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SERGIO VIÇOSA MÖLLER

PARA

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ASSUNTO

O ESCOAMENTO TURBULENTO EM FEIXES DE BARRAS

RESUMO

Estudos experimentais mostraram que as intensidades de turbulência nas direções axial e azimutal nos espaços estreitos entre as barras aumentam fortemente quando se reduz a distância entre as mesmas; as componentes da flutuação da velocidade possuem um comportamento quasi-periódico. Para determinar a origem deste fenômeno e suas características em função da geometria e do Número de Reynolds, o estudo experimental do escoamento turbulento em vários feixes de barras com diferentes razões de aspecto (P/D, W/D) foi realizado. Anemômetros de fio quente e microfones foram usados para medição da flutuação de velocidade e da pressão na parede do canal. Os dados foram avaliados para se obter espectros, autocorrelações e correlações cruzadas. Baseado nesses resultados um modelo fenomenológico é apresentado a fim de explicar este fenômeno. Por meio do modelo, o processo da troca de massa entre os subcanais é explicado.

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ON PHENOMENA OF TURBULENT FLOW THROUGH ROD BUNDLES

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ABSTRACT

Experimental studies have shown that the axial and azimuthal turbulence intensities in the gap regions of rod bundles increase strongly with decreasing rod spacing; the fluctuating velocities in the axial and azimuthal directions have a quasi-periodic behaviour. To determine the origin of this phenomenon, an its characteristics as a function of the geometry and the Reynolds number, an experimental investigation was performed on the turbulent flow in several rod bundles with different aspect ratios (P/D, W/D). Hot-wires and microphones were used for the measurements of velocity and wall pressure fluctuations. The data were evaluated to obtain spectra as well as auto and cross correlations. Based on the results, a phenomenological model is presented to explain this phenomenon. By means of the model, the mass exchange between neighbouring subchannels is explained.

INTRODUCTION

Experimental studies on turbulent flow along rod bundles have been performed during the last years with the purpose of obtaining data on flow velocity and turbulence distributions, necessary for turbulence modelling and code validation. A detailed review of the experimental works is given in Ref.

[1]. The results of these experiments show that the turbulence intensities in the gaps are strongly anisotropic and higher than in pipe flow. The azimuthal component of the turbulence intensity has local maxima at the center of the gaps between the rods and between the rod and channel wall, respectively, while the axial component shows local maxima at a position about 20° from the gap between the rods and at about 25° from gap between the rod and channel wall. The turbulence intensities increase when the gap width is reduced. Across the gaps there is a quasi-periodic flow process which can be called "flow pulsation".

This phenomenon was observed for the first time in 1964 by Hofmann [2], as he measured the local heat transfer coefficient in a 7-rod-bundle. By reducing the gaps between the rods and the channel wall he found unexpected high heat transfer coefficients. This was explained by the presence of a transverse component of the flow velocity, observed by means of flow visualisation experiments.

Relative maxima of the turbulence intensities in the axial direction on both sides of the gap, at positions of about 15° to 20° from the gap, were found by Rowe [3] in his experiments with rod bundles of P/D=1.25 and P/D=1.125 with water as working fluid using LDA-technique. His results show that the turbulence intensities increase when the gap width is reduced. Auto correlation functions of the axial fluctuating velocity indicated the existence of periodic flow pulsations in the gap region, which he associated with the mixing process between subchannels.

Hot-wire measurements in air flow through two rod bundles in a square array (P/D=1.194, P/D=1.107) were performed by Hooper [4]. The results showed the evidence of an azimuthal momentum transfer process across the gap, which was more intense in the rod bundle with the smaller P/D-ratio.

Hooper and Rehme [5,6] demonstrated with measurements the presence of quasi-periodic flow pulsations between neighbouring subchannels. Near the gap, the spectra of the axial and azimuthal components of the fluctuating velocity have a pronounced peak at a certain frequency. For one rod bundle, they showed this frequency to be a linear function of the Reynolds number.

The purpose of this paper is to determine the origin of the flow pulsations in rod bundles and their features as a function of the bundle geometry and the Reynolds number. More details may be found in Ref. [7].

APPARATUS AND EXPERIMENTAL TECHNIQUE

The experimental setup consists of a 7 m long rectangular channel with four aluminium tubes which simulated the rods. The geometry of the bundle could be changed by displacing one of the short walls or by using tubes with different diameters. The measurements were performed at about 20 mm before the outlet. Air was the working fluid. A schematic of the cross section of the channel is shown on Fig. 1 together with the locations of the measurements described below. Main dimensions of all geometries investigated are listed in Table I.

The experiments were controlled by a PDP 11/23 computer [8]. During an experiment, a Pitot tube placed in the center of one of the corner subchannels was used to measure a reference velocity, which for the standard conditions (p_{atm}=0.1 MPa, T=25°C) was U_{ref}=27.75 ms^{-1}. The value of U_{ref} was maintained constant by adjusting the speed of the air blower to compensate atmospheric variations and thus to keep the Reynolds number constant during an experiment.

The flow velocity was measured with a Pitot tube and the wall shear stress with a Preston tube; the outside diameter of the probes was 0.6 mm. Measurements of all Reynolds stresses were performed only on the rod bundle with P/D=W/D=1.072 by DISA constant temperature anemometers. A single wire perpendicular to the main flow was used to measure the turbulence intensity in the axial direction ($\sqrt{\overline{u^2}}$). The other components ($\sqrt{\overline{v^2}}$, $\sqrt{\overline{w^2}}$) and the shear stresses ($\overline{uv}$, $\overline{uw}$, $\overline{vw}$) were obtained using a slant-wire probe. The method used for the evaluation of the results was that proposed by Hooper [4,9].

For the determination of power spectra and correlations, microphones and hot-wires were used. Condenser microphones (Brüel & Kjær Type 4138) flush-mounted with the channel walls were applied for the measurement of the wall pressure fluctuations. The fluctuating velocities were measured by means of DISA double-hot-wire probes. The probes had one wire perpendicular to the main flow and one 45° slant wire, allowing the simultaneous measurement of two components of the turbulent velocity. The method proposed by Hooper was adapted for the evaluation of the signals of the hot-wires to obtain the momentary values of the fluctuating velocities.

