Large eddy simulation and measurement of the structure of turbulence in two rectangular channels connected by a gap

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ABSTRACT

Theoretical and experimental investigations of the structure of turbulent flow have been performed in a channel consisting of two rectangular channels which are connected by a gap near a wall. Hot-wire experiments showed that very high Reynolds stresses occur close to the gap. Large eddy simulations confirmed the experimental results and showed that large scale streamwise vortices move within the gap along the whole length of the channel.

1. INTRODUCTION

Unusual distributions of the Reynolds stresses have been found for turbulent flow near gaps connecting two large channels. Large scale coherent structures govern the fully developed turbulent flow which occurs in such disparate situations as in flow over river banks, axial flow through rod bundles, and flow in slots or between fins. The origin of our interest was the axial flow through rod bundles. Detailed measurements were performed to investigate the interchannel mixing and the unusual distributions of the Reynolds stresses. Rowe [1] observed a significant periodicity in the axial velocity autocorrelation and suggested that flow pulsations are responsible for the increasing turbulence intensities with decreasing gap width. Hooper and Rehme [2] performed measurements in a bundle of four parallel rods contained in a rectangular channel 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 in the same test rig Möller [3] 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. Quasi-periodic flow pulsations were confirmed to exist in other rod bundles or rod-wall arrangements also. In our laboratory we found them in a rod bundle with 37 rods (Meyer and Rehme [4] and Krauss and Meyer [5]); Wu and Trupp [6] and Guellouz and Tavoularis [7] found them in arrangements of a single rod contained in a four-sided channel. Subsequently, we investigated the flow in compound rectangular channels connected by a central gap to search for the necessary geometric boundary conditions for the occurrence of the periodic flow pulsations (Meyer and Rehme [8]). Large-scale quasi-periodic flow pulsations could be

detected in all geometries where the gap depth was more than twice its width. The frequencies 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 the flow pulsations consists 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 along the whole channel. Further experimental investigations showed that such flow pulsations also exist in axial slots, between fins and in multi-fin geometries (Meyer and Rehme [8, 9]).
The main purpose of this study was to examine if large scale periodic vortices which had been found in compound rectangular channels connected by a central gap also exist in a channel with a gap near one wall. Moreover, the turbulent flow through a channel with a gap near a wall was investigated numerically by large eddy simulation (LES) to confirm the flow model of the large vortices and to produce results which cannot be measured easily.

2. TEST SECTION AND INSTRUMENTATION

2.1. Flow configuration

The flow configuration used for this work was a vertical straight duct of rectangular cross section. The channel was constructed from Perspex and had a length of L=7000 mm. The rectangular channel had the dimension of T x B = 180 x 331.6 mm. The channel was subdivided by an insert of Perspex into two rectangular channels connected by a gap at one wall. The gap size was g x d = 10.2 x 40.6 mm (Fig.1). The fluid is air at atmospheric pressure and room temperature. The air is driven by a centrifugal blower. Before entering the working section the air passes through a filter to remove particles greater than 1 µm. A special effort

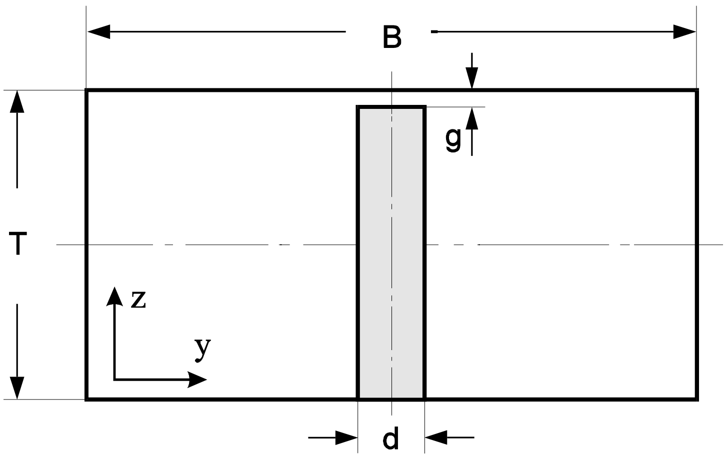

Fig. 1 Cross section, the flow is in x-direction

was made to obtain a symmetrical flow distribution at the entrance of the channel. Detailed measurements of the velocity distribution were performed before starting the measurement program. Finally, the flow was symmetric to within 1% by using a settling chamber, a honeycomb, different perforated plates, and a number of fine-grid screens.

