Index-Matching Technique for Effective Liquid Flow Diagnostics for Internal Combustion Engine

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An effective technique for visualization and measurement of liquid flows in a model of internal combustion engine (ICE) is presented. The technique is based upon the use of index-controlled fluid and transparent plastic models that have the same index of refraction as the fluid. This index-matching method allows unblocked flow visualization of any locations deep inside the model, locations that could not be observed or illuminated by other techniques. This advantage is enhanced by the use of rapid prototyping in which any complex geometry of the model can be fabricated directly and effectively from 3-D CAD data or 3-D surface data of the model. Some applications of this technique combined with PIV technique are presented.

Keywords: Testing, Flow Diagnostics, Flow Visualization, Flow Measurement, Index Matching, Particle Image Velocimetry (PIV), Rapid Prototyping

1. INTRODUCTION

Application of flow visualization and measurement techniques to industrial flow problems often requires the resolution of fluid behavior in very complex flow geometry. Examples are the flows in internal combustion engines (ICEs), those inside water-jackets of ICE, those around impellers of rotating machinery, those in fin-tube geometry of heat exchangers and so on. The existence of opaque and curved walls in such examples presents a challenge for flow visualization and measurement, particularly for Particle Image Veloimetry (PIV), that needs undisturbed optical access for both imaging and lighting. Conventional approach to avoid this problem is to make case-by-case modifications for better optical access. Such trial-and-error approach has, however, limited the range of applicability of visualization and measurement technique for flow diagnostics in industrial problems.

The authors have developed a new approach that can solve the problem mentioned above and therefore expand the applicability of flow visualization and measurement techniques to complex flow geometry. The approach is based on the utilization of index-matching and rapid prototyping. Perfect matching of refractive indices between the working fluid and the flow model provides an optical access for imaging and lighting adequate for flow visualization and measurement. The model is fabricated through rapid prototyping from three-dimensional surface data of the model. Some plastic materials, such as acryl, urethane, epoxy and so on), can be used for the rapid prototyping. The models are fabricated from their three-dimensional CAD data through laser modeling, numerical-controlled machining or vacuum casting.

This paper presents a flow visualization and measurement technique based on index matching and rapid prototyping along with its application combined with PIV to the flow inside a water-jacket model of ICE. It is demonstrated that the proposed technique is effective for revealing flow behaviors at locations deep inside the model having very complex geometry. It is concluded that the present technique can be a powerful tool for diagnostics of liquid flows in many industrial applications.

2. MTEHOD

2.1 Water Jacket Model

A water-jacket model of ICE is photo-fabricated from epoxy resin. The size of the model is approximately 450mm long, 300mm wide and 100mm high. The thickness of the model wall is 1-2mm. The 3D surface data of a commercial ICE is used for fabrication. The model is placed in an acrylic box that is for flow

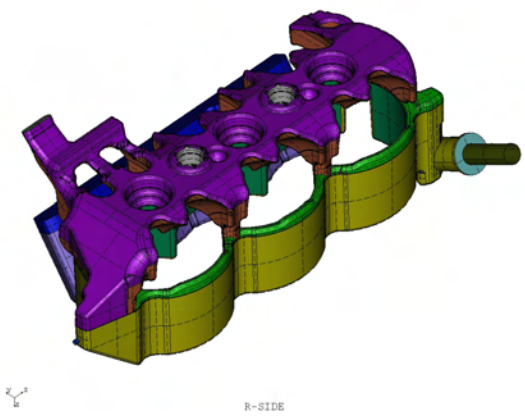

Fig. 1 3D surface data of the water-jacket model.

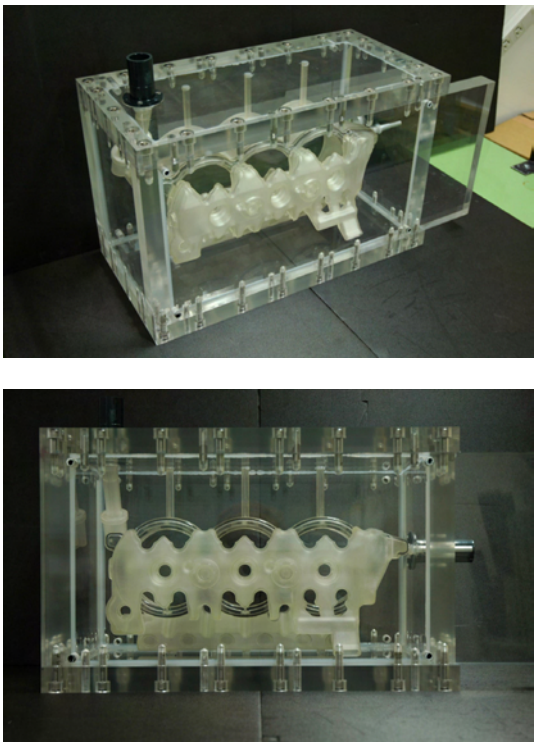

Fig. 2 The water-jacket model for flow visualization.

