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Experimental study of intermittent pipe flow using Pitot-tube probes with high frequency response

J. MESETH (GÖTTINGEN)

AN EXPERIMENTAL study was conducted on intermittent pipe flow up to a Reynolds-number of about 20000. Disturbances are introduced by injections of a thin water jet at the entrance over a short period of time, so a turbulent slug of pipe flow is produced which grows with time. The result is intermittent flow in the pipe without significant change in mean flow velocity. With specially designed Pitot-tube probes, pressure fluctuations can be measured up to a frequency of 1 kHz. Measurements were taken mainly in the regions where the laminar flow is followed by turbulent flow and vice versa. In these regions the velocity fluctuations are significantly larger than in a developed turbulent pipe flow. A model is presented to interprete the observations.

Przeprowadzono doświadczalne badania zaburzonego przepływu typu zmieniającego się od laminarnego do turbulentnego przez rurę w zakresie liczb Reynoldsa do 20000. Zaburzenia były wprowadzane przez krótkie wstrzykiwania na wlocie rury cienkich strumieni wody, powodujące wzmagającą się z czasem turbulizację przepływu. Wynikiem zaburzenia było powstawanie przepływów typu zmieniającego się bez znaczących zmian średniej prędkości przepływu. Fluktuacje ciśnienia mierzono za pomocą specjalnie zaprojektowanych rurek Pitot do częstości około 1 kHz. Pomiary prowadzono głównie w obszarach, gdzie przepływ laminarny i turbulentny następowały po sobie. W obszarach tych fluktuacje prędkości są znacznie większe niż w rozwiniętym turbulentnym przepływie przez rurę. Przedstawiono model teoretyczny interpretujący wyniki doświadczeń.

Проведены эксперименты с течениями через трубу типа изменяющегося от ламинарного до трбулетного для чисел Рейнольдса до 20 000. Коротко-временные инжекции на входе в трубу тонких струй воды возмущали течение, чего следствием являлось возникновение растущих со временем стержней турбулентного течения. Результатом было течение изменяющегося типа без значительных изменений средней скорости течения. Флуктуации давления измерялись специально с проектированными трубками Пито для частот не больше 1 кГ. Измерения велись главным образом в областях, где ламинарное течение чередуется с турбулентным или обратно. В этих областях флюктуации скорости значительно больше чем в развитом турбулентном течении. Представлена теоретическая модель объясняющая экспериментальные наблюдения.

1. The Pitot-tube probe

1.1. Design of the probe

COMMON Pitot-tubes measure time averages of pressure, and with respect to pressure fluctuations their sensitivity normally ends at frequencies of 1 Hz or so. For the measurement of fluctuating pressure in water flow, a specially designed Pitot-tube probe was constructed which has a flat frequency response up to 500 Hz. The cross-section of this probe is shown in Fig. 1. The inlet-tube has an inner diameter of 0.25 mm. The total head pressure is transformed into an electric signal by piezoelectric material. One limiting factor for high frequency response is the compressibility of the water which in this case cannot be neglected. It is therefore to minimize the volume of water enclosed in the probe. Another limiting factor is the elasticity of the material adjacent to the water. For this reason, all metal parts of the probe which have contact with water are made of steel.

Figure 2 shows the frequency response of the Pitot-tube probe. The output is constant at frequencies lower than 500 Hz. A 3-dB-deviation results near 1 kHz and the resonance

