Research report GAČR nr. 17-19444S Interaction of heterogeneous liquid with flexible wall

Measurement of pulsatile flow characteristics in interaction with rigid and flexible wall

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Keywords: Flexible wall, Fluid flow, Heterogeneous liquid, Particle Image Velocimetry, Pulsatile flow, Rigid wall

Work schedule – 2nd year of the solution

1. Velocity field Measurement of heterogeneous liquid in the flexible tube with the geometries described in the content of the project. Image processing and modal decomposition of the vortex structures.
2. Measurements of vortex structures and wear in long-term cavitation experiments. Image processing and modal decomposition of the vortex structures. Result of the study focused on the use of optical methods - PIV and micro PIV for velocity fields' measurements of the heterogeneous fluids in flexible tubes.
3. Presentations at conferences and results publication.

Abstract

Pulse flow was generated by a membrane pump. The nature of the pulsatile flow was measured with pressure sensors. We got information on the pressure development inside the circuit. Each phase of the pulse was evenly divided into 10 equal time slots. The individual slots were synchronized to the initial pressure change at 0.14Bar. The evaluation of the pressure measurement has already revealed the backward effect of the flexible wall. Especially when compared to glass rigid wall. Differences in pressures course are mostly significant in the peak width and lower stabilised pressure value. The flexible material absorbs part of pressure and expands its diameter.

The liquid flow can be divided into four regimes: The first regime corresponds to pressure increase. The liquid flow is accelerated. The maximal fluid velocities reach 440 mm/s (Re 8800). The second regime is the highest point of pressure increase, where physically occurs the maximum membrane inclination, and closure of the pumps valves. At this point, the fluid stagnates, resulting in slowing down of the flow rate to 70 mm/s (Re 1400), and changing the

characteristic velocity profile. This regime can be said as transient mode. The velocity profile is characterized with typical velocity decrease in the middle of cross section. This effect was found for both measurements – using rigid and flexible wall.
The other phase of liquid acceleration can be observed in the third regime. Here, the liquid is fed with the pump. This acceleration last during the pressure decrease. This regime is characteristic with turbulent profile shape, and maximal flow velocity reach 260 mm/s (Re 5200). The fourth regime is observed since $6/5\pi$ period, when the pressure drop and starts to be stabilized. Here we can observe the liquid flow slowdown that is close to laminar profile shape. The maximal velocities in this regime are 35 mm/s (Re 700).

There is an oscillation of a pressure, which leads to the formation of vortex structures near the wall. These structures are highlighted by the elasticity of the wall. The vortex structures were analysed using Proper Orthogonal Decomposition (POD). The most significant modes are for transient part of fluid flow and turbulent zone. The first 20 decomposition modes can be said as dominant. Here can be found vortex structures with kinetic energy of 10%. The nonstationary backward vortexes are developed close to the wall, as the fluid flow velocity is very small. The prevailing dominant effect on the fluid flow comes from the released kinetic energy from the relaxing flexible walls, especially in the fourth regime of pressure course. This effect is not significant for rigid walls.

There were set an experimental setup for studying of cavitation base on Ventury tube. The fluid flow was analysed using high speed visualization methods in two interrogation areas in cross-section. The region of interest was focused on the swirling cavitation structure. The experiments run in 2018 were run in rigid wall. The fluid was also seeded with fluorescent particles for PIV measurement so the simple visualization was filled with fluid motion data's. The investigated area was observed with synchronized two cameras recording parallel. The set of images were processed using supressing and dewarping algorithms. The experimental setup is prepared for the measurement on flexible wall and pulsatile flow.

Solution

The goal of the first point of solution for 2018 was to study heterogeneous flow and to compare the flow characteristics of different liquids generated by membrane pump pulsations. Heterogeneous liquid can be understood as a multi-phase liquid, i.e. supplemented with a solid and gaseous phase. The solid phase in our case was formed by defined particles. The gas phase was naturally present in the form of air bubbles. In both cases, the resulting behaviour, especially the second phase, depends on particle concentration and their size. Due to the interfacial forces, these particles are driven into larger units. These will also affect the ambient flow.

Methods

Hydraulic circuit was designed and manufactured from PVC-U pipes. The pipes from PVC-U made by Georg Fischer are solid enough not to influent or dump the pulsations in the circuit. The circuit was supplemented by end caps - hoses for connecting both rigid and flexible wall. The testing section was removable and suitable for fitting with glass and Tygon tubes. Both tubes have the diameter of 20 mm. The glass tube is a representative of full-solid - rigid tube. The Tygon tube is the representative of flexible wall tube. These tubes are made from flexible polymer, mostly used in medicine, food industry, chemical processing etc. The wall thickness of Tygon tube was 2 mm.

The design also took into account the connection of pressure sensors. The circuit was equipped with two pressure sensors – just below (Pressure Sensor 1) and above (Pressure Sensor 2) the observed tube. Sensor's analogue outputs were filtered, connected to the digital oscilloscope and saved for following analysis. Output from the above pressure sensor was also used as a trigger for PIV measurement. When the pressure value reached the proper value, the flip-flop circuit generated the TTL signal. That signal connected to the Timer Box (TB) triggered the PIV system with the required period shift (delay of the signal). Using different period shifts we provided ten repeatable measurements inside the pulse period. The trigger TTL signal was also connected and saved in the oscilloscope to verify correct timing of the measurement. With this setup we can reconstruct the behaviour of the flow and the pressure conditions in the water circuit simultaneously.

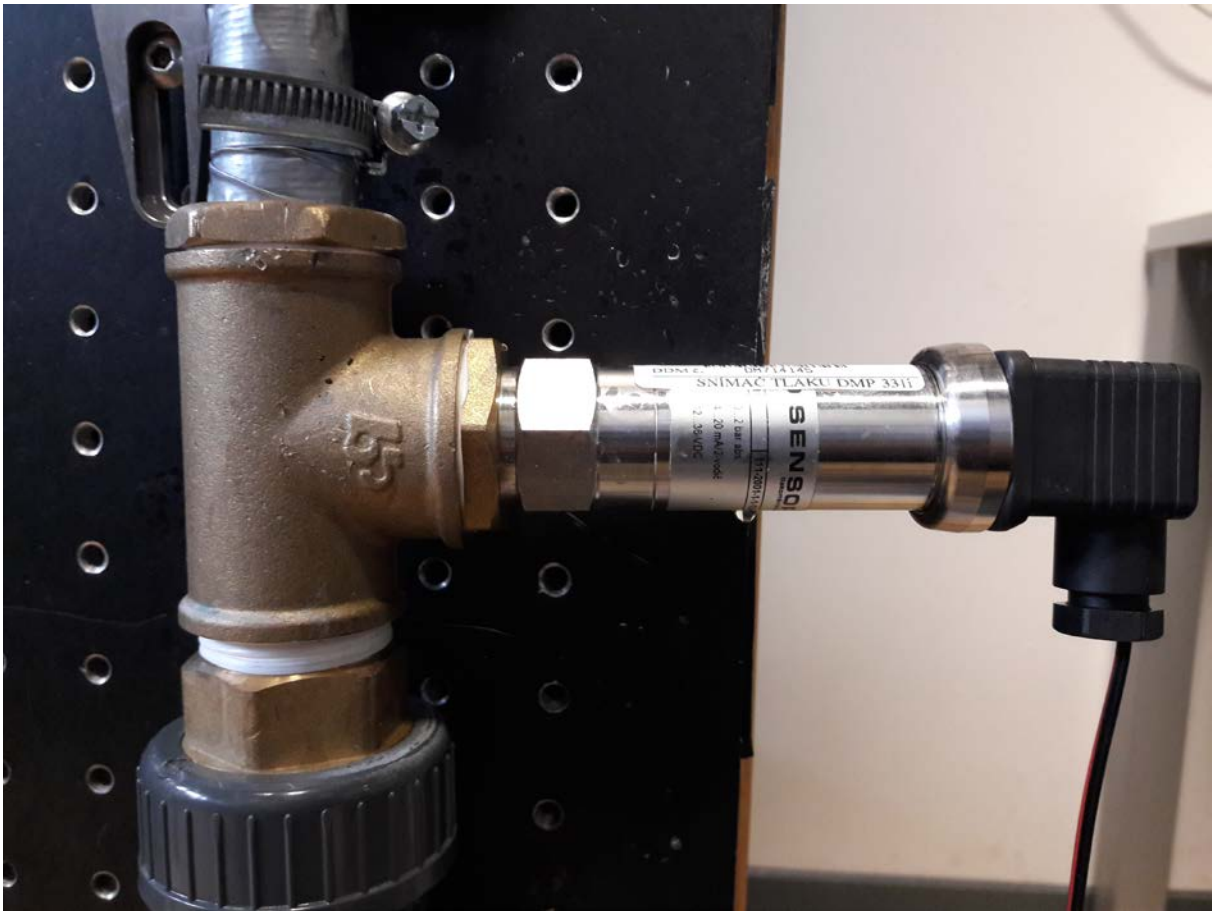


Figure 1. Pressure sensor in detail, and the connection to the hydraulic circuit.

