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ABSTRACT

Recent studies have provided the significant number of approaches to enhance the performance of a two-phase ejector, especially for transcritical CO2 cycles. However, the investigation of the mixing process is still challenging matter due to the high-speed fluid flow coupled with mixing of vapour and partially evaporated liquid stream. On the other hand, these phenomena directly influence the ejector efficiency. The behaviour of the aforementioned processes would be valuable for validation the numerical models as well as a required control of the system operation. Hence, in this work, the laboratory test rig for visualisation of the CO2 ejector mixing processes along suction nozzle, pre-mixing chamber and diffuser was developed and manufactured. The visualisation techniques used for this study include the high-speed camera recordings and PIV measurements. The work consists of installation description, including the measurement approaches, solution predicted by the computational model for the transparent construction of the ejector and visualisation procedures. The selected on- and off-design operating points were described having regard ejector performance factors and its correlation with the output of the visualisation procedure.

1. INTRODUCTION

The R744-based refrigeration system has been commonly installed in the large-scale commercial sector in supermarkets. Last commercial reports (Schecco, 2018) showed that the number of R744 refrigeration supermarket installations is above 14,000 in Europe, above 3,100 in Japan and around 500 in North America. Comprehensive reviews of the R744 ejector system indicated current standards of these systems such as parallel compression and two-phase ejectors. Resulting performance improvement and extended the application range of the R744 refrigeration system into the hot and tropical climate zones (Gullo, Hafner, & Banasiak, 2018) provided a continuous development of the R744 technology that concerns global features such as the improved layout of the systems as well as detailed investigation of the regulation methods and design tools for the particular components. The ejectors dedicated for the R744 systems were underlined in the last reviews delivered by the Elbel and Lawrence (Elbel & Lawrence, 2016) and Besagni et al. (Besagni, 2019). The design process of the R744 ejectors is mostly covered by numerical tools which need to be validated to ensure a well-designed shape of the two-phase carbon dioxide ejector. Thermodynamic conditions and mass flow rate could be measured at the ejector ports while significantly less data is available for validation of interior ejector ducts. Finally, the possibility to visualise the flow behaviour inside the two-phase ejector would be a crucial data for turbulence model selection.

Various methods could be utilised for flow visualisation, depending on the flow characteristics. Some examples could be found in the high-speed video camera (Hernández Cely, Baptistella, & Rodriguez, 2018), particle image velocimetry (Gagan, Smierciew, Butrymowicz, & Karwacki, 2014) or the shadow-graph visualisation (Little & Garimella, 2016). In the case of the R744 two-phase ejector with rectangular cross-section was also performed (Zhu, Wang, Yang, & Jiang, 2017). Those authors used the light film and a single-lens reflex camera to observe the liquid and vapour flow together with the expansion angle in the mixing chamber. In the aforementioned experiments, the evaporation line in the mixing section was presented and the vapour quality in the fluid flow was approximated based on the captured snapshots. On the other hand, most of the currently used R744 ejectors are constructed on the basis of a radial suction port that results in the improved mixing phenomenon due to the swirled flow of the secondary and primary streams (Bodys et al., 2016). To the best authors knowledge, the study of the circular cross-section R744 ejector with radial suction port installed in the transcritical refrigeration unit is not yet available in the literature. Finally, comparison of the aforementioned methods was not provided considering one case and comparable operating conditions.

The experimental investigation of the transparent R744 two-phase ejector focused on the analysis of premixing chamber and expansion cone of the motive nozzle stream is provided in this study. The ejector ducts were constructed in the same manner as standard commercial devices, radial inlet and circular cross-section were used. Moreover, preliminary results obtained using PIV and high-speed camera approaches were compared. The analysis included global parameters such as operating conditions and mass flow rate together with local flow analysis obtained from the visualisation procedure was presented. Benefits and drawbacks of the considered approaches were discussed on the basis of the same ejector and operating conditions. Visualisation results of the flow internal structures were discussed providing potential for field validation data. Further work on dedicated algorithms for grey-scale analysis was concluded.

