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EXPERIMENTAL IN-SITU INVESTIGATIONS ON TURBULENT FREE JETS UNDER HIGH PRESSURE BY MEANS OF LDA AND HWA

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LDA, HWA, high pressure, free jet
LDA, HDA, Hochdruck, Freistrahl

Abstract

In a tube injection system for High Pressure Processing (HPP) of biomaterials and foods, pressure transmitting medium is injected into the vessel to increase the pressure up to 1000 MPa generating a submerged liquid free jet. The presence of turbulence due to the free jet during the pressure build up phase and its positive influence on the homogeneity of the product treatment has already been examined by computational fluid dynamics investigations in literature. However, up to now no experimental data are reported, supporting the existence and properties of turbulence of a free jet under high pressure conditions due to difficulties in gaining in-situ insight into the high pressure vessel and the lack of high pressure withstanding probes. Thus, this contribution presents the development of two experimental setups: (1) HP-Laser Doppler Anemometry (HP-LDA), and (2) HP-Hot Wire Anemometry (HP-HWA). This paper shows first results of velocity profiles measured by LDA and HWA under high pressure conditions up to 300 MPa.

Introduction

High Pressure Processing (HPP) is a successful ongoing method investigated intensively during the last two decades in bio and chemical engineering where biomaterials are subjected to elevated pressures up to 1000 MPa to achieve microbial inactivation in foods or to generate unique structural properties, for example. HPP gains increasing importance in research and industry due to its unique effects on biomaterials in comparison to other processes. In order to understand and optimize HPP, thermofluiddynamic investigations are necessary, given that in any HPP of biomaterials, diffusive and convective mass, momentum and energy transport occurs and shows interactions. Delgado (2003) and Pehl et al. (2000) showed experimentally and theoretically that the pressure effect can be considered as instantaneous but not homogeneous in HPP due to local temperature inhomogeneities occurring during the pressurization phase and subsequent heat transfer effects. At the beginning of HPP, the flow is determined by forced convection caused by the injection of pressure transmitting medium into the vessel. This is followed by free convection which is dominating during the pressure holding phase as Pehl et al. (2000). found by experiments using HP-Digital Particle Image Velocimetry. For the first time Kitsubun et al. (2005) took turbulence into consideration using Large Eddy Simulation and showed that turbulent flow within the vessel may contribute to an improved homogeneity of the high pressure treatment. On the other hand, the possibility of measuring the characteristics of the liquid flow under high pressure conditions is highly desirable because the thermo physical properties of pressure transmitting mediums and biomaterials such as density, viscosity, heat conductivity (see Werner et al. 2008) and thermal capacity change drastically with increasing pressure leading to a strong modified character of the fluid flow. However, the comprehension of the high pressure effects in liquids is far away from that urgently required for making progress in this novel technology. The present contribution reports on development of experimental techniques to measure compressible turbulent liquid flows and, thus, investigates in-situ turbulent free jet and its structure at HP conditions up to several hundred MPa, which is missing in literature.

Material and Methods

Process conditions

In HPP in bio and chemical engineering there are two common types of pressure generation systems. One type is the cylinder piston system in which a piston moves to build up pressure by direct compression and the second type is a tube injection system in which a pressure transmitting fluid is issuing from an inlet nozzle into the vessel generating a free jet. In this paper the tube injection system is used for the experiments. The experimental setup consists of a high pressure vessel (Dustec, Germany) with a volume of 1.5 litres. It is constructed of stainless steel 1.4542 (X5CrNiCuNb16) and has three windows with an optical diameter (d_o) of 12 mm which allow for the measurement of the fluid velocity using LDA (Fig. 1). Synthetic sapphire (Al_2O_3) is used as window material. Additionally, a hot wire probe is implemented in the autoclave (Fig.4). The vessel is designed for a maximal operating pressure of 500 MPa in the temperature range from 273 to 373 K. Temperatures measured by three thermocouples at three different positions in the vessel as well as the pressure and the flow rate have been registered every second.

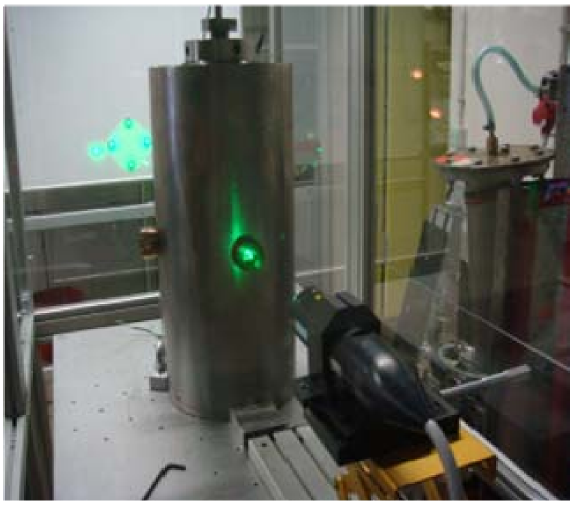

Fig. 1: Photograph of the experimental set-up consisting of HP vessel and LDA system.