Water in the circuit was actuated by the membrane pump (MP) Bran+Luebbe ProCam Smart DS500. The pump was controlled with the frequency driver (FD) Emerson Control Techniques Unidriver M200 to set optimal pulsation rate of 1Hz. Upper water tank was connected to the circuit to set up the initial pressure in the circuit. After that the tank was disconnected, so the pulsations run only in the circuit and were not dumped in the tank.

The PIV data were recorded using system from Dantec Dynamics and its HiSense Neo camera. The flow was illuminated by the pulse Nd:YAG laser NewWave Gemini (532 nm wavelength). One synchronised (period shifted) image was recorded in each period, so the frequency of the PIV system was also 1 Hz. We collected 250 images for each time stamp in the period; the period was sampled with 100 ms (10 samples in the pulse period). There were used Polyamide fluorescent particles (coloured with Rhodamine B with emitting wavelength of 570 nm, size 5 μm) as seeding particles. The fluorescent particles enable measurement close to wall as the laser light scattered from the wall is eliminated. The principle scheme of the measurement circuit and PIV system set-up is seen on Figure 2.

The PIV measurements were made in the measuring plane lighted by a laser cut in the middle of the tube. The dataset of images were processed using dewarping method. Differences of refractive indices between several materials (water, glass/Tygon, air) cause image distortion. This distortion causes erroneous evaluation of the velocity fields, especially near the wall, that is, the area of our interest. The image calibration was performed before the measurement using a chessboard calibration target placed inside the tube and filled with water. The datasets of measurements were analysed using Cross-Correlation method (using Interrogation Area of 64 px x 64 px with 50% overlap in both directions) and valuated with Moving Average Validation (Averaging matrix 3 x 3, without substituting vectors, and validation on boundaries).

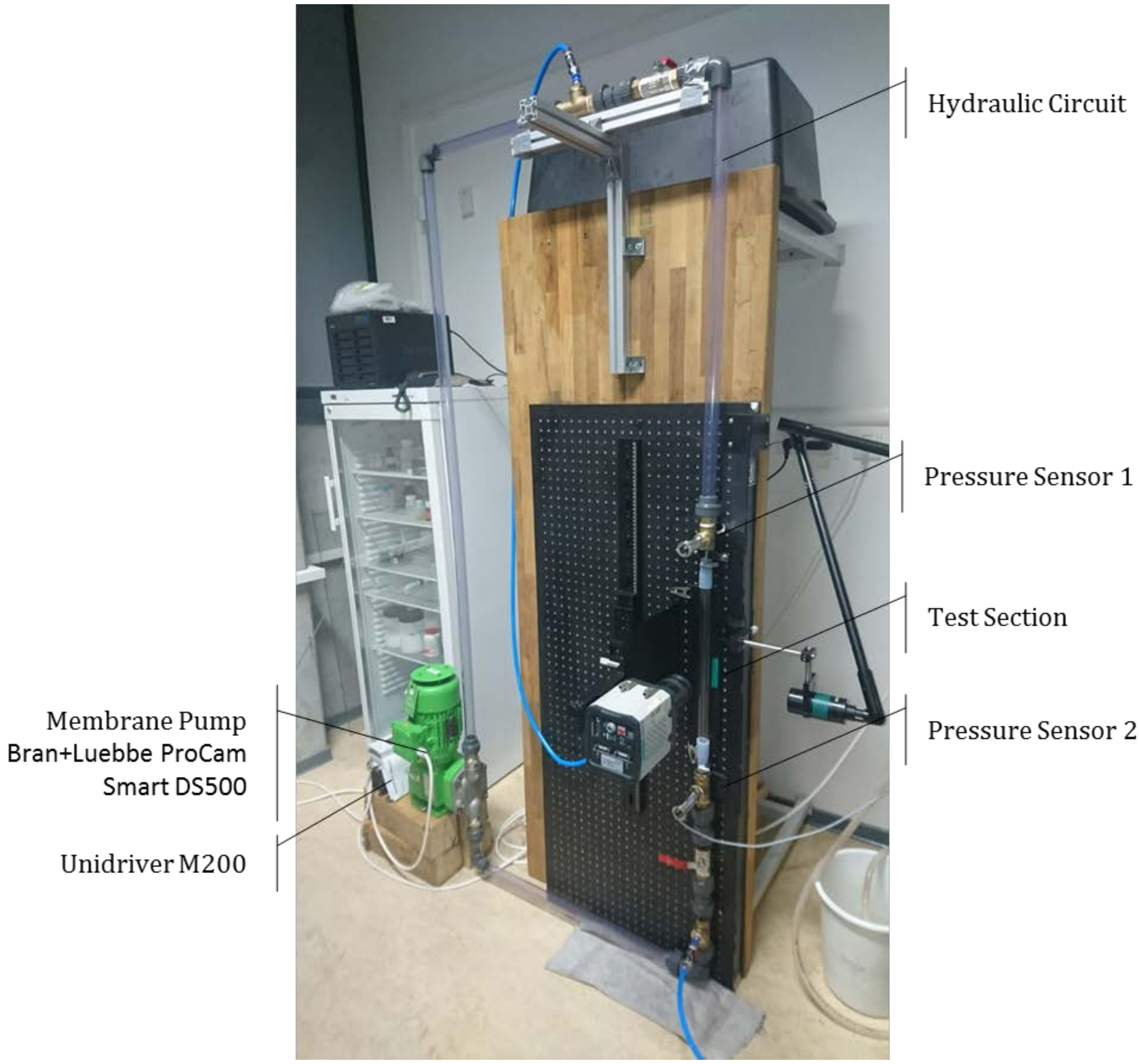


Figure 2. The hydraulic circuit in laboratory.

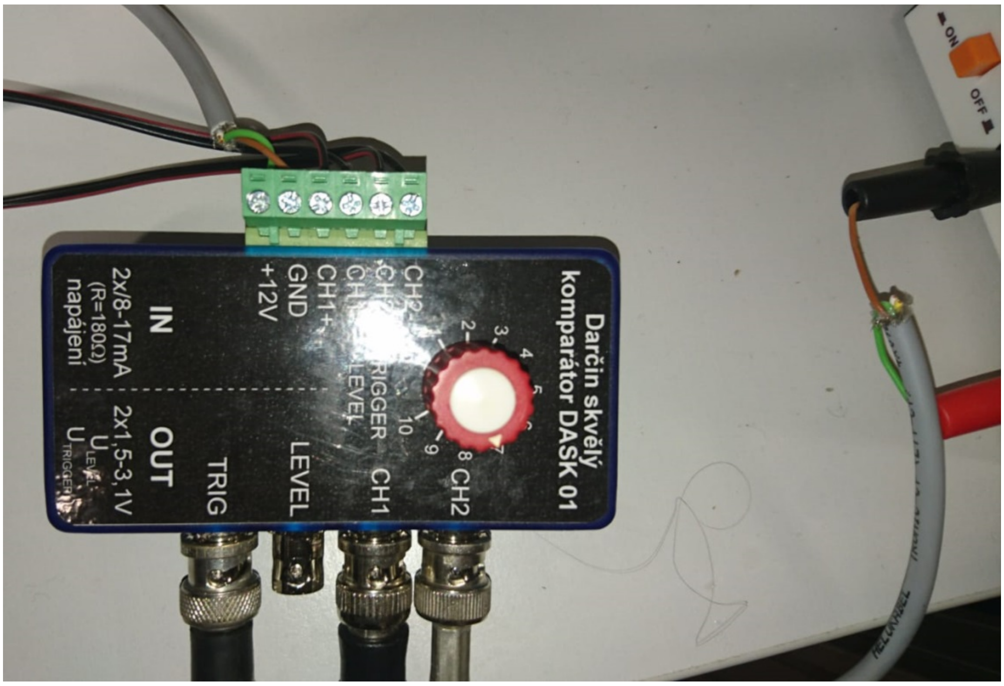


Figure 3. Comparator for converting analogue signal from pressure sensors to digital one with change of tracking to adjust output TTL pulse for laser and camera synchronization.

