STUDY OF NATURAL CONVECTION AROUND A VERTICAL HEATED ROD USING PIV/LIF TECHNIQUE

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Abstract

The Nuclear Training Reactor of the Institute of Nuclear Techniques (Budapest University of Technology and Economics, Hungary) is a pool-type reactor with light water moderator and with a maximum thermal power of 100 kW. The fuel elements are cooled by natural convection. An experimental setup was built to analyse the behaviour of natural convection around a heated rod. The flow field was investigated using an electrically heated rod, which models the geometry of a fuel pin in the training reactor. The electric power of the model rod is variable between 0–500 W. The rod was placed in a square-based glass tank. PIV (Particle Image Velocimetry) and LIF (Laser Induced Fluorescence) measurement techniques were used to study the velocity and temperature field in a two-dimensional area.

The thermal and the hydraulic boundary layers were detected near a rod in a lower section of the tank. The laminar-turbulent transition of the flow regime was observed, the maximum velocity of the up-flow was 0.025-0.05 m/s. From the temperature measurements the local heat transfer coefficient was estimated.

1. INTRODUCTION

The Nuclear Training Reactor of the Institute of Nuclear Techniques has light water moderator and cooling, and has a maximum thermal power of 100 kW. The core is built of EK-10 fuel assemblies with 10% enrichment. The EK-10 fuel assemblies are 10 mm in diameter, with an active length of 500 mm and an inactive length both in the upper and the bottom part of the fuel rods. The reactor core consists of 369 fuel rods in a square lattice, the lattice pitch is 17 mm.

The flow regime around the fuel rods is governed by natural convection. In certain operation states the cooling system injects colder water below the core, but even in these cases natural convection ensures the cooling of the fuel rods. The reactor tank contains 8.5 m^3 of water.

New safety analyses programs are under development in the Institute of Nuclear Techniques. The investigations showed that the process of the reactor excursion and the maximum energy release are determined basically by the efficiency of the natural convection around the rods, the velocity of the cooling water and the heat transfer coefficient. The goal of this paper is to help these programs by measuring the natural convection around a vertical heated rod.

A new experimental setup consisting of a model of a EK-10 fuel pin was built. PIV technique (Particle Image Velocimetry) was used to measure the two-dimensional velocity field, and LIF (Laser Introduced Fluorescence) technique was used to investigate the temperature field near the rod in the two-dimensional area.

In this study the experiment setup and measurement results are presented.

2. EXPERIMENTAL TECHNIQUES AND SETUP

In this section the experimental setup will be introduced. The velocity field was investigated with PIV technique (Raffel 2007). Small particles with a diameter of 50 μm were seeded to the water, the density of which is equal to the water density. Therefore, the velocity of the particles represents the velocity of the coolant. A fluorescent dye was added to the water too, the fluorescence intensity of the dye is proportional to the temperature. The fluorescence dye was Rhodamine B. Two cameras were used during the experiments, therefore it was possible to measure the temperature and the velocity field simultaneously.