At first the flow velocity and wall shear stress were measured. By integration of the measured velocities the mean subchannel velocity during an experiment was obtained for the calculation of the Reynolds number. Afterwards the hot-wires were installed: one probe was placed in the center of a gap while a second one was moved to different positions. The fixed probe was placed in the gap between the rods, while the other probe was moved to different positions on the symmetry line of the subchannel or along a line parallel to the rod wall; two microphones were placed symmetrically at the opposite channel walls. For the measurements in the region between rod and channel wall, the fixed probe was installed in the gap between rod and channel wall, while the second one was moved to several positions along a line parallel to channel wall; the microphones were placed on both sides of the gap. This case is shown in Fig.1 and refers to the experimental results shown in this paper.

The output signals of the hot-wires and of the microphones were recorded simultaneously with an analog "FM" tape recorder for spectra and correlation measurements. Afterwards they were digitized and stored on a digital tape for the evaluation of the results on the KfK main computer. Each record was digitized twice in order to obtain a good resolution of the results in the whole range investigated. The first digitization was performed with a sampling frequency of 2000 Hz with an anti-aliasing filter set at 640 Hz; for the second digitization, a sampling frequency of 32 kHz was used and the filter was set at 12,8 kHz. The resulting series had each 61440 elements. The corresponding real times were 30.72 s for the first digitization and 1.92 s for the second digitization. From the series of the first digitization, spectra up to 500 Hz with a bandwidth of 3.9 Hz as well as auto, cross correlations and correlation functions were determined. Spectra from 500 to 12800 Hz with a bandwidth of 62.5 Hz were determined from the second digitization. The FTFPS-subroutine of the IMSL-Library [10] was used for the calculation of spectra.

The measurements of the velocities, wall shear stresses and the Reynolds stresses were performed fully automatic controlled by a PDP 11/23 computer, which adjusted the speed of the blower, positioned the probes, and executed the measurements [8]. The recording of the output signals of the microphones and of the double-hot-wire probes was done by hand, while the computer controlled the blower and the positioning of the probes. The same computer was also used for the digitization of the signals and the subsequent recording of the series on the digital tape.

EXPERIMENTAL RESULTS

Axial velocities

The axial velocities measured with a Pitot tube in the rod bundle with P/D=W/D=1.07 are shown in Fig. 2 as contours. The experimental velocities are related to the reference velocity $U_{ref}=27.75\ ms^{-1}$.

Power Spectra

The spectra of two components of the fluctuating velocity in the gap between rod and channel wall are shown in Fig. 3 (P/D=W/D=1.072). The spectrum the axial component is similar to those observed in pipes [11], however, the azimuthal component shows a very pronounced peak at 62.5 Hz. At the location of this measurement, the azimuthal turbulence intensity has a local maximum [1].

At a location 20 mm from the gap, the peak in the spectrum of the azimuthal component is weaker than in the gap, but the spectrum of the axial component shows a pronounced peak at the same frequency as the azimuthal component, i. e. at 62.5 Hz (Fig. 4). Near this location on the line of the maximum distance normal to the walls, the axial turbulence intensity has a local maximum [1].

The spectra of the wall pressure fluctuation on both sides of the gap between rod and channel wall are shown on Fig. 5. The microphones were placed at 35 and 25 mm from the gap. The spectra exhibit not only the characteristic peaks of the flow near the gaps, but also various narrow peaks which disappear in the spectrum of the pressure difference p_a-p_b since they have same phase and intensity and are supposed to be produced by resonances of the test section. In the spectrum of the pressure difference, the peak corresponding to the flow pulsation is magnified, and lies at the same frequency as in the spectra of the fluctuating velocities.

The investigation of the dependence of the peak-frequency on flow velocityyields that the frequency increases with increasing the flow velocity. This confirms previous results by Hooper and Rehme with one rod bundle [6]. The frequency is also a function of the gap width: for the same Reynolds number, the frequency increases if the gap width is reduced. The non-dimensional frequency of the peaks in spectra is a Strouhal number

$$Str_{\tau} = f\ D\ /\ u^*, \qquad (1)$$

with the rod diameter D and the friction velocity

$$u^* = \sqrt{\tau_w / \rho}. \tag{2}$$

The inverse value is plotted in Fig. 6 versus the Reynolds number

$$Re = U_m D_e / \nu, \tag{3}$$

with D_e as the hydraulic diameter and the dimensionless gap width S/D (P/D-1 or W/D-1) as a parameter, for three different rod bundles with P/D=1.036, 1.072, and 1.148, all having a constant W/D=1.072. The Strouhal numbers do not depend on the Reynolds number, but they depend on the gap width: for the smallest S/D the Strouhal number is the highest (the lowest inverse value) of the three geometries investigated. This shows that the Strouhal number is a only function of the geometry, therefore, its inverse value can be expressed, by means of linear regression, as a function of the geometry, i.e. of the dimensionless gap width S/D, as shown on fig. 7, thus

$$Str_\tau^{-1} = 0.808\ S/D + 0.056. \tag{4}$$

The upper and the lower bounds denote the standard error (9.13 %) of the calculation of the spectra. In addition, there is the error due to the resolution of the spectra. The bandwidth is 3.9 Hz in the frequency range where the flow pulsations occur.

<u>Correlation analysis</u>

The cross-correlation function of two quantities x(t) and y(t) is the average product of x(t) at a time t with y(t) at a time (t+τ) for an appropriate averaging time t_b [12]:

$$R_{xy}(\tau) = t_b^{-1} \int_0^{t_b} x(t)y(t+\tau)dt. \tag{5}$$

The ratio of the cross-correlation function at a time lag τ to the square root of the product of the auto-correlation functions of the two quantities at τ=0 is called cross-correlation coefficient function:

$$C_{xy}(\tau) = R_{xy}(\tau) / \sqrt{R_{xx}(0)\ R_{yy}(0)}. \tag{6}$$

For simplicity $C_{xy}(\tau)$ will be called here cross-correlation.

Figure 8 shows the cross-correlation between the azimuthal components of the fluctuating velocity in the center of the gap between the rod and channel wall at the positions 1 and 2 (Fig. 1) for the rod bundle with P/D=W/D=1.072. The distance between gap and the locations 1 and 2 is 20 and 40 mm, respectively. The cross correlations oscillate with a period of 16 ms, and have very high maxima and minima. The functions correlate very strongly, even for the location with largest distance. Another important feature of these functions is that the absolute maximum appears on the negative time axis, with a delay time that increases with the distance. This demonstrates a preference of the direction of "w" always from the center of the sub-channel towards the gap.