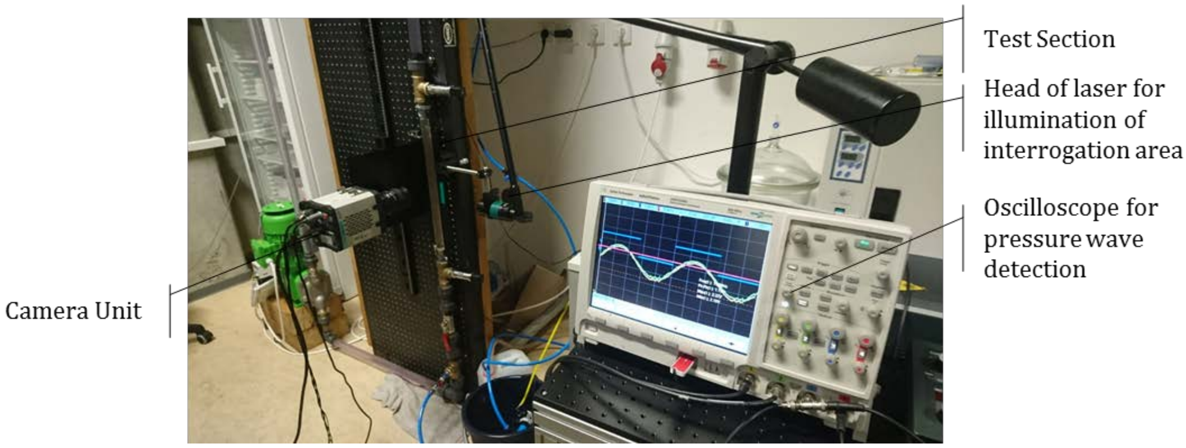


Figure 4. The experimental setup with estimation of pressure waves via digital oscilloscope. There is seen the initial signal of pressure waves.

Progresse in PDMS tube preparation

There was made an upgrade in preparation of PDMS tube, parallelly to finishment of vertical hydraulic circuit. The *PolyDiMethylSiloxan*, i.e. Sylgard 189 pipes of specified dimensions (outer diameter 23 mm, inner diameter 19 mm, length 500-700 mm) were cast using the centrifugal casting procedure developed previous year.

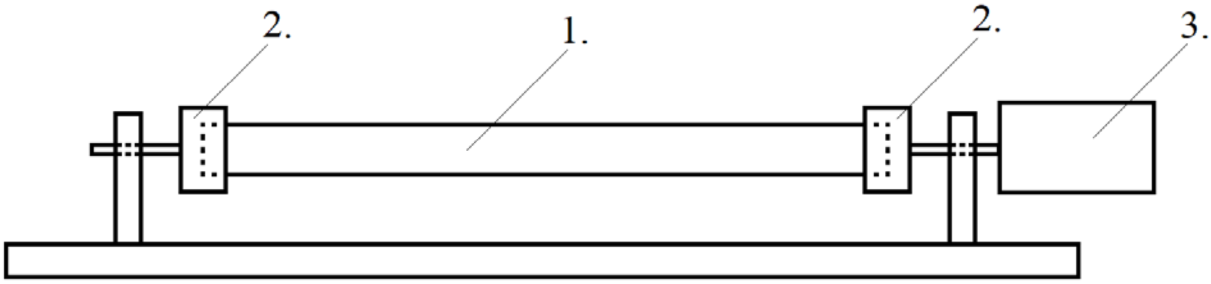


Figure 5. A Scheme of the device for centrifugal casting (1. the pipe mould, 2. rotating support serving also as cap, 3. motor).

The mould is a common thin-walled aluminium pipe. This makes it very cheap and thus the elastomer pipe can be extracted from the mould simply by cutting the aluminium pipe longitudinally in half. This is the only possible way of safely extracting the silicone pipe, because the cured silicone elastomer adheres very strongly to the walls of the mould.
The curing time of silicone elastomer at room temperature is about 48 hours. However it is possible to cure our elastomer using higher temperature, which greatly speeds up the whole procedure. For this purpose the mould temperature was increased to approximately 100 ^{0}C by forced airflow generated by a hot gun Steinel HL1400S. Since the material of the pipe mould is aluminium (with wall thickness 1,3 mm), which has excellent thermal conductivity. This allows it to transfer the heat from the hot gun almost immediately to its inside and thus heating up the solidifying elastomer with great thermal efficiency. This decreased the curing time to approximately 35 minutes.
The original manufacturing process produced pipes with non-uniform wall thickness. This issue was resolved by increasing the rotational speed of the mould during the casting process from originally used 1000 RPM to 1400 RPM. This greatly increased the uniformity of the pipe-wall thickness as we can see in Fig. 6.¨

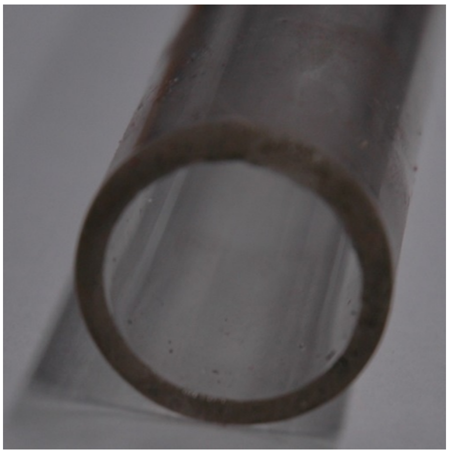


Figure 6. Picture of manufactured silicone elastomer pipe (sectional view)

A problem with optical transparency occurred during the experiments using the produced silicone pipes. During the casting the outer side of the pipes took the exact texture of the mould, which was not polished. To increase the optical properties of the surface, the pipes were then cleaned with ethanol, hung for ease of access and treated with a thin coating of the same silicone elastomer Sylgard 184, see Fig. 3. This time the solidification was not sped up to provide the elastomer outer layer enough time to smooth out due to surface tension and gravity. This is only possible due to the specific property of our silicone elastomer, which allows the newly formed layer of the elastomer to merge seamlessly with the already solidified original layer.

Figure 7. Picture of the manufactured pipes treated with a final thin coating of elastomer to increase their optical transparency.

This treatment makes the silicone pipes much more optically transparent and thus suitable for the precise optical measuring methods (PIV) used during the experiments with these manufactured pipes.

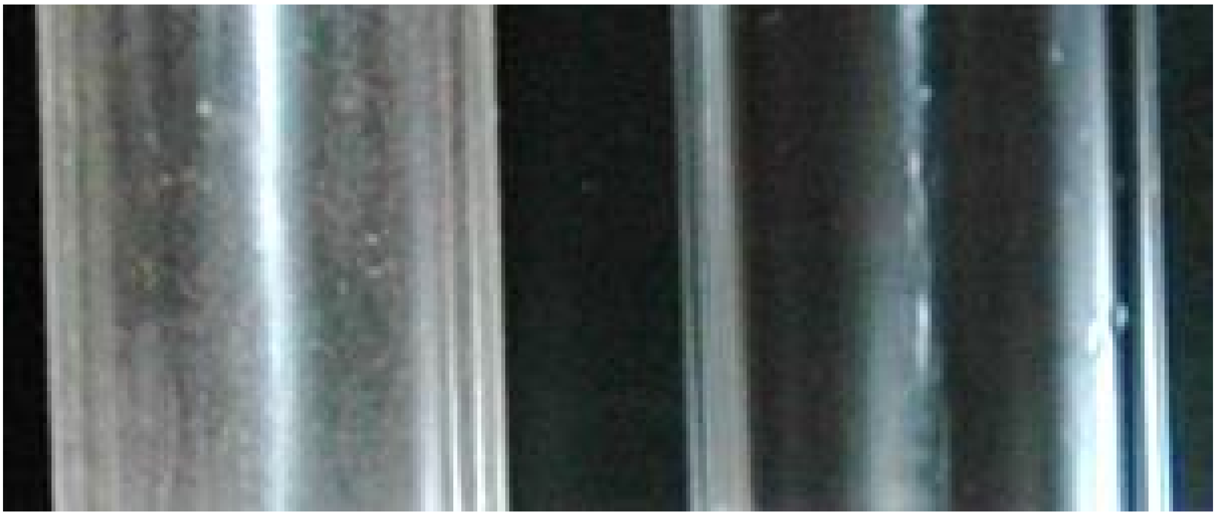


Figure 8. Picture comparing optically transparency of the untreated (left) and treated (right) manufactured pipe.

Discussion / Interpretation of Results

Pulse flow was generated by a membrane pump. The nature of the pulsatile flow was measured with pressure sensors. We got information on the pressure development inside the circuit. Each phase of the pulse was evenly divided into 10 equal time slots. The individual slots were synchronized to the initial pressure change. The minimal pressure change was set at 0.14 bar. The charastic pressure recording is seen in Fig. 9.

The evaluation of the pressure measurement has already revealed the backward effect of the flexible wall. Especially when compared to glass rigid wall. The pulsation of the liquid is partially absorbed by the elastic wall. The energy is again released into the flowing fluid in the second phase of the pressure wave. These interactions will be shown as the oscillations of the pressure curve (Pressure Sensor 1) in the chart of the pressure time course as it is seen in Fig. 9.