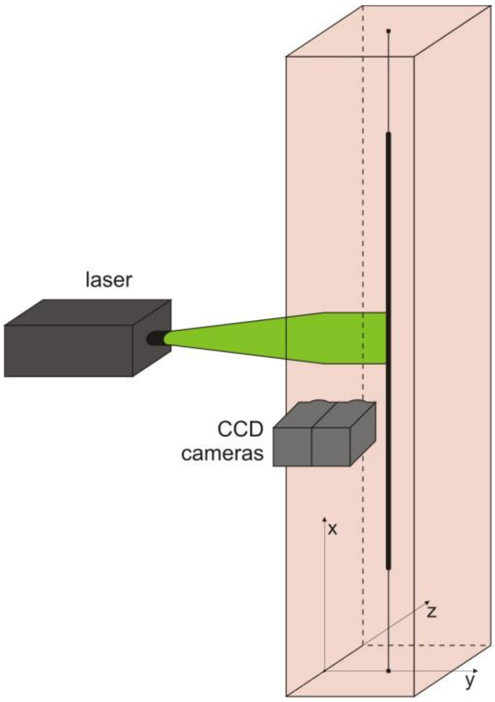

Fig. 1: The experimental setup

2.1. Experimental Setup

The experimental setup is shown in Fig. 1. There is a glass tank, which has the shape of a square-based prism. The height of the tank is 1m and the dimensions of the square are 0.15 m × 0.15 m. The electrically heated rod is placed in the middle of this tank, the rod is 0.15 m from the bottom. Spacers hold the rod in the centre of the tank in vertical position. The effect of the spacer on the flow is negligible.

The electrically heated rod has an active length of 500 mm and variable electric heating power with a maximum of 500 W. The rod is 700 mm long. It has an inactive length of 100 mm both in the upper and the bottom part. The diameter of the rod is 10 mm. The active length of the model is the same as the active length of the real fuel rods.

The laser beam is converted into a vertical planar light sheet, which is perpendicular to the tank wall and directed to the vertical axis of the rod. The two cameras are perpendicular to the laser sheet. The cameras and the laser and therefore the detected field can be shifted along the vertical axis.

A double cavity Nd:YAG laser was used with a wavelength of 532 nm, and the two CCD cameras with 1600 × 1200 pixels. The PIV camera was used in “double frame mode”, which allowed making

two images with very short time difference. The camera lens of the PIV camera was covered by a band pass filter around 532/533 nm. The lens of the LIF camera was covered by a high pass filter around 570 µm. The PIV camera detected only the scattered laser light, and the LIF camera recorded only the fluorescence light of Rhodamine B (Sakakibara, Adrian 1999 and Meyer 2002).
A vertical thermocouple line consisting of eight thermocouples was added to the setup. The thermocouple line allows us to control the temperature during a measurement, and helps to calibrate and check the LIF data. The coordinates of the thermocouples are in Table 1. The thermocouples measured the temperature with frequency of 1 Hz.

Table 1.: The position of the thermocouples in the tank

Number of the thermocouple	**t_01**	**t_02**	**t_03**	**t_04**	**t_05**	**t_06**	**t_07**	**t_08**
x coordinate (mm)	29	36	42	49	55	61	67	73
y coordinate (mm)	11.50	11.50	11.50	11.50	11.50	11.50	11.50	11.50
z coordinate (mm)	-40	-40	-40	-40	-40	-40	-40	-40

The collection and the processing of data, the synchronization of the devices were controlled by computer. The data analysis for PIV was performed using the commercial software package Dantec Dynamics v2.10 (Dantex 2008). The data analysis for LIF was performed using a self-developed C++ codes named lif_calibration and lif_calculation.

2.2. Natural Convection

The study of the natural convection near vertical surfaces is an extensively investigated area, because natural convection can be observed in technical applications as well as in the nature (George, Capp 1979 and Tsuji, Nagano 1988). Both theoretical and experimental research is widespread. Fig. 2 shows the character of the natural convection near a heated vertical plate.
In order to determine the flow characteristic around the heated vertical rod the Rayleigh number (*Ra*) has to be calculated (Gersten 1992). If $Ra < 10^8$, the flow is laminar, if $Ra > 10^{10}$ the flow is turbulent.

$$Ra = Gr \cdot Pr = \frac{g\beta}{\nu a}(T_s - T_\infty)L^3 \qquad (1)$$

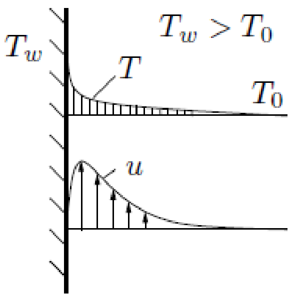

Fig. 2: Standard geometry for natural convection near the vertical plate

The letters are used as follows:

- Gr: Grashof number
- Pr: Prandtl number

- g: acceleration of gravity
- T_s : surface temperature
- T_∞: fluid temperature far from the surface
- ν: kinematic viscosity
- a: thermal diffusivity
- β: thermal expansion coefficient
- L: linear length of the system.

