EXPERIMENTAL INVESTIGATIONS ON THE TURBULENT FLOW OVER A PERIODIC HILL GEOMETRY

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ABSTRACT

In this paper experimental data of the flow over a periodic arrangement of hills in a channel are presented for three different Reynolds numbers. This investigation serves at providing reference data for this flow case that has been used by several initiatives as a benchmark test case for numerical methods. The case has all features of separating and reattaching flows at affordable computational costs, because it is designed to be periodic in streamwise and homogeneous in spanwise direction. The flow was monitored in terms of periodicity and homogeneity with high resolution pressure cells and PIV measurements at a low Reynolds number. The mean velocity components and the Reynolds stresses are checked in terms of adequacy of the experiment in comparison to highly resolved LES and DNS data. An outlook discussing Reynolds number effects summarises the results.

INTRODUCTION

The turbulent flow over a periodic arrangement of smoothly shaped hills was first investigated experimentally by Almeida and Heitor (1993), who obtained data at a Reynolds number $Re = 6 \cdot 10^4$ through LDV measurements. This case was used by some workshops and research initiatives as a benchmark case for numerical simulations (e.g. Jakirlić et al. (2002) and Šarić et al. (Marseille, France, July 18 – August 26, 2007)). A modified configuration was thoroughly investigated by LES by Mellen et al. (2000) and Fröhlich et al. (2005). They increased the distance between succeeding hills in order to achieve reattachment on the bottom of the channel. To save computational time the domain was down-sized by reducing the channel height. The impact of the lateral boundaries on the flow was eliminated by applying periodicity in spanwise direction. Since the modified geometry offers the opportunity to observe flow phenomena such as separation, reattachment and recirculation, it has been used as a standard test case for RANS and LES. So far detailed simulations up to $Re <= 10^4$ based on the mean velocity above the hill and the hill height h were carried out (Breuer et al. (2005)). These detailed simulations establish well resolved data, DNS at $Re = 5600$ and LES at $Re = 10595$, that can be taken as reference solutions.

The simulations conducted so far revealed several interesting features of the flow. The geometry is sketched in Figure 1. Due to the smoothly curved surface, the separation point is not fixed by the geometry. The main separation bubble strongly fluctuates in size and can cover the whole space between two consecutive hills. The mean reattachment point is at approximately 4-5 hill heights downstream of a hill crest, depending on Reynolds number. In front of the hill at about 7 hill heights downstream of the crest, a very small separation bubble was documented in the abovementioned studies. At Reynolds numbers higher than 10^4 another very thin recirculation bubble on top of the hill is expected upon observations from the numerical simulations. How the flow behaves at Reynolds numbers higher than 10^4 is unknown up to date, since there are no reliable reference data available.

To fill this gap and to make this flow feasable as benchmark case for higher Reynolds numbers, a physical model has been constructed at the Fachgebiet Hydromechanik of the Technische Universität München that aims at providing experimental reference data. Any effort has been made to accomplish similar conditions as they were used in the numerical simulations. In a first step, PIV measurements were conducted at Reynolds number $Re = 5600$, 10600 and 25000 in a water channel. In the remainder of the paper, we document the experimental setup and the conducted measurements. Special emphasis has been placed on controlling the periodicity and homogeneity of the flow. Data are presented from pressure and PIV measurements.

EXPERIMENTAL SETUP

The dimensions of the model (fig. 2) relate to the hill height h, that was chosen to be $50mm$. The distance between two consecutive hills is $9.0h$, where the length of one hill is $3.856h$. The hills constrict the channel height from $3.035h$ to $2.035h$. Contrary to the geometry used in the numerical simulations the channel width was chosen to be $18h$, instead of $4.5h$, to accomplish homogeneity in spanwise direction. The coordinates referred to are indicated in figure 1.

