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PERIODIC VORTICES IN FLOW THROUGH CHANNELS WITH LONGITUDINAL SLOTS OR FINS

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ABSTRACT

Large-scale, quasi-periodic coherent structures in longitudinal slots of various geometry were investigated by flow visualization and hot-wire anemometry. The flow within the slots is characterized by periodic vortices rolling along the slot with constant spacing. This spacing is only a function of the slot geometry. The flow within slots or between fins strongly affects the turbulent flow features in the main flow channel. The turbulence intensities in the vicinity of the slot are much higher especially for a multi-fin geometry, where this effect reaches far into the main flow channel.

INTRODUCTION

Axial flow in narrow longitudinal slots in a wall or in gaps connecting two large flow cross sections is a relatively new field of turbulence research. Large scale coherent structures govern this fully developed steady turbulent flow, which occurs in such disparate situations as in flow over river banks, axial flow through rod arrays and flow in slots or fins. The origin of our interest was the axial flow through rod bundles. Here the most detailed measurements were made to investigate interchannel mixing and the unusual distribution and magnitude of turbulent shear stress. Rowe (1973) observed significant periodicity in the axial velocity auto-correlation and suggested that flow pulsations are responsible for the increasing turbulence intensities with decreasing gap widths. Hooper and Rehme (1984) performed measurements in a geometry as in Fig 1.a and showed that an energetic and almost periodic flow pulsation exists through the gaps between the rods and between rods and channel walls. The frequency of this pulsation was found to be proportional to the Reynolds number. By measurements performed in the same test rig Möller (1991) established a relation between the gap width and the non-dimensional frequency, the Strouhal number, formed by the frequency, the diameter of the rods and the friction velocity; according to it the frequency increases with decreasing gap width. Subsequently, the quasi-periodic flow pulsations were confirmed to exist in other rod bundle or rod-wall arrangements also. In our laboratory we found them in a rod bundle with 37 rods (Fig.1b, Meyer and Rehme [1992], Krauss and Meyer [1995]); Wu and Trupp (1993) and Guellouz and Tavoularis (1995) found them in arrangements of a single rod contained in a four-sided channel (Fig.1c).

Subsequently, we investigated the flow in rectangular interconnected channels as in Fig.2a, to search for the necessary geometric boundary conditions for the occurrence of the periodic flow

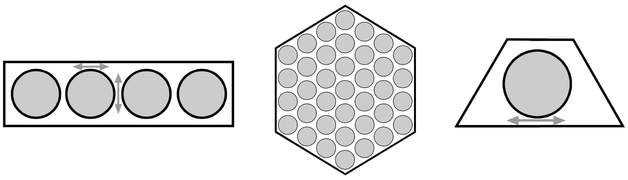

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FIG. 1. FLOW GEOMETRIES WITH RODS IN WHICH INTER-CHANNEL MIXING BY PERIODIC FLOW PULSATIONS WAS INVESTIGATED

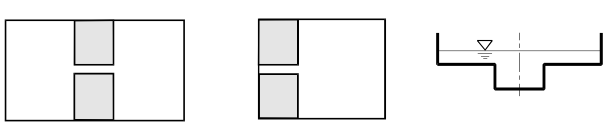

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FIG. 2. RECTANGULAR FLOW CROSS SECTIONS IN WHICH FLOW PULSATIONS WERE FOUND

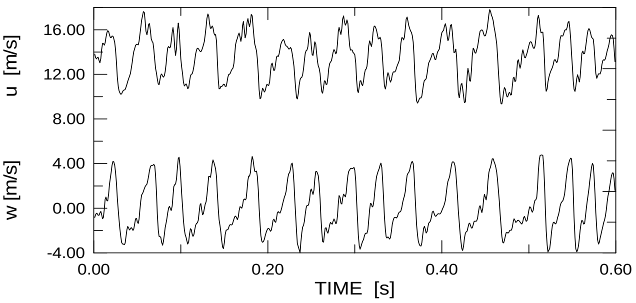

FIG.3 TIME RECORDS OF FLUCTUATING VELOCITY COMPONENTS IN A SLOT (LOW PASS FILTERED)