visualization and for giving static pressure resistance to the epoxy model of thin wall. The appearance of the model is shown in Fig. 1.

The model has one inlet and two outlets. The inlet flow rate is 24L/min and the outlet flow rates are 22.5L/min and 1.5L/min for main and side outlets, respectively. The Reynolds number defined at the main outlet is 14600, but the flow inside the model is observed to be laminar because of much narrower flow passage there. A thin metal gasket 0.5mm thick is inserted between the head and the main body of the model. The gasket has eight small holes serving as flow passage between the head and the main body.

2.2 Index Matching

The use of refractive index matching (merely, index matching in this paper) for flow visualization and measurement is not new idea and has been proposed by several researcher so far. Budwig (1994) summarized working fluids and model materials adequate for index matching. Typical combinations are listed in Table 1. The refractive index of model material ranges from 1.4 to 1.57. All the working fluids listed here are aqueous

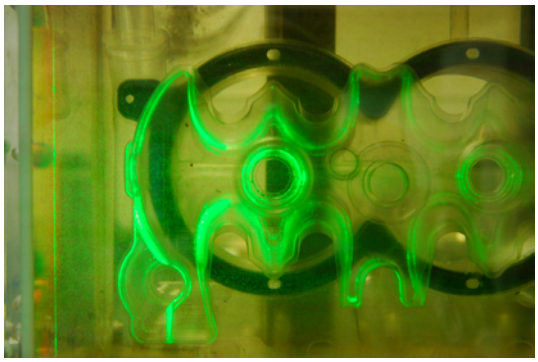

Fig. 3 Illumination with laser light for PIV measurement.

solutions whose refractive index can be adjusted by the concentration and the temperature of the solution.

As epoxy has relatively high index of refraction, zinc iodine solution is selected as working fluid. Its concentration is adjusted to achieve perfect index matching between the model and the fluid. The physical properties of the fluid at 30°C are as follows:

Index of refraction: 1.5365
Density: 2.14×10^{3}kg/m^{3}
Kinematic viscosity: 1.92×10^{-6}m^{2}/s

The effect of index matching is demonstrated in Fig.3. The model is immersed in the index-matching fluid in the acrylic model and the same fluid flows inside the model. This provides a good optical access to the location deep inside the model, as seen in Fig. 3. This feature is exploited in the PIV measurement described in the next section.

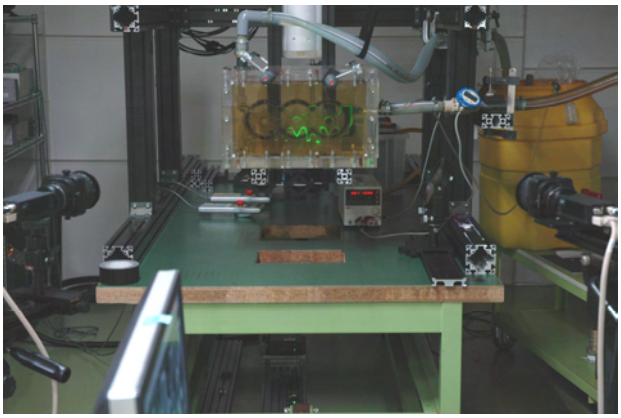

Fig. 4 Setup for stereoscopic PIV measurement.

Table 1 Typical combinations of model material and working fluid for refractive index matching.