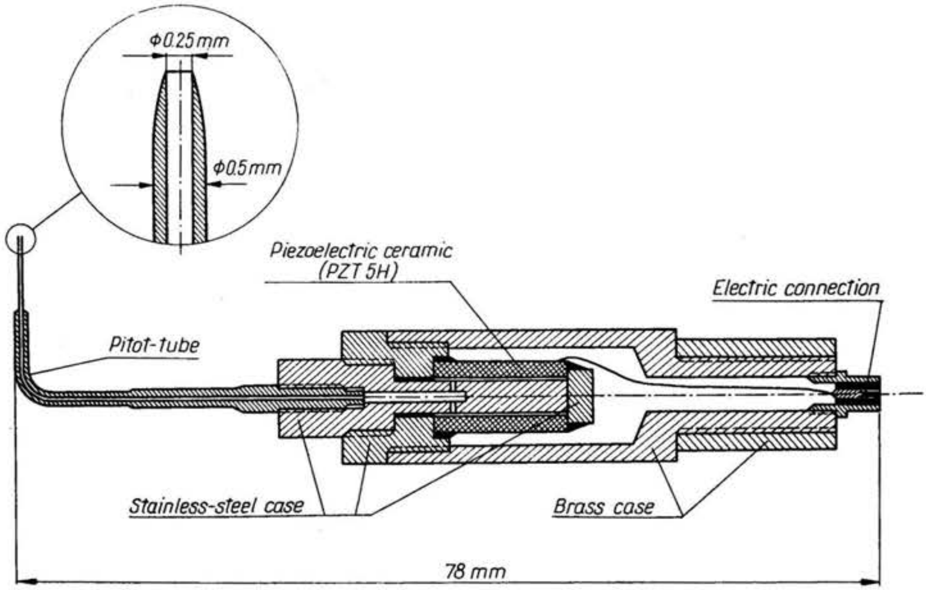

FIG. 1. Sectional drawing through the Pitot-tube probe.

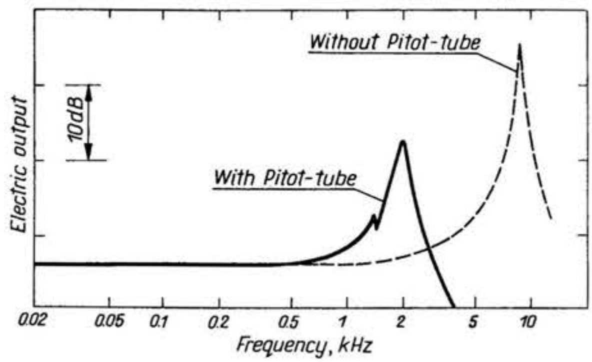

FIG. 2. Frequency response of the Pitot-tube probe.

frequency is about 2 kHz. The small maximum near 1.3 kHz is caused by transverse vibrations of the inlet tube.

1.2. Processing of the signals

The electric signals generated by the Pitot-tube probe are amplified, filtered by an analog low-pass filter with 1 kHz cutoff-frequency, digitized with a certain sample frequency and stored by a processing computer. As the piezoelectric element discharges into the input of the amplifier, the probe has a lower limiting frequency of about 0.1 Hz with the amplifier used here. This effect can be cancelled partly with the help of computer procedures. For each sample point, those voltage values are added which were lost by discharge. The signals of total head pressure corrected in this way have a lower limiting frequency of less than 0.01 Hz. They are transformed by the computer into a signal of flow velocity using Bernoulli's equation. The acceleration term and the term for the fluctuations of the static pressure in this equation are neglected because they could not be measured independently. Digital low-pass and high-pass filtering of the computed velocity signals is made using the so-called hanning procedure. Further details about the Pitot-tube probe and the calculation of velocity signals are described in [1].

1.3. Comparison with hotfilm anemometry

To see how serious the neglect of the acceleration term and the static pressure fluctuation term is, the velocity signal computed from the Pitot-tube measurements was compared with a signal which was simultaneously measured with a linearized hotfilm-anemometer.

Figure 3 shows results of such measurements. In the lower right corner of the diagram a sketch of the probes is given, viewed from the top. Both signals are normalized with respect to the mean flow through the pipe.