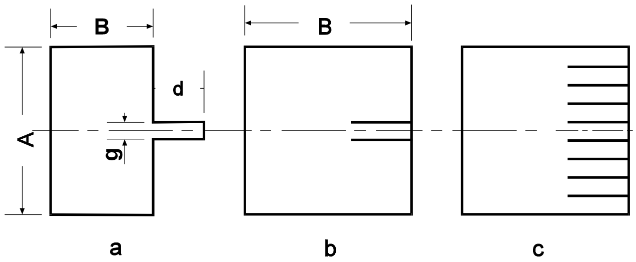

FIG. 5. FLOW CROSS SECTIONS INVESTIGATED IN THIS STUDY

pulsations (Meyer and Rehme 1994). Large-scale quasi-periodic flow pulsations could be detected in all geometries where the gap depth was more than twice its width. The frequency of these pulsations increased with both, decreasing gap depth and decreasing width. The wave length of the pulsations was found to be constant for a given geometry and was in the order of five times the gap depth. The proposed flow model of two vortices rotating in the plane of the gap in opposite directions, with their axes on both sides of the centerline, and being transported with a constant velocity axially within the gap was confirmed by LES-calculations by Biemüller (1995). A further step away from the rod bundle geometry was the investigation of the flow in axial slots as in Fig.2b (Meyer and Rehme 1994). Here too, similar flow oscillations were found. Fig.3 shows typical time records of the velocity in the slot (No.7, 10 mm within the slot, for definition of u and w see Fig.6). A picture from flow visualization in a water channel performed in the course of the present investigation shows the nature of the large scale coherent structures. Fig.4 shows the region of the slot (dark) and part of the main cross section (light) of a flow channel as in Fig.5a (No.23). Stable vortices keeping a constant spacing independent of the flow velocity are moving axially through the slot and are driven by the higher velocity outside of the slot.

A considerable number of experimental studies have been undertaken in open channels with a geometry similar to that shown in Fig.2c. These studies aim at the understanding of the turbulent flow in rivers or channels with lateral flood plains. Apart from distributions of turbulence intensities which resembles those which were found in our channels with a slot, Knight and Shiono (1990) published velocity time traces which were very similar to those of Fig.3. These similarities suggest that the flow mechanisms are the same, i.e. large eddies are rolling horizontally along the shallow banks of the open channel.

In this paper several aspects of the flow in slots (Fig.5a), fins (Fig.5b) and multi-fins (Fig.5c) are addressed:

- the effect of slot width and depth on the frequency, respectively on the axial spacing λ of the vortices,
- the effect of viscosity on the frequency,
- low Reynolds number flow within the slot,
- the effect of the channel wall on both sides of the slot, i.e. is there the same flow phenomena between fins (Fig.5b),
- if so, how do the vortices behave in neighboring slots and what is the effect on the flow in the main channel (Fig.5c).

EXPERIMENTAL FACILITIES

The investigations were performed in three different test rigs. Test rig Nos.1 and 2 were run with air, rig No.3 was run with water, respectively a mixture of water and glycol. The nominal dimensions of all three test rigs are given in table 1. In the large test rig No.1 detailed distributions of the turbulent velocities and Reynolds stresses were measured. The small test rig No.2 was designed to easily vary the geometry of one wall. This wall consisted of a large number of sheet metal with three different thicknesses of 2.0 mm, 3.9 mm and 0.3 mm. By putting these metal lamella into different packets, all the different geometries of Fig.5 could be built. The fins of rig 2b and c were built with the sheet metal of 0.3 mm thickness. Fin geometries were studied with a single slot (Fig.5b, rig 2b), and with multi-fins (Fig.5c, rig 2c). In test rig No.3 flow visualization studies in water flow were performed. Furthermore, measurements in water and water-glycol mixtures with different viscosities at low Reynolds number flow were done in this rig with two slot widths and four slot depths.

