Visualization of Distribution of Shear Stress due to Water Vortex Flow with SSLCC

Souichiro OKAZAKI[1,*], Toshiki Ezure[2], Hiroyuki OHSHIMA[2], Zensaku. Kawara[1], Takehiko. Yokomine[1], Tomoaki. Kunugi[1]

[1]Department of Nuclear Engineering, Kyoto University, Kyoto, Japan
[2]Japan Atomic Energy Agency, Ibaraki, Japan
* okazaki.soichiro.22m@st.kyoto-u.ac.jp

Abstract In the pool-type fast breeder reactor, the primary heat exchangers and pumps are immersed in the reactor tank filled with the liquid metal. At the top of intake pipes of the primary heat exchangers, the wall stress near the intake pipe sometimes causes the cavitation vortex and leads to the erosion at the wall. The gas extracted by the cavitation makes the single-phase liquid flow in the primary heat exchangers unstable due to the transition from single-phase flow to two-phase flow. The wall shear stress caused by the vortex flow will be predicted by the transient 3D-CFD (Computational Fluid Dynamics) code to evaluate the design credibility. In order to predict the cavitation and subsequent accurately by CFD code from the viewpoint of nuclear safety, the verification & validation of CFD code should be conducted regarding the shear stress distribution on the wall which influences prediction of the cavitation. The purpose of this study is, therefore, to evaluate experimentally the wall shear stress caused by a suction vortex water flow with the shear-sensitive liquid crystal coating (SSLCC). There is no investigation on the application of SSLCC to the liquid complex flow to visualize and determine the wall shear stress as far as we know. As the result of the suction vortex flow experiment, it was found that the peak value of wall shear stress is appeared at the center and edge of the projected area of suction pipe. The non-dimensional profile of wall shear stress obtained by suction vortex flow experiment agrees well with that of numerical simulation.
Keywords: Experiment, Visualization by SSLCC, Wall shear stress, Vortex suction flow

1 Introduction

In the pool-type fast breeder reactor, the primary heat exchangers and pumps are immersed in the reactor tank filled with the liquid metal. At the top of intake pipes of the primary heat exchangers, the wall stress near the intake pipe sometimes causes the cavitation vortex and leads to the erosion at the wall.[1,2] The gas extracted by the cavitation makes the single-phase liquid flow in the primary heat exchangers unstable due to the transition from single-phase flow to two-phase flow. The wall shear stress caused by the vortex flow will be predicted by the transient 3D-CFD (Computational Fluid Dynamics) code to evaluate the design credibility. In order to predict the cavitation and subsequent accurately by CFD code from the viewpoint of nuclear safety, the verification & validation of CFD code should be conducted regarding the shear stress distribution on the wall which influences prediction of the cavitation.
Therefore, the purpose of this study is to evaluate experimentally the wall shear stress caused by a water vortex flow with the shear-sensitive liquid crystal coating (SSLCC).
The shear stress vector measurement technique by means of the SSLCC has been developed with spectrophotometric analysis of the reflected light.[3,4] The SSLCC is comprised of helical aggregates of long, planar molecules placed in layers parallel to the surface. The SSLCC produces a color spectrum when illuminated by white light. The color of the SSLCC is known to vary with the magnitude and direction of the shear stress, the relative angle of a light source and SSLCC and the relative angle of a observer and SSLCC. When the color is calibrated against such parameters, the visualized color image can be converted into the shear stress vector field over the coated surface. There are several researches in which the SSLCC applied to the air flow[5-7], but no SSLCC study has been done on the water vortex flow. In this study, the SSLCC was firstly applied to the water vortex flow, and the wall shear stress distribution due to the water vortex flow was visualized.

2 Experimental details

2.1 Liquid crystals and transformation of color image to shear stress distribution

We used NDP/192 mixed with 2-propanol as SSLCC. The weight ratio of NDP/192 is 33 wt.% and that of 2-propanol is 67 wt.%. In order to apply SSLCC homogeneously, we warmed SSLCC before and after coating up to 50 ^{o}C by a dryer. Once SSLCC is warmed, the color-change of SSLCC gets more vividly.
The SSLCC coating manner is one of the key issue of this method because the uniformity of the coating film is very important. We, therefore, have examined several methods and finally chosen a wire bar coater not the usual air-spray method.
To analyze the color change of SSLCC, it is more useful to represent the signal in terms of hue, which is defined as “the degree to which a stimulus can be described as similar to or different from stimuli that are described red, green, blue and yellow”. The hue, H, can be calculated from

$$H = \tan^{-1}\left\{\frac{\sqrt{3}(G-B)}{2R-G-B}\right\} \quad (1)$$

where *R*, *G*, and *B* are the three primary colors, red, green and blue, respectively.

