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ON FLOW PROCESSES RELATED TO WALL PRESSURE FLUCTUATIONS IN TURBULENT PIPE FLOW

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ABSTRACT

Continuing the work of Langeheineken, Sieber, Reinhardt and Dinkelacker wall pressure fluctuations and velocity fluctuations in turbulent pipe flow have been investigated. The investigation reported here gives details on the scaling of events of "high" or "low" wall pressure and shows that these "small-scale" events are related to "large-scale" processes in the turbulent flow, the convection of which can be followed over a distance of at least 50 pipe radii.

INTRODUCTION

In the past three decades there have been many investigations on the fluctuating pressure field beneath turbulent flows. The motivation for these investigations was the desire to improve our understanding of turbulence and to provide data needed for the solution of practical engineering problems. Review articles on turbulent wall pressure fluctuations have been given by Willmarth (1975) and more recently by Eckelmann (1989). Investigations performed at the Max-Planck-Institut für Strömungsforschung especially have been concentrated on wall pressure fluctuations in developed turbulent pipe flow. Langeheineken (1979) has measured frequency spectra and correlation functions of the wall pressure fluctuations. Bull and Langeheineken (1981) have investigated apparent discrepancies between values of the ratio of root mean square values of pressure fluctuations to the dynamic pressure of the flow measured either by piezoelectric pressure transducers or by small condenser microphones. With the help of the method of conditional signal averaging Langeheineken (1981) has shown that events of "high" wall pressure as well as events of "low" wall pressure are related to characteristic flow processes occurring in the vicinity of the wall pressure transducer. Continuing this work Sieber (1987) and Reinhardt (1987) have shown that the "small-scale" processes occurring close to the wall pressure transducer are related to "large-scale" flow processes in the turbulent pipe flow, the convection of which can be followed over distances of at least 26 pipe radii. A survey on the work of Langeheineken, Sieber and Reinhardt is given in Dinkelacker (1989). In this paper more details on the scaling of the events of "high" and "low" wall pressure are given and the investigation of the large-scale flow processes related to the small-scale wall pressure fluctuations has been extended.

EXPERIMENTAL ARRANGEMENT

Figure 1 shows the experimental setup, the main part of which is a long straight pipe with diameter D = 2R = 5 cm and a pipe length L = 9.8 m, so that L/D = 196. Air was used as flow medium. At the pipe inlet early transition is ensured by means of a strip of sandpaper. The wall pressure fluctuations were measured with a "pinhole microphone" consisting of a hole in the pipe wall of diameter d = 0.5 mm and a 1/8" Brüel and Kjaer microphone. The pinhole was positioned 110 mm upstream of the pipe outlet. The velocity fluctuations were measured with hot-wire probes. Evaluation of the measurements was mainly done using the method of "conditional signal averaging".

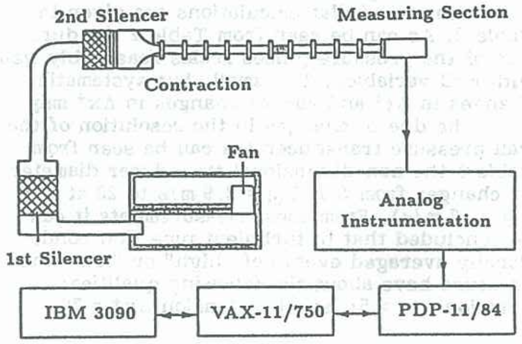

Figure 1. Experimental setup.

The measurements in the pipe were performed at different flow velocities. The choice of the flow velocity is a compromise: Higher velocities give a better signal to noise ratio; lower velocities give a better spatial resolution of the hot-wire and of the wall pressure transducer in terms of wall units (see Table 1). Cylindrical coordinates r, ϕ, x were used with the origin positioned so, that the wall pressure transducer had the coordinates r = R; ϕ = 0; x = 0, and with the x-axis directed in the mean flow direction. (For easier description of measurements in some cases, the distance from the pipe wall y and a coordinate at the wall in the azimuthal direction z were used.) The notation <u> and <p> is used for conditional averages of the velocity fluctuations u(t) and of the wall pressure fluctuations p(t).

centerline velocity $U_{cl}[\frac{m}{s}]$	2.9	11.0	17.0
shear velocity $U_\tau[\frac{m}{s}]$	0.147	0.47	0.69
velocity ratio U_τ/U_{cl}	0.051	0.043	0.041
Reynolds number $Re = U_{cl} \cdot D/\nu$	9600	36500	56500
wall time $t_w = \nu/U_\tau{}^2[ms]$	0.71	0.068	0.032
wall length $l_w = \nu/U_\tau[mm]$	0.105	0.032	0.022
pipe diameter in wall units D/l_w	480	1560	2270
pinhole diameter in wall units $d^+ = d/l_w$	5	16	23