The materials used are mainly polyvinilchloride, plexiglass and glass whereas the hills were casted from polyurethane in monolithic blocks. The water channel is fed by a pump with a maximum discharge of $70l/s$ which is sufficient to reach $Re_b = 37000$. To damp fluctuations, an intake reservoir with several fixtures is used before the water enters the rectangular channel that is constant in

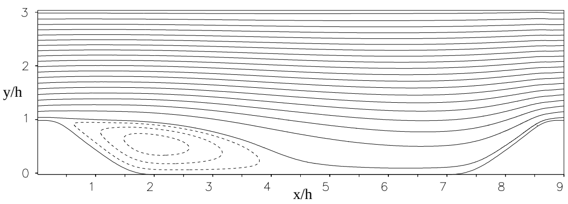

Figure 1: Geometry of the periodic hill testcase

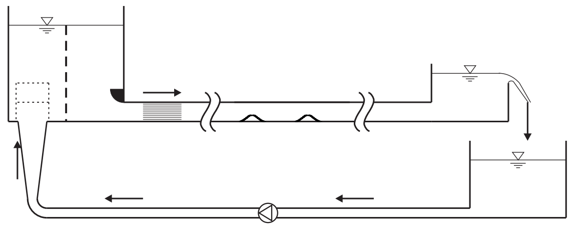

Figure 2: Experimental setup

width ($18 \times h$) and in height ($3.035 \times h$). The first part of the channel ($10 \times h$ long) is followed by flow straighteners that are $10 \times h$ in length. A distance of 20 hill heights lies between the flow straighteners and the foot of the first hill. A total of ten hills was chosen to achieve periodicity in the flow, whilst the measurement area lies between the crests of hill seven and eight. The channel ends 34 hill heights downstream the last hill in an outlet reservoir. The water levels in the inlet and the outlet reservoir determine the pressure gradient and therefore the Reynolds number. The discharge has been recorded at any time as well as the water temperature.
The fluid that was chosen is water as its density is 800 times higher than that of air; its viscosity is 13 times lower. Therefore the pressure is 4.5 times and the characteristic time is 13 times greater at the same model scale (Eckelmann (1997)). The water had been filtered, decalcified and chlorinated.

PRESSURE MEASUREMENTS

To check the periodicity in the streamwise direction all in all 19 holes were drilled into the top cover of the channel at local positions $x/h = 1.3$ and $x/h = 6.3$. They are located one hill height off the center plane in order not to disturbe the PIV measurements that were carried out in the center. For control of the homogeneity in the spanwise direction the pressure was recorded at 14 locations at local position $x/h = 1.2$ and $x/h = 7.8$ at hill eight.

Two Keller S-41X pressure cells with an effective range of $1000Pa$ and a specific error of 0.1% were chosen to acquire the pressure drop and the spanwise pressure distribution whilst the stagnation pressure at $Re = 5600$ equals $6.05Pa$. The pressure was recorded relative to the one on hill crest eight. The pressure was acquired at a sample rate of $1000Hz$ until the change in variance was less than 10^{-5}. Due to the length of the hoses connecting the holes and the pressure cells instantaneous data could not be acquired. Nevertheless the mean values will be discussed in the following.

The periodicity was investigated at $Re = 5600$ through pressure drop on the channel top between two consecutive hills at the local position $x/h = 1.3$ (see fig. 3).

It can be seen that the pressure drop from hill to hill is almost constant in the range of the accuracy of the pressure cells. however, the accuracy of the pressure cells seems not to be sufficient to assure full periodicity for this low Reynolds number. Measurements at higher Reynolds numbers, still to be conducted, will exhibit a better signal to noise ratio because of the higher stagnation pressure.

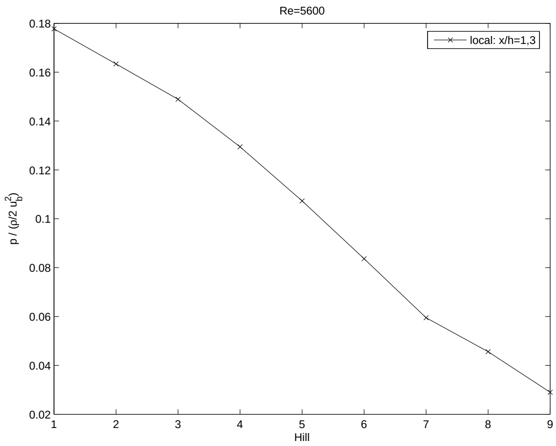

Figure 3: Pressure drop at the channel top

The homogeneity in the spanwise direction was first controlled for $Re = 5600$ because the influence of the lateral boundaries should decrease with increasing Reynolds number. The pressure distribution along the lee- and luvward side of the hill is in the range of accuracy of the pressure cells for about 14 hill heights, with visible influence of the side walls. For the same reasons as in the control of periodicity, these measurements will be repeated at higher Reynolds numbers.

