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RELAMINARIZATION VON TURBULENTEN ROHRSTRÖMUNG DURCH HOCHDRUCK

REVERSE TRANSITION OF TURBULENT PIPE FLOW BY HIGH PRESSURE

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High pressure, relaminarization, LDA, hot-wire anemometer

Abstract

A majority of engineering flow is turbulent and the presence of velocity fluctuations enhances the rate of mass, momentum, and energy transfer in the fluid. Moreover, Kitsubun et al. [1] showed numerically, turbulence may enhance the process homogeneity in the High Pressure Processing (HPP). There are, however, few experimental data concerning turbulence in the liquid flow under pressure up to 400 MPa so far. In the present paper quantitative and qualitative measurements of turbulence behavior under rapid pressure variation are reported employing a laser Doppler anemometer and a hot-wire anemometer operated in constant temperature and constant current modes. Reverse transition from turbulent towards laminar flow was studied by progressively increasing the pressure up to 400 MPa in a fully developed pipe flow operated with silicon oil as working fluid [2,3]. It is shown that rapid increase in pressure modifies the turbulence dynamics owing to an increase in dynamic viscosity and density of fluid at high pressure.

1. Introduction

Pressure in the range of several hundred MPa offers unique possibilities on different fields of industry and research. Applications can be found in polymer production, hydraulic systems, fuel injection in engines and life sciences. High Pressure Processing (HPP) is a successful ongoing method investigated intensively during the last two decades in bio-chemical and food engineering where biomaterials are subjected to elevated pressures up to 1000 MPa to achieve microbial inactivation in foods or to generate unique micro-structural properties of pressure-sensitive compounds, for example. As a thermodynamic parameter, hydrostatic pressure was known for many years to act on biological materials in a similar but not identical way as temperature. That results in high demand for experimental data as well as theoretical background of various phenomena occurring in the fluids under elevated pressure. Most notably, thermofluiddynamic investigations are inevitable in order to understand and optimize HPP given that in any HPP of biomaterials, diffusive and convective transport of mass, momentum and energy occurs and show interactions. Up-to-date research shows that HPP can be considered as instantaneous but not homogeneous due to local temperature inhomogeneities occurring during the pressure build-up phase and subsequent heat transfer phenomena [4]. On the other hand, possibility of measuring the characteristics of liquid flow under high pressure conditions is highly desirable because thermo physical properties of pressure transmitting mediums and biomaterials such as density, viscosity, heat conductivity and thermal capacity change drastically with increasing pressure leading to a strong modified character of the fluid flow [5, 6]. However, the difficulties in the construction of experimental set-up for turbulent flows has caused problems in understanding high pressure effects in liquid which is urgently required for making progress in this novel technology. Particularly, the flow regime, whether laminar or turbulent, is important in the design and operation of any fluid system. Amount of fluid friction, which affects the amount of energy required to maintain preferred flow, depends upon the state of flow. This is also an important consideration in certain applications that involve heat transfer to the fluid. Thus pioneering experimental techniques which enable to investigate turbulent liquid flows at high pressure conditions up to several hundred MPa are expected to advance and to predict turbulence development under high pressure relevant for engineering applications.

2. Experimental Investigations

There are usually two types of pressure generation systems in HPP systems of biological, chemical and food engineering. One type is the cylinder piston system where a piston moves up and down to build up and to release pressure by direct compression. The second type is a tube injection system in which a pressure transmitting fluid is issued from an inlet nozzle into the vessel generating a free jet. In present work the latter system is used for experiments. Therefore, to perform detailed investigations of effects provoked by sudden pressure variation in a fully developed turbulent pipe flow a special set-up is designed and built. Its major components are shown in fig. 1. It consists of (a) high pressure hydraulic pump, container with pressure transmitting medium under investigation, (b) hydraulic pressure intensifier, produced by DUSTEC Hochdrucktechnik GmbH, for increasing the working pressure 14 times of that produced by the pump and (c) a high pressure vessel capable to withstand pressures up to 500 MPa at working temperatures between 273 and 373 K. Maximum pressure reached by the hydraulic pump is 50 MPa. Therefore, the pressure intensifier is required to reach the demanded value. This is realized by a simple hydraulic mechanism: The driving pump pushes the large area of the piston whereas the smaller surface of piston compresses the working fluid in the pressure chamber. All pieces of equipment are connected with piping, fittings and valves manufactured by SITEC-Sieber Engineering AG. Following additional experimental data are gathered on another PC unit:

- Mean temperature in the pressure vessel (T)
- Pressure after the compressing piston (p_1)
- Pressure in the pressure chamber (p_2)
- Relative stroke of the compressing piston (s)

Temperature of the working fluid is measured with three thermocouples located at different positions in the vessel. Pressure measurements are carried out with transducers manufactured by EBM Brosa GmbH & Co. KG which are located close to the vessel entrance.

