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Untersuchung von Strömungsfeldern in strukturierten Rohren durch LDA Messungen

Investigation of flow fields in corrugated tubes by LDV measurements

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Abstract

For heat recovery purposes, shell and tube heat exchangers are often used to transfer heat from a hot exhaust gas to a colder liquid. The gas flow passes through the inner side of the tube bundle. Since the thermal resistance of this gaseous side dominates the overall thermal resistance, the heat flux can be increased by using corrugated tubes instead of smooth tubes. An economic corrugation of stainless steel tubes can be achieved by deforming the wall material with well-proportioned depressions in magnitude of 1/20 of the tube diameter. Thus, the acceleration and deceleration of the bulk flow will be negligible and the flow modification will only occur close to the wall, where the heat transfer coefficient will be set by favorable velocity and temperature gradients.

Recurring zones will be created with a thinner viscous sublayer than before as well as with higher temperature gradients perpendicular to the wall. These zones of reduced viscous sublayer thickness alternate with zones of increased sublayer thickness and stagnant eddies. For better overall heat transfer, the effect of rising temperature gradients must dominate the isolating influence of areas with higher sublayer thickness and stagnant eddies. The alteration of the flow character will also change the pressure drop on the gaseous side, which must be considered simultaneously as it is always a further important feature of exhaust gas heat exchangers. It is evident that a close understanding of the velocity field in the corrugations is needed to improve the decisive parameters of the contour, such as depth and distance of the grooves. For a detailed understanding of the flow field in corrugated tubes, local measurements by a Laser Doppler Velocimeter were done.

The measurements were focused on the close-to-the-wall region, to examine the viscous sublayer and the stagnant eddies. For practical reasons, the measuring technique LDV was applied to isothermal flow in a corrugated tube made by acrylic glass. It is assumed that the near wall effects of non-isothermal flow in real applications will have a minor effect on the flow shape in the wall grooves. The localization of upflow and downflow areas will be shown.

Introduction

The performance of corrugated surfaces with regard to heat transfer improvement is investigated for several applications. It is known, that the corrugations can improve the heat transfer by producing additional turbulence [1], and local reduction of the viscous sublayer, which causes higher heat transfer rates (see Figure 1).

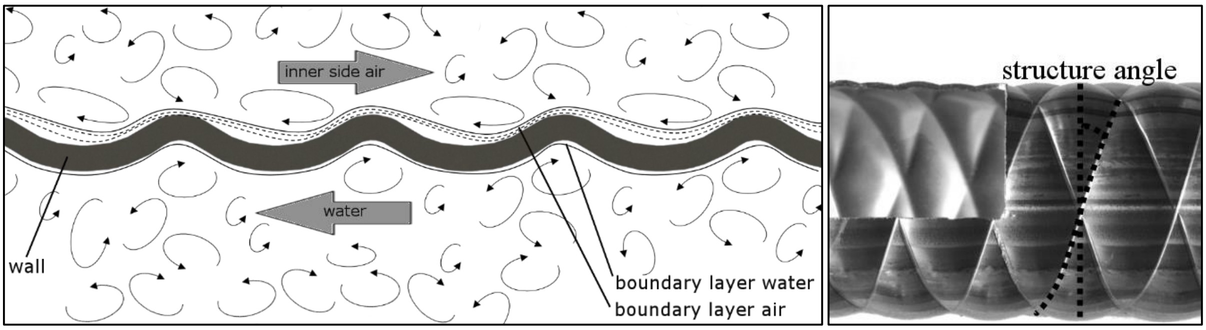

Figure 1: Turbulent flow in a corrugated tube (l) Cross Structured Tube (r) [2]

To date, most of the published investigations concentrate on the improvement of corrugated tubes with water flow at laminar flow conditions. Furthermore, the focus is on global values like global Nußelt-number and pressure drop.