VELOCITY MEASUREMENTS

Measurement Device

The velocity measurements were carried out with a 2D PIV system from TSI. It consists of a $190mJ$ Quantel BigSky NdYAG Laser emitting 532nm pulses. The camera that was used is a $4MP$ TSI CCD camera. The images were streamed through a RAID system so that 10000 double frames could be recorded at a frame rate of $7f/s$. To avoid laser light reflections at the walls the camera position had been adjusted in the particular optical axis. Therefore six camera positions were chosen recording partially overlapping frames of which each had a size of $289mm$ corresponding to 5.79 hill heights. With 16×16 pixel interrogation areas, the spatial resolution is $2.26mm$ which corresponds to 0.045 hill heights. To save computational time the individual images were evaluated in certain regions of interest only. The data shown in the plots below are point measurements that are at the furthest 1/2 interrogation area away from the indicated x/h locations.

For each of the six different frames 10000 double images were taken in a separate experimental run. To control the experimental conditions, simultaneous temperature and discharge measurements (by a magneto inductive device, MID) were taken. During the individual experimental runs, the temperature changed by less than $0.4°$ and with it the viscosity by less than 1.0%. During the whole PIV test period the temperature changed by about $2°$ which corresponds to a change in viscosity of about 4%. With these boundary conditions, the Reynolds numbers achieved varied slightly (see next section). In the following sections the reference is the Reynolds number aimed at and the range of the actual one is specified. The merging of the six different frames into joint profiles was done after determining the actual u_b by integrating the velocity profile at the hill crest and calibrating by the mean discharge recorded during the respective experimental run.

Seeding Particles

Hollow glass spheres were chosen to seed the completely particle free water. The major advantage of these particles is the dispersion behaviour in water so that no clustering occurs whilst bright scattering can be observed. The diameters of the spheres range from $8\mu m$ to $12\mu m$, whereas the density varies from $0.1g/cm^3$ to $1.5g/cm^3$. The maximum Stokes number of the particles, defined as:

$$St = \frac{t_p}{t_k} \tag{1}$$

with the Kolmogorov time scale

$$t_k = \sqrt{\frac{\nu}{\epsilon}} \tag{2}$$

and the particle time scale

$$t_p = \frac{\rho_P}{\rho_F}\frac{d^2}{18\nu}\ , \tag{3}$$

is $St = 1.32 \times 10^{-2} << 1$, hence it can be assumed that they follow the flow.

Algorithm

The background image was subtracted from the images so that the bright contrast of the particles led to high correlation peaks during evaluation (see fig. 4). The image shows that the laser light reflexions were avoided by capturing the images in the optical axis. For saving computational time cross correlations have been conducted in Fourier space. The average intensity of the interrogation area was subtracted before processing. Velocity vectors were evaluated for 16×16 pixel interrogation areas. They were considered as valid if the magnitude of the streamwise component was within $[-0.5u_b; 1.5u_b]$ and the magnitude of the vertical component was within $[-0.5u_b; 0.5u_b]$.

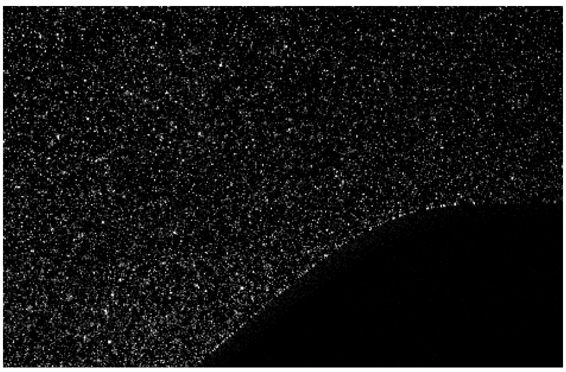

Figure 4: Part of the frame

Skipped vectors ($<= 4\%$) were interpolated by means of 5×5 surrounding vectors. The post processing was conducted for data using first correlation peak vectors only and for data including also the interpolated vectors. A comparison of the two differently obtained results showed no deviations.

Table 1: List of Experiments.