2. TEST RIG DESCRIPTION

The scheme of a laboratory R744 vapour compression test rig dedicated for two-phase ejector tests is presented in Fig. 1. The construction of the ejector with the transparent mixing and diffuser section was designed and manufactured in Gliwice, Poland.

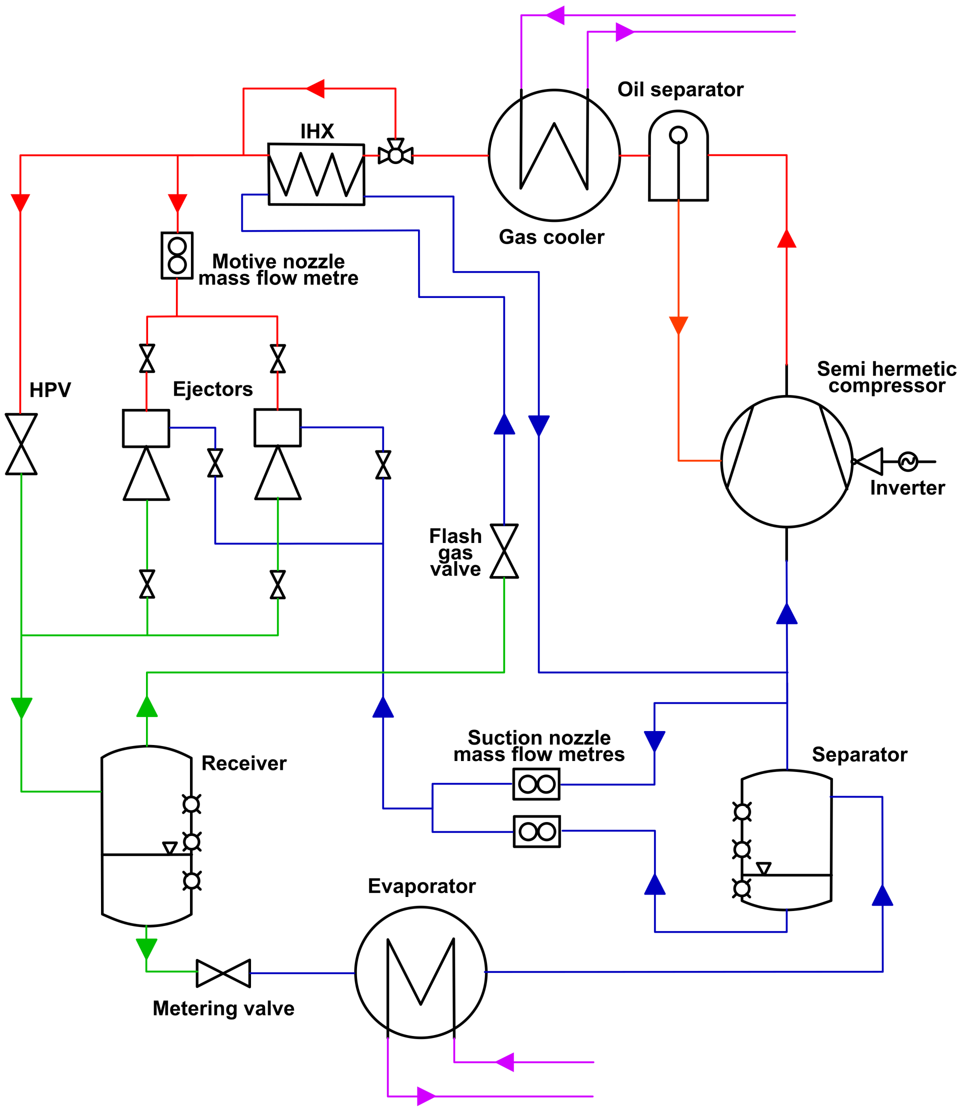

Figure 1: Scheme of the laboratory R744 refrigeration unit dedicated for ejector tests.

