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EXPLORATORY INVESTIGATION ON THE MEASUREMENT OF SKIN FRICTION BY MEANS OF LIQUID CRYSTALS

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SKIN FRICTION BY MEANS OF LIQUID CRYSTALS[1]

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SUMMARY

A new method is proposed for directly measuring local skin friction in aerodynamic testing. It makes use of thin coatings of cholesteric liquid crystal mixtures that respond to shearing forces by changes in the wavelength of maximum light scattering. A calibration of shear versus wavelength was obtained for a sample substance; a static calibration was made to measure the effects of temperature, pressure, and angle of viewing; and the behavior of the substance was observed in a pipe-flow experiment. Preliminary results showed that the method appears feasible. However, for such a method to become widely applicable in wind-tunnel testing, further research will be needed in (1) obtaining liquid crystal mixtures sensitive over appropriate ranges on the shear scale, (2) preventing the occurrence of roughness on the surface of liquid crystal coatings subjected to aerodynamic shear forces, and (3) developing a suitable optical measuring technique for data acquisition.

INTRODUCTION

Estimating the drag and other flight characteristics of a full-scale aircraft, cn the basis of wind-tunnel data from small-scale models, requires an important correction for the differences in local skin friction between the aircraft and the model. The usual procedure for computing total drag for the full-scale aircraft includes an evaluation of the drag due to skin friction on the model. The evaluation of the total skin friction drag on the model requires a knowledge of the local skin friction over the entire surface. The difficulties of determining local skin friction in the wind tunnel are characterized by the laboriousness and impracticality of direct measuring methods currently in use, involving such devices as Preston tubes, Stanton tubes, and floating element balances. Indirect methods are usually fraught with uncertainties. Typically, such methods require the location of boundary-layer transition on the model surface followed by computations of skin friction based on theoretical considerations, or the experimental determination of

local heat-transfer rate, and the subsequent application of the Reynolds analogy. The method proposed in this paper is based on the use of shear-sensitive liquid crystal mixtures. It would provide a direct correlation for determining skin friction over the entire surface of a model.

This work was prompted by the senior author's previous experiences in the application of liquid crystals to aerodynamic testing (refs. 1 and 2), which involved the use of temperature-sensitive mixtures in boundary-layer-flow visualization studies.

The principal objective of this investigation is to lay the groundwork in the development of a liquid crystal method for measuring local skin friction. A complete method, as envisaged at this time, would consist in having a set of suitable liquid crystal mixtures, appropriate model coating techniques, and sensing and recording equipment capable of giving in digital form the distribution of local skin friction over the surface of a model. This investigation reports on results from the preliminary calibration and pipe-flow tests of liquid crystal mixtures and provides guidelines for the future development of a complete method.

The authors would like to express their appreciation to Messrs. J. L. Fergason and E. Sharpless of the Liquid Crystal Institute in Kent, Ohio, for their advice and for supplying the initial liquid crystal samples.

LIQUID CRYSTAL MIXTURES

Liquid crystals are mostly derivatives of cholesterol. In their cholesteric phase (ref. 3), they appear as viscous liquids and yet show many of the features of solid crystals. One of these features is selective light scattering, that is, when illuminated with unpolarized white light incident at a given angle, liquid crystals reflect only one light wavelength strongly at each viewing angle. Small changes in temperature, shear, electromagnetic radiation, or chemical contamination can cause a change in the molecular structure of the liquid crystals and shift the wavelength of the reflected light in a continuous manner, usually from colorless, through a sequence of brilliant colors, and again to colorless. This phenomenon is reversible except in the case of permanent chemical contamination. A comprehensive paper on the optical properties of cholesteric liquid crystals and on their use in thermal mapping has been authored by J. L. Fergason (ref. 3).

So far liquid crystals have been used mainly for thermal mapping. This application is favored by current capabilities for preparing liquid crystal mixtures with a color indication over the entire visible spectrum within a desired temperature span, on a wide range of temperature levels (refs. 3 and 4). No such capabilities are currently available for the preparation of liquid crystal mixtures sensitive to shear.

The criteria considered in selecting a liquid crystal mixture for this investigation were: (1) shear sensitivity, (2) insensitivity to temperature, and (3) chemical stability around the operating temperatures.

A liquid crystal mixture, conforming reasonably well to the above criteria, was obtained by an entirely empirical approach. This mixture, LCS-15, had the following composition: 60 percent cholesteryl nonanoate, 26.75 percent cholesteryl chloride, 8.25 percent cholesteryl benzoate, and 5 percent cholesteryl oleyl carbonate.