Table 1. Flow parameters (ν = kinematic viscosity)

WALL PRESSURE EVENTS

The wall pressure fluctuations measured with the pinhole microphone have been investigated with the help of the method of conditional signal averaging. Figure 2 shows some results. For six different amplitude conditions ($p > 6\,p_{rms}$ to $p < -6\,p_{rms}$, p_{rms} = root mean square value) the conditionally averaged pressure functions <p> (in short: p-signatures) are shown. The figure demonstrates that the duration of the events of "high" or "low" pressure is nearly constant for all the different amplitude conditions. In the case shown in Figure 2 (centerline velocity $U_{cl} = 11.0$ m/s) this duration is about $\Delta t = 0.4$ ms. Taking into account that the convection velocity of the wall pressure patterns is about $0.75\,U_{cl}$ one can calculate a longitudinal extension Δx of the level flow process related to these pressure pulses as $\Delta x = 0.75 \bullet U_{cl} \bullet \Delta t = 3.3$ mm. Similar measurements performed with four different flow velocities and similar calculations are given in Table 2. As can be seen from Table 2 the duration of the pressure pulses scales reasonably well with wall variables. The small, but systematic changes in Δt^+ and similar changes in Δx^+ may partly be due to changes in the resolution of the wall pressure transducer (as can be seen from Table 1 the non-dimensional transducer diameter d^+ changes from 5 at $U_{cl} = 2.9$ m/s to 23 at $U_{cl} = 17$ m/s). From these measurements it can be concluded that in turbulent pipe flow conditionally averaged events of "high" or "low" wall pressure have about the following qualities: duration $\Delta t+ = 5$; length extension $\Delta x^+ = 75$.

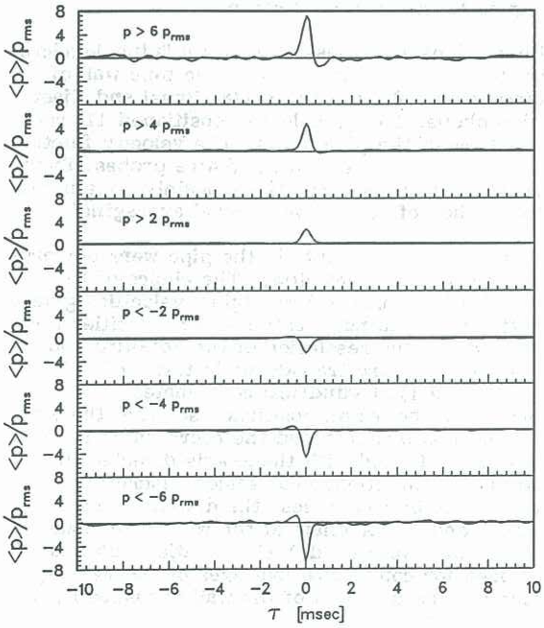

Figure 2. Conditionally averaged wall pressure fluctuations <p> (in short: p-signatures) for six different conditions ($p > 6\,p_{rms}$ to $p < -6\,p_{rms}$; centerline flow velocity $U_{cl} = 11.0$ m/s).

U_{cl} [m/s]	Δt [ms]	$\Delta t \cdot U_{cl}/D$ [-]	Δt^+ [-]	Δx [mm]	Δx^+ [-]
2.9	3.6	0.21	5.0	7.8	75
7.0	0.9	0.13	5.7	4.7	96
11.0	0.4	0.09	5.9	3.3	103
17.0	0.2	0.07	6.3	2.6	116

Table 2. Duration Δt and length extension Δx of conditionally averaged wall pressure events

Another very interesting result is the asymmetry in the p-signatures which can be detected in Figure 2. As can be seen (compare especially the function for $p > 6\,p_{rms}$ with the function for $p < -6\,p_{rms}$) in the average events of high wall pressure are followed immediately by events of low wall pressure. From this observation an asymmetry in the distribution of $\partial p/\partial t$ can be expected and in fact the skewness factor of $\partial p/\partial t$ came out to be $SK = -0.48$. Further experiments are needed to clarify whether the observed asymmetry is a genuine feature of wall turbulence or if we are investigating some odd instrumentation effect.