The ejector section is located at separate rack than the other components to provide a complex measurement of each investigated ejector. The test rig was designed for the cooling capacity of 50 kW operated in the refrigeration and air-conditioning application at subcritical and transcritical conditions. The system layout is a standard transcritcal system with a compressor manufactured by DORIN. The brazed-plate type heat exchangers produced by SWEP were used to control heat absorption and rejection. The suction accumulator tank located at the evaporator outlet allows for the operation of the two-phase ejector either as the vapour ejector or the liquid ejector. The expansion process is also supported by the Danfoss CCMT type electronic expansion valve and the flash gas from the separator is expanded by the flash valve.

2.1 Auxiliary loop

The glycol loops are installed as auxiliary loops to control the cooling capacity and heat rejection in the gas cooler. Both loops are also integrated by an additional internal heat exchanger to minimise heat rejection to the ambient and control the operating conditions in an efficient way. The gas cooler outlet temperature is controlled by the heat rejection to the ambient by the dry cooler located on the roof of the laboratory. The evaporator conditions are set by six heaters located in the glycol tank to ensure the reference cooling capacity of 50 kW. Both glycol loops are charged by an individual pump.

2.2 Measurement equipment

The test rig is fully equipped with measurement instruments to control the operating conditions and cooling capacity of the system. The pressure transmitters Danfoss AKS 32R and AKS 2050 are used to measure and control the pressure levels in each section of the R744 loop up to the pressure level of 160 bar. The temperature is measured by the temperature sensors AKS-21 PT1000 that allow for the temperature range measurements from -70°C up to 180°C. Moreover, additional pressure and temperature sensors are installed directly at the ejector inlets and the outlet. The refrigerant mass flow rate at the motive and suction ports of the ejector was measured by three precise Coriolis type mass flow meters manufactured by Endress+Hauser.

2.3 Control system and data acquisition system

The AK-PC-782A Danfoss control system is used to carry out the test campaign at different operating conditions and cooling capacity. In addition, all measurements are recorded and stored by Danfoss StoreView with a recording frequency of 5 seconds. The quasi-steady state conditions of the investigated operating point was set by constant ejector parameters or with small deviations within the period longer than 10 minutes (approx. 120 recorded points). Hence, the NIST guidelines were used to evaluate and calculate the uncertainties from experimental tests (Taylor & Kuyatt, 2001).

3. PIV APPROACH

Visualisation procedure using PIV approach requires high accuracy of camera and light source positioning. The arrangement of the visualisation procedure is presented in Fig. 2, where global view is on the left-hand side and the zoomed view at the ejector is presented in Fig. 2 (b) and the safety box in Fig. 2 (e). As shown in that figure, the ejector transparent section is set in horizontal position. To highlight the core of the ejector, laser stream (marked by the green dashed line in Fig. 2 (a) is pointed perpendicularly on the transparent section. Then the camera is pointed vertically and perpendicularly to the laser stream. The ejector case is covered with the black paper in order to minimise distractions and refraction of the laser stream. Moreover, the safety box is covered in order to reduce undesirable external light sources. Furthermore, the high accuracy of the positioning is ensured on the basis of a dedicated frames presented in Fig. 2 (c) for the laser and in Fig. 2 (d) for the camera. Namely, the horizontal position of the laser is provided by its pocket, while two screw rails which allow for a very precise regulation of the laser vertical positioning. The vertical positioning of the camera is adjusted on the basis of four dedicated legs of its frames. Moreover, the positioning of the lens is controlled by another set of two screw rails.