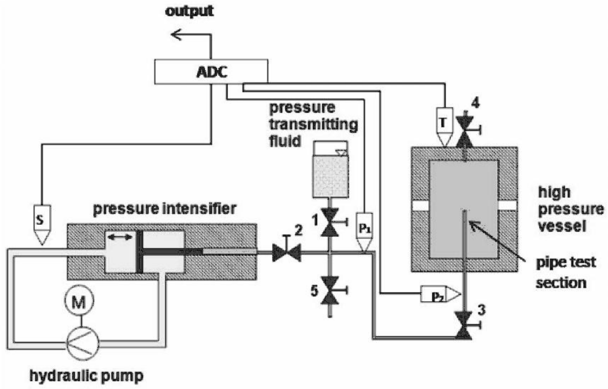

Fig. 1 Experimental set-up for investigation of fluid flow during rapid pressurization up to 500 MPa

During pressurization process it is assumed that a fully developed flow is established in the pipe and is maintained by computer controlled regulation system in such way to produce desired increase in pressure without any disturbances produced by the regulation system itself. The system operates in the following manner: Before series of experiments, the fluid is sucked into the pressure intensifier via valve 1 from the container. Then valve 1 is closed. The pressure vessel is filled independently from the top and valve 4 is later used for de-aeration. After filling of the vessel, valves 2 and 3 are opened and the pressurization takes place. Valve 5 is used to completely empty the system.
The high pressure vessel with maximal working pressure of 500 MPa is specially designed for in-situ optical investigation and manufactured by DUSTEC Hochdrucktechnik GmbH, see fig. 2. The pressure vessel consists of two layers. The inner layer is made up of alloy steel 1.4542 and the outer layer of alloy steel 1.6580 (Remystahl, Germany) according to DIN 668, solution annealed and aged. Allowable stress is assumed to be not higher than the yield stress with a 1.8 safety factor. Reduced stress is considered according to the Huber–von Mises criterion. Internally the vessel has cylindrical form with 0.080 m diameter and 0.30 m usable length providing the effective volume of 1.5 liter. Fig. 2 shows the outlook with construction of a large screw which closes the vessel entrance and the assembly of three round windows with an optical diameter of 0.012 m which allow optical access for the application of High Pressure- laser-Doppler Anemometry (HP-LDA).

Fig. 2 Photograph (left) and technical drawing (right) of high pressure vessel with optical windows

Synthetic sapphire (Al_2O_3) is used as window material. The sapphire window is a cylinder with 15 mm thickness and 24 mm diameter mounted as a Poulter type on a hole with 12 mm in diameter. The c axis of the sapphire crystals is parallel to the axis of the cylinder. The transmission range of such a window extends to 0.25 μm in the UV and to about 4 μm in the IR. A description of these windows has been given by Paul et al. [7]. The opposite two windows are used for laser beams to pass through the pressure chamber and the other one is for observation with CCD camera. All windows are sealed with two synthetic gaskets (PU, UHMW-PTFE, no 6 and 5 in fig. 2, respectively) and a metal ring (CuBe2v, no.4) as shown in fig. 2. Plug screw (no.3) fixes the window from outside and allows high pressure treatment up to 500 MPa. One of the windows can be removed in order to install the plug which connects internal cable with external power supply of High Pressure- Hotwire Anemometry (HP-HWA). Top lid closes the chamber and carries three thermocouples capable of measuring temperature at different position in the vessel and a de-aeration valve (no.1).
Deionized water is used both as a pressure transmitting medium and as a probe material for HP-LDA whereas glycerol and hexamethyldisiloxane (HMD) are used due to low electrical conductivity for HP-HWA. Change of dynamic viscosity and density due to pressurization are experimentally determined in order to find conditions which alter the characteristic of flow such as Reynolds number. The rolling-ball viscosimeter is used to find the change of viscosity of the fluid. Also, the determination of the fluid's compressibility with the pressure and

temperature variation has been carried out. This is carried out by the manually operated compressing device. Fig. 3 shows dynamic viscosity of HMD and water at various pressures and temperature. It is assumed that both media behave as Newtonian because experiments are carried out up to a certain distance from the phase boundary.