The correlation function, which was first introduced by Taylor, can give a quantitative statement regarding the spatial structure of turbulence by simultaneously observing the velocity fluctuations at two different points of the flow field [13]. Taylor's correlation function can be defined as the value of the cross-correlation at a time lag of zero.

In Fig. 9 C_{uu} is the correlation function of the axial fluctuating velocity and C_{ww} of the azimuthal velocity taken on a line parallel to the channel wall and referred to the corresponding fluctuating velocities at the center of the gap (P/D=W/D=1.072). The extension of the correlation functions of both components of the fluctuating velocity indicates the presence of a large scale turbulence structure in the gap region and that the effects of the flow pulsations propagate over a large region of the sub-channel.

THE PHENOMENOLOGICAL MODEL

Turbulence is a phenomenon of strong vortex motion in a flow, where curl U exists and does not vanish [14]. The vorticity vector can, in vectorial notation, be expressed as

$$\Omega_i = e_{ijk} \frac{\partial}{\partial x_j} U_k \quad . \tag{7}$$

It is often possible to obtain a qualitative view of the distribution of vorticity throughout the fluid from the inspection of the boundary conditions [15]. In the flow field shown in Fig. 2 a strong rotational field can be seen, not only parallel to the walls, but also perpendicular to the walls due to the strong azimuthal velocity gradient on both sides of the gap.

From equation (7) it is clear that the vorticity at a wall is the partial derivative perpendicular to the wall of the velocity vector, therefore, wall turbulence consists of large eddies rotating toward the wall, fig. 10. Their motion is obstructed by the wall, and they decay in smaller eddies while transported by the main flow. In this motion, large eddies whithdraw energy from the main flow and transfer it to the small eddies, in a constant "stream of energy" from the larger to the smaller eddies [16].

In the gap a similar phenomenon occurs, but there is no wall to obstruct the motion of the eddies which stem from the vorticity field perpendicular to the walls and which are strongly influenced by vorticity parallel to the walls. Assuming that the turbulent flow is fully developed and that the test section is long enough to complete flow redistribution caused by the inlet conditions, the flow on both sides of a gap between two identical subchannels is symmetric with respect to the gap, with identical velocity profiles, i. e. identical vorticity fields. The eddies are generated on both sides of the gap turning one against the other in a meta-stable equilibrium. There is no mass or momentum exchange between the subchannels, as shown in Fig. 11.

However, these ideal conditions cannot exist, since the subchannels are not equal due to geometrical tolerances. Therefore, different velocity profiles with different vorticities will occur on both sides of the gap. Since no wall is there to obstruct the motion of the eddies, they continue to rotate and cross the gap, while they are transported by the main flow. From the adjacent subchannel, in a similar way, eddies rotating in the opposite direction cross the gap and so forth, Fig. 12. This local phenomenon propagates throughout the subchannel and, thus, destroys a meta-stable equilibrium which may occur in other gaps. The resulting motion, shown schematically in Fig.13, is very similar to a von Kármán vortex street with a stable and ordered pattern:

A - At some distance from the gap, corresponding to the local maximum of the axial turbulence intensity, the spectrum of the axial component of the fluctuating velocity has a peak at a certain frequency as well as the azimuthal component.

B - Directly in the gap, corresponding to the maximum of the azimuthal turbulence intensity, a peak appears only in the spectrum of the azimuthal component of the fluctuating velocity.

The quasi-deterministic features of this motion, the large distances over which the turbulence components correlate and the size of the eddies, allow to classify the turbulence structure in the gap region of rod bundles as a coherent structure [17]. This motion is responsible for the mass exchange between subchannels of rod bundles.

The analysis can be suported by a comparison between the distribution of the vorticity perpendicular to the wall and the azimuthal component of the Reynolds stress uw, Fig. 14. Both show a similar distribution with local maxima located at almost the same positions. This means that the flow pulsations between subchannels of rod bundles is a phenomenon generated by the turbulent motion itself. The particular geometry of rod bundles leads to this quasi-periodic behaviour.

SUMMARY AND CONCLUSIONS

An experimental study of the turbulent flow through rod bundles with several aspect ratios was performed to determine the origin of the flow pulsations between the subchannels. Based on the distribution of velocity and turbulence measurements a phenomenological model was suggested which describes the formation of large eddies near the gaps and their effect on the fluid motion through rod bundles.

An empirical equation was developed for the determination of the frequency (Strouhal number) of the pulsation as a function of the geometry. The flow pulsation is the origin for the good mixing between subchannels. By this means, the high local heat transfer coefficients, as well as the transverse flow component, which were observed by Hofmann, are explained. The cyclic momentum exchange between the subchannels observed by Hooper and Rehme is also explained.

Since the flow pulsations consist of large regular eddies, with a regular frequency, generating a pressure field around the rods with the same frequency of the pulsations, it is possible that they give rise to one of the generating mechanisms of flow induced vibrations in rod bundles [18].

ACKNOWLEDGEMENTS

This research work was performed at the Institut für Neutronenphysik und Reaktortechnik of the Kernforschungszentrum Karlsruhe. The Author is greatfully indebted to Prof. K. Rehme, for his guidance, trust, and encouragement during the execution of this work.

Author wants to thank the DAAD - Deutscher Akademischer Austauchdienst, F. R. Germany, for granting him a fellowship. Thanks are also due to the CNEN - Comissão Nacional de Energia Nuclear, Brazil, for the additional financial support.

NOMENCLATURE

$C_{xy}(\tau)$	Cross correlation coefficient function.
D	Rod diameter - m.
D_e	Hydraulic diameter - m.
e_{ijk}	Unity tensor.
f	Peak frequency in spectra - Hz.
fs	Sampling frequency - Hz.
L	Channel width - m.
p	Pressure fluctuation - Pa.
p_{atm}	Atmospheric pressure - Pa.
P	Pitch - m.
x	Coordinate - m.
Re	Reynolds number $(U_m D_e/\nu)$.
$R_{xx}(\tau)$	Auto correlation function.
$R_{xy}(\tau)$	Cross correlation function.
S	Gap width - m.
Str_τ	Strouhal number (f D/u*).
t	Time - s.
t_b	Integration time for correlation - ms.
T	Temperature - °C.
u	Axial fluctuating velocity - m s^{-1}.
u*	Friction velocity - m s^{-1}.
U_m	Mean subchannel flow velocity - m s^{-1}.
U_{ref}	Reference velocity - m s^{-1}.
$\bar{U}$	Time average flow velocity - m s^{-1}.
v	Radial fluctuating velocity - m s^{-1}.
w	Azimuthal fluctuating velocity - m s^{-1}.
W	Distance between rod and channel wall plus rod diameter - m.
ϕ	Angular position - deg.
ϑ	Normalized standard error.