2.2 Preliminary experimental apparatus and procedure

The preliminary experiment was carried out to decide the relative angle where the color changes most vividly and to relate the color-change of SSLCC to the magnitude and direction of the shear stress before main experiment.
The layout of apparatus for preliminary experiment is given diagrammatically in Fig. 1. The white light source is LED light (IDT LED120) whose color temperature is 5,600 K. The light source was mounted on the pillars which allow the light source to change its degree to the horizontal plane. The image system employed in this investigation was three digital cameras (Nikon D7100). Each camera was set to the manual 6000 pixel×4000 pixel mode. Personal computer captured the photographed images and eliminated their noise by using median filter. The LED light and three digital cameras are located on the spherical shell of which center was test section and the radius was 900mm. The angle interval of each camera is 20 degree.
The test section of preliminary experimental system was installed in the center portion of the circular platform of radius 20mm, which is appeared as hatching area in Fig. 1. The circular platform was rotated parallel to the floor. For the main experiment to be hereinafter described, the circular platform was common as well as the light source and the image system and the test section of main experimental system was also located in the center of the circular platform. The preliminary experiment system is shown in Fig. 2, which consists of the test section, the flowmeter and the compressor. The test section was rectangular channel: 205mm length × 100mm width × 0.5mm height. The SSLCC is covered the area of 100 mm length × 56mm width on the upper wall from the outlet of the channel by means of wire bar coater. The air flow (20^{o}C) from the compressor was pass through the test section channel after adjusting the flowrate to realize the plane Poiseuille flow.
Given the volumetric flow rate of the parallel channel *Q* [L/min], the width of the channel *b* [m], the height *h* [m], viscosity of air μ [Pa×s] and kinetic viscosity ν [m^2/s], the flow rate *u* [m/s] and Reynolds number *Re* can be calculated as follows.

$$u = \frac{Q}{6000bh} \quad (2)$$

$$Re = \frac{2ch}{\upsilon} \quad (3)$$

With the length of the flow path *l* [m], the pressure loss ΔP [Pa] and the wall shear stress τ [N/m^2] are obtained on the assumption of the plane Poiseuille flow.

