $0 < x/x_R < 3$, as shown in figure 2. This implies that the wall-pressure fluctuations in this region are dominated by the turbulence created by the insertion of the orifice-plate into the flow. Further, for four flows through two different

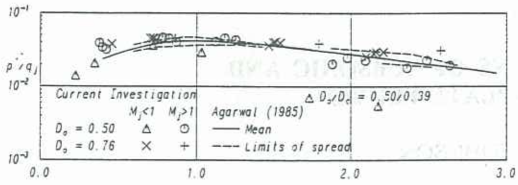

Figure 2. RMS wall-pressures near flow-reattachment.

orifice-plates, at X = 1.03 in the separated flow region, Agarwal showed that the wall-pressure spectra were similar when expressed in the form $\Phi_p = [\phi_p U_j/q_j^2 a]$ as a function of $\Omega = \omega a/U_j$ (where ϕ_p is the power spectral density [p.s.d.] of the wall-pressure fluctuations, U_j is the orifice-jet velocity, a is the pipe radius and ω is the radian frequency) over the range of frequency $1.0 \le \omega a/U_j \le 10.0$.

Bull and Johnson (1986) investigated the p.s.d. of the wall-pressure fluctuations just upstream and downstream of flow reattachment for nine different orifice-flows (both subsonic and supersonic) with two orifice-plates $D_o = 0.50$ and 0.76. It was found that, despite some differences between the supersonic and subsonic spectra, p'/q_j values were in fair agreement with Agarwal's (1985) scaling. The most notable discrepancy was for a completely subsonic flow with $D_o/D_c = 0.50/0.39$, which gave a p'/q_j value at $x/x_R = 2.2$ some 9dB below Agarwal's data. Bull and Johnson were unable to provide a completely satisfactory explanation of this apparently anomalous result. Additional data for this flow case have since been obtained and are presented here.

4. RESULTS AND DISCUSSION

4.1 Mean-flow Characteristics

Figures 3(a) and (b) show, for various D_c, the streamwise variation of the centre-line flow Mach Number M_{CL} for the $D_o = 0.76$ and $D_o = 0.50$ orifices respectively, and values of Mach Number at "inlet" M_I (X = -8) and "exit" M_E (X = 50) and the position of flow reattachment X_R. Values of the flow-rate parameter $J = m/\rho_* c_* A_p$, where m is the mass-flow rate, A_p is the pipe cross-sectional area, and ρ_* and c_* are respectively the fluid density and velocity corresponding to isentropic expansion from the (atmospheric) reservoir to sonic conditions, are also given.

When the flow is entirely subsonic M_{CL} reaches a maximum value Mj at the vena contracta in the separated free jet issuing from the orifice. When supersonic flow occurs, there are several local maxima and minima in M_{CL} corresponding to the cellular pattern of an under-expanded jet: in this case Mj is taken at the point where the p.s.d. scaling parameter q_j^2/U_j is a maximum. For the subsonic jets the locations of maximum values of q_j^2/U_j and M_j are coincident. In both cases, both the position at which M_j occurs and the position of reattachment move upstream as J and M_j increase.

4.2 Wall-pressure Spectra

Before discussing the spectral results in detail, we note that, in a flow disturbed by an orifice plate, wall-pressure fluctuations derive from three sources:

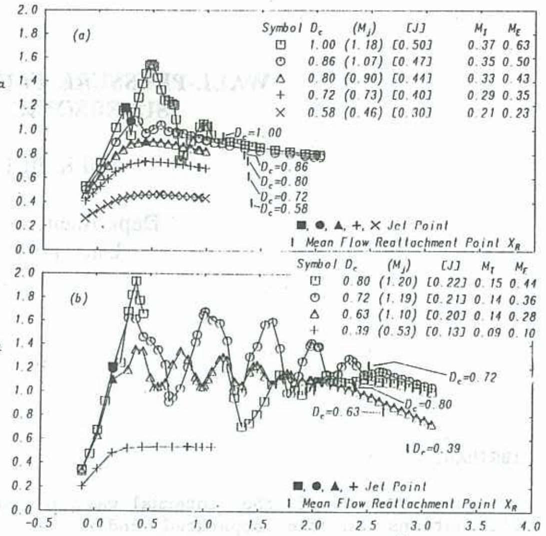

Figure 3. Centre-line Mach numbers for (a) $D_o = 0.76$ and (b) $D_o = 0.50$

(i) turbulence generated by undisturbed fully-developed turbulent pipe-flow;

(ii) additional turbulence generated in the mixing layer of the free jet issuing from the orifice; and

(iii) the internal acoustic field.