Experimental investigations of spirally corrugated tubes were done by T.S. Ravigururajan and A. Bergles [3]. The paper describes a qualitative study on the flow phenomena near an enhanced surface with water as the working fluid. The experiments were conducted for Reynolds numbers between 150 and 2600. Further investigations were done by S. Pethkool et al. [4]. The experimental results show that the heat flux of the corrugated tubes is considerably higher than the heat flux of the smooth tube. The mean increase in heat transfer rate is between 123% and 232% within the test range 5500 < Re < 60000, depending on the rib height/pitch ratios and Reynolds number.

In the present study, the flow behavior in a spirally corrugated tube with two opposite helixes (see Figure 1) is measured by a LDV in the near wall region. The gas flow is realized by air which can be seen as an incompressible ideal gas. The investigated Reynolds range is $4000 < Re < 8200$. For validation, the measured values are compared to simulated values by using the Reynolds Stress Model at steady state conditions.

Numerical setup

For the numerical simulation, a high resolution mesh was generated. According to Mac Nelly et al. [5] a 360° full model is needed because the use of symmetry boundary conditions would interrupt the transport of anisotropic turbulence across the axis of symmetry. To realize a smooth formation of the wall adjacent cells, an O-grid is used with $y^+ < 1$ and at least 10 layers within the viscous sublayer (see Figure 2).

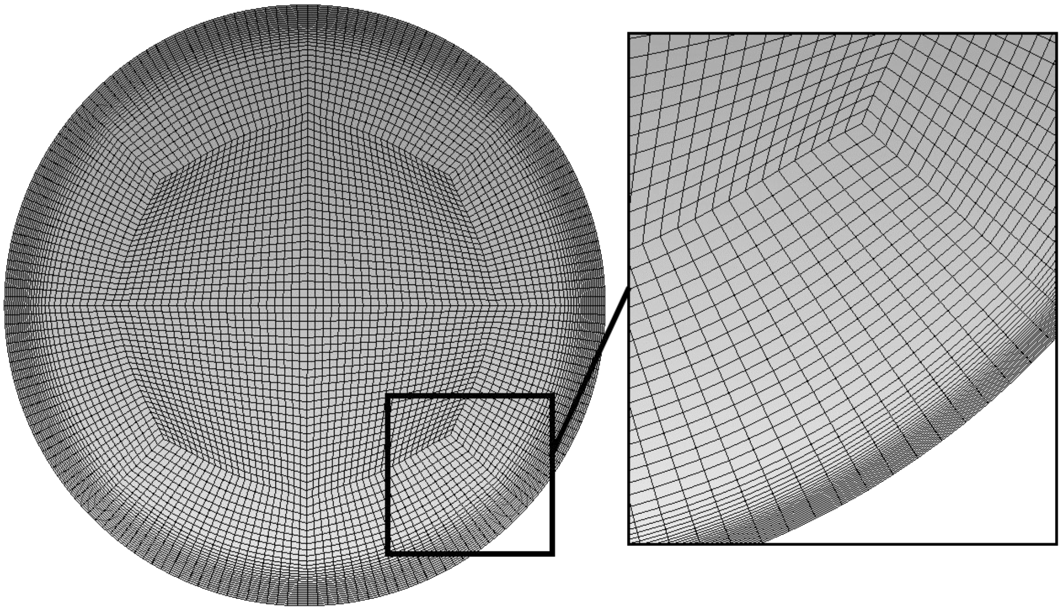

Figure 2: Used mesh with an O-grid [5]

The grid independence study confirms the necessity of a 360° full model, as a third or sixth model show deviations compared to those of a full model. For the simulation of a tube segment with a length of 0.7 m, a mesh size of 20 million cells is needed (Table 1).