The Rayleigh number was calculated for this experiment series. The surface temperature was measured with thermocouple, the value is $T_s = 60\ °C$. The Rayleigh number was calculated by equation (1), in our case $Ra = 1.07 \cdot 10^{11}$, therefore a turbulent natural convection flow is expected next to the rod.
The Nusselt number can be calculated by equation (2) from the Rayleigh number. This equation is true in natural convection with high Rayleigh number.

$$Nu = 0.135 \cdot Ra^{1/3} \tag{2}$$

Heat transfer coefficient (α) can be derived from the definition of Nusselt number (3).

$$Nu = \frac{L \cdot \alpha}{\lambda} \tag{3}$$

In this case the heat transfer coefficient is independent from the linear length of the system. The value of the average heat transfer coefficient is: $\alpha = 784\ \frac{W}{m^2K}$ in the experimental setup.

2.3. Velocity Measurement (PIV)

For the experiments the flow was seeded with polyamide particles of 50 μm diameter. Preliminary measurements showed that the expected absolute value of the velocities is of order of magnitude 0,001-0,02m/s. Therefore the time between laser pulses was set to 10000 μs. Data processing technique was adaptive correlation method of Dantec Dynamics. The final interrogation area was 16 × 16 pixels (0.62 mm × 0.62 mm), starting at 256 × 256 pixels. The overlaps of the interrogation area in the horizontal and vertical direction were 50-50%.
Hundred images were made consecutively with the frequency of 10 Hz. The mean of ten sequential velocity fields was calculated, the results of the experiments were these velocity fields for every measured second.

2.4. Temperature Field Measurement (LIF)

The LIF measurement technique is designed to determine a temperature field in a planar cross section of a flow field. The necessary devices of the experiment are a laser, a CCD camera, and temperature sensitive marker in the water. In this study Rhodamine B fluorescent dye was used.
The temperature sensitive marker Rhodamine B was excited by the same laser, which was used for PIV measurement. The intensity of the local fluorescent light depends on the Rhodamine concentration, the exciting laser power as well as the temperature of the water. Therefore it is necessary to keep the laser power, the concentration and the experimental geometry fixed. The

calibration of the LIF data is indispensable before each measurement. The inhomogeneity of the laser beam can be eliminated by doing the calibration for each pixel individually. The calibration lines for each pixel were calculated by program lif_calibration at seven calibration temperatures with least squares fitting. The self-written lif_calculation program performed the proceeding of calculation. Hundred images were made, with frequency of 10 Hz. The LIF images are mean pixel value images of one hundred successive images. This procedure was applied for both the LIF calibration and evaluation.
Seven temperature fields were used for the calibration of the LIF data, the temperatures are shown in Table 2.

Table 2.: Calibration temperatures

calibration temperature (˚C)	18.1	25.0	27.7	30.6	34.1	38.5	40.7

2.5. Measurement Procedure

The interest of the investigation was the natural convection near of the rod, and the detection of the hydraulic and thermal boundary layers. Therefore the detection area was chosen in vertical plane as it is shown in Fig. 1. The setup was symmetrical hence it was enough to investigate the half of the tank.

