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EXPERIMENTAL INVESTIGATION OF FLOW CHARACTERISTICS OF CORRUGATED CHANNEL FLOW USING PIV

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ABSTRACT

The aim of the study is to determine the flow characteristics of corrugated duct. The whole study has been conducted for Reynolds numbers, Re=4000 and 6000. The corrugated duct geometry was designed for aspect ratios, s/H=0.3 and phase shift angle, $\varphi=180^\circ$. Variations in flow characteristics of corrugated duct were investigated using the Particle Image velocimetry (PIV) technique. Time-averaged velocity distributions, patterns of streamline and corresponding turbulent statistics were determined. Augmentation of the Reynolds number leads to an increase in velocity due to the sharp corner edges of cavity. Dimensionless turbulent kinetic energy, <TKE> contours indicate that the magnitude of turbulent kinetic energy, <TKE> increases as a result of sharp corner edges of the cavities. High rate of momentum transfer is expected due to an increase of turbulence intensity.

INTRODUCTION

Heat exchangers are widely used for heat transfer of in wide variety of industrial processes. Many researchers have paid attention to the improvements in the performance of the heat exchangers since these energy systems are substantially important in terms technical applications, economic and ecological viewpoints, Ahmet [1] stated that corrugated surface geometry is one of the many suitable passive techniques which are utilized with the aim of enhancing heat transfer as a result of growing recirculation regions near the corrugated channel and improving the mixing of fluid.

In the related literature, you can find many studies either experimental or numerical on the subject of heat transfer enhancement along with pressure drop through the grooved and corrugated channels.

Mendes and Sparrow [2] conducted an experimental work on the turbulent flow in the converging and divergent tubes. Their main purpose was to analyze the alteration of heat transfer for different aspect ratios, s/H and taper angles, in the entrance region corrugated channel. It was shown that the highest heat and mass transfer were accompanied by a large pressure drop. The researchers affirmed that this result is due to the existing off the flow circulation zones and the enhancement of the heat transfer is related to the converging-diverging channels compared to the straight tubes. Ali and Ramadhyani [3] underlined the heat transfer occurred in the case of different channels spacing with especially triangular corrugated channel. They stated the fact that effectuation of a larger spacing channel was much better than a smaller one. Their experiment reported that the corrugated channels have a higher implication of Nusselt number, Nu comparing to the parallel plate channel.

Studies of mass transfers within channels with sinusoidal waves with respect to the different Reynolds number, Re and distances between the plates were performed by Gschwind et al. [4]. Their results showed that there were a large variations and series of instabilities of flow characteristics. Experimental studies on the wavy channels were also made by Rush et al [5]. Their main purpose was to observe the influence of undulation and of the Reynolds number, Re in the heat transfer rate of the geometric parameters. They mostly observed mixing and chancing of flow structures in the macroscopic scale which influenced enhancement of heat transfer for both steady and unsteady flow cases. It was observed that mixing of fluid is related to the Reynolds number, Re and to the geometry of the channel. Gradeck et al. [6] established their main purpose of experimental studies concerning the enhancement of a heat transfer for flows with a single phase, under the effect of laminar and turbulent forced convections. The results of the experiment revealed the fact that the heat transfer coefficient had a higher degree of sensibility on the top of the geometrical corrugation, even if the highest disorder was observed at the bottom part of the undulation, with its negligible effects.

Wahidi et al. [7] conducted their study on the coefficient of skin-friction, C_f mean velocity, u and turbulence intensity, TI, of turbulent flow over a smooth wall with transverse square grooves using Laser–Doppler Anemometer (LDA). Jaurker et al. [8] reported the rate of heat transfer and friction characteristics on a heated wall which had a large aspect ratio, s/H duct and different properties. Bilen et al. [10] experimentally studied heat transfer and friction characteristics of a fully developed turbulent air flow in a different grooved tubes (circular, trapezoidal and rectangular) and suggested that heat transfer enhancement was around 63% for a circular groove, 58% for the trapezoidal one and 47% for the rectangular at the highest Reynolds number, Re=38000.