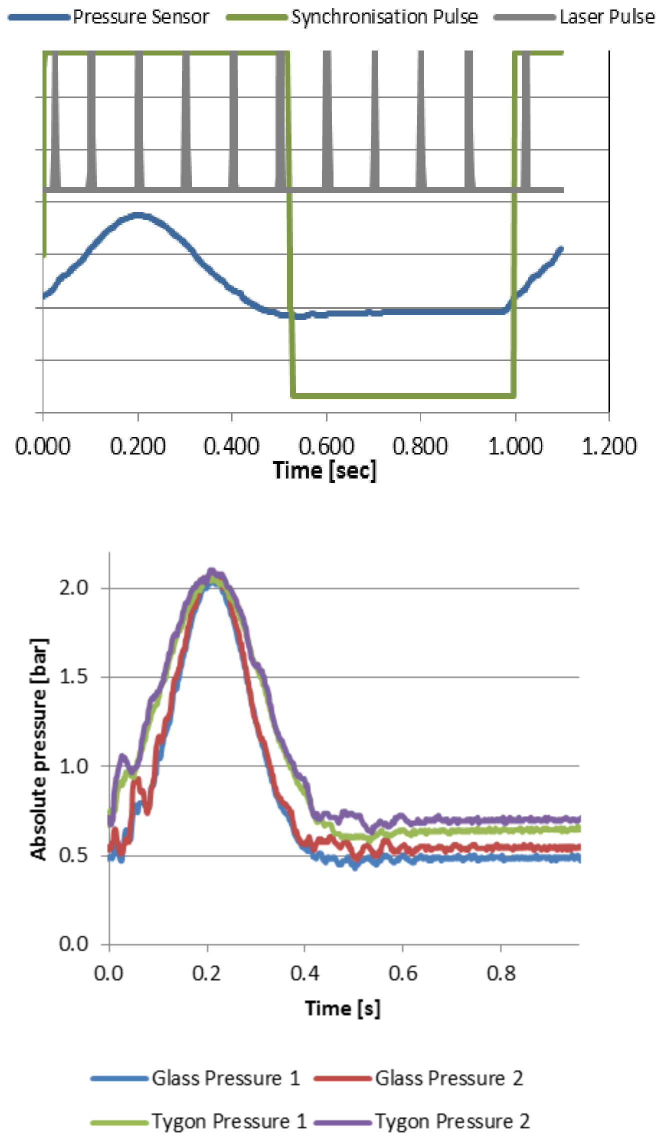


Figure 9. Scheme of synchronization. The green line represents the synchronization pulse; the grey line represents 10 time slots for PIV measurement using laser pulse, and The effect of flexible wall on the pressure response. Comparison of pressure course between glass and Tygon tubes.

There is also seen in Figure 9 that the maximal pressure peak was set equal for all measurement regimes to get comparable results of different materials. We used reducing valve set to 2.1 bar to ensure the same pressure peak. Differences in pressures course are mostly significant in the peak width and lower stabilised pressure value. The Tygon material absorbs part of pressure and expands its diameter. The pressure oscillations are stronger for Tygon, also caused by the flexible wall. The pressure oscillations at the lower peak of the measured pressure are caused by the uniform action of the liquid on the walls of the flexible tube.

The liquid flow can be divided into four regimes: The first regime corresponds to pressure increase. The liquid flow is accelerated. The maximal fluid velocities reach 440 mm/s (Re 8800) The second regime is the highest point of pressure increase, where physically occurs the maximum membrane inclination, and closure of the pumps valves. At this point, the fluid stagnates, resulting in slowing down of the flow rate to 70 mm/s (Re 1400), and changing the characteristic velocity profile. This regime can be said as transient mode. The velocity profile is characterized with typical velocity decrease in the middle of cross section. This effect was found for both measurements – using rigid and flexible wall.

The other phase of liquid acceleration can be observed in the third regime. Here, the liquid is fed with the pump. This acceleration last during the pressure decrease. This regime is characteristic with turbulent profile shape, and maximal flow velocity reach 260 mm/s (Re 5200).
The fourth regime is observed since 6/5π period, when the pressure drop and starts to be stabilized. Here we can observe the liquid flow slowdown that is close to laminar profile shape. The maximal velocities in this regime are 35 mm/s (Re 700).

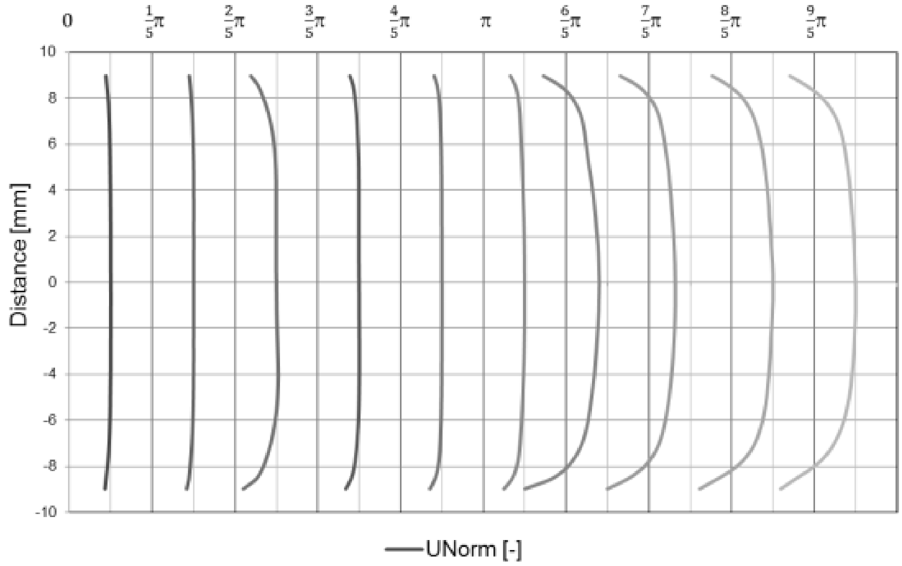
The nature of the fluid flow at the corresponding times of synchronization is the same for rigid and flexible wall, so the maximum fluid flow velocities are similar, but the velocity profile varies especially close to the wall. An apparent difference is seen in comparing the rigid and flexible walls. Liquid interaction with the flexible wall occurs in the phase of slowing down the liquid flow, i.e. laminar regime and transient one.

Table 1. Maximal fluid velocity across the velocity profile and Reynolds Number of the liquid flow

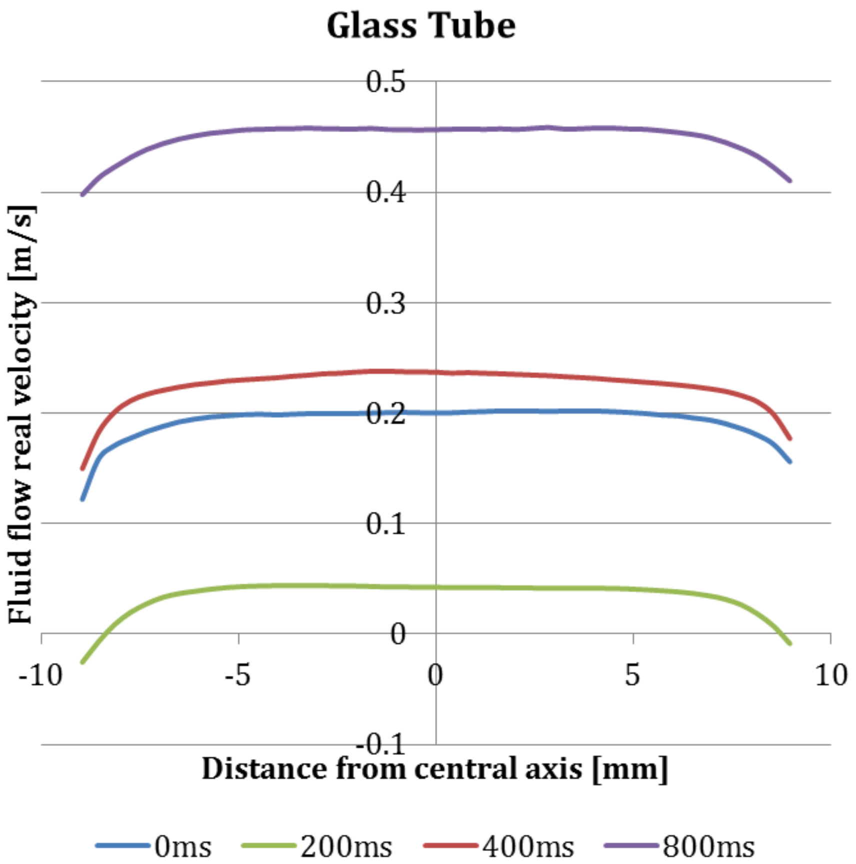
Time in Period	*Max. Velocity [mm/s]*	*Reynolds Number*
0 ms	440	8800
100 ms - 1/5π	380	7600
200 ms - 2/5π	70	1400
300 ms - 3/5π	220	4400
400 ms - 4/5π	260	5200
500 ms - π	140	2800
600 ms - 6/5π	36	720
700 ms - 7/5π	28	560
800 ms - 8/5π	40	800
900 ms - 9/5π	35	700