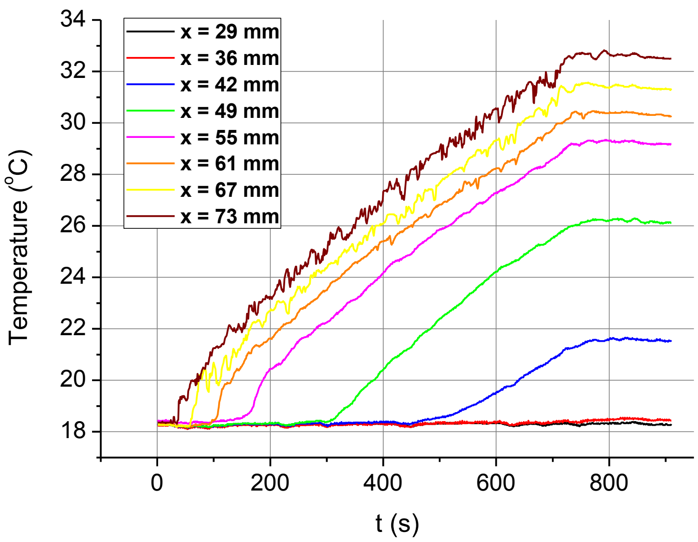

Fig. 3: The temperature data of the thermocouples in the tank during continuous heating

The aim of the measurement is to analyse the heating process while applying maximum heating power (500 W). Our goal was to have scanning with very fine resolution, therefore the detected area was restricted to a close area near the rod. $Z = 0\,mm$ plane was the investigated area. Several measurements were made along the height of the tank. Each measurement started with turning on the heating. The heating was continuous for 10-30 minutes. The temperature and the velocity field were measured every two minutes with a frequency of 10Hz, for 10 seconds. One of the experiments was chosen to be presented in this study. During the measurement ambient water temperature was measured with the thermocouple line. The data of the thermocouples are shown in Fig. 3. By this measurement the heating period was between t=0s and t=780s. The end of the measurement was at t=910s.

The temperature of the ambient water was constant for about 300 seconds at *x = 49 mm*. The flow can be considered stationary for 300 seconds.
Each thermocouple recorded a period of constant temperature. The length of this period depends on the vertical location of the thermocouple. The thermocouples above 61 mm had an intensive noise. At the lowest levels the temperature increase is smoother. The thermocouples below 36 mm do not show any increase in temperature.
The detected area was 464 – 511 mm from the bottom of the tank. The right side of the area was at the rod surface, and the width of the pictures was 60 mm.
The heating procedure was the same as above. The heating started at 0 s, and it stopped at 780 s. Table 3. shows the summary of the measurements, each one took 10s, and the sampling frequency was 10 Hz. The velocity and the temperature fields were measured simultaneously. Six measurements were made during the heating, and two measurements were made after turning off the heating.

Table 3.: Chronology of the experiment

measurement	p_l_01	p_l_02	p_l_03	p_l_04	p_l_05	p_l_06	p_l_07	p_l_08
start time	0 s	120 s	240 s	360 s	540 s	660 s	780 s	900 s
Electric power	500 W	500 W	500 W	500 W	500 W	500 W	0 W	0 W
technique	PIV, LIF	PIV, LIF	PIV, LIF	PIV, LIF	PIV, LIF	PIV, LIF	PIV, LIF	PIV, LIF

3. Experimental Results

Fig 4. shows a temperature field of the measurement p_l_03 (t = 240 s). Y coordinate shows the distance from the bottom of the tank. (The bottom of the rod's heated part is at y = 250 mm.) The rod surface is at x = 70 mm, the wall of the tank is at x = 0 mm. Each measured temperature field is similar to the temperature field in Fig 4. The thermal boundary layer is visible near the rod in every image. The ambient water (further from the rod) has almost a constant temperature, but the upper side of the detected area shows lightly warmer areas. The difference is less than 2 °C. The velocity should be much lower, than the up-flow near the rod.