Layek et al. [12] and Naphon [9] were interested in the heat transfer characteristics and pressure drop in a channel of different corrugation angle under constant heat flux. It was concluded that heat transfer and pressure drop were tremendously enhanced when compared to those of parallel plate channel for laminar as well as turbulent flows. They also indicated the promoted recirculation zones and flow separation in corrugated channel flow. Laohalertdecha and Wongwises [11] investigated the effect of corrugation pitch on the heat transfer coefficient and pressure drop of R-134a inside a horizontal corrugated tube. The results showed that the corrugation pitch had significant effect on heat transfer heat transfer coefficient and pressure drop augmentations. Faizal and Ahmed [13] on the heat transfer and the pressure drops using corrugated plate heat exchanger with variables having the water flows by using temperature analysis all over the plate exchanger. The results showed that by increasing the volume flow rate of hot water, the average heat transfer, between two streams increased owing to higher turbulence at higher velocities. Numerically studies were performed by Zhang and Che [14] on the effect of corrugation profile for cross-corrugated plates on the heat and flow characteristics. They considered different corrugation profiles and carried out the numerical simulations using the finite volume method. Results revealed that Nusselt number, Nu and friction factor, f were higher for the trapezoidal channel than for the elliptic channel. Sawyers et al. [15] combined the analytical and the numerical techniques investigated the effects of the three dimensional hydrodynamics in a corrugated channel of the heat transfer. They found that in three-dimensional case, a small mean flow in the transverse direction led to increase heat transfer, while there was a decrease in heat transfer as the transverse flow movement became stronger.

Vicente et al. [16], and Mohammed et al. [17] are also studied about corrugated channels. Yet, all of studies about corrugated channels are mainly related with perspectives of heat transfer. For this reason, PIV is utilized to investigate the flow structure in the corrugated channel which has not hitherto been available in the literature.

The main objective of this work is to investigate the flow structure [22] in the corrugated channel experimentally in order to observe hydrodynamics of flow of cavities in the corrugated channels for Reynolds numbers, Re=4000 and 6000. In general, that is the range of Reynolds numbers which is most comment used in case of heat exchangers. It is also found similar Reynolds numbers ranges have been used by other research that are available in the open literature, for example, see ; Elshafei et al. [18] studied for the range of $3220<Re<9420$, Vanaki et al. [19] for $6000 \leq Re \leq 18,000$, and Yin et al. [20] for range of $2000 \leq Re \leq 10000$.

In addition to other studies PIV measurement [21] is being provided hydrodynamics of flow structures, domain of the wake region, locations of the singular points, and locations of the peak values of turbul12ence quantities, such as, the concentration of vorticity, Reynolds stresses, velocity fluctuations and turbulent kinetic energy which are substantially affected by the variation of the Reynolds numbers. The presence of a reversed flow in the region of cavities magnifies the level of these flow characteristics when the Reynolds number is increased.

MATERIAL AND METHOD

Variations in flow characteristics of corrugated duct were investigated using the Particle Image velocimetry (PIV) technique. PIV refers to a non-intrusive technique utilized so as to measure an instantaneous two dimensional velocity vector field over investigated area. The velocity is determined via measurement of the displacement of seeding particles in a flow field illuminated by a laser sheet. Experiments were conducted in an open water channel which was available at the Fluid Mechanics Laboratory of Mechanical Engineering Department at Çukurova University. The corrugated rectangular channel shown in Figures 1 and 2 placed in an open channel which has a test section of 8mx1mx0,75m and was constructed from a 15 mm thick transparent plexiglass sheet. Experiments were carried out with corrugated channel model which is presented in Figure 1.

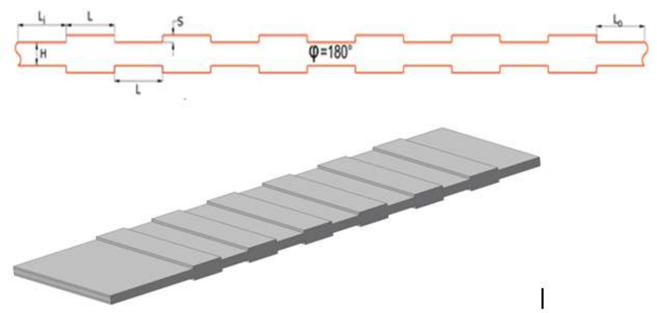

Fig. 1. Schematic view of corrugated channel with phase shift (φ) 180˚

Length (L) and depth (S) of corrugation is 100 mm and 10 mm respectively. Inlet length of cavity (I) and outlet length of cavity (O) is 900 mm and 500 mm respectively. Total length of cavity is 2.5 m and aspect ratio; s/H is 0.3 for experimental model. The width of the channel (400 mm) is very large when compared to the height of channel as seen in figure1. The overall field of view is 117 x 88 mm2. An overview of experimental setups for corrugated channel is presented in figures 2. In each test, 1000 instantaneous images were captured, recorded and stored with the aim of obtaining averaged-velocity vectors and other statistical properties of the turbulent flow field.