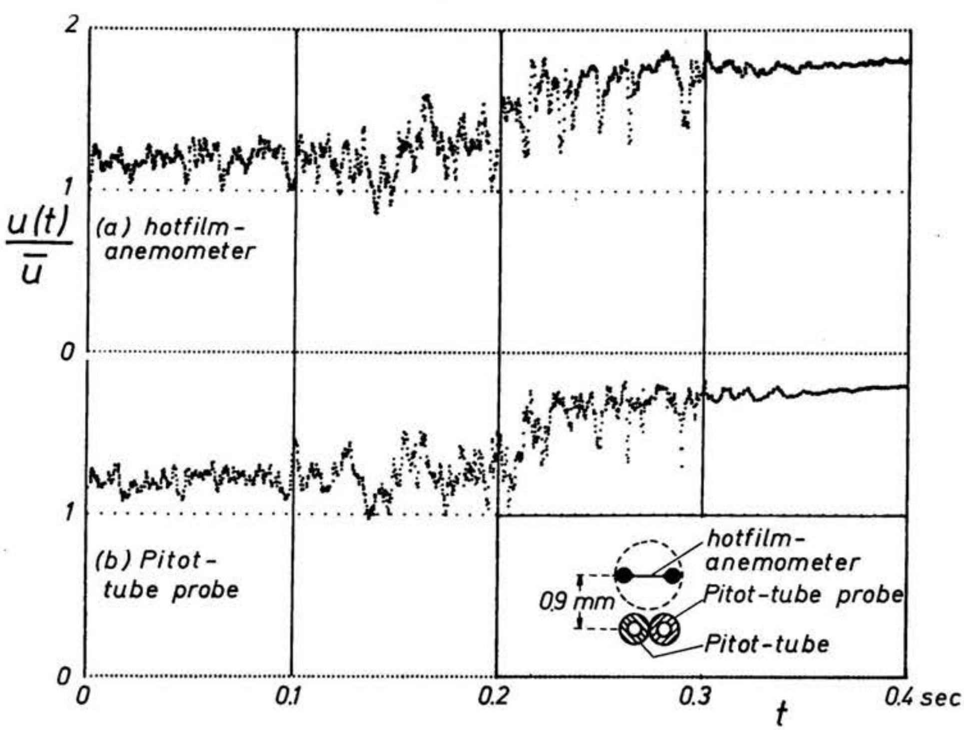

FIG. 3. Comparison of signals obtained with a hotfilm-anemometer and with the Pitot-tube probe.

As can be seen, the correlation between both signals is appreciably high. Differences in the microstructure of the signals can be explained by the facts that the local distance between the probes is larger than the microscale of the turbulent field and that the spatial resolution of the hotfilm probe is better than that of the Pitot-tube probe. It follows from the high correlation of the two signals that the neglected terms in Bernoulli's equation do not contribute significantly to the total head pressure signal.

2. Experimental arrangements

Figure 4 illustrates the type of pipe flow which was investigated in the experiments. In a pipe with 13 mm inner diameter, about 5 m length and smooth entrance, water flow can be maintained laminar until a Reynolds-number of about 20000. Near the entrance

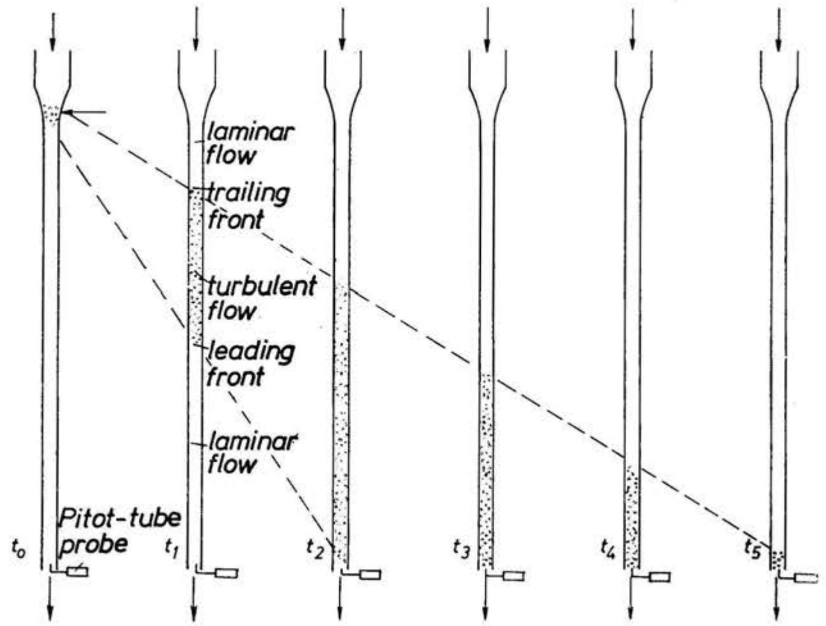

FIG. 4. Schematic view of intermittent pipe flow.