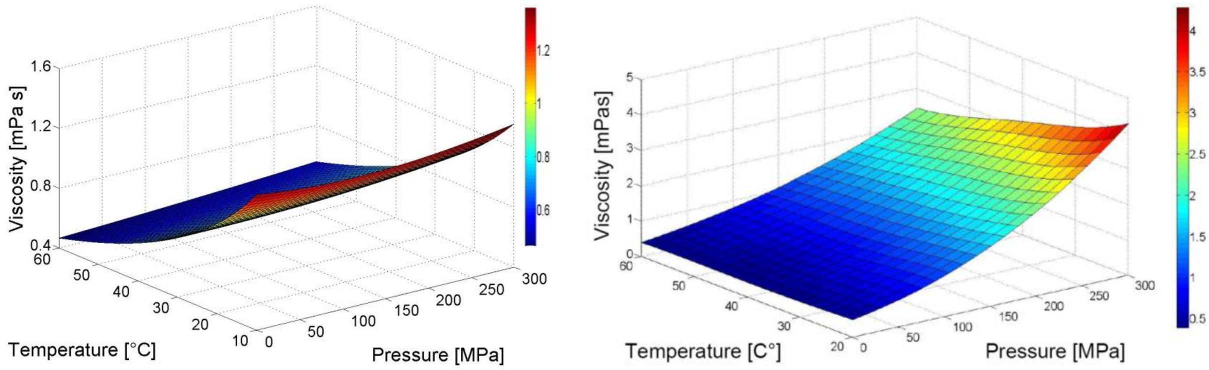

Fig. 3 *P-T* diagram of dynamic viscosity of water (left) and of HMD (right)

Fig. 4 presents density of HMD and water in terms of pressure and temperature.

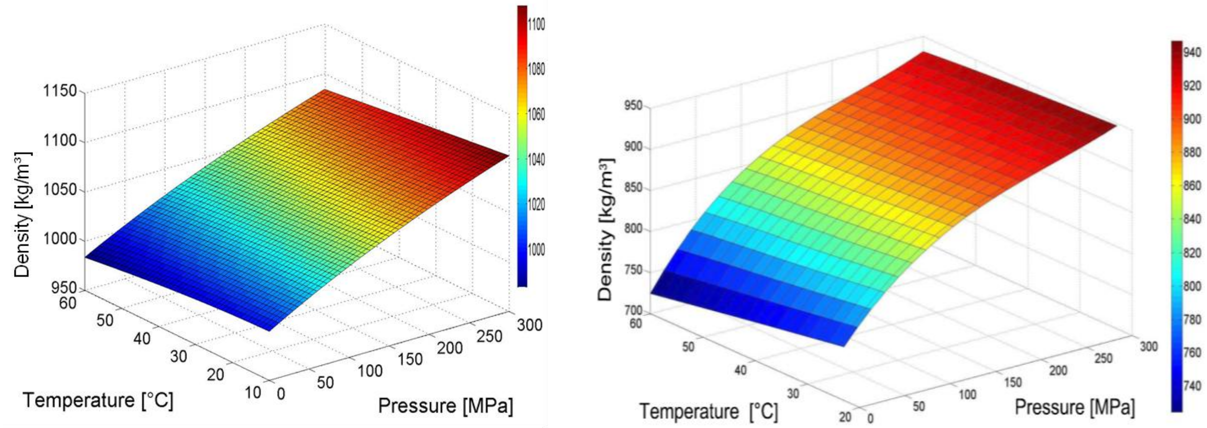

Fig. 4 *P-T* diagram of density of water (left) and of HMD (right)

LDA measurement system applied in this work is a one-component backscattered LDA. Transmitting and receiving optics are integrated together in one probe. A laser with a wavelength of 488 nm is used as a light source to measure the flow velocities perpendicular to the probe beam direction. Whole system is made by Dantec Dynamics A/S with a commercial model FlowLite 1D. Overall set-up of the HP-LDA system is illustrated in fig. 5. Two laser beams with equal light intensity are generated from a single laser by a half silvered mirror (beam splitter). One laser beam passes through a Bragg cell to get a frequency shift of 40 MHz, while the other one has the incident light frequency. Both incident beams are focused at one point by a lens. Interference of the two beams creates a set of equally spaced fringes which are parallel to the bisector of the beams. The region where the beams intersect, defines the measurement volume. Signal processor (BSA, Dantec) is used to determine frequency of the signal and then calculate the measured velocity.

