A NANO-MICRO-COMPOSITE SENSOR FOR THE MEASUREMENT OF FLOW SHEAR STRESS

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ABSTRACT

This paper focuses on the development and testing of a sensor to measure the wall shear stress in a liquid flow environment. The sensor is based on a liquid crystal wall coating which can be considered as a type of nano-composite in which the liquid crystal nano-domains may rotate and align depending on the direction and level of applied stress. To avoid the problem of the liquid crystal coating being washed away by the flowing liquid, a micro-composite coating was developed in which the liquid crystal compound was dispersed in a silicone matrix. This nano-micro-composite sensor was used successfully in different types of water flows for the measurement of wall shear stresses in the range of 30 to 200 Pa.

1. INTRODUCTION

The value of the wall shear stress is an important parameter in several applications including cardiovascular implants, liquid flow in pipes, boundary layers (e.g. over submarines) and mixing vessels. In many of these applications water is the main liquid medium.

There are several methods that may be used to determine shear stress. Hot wire anemometry is the most accepted surface method [1]. It determines the value of shear stress from the change in the heat transferred to an electrically heated wire or film, which causes a change in the resistance of the wire that can be measured as a change in voltage. The oil dot washout method involves a mix of oil with a pigment which is applied onto the test surface in the form of tiny dots. During flow past the surface the shear stress developed causes deformation of the coloured dots, which after appropriate calibration at the same temperature can be translated into shear stress [2]. Oil film interferometry involves a thin layer of oil applied onto the test surface [2]. The thickness of the film is related to the wall shear stress, oil viscosity and time. Reflected light forms interference fringes and the distance between them is directly related to the film thickness. This technique provides a cumulative effect of a shear field over a certain period of time and the temporal resolution is therefore rather limited. Particle image velocimetry [3] provides a two-dimensional velocity field by correlating two rapidly imaged frames of suspended tracer particles. This procedure is accurate in the determination of velocity, but it requires extensive image processing and statistical analysis, and might involve substantial error in the estimation of shear stress in rapidly changing flows. This error is reduced in the laser doppler anemometry (LDA) method since it is associated with much smaller tracer particles. However, it is difficult to obtain full-field shear in LDA. Furthermore, LDA is incapable of measurements very near the fluid-solid boundary [1]. Pathline imaging uses suspended particles and a relatively long camera expose time to create streaks of light. Although this type of technique provides velocity and shear stress estimates over a large flow region, it severely lacks accuracy in the high-gradient regions as in the case of wall shear stress. Besides, it is not applicable to highly three-dimensional flows [4].

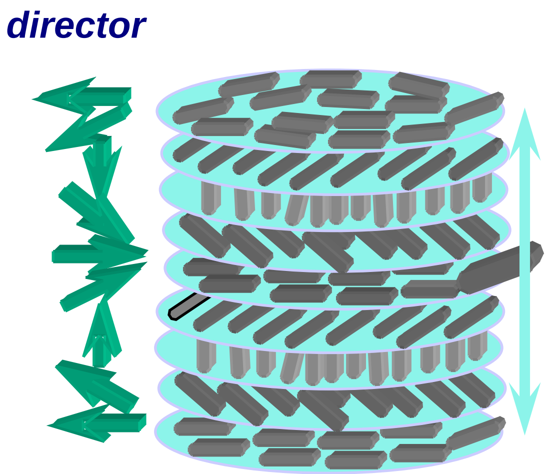
A liquid crystal (LC) coating onto the test surface may have initially a cloudy appearance of a certain colour. Wall shear stress under flow conditions aligns the liquid crystal domains so that they reflect light of a particular wavelength. Changes in the refractive properties may be controlled by temperature or shear stress. The temperature-sensitive variety (thermochromic LC) has been used as a shear stress indicator in transition flows in the start-up period.