ν	Kinematic viscosity - m^2s^{-1}.
ρ	Density - kg m^{-3}.
τ	Time lag - ms.
τ_w	Wall shear stress - Pa.
$\Phi_{ii}(f)$	Frequency spectrum - $(m/s)^2Hz^{-1}$ or Pa^2Hz^{-1}.
Ω	Vorticity vector - s^{-1}.

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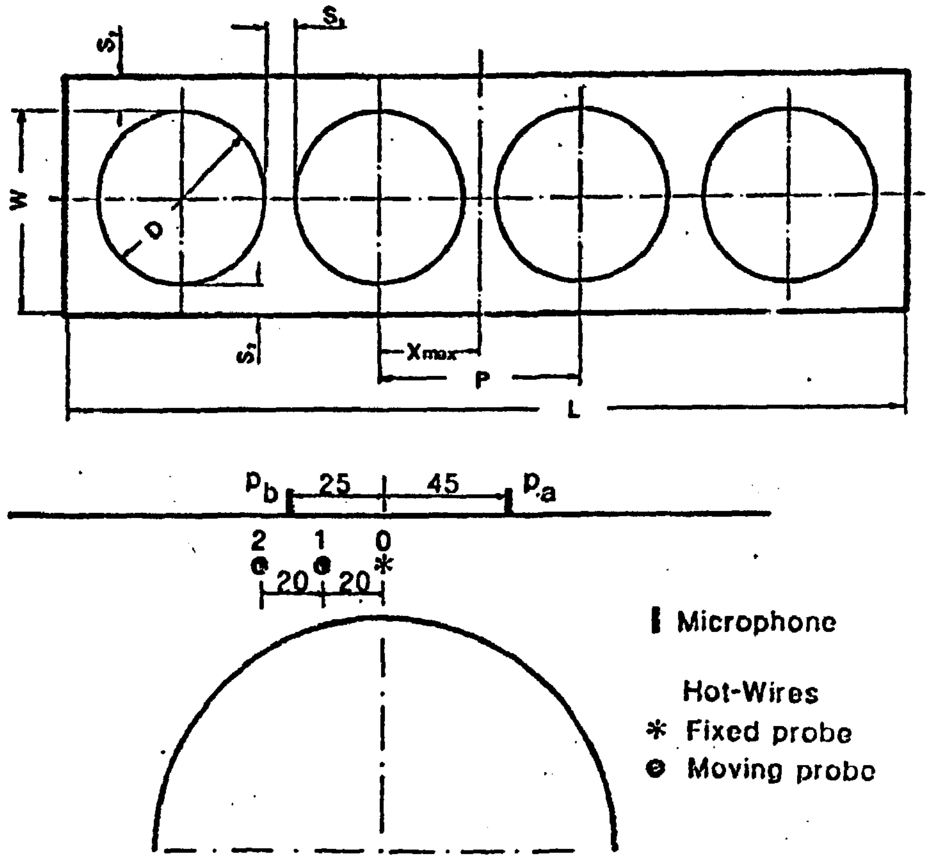


Fig. 1: Cross section of the channel with location of the measurements.

Table I - Main dimensions of the test section.

- Symmetrical arrangement:

W/D	P/D	D_e	D	S_1	S_2	L
-	-	mm	mm	mm	mm	mm
1,045	1,149	47,29	139,0	20,66	6,09	700,0
1,071	1,007	44,67	157,5	1,14	11,24	656,0
1,071	1,017	45,92	157,5	2,75	11,24	661,2
1,071	1,036	48,11	157,5	5,72	11,19	669,7
1,072	1,072	52,65	157,5	11,35	11,39	686,8
1,071	1,100	55,57	157,5	15,79	11,19	700,0
1,071	1,148	60,85	157,5	23,24	11,18	722,6
1,147	1,037	59,22	139,0	5,12	20,38	612,2
1,147	1,147	71,58	139,0	20,50	20,46	658,9
1,183	1,224	76,10	139,0	31,09	25,50	700,0

- Asymmetrical arrangement:

W/D	P/D	D_e	D	S_1	S_2	L
-	-	mm	mm	mm	mm	mm
1,072	1,036	42,56	139,0	5,00	9,96	612,2
1,223	1,036	76,10	139,0	5,00	31,06	612,2