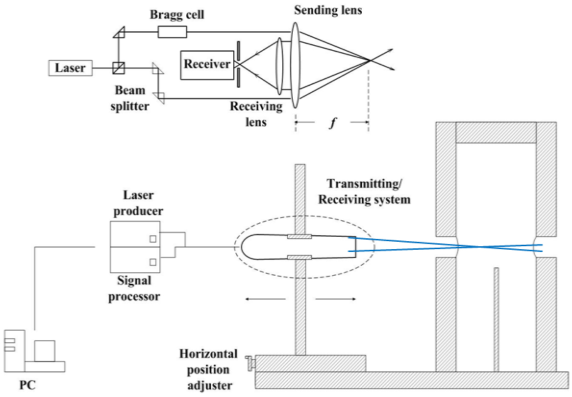

Fig. 5 Experimental set-up for HP-LDA

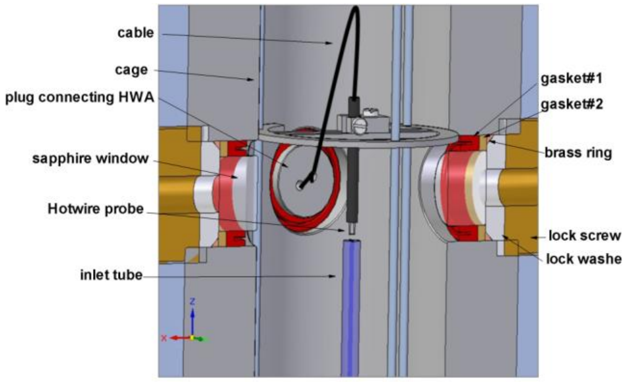

Fig. 6 Layout of the hot-wire probe at the exit of pipe

After successful preliminary experiments suggesting the potential of HP-HWA as a viable technique for measuring fluid velocity under high pressure conditions, the measurement techniques are refined for 1.5 liter pressure chamber. By varying the pressure ramps and by measuring the volume flow rate, pressure and temperature during pressurization well-defined conditions were ensured to study effects caused by rapid pressure increase on shear flow turbulence at very low Mach numbers. Probe consists of stainless steel prongs which are separated 1 mm apart. Tungsten wire 5µm in diameter is suspended between two prongs to which they are welded. The hot-wire probe is mounted at a frame placed in the vessel and thanks to the sophisticated construction its position can be adjusted vertically as well as horizontally as shown in fig. 6. The hot-wire probe is installed at the pipe centerline and very close to its exit $z/d \approx 1$ so that the measured results reflect all essential features of a fully developed state inside the pipe. No attempts are made during present investigations to calibrate hot-wire probes or to account for the effect of spatial integration of measured signals over the hot-wire length since the prime interest was to detect qualitative features of turbulence development.

3. Experimental Results

The results presented in this work consist of two parts. The first part is the results of HP-LDA used to investigate the fluid free jet. The axial velocities of free jet during pressure building phase are measured using HP-LDA at different position in the fully developed jet region. Measured results are analyzed and the basic relations of flow properties are obtained. Results are compared with previous measurements, thus a better understanding of turbulent free jet under high-pressure is achieved. The second part of this chapter concerns the results of HP-HWA used to investigate flow in the wall bounded pipe using glycerol and HMD as working material. In this part, the results of velocity and temperature fluctuations and turbulence-laminar reverse transition of pipe flow due to the rapid pressure ramp are presented.