Model material	Refractive index	Working fluid
Silicone rubber	1.40-1.43	Glycerol solution
Acrylic	1.49-1.53	Sodium iodine solution
Urethane	1.49-1.52	Zinc iodine solution
Epoxy	1.55-1.57	Zinc iodine solution

* all working fluids are aqueous solutions

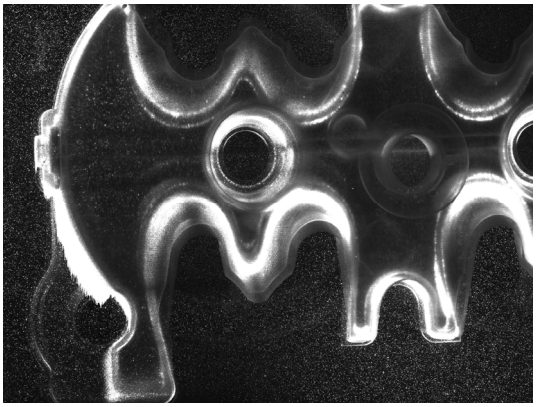

Fig. 5　Particle image acquired.

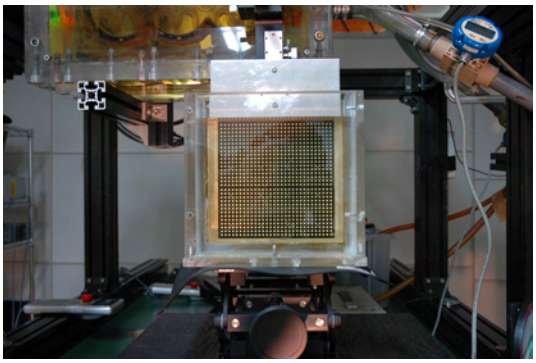

Fig. 6　Camera calibration for stereoscopic PIV measurement.

2.3 PIV Technique

The present PIV system consists of two digital CCD cameras (1,600×1,300 cells), a double-pulsed Nd:YAG laser (200mJ/pulse at 10Hz) and a timing controller. Perspective control micro-Nikkors (85mm focal length and F2.8D) are used for Scheimpflug configuration for stereoscopic PIV. Metal-coated spherical particles 20μm in diameter are used for flow tracers. A total of 1000 image pairs are acquired at each measuring location for taking ensemble average of the flow field. The direct cross-correlation method is used for PIV analysis, where interrogation windows of 45×45pixel are defined along with 64% overlap ratio. The present setup for stereoscopic PIV measurement is shown in Fig.4. An example of particle image acquired is given in Fig.5.

The camera calibration must be done for stereoscopic measurement. A target plate (or calibration plate) is placed in the flow field to provide target positions. It is shown in Fig. 6, where each white dot serves as a target mark. The calibration plate is placed in a surrogate box made of acrylic plate having the same thickness with that for the water-jacket model.

3. RESULTS AND DISCUSSION

3.1 Flow Patterns in the Head Section

The flow patterns in the head section are measured in two blocks separately as indicated in Fig. 7. Each block covers a region of 150mm wide and 120mm high. The results are presented in Figs.8 and 9 for Blocks 1 and 2, respectively. In-plane velocity component, out-of-plane velocity component and bird's eye view of all three velocity components are plotted in each figure. The flow enters in this section from the inlet located at the right-bottom corner of Block 2. Strong upward flow patterns seen in the in-plane velocity component in Fig. 9 correspond to the flow entering in this section. The flow is then oriented toward the left of the model and therefore the general flow patterns seen in Figs. 8 and 9 are those going from the right to the left of the model.

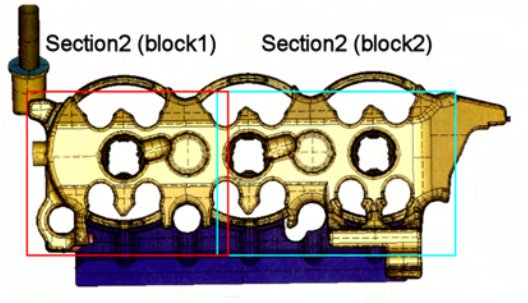

Fig. 7　Measuring blocks of the head section.

While going through the head section, the flow rate decreases gradually because of the flow escape through the small pipelines connecting the head section and the main body. The flow rates through the pipelines are determined by the pressure difference between them and also by the flow resistance at each hole in the gasket. This complexity makes numerical prediction of the flow rates difficult even though the flow is laminar. The flow finally goes out of the head section at the left-bottom corner of Block 1, where a strong downward flow motion is observed in the in-plane velocity component.

The flow patterns presented in Figs. 8 and 9 are very complex and three dimensional, exhibiting vortical or circulating patterns at several locations. It is demonstrated that the present technique is very effective to clarify such a complex flow.