Table 1: Investigation of the grid independence [5]

mesh size	symmetry	Δ p	Nu
2.5 million	1/6	3.94	22.08
	1/3	3.75	34.31
	full	3.91	23.92
5 million	1/6	3.60	21.50
	1/3	4.36	40.87
	full	3.24	22.67
10 million	full	3.10	21.50
20 million	full	3.04	20.75
30 million	full	3.04	20.75

As we know that there are anisotropic effects by secondary flow caused by the corrugations, the Reynolds Stress Model with calibrated parameters for heat transfer and pressure drop by Mac Nelly et al. [5] is needed for the CFD. Models with an isotropic treatment of the turbulence like K-ε RNG and k-ω SST are not suitable as they cannot consider the effect of secondary flow. It is decisive for the quality of the model, that the fluid properties like specific heat, thermal conductivity and viscosity are used as temperature dependent functions, because there is always a high temperature difference between tube in- and outlet in the considered exhaust gas applications.

Influence of the curved wall on the temperature profile

The corrugations lead to local changes of the flow direction. Thus, zones with thinner and thicker viscous sublayer occur. The thickness of the viscous sublayer has a high influence on the heat transfer in case of non-isothermal fluid flow. In Figure 3 the temperature distribution near the wall in a corrugated tube with an inner diameter $d_i = 28\ mm$, a wall temperature $t_w = 15\ °C$ and a core temperature $t_{max} = 450$ °C can be seen. The viscous sublayer is compressed between position 1 and 2 - which is the area directly in front of a corrugation - up to a position slightly behind the smallest cross-sectional area. Since the thickness of the viscous sublayer has a great influence on the heat transfer coefficient, the zones with lower thickness produce higher heat transfer rates. In contrast to that, the zones behind the corrugations cause flow separations and stagnant eddies. The heat flux has to overcome a large viscous sublayer where thermal diffusion becomes dominant.

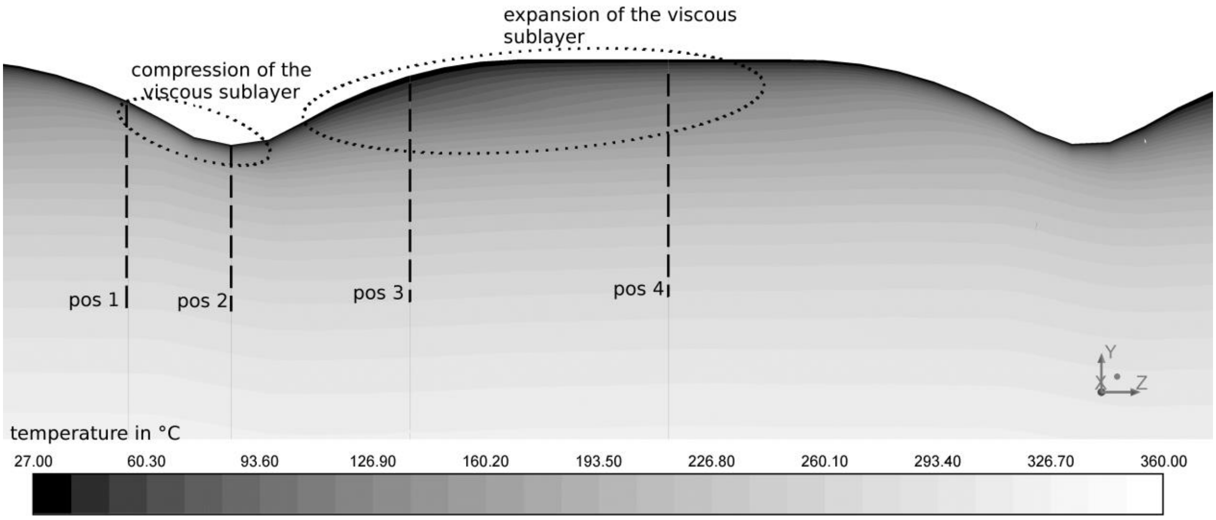

Figure 3: Temperature distribution in a corrugated tube

The different temperature gradients of the positions 1 to 4 in Figure 3 can be seen in Figure 4. It can be observed that the highest heat transfer rate in radial direction $\dot{q}_r = \lambda \frac{dT}{dr}$ is shown by position 2 followed by position 1. Both positions represent areas of reduced sublayer thickness.

Low heat transfer rates can be identified in the backflow area far behind the peak of the corrugations (position 4), followed by position 3, where stagnant eddies can be assumed.

