IN-SITU INVESTIGATION OF TURBULENT FLUID FLOW UNDER HIGH PRESSURE CONDITIONS BY MEANS OF LASER DOPPLER ANEMOMETRY AND NUMERICAL SIMULATION

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Abstract

High pressure processes up to 1000 MPa have a wide spectrum of application in engineering and natural science ranging from chemistry, bio and chemical engineering to mechanical engineering. In all areas flow processes are of major importance e.g. for transport and mixing phenomena. Nevertheless, especially the characteristics of the flow like laminar and turbulent flow and its transition are not well understood under high pressure conditions. This contribution shows that some thermophysical properties (e.g. viscosity) of fluids and thermofluid-dynamical phenomena (e.g. laminar-turbulent transition) differ under increased pressure significantly from ambient conditions. The present work presents results gained with specially developed High Pressure-Laser Doppler Anemometry (HP-LDA) and numerical simulations for in-situ flow investigations under high pressures up to 300 MPa. The experimental results show for the first time that sudden increase of pressure in liquids can relaminarize turbulent flow. This paper reports on quantitative mean velocity and turbulence properties of a water free jet leading to a pressure increase. The axial mean velocity profile against the cross-stream (radial) coordinate in a turbulent free jet during the pressure increase phase is obtained by using HP-LDA as well as the reduction of the turbulence intensity of the flow due to compressibility effects. The experimental achievements are additionally compared with results obtained by numerical simulations of the flow. The comparison indicates very good agreement between the numerical and experimental results.

1. Introduction

In recent years, the investigation of fluid behavior under very high pressure has been developed extensively especially as more and more technological processes run under pressures of several thousands of bars. The importance of High Pressure Processing (HPP) in research and industrial application increased due to its high potential, e.g. unique effects on biomaterials in comparison to other processes. The range of application of high-pressure technologies spreads from (bio-) chemical to car industry. This results in a high demand for experimental data as well as theoretical background of various phenomena occurring in fluids. It is well-known that thermophysical properties of many substances and phenomena occurring under high pressure differ significantly from these under ambient conditions. The thermophysical properties of pressure transmitting media and biomaterials such as density, viscosity, heat conductivity, and thermal capacity change drastically with increasing pressure [6-7]. Additionally, HPP can be considered as instantaneous but not homogeneous due to

local temperature inhomogeneities occurring during the pressurization phase and subsequent heat transfer phenomena [1, 2].
Concerning fluid flow turbulent-laminar transition is an important phenomenon influencing, e.g. transport processes in a crucial manner. In recent studies the feasibility of in-situ flow investigations under high pressures up to 300 MPa by means of high pressure-Digital Particle Image Velocimetry (HP-DPIV), high pressure-Laser Doppler Anemometry (HP-LDA) and high pressure-Hot Wire Anemometry (HP-HWA) has been shown [2-5]. The experimental results show for the first time that sudden increase of pressure in liquids can relaminarize turbulent flow [3-4].
This paper focuses on the presentation of experimental, optical in-situ techniques to measure compressible turbulent liquid flows and, thus, investigate turbulent fluid flow and its development under HP conditions up to several hundred MPa. In the present work, HP-LDA is used to measure axial mean velocity and turbulence intensity in a turbulent free jet during the pressure increase. The obtained results are in a good agreement with experimental findings using HP-HWA conducted by Song et al. [3] and current numerical simulations.

2. Experimental investigations

In the present experimental investigation of the turbulent fluid flow under high pressure conditions consists of three stages. The pressure vessel is pressurized up to 300 MPa with a pressure ramp of 12.2 MPa/s (Fig. 1). Afterwards the pressure is held at 300 MPa for one minute. In the last stage, the pressure is released again to ambient pressure. Distilled and bled water at room temperature is used both as pressure transmitting medium and probe material.