The turbulence generated in the jet mixing-layer is of significantly greater intensity than that corresponding to undisturbed fully-developed turbulent pipe-flow at the same mass-flow rate. It decays with downstream distance as the flow returns to its undisturbed state; however it is also the source of the acoustic field, consisting of plane waves and higher-order modes, which propagate throughout the flow. Thus in the vicinity of the orifice the pressure fluctuations are dominated by hydrodynamic fluctuations arising from mixing-layer turbulence and acoustic fluctuations, while at large distances from the orifice the pressure fluctuations are predominantly acoustic with a small contribution from undisturbed or re-established fully-developed turbulent pipe flow.

Wall-pressure spectra for the $D_o = 0.50$ and 0.76 orifices at x/h = 8.3 and 25 are shown in figure 4 in the form Φ_p as a function of Ω. There is some degree of similarity within each data set; but in general it is noticeable that there is a progressive increase in spectral level as the jet Mach number M_j increases for $\Omega \ge 5$, and that to a lesser extent the reverse effect occurs at low $\Omega \le 3$. (Note that for the $D_o = 0.50$ orifice, there is a large gap in M_j between the one subsonic flow and the supersonic flows). Similarity between the $D_o = 0.50$ and $D_o = 0.76$ spectra at x/h = 8.3 (figures 4(a) and (b)) can, at best, be described as fair. There is very little similarity between the two at x/h = 25 (figures 4(c) and (d)). Large peaks in the spectra at higher frequencies can be associated with the higher-order acoustic modes of the fluid in the pipe, and it is clear that at supersonic speeds the $D_o = 0.50$ spectra have a relatively larger acoustic content than the $D_o = 0.76$ spectra.

Figure 4 shows that between the two measuring stations there is a drop in pressure-spectral level for both sets of flows. For the $D_o = 0.76$ flows, the spectra do not change significantly in shape, and there is a general decrease in level

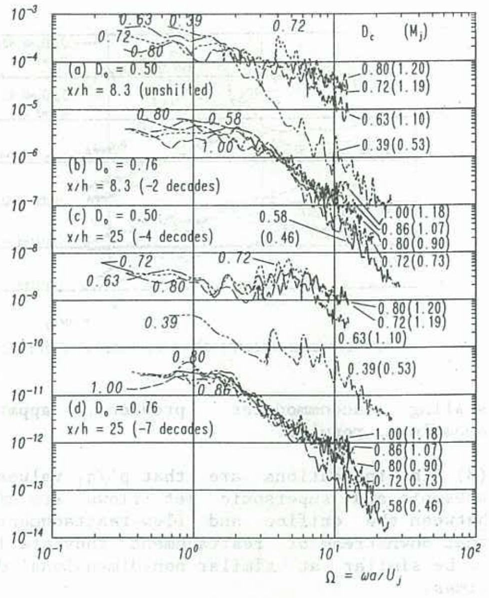

Figure 4. Wall-pressure spectra near flow reattachment.

of about 3 dB across the whole spectrum. In contrast, for the $D_o = 0.50$ flows there is considerable change in spectral shape: levels decrease by about 5 dB for $\Omega \geq 2$, but by larger amounts at lower frequencies – up to 10 dB in general and as much as 20 dB for the entirely subsonic 0.50/0.39 flow. However, this apparently inconsistent behaviour can be explained, at least qualitatively, if the characteristics of decay of orifice-generated turbulence are taken into account.