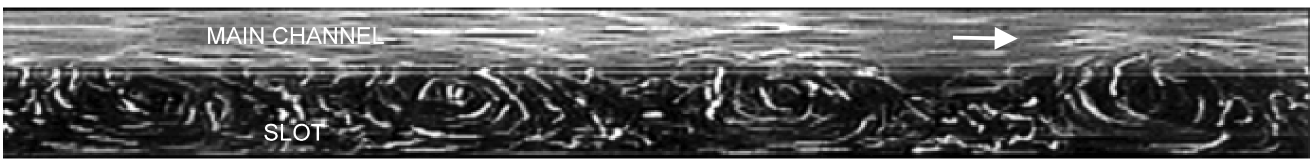

FIG. 4. VISUALIZATION OF EDDIES MOVING FROM LEFT TO RIGHT IN THE LONGITUDINAL SLOT

TABLE 1: FLOW CONFIGURATIONS (DIMENSIONS IN MM)

No.	rig	fluid	length	A	B	d	g	d/g	sym
1	1	air	7000	180	136	16.6	10	1.66	◇
2	1	air	7000	180	136	29.0	10	2.90	▽
3	1	air	7000	180	136	36.9	10	3.69	○
4	1	air	7000	180	136	48.6	10	4.86	△
5	1	air	7000	180	136	57.8	10	5.78	▷
6	1	air	7000	180	136	68.0	10	6.80	◁
7	1	air	7000	180	136	77.0	10	7.70	□
8	1	air	7000	180	136	77.0	20	3.85	⊕
9	2a	air	3000	32	22	9.5	3.9	2.44	◇ (bold)
10	2a	air	3000	32	22	9.5	2.0	4.75	△ (bold)
11	2a	air	3000	32	22	20.0	3.9	5.13	□ (bold)
12	2a	air	3000	32	22	20.0	2.0	10.0	⊞
13	2b	air	3000	32	32	5.0	2.0	2.50	▼
14	2b	air	3000	32	32	10.0	2.0	5.00	▲
15	2b	air	3000	32	32	15.0	2.0	7.50	■
16	2b	air	3000	32	32	10.0	3.9	2.56	◆
17	2b	air	3000	32	32	15.0	3.9	3.85	●
18	2c	air	3000	32	32	5.0	2.0	2.50	★
19	2c	air	3000	32	32	10.5	3.9	2.69	✶
20	3	w./gl.	2000	66	30	30.0	6.0	5.00	✖
21	3	w./gl.	2000	66	30	18.0	6.0	3.00	✚
22	3	w./gl.	2000	66	30	24.0	4.0	6.00	✳
23	3	water	2000	66	30	18.0	4.0	4.50	×
24	3	water	2000	66	30	12.0	4.0	3.00	+

MEASUREMENTS

In air

Most measurements were performed at positions 10 to 20 mm upstream of the open outlet of the test sections. Five different flow rates, with bulk velocities between 13 and 29 m/s in rig No.1 ($Re \approx 2\cdot10^5$) and between 10 and 35 m/s in rig No.2 ($Re \approx 4\cdot10^4$) were employed. The time-mean values of the axial velocity and wall shear stresses were measured by Pitot and Preston tubes (O.D. D = 0.6 mm) respectively. The turbulent normal and shear stresses were measured by hot-wire anemometry using an x-wire probe. The x-wire probe had a wire length of 1.2 mm, a diameter of 5 μm and a spacing of 0.35 mm. The probes were fabricated in our laboratory. The calibration and evaluation methods use look-up tables as described by Lueptow et al. (1988) and are discussed in detail by Meyer (1992). For correlation measurements two x-wire probes were used. The probes were run by CTA-bridges of an AN-1003 anemometer system. The filtered signals were digitized at sample rates of 2 kHz or 0.8 kHz per channel, depending on the type of measurement, by a DT2828-card which provided sample and hold digitization with 12 bit resolution. Measuring times of 48 s per point were realized. In addition to the measurement of the Reynolds stresses, power spectral densities of the fluctuating velocities *u* and *w* and the cross spectra *uw* were measured at a number of measuring positions in the slot and in the channel in the vicinity of the slot. Spatial cross correlations of axial and transverse velocity components using two x-probes simultaneously were also measured. The spectra and correlations were determined on-line by Fast Fourier Transformation with a DT7010 Floating Point Array Processor using 128 blocks with 1024 data each. With the stationary flow the statistical error is less than 10 %.