The R744 flow field inside the ejector mixing section was captured with the high-resolution PIV system. That system was equipped with Dantec Dynamics Flow Sense 4M MK4 II camera which has a 2048x2048 CCD sensor with a pixel size of 7.4 μm. The maximum frame rate for the mentioned camera was 14 frames per second. A Nikon Nikkor AF 200 mm F/4D ED-IF Micro lens was paired with the specified camera. It is also worth mentioning that the macro reproduction ratio for that lens is equal to 1:1. In order to illuminate the analysed ejector section, a double-pulse Quantel Twin BSL 200 laser was used. The maximum energy output for that device is 200 mJ @ wavelength of 532 nm. All the devices of the utilised PIV system were synchronised using a Dantec Dynamics Synchronizer controlled

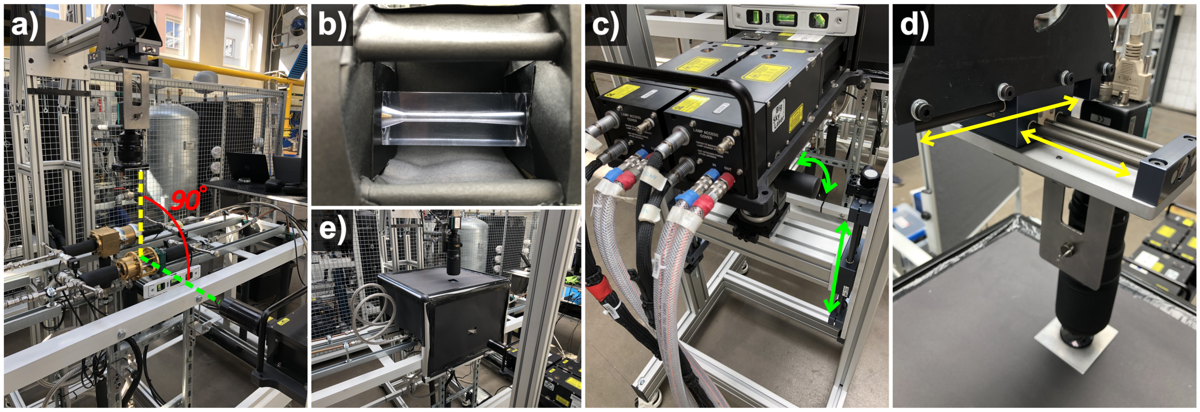

Figure 2: Visualisation equipment for the PIV approach

with commercial software Dantec Dynamic Studio v. 3.41. Moreover, the mentioned software was used to postprocess the captured frames.

The preliminary result of the PIV visualisation procedure is presented in Fig. 3. Hence, the resulting ejector efficiency according to (Elbel & Hrnjak, 2008) is equal to 19.99% ±1.0% with the mass entrainment ratio of 0.36 ±0.01. The motive nozzle outlet is located on the right-hand side of the picture in Fig. 3. Absolute pressure of 80 bar and temperature equal to 32°C was set for the motive port. Suction and outlet ports were supplied by 28 bar and 8°C and 32 bar and -1°C respectively. The resulting motive and suction nozzle mass flow rates were at the level of 206 kg/h and 75 kg/h respectively. The expansion cone of the motive stream can be characterised on the basis of the α angle. The expansion cone is less visible at the beginning of the constant area cross-section of the mixer. A shape of the aforementioned cone could be a crucial data for the assessment of the expansion process modelling. Due to the radial suction port and resulting swirled flow, highly turbulent flow is visible along the mixing zone. The video recording allows for the analysis of bubbles path alignment and the resulting δ angle. The behaviour of the outer annular stream paths would be a very valuable information for the turbulence model selection in the CFD analysis of the R744 ejector. Moreover, further visualisation study for different motive nozzle conditions should be proceeded.