2.2. Measurements

The measurements were performed at a position 30 mm upstream of the open outlet at a Reynolds number of Re = 2 x 10^5. The length-to-hydraulic diameter ratio of the measuring plane was L/D_h = 42.1. The hydraulic diameter is defined for the channel neglecting the gap. The time-mean values of the axial velocity and the wall shear stresses were measured by Pitot and Preston tubes (O.D. D = 0.6 mm), respectively. The wall shear stress was evaluated with the correlations by Patel [10].
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 by Lueptow et al. [11] and are discussed in detail by Meyer[12]. There are several errors typical for x-wire probes, such as the error due to the velocity component normal to the x plane and errors due to the finite length of the wires and the distance between them. These errors also depend on the velocity gradient [12-14]. Maximum absolute uncertainties for the present results, including the drift of the anemometer, were estimated to be ±3% for the instantaneous value of U+u and ±0.2 ms^{-1} for v and w. Since the fluctuating components u, v, and w are evaluated by the difference between the instantaneous values and the time integrated average U, the uncertainties for the turbulence intensities u', v', and w' are only in the order of ±1%. The error for the turbulent shear stresses $\overline{uv}$ and $\overline{uw}$ can go up to ±5% close to the walls. The uncertainty of the velocity measurements was estimated to ±0.7%, and the uncertainty of the wall shear stress data was estimated to ±1.0% by using the procedure of Moffat [15].
The performance of the calibration and of the measurements is fully automated. The mass flow rate and the traversing of the measuring probes are controlled by a microcomputer. 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 2kHz or 0.8 kHz, 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 $\overline{uw}$ were measured at a number of measuring positions in and close to the gap. 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.

3. LARGE EDDY SIMULATION

The experimental data had shown that the flow pulsation is a large scale effect, therefore, the large eddy simulation obviously is well suited for a numerical treatment of the flow situation. Another advantage of the large scale effect is that a relatively coarse mesh can be used for the simulation. For the large eddy simulation a modified version [16] of the TURBIT-code [17] was used. The method is based on the numerical representation of the full Navier-Stokes equations in a finite volume procedure. Only the small scales of turbulence have to be modeled by a Schumann subgrid scale model, but the results are rather insensitive to the model coefficients. A non-equidistant grid was used in the direction of z in order to be able to model the gap by a rather fine mesh. The geometry of the simulation was chosen to be similar to the experiment as far as possible. Differences exist for the boundary conditions. The no-slip boundary conditions are applied at all walls together with wall functions except for the "walls" in the direction of y. The cross section is assumed to be infinite in this direction for the simulation and therefore periodic boundary conditions are applied. Periodic boundary conditions are also applied in the streamwise direction. The grid used for the simulations of the results shown in this paper is 64 x 40 x 24, the gap was modeled by 64 x 8 x 8 grid points (Fig. 2). The nondimensional periodicity lengths used in this simulation were X x Y = 2.8 x 2.0. The periodicity length is made dimensionless by the distance between the plates T.

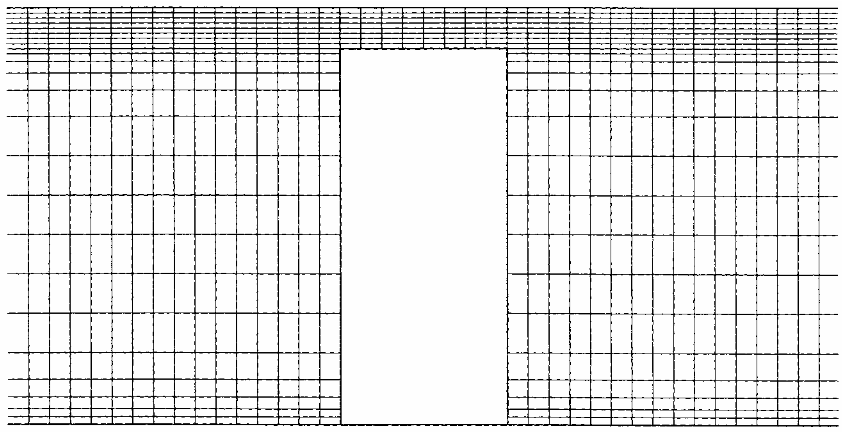

Fig. 2 Grid used for the simulation

The gap region which is important for the phenomena observed was simulated correctly. The ratio between depth and width of the gap is d/g = 4 as for the experiment. Different grid sizes have been tested, the only differences in the results were smoother contours for finer grids. The Reynolds number was varied in the range between 3.3 x 10^3 to 5,8 x 10^5. The results for