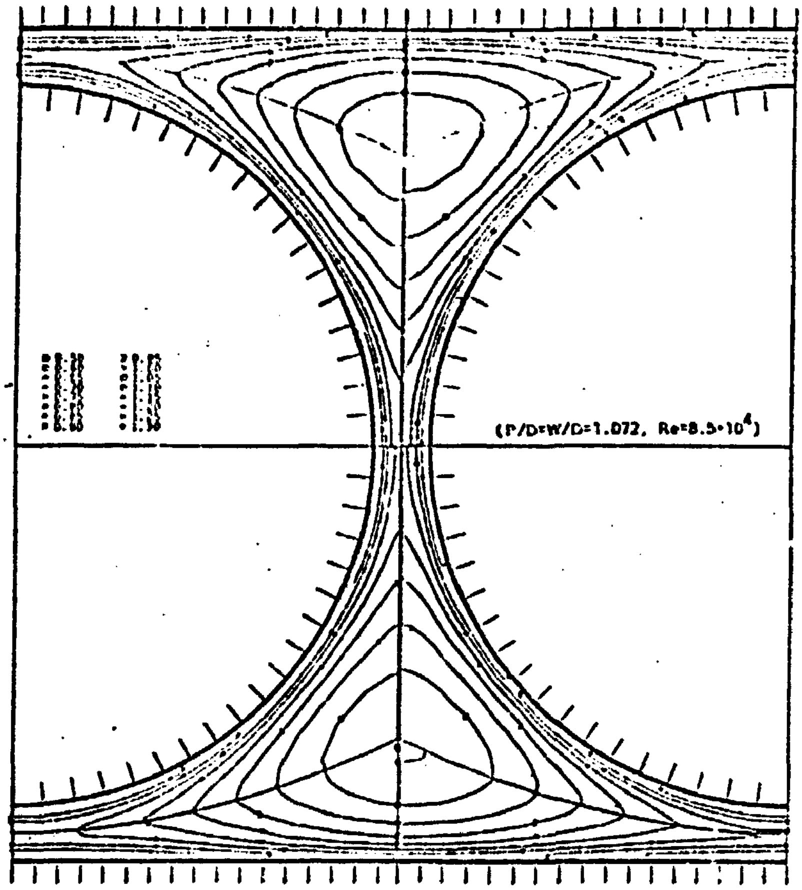
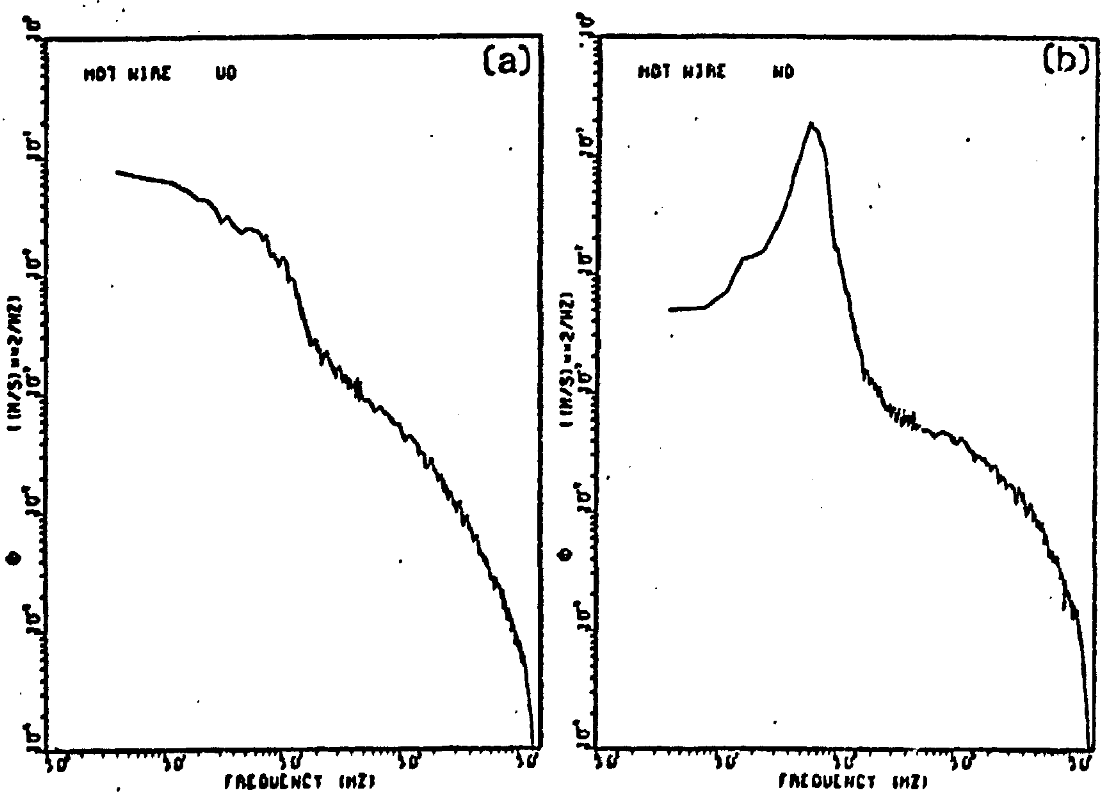
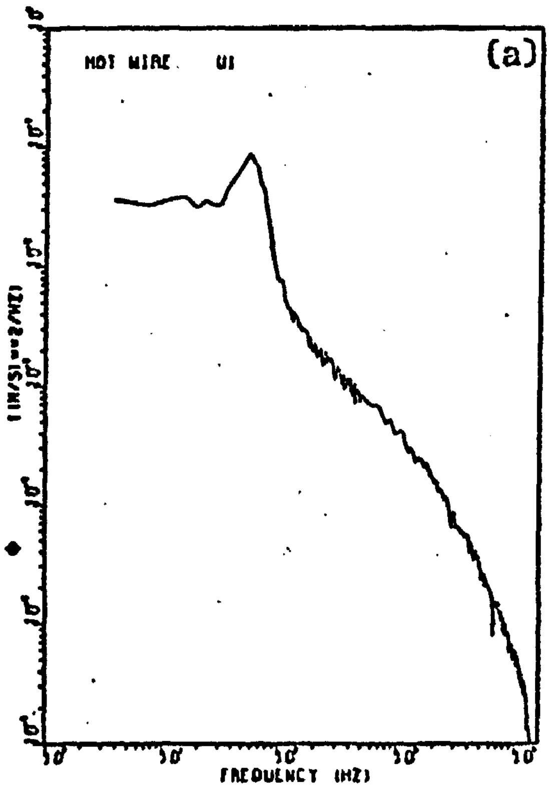


Fig. 2: Contours of the axial velocity.



(P/D=W/D=1.072, Re=8.5·10[4])

Fig. 3: Spectra of the axial (a) and azimuthal (b) components of the fluctuating velocity in the center of the gap between rod and channel wall.



(P/D=W/D=1.072, Re=8.5·10^4)

Fig. 4: Spectra of the axial (a) and azimuthal (b) components of the fluctuating velocity at a location of 20 mm from the gap between rod and channel wall.