Notation	Re_{max}	Re_{min}
5600_{6-7}	6307	6194
5600_{7-8}	6762	6422
$5600_{z/h=1}$	6519	6408
$5600_{z/h} = 2$	6151	5905
10600	11593	10221
25000	25547	24154

CONDUCTED EXPERIMENTS

The experiments conducted aimed in a first step at investigating the adequacy of the experimental rig with respect to periodicity and homogeneity. To this end, we conducted five experiments at $Re = 5600$ and $Re = 10600$, i.e. we recorded five different two dimensional planes at different spanwise positions and between two consecutive hill gaps. Being aware that these low Reynolds numbers are probably the most difficult ones to ensure clean experimental conditions, we have chosen these two Reynolds numbers, because there are highly resolved DNS and LES data available for comparison. Another experiment ($Re = 25000$) gives an outlook of the development of the flow for increasing Reynolds numbers. In table 1 the different experiments are listed with their notation, the maximum and minimum Reynolds number of the six respective frames within one experiment.

PERIODICITY AND HOMOGENEITY

Periodicity

The periodicity in streamwise direction was investigated at $Re = 5600$ by means of PIV measurements at two consecutive periods (between hills six and seven and seven and eight respectively). Figure 5 compares the mean streamwise velocity component at local positions $x/h = 2$ between hills six and seven (circles), hills seven and eight (crosses) and a DNS (line) from Peller and Manhart (2006). The shapes of the curves are similar, but small differences in magnitudes can be found. The measurements of section 7-8 fit perfectly to the numerical simulation at the lower part of the flow, whereas on top of the channel the differences reach about 3%. The effect of the slightly different Reynolds numbers can be neglected in this context as the curves of the different frames at the particular experiments fit perfectly. The velocity magnitudes at these different camera positions are almost identical so that one can assume that splitting up the flow field into the six particular frames does not have an impact on the mean values. According to these measurements, the periodicity seems not to be fully reached yet at this Reynolds number.

Figure 6 compares Reynolds shear stresses between two consecutive periods. A reasonable compliance of the Reynolds stresses $< u'v' > /u_b^2$ at $x/h = 1$ can be observed. The shape of the DNS generated curve can be identified in the measurements as well. Although the Reynolds number in the experiment is in every case higher than in the simulation, the peak in the experiment is about 8% lower.

Homogeneity

To investigate the influence of the lateral boundaries two measurements at the center and $z/h = 2h$ off the center

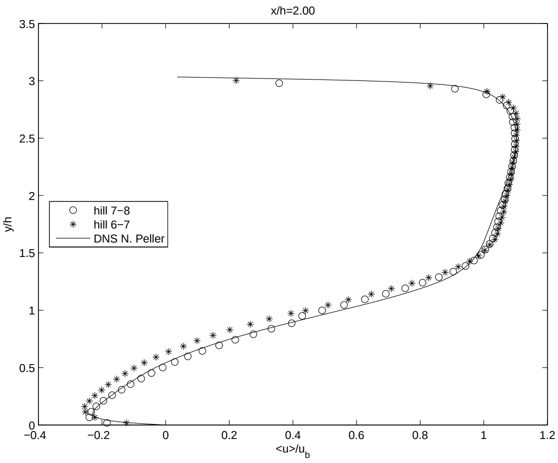

Figure 5: Periodicity, $< u > /u_b$ at $x/h = 2$

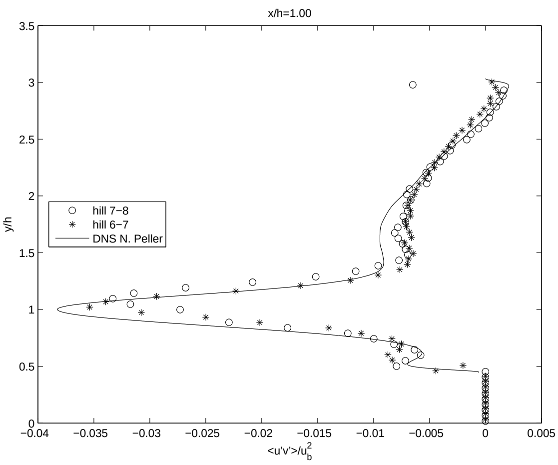

Figure 6: Periodicity, $< u'v' > /u_b^2$ at $x/h = 1$

were carried out. In figure 7 the two planes are compared with each other and the DNS. Differences can be seen in the upper part where the velocity gradient is steeper in the simulation. Figure 8 shows a good agreement of the mean wall normal velocity component considering the sensitivity of this variable. Three-dimensional vortices from the side walls do not seem to reach the measurement sections $2h$ apart from the center plane. The mean point of reattachment is at $x/h = 4.0$ for every case.