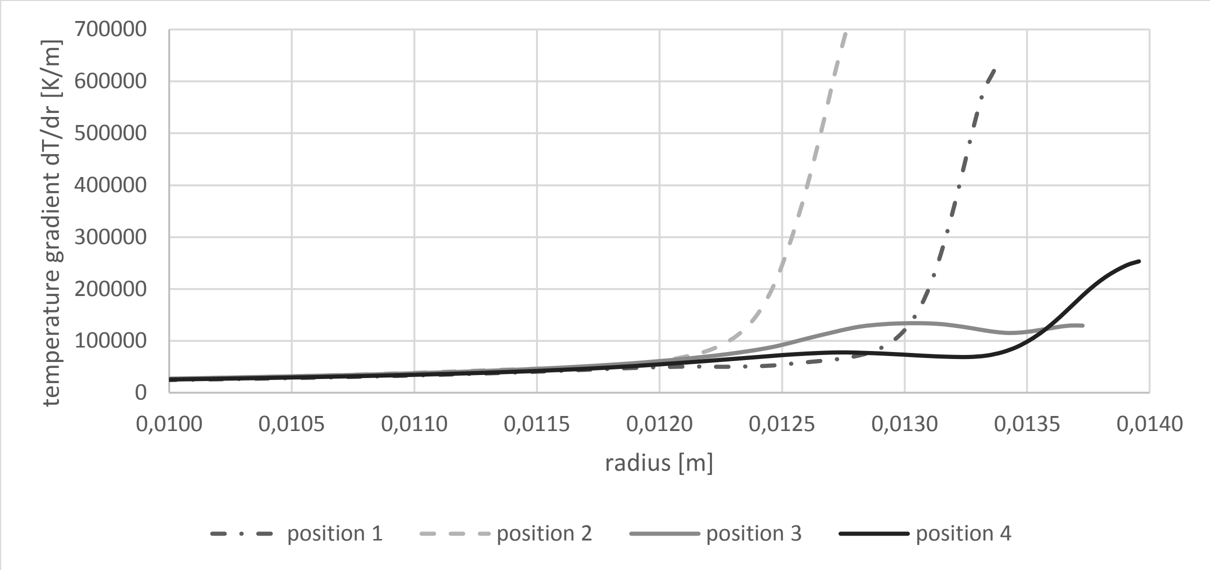

Figure 4: Temperature gradient in the near wall zone at different positions

Experimental setup

The velocity profile of the flow field at the near wall region was measured with a Laser Doppler Velocimeter. Therefore, a test facility for 1D velocity measurements in mean flow direction according to Figure 5 was arranged with an appropriate mount for the test tubes.