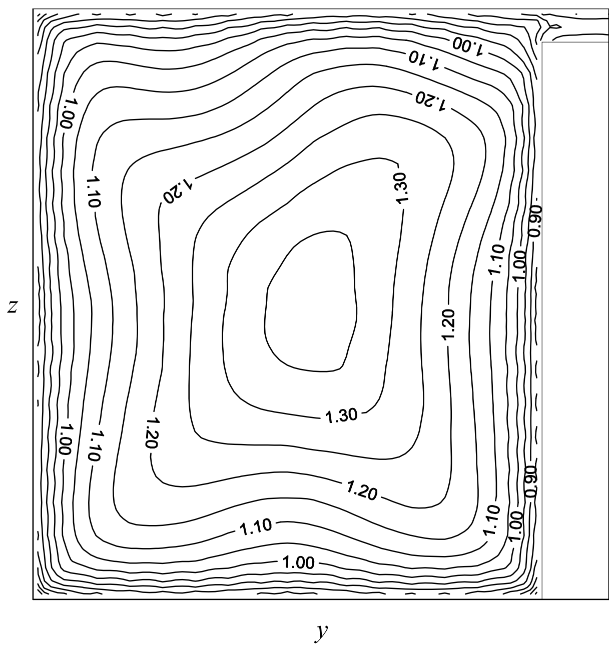

Fig. 3 Contours of the axial mean velocity

lower Re numbers were qualitatively the same, however, the peaks in the Reynolds stresses were higher. Again, the contours were smoother for lower Reynolds numbers. To investigate the effect of different periodicity lengths in the streamwise direction, simulations were

performed first for one periodicity length in which one pair of vortices appeared. Then, the periodicity length was doubled and two pairs of vortices were visible.
The results of the simulations shown in this paper were computed for a Reynolds number of Re = $1,3 \times 10^4$. To increase the statistical quality of the analyzed data it is necessary to average not only in the time domain but also in space. The special geometry allows averaging in the homogeneous main flow direction. Moreover, the symmetry of the geometry can be used to average over both sides of the symmetry axis taking the sign into account.

4. RESULTS

It is not possible to discuss all results in this paper; more detailed results can be found in [16]. The difference in the geometries must be considered for the comparison between experiment