and about 3 m downstream of the entrance, respectively, a thin water jet which disturbes the laminar flow can be injected transverse to the flow direction. In this way it is possible to generate a region of turbulent flow (slug) in the pipe which is embedded in laminar flow. This turbulent slug grows with time. The convective velocity of its leading front is higher and of its trailing front is lower than the mean flow velocity. The mass flow through the pipe is controlled with the help of a flow resistance, so that no significant flux changes can take place during a laminar-turbulent period.

Near the end of the pipe five of the described Pitot-tube probes are arranged equidistant over the pipe diameter. Their electric signals are registered in five separate channels.

3. Experimental results and discussion

3.1. Convective velocities of the leading and the trailing fronts

The velocities of the fronts were calculated from the measured time intervall between the beginning of the water injection and the appearance of turbulent fluctuations from

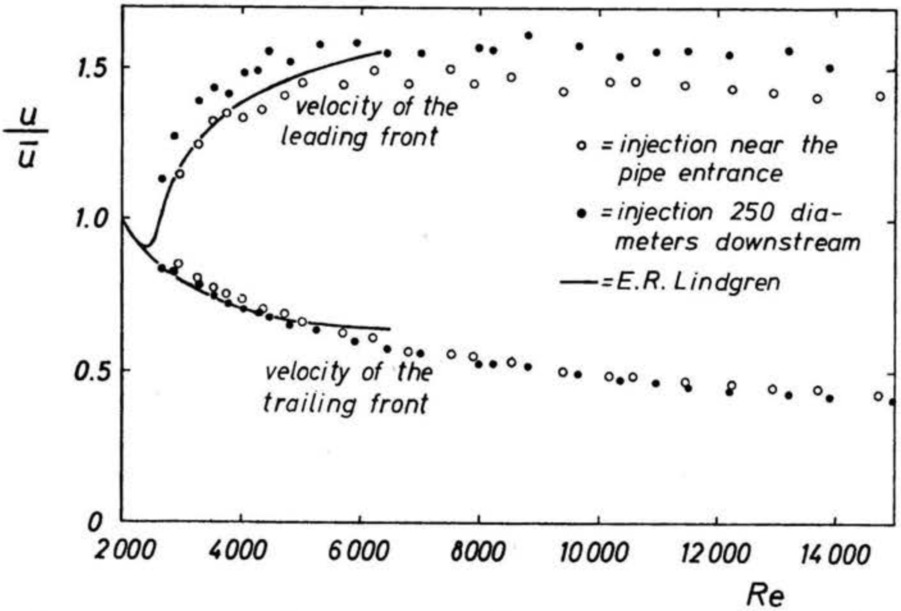

FIG. 5. The convective velocities of the leading and the trailing front as a function of the Reynolds-number.

the Pitot-tubes' signals for the leading fronts, and between the end of the water injection and disappearance of turbulent fluctuations for the trailing front, respectively.

Figure 5 shows the convective velocities as a function of the Reynolds-number. For comparison, results published by LINDGREN [2] are also given. The following results can be seen from the graph:

a) The convective velocity of the leading front is higher when the water jet is injected into a pipe flow with fully or mainly developed velocity profile than when it is injected into a pipe flow with nearly rectangular profile.

b) The convective velocity of the trailing front is but little influenced by entrance pipe flow effects.

c) At Re > 5000, the velocity of the trailing front is smaller than $0.64 \cdot \bar{u}$, calculated by LINDGREN as an asymptotic value for $Re \to \infty$. From the experiments, one cannot deduce that an asymptotic value really exists.