RELATIONS BETWEEN WALL PRESSURE FLUCTUATIONS AND VELOCITY FLUCTUATIONS

The investigations of Langeheineken, Sieber and Reinhardt have shown that there exist close relations between events of "high" and "low" wall pressure and "characteristic structures" in the developed turbulent pipe flow. These investigations have been continued and in the following some newer results will be discussed.

Figure 3 demonstrates some of the basic observations. Curve 3d shows the conditionally averaged function <p> of the wall pressure fluctuations normalized with p_{rms}. The three other curves (curve 3a, 3b and 3c) show conditionally averaged functions <u>, normalized with u_{rms}, of the streamwise velocity fluctuations. For the measurement of these curves the hot-wire probe was positioned at three different locations in the pipe. Sampling condition for all four curves was "high" wall pressure ($p > 4\,p_{rms}$ at time $\tau = 0$). While curve 3c is measured with the hot-wire probe positioned very close to the wall ($y_h^+ = 15$), for the measurement of curves 3b and 3a the hot-wire probe had larger distances to the wall ($y_h^+ = 62$ respectively $y_h^+ = 312$). The suffix h denotes the position of the hot-wire probe. The curves given in Figure 3 demonstrate mainly the following three results: Firstly, curve 3c shows a steep increase in <u> close to time $\tau = 0$, when the "high" wall pressure occurs, curves 3a and 3b do not. This steep increase in <u> indicates a "short-time", small-scale flow process occurring

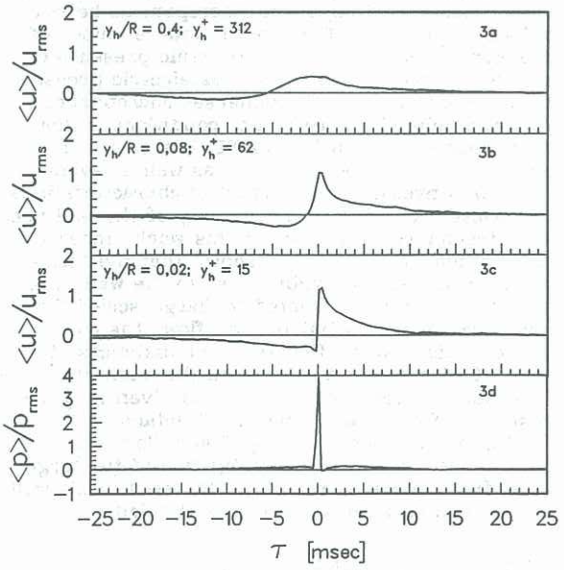

Figure 3. Conditionally averaged streamwise velocity fluctuations <u> (in short: u-signatures) at three different distances from the wall. Lowest curve is p-signature (condition: $p > 4\,p_{rms}$; $U_{cl} = 11.0$ m/s; hot-wire positions: $x_h = 0$, $y_h/R = \ldots$, $\phi_h = 0°$).

close to the pipe wall. The duration of this increase is about the same as the duration Δt of the conditionally averaged pressure pulse, i.e. $\Delta t^+ = 5$. Measurements with the hot-wire probe positioned in different azimuthal positions indicate that this flow process has a spanwise extension of about $\Delta z^+ = 50$ (for details see e.g. Sieber (1987)). Physically this small-scale flow process can be interpreted as impingement of "high speed" fluid on "low speed" fluid. By this process a sort of "stagnation pressure" is generated, which at the neighbouring wall is detected as an event of high wall pressure. Of course the wall pressure at the position of the wall pressure transducer is also influenced by flow processes occurring elsewhere in the flow, but evidently the local process dominates. The interdependence of $\langle u\rangle$ and $\langle p\rangle$ can also be demonstrated if one uses large values of $\partial u/\partial t$ in the flow as a sampling condition and measures $\langle p\rangle$ at the neighbouring wall (see e.g. Langeheineken (1981)). Secondly, the "short-time" flow process (steep increase in $\langle u\rangle$) is embedded in a "long-time" flow process which consists of a period of negative $\langle u\rangle$ followed by a period of positive $\langle u\rangle$ (see curve 3c). With increasing distance of the hot-wire probe from the pipe wall the steep increase in $\langle u\rangle$ disappears while the "long-time" process in the u-signatures is maintained. The duration of the long-time process in Figure 3 (defined by $\langle u\rangle \neq 0$) is about $\Delta t = 30$ ms or $\Delta t^+ = 440$. Applying the same arguments as in the previous section this time corresponds to a length in streamwise direction of about $\Delta x = 250$ mm or $\Delta x = 10R$ or $\Delta x^+ = 8000$. Thirdly, as can be seen from Figure 3 the zero crossings of the u-signatures are shifted to negative times τ with increasing distance y_h. Out of this time shift one can construct an inclined front which separates a flow regime with negative $\langle u\rangle$ from a flow regime with positive $\langle u\rangle$. This inclined front is in agreement with conclusions drawn by Thomas and Bull (1983).