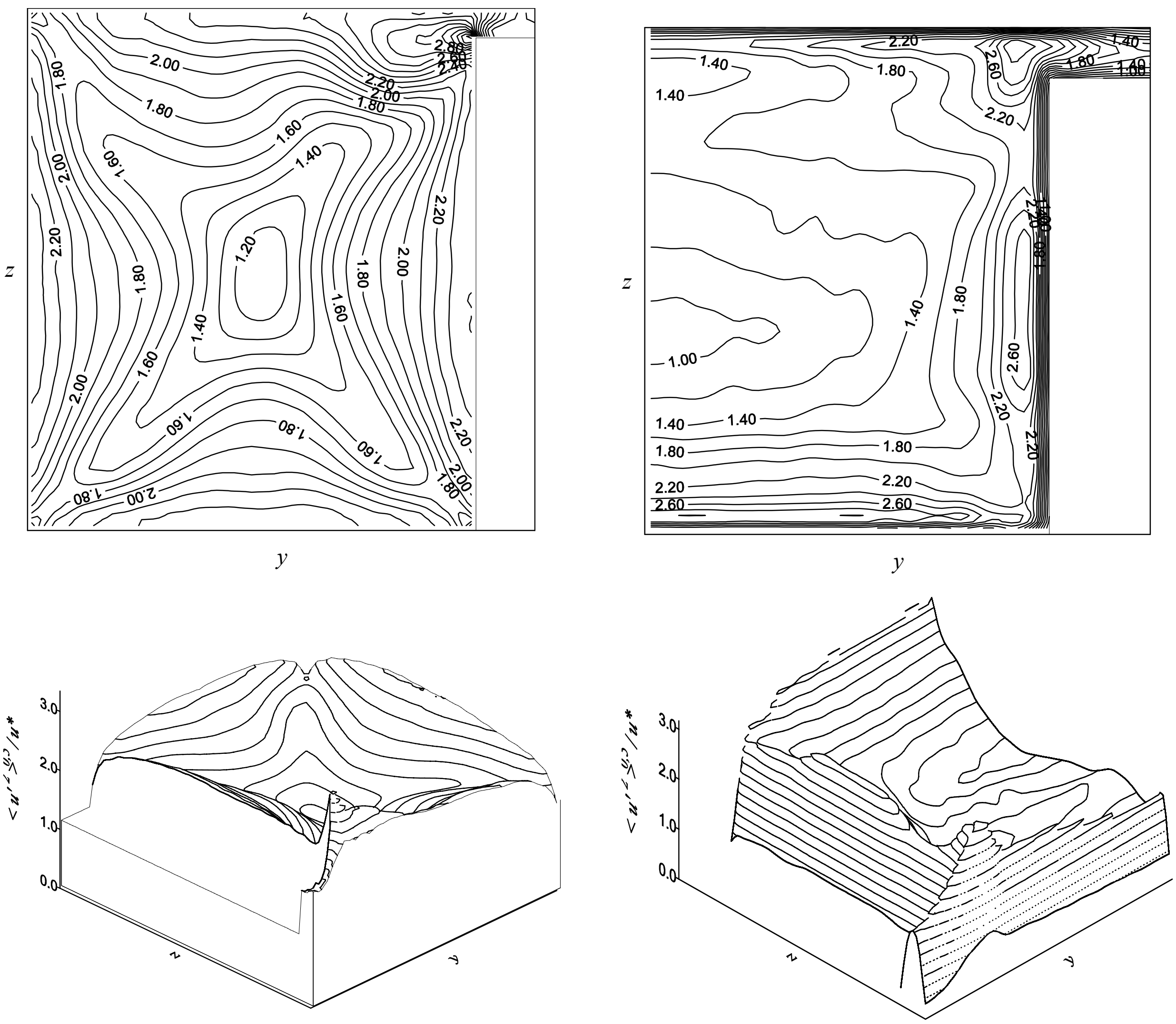

Fig. 4 Dimensionless streamwise turbulence intensity: experimental data (left) and simulation (right)

and simulation. The boundaries in the direction of y can be interpreted as symmetry lines and correspond to the plane in the middle of the experimental channel. These differences are not important since the special flow phenomena only occur close to the gap.

The experimental results show how the gap affects the velocity distribution (Fig. 3). The velocities measured by a Pitot tube are made dimensionless by the mean velocity. The bulging of the contours caused by secondary flows is clearly visible in three corners of the rectangular cross section. However, there is a quite different velocity distribution in the corner with the gap.

Figure 4 shows the streamwise turbulence intensities related to the average friction velocity for the experiment and the simulation as a contour and 3D-plot. The experimental results are in agreement with the well known results of rectangular channels in most of the cross section. But close to the gap there is a deviation. The streamwise turbulence intensity has a strong peak with a maximum value of 3.3 as the highest value in the channel. The simulation displays the experimental results in and near the gap with a good agreement.

The Fig. 5 shows the turbulence intensity in the y-direction, that is the direction through the