The results a) and b) can be explained by the plausible assumptions that the velocity of the leading front is controlled mainly by the flow near the pipe axis, and the velocity of the trailing front mainly by the flow near the pipe wall. These assumptions are reasonable because the velocity profile near the wall is established after a shorter pipe length compared with the pipe axis.

3.2. The flow near the leading and the trailing front

Figure 6 gives the local velocities of the flow near the leading front calculated from the five Pitot-tube probe signals. As can be seen from this figure, transition begins near the pipe centre with a decrease of local flow velocity without occurence of larger fluctuations,

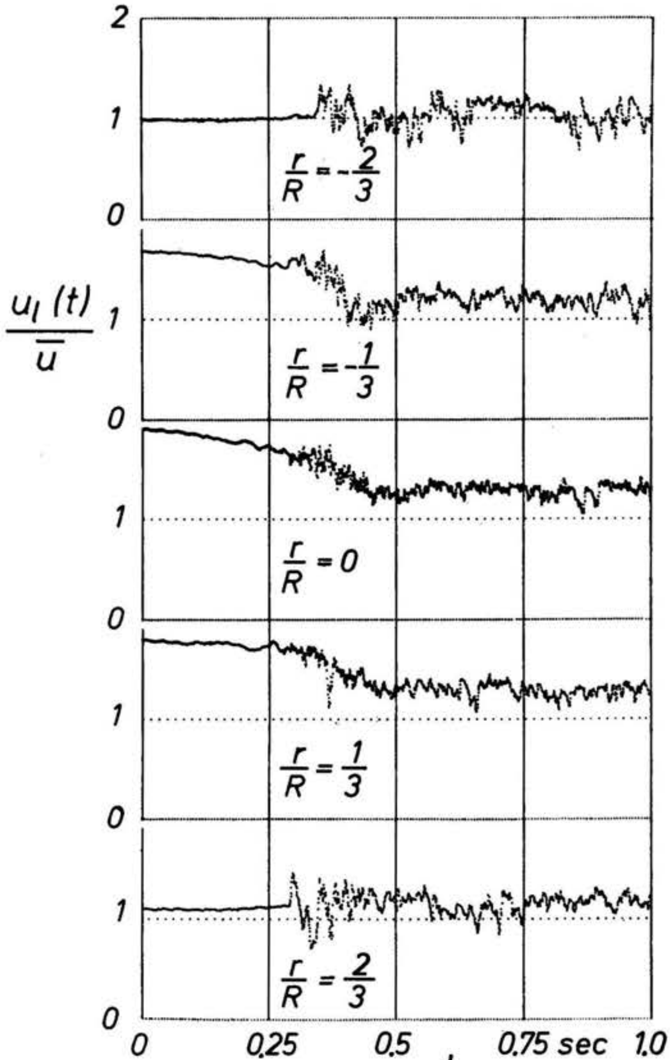

FIG. 6. Velocity measurements at the leading front of a turbulent slug (simultaneous measurements using five Pitot-tube probes, mounted near the pipe end equidistant over the pipe diameter, $\bar{u}$ = 43.2cm/sec., Re = 5850).

i.e., the flow is still laminar. Depending on continuity, the flow velocity near the pipe wall must increase at the same time. The decrease near the pipe centre remains when there appear fluctuations with relatively small amplitudes and low frequencies. They change quite suddenly into turbulent fluctuations which have amplitudes similar or somewhat higher than the fluctuations in the fully developed turbulent pipe flow. Near the pipe wall the turbulent fluctuations begin later and more suddenly than the fluctuations near the pipe centre. The transition region ends when the local mean velocities reach nearly constant values and when the fluctuations do not change significantly in amplitudes. In Fig. 6 this