The working pressure of 300 MPa is built up with five different pressure ramps (2.5 MPa, 4.8 MPa, 6.9 MPa, 9.3 MPa, 12.2 MPa) in order to generate different flow regimes in respect of the nozzle exit velocity and the Reynolds number (see Fig. 2, Tab. 1). Since the pressure ramps for the first 9 s are identical (6.7 MPa/s) at all pressure ramps due to technical reasons the results are taken into consideration after this point.

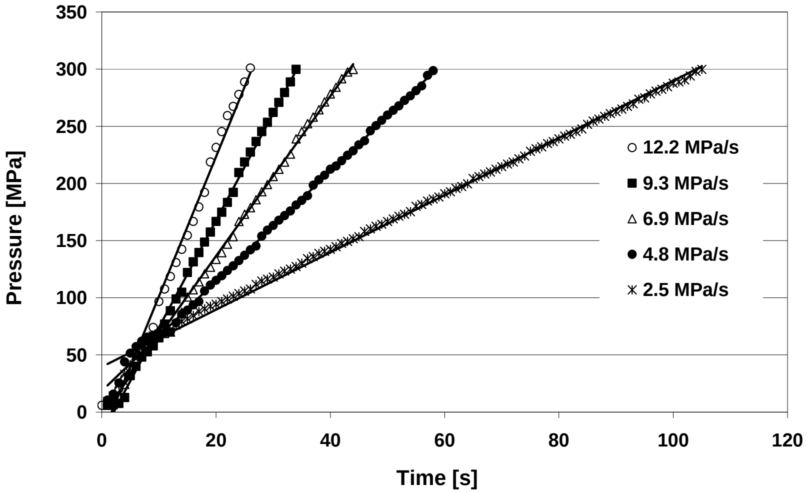

Fig. 2: Different pressure ramps applied in the present experiments. The value of pressure in MPa is recorded every second.

The flow rates and Reynolds numbers corresponding to pressure ramps are listed in Tab.1. The Reynolds number of the jet, based on the tube diameter of 1.6 mm, the kinematic viscosity of water at atmospheric conditions ($\nu = 1.00338$ x·10^{-6} m^2/s) and the tube exit velocity varied between 1388 and 5373. The exit velocity is calculated out of the flow rate in the tube operated by the pressure intensifier used to inject the water into the vessel.

Tab. 1: Reynolds number of the experiments with different pressure ramps.

Pressure ramp [MPa/s]	12.2	9.3	6.9	4.8	2.5
Flow rate [m^3/s]	6.77×10^{-6}	5.25×10^{-6}	4.38×10^{-6}	3.23×10^{-6}	1.75×10^{-6}
Reynolds number	5373	4164	3470	2562	1388

Laser Doppler Anemometry

LDA is a non-invasive optical technique to measure flow velocities. The arrangement of the experimental set-up is shown schematically in Fig. 3. The main parts of this set-up are the HP vessel and the measuring instruments. The measuring instruments are the laser optic and the processor used for data acquisition and data evaluation. Nd:YAG 2-component fibre optic LDA system (Dantec, Denmark) with a wavelength of 523.5 and 532 nm is used in back scattered mode for the measurement of vertical (v_x) and horizontal (v_r) velocity components, respectively. Hereby, a laser beam split into two focussing beams defines the ellipsoidal measurement volume (0.12 mm x 0.12 mm x 2.55 mm). A seeding particle (Nylon, Ø 4 µm) passing through the fringes of the measurement volume produces the Doppler burst. A photo multiplier converts the scattered light into an electrical signal which is analysed by a Burst Spectrum Analyser. Parameters of the LDA system are summarized in Tab. 2.

Tab. 2: Optical parameters of LDA system.

Wavelength	523.5 / 532 nm	Half angle of beams	2.71°
Fringe distance	5.517 / 5.606 µm	Measurement volume, length	2.55 mm
Focal length	400 mm	Measurement volume, height, width	0.12 mm

Tubes with variable length can be assembled at the inflow nozzle to enable measurements at different vertical distance from the flow exit in the range from 2 to 150 mm as shown in Fig. 3. Distilled and degased water is used both as a pressure transmitting medium and as a probe material.