Sieber (1987) and Reinhardt (1987) have shown that the convection of the large-scale structures related to events of "high" wall pressure can be followed along the pipe over a distance of at least 26R (R = pipe radius). Their measurements have now been repeated and extended with more reliable equipment. Some results are given in Figures 4 to 6. For all curves in these figures the sampling condition was $p > 4p_{rms}$ at time $\tau = 0$ and at position $x = 0$, $y = 0$, $\phi = 0$. The curves in these 3 figures show especially the following four results: Firstly, the convection of the large-scale flow pro-

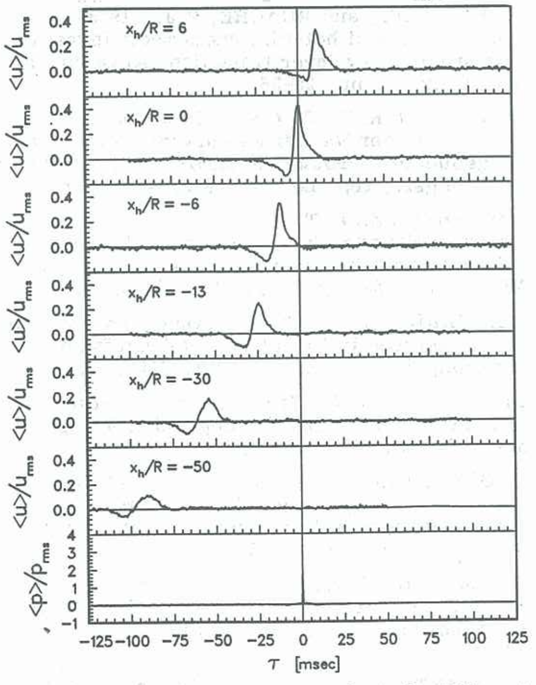

Figure 4. u-signatures measured at six different positions along the pipe and in the jet leaving the pipe (condition: $p > 4p_{rms}$; $U_{cl} = 17.0$ m/s; $x_h/R = \ldots$, $y_h/R = 0.4$; $\phi = 0°$; pipe end is located at $x = 4.4\,R$).

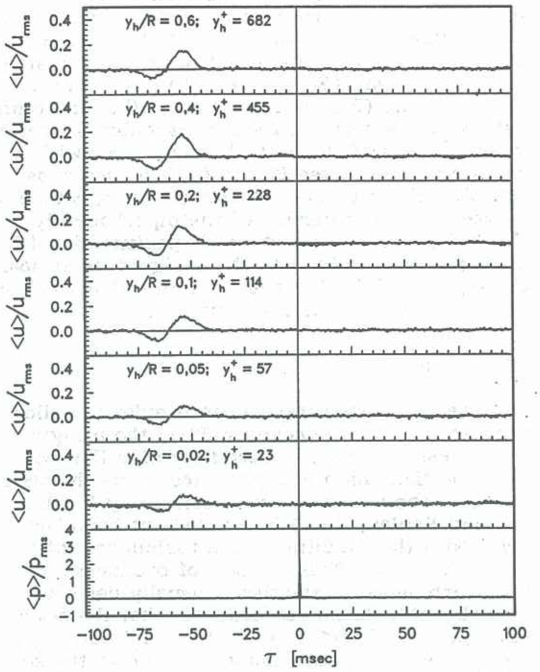

Figure 5. u-signatures measured at six different distances from the wall and 29.7 pipe radii upstream of the wall pressure transducer (condition: $p > 4p_{rms}$; $U_{cl} = 17.0$ m/s; $x_h/R = -29.7$, $y_h/R = \ldots$, $\phi_h = 0°$).