Agarwal's (1985) measurements indicate that, in subsonic orifice-flows, maximum turbulence intensity occurs at a streamwise location close to that of reattachment of the jet flow to the pipe wall, with decay as x increases beyond x_R. The time scale of decay of the orifice-generated turbulence T* can be taken to be proportional to $(\nu/\epsilon)^{\frac{1}{2}}$ where ν is the kinematic viscosity of the fluid and ϵ is the energy dissipation rate per unit mass. Since ϵ is proportional to u^3/ℓ, where u is the rms velocity fluctuation and ℓ the scale of the larger turbulent eddies involved in this motion, T* can be taken as $(\nu\ell/u^3)^{\frac{1}{2}}$. The scale of turbulence in the orifice-jet mixing-layer will increase with downstream distance, but will be limited by the pipe size to a scale of order d_p in the region of reattachment; so we make the assignment $\ell = d_p$. Further, the local rms wall pressure fluctuation $p' \sim \rho u^2$ and hence, in the vicinity of flow reattachment, $u^2 \sim (p'/q_j).U_j^2$. We therefore finally obtain $T^* = [\nu d_p/(p'/q_j)^{3/2}.\ U_j^3]^{\frac{1}{2}}$. The extent to which the decay of orifice-generated turbulence has progressed at a given streamwise position in a given flow will depend on the ratio of time T taken for the fluid to traverse the distance $(x-x_R)$ to the time-scale T*.

Now consider the transit times T for the 0.50/0.39 and 0.76/0.58 flows between reattachment and x/h = 25; these have been estimated by streamwise integration of $1/U_{CL}$ to be 5.4 ms and 0.98 ms respectively. The corresponding values of T* are 8.3 μs and 6.3 μs. The respective values of T/T* are therefore 651 and 156, indicating that at x/h = 25 the orifice-turbulence in the 0.50/0.39 flow is in a much more advanced state of decay than that in the 0.76/0.58 flow, a result consistent with the spectra shown in figure 4.

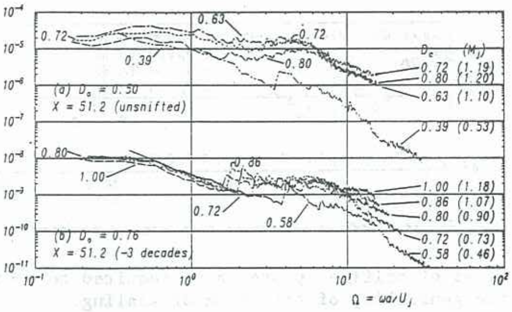

Figure 5. Wall-pressure spectra at X = 51.2 a) D_o = 0.76 b) D_o = 0.50

The argument that the different rates of decay of orifice-generated turbulence are responsible for the marked differences in the wall-pressure spectra at x/h=25, gains additional support from further consideration of the 0.50/0.39 and 0.76/0.58 flows. These two flows have similar M_j values, 0.53 and 0.46 respectively, and would therefore be expected to produce internal acoustic fields of comparable strengths. Thus, even through the pressure spectra will not be similar at different stages in the decay of the orifice-generated turbulence, they should become similar at downstream distances sufficiently large for the turbulence decay to be essentially complete in both cases. This expectation is confirmed by the measurements: the spectra show a degree of similarity at x/h = 8.3 (figures 4(a) and (b)) where both flows have maximum turbulence intensity; they are quite dissimilar at x/h = 25 (figures 4(a) and (d)); but similarity occurs again at X = 51.2 (figure 5).

That the spectra for flows with supersonic jet velocities do not undergo such large changes as those for the low-M_j subsonic flows, as x/h increases from 8.3 to 25, can be attributed to very much smaller transit times which lead to smaller values of T/T* even though the T* values are themselves reduced.

Thus, while Φ_p as a function of Ω is a convenient form of spectral scaling, it is clear that decay of the orifice-generated turbulence precludes spectral similarity in this form downstream of flow reattachment when comparisons are made at the same value of x/h; an improvement might be expected if comparisons could be made at the same value of T/T*. Likewise, it might be expected that the difference in the spectra in this form at x/h = 8.3, with M_j increasing from subsonic to supersonic values, require for their explanation an examination of the process of turbulence development between the orifice and flow reattachment.