The Reynolds normal stresses $< u'u' > /u_b^2$ at $x/h = 1$ (Figure 9) and $< v'v' > /u_b^2$ (Figure 10) show slightly higher values than the DNS in the upper part of the channel. This is true for both, the center and the off-center plane and could be an indication for low-frequency discharge fluctuations. The peaks are a little lower than the ones of the DNS which in turn could be explained by the spatial filtering due to the size of the interrogation areas. The Reynolds shear stress $< u'v' > /u_b^2$ (fig. 11) shows the best agreement in this comparison. For all Reynolds stresses measured, the homogeneity is fully satisfying.

COMPARISON OF THE DATA WITH LES AT $RE = 10600$

Highly resolved LES at $Re = 10600$ has been performed by Breuer (documented in Breuer et al. (2005)). In the following the experiment is compared with this simulation at a streamwise position of $x/h = 4.0$ which is close to the

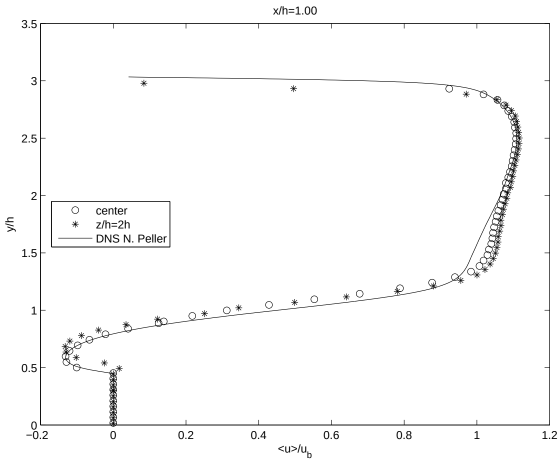

Figure 7: Homogeneity, $< u > /u_b$ at $x/h = 1$

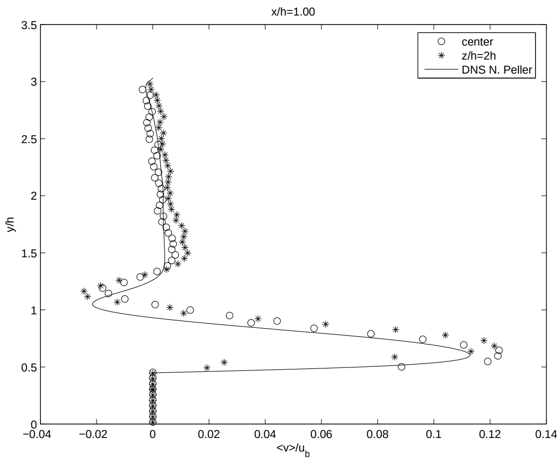

Figure 8: Homogeneity, $< v > /u_b$ at $x/h = 1$

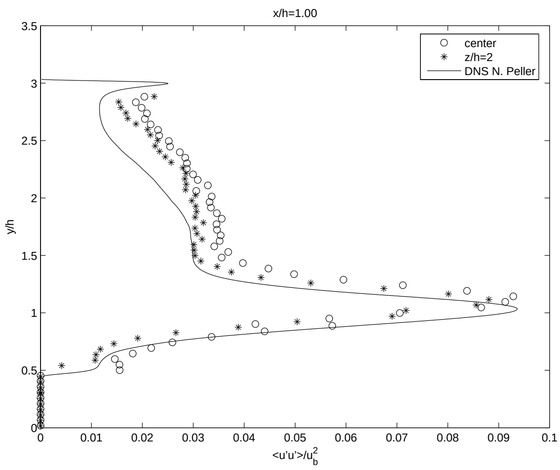

Figure 9: Homogeneity, $< u'u' > /u_b^2$ at $x/h = 1$

reattachment point. The match between experiment and simulation is fully satisfying for the mean streamwise and vertical components (Figure 12 and 13) although the vertical component is slightly higher in the measurements. Looking at the streamwise Reynolds stress however (Figure 14), significantly higher experimental values have to be noted. This again could be the result of low-frequency discharge fluctuations and has to be examined further. The vertical Reynolds