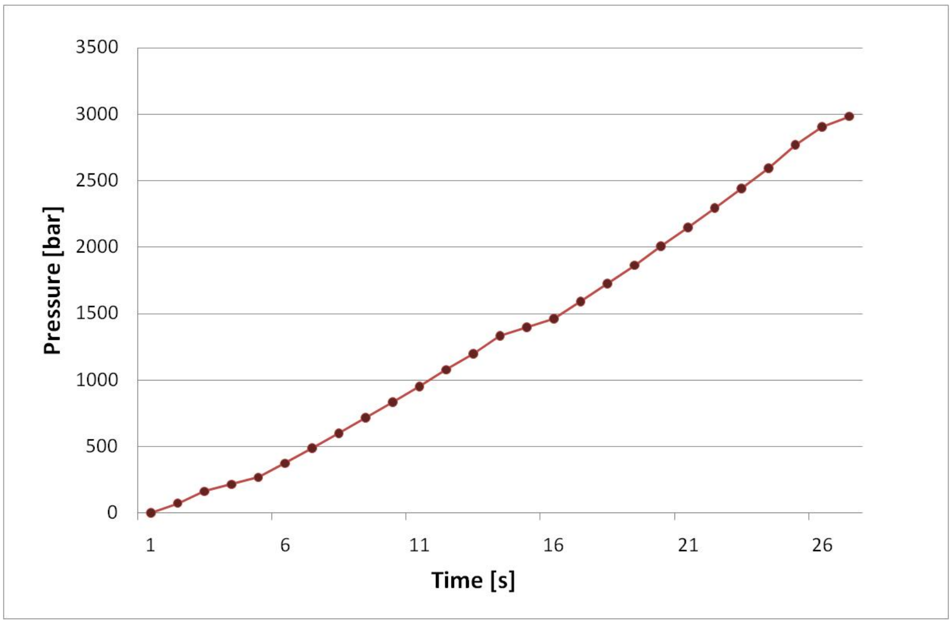


Fig. 1: Pressure ramp applied in the present experiment

A pressure generation system is used for pressurization (Fig. 2) which is able to deliver a constant mass flux of high pressure medium at a prescribed pressure. It consists of a tube injection system in which a pressure transmitting fluid is issued from an inlet nozzle into the vessel generating a free jet. This means that the mass flux, process pressure, pressure ramp, and pressure holding time are controlled.
The pressure vessel is constructed from stainless steel 1.4542 (X5CrNiCuNb16) (Fa. DUSTEC) and has a volume of 1.5 l. The vessel is designed for a maximal operating pressure of 700 MPa and a temperature range from 0 to 100 ºC. The pressure vessel has been designed for the experiments carried out at LSTM-Erlangen. The fluid is supplied from the

bottom by the hydraulic system. The temperature is measured by three thermocouples at three different positions in the vessel. Pressure and piston movement are recorded every second. In order to enable flow measurements at different vertical positions in the vessel a metal tube (diameter of 1.6 mm) with a variable length is assembled at the flow inlet nozzle [3]. The length of the tubes varies from 2 to 148 mm.