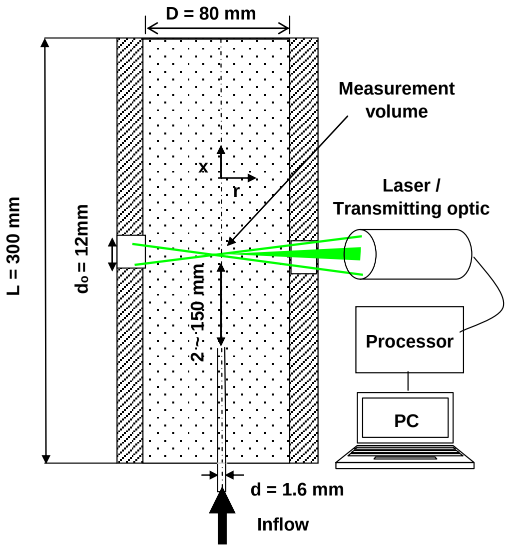

Fig. 3: Schematic arrangement of the experimental characterization of the free jet flow in a tube injection system by LDA.

Hot Wire Anemometry

HWA is a commonly applied technique for determination of fluid velocity. Thanks to its high frequency response and sensitivity, the hot wire probe can capture turbulent velocity fluctuations. The electrically heated thin wire is cooled by the flowing fluid through free and forced convection. In order to keep the wire temperature constant the electrical resistance has also to be held constant for which the adjustable electrical current source is required. Out of the resulting voltage the velocity of the flow is determined. The hot wire probe is mounted at a frame placed in the vessel as shown in Fig. 4. The probe position can be adjusted vertically as well as horizontally. Thanks to the sophisticated construction of the experimental setup, the measurement points can be mainly located near the pipe centerline. Standard Dantec 55P11 probe with a diameter of 5 µm is applied here. In the experiment shown in this contribution, glycerine is used as a pressure transmitting fluid and a probe material due to its low electric conductivity.

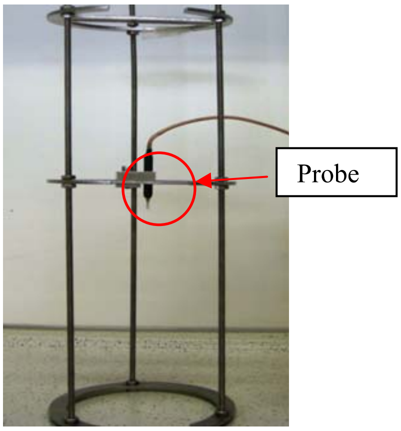

Fig. 4: Hot wire probe mounted at a frame which is placed in the vessel.

Results and Discussions

The axial velocity of the flow during compression was measured using HP-LDA at various points along the x-axis of the jet (see Fig. 3) for a range of relative downstream distances from x/d = 1.3 to x/d = 42.5, where x is the distance between the tube and the measurement volume and d is the tube diameter of 1.6 mm. These measurements were repeated for several values of the Reynolds number of the jet. In order to determine the axial time averaged velocity, the LDA data were gathered every three seconds for one second during the whole compression phase.

The development of the axial mean velocity of the jet for Reynolds numbers of 5373, 4164, 3470, 2562 and 1388 is given in Fig. 5 which indicates significantly the decay with time of the axial velocity during the compression phase at all Reynolds numbers.

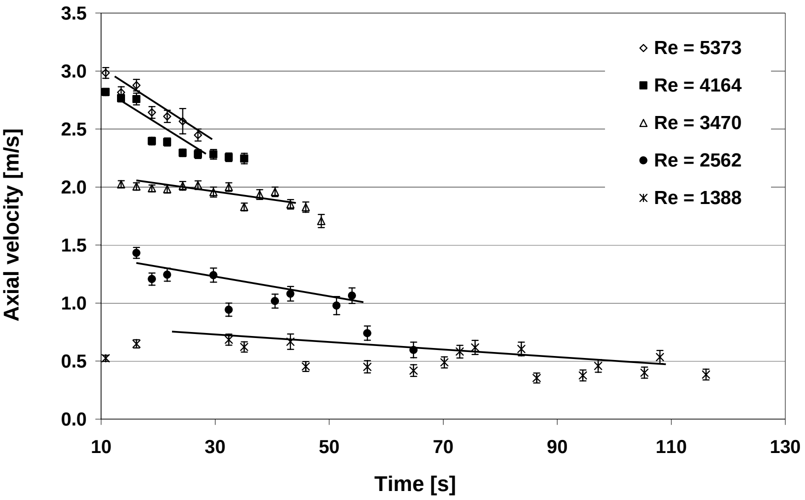

Fig. 5: Development of axial mean velocity along the centerline during compression at different Reynolds numbers. The velocity measurements were conducted at the jet exit 2 mm above the tube corresponding to the normalized distance x/d = 1.3.