During compression fluid motion in the vessel is dominated by forced convection due to free jet of the fluid pumped into the vessel by pressure intensifier. Dimensionless axial mean velocity at the center of the tube versus process time is plotted in fig. 7. The non-dimensional axial velocity U^+ reaches the highest value at 4 s after pressurization and immediately decreases very slightly with increasing process time and pressure at all vertical distances z^*. The decay of velocity with time can be explained as following. When fluid emerges from nozzle into the large stagnant mass of same fluid, a free jet is generated immediately, so velocity reaches its peak value in a very short time. As the time further increases, compressibility of water declines with increasing pressure, thus the flow rate into the chamber decreases at constant pressure build-up rate.

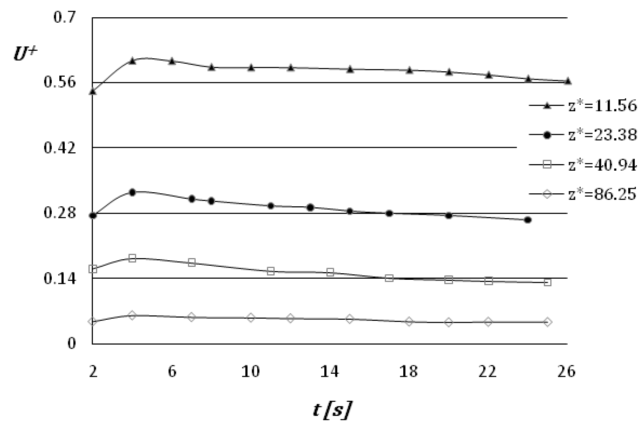

Fig. 7 Development of the non-dimensional axial mean velocity U^+ at centerline (r = 0) for different normalized downstream distances z^*, $U^+=U/U_0$, $z^* = z/d$ (U_0 = 4.2 m/s, d =1.6 mm)

Fig. 8 shows the radial distributions of dimensionless mean axial velocities of the turbulent jet at different Reynolds numbers and pressures. The velocity is normalized by the inlet velocity U_0 where U_0, 3.6, 3.9, at p = 300, 200 MPa, respectively. The radial distance r and axial distance z are scaled by the diameter of the tube (d = 1.6 mm).

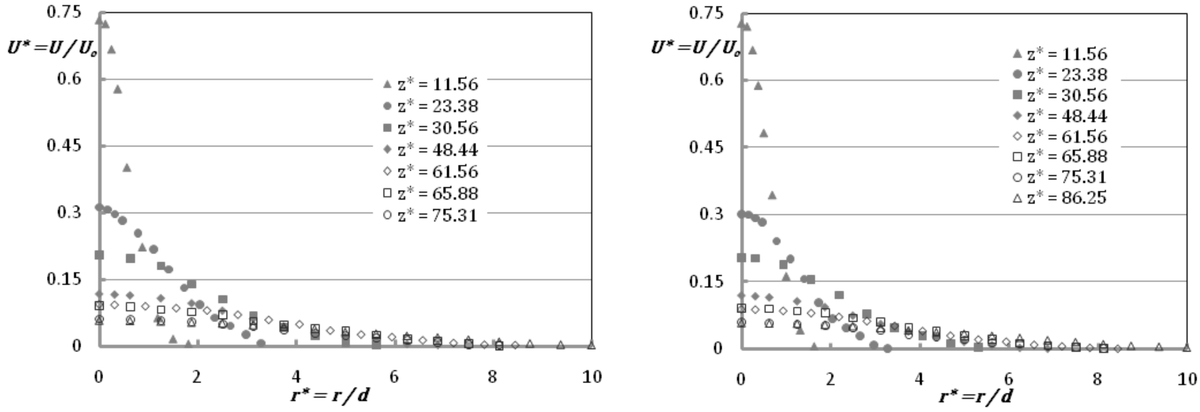

Fig. 8 Radial profile of mean axial velocity in the fully developed flow region at Reynolds number 6800 (left) and 7400 (right), left, p = 300 MPa, right, p = 200 MPa