The basis for LCS-15 is a mixture of cholesteryl nonanoate and cholesteryl chloride, as reported by Fergason et al. (ref. 4). In given proportions, this mixture shows little sensitivity to temperature over wide temperature spans, displays a remarkable shear sensitivity, but crystallizes at room temperature in a matter of minutes. Cholesteryl benzoate was used to improve temperature insensitivity, and cholesteryl oleyl carbonate was added to lower the melting point of the mixture, maintaining it liquid at room temperature for about 24 hours.

CALIBRATION AND EXPERIMENTAL TECHNIQUES

Three separate experiments were devised to calibrate and test the response of liquid crystal mixtures:

1. A static calibration experiment designed to measure the effect of temperature, pressure, and angle of viewing on the wavelength of maximum scattering from a liquid crystal mixture.

2. An experiment for the direct measurement of shear versus wavelength of maximum scattering.

3. A pipe-flow experiment to determine the behavior of the liquid crystal mixture in a wind-tunnel-like environment.

STATIC CALIBRATION EXPERIMENT

The diagram in figure 1 shows the general arrangement of the components used in the calibration of liquid crystal mixtures with temperature, pressure, and a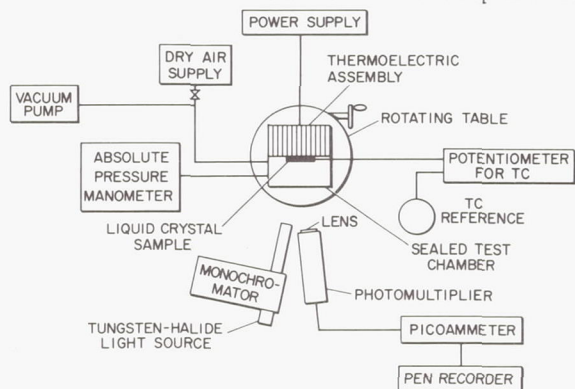ngle of illumination and viewing. The optical measuring apparatus, which is part of this arrangement, is shown in figure 2. In this test, a narrow beam of monochromatic light of continuously variable wavelength was focused on the liquid crystal sample within the sealed test chamber. The optical axis of the monochromator was tilted away from the horizontal while the liquid crystal sample was kept in the vertical plane in order to divert the light reflected from both the glass window of the sealed chamber and the liquid crystal surface from the

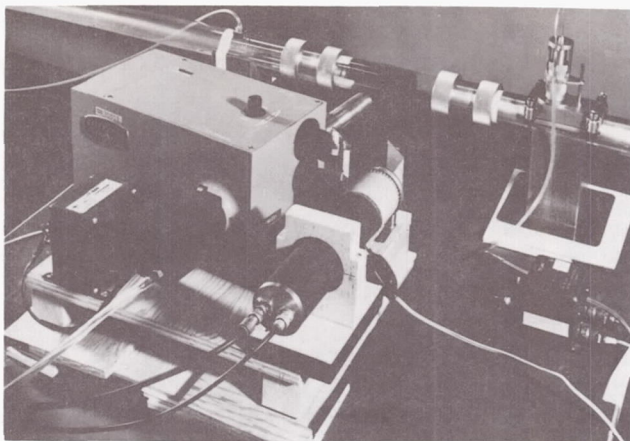Figure 1.- Schematic layout of the static calibration equipment.

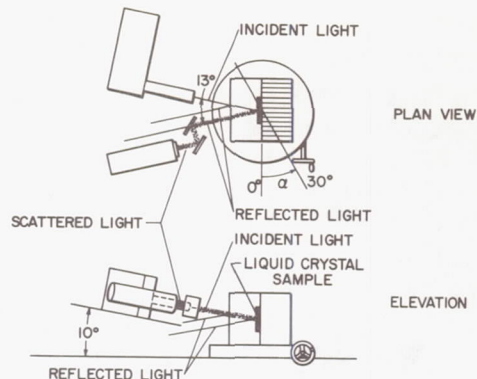Figure 2.- Optical apparatus for the measurement
of wavelength peaks.