At the beginning of the compression phase the velocity has the highest value and decreases with time. Since the compressibility of water declines with increasing pressure the flow rate into the vessel decreases at constant pressure ramps. Additionally, the significant qualitative and quantitative dependency of the axial velocity on the Reynolds number is clearly observable. The slope of the velocity in terms of time grows with increasing Reynolds number. This may be explained also by considering the compressibility which decreases faster in higher Reynolds number due to the faster pressure building of 300 MPa.

Fig. 6 shows the normalized axial mean velocity versus time for different normalized axial distances. The velocity decreases with increasing axial distance during the whole compression phase. However, the decrease of velocity in region close to the nozzle is more pronounced than larger distances from the nozzle.

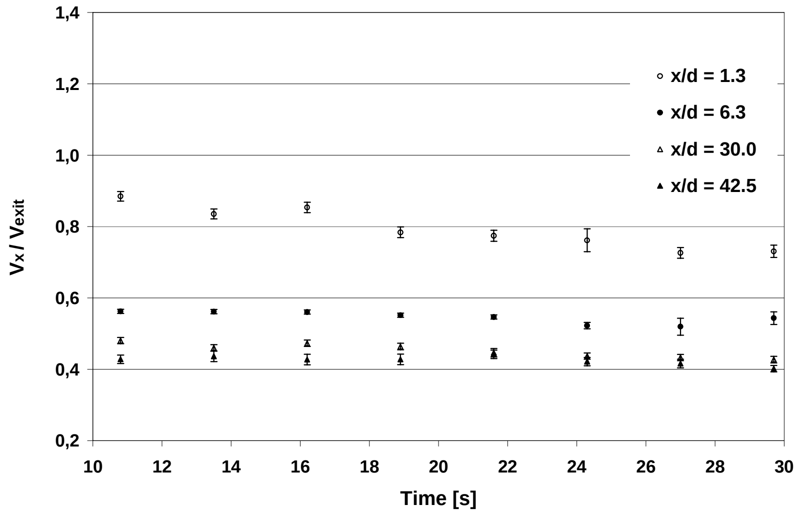

Fig. 6: Development of the normalized axial mean velocity by the tube exit velocity (V_{exit}) of the jet for different nondimensional downstream distances x/d (d: tube diameter) at Reynolds number of 5373.

Fig. 7 presents results of the measurements by means of HP-HWA. The diagram confirms a typical fluctuating voltage signal of HWA with respect to time during a HPP. This indicates for the first time the capability of the HWA technique to measure velocities under HP up to 300 MPa. In several repeated experiments, we observed that hot wire probes and holders could withstand high pressures and the signals were repeatable.

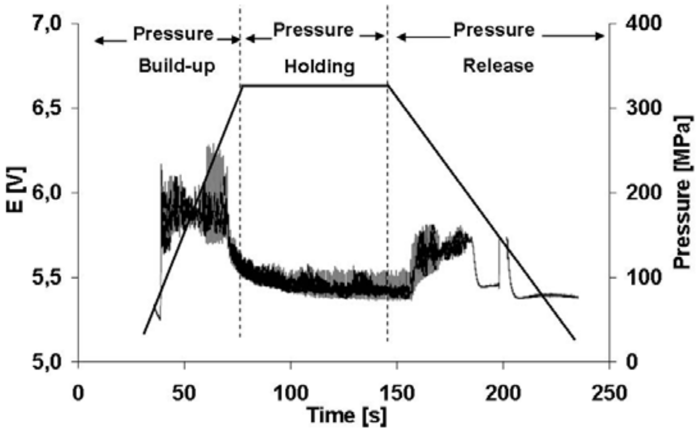

Fig. 7: Typical hot wire traces recorded along the centerline of the vessel.

Conclusions

This contribution presents the development of experimental techniques suitable for in-situ optical measurement of turbulent flow fields under high pressure up to 300 MPa. The appearance of a free jet during HPP can be shown, suggesting the potential of HP-LDA and HP-HWA as a viable technique for measuring fluid velocity under high pressure. Disturbances of the position of the measurement volume due to refractive index fluctuations of water caused by density increase during compressing may bias the value of velocity fluctuations. However, the bias is considered to be very small and does not affect seriously the results. The HP-HWA is performed for the first time under high pressures up to 300 MPa and shows the applicability of this technique for turbulence measurements. In further studies the measurement techniques will be refined and turbulence in liquids under HP conditions will be investigated in more detail.

Acknowledgement

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