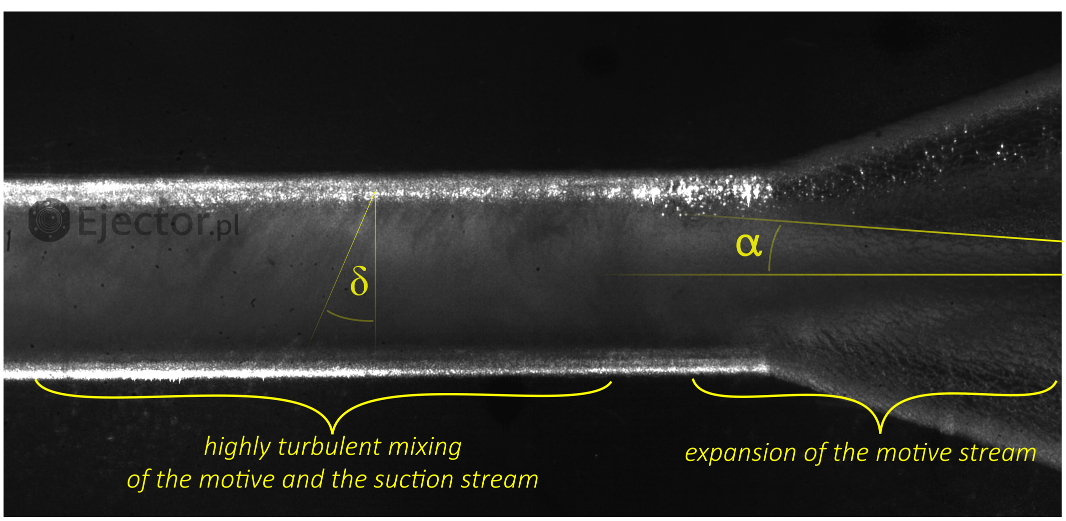

Figure 3: Photography of the R744 flow in the two-phase ejector obtained from PIV approach

4. HIGH-SPEED CAMERA APPROACH

Arrangement of the equipment in the second approach required less precision according to the lack of necessary angles between the glass and the camera sensor as presented in Fig. 4. On the other hand, the strong light source pointed on front and back side of the transparent section was crucial in the visualisation process. The high-speed camera type VEO340L produced by Photron was utilised with the same lens as described in PIV approach. The camera was able to record up to 200000 frames per second with the resolution of 128x128px. The PCC Studio software was utilised for the recording set up and frames selection. The visualisation of the motive nozzle opening and steady state operation in off- and on-design conditions were considered. An analysis of the steady-state operation is planned as next work package.