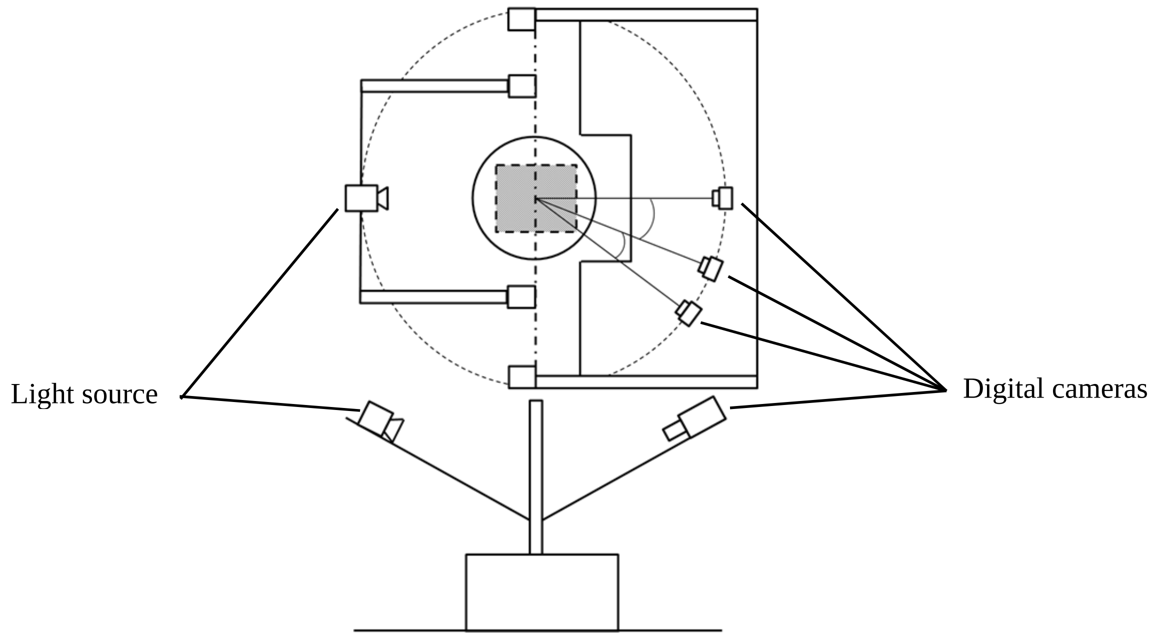

Fig. 1 Layout of experimental apparatus

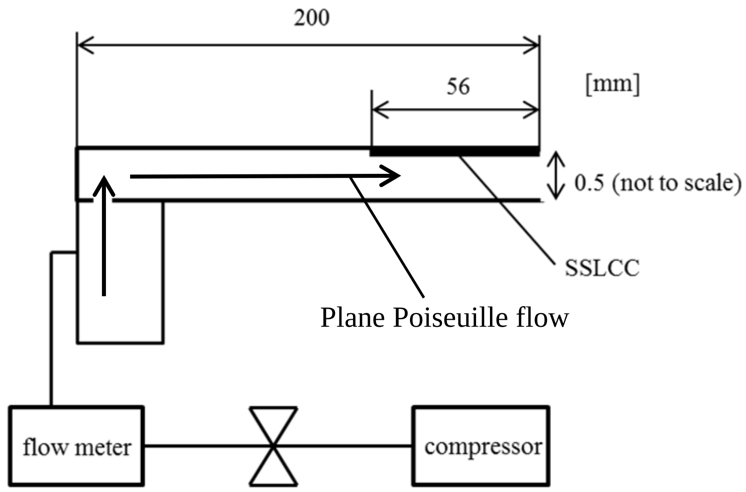

Fig. 2 Schematic view of preliminary experiment system

$$Q = \frac{6000b\Delta P h^3}{12\mu} \tag{4}$$

$$\tau = \frac{\Delta P h}{2l} \tag{5}$$

Then the wall shear stress can be expressed by only the known value.

$$\tau = \frac{6Q\mu}{6000bh^2} \tag{6}$$

The air flow rates, Reynolds number and calculated wall shear stresses in this preliminary experiment are summarized in Table 1.

Table 1 Parameters for preliminary experiment

volumetric flow rate (L/min)	flow rate (m/s)	Reynolds Number	shear stress for Poiseuille flow (Pa)
20	11.9	397	2.5
40	23.8	794	5.1
50	29.7	992	6.4
60	35.7	1190	7.7
70	41.6	1389	9.0
80	47.6	1587	10.3
100	59.5	1984	12.9