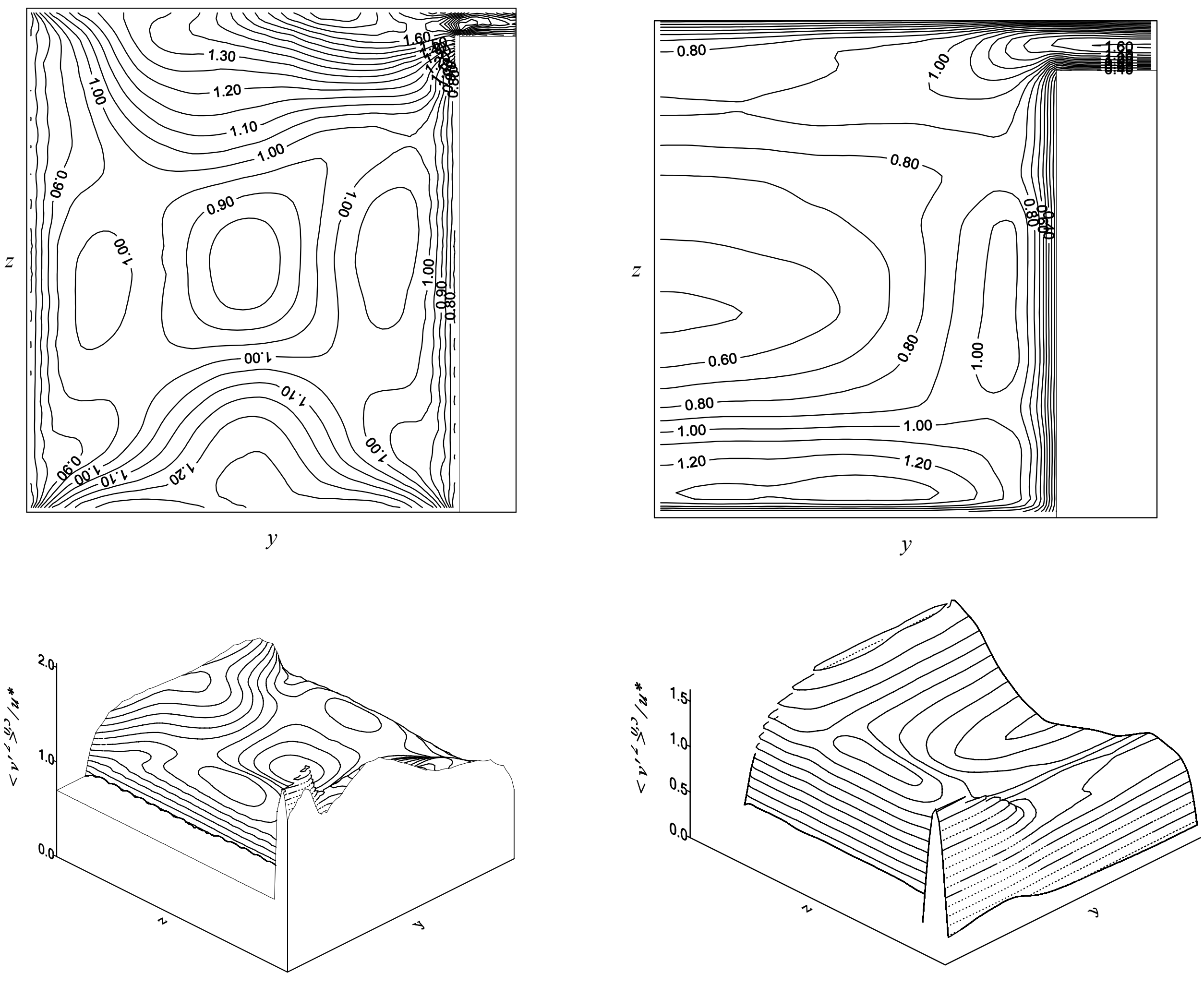

Fig. 5 Dimensionless gap-parallel turbulence intensity in the direction through the gap: experimental data (left), simulation (right)

gap. The experimental results exhibit the well known behavior for rectangular channels in most of the cross section except close to and in the gap. At this position very high intensities are observed with a sharp peak with a maximum of 2.0 at the beginning of the gap. The turbulence intensities slightly decrease towards the middle of the gap. The same features are

observed in the simulation. The maximum value of the gap-parallel turbulence intensity of the simulation is 1.9 and is found to be constant in the gap. A peak at the beginning of the gap which was found in the experiment cannot be detected in the results of the simulation.
A very high peak at the beginning of the gap is found for the gap-parallel turbulent shear stress (Fig. 6). The data are made dimensionless by the square of the friction velocity. The experimental results have a peak with a value of 3.9. The gap-parallel shear stress decreases from the peak both towards the center of the gap and towards the channel. In the main part of the channel the values of the gap-parallel shear stress reach values of about 1.0 and the distribution of the contours shows the usual picture for rectangular channels. In the middle of the channel the shear stress is zero which is also the case for the middle of the gap. The simulation gives quantitatively the same result as the experiment with a very high peak at the beginning of the gap. However, the maximum value of 2.4 is lower than in the experiment.
The planar turbulent shear stress is presented in Fig. 7. For this shear stress there are only results of the simulation since it is difficult to measure the planar turbulent shear stress. The