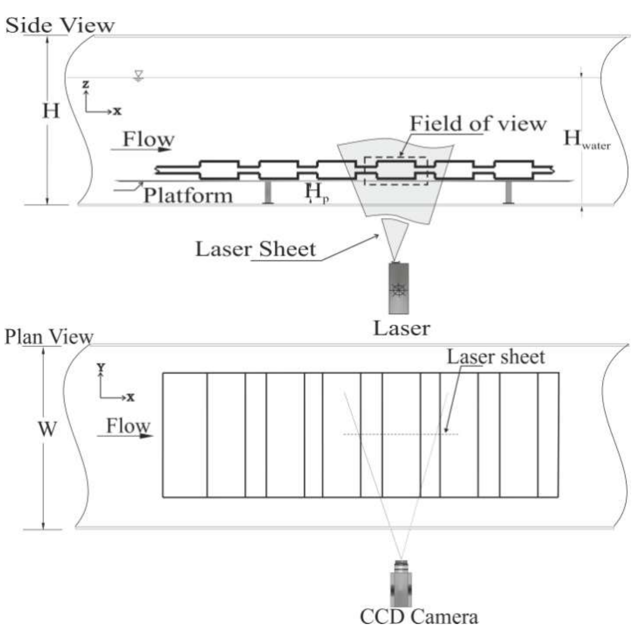

Fig. 2. Schematic of the experimental system and definition of parameters for the corrugated channel

This paper only contains experimental results. The particle image velocimetry technique measures thousands of data in a flow field instantly. For analysis of data the flowing mathematics have been used. In side-view plane, the value of the instantaneous velocity vectors, **V** consisted of axial velocity component, u in x direction and lateral velocity component, v in y direction were calculated using the following equation (1);

$$\mathbf{V} = \sqrt{u^2 + v^2} \tag{1}$$

After that, the time-averaged velocity vectors, <V> were calculated using the following equation (2) ;

$$< V > \equiv \frac{1}{N}\sum_{n=1}^{N} V_n(x,y) \tag{2}$$

For two-dimensional incompressible and steady flow in x and y plan, vorticity in the out-of-plane direction is given by equation (3)

$$\omega_z = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \tag{3}$$

The partial derivatives were approximated by finite differences as seen in equation (4)

$$\omega_{ij} = \frac{1}{2}\left(\frac{v(i+1,j) - v(i-1,j)}{2\delta_x} - \frac{u(i,j+1) - u(i,j-1)}{2\delta_y}\right) \tag{4}$$

For the flow domain near the boundaries of the image and solid body, forward and backward finite difference formulae were applied.

Any computation involving derivatives is very sensitive to noises that are the primary reason to try to smooth out the velocity field before computation of the vorticity. For this reason, the Stokes theorem is preferred to use for eliminating the noise problem for the particular case of computation of vorticity. The circulation method derived from the Stokes theorem was used for interior domain.

The Stokes theorem can be formulated as equation (5);

$$\Gamma = \oint \vec{V} \cdot d\vec{l} = \iint \left(\nabla \times \vec{V}\right) \cdot d\vec{s} = \iint \vec{\omega} \cdot d\vec{s} \tag{5}$$

where $\vec{l}$ defines the integration path enclosing the surface $\vec{s}$. By defining a rectangular path about the grid point (*i,j*), instantaneous vorticity $\omega_z(i,j)$ within the enclosed area can be expressed equation (6);

$$\omega_z(i,j) = \frac{1}{4\delta x \delta y}\Gamma(i,j) = \frac{1}{4\delta x \delta y}\oint_{l(x,y)} \vec{V} \cdot d\vec{l} \tag{6}$$