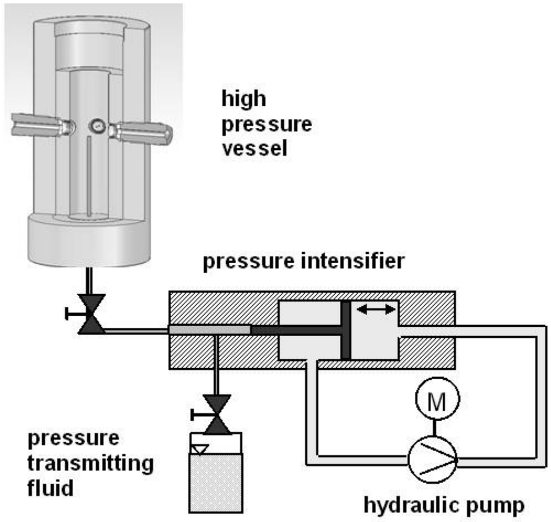
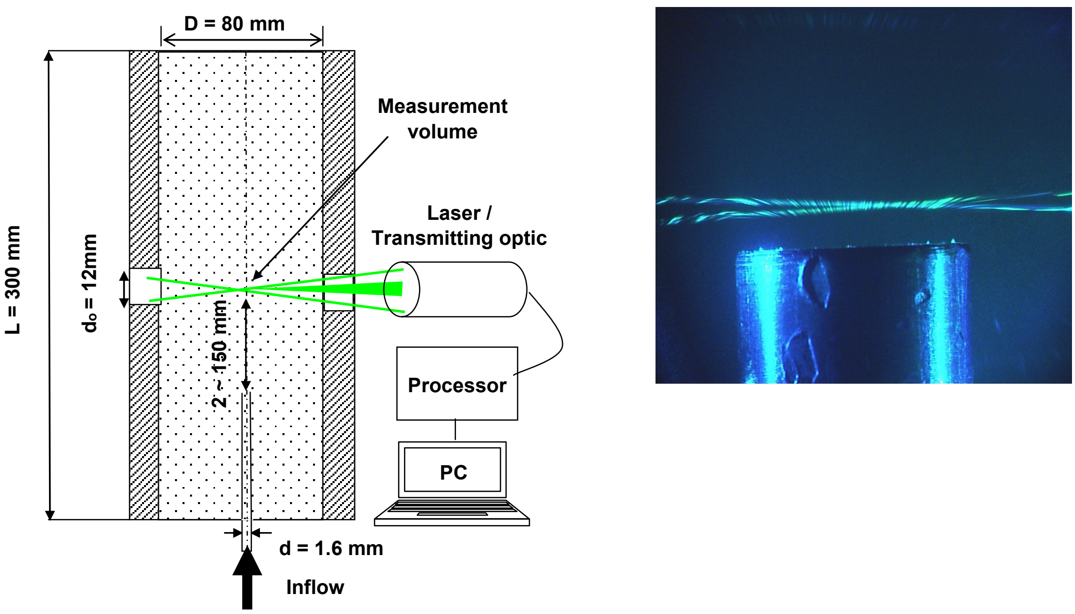


Fig. 2: Experimental set up for pressure generation

The high pressure vessel has three synthetic sapphire (Al_2O_3) windows with an optical diameter of 12 mm each. The windows allow for the measurement of the fluid velocity using optical techniques, e.g. innovative HP-LDA derived from the well known LDA under ambient conditions [8]. A schematic sketch of the high pressure vessel with HP-LDA system (backward scattered mode) is shown in Fig. 3. A Nd:YAG fibre optic HP-LDA system with a wavelength of 488 nm is used and seeding particles (Nylon) with an average diameter of 4 µm. The measurement volume of the two laser beams is 0.12 mm x 0.12 mm x 2.55 mm. The optical parameters of the HP-LDA system are summarized in Table 1.



(a): HP-LDA system (b): HP-LDA measurement volume

Fig. 3: HPP vessel with HP-LDA system (a); HP-LDA beams crossing over the inlet nozzle (b)

Table 1: Optical parameters of the HP-LDA system

Parameter	Value
Wavelength	488 nm
Fringe distance	5.143 µm
Focal length	400 mm
Half angle of beams	2.71°
Measurement volume, length	2.55 mm
Measurement volume, height	0.12 mm

In order to estimate the Reynolds number during the process experimental data are needed obtaining the compressibility and viscosity of the fluid. Auxiliary measurements deliver the change in the fluid viscosity with varying pressure and temperature. A rolling-ball viscosimeter (Höppler viscosimeter) is used to measure the change of viscosity of the fluid. The viscosity of a fluid is proportional to the time the ball needs to pass a known distance and the density difference between fluid and rolling ball:

$$\mu = k(p) \cdot \Delta t \cdot (\rho_s - \rho_f) \tag{1}$$

where μ is the dynamic viscosity of the fluid, $k(p)$ the rolling ball resistance constant, Δt the time needed to pass a known distance, and ρ_s, ρ_f the density of the rolling sphere and the fluid, respectively. Here, a series of measurements for temperatures of 20, 30, 40, 50 and 60 ^{o}C with pressures of 0.1, 100, 200 and 300 MPa are carried out.
The determination of the compressibility of the fluid with pressure and temperature variation is carried out by a manually operated compressing device containing a constant mass of the fluid compressed in a vessel. Knowing the initial mass of the fluid m_0 and the initial volume of the chamber V_0 the density of the fluid can be calculated as:

$$\rho(p,T) = \frac{m_0}{V_0(T) - \Delta V} \tag{2}$$

where ρ is the fluid density and ΔV the volume change.