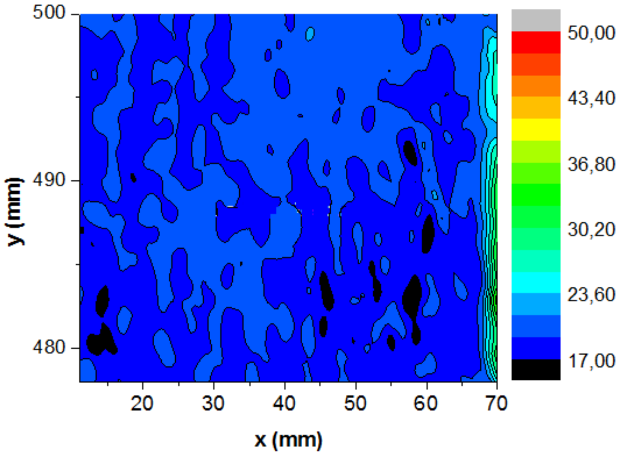

Fig. 4: Temperature field, t = 240 s

For qualitative analyses Y = 490 mm line was chosen to investigate the results. The height of the fourth thermocouple was the same. The temperature data of sixteen continuous lines were averaged in this elevation (from 489.68 mm until 490.30 mm). In this way the same scanning was achieved as the scanning of the velocity field. The last three data for every horizontal line (3 pixels = 0.1 mm) were removed from the temperature curves, because a very strong laser light reflection caused non-physical results in this range. The temperature curves were extrapolated to the rod (this means 0.1mm) and a smoothing process was applied. Fig 5. shows the temperature distribution along a horizontal line for five measurements.

Distribution along the detected area are shown in Fig. 5.a. The temperature of the ambient water can be investigated, and it can be said, that the temperature far from the rod is almost constant, and the value attend to the value of the fourth thermocouple. The boundary layers are shown in Fig. 5.b. The temperature has a similar distribution in each measurement. The boundary layer is about 3-4 mm thick.

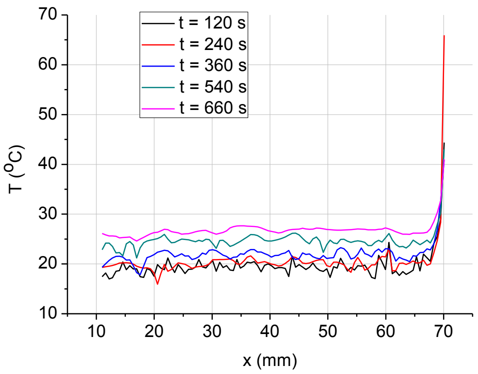

Fig 5.a: Temperature distributions

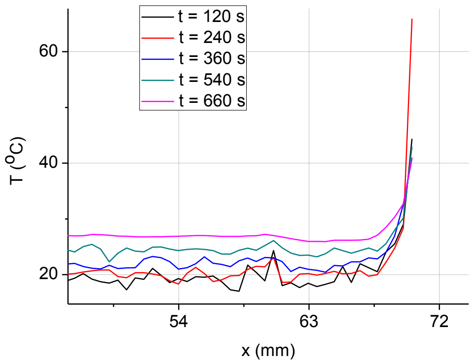

Fig 5.b: The thermal boundary layers

From the LIF results the local heat transfer coefficient was calculated along the y = 490 mm line. Newton's Law of Cooling (4) was used. The heat flux was $31.8\frac{kW}{m^2}$ in this case. The result of the local heat transfer coefficient is shown in Table 4.

The order of magnitude of the heat transfer coefficient is in agreement with the theoretical expectation. Local parameters were used, therefore the value depend on the local characteristics of the flow. The assumption was that the flow in this location is laminar in the early measurements, then the flow becomes turbulent. The turbulent flow regime improved the heat transfer.

$$\dot{q}" = \alpha \cdot (T_{max} - T_{\infty}) \quad (4)$$

Table 4.: The calculated local heat transfer coefficient

	T_{max} (°C)	T_{∞}(°C)	α (W/m²K)
t = 120 s	44	19.5	1298
t = 240 s	65	20	707
t = 360 s	41	22	1674
t = 540 s	39	25	2271
t = 660 s	40	27	2446

The results of the PIV measurements confirm the temperature measurements. The water far from the rod flows down, the values are 0.0005-0.001 m/s, and the flow velocity is constant in time. Near the rod there is an up-ward flow, with a maximum value of 0.02-0.05 m/s.
The hydraulic boundary layer can be investigated based on the two dimensional velocity fields. The measurement p_l_01 started when the heating was turned on. The evolution of the boundary layer was detected. Fig. 7.a show this process along the horizontal line y = 490 mm. The wide of the up-flow increased in time as well the maximum velocity of the boundary layer.