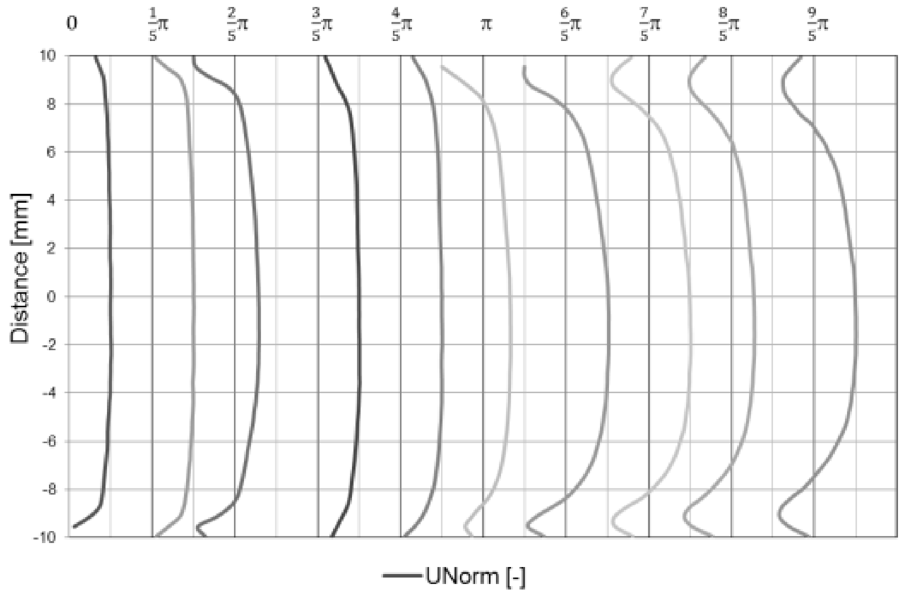
Statistical Evaluation

The series of following charts (Fig. 10) represent velocity profiles of fluid flow. There is an oscillation of a pressure, which leads to the formation of vortex structures near the wall. These structures are highlighted by the elasticity of the wall. There is developed nonstationary backward vortex close to the wall, as the fluid flow velocity is very small. The prevailing dominant effect on the fluid flow comes from the released kinetic energy from the relaxing flexible walls, especially in the fourth regime of pressure course.



a)





b)

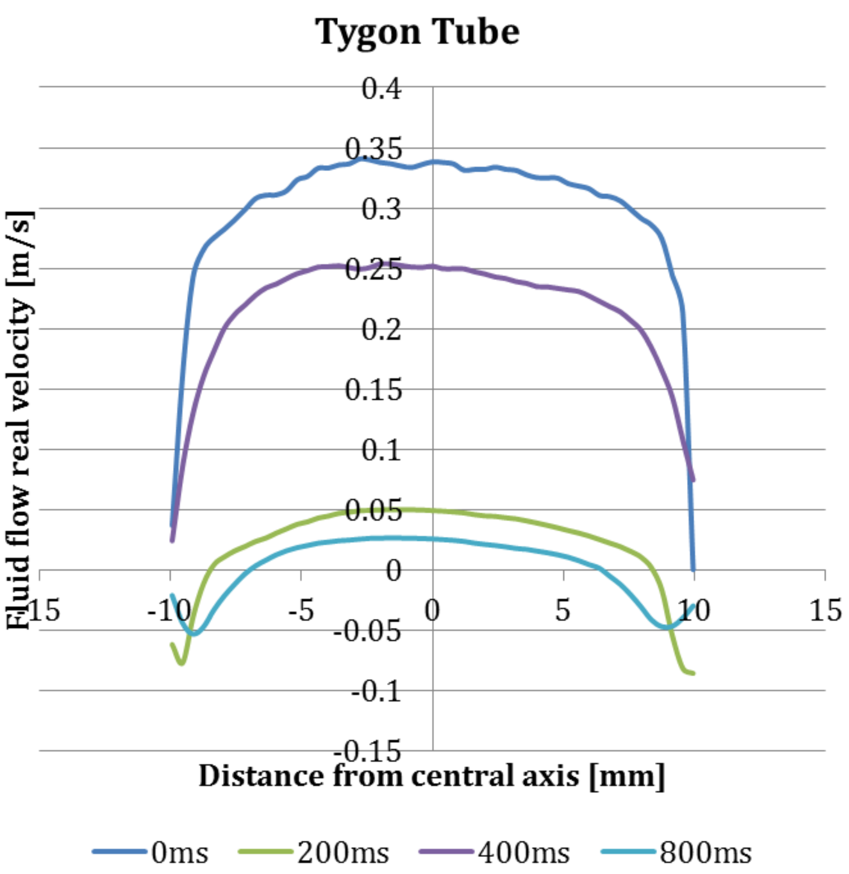
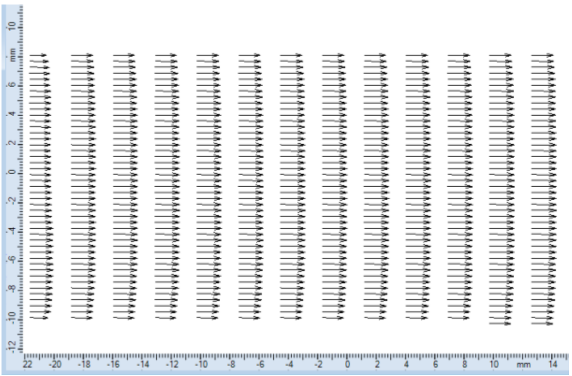


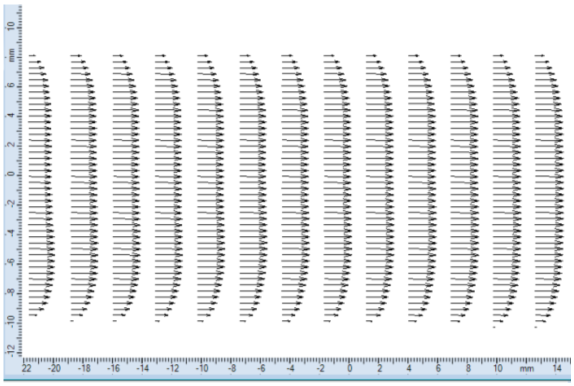
Figure 10. Comparison of characteristic velocity profiles in the middle cross section using normalized velocity u_{norm} against maximal velocity of the fluid flow, and selected real no-normed fluid velocities of a) glass tube, and b) Tygon flexible tube.

This effect is not significant for rigid walls. Here it is caused by very slow motion of fluid that generates tiny vortex structures that response to the fading shock wave from the membrane. There is generated backward flow, rapid reverse effect close to wall in this regime.

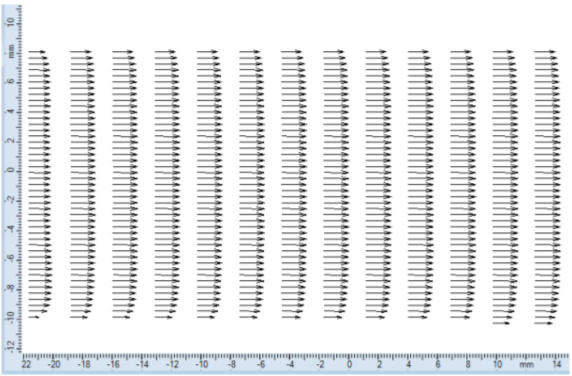
0ms



200ms - 2/5π



400ms - 4/5π



800ms - 8/5π

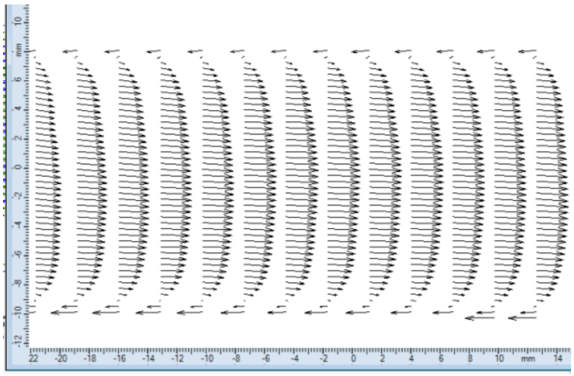
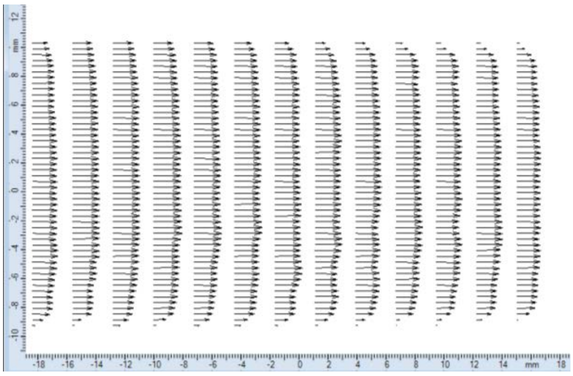


Figure 11. Flow field of the liquid inside the rigid glass tubes.