3. Numerical simulations

Three dimensional numerical simulations are carried out to investigate the flow distribution of a turbulent free jet under high pressure conditions. The geometry of the vertical high pressure autoclave is setup using the commercial software Pro/E. The commercial finite volume code CFX v11.0 (ANSYS) is employed for CFD calculations. The second order backward Euler scheme [9] is applied for time discretization of the differential equations. The discretization in space applies the high resolution scheme. Different computational meshes were implemented to determine a grid independent solution. The used mesh consists of 1291297 elements. The mesh is refined in the free jet region to resolve velocity gradients. To account for velocity and temperature gradients near the walls the grid is also refined near the walls. It is necessary to implement into CFX the pressure and temperature dependency of the thermophysical properties of water (e.g. density, viscosity, thermal conductivity, thermal capacity [10, 11]) by own developed FORTRAN codes. As the experiments show almost adiabatic conditions during the compression phase the walls of the autoclave are assumed to be adiabatic. The turbulence inside the vessel is modelled by the k-ε and SST model.

4. Results of experiments and numerical simulations

The time average of the vertical flow velocity during compression is measured by HP-LDA at various points along the steamwise and spanwise direction of the free jet at the inlet nozzle as shown in Figs. 4 and 5. Fig. 4 shows a slight decay of the vertical velocity during the compression phase especially in the second half of the compression. The velocity measurements were conducted at 2 mm above the tube corresponding to the normalized distance $z^* = z/d = 1.3$, where z is the distance between the tube and the measurement volume and d the tube diameter. The results shown in Fig. 5 cover a range of relative vertical distances from $z^* = z/d$ = 11.56 to 86.25. The relative flow velocity U** is plotted as a function of the relative radial distance R** for different values of relative downstream distances z*. The relative flow velocity U** is the ratio between the flow velocity to the velocity at the center of the tube directly at the tube exit. The relative radial distance R** is the normalized spanwise distance from the tube center calculated as ratio of the distance to the diameter of the tube. Fig. 5 shows that the flow velocity decreases significantly with increasing axial and radial distance and the width of the free jet grows with increasing axial distance. Finally, Fig. 6 shows that the turbulence intensity decreases with time during the compression process which supports previous results obtained by the same authors about the relaminarization phenomena occurring during fluid pressurization [3]. The results shown in Fig. 7 present results carried out using high pressure Hot-Wire-Anemometer (HP-HWA) showing the same tendency. The relaminarization phenomenon is still under investigation and study.

Fig. 8 and 9 shows a result of the numerical simulations for the velocity field of the turbulent free jet. As shown in Fig. 8 and 9 a free shear layer occurs when the pressurized fluid enters the chamber, the radius of the free jet increases linearly with its length, and the flow velocity in the center of the jet decreases with increasing downstream distance. Fig. 9 shows a comparison of the experimental and numerical results of the relative flow velocity as a function of the relative radial distance at a certain value of relative downstream distance (z* = 37.4 mm). The different agreement of the experiments and numerical simulations of the turbulent free jet with the two turbulence models SST and k-ε model is shown. At the center the flow velocity matches very well with the experimental data, but the deviation becomes larger with increasing radial distance for the k-ε model. The numerical simulation implementing the SST model is more suitable to solve the present free jet case. Nevertheless, the results of the k-ε model seem to fit better for heat transfer and transition phenomena.