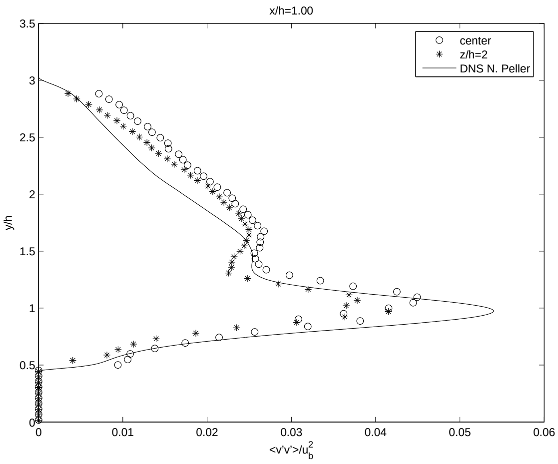

Figure 10: Homogeneity, $< v'v' > /u_b^2$ at $x/h = 1$

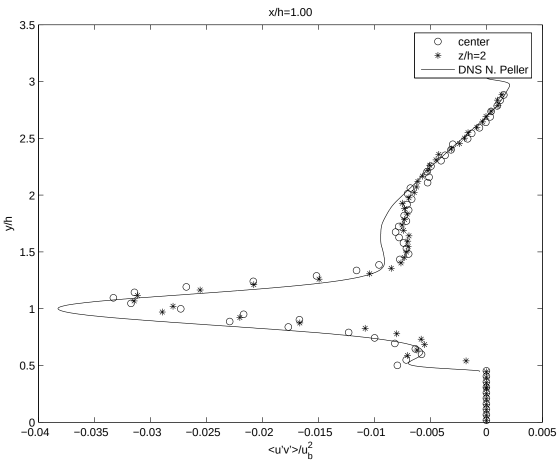

Figure 11: Homogeneity, $< u'v' > /u_b^2$ at $x/h = 1$

stresses (Figure 15) show better agreement while the fit of the respective Reynolds shear stresses can be regarded as perfect (Figure 16)

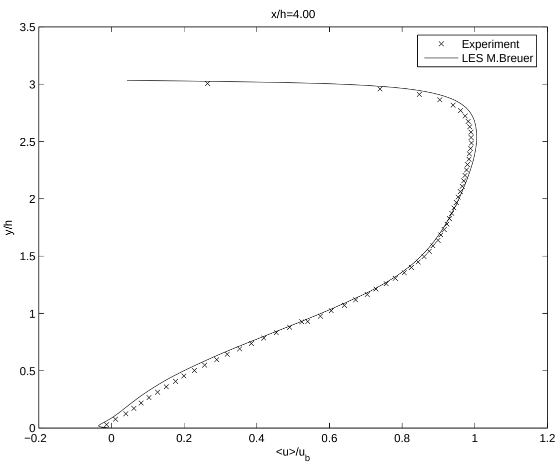

Figure 12: Experiment - LES, $< u > /u_b$ at $x/h = 4$

OUTLOOK

First results of Reynolds number dependence are presented in Figure 17 for the mean streamwise velocity at