4.3 Overall r.m.s. Wall-pressure Fluctuations

Results for p'/q_j are shown in figure 2 as a function of x/x_R. Some divergences from this form of scaling are apparent, and, in particular, the now more-comprehensive measurements for the 0.50/0.39 flow clearly show that in this case x/x_R scaling becomes inappropriate as x/x_R increases beyond unity. Thus, while Agarwal's (1985) scaling of p'/q_j with x/x_R appears to be valid for $x/x_R < 1$, it requires modification for $x/x_R > 1$. In the light of the preceding discussion of pressure spectra, it might be expected that, for $x/x_R > 1$, p'/q_j will scale with T/T*. Figure 6 shows that a fairly good collapse of the data for subsonic flows is obtained when they are plotted in this form. The one set of 'anomalous' results for the 0.50/0.39 flow now conform more closely to those for the D_o = 0.76 flows, but additional tests with other

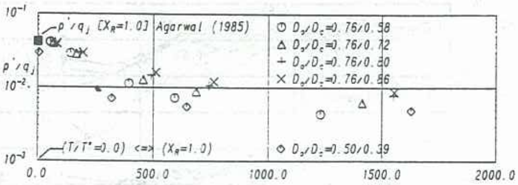

Figure 6. RMS wall-pressure as a function of decay time.

sizes of orifice plate are required to confirm the generality of this form of scaling.

It might be noted that the values of p'/q_j for supersonic flows shown in figure 2 will in general be associated with the smaller values of T/T*, and consequently will not be greatly different from the subsonic-flow values in this range.

4.4 Comparison of Valve-model and Orifice Flows

Wall-pressure spectra for the valve-model with $D_v = 0.65$, at various streamwise locations, are shown in figure 7, and compared with corresponding data for a $D_o = 0.62$ orifice plate. In both cases the orifice-jet is supersonic, and the M_j values (1.28 and 1.11 respectively) are very similar. The two mean-flows are also very similar, the greatest difference being a lower q_j for the valve as a result of higher friction losses. It can be seen that the spectra show a considerable degree of similarity at all downstream locations (figures 7(b)-(d)) with the spectral levels of the valve model consistently about 3dB below those of the orifice. Because the mean-flow parameters (M_I, M_E and X_R) are similar, the rates of decay of the flow-disturbance turbulence are also similar; hence the spectral similarity extends into the region of decay of the turbulence produced by the flow disturbance, x/h = 25, figure 5(c). The most notable differences in the wall-pressure spectra occur upstream at X = -3.31 (figure 7(a)), where the valve-model has higher general levels than the orifice at the higher frequencies, $\Omega > 3$. Presumably this is due to locally increased turbulence associated with disturbed flow into the holes in the valve model. The high degree of similarity downstream indicates that the internal pressure field (acoustic and hydrodynamic components) is primarily determined by the basic nature of the separated fluid flow which is produced, rather than the differences in the geometry of the orifice and valve-models.

5. CONCLUSIONS

For the range of orifice sizes and flow rates investigated the following conclusions can be drawn.

(1) Just upstream of reattachment to the pipe wall of the free jet issuing from the orifice, wall-pressure spectra in the form of Φ_p as a function of Ω do not show complete similarity, changing progressively as the jet Mach number rises from subsonic to supersonic values. The dissimilarity becomes greater downstream of reattachment, which can be explained in terms of the streamwise decay of the orifice-generated turbulence.

(2) Downstream of reattachment the ratio of rms wall-pressure fluctuation to jet dynamic pressure p'/q_j appears to scale with the decay time of the orifice-generated turbulence; and this form of scaling accommodates previous, apparently anomalous, results.

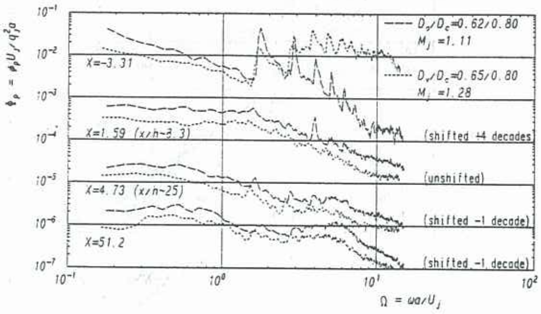

Figure 7. Wall-pressure spectra of valve-model and orifice.

(3) The indications are that p'/q_j values for subsonic and supersonic jet flows are similar between the orifice and flow-reattachment, and that downstream of reattachment they are likely to be similar at similar non-dimensional decay-times.

(4) Tests of a valve model and an orifice plate show that the wall-pressure field is determined by the basic geometry of flow separation and reattachment in a disturbed flow, despite marked differences in the detailed geometry of the devices producing the disturbance.

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