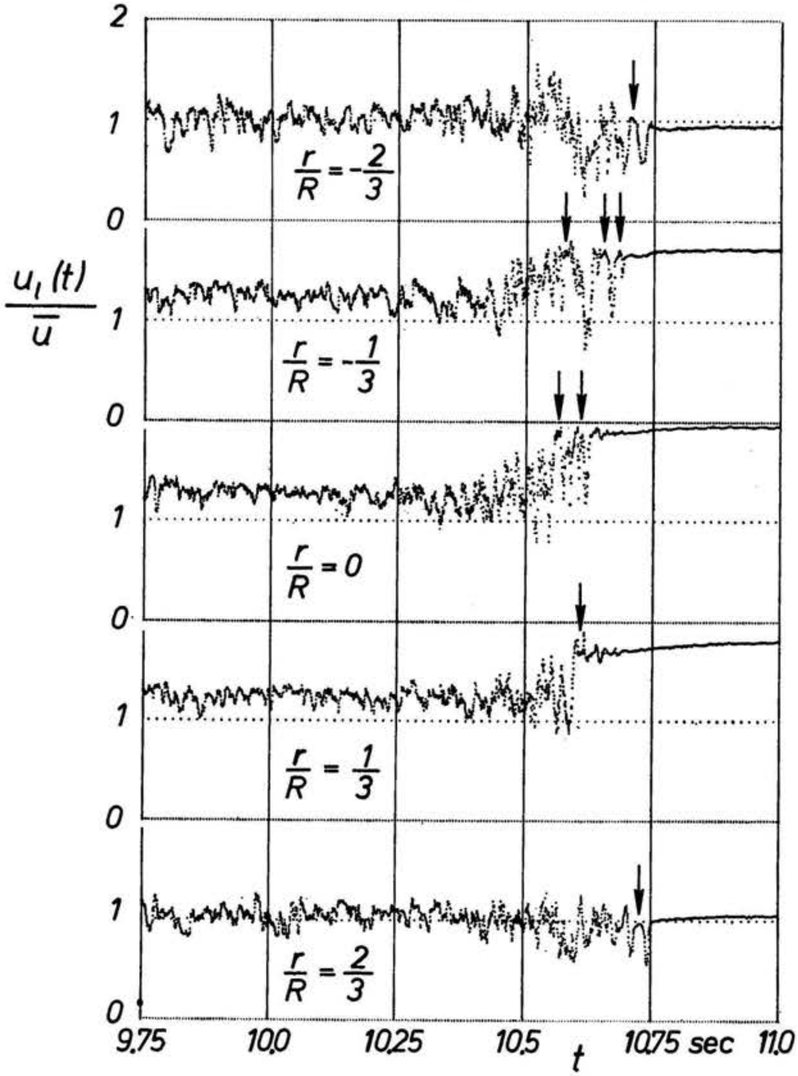

FIG. 7. Velocity measurements at the trailing front of a turbulent slug (the same measurement as Fig. 6).

end of the transition is at about 0.6sec. This means that the transition region here has an extension over about 30 pipe diameters.

Figure 7 shows the flow near the trailing front of the same turbulent slug. As can be seen, transition starts with increasing fluctuation amplitudes in the centre of the pipe. But in contrast to the leading front, fluctuations here reach amplitudes in the order of the mean flow velocity. The difference of turbulence intensity between leading and trailing front can be explained with the following argument: At the leading front, the water, on an average, enters the turbulent region near the wall, so its kinetic energy is relatively small. At the trailing front, the kinetic energy of the water becoming turbulent is relatively high because the water entering the turbulent region, on an average, flows close to the pipe centre. The energy which exceeds the kinetic energy contained in developed turbulent pipe flow must be reduced by dissipation. This is done by the high fluctuation amplitudes at the trailing front, which lead to a higher shear rate and so to a higher dissipation than in the region of developed turbulent flow.

Furthermore, it can be seen that laminar flow begins near the pipe centre earlier than near the pipe wall. In Fig. 7 transition starts at about 10.25sec. and ends at about 10.85sec. This means that the transition region here has an extension over about 12 pipe diameters.

Near the end of the turbulent region an effect can be observed which will be called "small-scale intermittency": the flow velocity nearly reaches the velocity of laminar flow for a short period of time (in Fig. 7 marked by arrows), but there follow again strong fluctuations (compare also Fig. 3). The length of these weakly disturbed regions is about 1/2 to 1 pipe diameter.