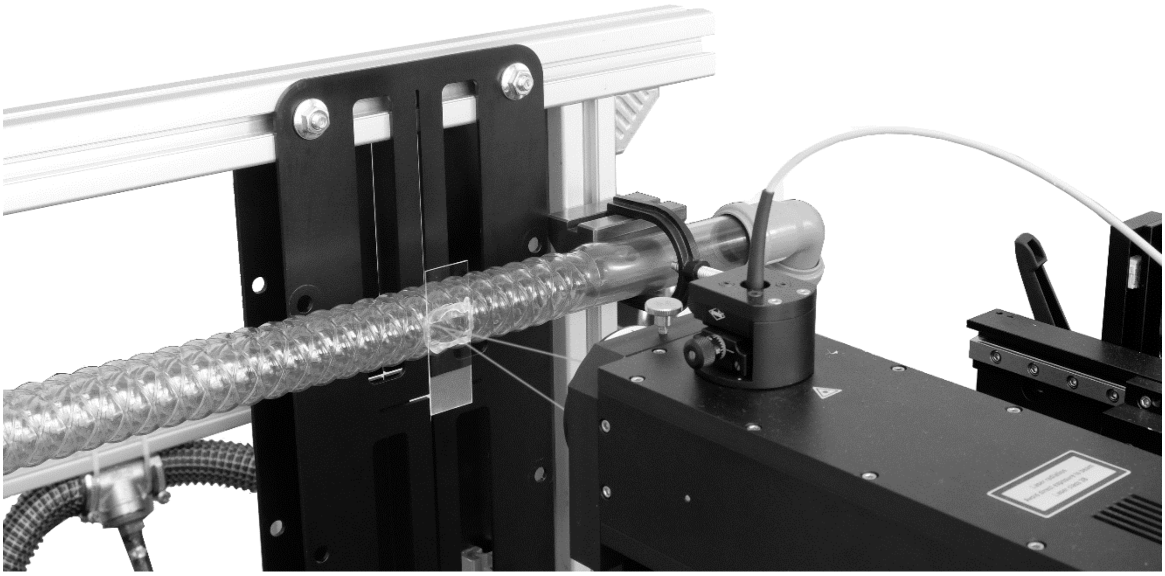

Figure 5: LDV test facility with a mounted corrugated tube [2]

As corrugated tubes made of steel would reflect the laser light too much, the test tubes were made of acrylic glass. The corrugated glass tubes were manufactured by using a thin steel mesh template which is first of all a flat laser cut in the shape of the corrugations. In a second step, the laser cut is bent around the acrylic smooth glass tube. After coating the acrylic glass tube with the template, the tube has to be put under pressure ($p \approx 2\ bar_a$). By heating the acrylic glass tubes to a temperature of 210°C, the corrugations appear. The depth of the corrugations depends on the pressure inside the tube (see Figure 6).

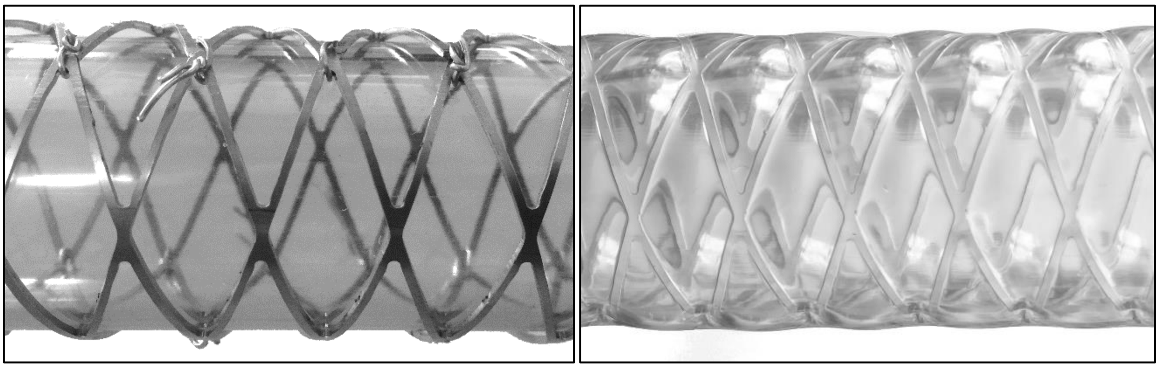

Figure 6: PVC smooth tube with steel template (l); PVC tube with corrugations and removed steel template (r)

After the deformation of the tube, a window for the positioning of the measuring volume is needed. Therefore, a small cut on the opposite wall of the investigated near wall zone is milled. The hole is sealed by a flat glass plate with a depth of 0.15 mm (see Figure 7). Using the acrylic glass as tube material instead of steel, the reachable wall distance can be reduced from $\Delta d_{wall_{metal}} = 3.8\,mm$ to $\Delta d_{wall_{acryl}} = 0.15\,mm$.