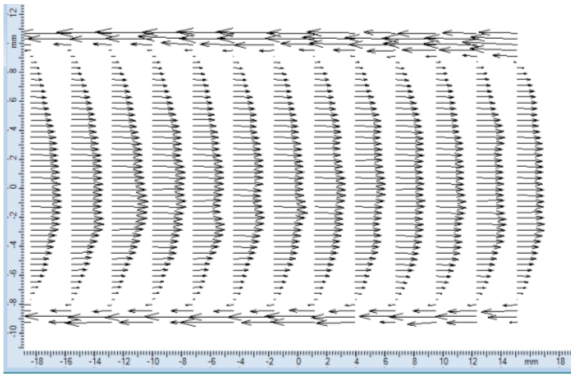
This phenomenon is physically explicable by the principle of closing the valves at the oscillation phase of the membrane. Vortex structures close to the wall can already be generated in the pump itself and spread through the pipeline due to the decaying pressure waves.
The sudden change in the flow direction of the liquid will affect the region of slowest fluid flow, i.e. near the wall. Due to inertia, the main liquid stream does not slow down significantly, compared to the situation near the walls, where we expect the flow velocities to be lower, close to zero.

In general, the Newtonian fluid reaction is fast, which is confirmed by rapid transitions between the laminar, and turbulent fully developed velocity profile. The transition from the laminar to turbulent regime is followed by development of small disturbances. The laminar flow regime is unstable in time. The vector statistics that is seen in Fig. 11, and Fig. 12 are time averaged liquid flow characteristics. It can be said as a transfer from stable (turbulent) to unstable (laminar) mode. Here we can express the balance between the viscous liquid forces and elastic forces in the wall, when the flow close to wall becomes unstable followed by vortex structures.

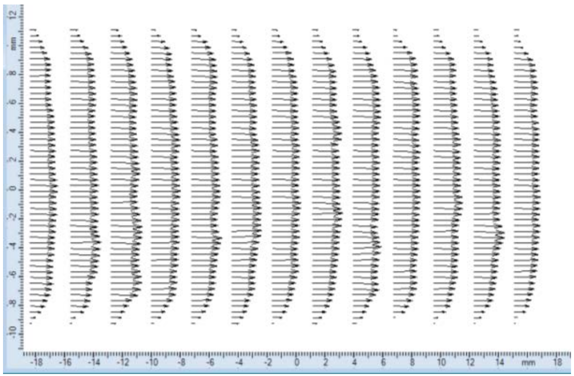
0ms



200ms - 2/5π



400ms - 4/5π



800ms - 8/5π

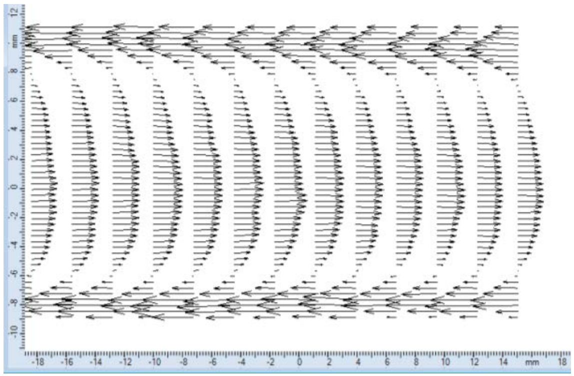


Figure 12. Flow field of the liquid inside the flexible Tygon tube.

POD Analyze

Measured data were evaluated not only statistically with results in Vector Statistics, as it is seen in figure 11, and 12; but also by the method Proper Orthogonal Decomposition (POD). The Proper orthogonal decomposition analysis was applied on 2D vector maps, those including u, v velocity compounds. It is a mathematical method that gains and clarifies the flow structures based on extracting a basis for modal decomposition from an ensemble of signals. We can reconstruct flow field and demonstrate the influence of different flow structures by the selection of main dominant POD modes. The major POD mode that affects the dominant flow is seen in figure 13. The POD Snapshot is based on autocorrelation function and depends on the number of instantaneous acquired samples acquired. We can see in figure 14, and 15 two dominant Modes (3, and 4) that are significant for flow regime. For comparison to this we chose the third and fourth dominant mode.

The significance of the Modes is also reflected in the transition from laminar to turbulent flow, i. e. for the time 4/5π, and 8/5π of the period.

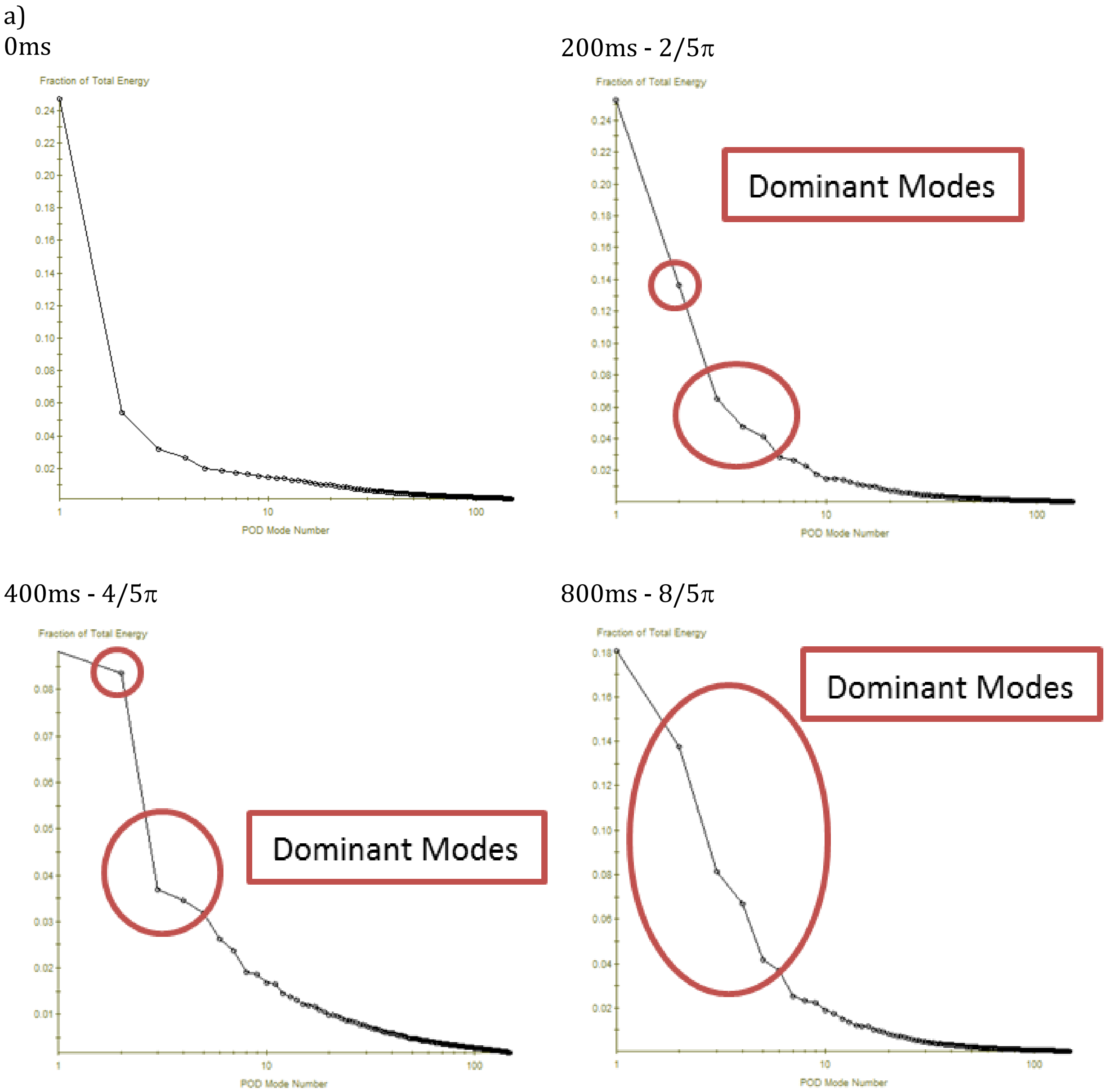


Figure 13 a). The chart of percentage of fraction contribution on complex kinetic energy in the system for a) rigid glass tube.

b)