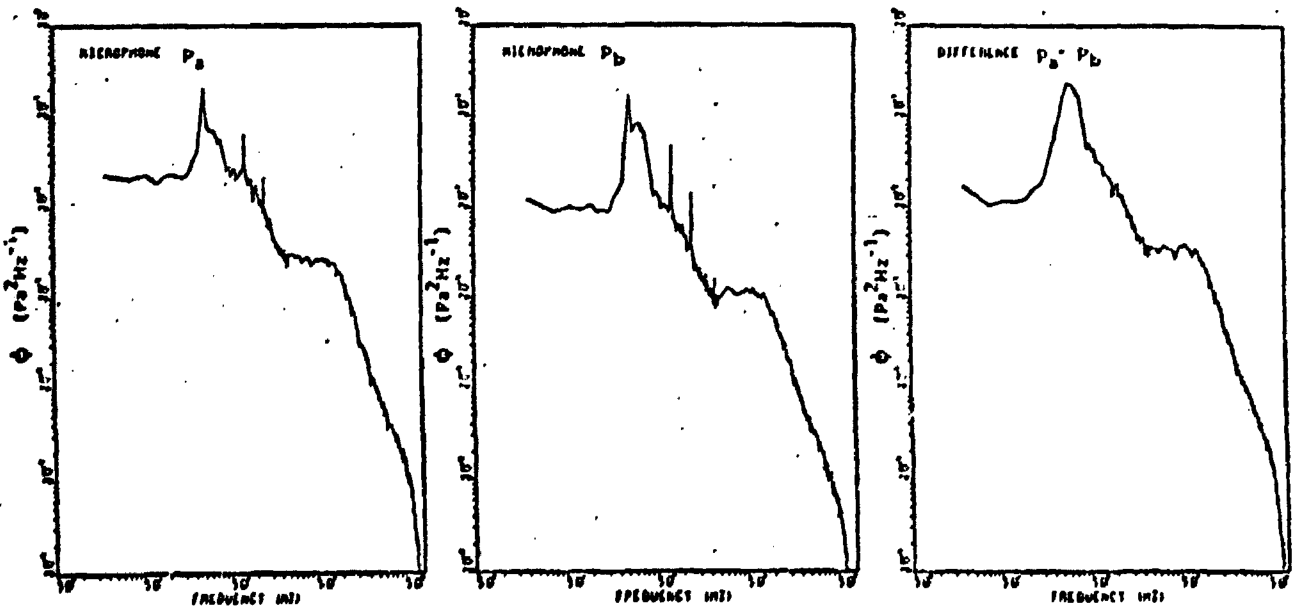


Fig. 5: Spectra of the pressure fluctuation at locations near the gap between rod and channel wall and of the pressure difference..

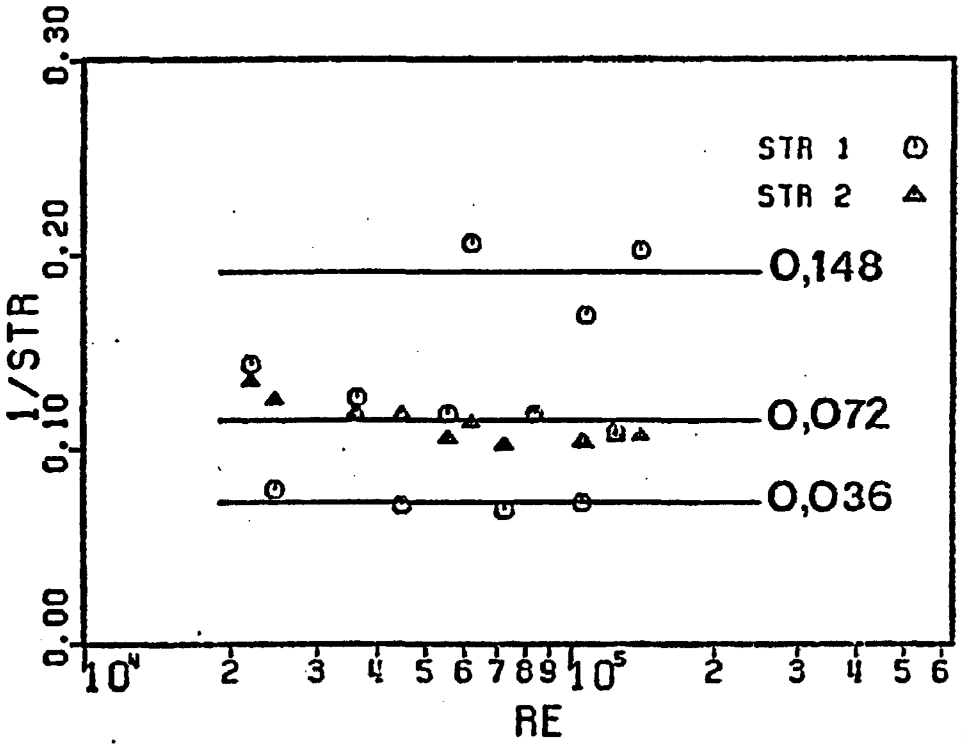


Fig. 6: Strouhal number (Str_τ) as a function of the Reynolds number with the dimensionless gap width as parameter.

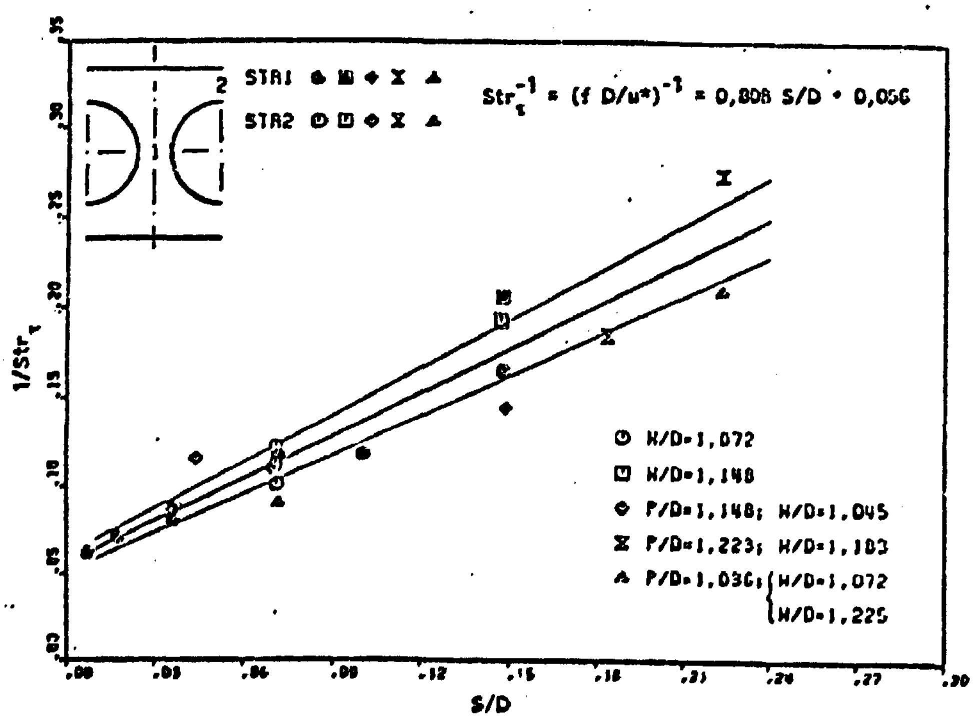
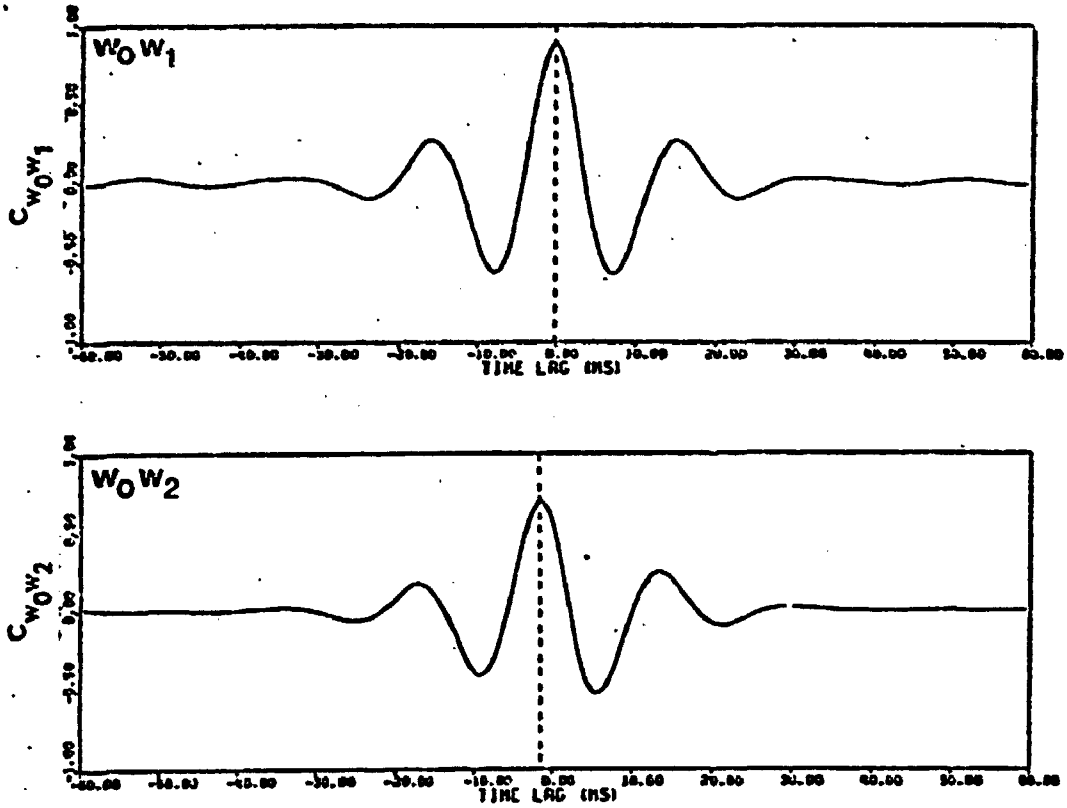