In water / glycol

The water channel is a closed loop channel with a controlled fluid temperature of ±0.5°C in the range of 10 to 35 °C . The bulk velocity was varied between 1.0 and 3.0 m/s. By mixing different amounts of glycol with water the viscosity could be varied by a factor of 13. Thus the bulk Reynolds number ranged from 2300 to 10^5 , while the Reynolds number in the slot, formed with the width g of the slot and the transport velocity of the vortices U_c , varied between 150 and 9000. The time-mean values of the axial velocity were measured by a Pitot tube. A hot film probe was used to measure the axial component of the fluctuating velocity. The measurements were performed 15 mm upstream of the end of the test section in the symmetry plane of the slot. Flow visualization was performed using a reflecting tracer. Pictures were taken with a still camera and a video camera, both moving along the channel with the transport velocity U_c of the vortices.

RESULTS

Structure of turbulence in main channel and slot

The effect of the flow within the slot on the flow in the main channel is shown in Fig.6. The vortices in the slot effectively transport mass out of the slot, having a low velocity, into the main channel and there reduce the velocity across the whole width of the channel along the symmetry line. Thus, we have two velocity maxima in the main channel. As an example for distributions of turbulent intensities and Reynolds stresses Fig.7 shows the intensity w´ parallel to the slot normalized by the average friction velocity u_τ, with a maximum of $w'/u_\tau = 2.0$ near the edge of the slot. The structure of these high intensities is revealed in the power spectral density function which shows a peak at a certain frequency. This frequency is proportional to the flow velocity as depicted in Fig.8 for the w-component. The corresponding functions for the u-component are similar at a somewhat higher level. The peaks correspond to the most likely convection frequency of the vortices which we see in Fig.4. The pictures from our flow visualization showed that the axial spacing of the vortices varied within a certain range. This fact is reflected in the width and height of the peaks in the power spectra.

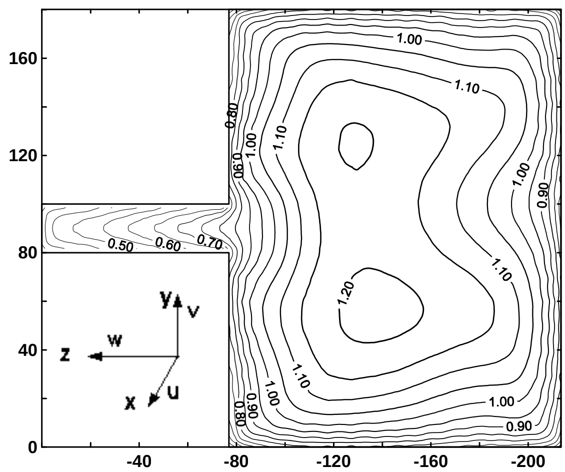

FIG. 6. CONTOURS OF THE NORMALIZED AXIAL VELOCITY U/U_b IN GEOMETRY NO. 8

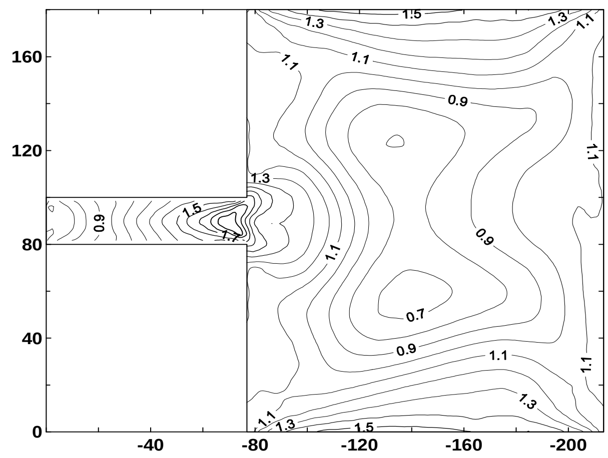

FIG.7. CONTOURS OF THE NORMALIZED TRANSVERSE INTENSITY w'/u_τ (maximum is 2.0)

We found peaks in all three flow cross sections of figure 5, but with different distinctness. Generally, the peaks are narrower and higher with increasing d/g-ratio, i.e. with relative deeper slots. However, beginning at a ratio of 5, a second, smaller peak appears at double the base frequency. At lower d/g-ratios, e.g. d/g=10/4, the peaks get wider and lower at low flow velocities. An exception to that trend was found in the spectrum of the multi-fin geometry No.19, with the most distinct peak in the w-component at the lowest velocity. Here a second anomaly occurred; the frequency of that peak was approximately twice as high as expected by the general rule of a proportionality between flow velocity and peak frequency. In fact, the frequency of that peak was higher than the frequency at the next higher flow velocity. Similar irregularities occurred at the geometries Nos. 9, 16 and 17 at the lowest and second lowest velocity, although the frequencies were not quite two times the expected value.