As clearly shown in the fig. 8, the axial mean velocity decreases continuously from a maximum value to a zero value at various radial distances r^* from the axis. This distance where the velocity tends to be zero defines half width of the free jet $B_{1/2}$. It is obvious that $B_{1/2}$ increases steadily as the fluid is issued away from the nozzle and the maximum axial velocity decays with increasing downstream distance z^*. Additionally, due to difference in temperature and density between entering and surrounding fluid, buoyancy can take place. Therefore, penetration length of the jet does not only depend on Reynolds number of the flow and its momentum, but also on the buoyancy forces acting upon the jet. It can be observed that the free jet cannot reach top of the vessel even at high Reynolds number of 7400 what may lead to poor mixing effect during the HPP. Generally it is assumed that the free jet flow becomes instable at Reynolds number as small as 33 [8]. Thus the presented free jet flow can be considered as fully turbulent. Moreover, observation across the jet reveals that the velocity profiles at different pressure level have a similar shape. In order to prove its similarity, the mean axial velocity normalized by the centerline velocity $U(r,z)/U_c(0,z)$ is plotted in fig. 9 in terms of non-dimensional radial coordinate $\zeta = r/r_{1/2}$, where $r_{1/2}$ is the distance at which the velocity drops to half of its maximum value.

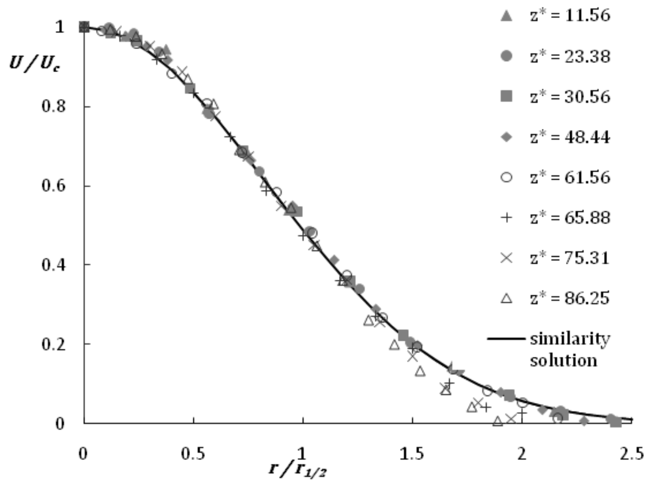

Fig. 9 Similarity solution: U/U_c vs. $r/r_{1/2}$ for different distances from the nozzle z^* at Reynolds number 7400 (p = 200 MPa)

Results of first exploratory measurements using glycerol as the working fluid are displayed in fig. 10 (left). These measurements correspond to laminar flow at very low Reynolds number, Re < 10 due to a viscosity of glycerol. Such low values of Reynolds number are not only of crucial interest for getting a better understanding of laminar and transitional flows but also for estimating the effect of high pressure on highly viscous fluids. Measured signals show that shortly after initial pressurization the control system requires about 20 s in order to force the pumping system to produce a monotonic increase in pressure so that only physical effects originating in the flow can be clearly distinguished in the hot-wire signals from other disturbances. The hot-wire signal reveal that during the period of monotonic increase in pressure 20 s < t < 60 s, the amplitude is almost constant without any noticeable evidence of turbulence, indicating qualitatively that stable laminar flow is maintained during pressurization. By repeating experiments many times, it is found that hot-wire probes can withstand high-pressure ramps during the pressure build-up, pressure holding and pressure release phases. No damage to the probes occurred during repeated tests carried out at pressures up to 400 MPa. This suggests that hot-wire anemometry can be safely employed for flow investigations at very high pressures.