Time-averaged vorticity, <ω> is defined as; equation (7);

$$< \omega > \equiv \frac{1}{N} \sum_{n=1}^{N} \omega_n (x, y) \tag{7}$$

RESULTS AND DISCUSSION

Information of flow details in the corrugated channels is important in the purpose of optimization and design of corrugated channel as a heat exchanger. In order to prove the flow details for designers and other researchers, instantaneous velocity distributions, streamline patterns, <Ψ>, contours of vorticity, <ω>, Reynolds stress correlations, and turbulence kinetic energy, <TKE> correlations are presented. Time-averaged flow data are determined by averaging of 1000 PIV images. There were six fields of view for channel with phase shift, φ=180 degree as seen in figure 3.

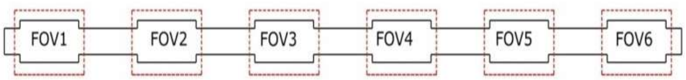

Fig. 3. Field of view (FOV) for channel with phase shift, φ of 180˚

Time averaged streamwise velocity, <u> contours are shown in figure 4 for Reynolds numbers of 4000 and 6000, with 180 degree phase shift, φ for three field of views (i.e., FOV2,4,6 respectively). Time average velocity of channel which has a phase shift, φ of 180 degree is higher than straight channel because of the sharp edges of cavity. Corrugated structure of channel which owns sharp corners leads to manipulate the direction of fluid flow and momentum hereby and tend to augment through the flow direction. For a given Reynolds number, Re velocity profile upstream of sudden expansion or straight duct is sensibly uniform over the cross-section. Downstream of sudden enlargement or entrance of cavities energetic flow mixing between core and wake flow regions caused by frequently shedding vortices. This shedding vortices rotates clockwise or counter clockwise depending on upper or lower side of cavity is taking the central axis as a reference line. Increasing the Reynolds number, Re time average velocity, <u> contour values were increased.

The time-averaged patterns of streamlines, <Ψ> contours can be seen in figures 5 for straight and corrugated channel with phase shift angle of 180̊. It can be seen that from the figurer the patterns of streamlines are symmetric with the centerline through the corrugated channels. It is better to state that the upper and lower walls have similar geometry of corrugation. Nevertheless symmetric recirculation flow regions have been observed from the streamline, <Ψ> contours which appear near the upper and lower corrugated walls. Patterns of streamlines indicate that well defined recirculation flow bubble rotate counter clockwise at the upper cavity and other recirculation flow bubble rotate clockwise at the lower cavity. Two well-defined foci, F are developed and they are almost symmetrical with respect to the centerline of the channel.

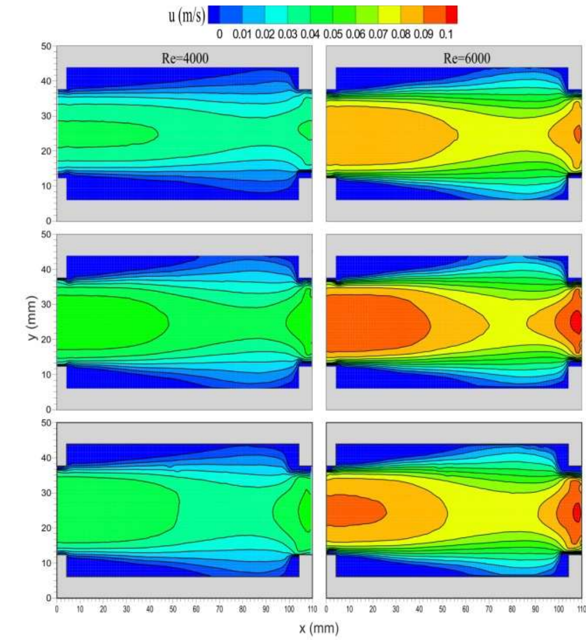

Fig. 4. Time averaged streamwise velocity, *<u>* contours for Re=4000 and 6000

Patterns of instantaneous particle images (total of 1000 images for a continuous series) are taken at a rate of 15 Hz. There are several scientific papers available in the scientific literature using PIV with similar frequency. In order to show the accuracy of the set of data, for FOV 6, total of 500 and 1000 instantaneous images were analyzed and optioned results are shown in figure stated below. As a result from the averaged velocity contours, there is no significant difference between them.