This effect seems to be equivalent to the intermittency region of a turbulent boundary layer (see for example [3]). Depending on the complicated shape of the boundary between laminar and turbulent regions, the measuring probe lies sometimes in the turbulent and

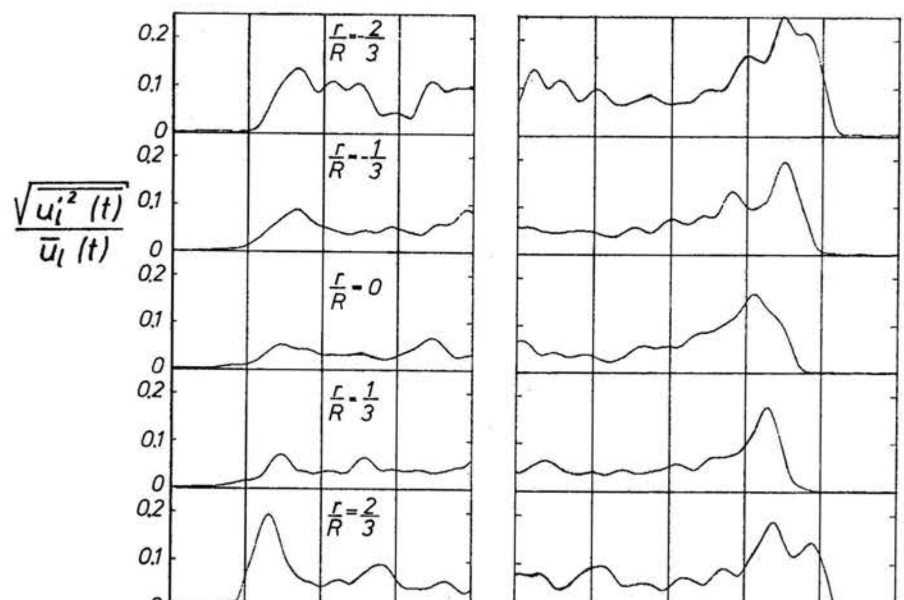

FIG. 8. Measurements of short-time averaged turbulence intensity at the leading and the trailing front of a turbulent slug (computer evaluation out of the measurements given in Fig. 6 and Fig. 7, length of averaging data window for the hanning procedure = 0.125sec.).

sometimes in the laminar flow region. At the trailing front, the mean velocity of the turbulent flow is reduced by the strong interaction with the tube wall. Hence it is clear that fluctuations in the region of small-scale intermittency normally tend to values of velocity smaller than in the laminar region.

Figure 8 gives the short-time averaged local turbulence intensity which was computed from the measurements shown in Figs. 6 and 7. The bars in this figure denote short-time averaging. As can be seen here, the turbulence intensity near the pipe centre is much smaller at the leading than at the trailing front. The turbulence intensity in the regions of developed turbulent flow agrees fairly well with measurements using hotwire anemometers [4]. This fact confirms again that the calculation of velocity signals from the measurements of the Pitot-tube probes does not lead to a serious inaccuracy.

Figure 8 also shows that there exists only approximate axial symmetry for the flow near the leading and the trailing front. This is in contrast to WYGNANSKI and CHAMPAGNE who in their recently published article [5] assumed axial symmetry.

3.3. Transformation to steady flow

Figure 9 gives sketches of the leading and the trailing fronts in coordinates convected with the velocities of these fronts. In this coordinate system, the flow becomes steady.