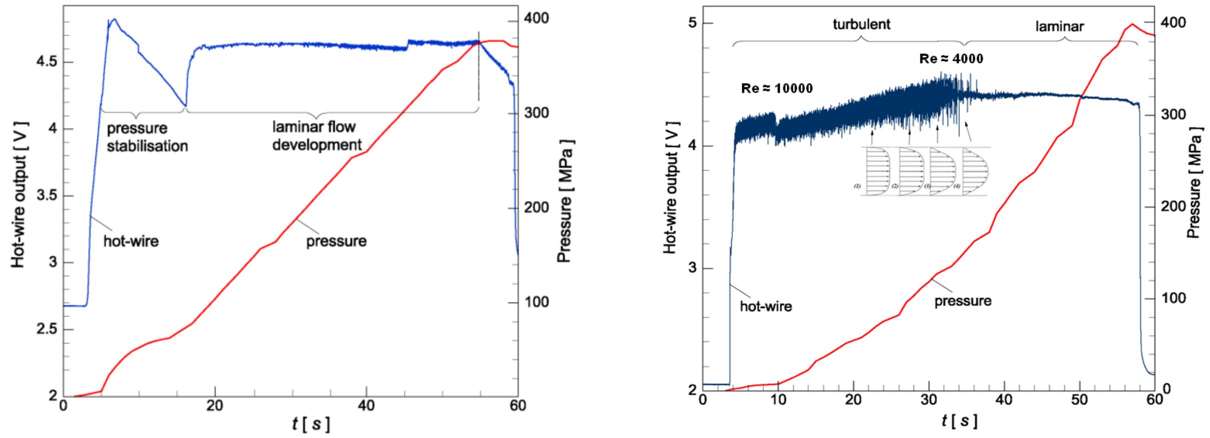

Fig. 10 Trace of hot-wire recorded close to the pipe exit and the pressure signal measured during rapid pressurization of the vessel using glycerol (left) and HMD (right) as the working fluid

Fig 10 (right) shows traces obtained from the hot-wire probe and the pressure transducer during rapid pressurization using silicone oil as the working fluid. In recorded signal, it is possible to distinguish periods of turbulent and laminar flow states during the pressure build-up phase. Owing to low viscosity of the oil during pressure build-up phase, initially fully developed turbulent flow is established with a Reynolds number of Re ≃ 1 × 10^4. Fig. 10 (right) suggests that suppression of turbulence leading to flow relaminarization occurs at t ≈ 35 s, corresponding to a pressure of 150 MPa at a Reynolds number of Re ≈ 4×10^3, higher than the $(Re)_{crit}$ ≃ 2320 which is commonly reported in the literature for highly disturbed inlet conditions as in the present experiments. These results demonstrate that high pressure ramps are capable of producing complete relaminarization of a fully developed turbulent pipe flow. Increase in dynamic viscosity and compressibility effect i.e. the reduction of velocity with increasing pressure are the major factor which determines this turbulence-laminar reverse transition. During the turbulent regime in the beginning of compression the flow is highly irregular and characterized by fluctuations which enhance the transfer of mass, heat, and species. The flow velocity profile is fairly flat across the center section of a pipe and drops rapidly extremely close to the walls thus the average flow velocity is approximately equal to the velocity at the center of the pipe. Between turbulent and laminar regime is the transition zone which can be described in terms of an intermittent flow exhibiting alternatively turbulent and laminar behaviors. On the contrary, in the laminar regime the fluid motion is highly ordered and fluid pathlines can be identified. The flow velocity profile for laminar flow in the pipe is parabolic in shape and the width of mixing region might be reduced. Moreover, in laminar fully developed flow, the Nusselt number is constant for constant wall heat flux and constant wall temperature. In the case of HPP for example, in HP-sterilization of bio materials, where more homogeneous temperature or concentration field is preferred, maintenance of turbulent regime plays a crucial role.

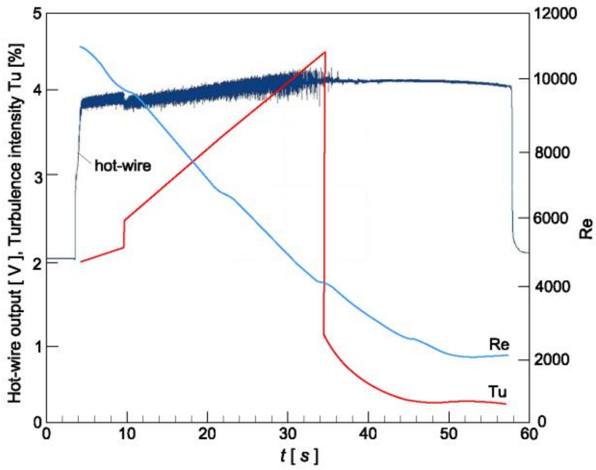

Fig. 11 Variations of estimates of the turbulence intensity (Tu) and Reynolds number (Re) during rapid compression of HMD leading to flow relaminarization

To provide a more qualitative indicator of transition the statistical features are extracted from hot-wire measurements. Turbulence intensity (Tu) is computed by moving averaging of 100 experimental values. Mean voltage $\bar{V}$ for the first point is calculated from first to 100th values and for the next point from second to 101st values. Fig. 11 shows estimates of the relative turbulence intensity and the bulk Reynolds number during the process of reverse transition. The turbulence intensity increases due to the intermittency with decreasing Reynolds number till the flow becomes fully laminar. These trends in hot-wire readings can be explained by alternating the instantaneous flow between fully turbulent and laminar states. Breakdown of the turbulence is illustrated by the rapid drop of turbulence intensity at Reynolds number Re ≈ 4000 which is much higher than of Fischer under ambient pressure [9].