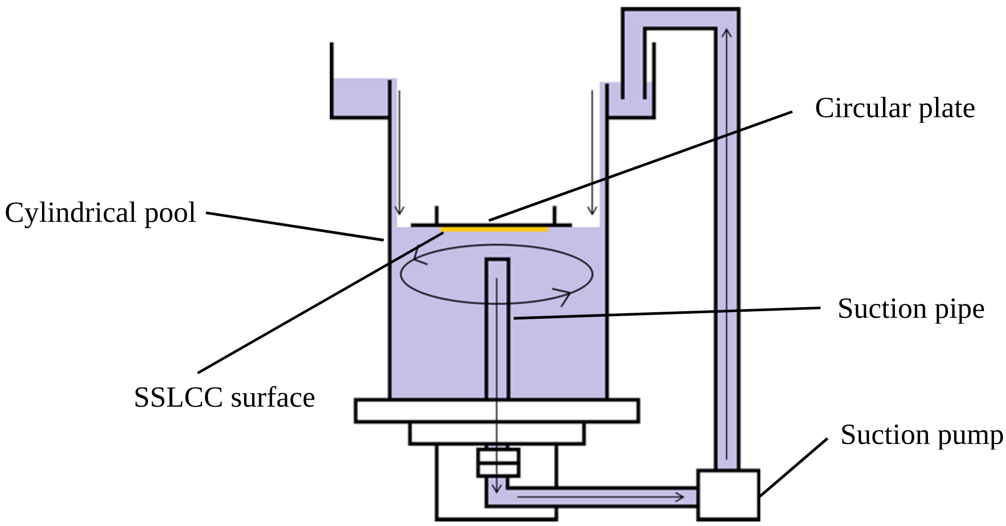

Fig. 3 Schematic view of test section system for vortex suction flow experiment

2.3 Experimental apparatus for vortex suction flow

As previous mentioned, we shared the experimental apparatus except the test section with the preliminary experiment. Figure 3 shows schematic view of test section system. The test section system consisted of the cylindrical pool (acrylic resin, 300mm height × diameter 500mm), circular plate (acrylic resin, 7mm thickness × diameter 200mm), the rotating table and the suction pump. The working fluid is water (20^{o}C). The cylindrical pool was placed on the rotating table and rotated by the motor. The circular plate was suspended independently of rotating cylindrical pool and the SSLCC is coated on the center square area (50mm × 50mm) on the water side surface of the circular plate. In the cylindrical pool, the suction pipe (PIV, 7mm inner diameter and 13mm outer diameter=13mm) is inserted from the bottom of the pool. The gap between inlet of the suction pipe and SSLCC wall of the circular plate was set to 3 mm. The water sucked from the pool through the suction pipe by the suction pump rose to the top of the cylindrical pool and fell freely along the wall of the cylindrical pool. The volumetric flow rate is 0.3 [L/sec] and the cylindrical pool was rotated 30 [r.p.m]. The rotation of water inside the pool makes the vortex in vicinity to the SSLCC wall of the circular plate.

3 Results and discussion

3.1 Calibration by preliminary experiment

We firstly obtained the optimum angle of the light source and the digital cameras to the SSLCC surface. The test was performed under the condition that the flow rate was fixed to the value of 40 L/min. The angle between the light source and SSLCC surface was varied 50° and 60°, while that between the line of sight of the camera and SSLCC surface was varied from 50° to 70° per 10 degrees. The color-change was evaluated by the differential of hue *H'* between flow and non-flow conditions as below,

$$H' = H - H_0 \tag{7}$$

where H means a hue at any flow rate and H_0 means the hue at the non-flow condition. Figure 4 shows the H'-θ curves for different combination of relative angles. According to the figure, it is decided that the combination of relative angles to the SSLCC surface is 50° and 70° for the light source the line of sight of the camera, respectively, is most suitable for calibration experiment because the color change is relatively big and the peak is clear. Though the color change is biggest in the case of the combination of 50° and 50°, the peak is not clearly appeared.

Next, H'-θ curves for different flow rate, that is absolute values of shear stress was obtained to determine the distribution of shear stress with arbitrary magnitude within the preliminary experimental condition. We changed the flow rate from 10 to 70 [L/min], which corresponds to the magnitude of the shear stress from 2.57 Pa to 12.86 Pa. The resultant H'-θ curves is shown in Fig. 5.