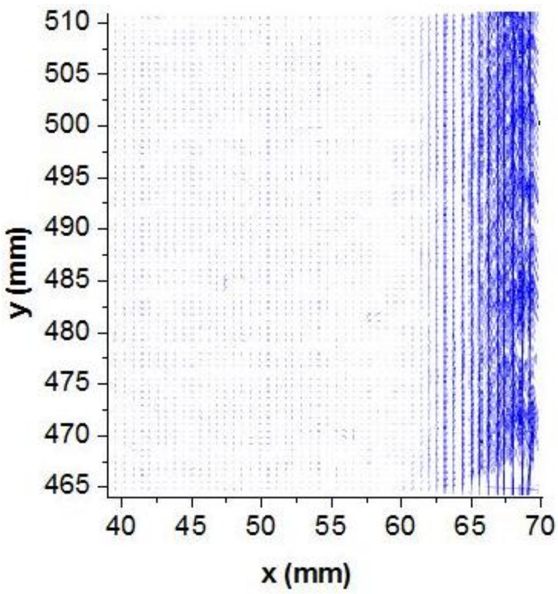

Fig. 6.a: t = 122 s, velocity field

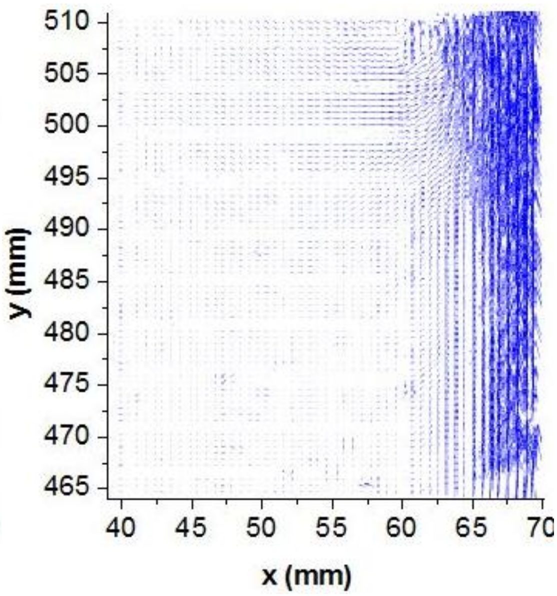

Fig. 6.b: t = 129 s, velocity field

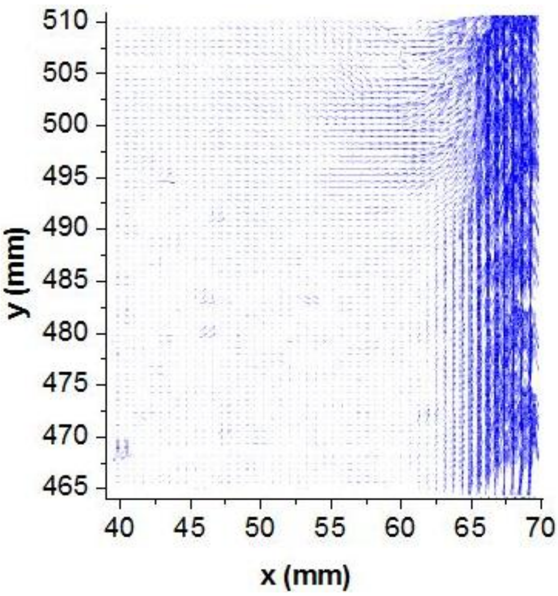

Fig. 6.c: t = 242 s, velocity field

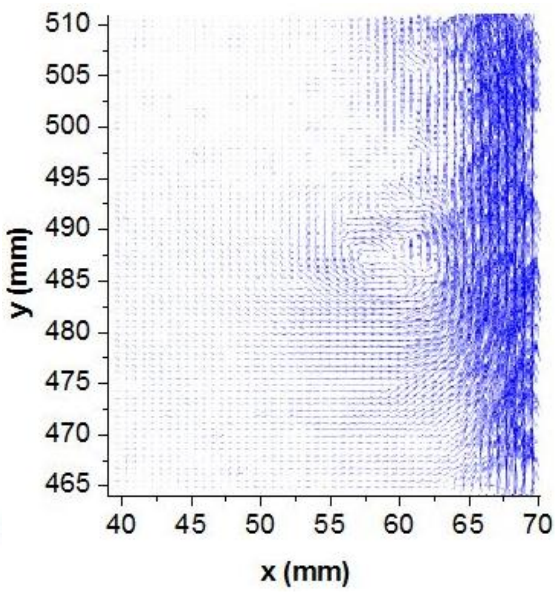

Fig. 6.d: t = 665 s, velocity field

The subsequent measurements show the development of the flow regime. Until t = 125 s the flow was laminar in the detected area. After that, the laminar – turbulent transition can be observed above y =

495 mm. Fig. 6.a and Fig. 6.b represent the change. In the lower part of the area laminar flow regime was typical for a long time, Fig. 6.c shows the same structure as Fig. 6.b. Time elapsed between the two images was more than two minutes. About six minutes after the start of the heating the turbulent nature of the flow can be observed in the lower section of the flow field. One example is Fig. 6.d. In this figure the up-flow has vortices, the flow is turbulent.

In Fig. 7.a-g the velocity distribution are shown along a horizontal line y = 490 mm. Fig. 7.a shows the development of the boundary layer, Fig. 7.g shows the decreasing the up-flow after the heating process shut down. The hydraulic boundary layer has an almost constant width in the experiment, it is about 10 mm. The turbulent regime is a little thicker. Maximum velocities are shown in Fig. 7.c, for measurement p_l_03. Mean value of the maximum velocity is 0.05 m/s. After that velocity decreases constantly, because the turbulent behaviour or the flow intensifies. In measurement p_l_06 the velocities are 0.017-0.028 m/s.

The velocity distributions agree with the fluctuation of local heat transfer coefficient. A turbulent regime of the flow caused more intensive interaction between the up flow and the ambient water, the layer became thicker. As a consequence heat transfer is the more effective heat and velocities decrease in the boundary layer. Both the temperature and the velocity measurement confirm this conclusion.