Employing the constant-current mode, low heating currents, *i* = 3~5 mA (for which self-heating of the wire can be neglected), and high signal amplification, between 2500 and 3000 times, an attempt is made to complement the results presented above with measurements of the temperature variations during the relaminarization process. From the measured voltage across the wire, current, gain and temperature coefficient of sensor resistance, it is possible to deduce an increase in the bulk temperature of ΔT ≈ 30 °C in the vessel due to rapid compression of the liquid. Development of temperature fluctuations induced by rapid compression is displayed in fig. 12. These results show a similar trend to the measurements presented in fig. 10 (right) and 11. Initially the temperature fluctuations increase gradually and show a peak value with the appearance of intermittency just prior to reversion to the laminar state. Conditions at the reversion point deduced from hot-wire data and from temperature measurements are almost identical, implying that the scalar field closely follows the velocity field, as can be expected from the Reynolds analogy.

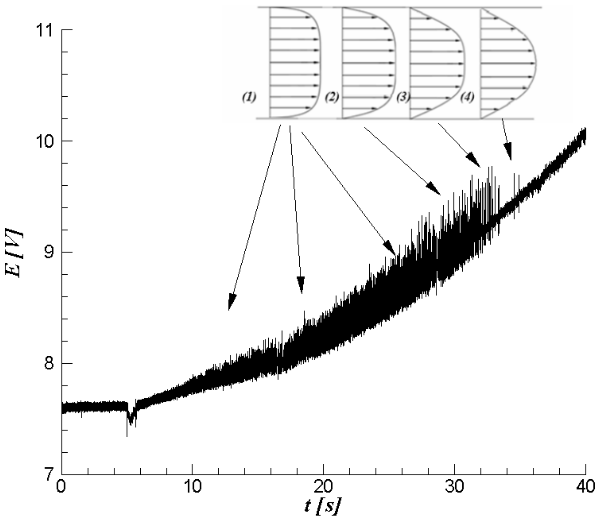

Fig. 12 Output of the wire showing the variation of temperature rapid compression leading to relaminarization. Initially fully turbulent flow (1), breaks down (2, 3) to completely laminar state (4)

Velocity profile in the fig. 12 shows evolution of the pipe flow. The velocity profiles show only stream-wise velocity component. Initially fully turbulent flow starts to be damped by increasing viscous forces which grow due to the pressure ramp. When viscous forces prevail over fluid's inertia, the turbulence breaks down. The flow becomes laminar, thus only stream-wise velocity exists. The jet is no longer mixing with warmer silicon oil present in the vessel. Thus, the relaminarization serves as a kind of thermal insulation leading to the less homogeneous temperature field and thus product conversion in HPP. Particularly, in the case of HP-pasteurization of food it should be avoided because most of the expected changes in the food are strongly dependent on the temperature.

4. Conclusions

The investigation of turbulence development during HPP is very important because of the various utilization of high pressure process in food processing industry and in medical and pharmaceutical industries. The present experimental investigations used HP-LDA and HP-HWA as technique to measure the flow velocity and turbulence, respectively, at high pressure in order to understand the behaviour of the flow during the HPP. The conclusion to be drawn from the presented experimental results is that the observed effect of flow relaminarization is in agreement with the expectation that rapid changes in the fluid properties during compression process reduce the turbulent dissipation and therefore the spectral separation between large and small scale motions which finally lead to complete relaminarization. Consequently, pressure ramp is a highly-efficient method of controlling flow behaviour. Knowledge gathered in the experiments can be adapted in various fields of industry. For example in IC-engines it would enable keeping fully laminar flame thus controlling the combustion better and obtaining better efficiency. On the other hand, when the laminar flow is undesired, e.g. in food processing the turbulence in HP vessel assured more uniform pasteurization, such conditions could be avoided.

Future studies using developed HP-LDA and HP-HWA on pressure dependence of jet penetration length change could also provide insight into field homogeneity involved in HPP. Additionally, visualizations of the jet at different pressure with a relevant discussion would be of great use.

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