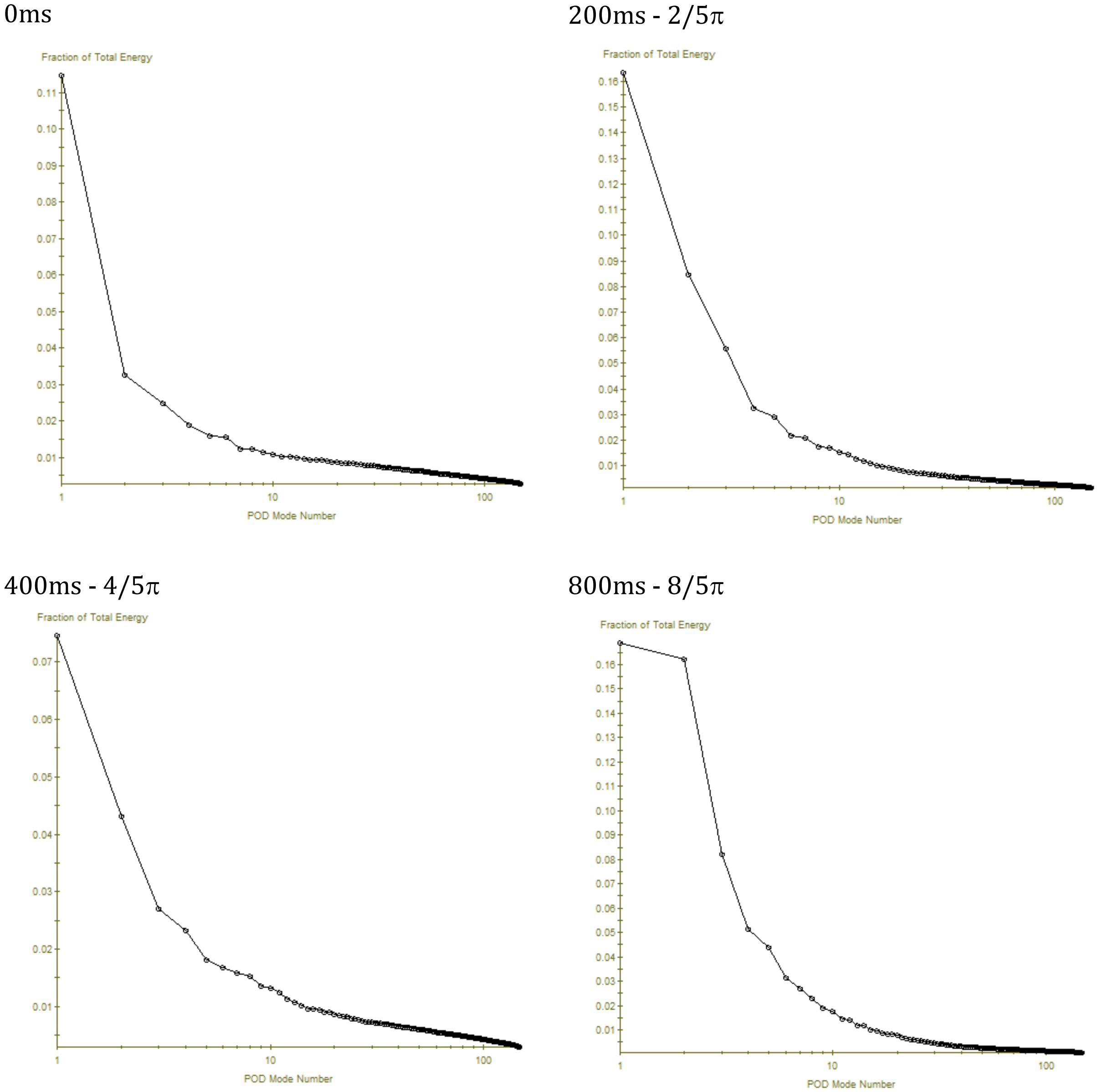


Figure 13 b). The chart of percentage of fraction contribution on complex kinetic energy in the system for b) flexible, Tygon tube.

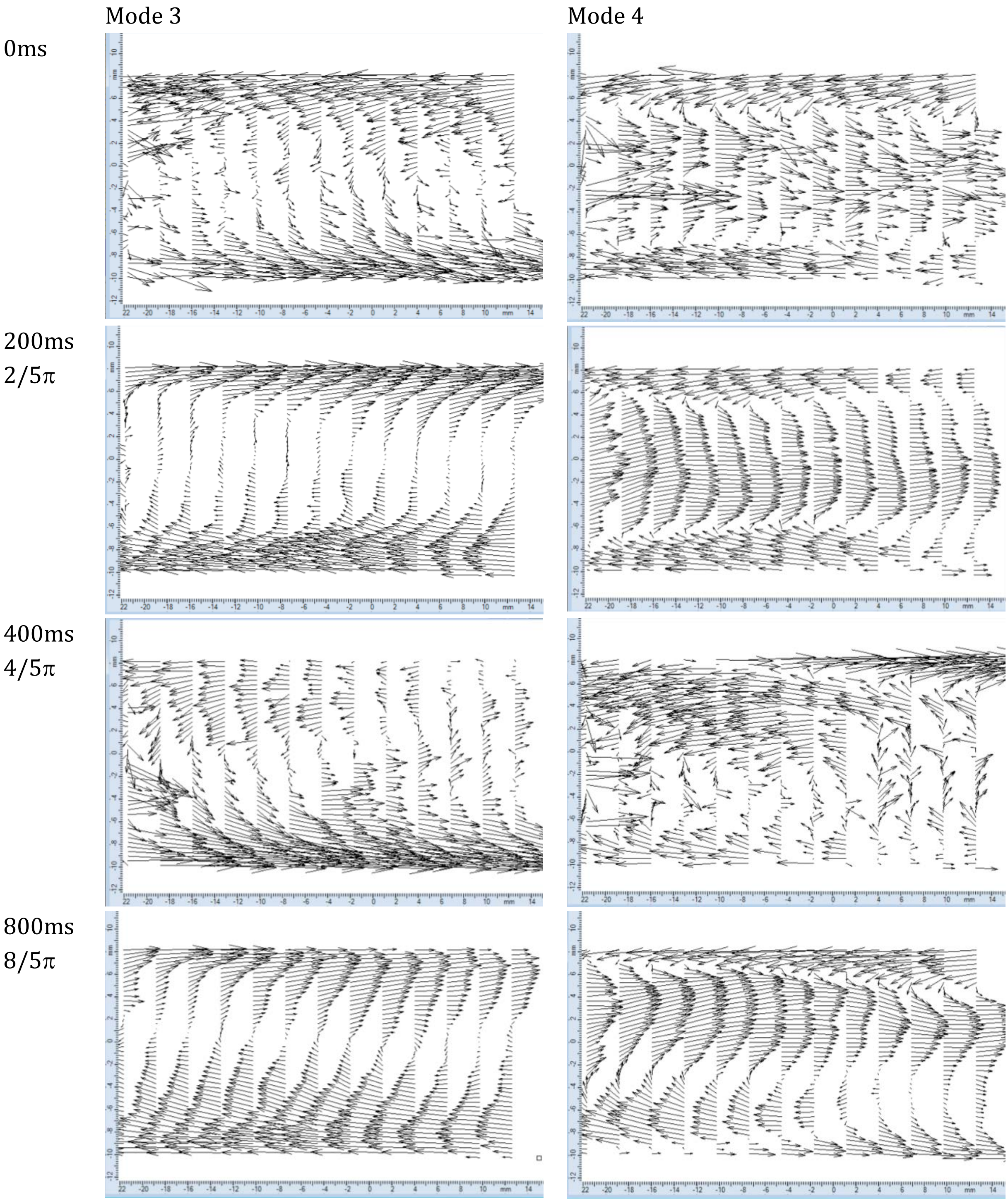


Figure 14. The modal structure analysis using POD method for the fluid flow in rigid, glass tube.