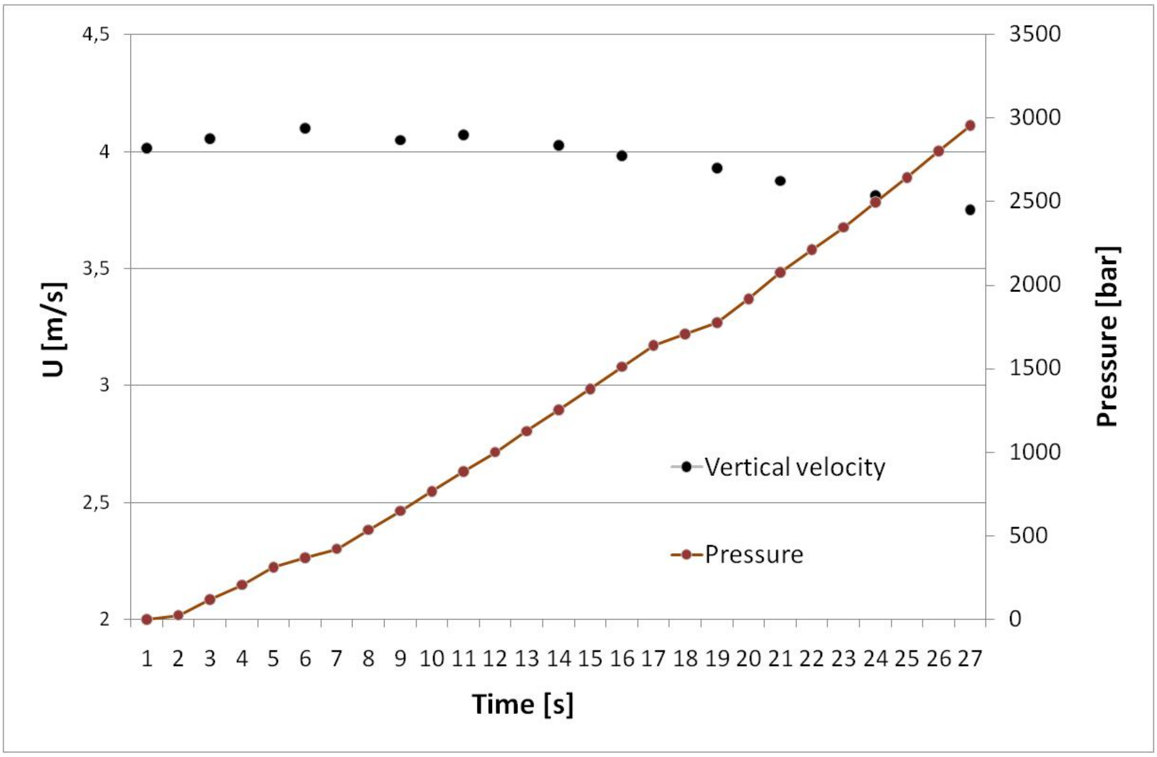


Fig. 4: Vertical velocity of the free jet

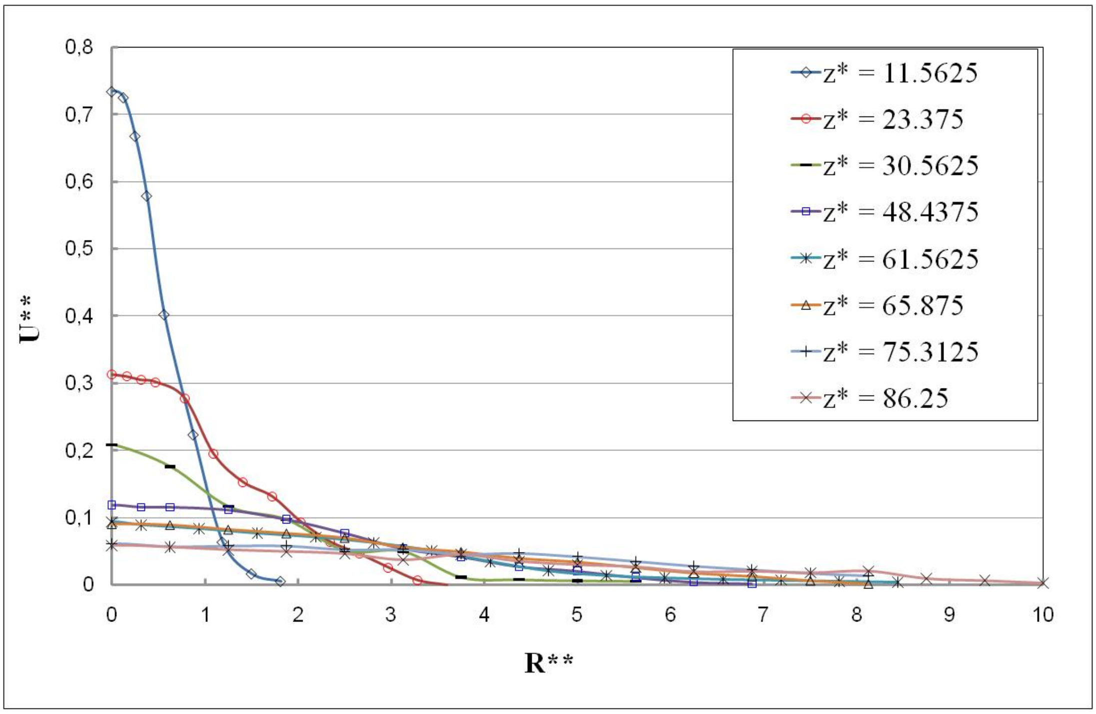


Fig. 5: Normalized axial velocity of the free jet

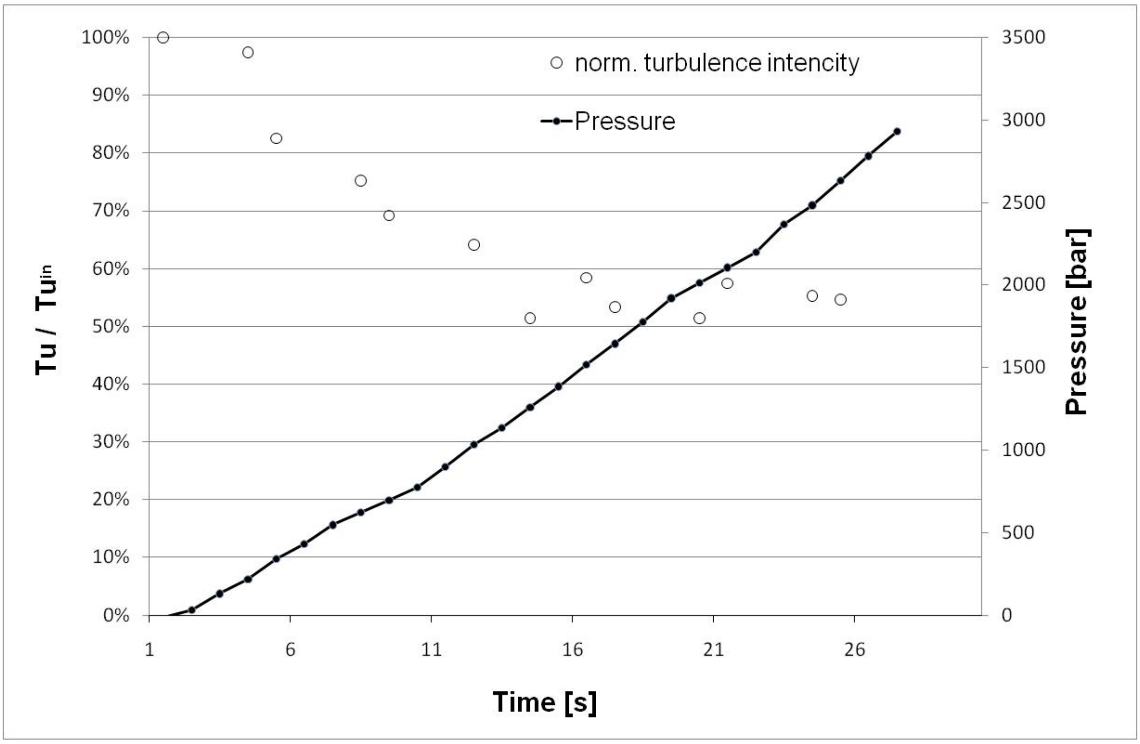


Fig. 6: The turbulence intensity of the fluid flow velocity

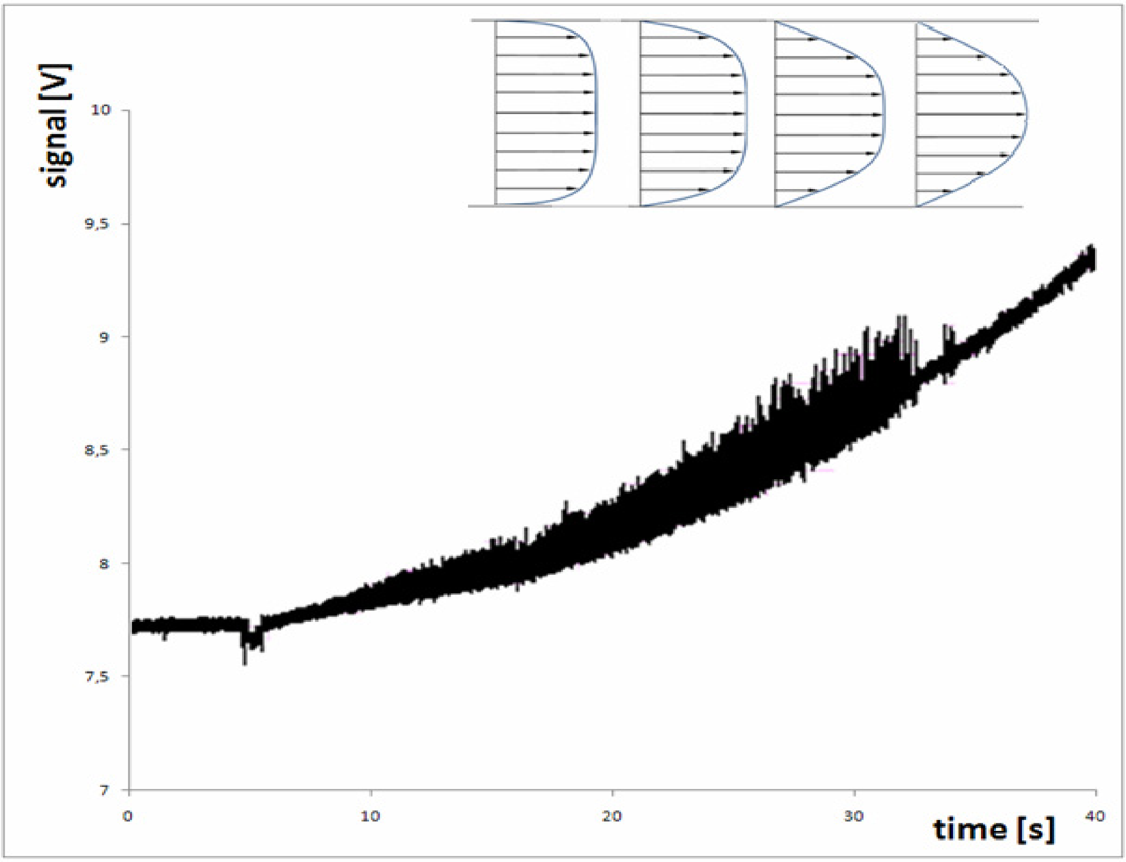


Fig. 7: Velocity fluctuation obtained by Hot-Wire- Anemometer

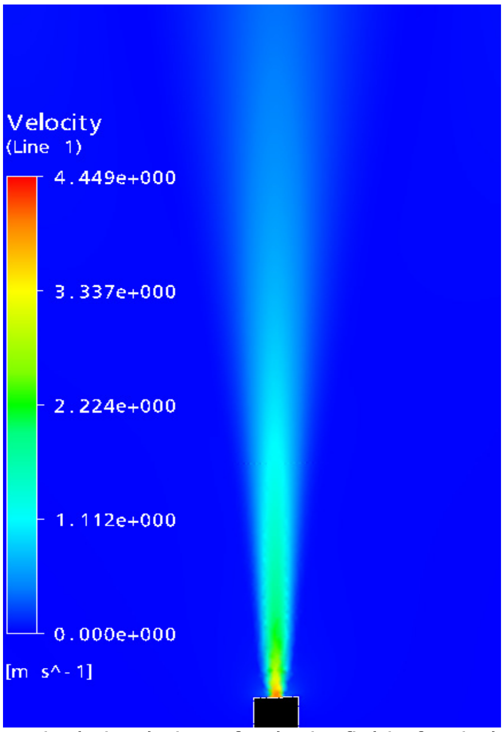


Fig. 8: Numerical simulation of velocity field of turbulent free jet