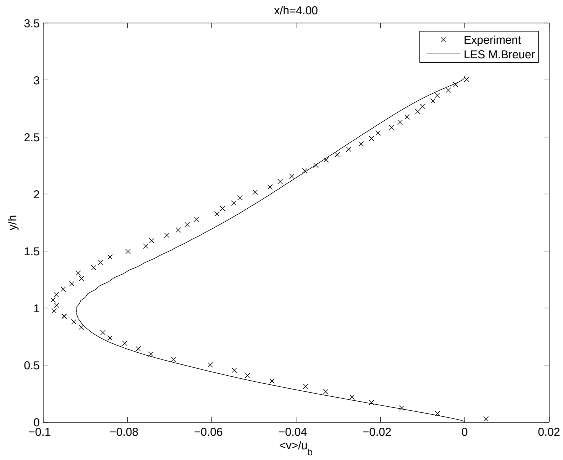

Figure 13: Experiment - LES, $< v > /u_b$ at $x/h = 4$

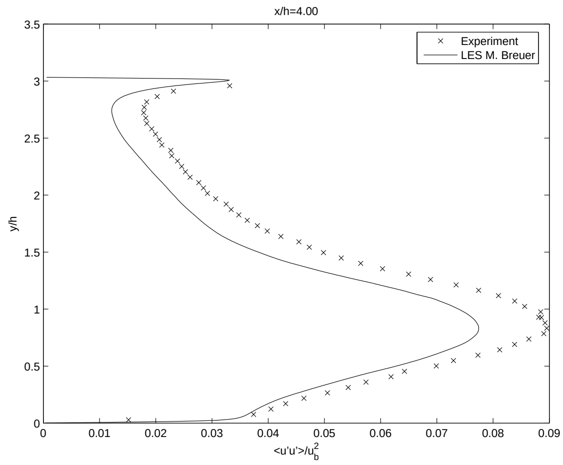

Figure 14: Experiment - LES, $< u'u' > /u_b^2$ at $x/h = 4$

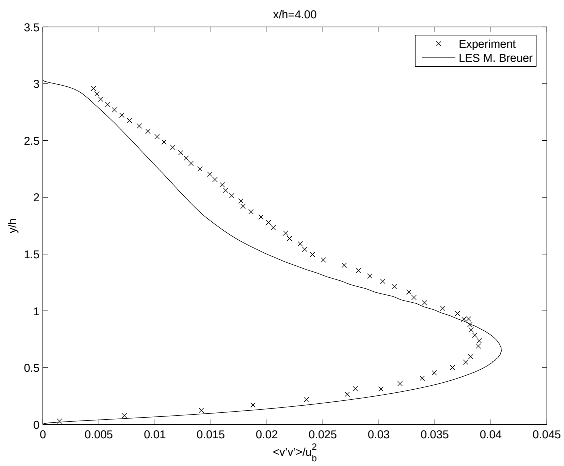

Figure 15: Experiment - LES, $< v'v' > /u_b^2$ at $x/h = 4$

$x/h = 4$. The flow attaches significantly further upstream at $Re = 25000$. More data will be presented in the poster.

The results of the first measurements in the newly built experimental channel are promising. We are in the rare situation that the measurements have to concur to highly resolved DNS results at $Re = 5600$. The remaining uncertainty in periodicity will be checked with measurements at higher Reynolds numbers. The spanwise size of 18 hill

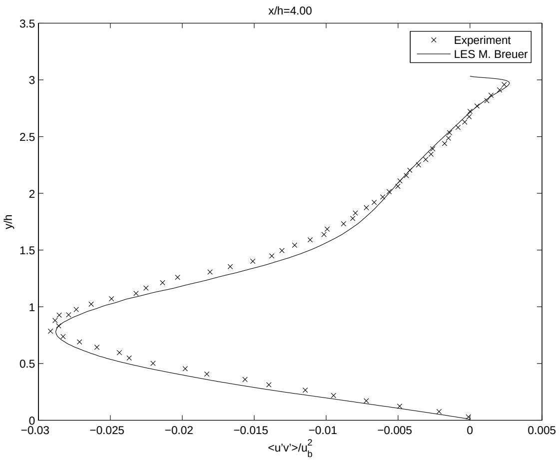

Figure 16: Experiment - LES, $< u'v' > /u_b^2$ at $x/h = 4$

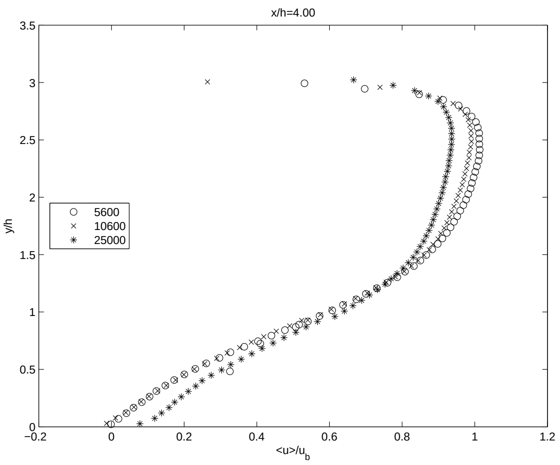

Figure 17: Reynolds number effect $< u > /u_b$ at $x/h = 4$

heights seems to be sufficient for homogeneity in the core part of the channel, even at the lowest Reynolds number considered. The streamwise Reynolds stresses have consistently higher values than the DNS and LES to which they were compared. This could be an indication for low-frequency discharge fluctuations coming from the pump and will be checked by high-pass filtering of the raw data.

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