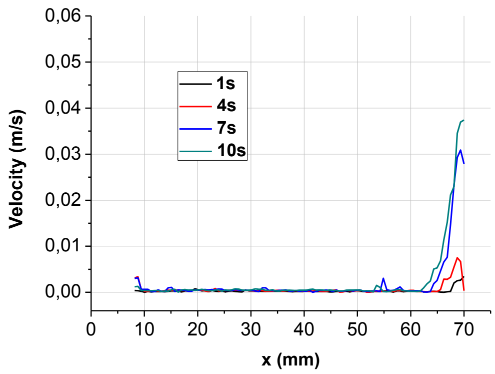

Fig. 7.a: p_l_01

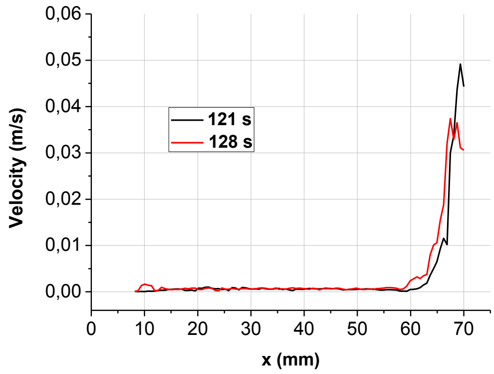

Fig. 7.b: p_l_02

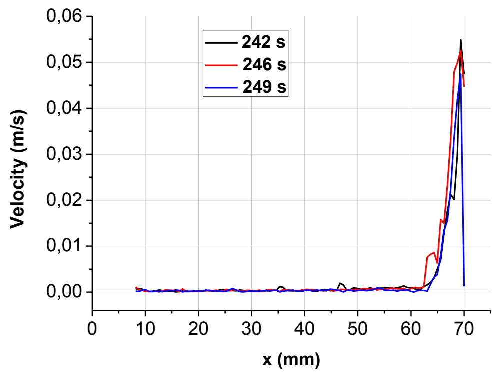

Fig. 7.c: p_l_03

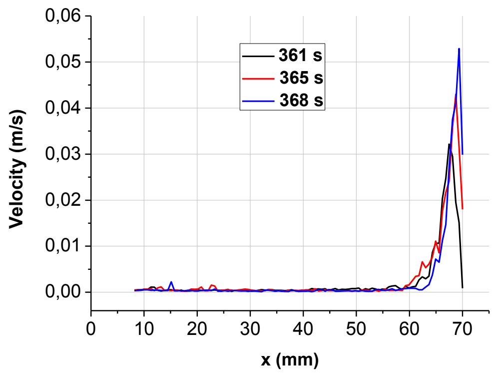

Fig. 7.d: p_l_04

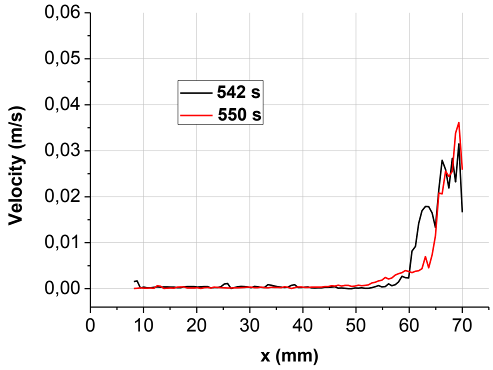

Fig. 7.e: p_l_05

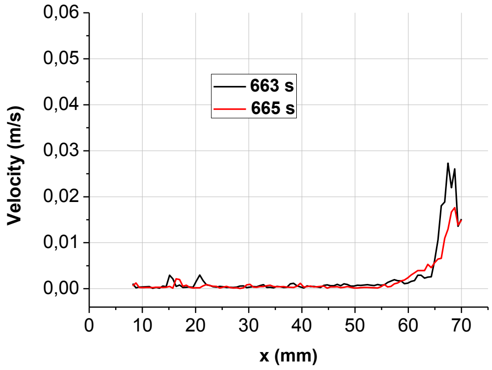

Fig. 7.f: p_l_06

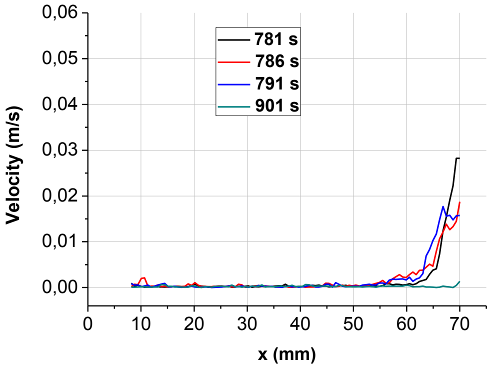

Fig. 7.g: p_l_07 and p_l_08

4. Conclusion

Simultaneous measurements of velocity and temperature fields were performed applying a combined PIV and LIF setup to investigate natural convection around a vertical heated rod. The design and optimization of the experimental setup was achieved. One of the performed measurements is presented in this paper.

The boundary layer was detected and the velocity and temperature distributions along a horizontal line were analysed. The evolution of the flow regime was observed in time from the start of the heating over the stop of the heating until the stationary state. The laminar – turbulent transition was identified clearly. The local heat transfer coefficient was calculated, the value match with the expectations. The velocity measurement and the temperature measurement complete each other, and are in accordance.

The determination of both the velocity distribution and the heat transfer coefficient will be essential for future reactor excursion calculations of the Training Reactor.

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