2. THEORETICAL BACKGROUND

A chiral nematic type of liquid crystal was used in this study with a chemical formula:

$R\text{-}O\text{-}C_6H_4\text{-}COO\text{-}C_6H_4\text{-}$

This type of LCs are characterised by a segregated structure of lamellae of only a few angstroms thickness whereas the molecular rigid units have the same average alignment within each lamella. However, the alignment director in each adjacent lamella is slightly rotated in relation to the previous one, forming an overall helical structure along the z-axis (see Fig.1).



"**Fig. 1.** Diagram of a chiral nematic liquid crystal"

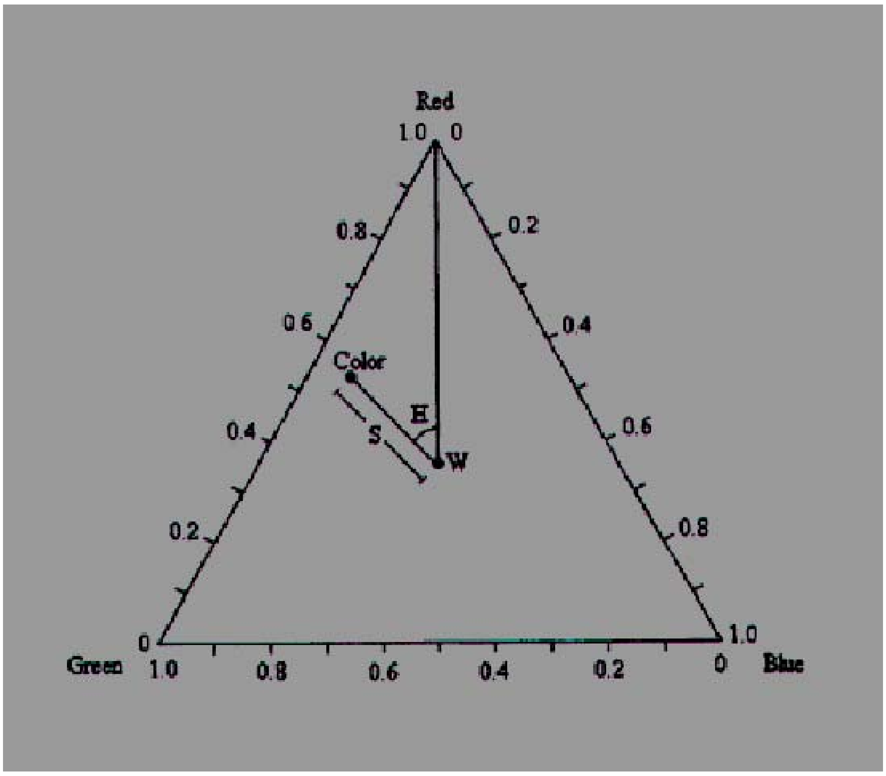
The colour of the light reflected by the liquid crystal substance depends on the state of alignment of the director, which in turn depends on the shear stress for a certain temperature. The obtained colour image is analysed into its component parts, Red (R), Green (G) and Blue (B). The values of R, G and B are converted into hue (H), saturation (S) and intensity (I) (HIS coordinates in Fig.2) according to the relations:

$$I = \frac{R+G+B}{3} \tag{1}$$

$$S = 1 - \frac{\min(R,G,B)}{I} \tag{2}$$

$$H = \frac{90 - \arctan\left(\dfrac{2R-G-B}{\sqrt{3}(G-B)} + C\right)}{360} \tag{3}$$

Where C = 0 if G≥B and C = 180 if G<B.



"**Fig. 2.** The RGB triangle and the HIS coordinates."