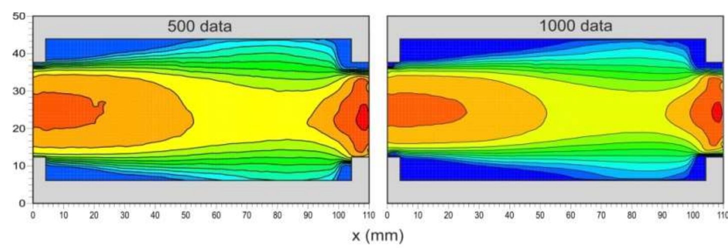

Fig. 5. Time averaged streamwise velocity, <u> contours for different data

The contours of dimensionless turbulent kinetic energy, <TKE> are presented in figures 6 and 7 for both Reynolds numbers (Re=4000 and Re=6000). Both minimum and incremental values are taken as 0.005. The rows of the figures show the patterns of turbulent kinetic energy, <TKE> for field of views (FOV) 2, 4 and 6, respectively. Maximum value of the <TKE> in the first cavity plane and last cavity plane are 0.073 and 0.094, respectively for Re=4000. On the other hand, increasing the Reynolds number to the value of Re=6000 causes an increase in the turbulent kinetic energy, <TKE> values. Maximum value of the <TKE> in the first cavity plane and last cavity plane are 0.081 and 0.14 respectively for Re=6000. The contours of dimensionless turbulent kinetic energy, <TKE> as a result of combination of streamwise Reynolds normal stress, $< u'u' >$ and transverse Reynolds normal stress, $< v'v' >$. The intense mixing of the fluid in turbulent flow results in enhancement of heat and momentum transfer between core and wake flow regions as well as fluid layers as a result of rapid velocity fluctuations, which in turn rises the friction force on the surface or pressure drop as well as the convection heat transfer rate.

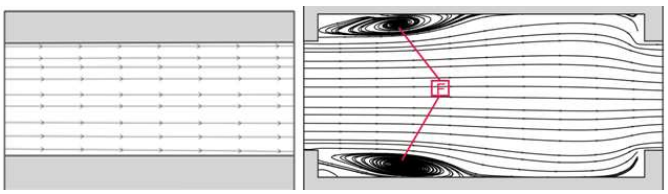

Fig. 6. The time-averaged streamline topologies, <Ψ> for straight and corrugated channel

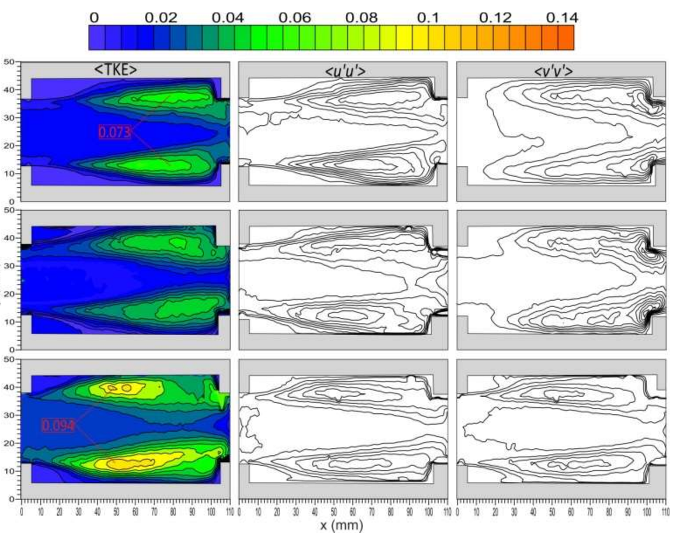

Fig. 7. Patterns of Turbulent kinetic energy for Re=4000

Time averaged vorticity, <ω> contours are shown in figure 8. The positive (counterclockwise) vorticity layers and the negative (clockwise) vorticity layers are drawn as a solid and dashed line, respectively. In order to understand the effect of the Reynolds number on the flow structure in detail, it is better to compare columns of the figures which show the time averaged vorticity, <ω> contours with reference to foregoing Reynolds numbers. When the vorticity, <ω> contours are investigated, the peak magnitude of vorticity, <ω> increases with increasing the Reynolds number, Re. In the case of the corrugated heat exchangers, development of energetic vortices in cavities results in better flow mixing between wake and main flow regions and hence heat transfer increase in the junction region.