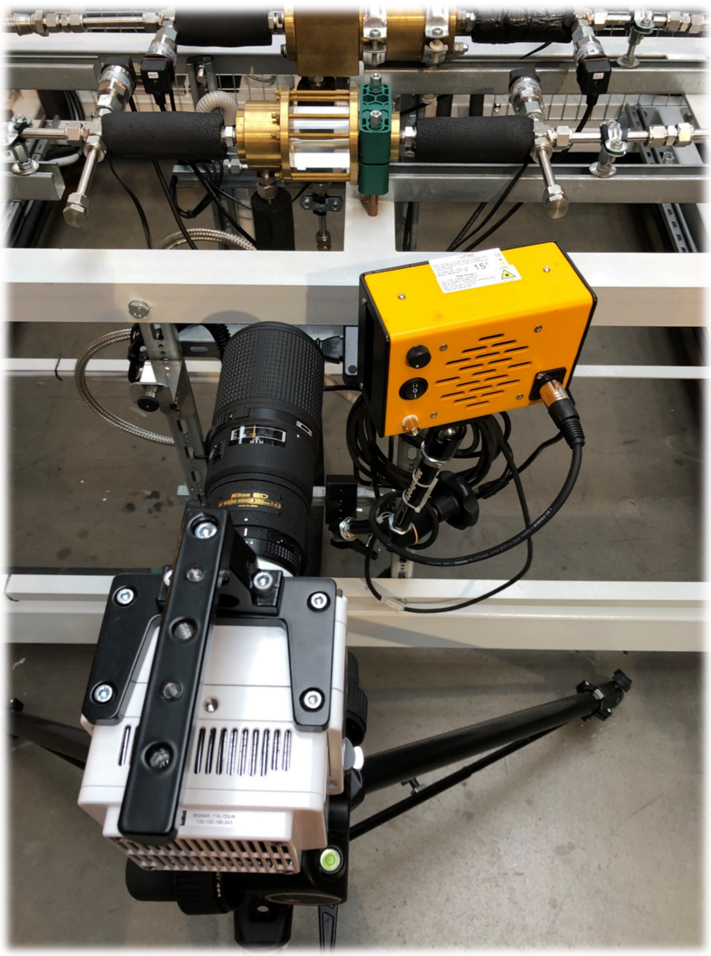

Figure 4: High-speed camera and led lights arrangement

Regarding possibility of recording with substantially increased rate of frames per second, recording of the motive nozzle opening was considered as a first case. Three motive nozzle conditions was selected as presented in Table 1. The suction nozzle port was closed and the receiver pressure was set at constant level of 30 bar.

The recordings of the three cases were presented on the basis of selected frames in Fig. 5. The front contours of the motive jet were visible in earlier frames for higher motive pressure, what was in accordance with expectations. In case A and B fluctuations of the flow were more visible than in the case C - the video for illustrating this phenomenon will be presented during the conference. The motive jet developed in case C covered larger area than cases of lower motive pressure. Finally, the time period around the 25 ms of case C was analysed more deeply in further paragraphs.

The short period of time could provide some insight to an internal flow structure. As presented in Fig. 6 approximately

Table 1: Operating conditions selected for the motive nozzle opening records

Operating condition	Absolute pressure, bar	Temperature, °C
A	50	10
B	70	20
C	92	36

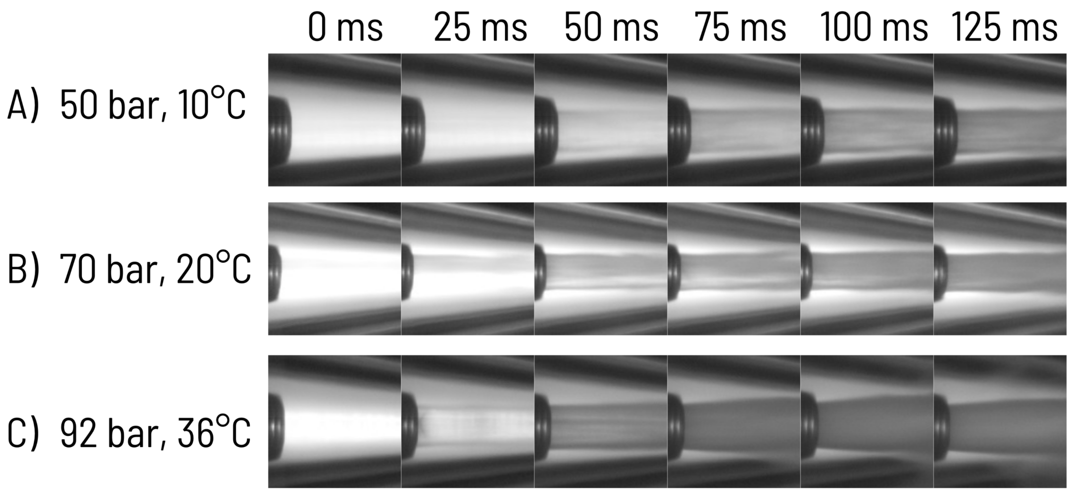

Figure 5: Three series of frames of the R744 flow during motive nozzle opening captured using high-speed camera

10 ms time allowed for some additional investigation of the Prandtl-Meyer flow in the pre-mixing chamber. Hence, the filtration and selection of proper frames should be characterised as challenging due to the large number of frames and the short period which could be used in the investigation of the internal structures. However, regarding the frame from 27.5 ms further analysis was provided below.