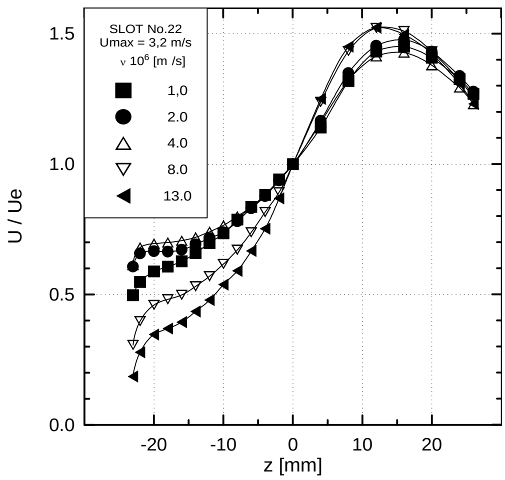

FIG.9. VELOCITY PROFILES AT DIFFERENT VISCOSITIES

Effect of viscosity

One reason for performing experiments in a water-glycol mixture was to study the viscosity effect, respectively the vortex structure at extremely low Reynolds numbers within the slot. Although the velocity profiles changed with different viscosities (Fig.9), a systematic variation of the peak frequency could not be detected. Distinct peaks in the power spectra were present even at the lowest Reynolds number, with $Re_{SLOT} = 150$.

Geometry effect on vortex structure

Except for the anomalies mentioned above, the ratio of the peak frequency and a characteristic velocity, such as the velocity at the edge of the slot, is - with some scatter - a constant for a specific slot geometry. This specific frequency decreases with both, increasing

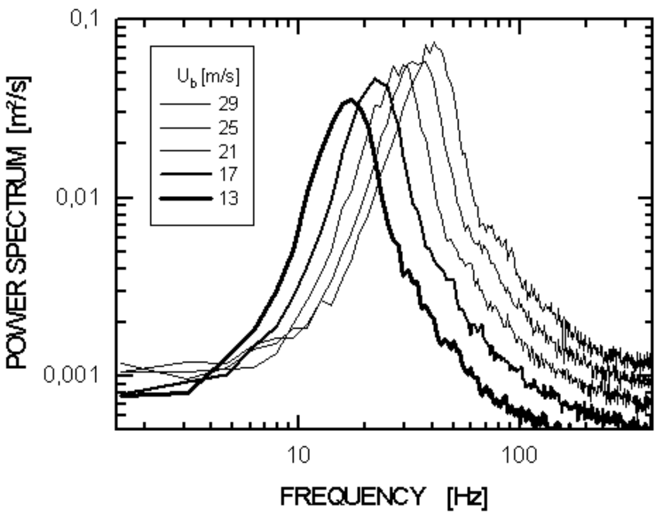

FIG.8. AUTOSPECTRAL POWER DENSITY OF THE TRANSVERSE VELOCITY COMPONENT w', MEASURED AT

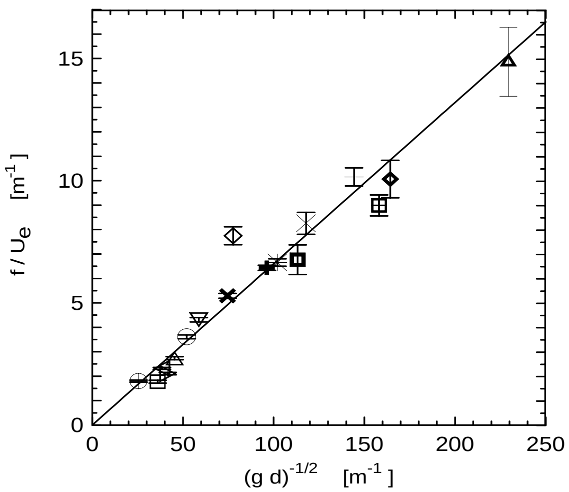

FIG.10. STR-NUMBER VERSUS SLOT GEOMETRY FOR TYPE A-SLOTS

TABLE 2. VORTEX DATA FOR ALL THREE SLOT TYPES

TYPE	Str	σ	U_e/U_c	σ
Fig.5 a	0.066	0.011	1.37	0.14
Fig.5 b	0.080	0.010	1.44	0.11
Fig.5 c	0.050	0.005	1.23	0.20