Fig. 7: Strouhal number (Str_τ) as a function of the dimensionless gap width.



(P/D=W/D=1.072, Re=8.5·10^4)

Fig. 8: Cross-correlation of the azimuthal fluctuating velocities in the gap between rod and channel wall and at locations 1 and 2.

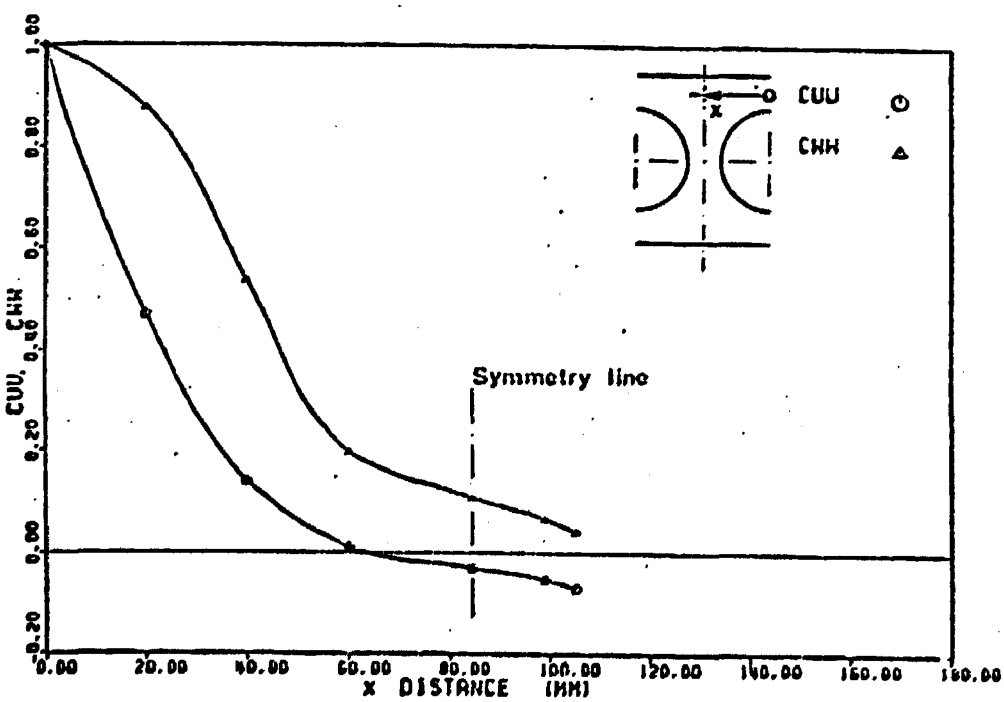


Fig. 9: Correlation function of the axial and azimuthal components of the fluctuating velocity along a line parallel to channel wall.

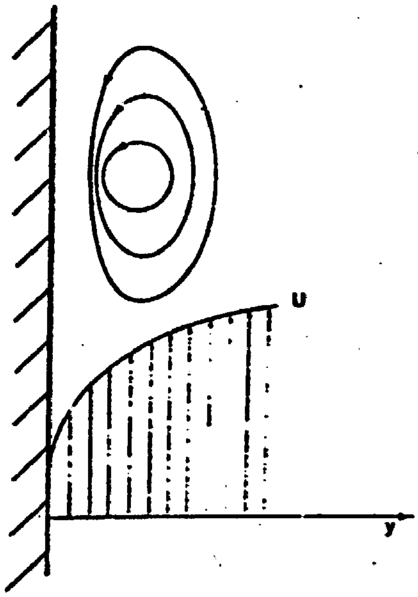


Fig. 10: Large eddies at a wall (schematic).