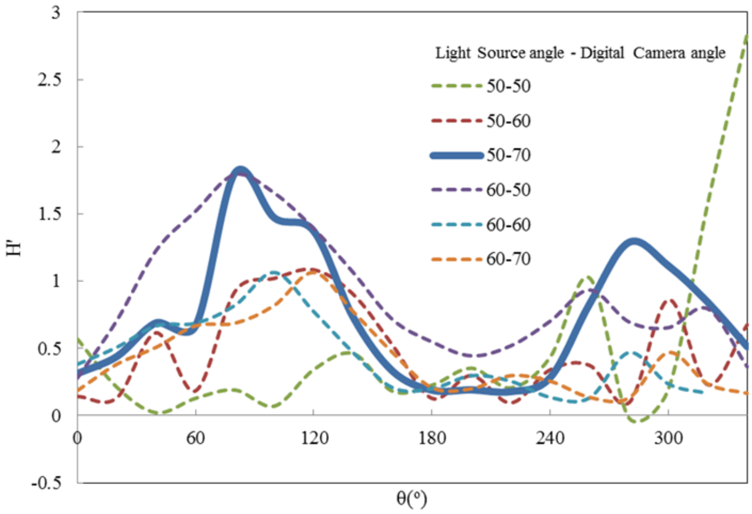

Fig. 4 Hue'-θ curves for different relative angles

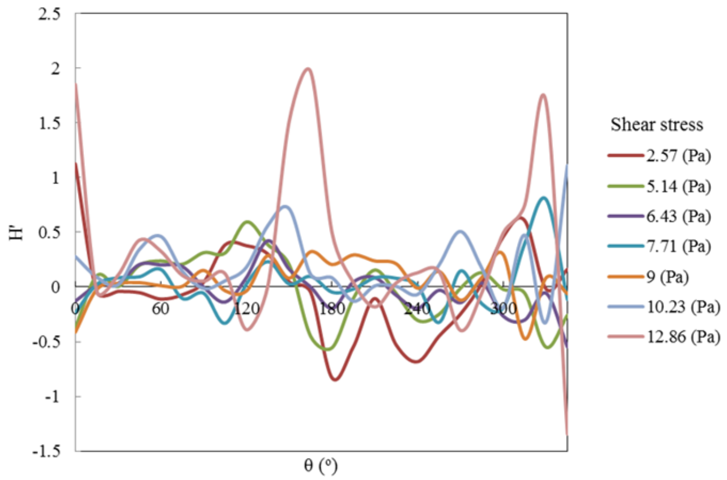

Fig. 5 Hue'-θ curves for shear stresses

3.2 Measurement of wall shear stress of vortex suction flow

The analysis to determine the magnitude and direction of the shear stress for the vortex suction flow experiment was conducted by the spline approximation using the calibration curves shown in Figure. 5. We firstly decided the relative angle α between the line of sight of the digital camera and the SSLCC surface in the plane Poiseuille flow to minimize the following E_{C1}.

$$E_{C1} = \Sigma(H'_{11}(x,y) - h'_{11}(\alpha))^2 + (H'_{21}(x,y) - h'_{21}(\alpha))^2 + (H'_{31}(x,y) - h'_{31}(\alpha))^2 \quad (8)$$

where C=1,2,3 correspond to the values obtained by Camera1, Camera2 and Camera3, respectively. Furthermore, H_{C0} and H_{C1} mean the hue under the non-flow condition and under the flowing condition, respectively.
Then, we chose the calibration curves with given α. We calculated following E_{C2} by round-robin with the magnitude and direction of the shear stress, τ and γ at all pixels for resultant photographs of vortex suction flow experiment.

$$E_{C2} = (H'_1(x,y) - h'_1(\tau,\gamma))^2 + (H'_2(x,y) - h'_2(\tau,\gamma))^2 + (H'_3(x,y) - h'_3(\tau,\gamma))^2 \quad (9)$$

The combination of τ and γ which can minimize E_{C2} is applied for each pixel.
Figure 6 represents the distribution of the wall shear stress of vortex suction flow. The round-shaped red and orange area in this figure corresponds to the projection of the suction pipe location. At the center and the edge of the suction pipe, the magnitude of the shear stress caused by a suction flow has its peaks.
The numerical simulation in similar configuration of present vortex suction flow experiment has been performed, provided however that the inner and outer diameters of the suction pipe are 55 mm and 61 mm, respectively, the flow rate is 4.5 [L/sec] and 5.5 [L/sec] and gap between the inlet of suction pipe and the wall is 45 mm. The comparison between the experimental result and the simulation data is shown in Figure 7. In order to compare the both results, the shear stress and the distance from the center of projection area of suction pipe are non-dimensionalized by the maximum value of shear stress and the inner diameter of suction pipe suction, D, respectively. The values of 0.95 and 0.55 of r/D correspond to the edge of the outer wall of suction pipe for experiment and simulation, respectively. The non-dimensional profile of wall shear stress obtained by present experiment agrees well with that of numerical simulation in the inner region of suction pipe. For the region lager than r/D=0.5, the comparison between both results cannot be done because of the effect of wall thickness difference of suction pipe.