3. MATERIALS

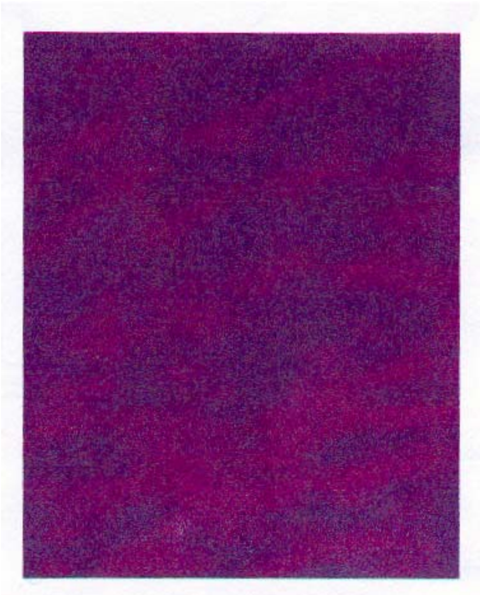
A TI 511 chiral nematic liquid crystal was used of the shear rate sensitive type with a viscosity of 250 mPas at room temperature. The liquid crystal was dispersed in a silicone matrix containing 50% active silicone ingredients in mixed tetrahydrofuran and dioxane solvents. The silicone was a polydimethylsiloxane polymer of a viscosity of 300 mPas at room temperature. The silicone begins curing when it comes into contact with atmospheric moisture.

Silicone was selected as a matrix in the micro-composite to protect the liquid crystal from been dissolved/removed by the flowing water. Silicone is an elastomeric material making a pliant coating, does not dissolve in water, can be easily mixed with the liquid crystal while uncured and it is transparent to allow observation of the colour change.

To facilitate the micro-dispersion of liquid crystal, the solvent chloroform was used to lower the viscosity initially. Chloroform evaporates quickly allowing the curing to start in the mixture.

4. EXPERIMENTAL PROCEDURE

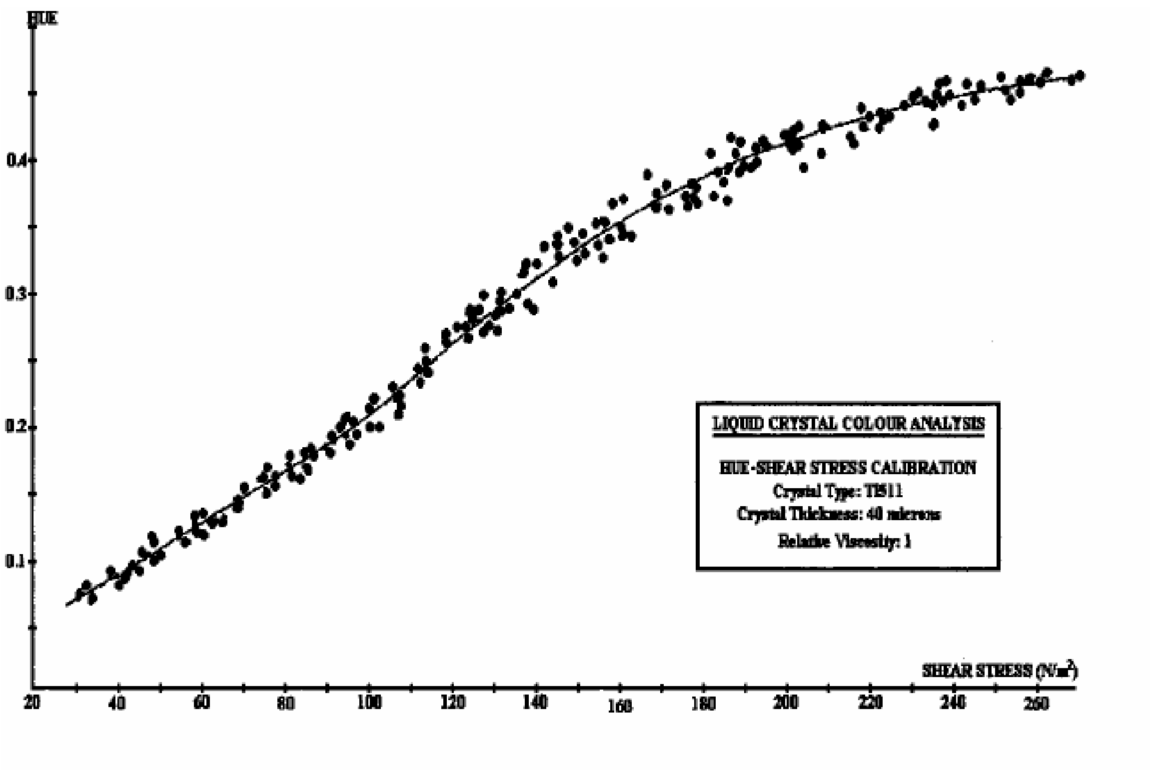
An optimal mixture was determined to consist of one part of silicone and four parts of liquid crystal. 13 parts of chloroform was added to one part of liquid crystal. The mixture was mixed in a glass container until a clear solution was formed. The mixture was poured onto a transparent tape and was spread to a 65 μm layer. The solvent was allowed to evaporate at room temperature and the LC-silicone mixture was allowed to cure for 36 h. Fig.3 presents an LC-silicone coating of a 4:1 composition.