3.2 Flow Patterns in Gasket Holes

As mentioned above, the flow resistance at each hole in the gasket is an important factor that determines the flow rate through the hole and thus affects the flow pattern in the head section. The flow patterns also provide a good test case for the verification of CFD codes. The present gasket has a total of eight holes as depicted in Fig. 10. Holes 1-6 are elliptic (about 7mm×5mm) while Holes 7 and 8 are circle (about 8mm and 4mm in diameter, respectively). To measure three-dimensional flow patterns through these holes, a close-up imaging of stereo-configuration is used as shown in Fig. 11.

The results for Holes 7 and 4 are presented in Figs. 12 and 13, respectively. Hole 7 is the largest in size and thus has the largest flow rate measured (3.0L/min), while Hole 4 has the largest flow rate (2.1L/min) among Holes 1-6. The in-plane

velocity component of Hole 7 exhibits a clear counter-clockwise circulation reminiscent of a gravity-driven swirling motion that would be observed at a drainage hole. It is conjectured that a strong pressure difference at this location actually sucks the fluid from the head section into the main body of the model. Similarly interesting flow pattern is seen in Hole 4, but the out-of-plane velocity component is directed simply from the head section to the main body.

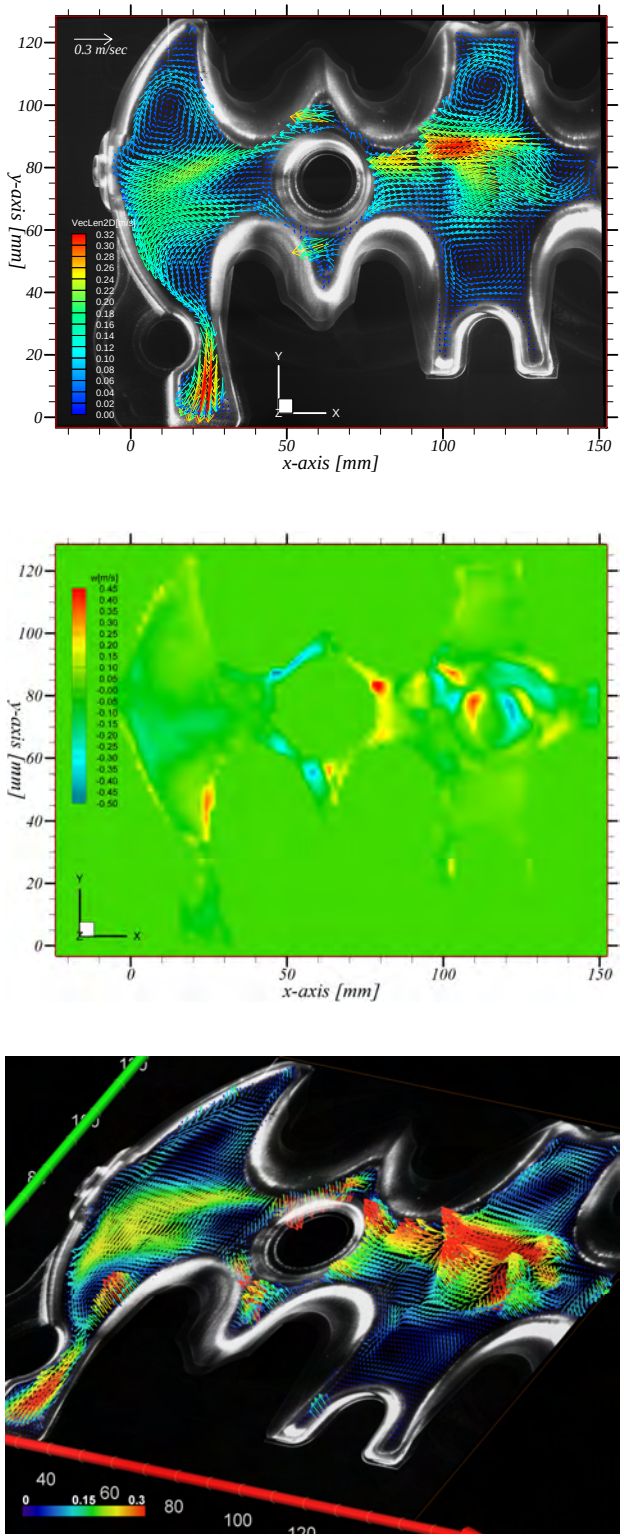

Fig. 8 Flow pattern in Block 1: (top) in-plane velocity component, (middle) out-of-plane velocity component, and (bottom) bird's eye view of all three velocity components.