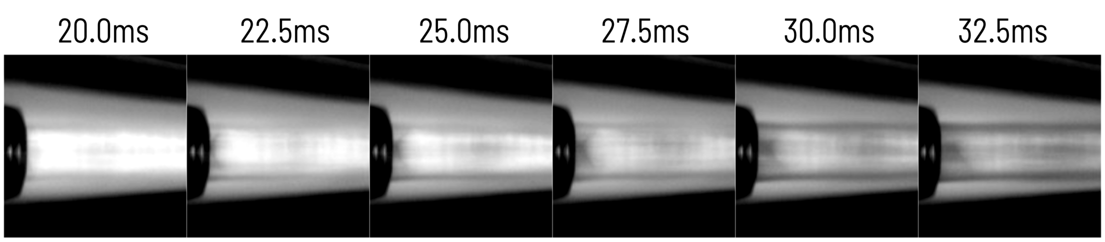

Figure 6: Series of frames of the R744 flow during motive nozzle opening for motive nozzle conditions C

The aforementioned frame was presented in a zoomed view and adjusted grey-scale balance in Fig. 7 where potential lines for shock-wave pattern contours were marked (green dashed lines). Nevertheless, some additional colour correction could allow for more sharpened colour separation. In the selected frame, areas of prevailing white or grey colour could be indicated. Regarding these areas, the distance between them could be estimated to present the regions of low and high density and correlated pressure.

5. CONCLUSIONS AND FURTHER WORK

Utilised approaches could be compared and at this stage of the investigation the high-speed camera delivers higher potential for quantitative analysis of the results. First of all, the equipment set up in the PIV approach is very challenging due to the small area where the laser and camera sensor should be arranged in a perpendicular manner. Secondly, the

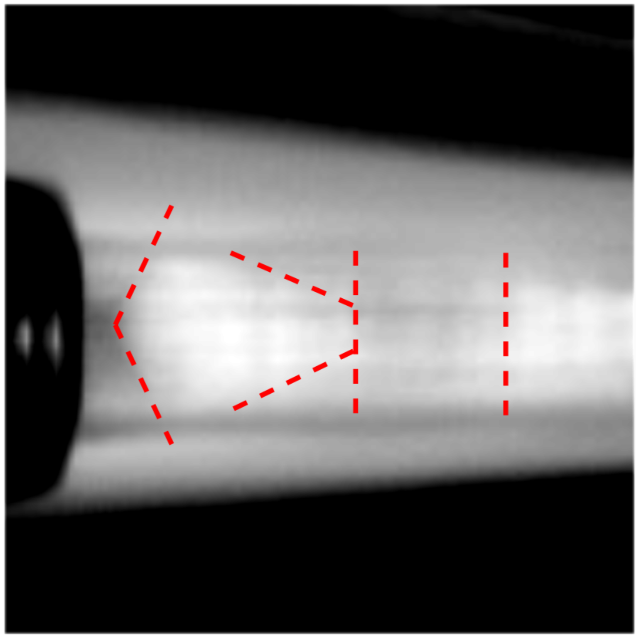

Figure 7: Selected frame from 27.5 ms of the motive nozzle opening captured using high-speed camera

nature of the flow delivers a superiority to the high-speed camera and its large FPS capability what could not be achieved with the utilised PIV equipment. However, the recordings obtained with the PIV approach were more sharpen than from the high-speed camera.

The analysis of the high-speed camera recording should be supported by the algorithms for grey-scale analysis to select frames with visible internal structures. Moreover, the analysis of the selected frame could deliver a data for turbulence models based on the shape of the internal structures. On the other hand, turbulence model validation should be considered along the transient numerical simulation. Properly selected boundary conditions will be characterised by varying motive pressure regarding the opening scenario.

Further work should be focused on the software development for reliable selection and analysis of the recordings. Analysis of the steady-state conditions with an opened suction nozzle should be investigated using high-speed camera, especially in the low speed region of the suction nozzle. According to the transparent section length, the diffuser would be selected as the next region of interest.

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