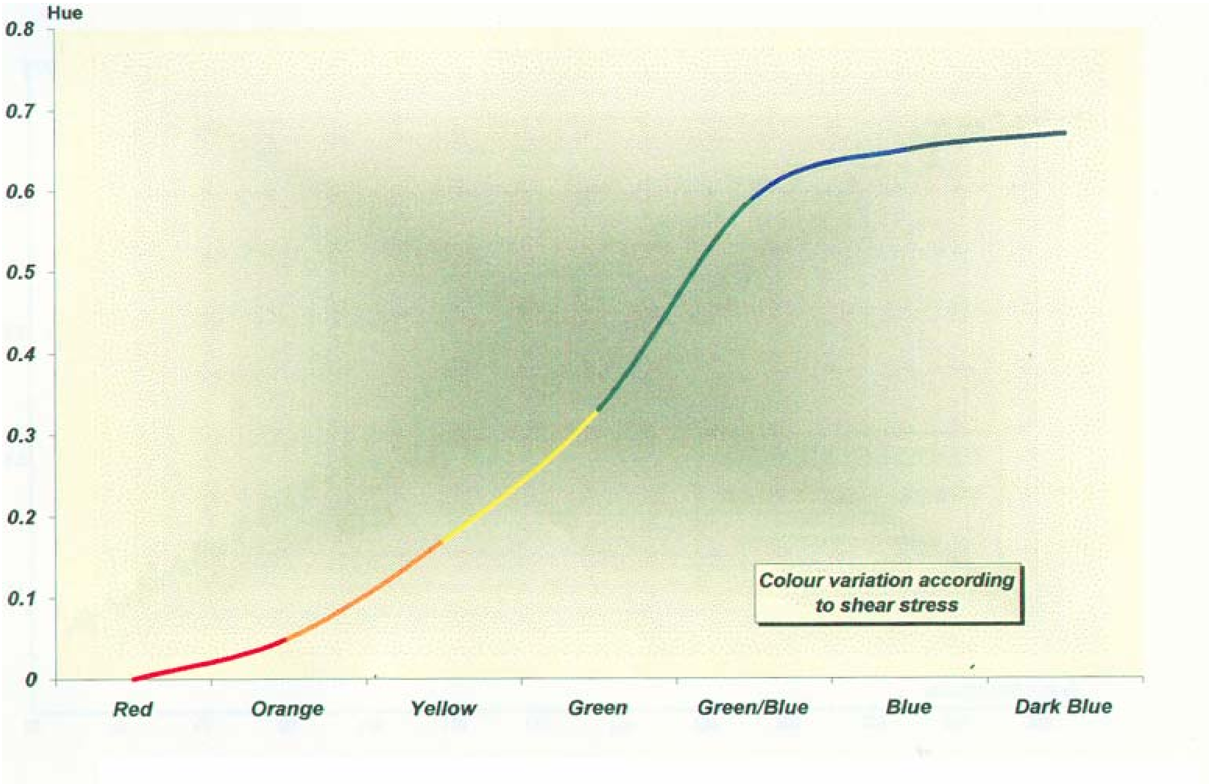
"**Fig. 3.** Micrograph of an LC-silicone coating."