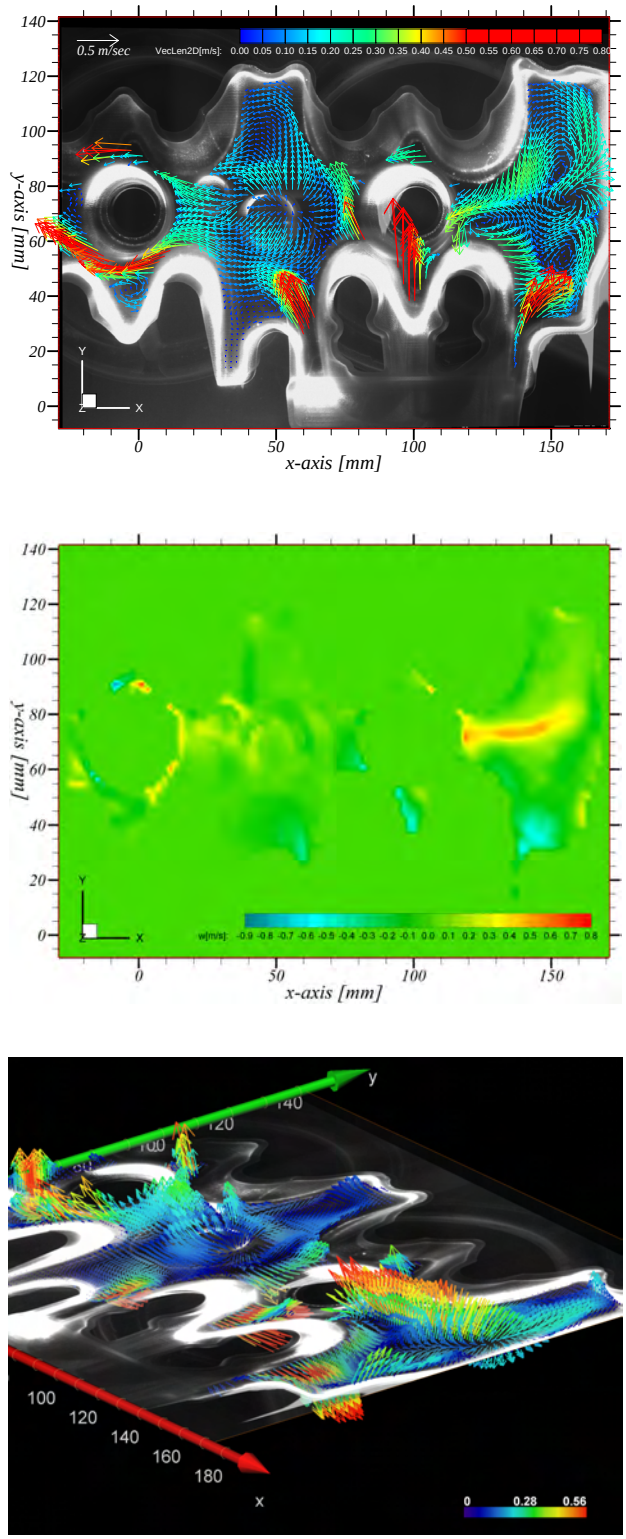

Fig. 9 Flow pattern in Block 2: (top) in-plane velocity component, (middle) out-of-plane velocity component, and (bottom) bird's eye view of all three velocity components.

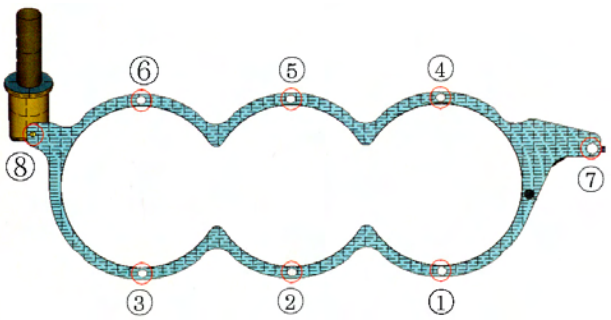

Fig. 10 Locations of gasket holes.