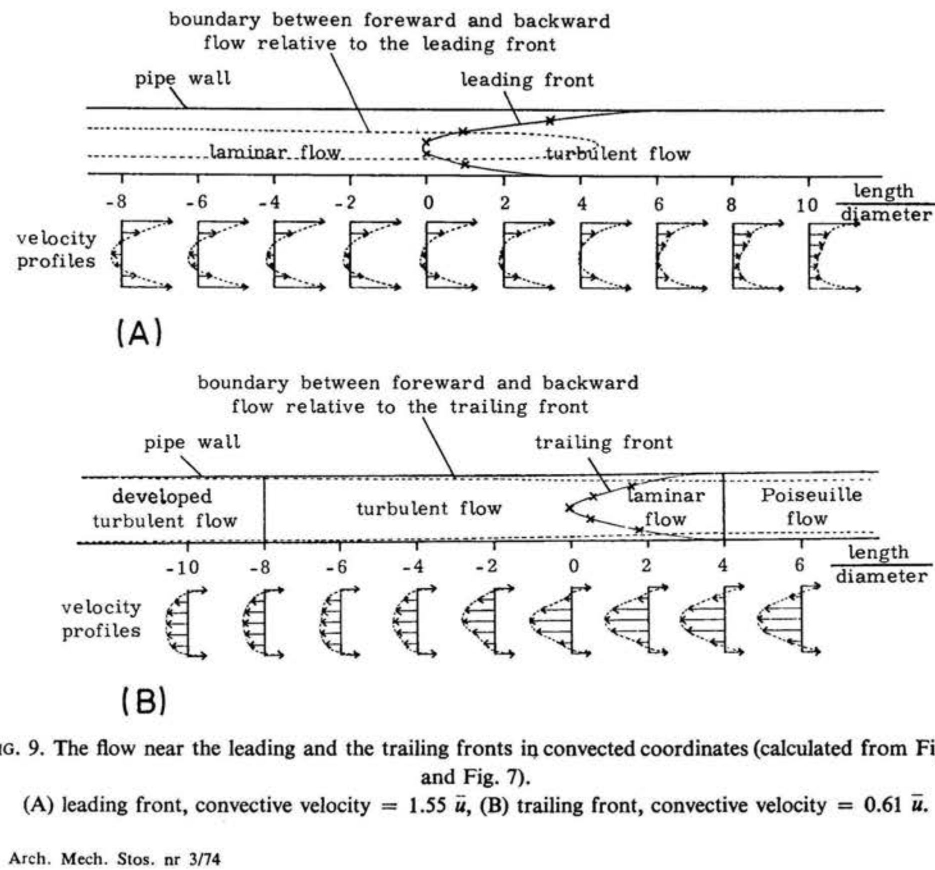

FIG. 9. The flow near the leading and the trailing fronts in convected coordinates (calculated from Fig. 6 and Fig. 7).
(A) leading front, convective velocity = 1.55 $\bar{u}$, (B) trailing front, convective velocity = 0.61 $\bar{u}$.

For the construction of Fig. 9, the time intervals of the original measurements (Fig. 6 and Fig. 7) are transformed into space intervals with the help of the convective velocities of the fronts. The outlined shape of both fronts is based on five measuring points and is therefore only approximate. Below the sketch the velocity profiles are given, which were calculated from Fig. 6 and Fig. 7 by short-time averaging.

As can be seen, both fronts lay in regions with foreward and with backward flow. That means: relaminarization occurs at both fronts, at the leading front near the pipe centre and at the trailing front near the pipe wall. This explains the fact that fluctuations with small amplitudes and low frequencies were found near the leading front at the pipe centre, but were not observed near the pipe wall. These fluctuations belong to water flow which a short time earlier was turbulent and now becomes laminar.

WYGNANSKI and CHAMPAGNE [5] found relaminarization only at the trailing front. One explanation for this difference in the results could be that WYGNANSKI and CHAMPAGNE took measurements in a pipe flow with natural intermittency. There the regions of laminar pipe flow should be indifferent or only slightly stable. In the experiments reported here, natural intermittency was found at $Re > 20000$ and the measurements were made between $Re = 3000$ and 12000 in a region far below the Reynolds-number, where the laminar flow became indifferent or unstable. That means, the stability of laminar regions of pipe flow in the experiments reported here should have been much better than in the experiments of WYGNANSKI and CHAMPAGNE. So here, considerably higher disturbance amplitudes should have been damped out, leading to a significant relaminarization.

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MAX-PLANCK-INSTITUT FÜR STRÖMUNGSFORSCHUNG, GÖTTINGEN.