slot depth and width. This corresponds to the findings in rod bundle geometry and in interconnected channels. Similarly a Strouhal number can be formed with the slot parameters *d* and *g*, the peak frequency *f* and the velocity at the edge U_e.

$$\mathrm{Str} = \frac{f}{U_e}\sqrt{gd} \qquad (1)$$

The Strouhal numbers with the standard deviations for all slots, the double-fin and multi-fin geometries are given in table 2. It is surprising, that the product of slot depth and slot width correlates the specific frequency. this means that a slot twice as deep but half as wide as another slot produces the same specific frequency. The correlation of the results by means of a Strouhal number shows some considerable scatter and is certainly not conclusive. The largest deviations occur for extreme d/g-ratios, such as d/g=1.66 or d/g>7. For d/g < 2, vortices, respectively peaks in the power spectrum could hardly be detected. In deep slots with d/g > 7 the vortex structure might change; the bottom of the slot is no longer the governing factor for the shaping of the velocity profile. For 2 < d/g < 5 the non-dimensional velocity profiles usually collapsed for different mass flow rates and different slot depths. The velocity profiles in slot No.12 (d/g = 10) showed a distinct difference compared to those in No.11 (d/g= 5) (Fig.11). The choice of the velocity U_e is arbitrary. It increases with increasing slot width and is almost invariant with changing slot depth. This means that the actual frequency is lower for the wider slot of two having the same value of *gd*. With the transport velocity of the vortices, U_c, the streamwise spacing between two consecutive vortices, or wavelength λ, is defined by

$$\lambda = U_c / f . \qquad (2)$$

Except for the measurements in the water channel and Nos. 1,2,4

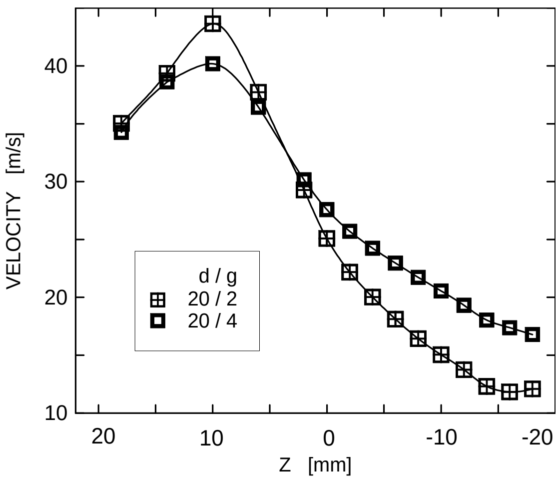

FIG.11 VELOCITY PROFILES IN DEEP SLOTS

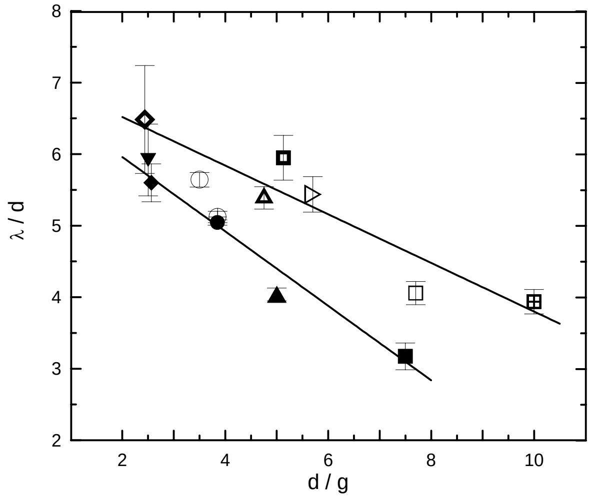

FIG.12. SPACING OF THE VORTICES AS A FUNCTION OF THE RELATIVE SLOT DEPTH

and 6 in rig 1, two-point measurements at two axial positions provided data on the wavelength λ. As already mentioned before this wavelength is independent of the flow velocity. Fig.12 shows a function of the relative wavelength versus the relative slot depth for the simple slot and the double fin geometry, respectively. Again, there is considerable scatter.