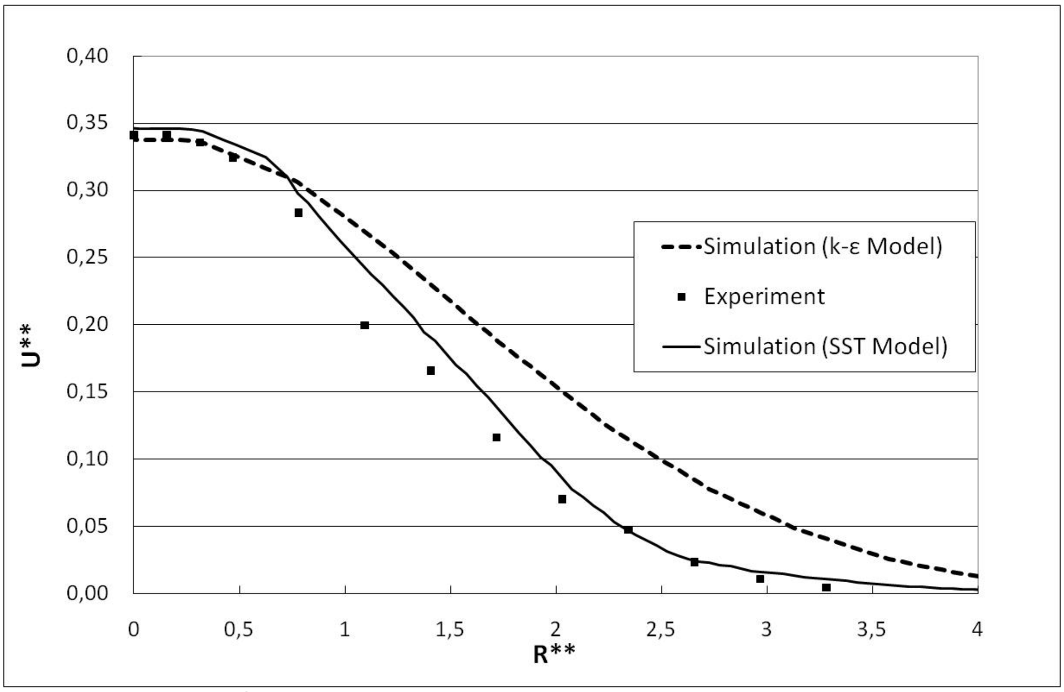


Fig. 9: Comparison between experimental and numerical results

5. Conclusions

The investigation of thermofluiddynamical phenomena under high pressure conditions is highly important to examinate effects only achievable with this innovative process. To be able to take advantage of HPP in research and industry the fundamentals of the unique phenomena have to be elucidated. One interesting phenomena is the behaviour of turbulence under high pressure conditions especially during pressurization. The present experimental investigations used HP-LDA as technique to measure the flow velocity and turbulence intensity at high pressures (up to 300 MPa). The found suppression of turbulence and relaminarization phenomena seem to be based on the decreasing compressibility and strong variations of molecular properties of the compressed fluid. This phenomenon is still under investigation and needs more studies. 3-D numerical simulations are carried out to investigate the flow field of the turbulent free jet under high pressure condition. Two turbulence models SST and k-ε model were compared in the numerical simulation of the turbulent free jet. A comparison between the results of the experiments and the numerical simulations shows a very good agreement between the numerical simulations (especially with SST model) and experimental data.

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