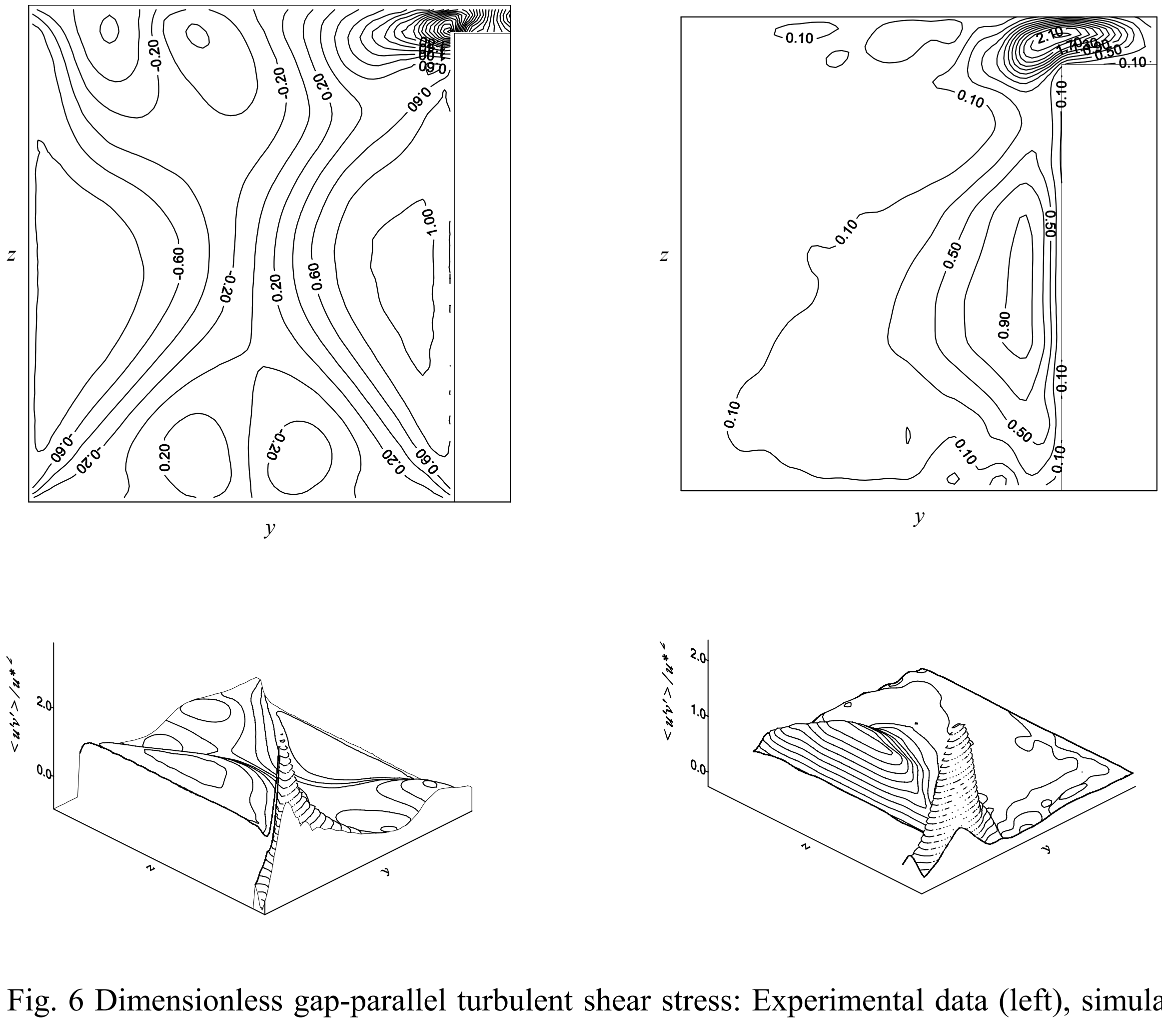

Fig. 6 Dimensionless gap-parallel turbulent shear stress: Experimental data (left), simulation (right)