Flow in multi-fin geometry

In the multi-fin geometry (Fig.5c) the vortices within separate slots are synchronized, i.e., there is no phase shift between the large scale transverse velocity components measured in different neighboring slots. This can be deduced from spatial cross correlation measurements, which were performed with two probes, spaced three slot widths apart, positioned at identical x- and z-positions. The axial velocity components show a high correlation deep down in the slots (Fig.13) and low correlation values in the main channel, while the transverse components show high correlations far into the main channel. The power spectra measured at the same z-positions display high peaks at those positions with high correlation values (Fig.14 and 15). This means also, that the flow between the fins strongly affects the flow far into the main channel nearly up to the opposite wall.

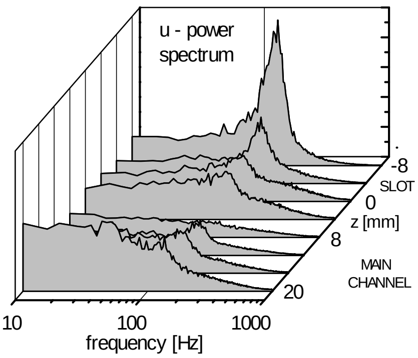

FIG.14 POWER SPECTRA OF THE AXIAL VELOCITY COMPONENT BETWEEN FINS AND IN THE MAIN CHANNEL OF NO.19

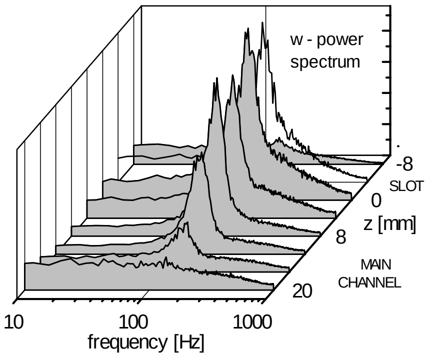

FIG.15 POWER SPECTRA OF THE TRANSVERSE VELOCITY COMPONENT IN CHANNEL NO.19

CONCLUSION

The presence of large-scale, quasi-periodic vortices in any longitudinal slot with d≥2g, or between fins has been demonstrated through flow visualization and two-point space-time correlation measurements. These vortices are present down to very low Reynolds-numbers in the slot, e.g. Re = 150. The axial spacing of the vortices is exclusively a function of the geometry of the slot, independent of velocity and viscosity, within the range of our experiments. It is approximately six times the slot depth, decreasing to 3 - 4 times the slot depth for deep slots. The same phenomena occur at longitudinal finned surfaces. Here the vortices are synchronized in all the parallel slots and the periodic transverse velocity components are found far into the main channel.

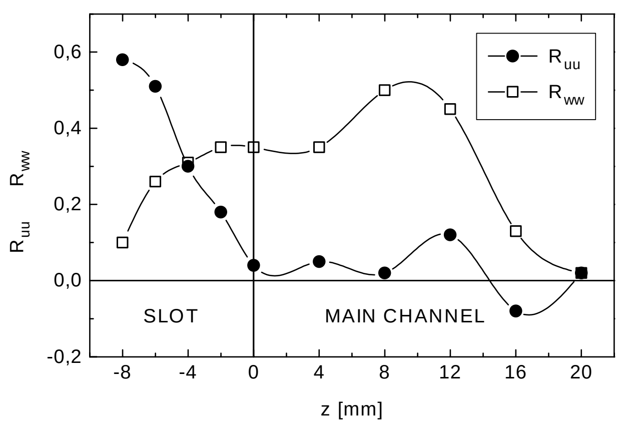

FIG. 13. SPATIAL CROSS CORRELATION IN MULTI-FIN GEOMETRY NO.19

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