5. RESULTS AND DISCUSSION

Fig.4 presents the results of calibration of the liquid crystal TI 511 (single phase-no silicone matrix) in gas flow where the shear stress is related to hue. Fig.5 illustrates the corresponding translation of hue to actual colour ranges. Hence, TI 511 is red at low shear stresses becoming orange and yellow at higher shear stresses. Fig.3 illustrates that the LC regions in the LC-silicone micro-composite are indeed in the red colour region under no flow conditions.



“**Fig. 4.** Shear stress calibration for LC TI 511 in gas flow”



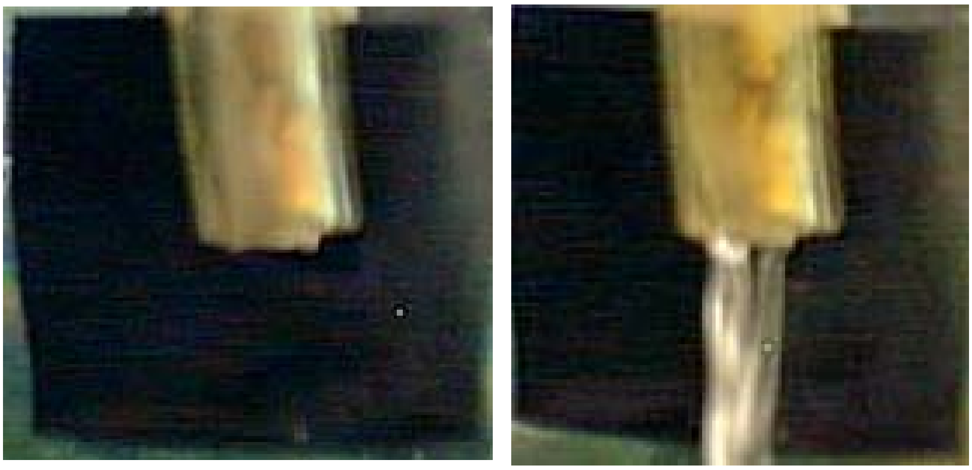
“**Fig. 5.** Hue-colour curve corresponding to the shear stress calibration curve of Fig.4.”

The first set of experiments using the nano-micro-composite flow sensor involved applying the LC-silicone coating on a disc rotating in the air environment, at different disc rotation speeds. The colour of the LC regions changed from red to orange to yellow, yielding hue values that corresponded to the stress levels of 6, 24 and 67 Pa which fall within the colour regions presented in Fig.4 and 5 for a single phase LC.

The second set of experiments involved the LC-silicone coating placed on the internal wall of a glass container, water poured in and stirred using a magnetic stirrer. The flow was maintained for 30 min going up to the yellow colour range of the flow sensor without the LC being dissolved in the water nor the colour losing its intensity.

The third set of experiments involved the LC-silicone coating placed on the internal wall of a transparent tube which was incorporated in a water flow rig. Fig.6 presents the colour change from before the flow start to the steady state flow. The hue determined from the digital photographs was translated to a shear stress value using the calibration curve in Fig.4. The obtained shear stress values were 49 Pa and 50.5 Pa from two independent experiments. When they are compared to the value of 49 Pa obtained from theoretical Poisseuille pipe flow calculations, excellent agreement can be seen.

However, when a larger diameter tube was used yielding a theoretical shear stress of 8.7 Pa, the nano-micro-composite sensor yielded a value of 40 Pa, which is very different from the expected theoretical value. This can be attributed to the fact that this level of shear stress is outside the range of shear stress of TI 511 as is presented in Fig.4.



(a) (b)

“**Fig. 6.** Change of colour of the nano-micro-composite shear stress sensor from (a) orange before the start of water flow to (b) bright yellow during the water pipe flow.”

6. CONCLUSIONS

A nano-micro-composite sensor was made and tested for the measurement of the wall shear stress in water flows. The micro-composite consisted of a liquid crystal phase dispersed in a silicone matrix, which after curing prevented the LC from being washed away by the water flow. The rigid units in the LC nano-domains changed alignment under the influence of shear stress, leading to a change of colour reflected from the sensor which was related successfully to wall shear stress values in water flows for wall shear stresses higher than 30 Pa.

References

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