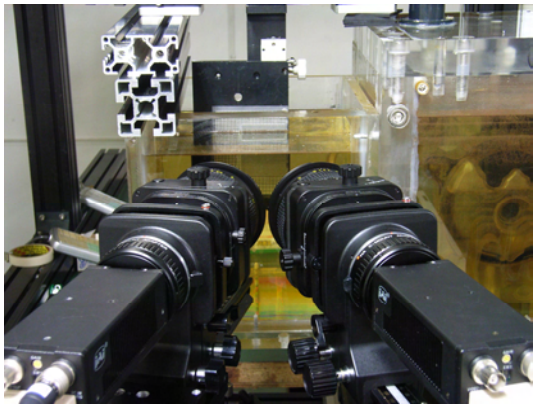

Fig. 11 PIV setup for the flow rate through gasket hole.

4. CONCLUSIONS

An effective technique for visualization and measurement of liquid flows in a model of internal combustion engine is presented. The technique is based upon the use of index matching and rapid prototyping. This unique flow visualization technique is combined with the stereoscopic PIV technique to provide quantitative information of the flow field inside complex geometries. This technique is applied to a water jacket model made of epoxy resin. It is shown that the three-dimensional flow patterns in the head section is revealed by the present technique. It is also shown that the flow patterns in the small holes made in the gasket are captured as well. These results demonstrate that the technique proposed in this paper can be an effective tool for diagnosting flow behaviors in complex geometry.

REFERENCES

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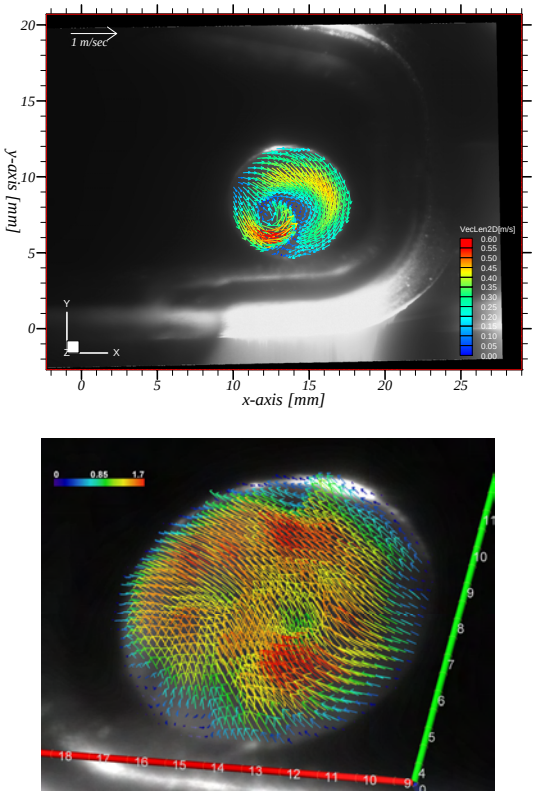

Fig. 12 Flow pattern in Hole 7: (upper) in-plane velocity component, (lower) bird’s eye view of all velocity components.

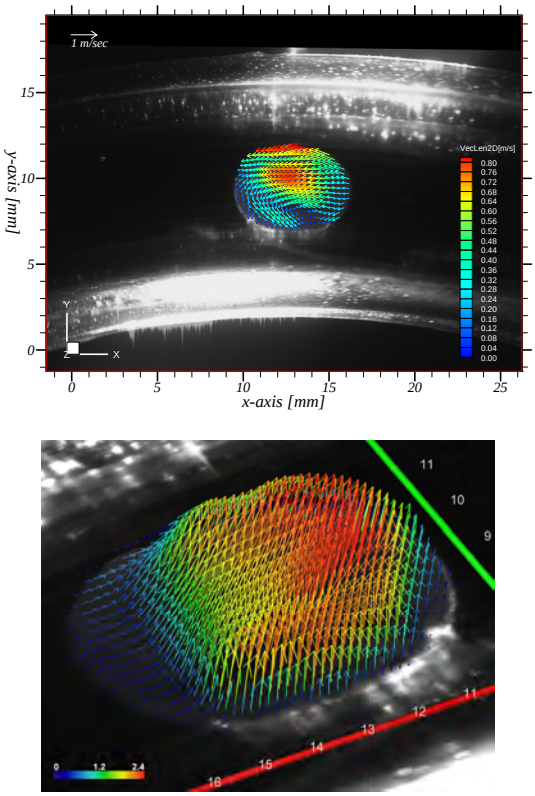

Fig. 13 Flow pattern in Hole 4: (upper) in-plane velocity component, (lower) bird’s eye view of all velocity components.