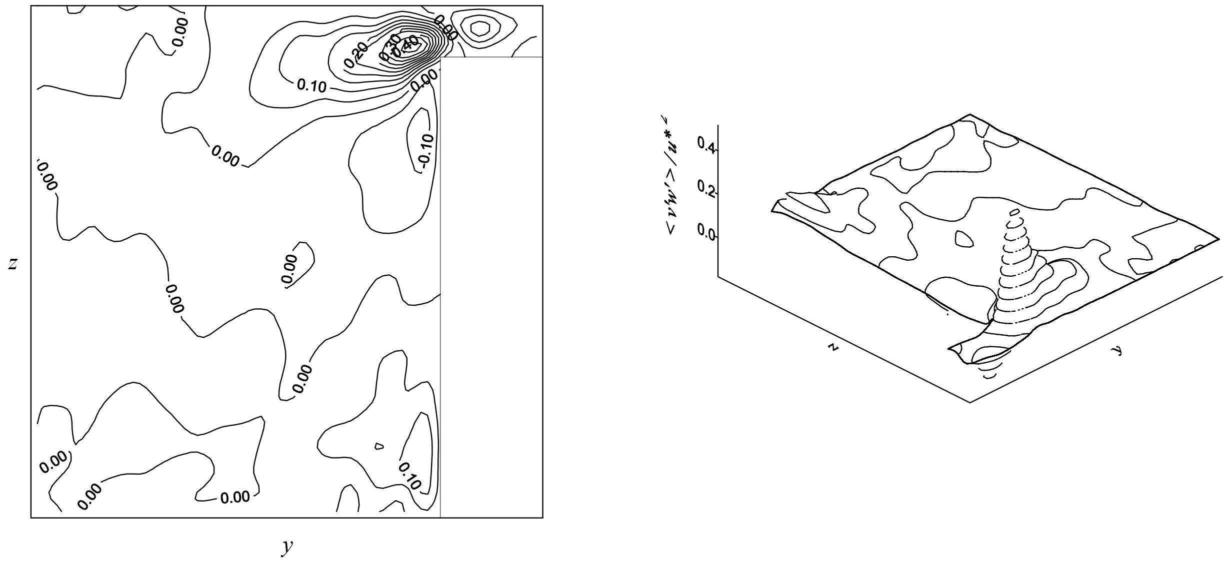

Fig. 7 Dimensionless planar turbulent shear stress: result of the simulation

planar turbulent shear stress is close to zero for most of the channel. Only close to the gap this shear stress shows a peak, however with a relatively small value of 0.5. In the gap an even smaller peak is visible with a negative sign.

The structure of the large-scale flow pulsation in the gap was made visible from the simulations by a special averaging procedure. The average transport velocity of the large vortices in the gap was subtracted from the computed velocity vectors. This means that an observer of the flow moves with the transport velocity. The result is presented in Fig. 8 which shows the averaged vectors of the velocity in the gap which is indicated in gray. Two vortices are visible which rotate in opposite directions and are driven from the higher velocities outside the gap. The centers of the vortices are on both sides of the gap axis but within the gap. The stable vortices are transported in the streamwise direction with a transport velocity of 0.66 of the bulk velocity in the gap along the whole channel. The model of the flow pulsation