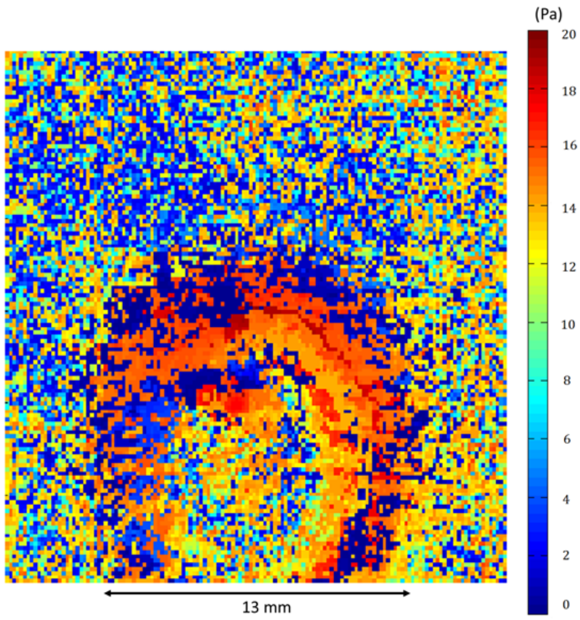

Fig. 6 Distribution of the shear stress

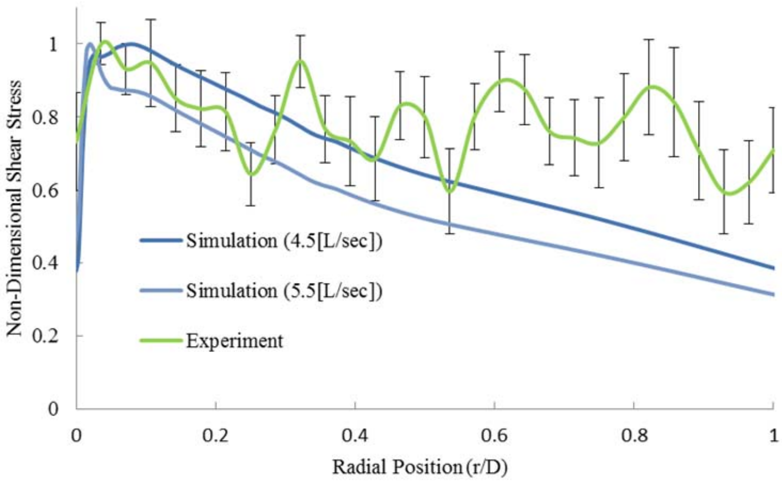

Fig. 7 Comparison of results between experiment and simulation

4 Conclusion

The wall shear stress caused by the suction vortex water flow was visualized by SSLCC and determine its magnitude by using spectrophotometric analysis.
For the calibration experiment to determine the hue and relative angle curve, the optimum angles to the SSLCC surface is obtained as 50^o and 70^o for the light source and the line of sight of the camera, respectively.
For the suction vortex flow experiment, it was found that the peak value of wall shear stress is appeared at the center and edge of the projected area of suction pipe. The non-dimensional profile of wall shear stress obtained by present experiment agrees well with that of numerical simulation.
There is no precedence investigation on SSLCC visualization and measurement of wall shear stress by means of liquid (water) as far as we know. From present investigation, we found several issues for use of water and application of SSLCC method to strong non-uniformity of the flow. The next step will surely generate the vector map of wall shear stress for vortex suction water flow by resolving these issues.

References

[1] Ezure T, Kimura N, Kobayashi J, Kamide H (2011) Experimental study on influences of kinematic viscosity on occurrences of cavitation due to sub-surface vortex. Proceedings of the 14th International Topical Meeting on Nuclear Reactor Thermalhydraulics, Toronto, Canada, September 25-30.

[2] Ezure T, Kimura N, Kobayashi J, Kamide H, Kameyama Y (2013) Effects of fluid viscosity on occurrence behavior of vortex cavitation -vortex structures and occurrence condition-. Proceedings of the 15th International Topical Meeting on Nuclear Reactor Thermalhydraulics, Pisa, Italy, May 12-17.

[3] Reda D C, Jnr Muratore (1994) Measurement of surface shear stress vectors using liquid crystal coatings. AIAA Journal, vol. 32, pp 1576-1582. doi: 10.2514/3.12146

[4] Reda D C, Wilder M C, Farina D J, Zilliac G (1997) New methodology for the measurement of surface shear stress vector distributions. AIAA Journal, vol. 35, pp 608-614. doi: 10.2514/2.165

[5] Fujisawa N, Shibuya S, Nashimoto A, Takano T (2001) Aerodynamic Noise and Flow Visualization around Two-dimensional Airfoil. *Transactions of the Visualization Society of Japan* vol.21 No.9 pp. 123-129.

[6] Zhao J S, Scholz P, Gu L X (2012) Measurement of surface shear stress vector distribution using shear-sensitive liquid crystal coatings, *Acta Mechanica Sinica* (2012) vol.28, pp 1261-1270. doi:

10.1007/s10409-012-0144-1

[7] Zhong S (2002) Detection of flow separation and reattachment using shear-sensitive liquid crystals. *Experiments in Fluids* vol.32, pp.667–673. doi: 10.1007/s00348-002-0409-8