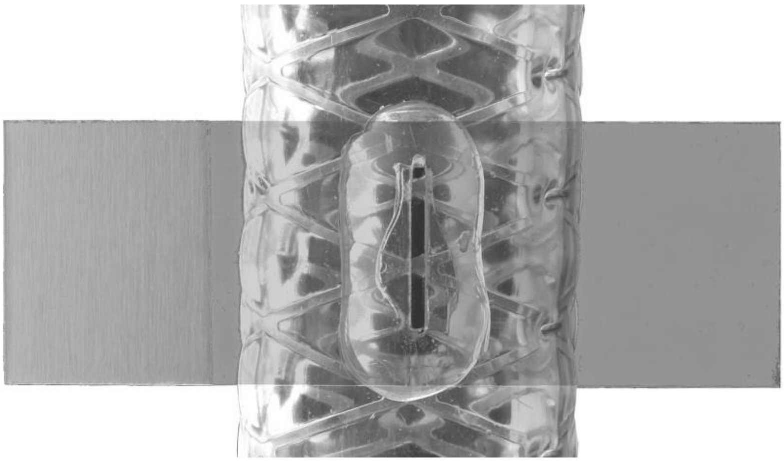

Figure 7: Flat glass plate for positioning the measuring volume and proofing the gas flow

Velocity profiles in corrugated tubes

The measured 1-D velocity profiles were compared to simulated values. The velocities were measured in two positions inside the pockets of the corrugations. The first position is directly behind the corrugation peak; the second one is in the middle of the pocket.

Figure 8 shows the velocity distribution of an isothermal gas flow in a corrugated tube with an inner diameter of $d_i = 28\,mm$ at $Re = 4000$. The black colored zone represents a back flow area which is an indicator of a stagnant eddy behind the corrugation inside the pocket. The measured values confirm the velocity trend. Furthermore, at this Reynolds-number, a smaller second stagnant eddy is located directly behind the first one.

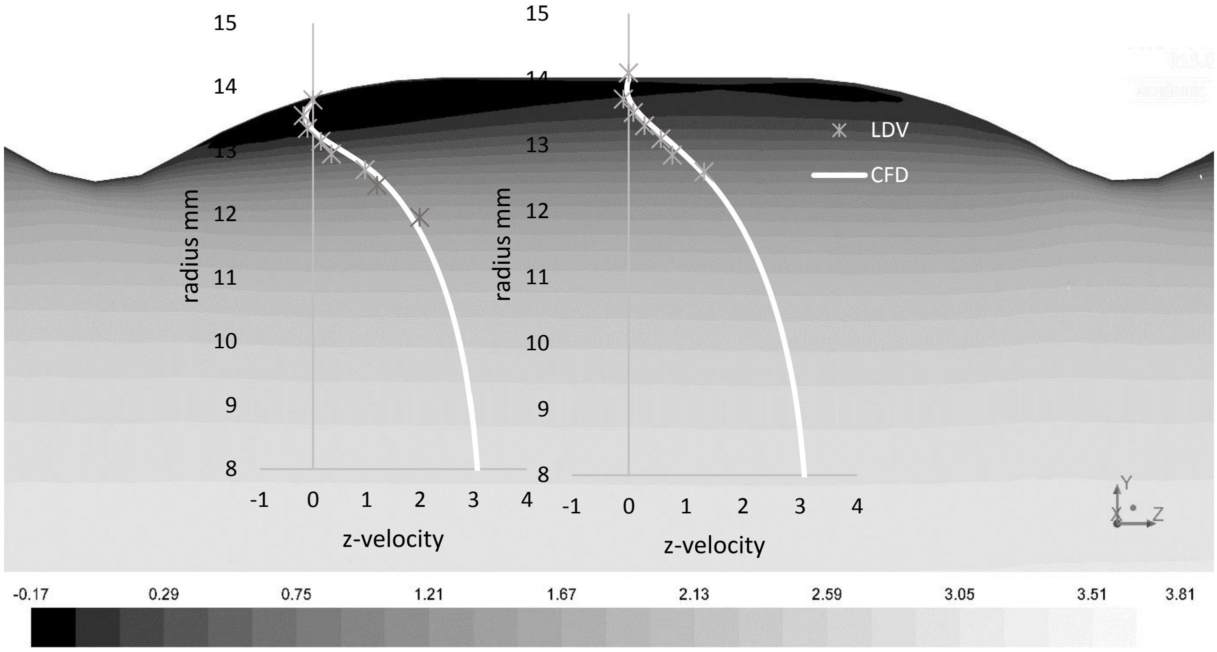

Figure 8: Velocity distribution in mean low direction in the near wall zone of a corrugated tube at Re = 4000

Figure 9 shows the velocity distribution of the corrugated tube from Figure 8 at higher Reynolds-number Re = 8200. In this case, the two stagnant eddies merge to one larger eddy filling the whole pocket. The simulated velocity in Figure 8 was as well confirmed by the LDV measurements.