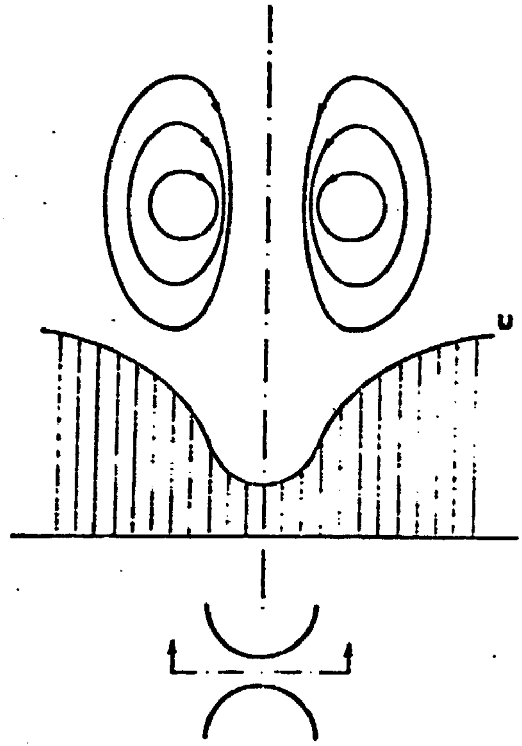


Fig. 11: Large eddies at the gap - ideal case (schematic).

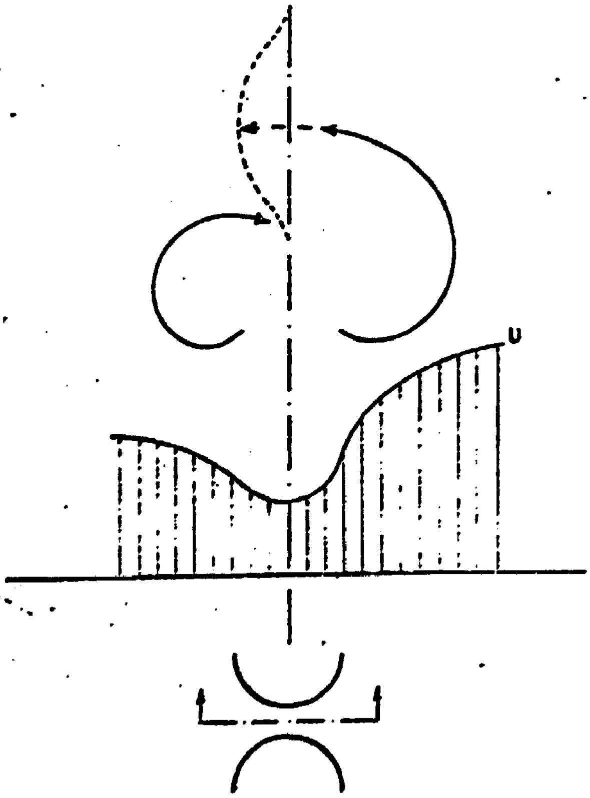


Fig. 12: Large eddies at the gap - actual case (schematic).

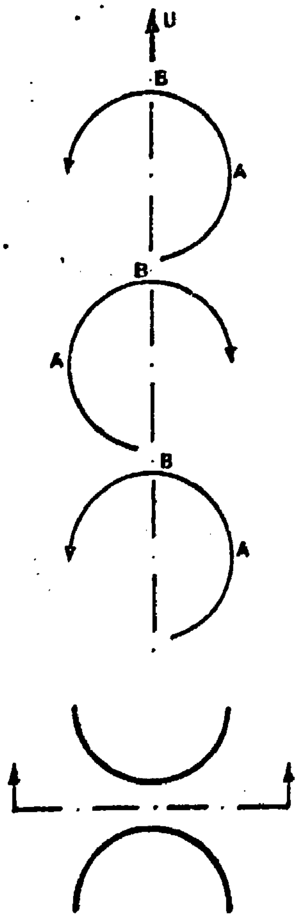
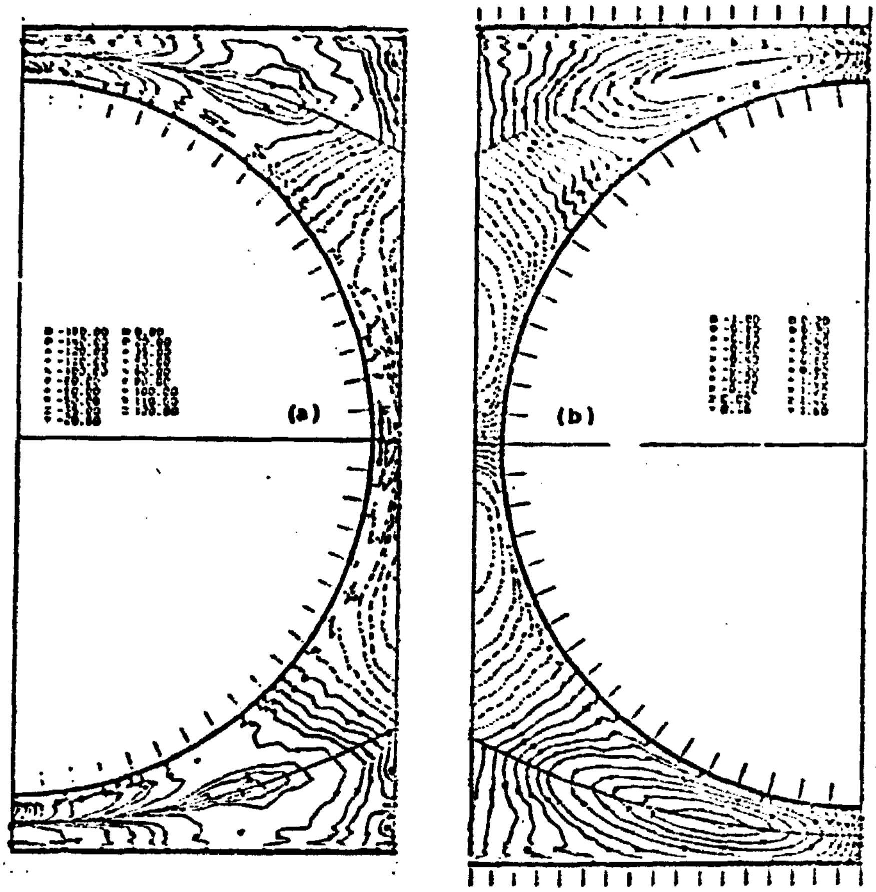


Fig. 13: Schematic representation of the eddy flow at the gap.



(P/D=W/D=1.072, Re=8.5•10^4)

Fig. 14: Vorticity field normal to the walls (a) and Reynolds stresses parallel to the walls (b).