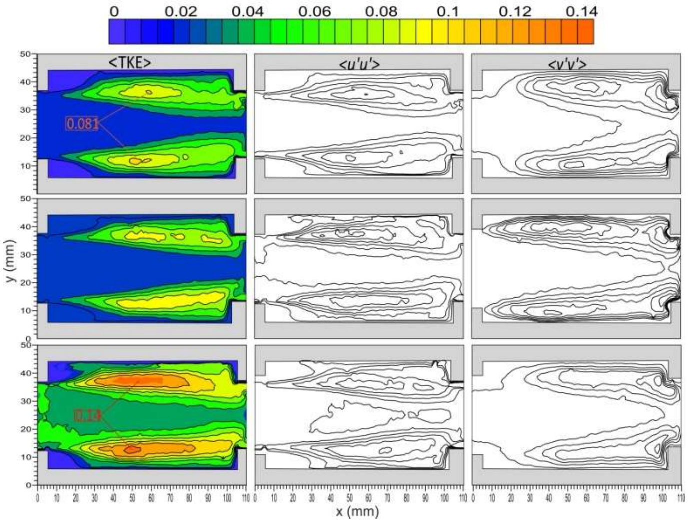

Fig. 8. Patterns of Turbulent kinetic energy for Re=6000

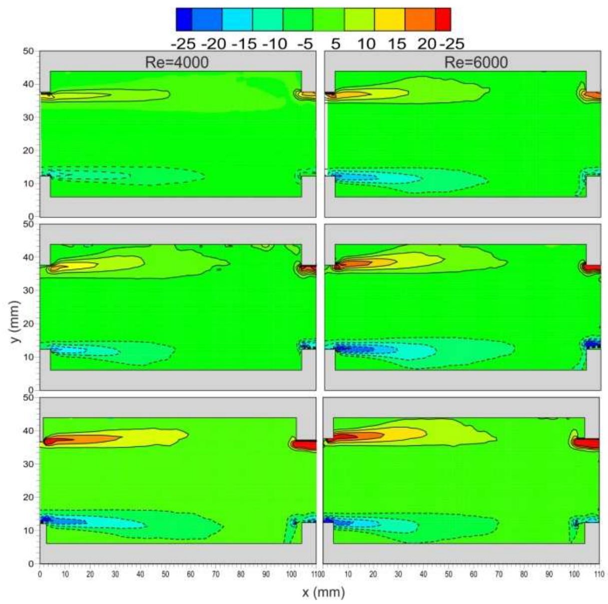

Fig. 9. Time averaged vorticity, <ω> contours

CONCLUSION

The main purpose of the present study is to provide details of flow structures of the corrugated channel which has aspect ratio such as 0.3 and phase shift angel of φ=180° experimentally. The experiments were performed using the Particle Image Velocimetry (PIV) technique. Augmentation of the Reynolds number leads to an increase in velocity fluctuations, mass and momentum transfer between wake and core flow regions due to the sharp corner edges of cavity and as a result, heat transfer ratio is expected to enhance when compared to the straight channel. Dimensionless turbulent kinetic energy, <TKE> contours indicate that the magnitude of turbulent kinetic energy, <TKE> increases as a result of sharp corner edges of the cavities. Experimental test results may provide good opportunity for validation of numerical prediction.

NOMENCLATURE

x	streamwise direction
y	transverse direction
u	velocity in x direction
v	velocity in y direction
U_∞	free-stream velocity
μ	dynamic viscosity
ν	kinematic viscosity
u'	streamwise velocity fluctuation
v'	transverse velocity fluctuation
$\langle u \rangle$	time-averaged velocity components in x direction
$\langle V \rangle$	time-averaged velocity fields
$\langle \Psi \rangle$	time-averaged streamline
$\langle \omega \rangle$	time-averaged vorticity
$u'u'$	streamwise Reynolds normal stress
$v'v'$	transverse Reynolds normal stress
$\langle u'v' \rangle$	time-averaged Reynolds shear stress correlations
<TKE>	time-averaged turbulent kinetic energy
u_{rms}	RMS value of the streamwise velocity fluctuations
v_{rms}	RMS value of the vertical velocity fluctuations
Re	Reynolds number

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