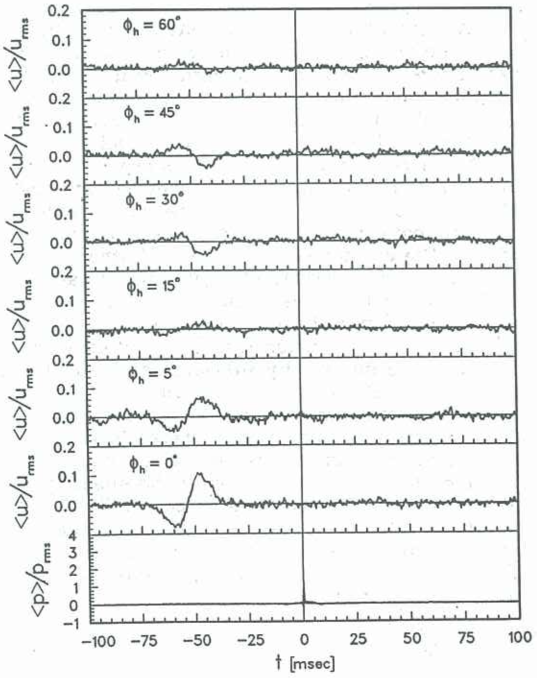

Figure 6. u-signatures measured at six different azimuthal positions and 26 pipe radii upstream of the wall pressure transducer (condition: $p > 4p_{rms}$; $U_{cl} = 17.0$ m/s; $x_h/R = -26$; $y_h/R = 0.6$, $\phi_h = \ldots°$).

cess related to the small-scale wall pressure events can now be followed over a distance of at least $\Delta x = 56\,R$. The quality of the measured curves (see Figure 4) indicates that this distance again - as in the case of Sieber and Reinhardt - is only a lower limit. So one can conclude that the large-scale flow process related to the local wall pressure events has a lifetime of $\Delta t > 100$ ms or $\Delta t^+ > 3000$. Secondly, the convection velocity calculated out of the zero crossings of the u-signatures is $U_c = 0.75\ U_{cl}$. Thirdly, measurements performed well upstream of the wall pressure transducer with the hot-wire probe positioned in different distances y_h from the wall (Figure 5) and in different azimuthal positions (Figure 6) indicate rather interesting details of the u-signatures. Remarkable is especially the change of shape in the signatures with increasing angle ϕ (see Figure 6). It is also remarkable that there is no characteristic u-signature to be seen at the centerline of the pipe. Fourthly, as the wall pressure transducer is positioned 4.4 R upstream of the pipe end the u-signature at position $x_h/R = 6$ (first curve in Figure 4) is measured in the jet leaving the test pipe.

DISCUSSION

As has been mentioned in previous publications (e.g. Langeheineken (1981)) the u-signatures measured here in turbulent pipe flow with the condition "high wall pressure" have the same shape as the u-signatures measured by Blackwelder and Kaplan (1976) in a turbulent boundary layer with the condition "high turbulence intensity at $y^+ = 15$". This process of production of high turbulence intensities is usually described as a "burst". So we can conclude that the small-scale process found here for the condition "high wall pressure" is essentially the same as the so-called "burst". Hence from the observations described here, especially from the connection between "small-scale" processes with "large-scale" processes one can learn more on the "burst". According to our observation, the "burst" is not an isolated local event, but part of a flow process which is travelling downstream in the pipe.

Asking what sort of flow structures could be behind these observations we came to the idea that "ring-like" structures might be involved, and that these rings undergo instabilities similar to those of vortex-rings. There are several reasons for this idea: (I) The mean vorticity in pipe flow has a ring structure and occurrence of local concentrations of this vorticity can be expected. (II) Measurements of u-signatures in the half space opposite to the wall pressure transducer indicate the existence of "ring-like" structures (see Reinhardt (1987)). (III) The wavy nature of the ring instabilities could explain the existence of hairpin or horseshoe vortices in the flow which have been discussed in the context of wall pressure fluctuations by Willmarth and Tu (1967) as well as by Thomas and Bull (1983). Furthermore these structures could explain the existence of low speed and high speed streaks in the flow as observed in many investigations, especially by Kline et al. (1967). Carrying the speculations one step further it seems to be not unlikely that in fully developed turbulent pipe flow similar processes occur as those observed by Knapp and Roache (1968) in the flow along a body of revolution for the transition process.

CONCLUSIONS

(1) Duration and length extension of events of "high" or "low" wall pressure in developed turbulent pipe flow scale reasonably well with inner variables. The duration is about $\Delta t^+ = 5$, the length extension is of the order of $\Delta x^+ = 100$ and the spanwise extension of the order of $\Delta z^+ = 50$.

(2) These wall pressure events are related to "small-scale" flow processes which occur close to the wall pressure transducer and which seem to be the same as the burst processes found e.g. by Blackwelder and Kaplan (1976).

(3) These "small-scale" flow processes are related to "large-scale" flow processes in the turbulent pipe flow the convection of which can be observed now over a distance of more than 50 pipe radii.

(4) It seems to be desirable to compare the results gained here for developed turbulent pipe flow with similar measurements performed for turbulent boundary layer flow.

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