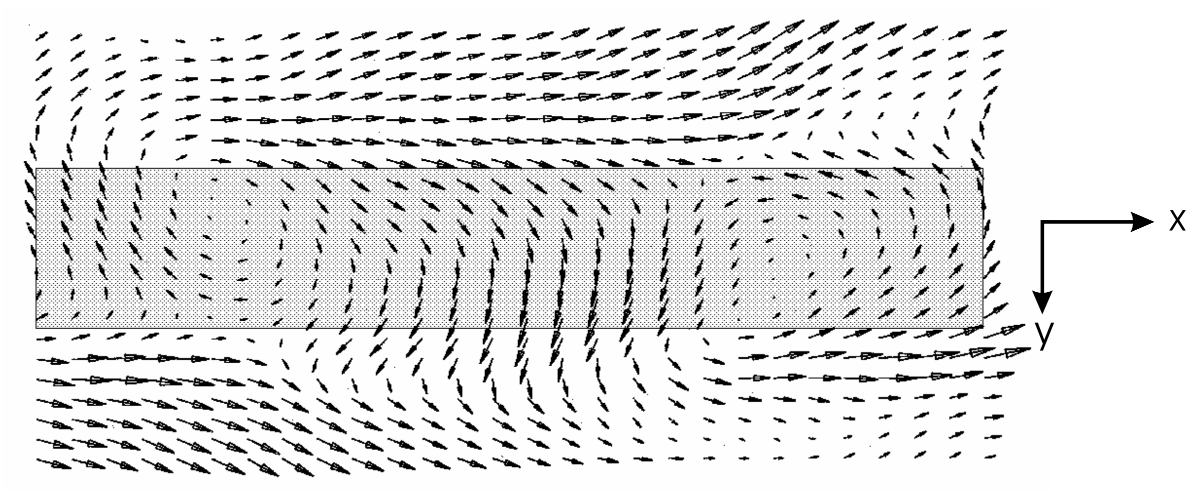

Fig. 8 Velocity vectors of the large scale vortices in the gap

which was mentioned in the introduction was thus confirmed. The production term of the turbulent kinetic energy in the gap-parallel direction (the gap-parallel turbulent shear stress times the velocity gradient in gap-parallel direction) has a very strong peak at the beginning of the gap with a level which is normally only found close to the walls. This means that turbulent kinetic energy is produced in and close to the gap and away from walls.
The figure of the vortices also shows that the large eddy simulation is an adequate tool for computing the effects of the flow pulsations. The calculated vortices extend over more than ten meshes and are resolved by the mesh sizes used.

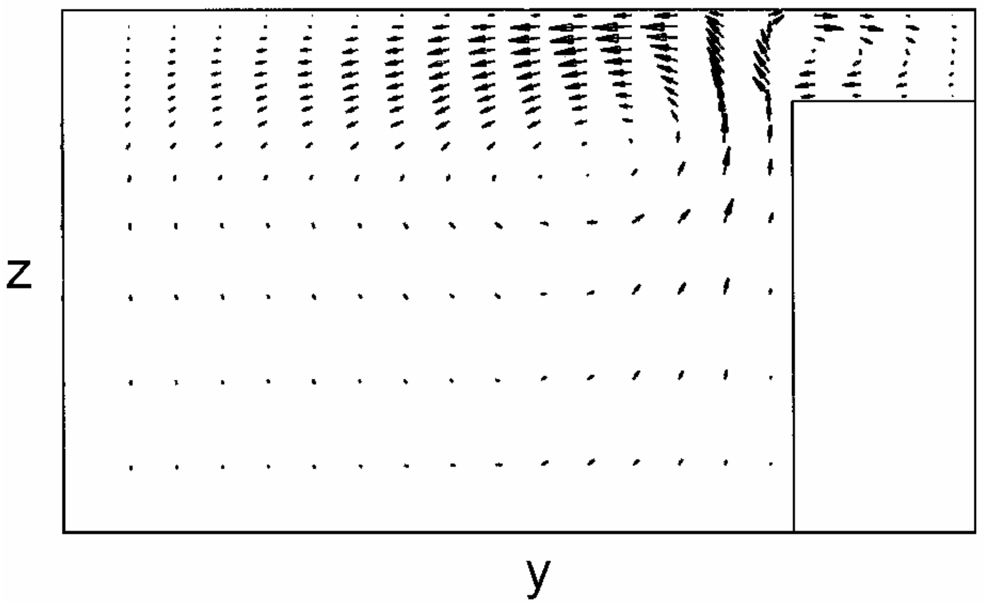

Fig. 9 Computed secondary flows in the y-z-plane

The computed secondary velocities in the y-z-plane are shown in Fig. 9. The results agree qualitatively with the results of the large eddy simulation by Thomas and Williams [18] for a compound open channel with one floodplain. However, it is important to note that the large vortices in the gap in the streamwise direction (Fig. 8) are about 2.3 times stronger than the secondary flow in the gap.

5. CONCLUSIONS

An experimental and numerical study has been performed on the turbulent flow through two rectangular channels which were connected by a gap at the wall. Unusual high Reynolds stresses were found by hot-wire measurements. An energetic and almost periodic flow pulsation was the reason for the untypical phenomena.
The numerical investigation using the large eddy simulation displayed similar results. The computed Reynolds stresses were in qualitative agreement with the experimental findings. Quantitatively, there were some differences which may be attributed to the difference in the Reynolds numbers between experiment and simulation. The simulation showed one pair of vortices rotating in opposite directions which is in agreement with an earlier proposed flow model.

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