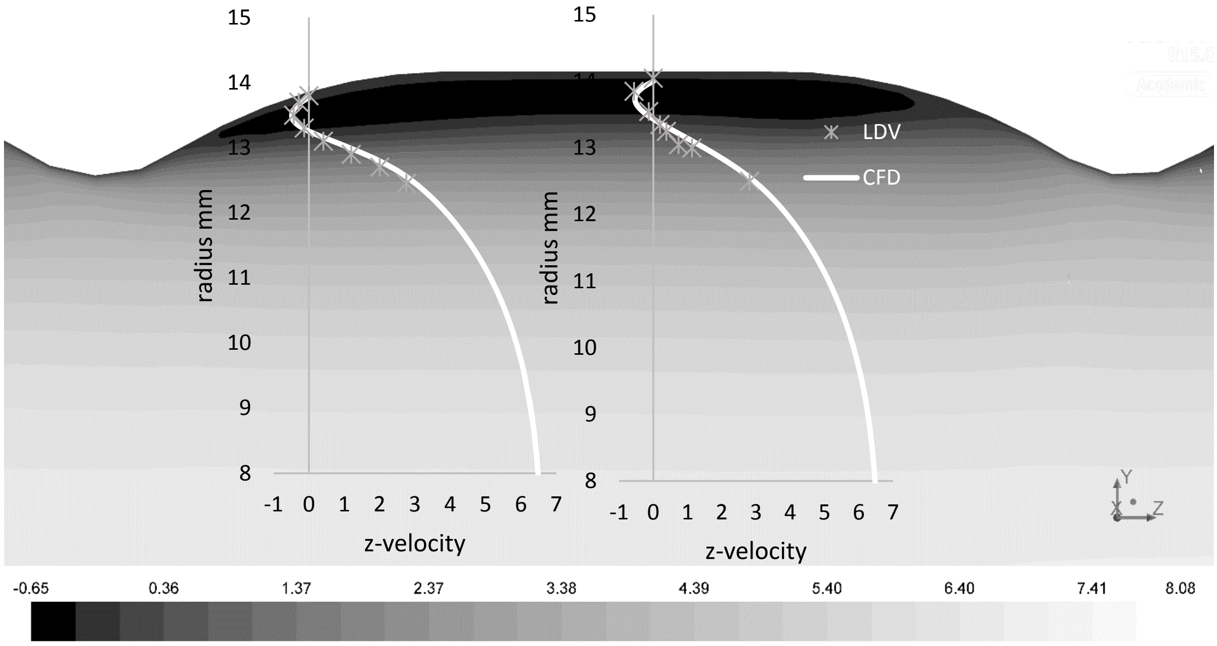

Figure 9: Velocity distribution in mean flow direction in the near wall zone of a corrugated tube at Re = 8200

Conclusions

The investigation shows that the use of corrugations can distinctly improve the heat transfer locally.

The essential findings can be summarized as follows:

(1) The thickness of the viscous sublayer is responsible for the heat transfer rate from the fluid to the wall. Zones in front of and at the narrow point of the of the flow provide the highest temperature gradients.
(2) The corrugations produce stagnant eddies inside the pockets, which therefore have the effect of an isolator.
(3) The simulated values by a RSM model of the velocity in mean flow direction have been confirmed by LDV measurements.
(4) For LDV measurements, corrugated tubes have to be made of material with high light-transmissivity to enable measurements up to a wall distance of $\Delta d_{wall} = 0.15\,mm$.

Acknowledgments

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