Mode 3 Mode 4

0ms

200ms 2/5π

400ms 4/5π

800ms 8/5π

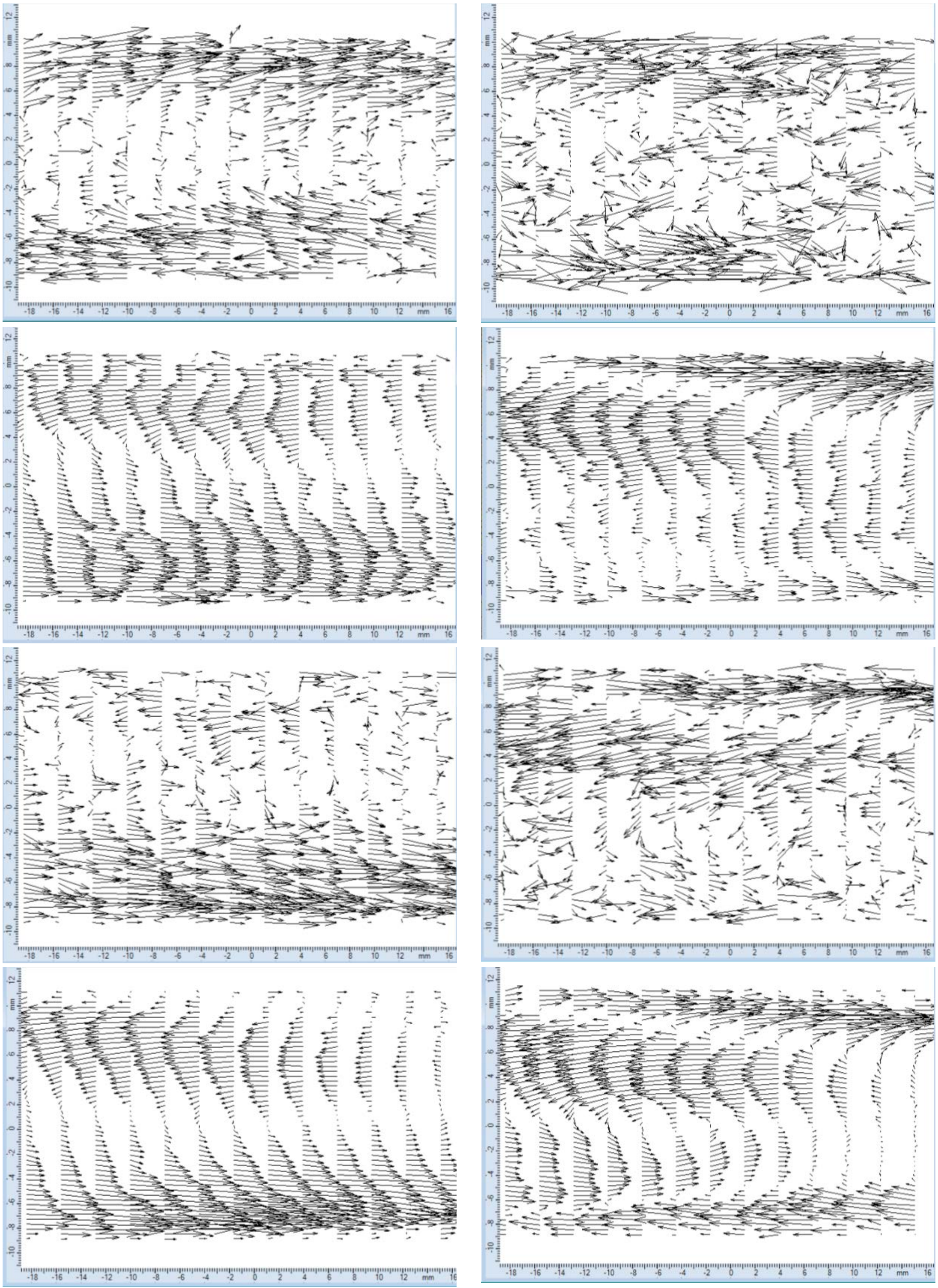
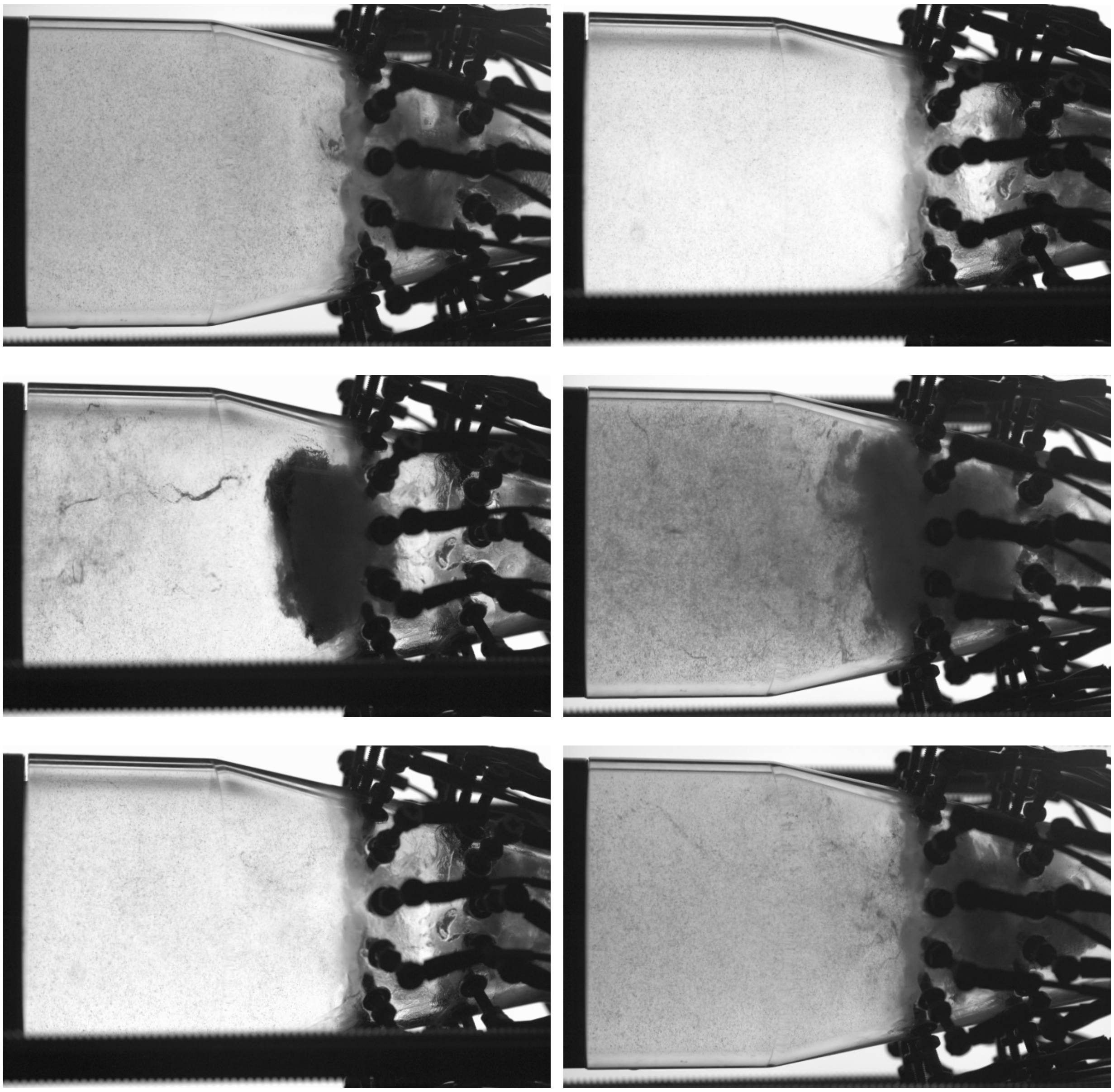


Figure 15. The modal structure analysis using POD method for the fluid flow in flexible, Tygon tube.

The study of heterogeneous liquid was studied using optical visualization methods. The cavitation cloud was studied in a laboratory pipe setup with a mechanical cavitation generator, i.e. Ventury tube.

The cavitation cloud originating on the cavitation generator varies in volume in relation to the flow rate through the pipe system. Since we are able to change the flow rate on a wide scale, we are able to study the cavitation cloud in several different states. The following set of images describes the complex of the situation (Fig. 16). The cavitation vortex structure is in this regime very unstable.



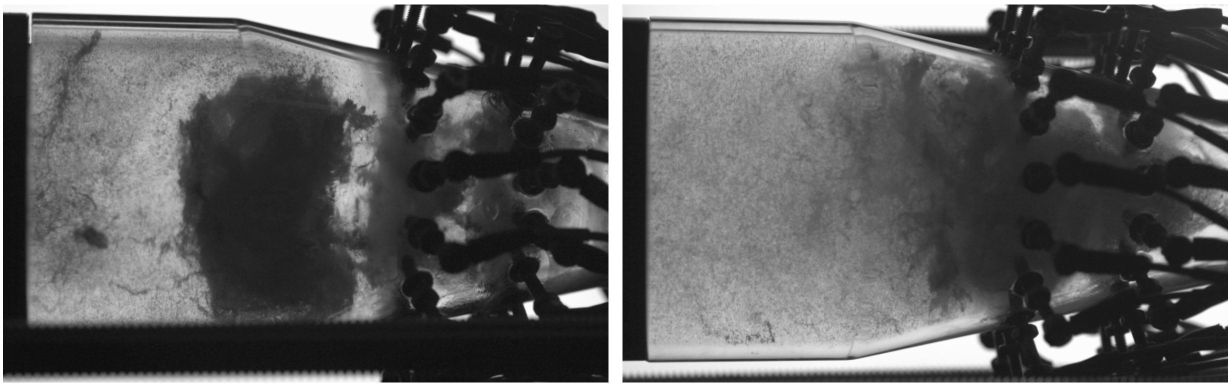


Figure 16. Development of cavitation vortex depending on the flow regime.