Figure 3.- Plan view and elevation of the
optical arrangement.

photomultiplier for all angles α of the sample (see fig. 3). This allowed
the measurement of only the weak, scattered light reflected into the photo-
multiplier by two front surface mirrors. Because of the very low intensity of
the scattered light, the entire apparatus was covered to minimize extraneous
light. The scattered light was measured at an angle of 13° to the incident
light. A small angle was chosen so as to obtain near maximum intensity. The
plane of the liquid crystal sample can be rotated by an angle α of 0° to 30°
with respect to the bisector of the incident and measured light rays. The
photomultiplier gave a readily identifiable peak indication when the wave-
length of the light incident on the liquid crystals corresponded to their
wavelength of maximum scattering. The optical system included an air-cooled,
200-watt, tungsten-halide lamp that illuminated the monochromator slit. The
monochromator was of the grating type, with a 1-nm spectral bandwidth. The
output of the photomultiplier was read on a picoammeter and could be recorded
with a pen recorder.

The remaining components of this system were used in setting and measur-
ing the temperature, pressure, and angle of the liquid crystal sample. For
the tests, a 10 percent solution of liquid crystals in petroleum ether was
applied with an artist's air brush to provide a uniform coating about 0.15 to
0.2 mm thick, and the solvent allowed to evaporate. The substance was sprayed
on a copper plate covered with a coat of flat black lacquer. This plate was
attached to the surface of a thermoelectric assembly operated by a direct
current power supply, capable of cooling down to about -17° C. Temperatures
were measured with a copper-constantan thermocouple clamped to the copper
plate, referenced to an ice bath, and connected to a potentiometer. The
liquid crystal sample was enclosed in the sealed test chamber. The pressure
in this chamber was regulated from atmospheric to a few torr by means of a
vacuum pump and dry air for pressurizing. Pressure was measured by an abso-
lute pressure manometer. The entire assembly containing the liquid crystal
sample was mounted on a rotating table with graduations in degrees.

The calibration consisted in taking peak wavelength measurements for
several values of the angle α after the temperature and pressure became
steady at the liquid crystals in the test chamber.

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Experience indicated that the liquid crystals were unaffected by the substrate coating upon which they were sprayed, provided the two did not combine chemically. Thermal expansion of the substrate would not affect the wavelength indication since liquid crystals respond only to dynamic forces. Dry air was used in the test chamber to simulate the conditions of a wind-tunnel environment, even though water vapor in the ambient air had no effect on the liquid crystals.

SHEAR CALIBRATION

The artist's representation in figure 4 shows the apparatus devised for the calibration of liquid crystals with shear. In this test, falling weights drive a shaft carrying a wheel with a flat-faced annulus protruding from its side. Another annulus on a second wheel is matched to the first. This second wheel is made of transparent material, mounted on a separate shaft, and restrained from rotating by a force gage and counterweights. The interstice between the annuli was filled with a liquid crystal mixture and the angular velocity of the first wheel was set. Values of shear and the corresponding wavelengths of scattered light could then be obtained. Various driving weights were used to chan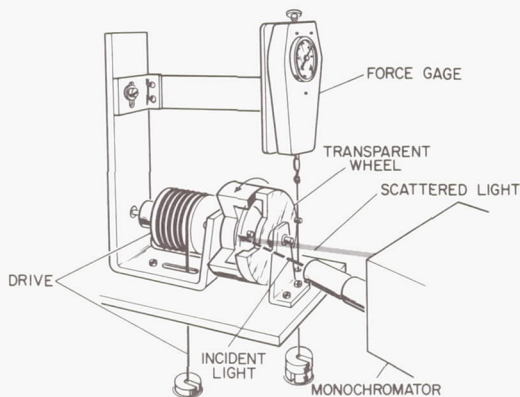ge the angular velocity of the first wheel to adjust the shear. The shear was calculated from the difference between the force gage readings under equilibrium (running and static) conditions divided by the area of the coated annulus. The wavelength of scattered light was measured by using the technique and optical equipment described in connection with the static temperature calibration experiment.

Figure 4.- Apparatus for the calibration of liquid crystals with shear.

In the shear calibration apparatus, the first wheel was made of solid aluminum, with the annulus of 97.75 mm outer diameter and 87.80 mm inner diameter, giving an area of 14.50 cm^2. The annulus surface was coated with flat black lacquer. The second wheel was made of transparent plastic material with an annulus matching that of the first wheel. The force gage was of the coil-spring type, with a range from 0 to 500 g.

PIPE-FLOW EXPERIMENT

The apparatus shown schematically in figure 5 is modeled on that used by Preston (ref. 5) for the calibration of pitot tubes in contact with the wall as a means for measuring skin friction. This pipe-flow experiment can provide a simple method for calibrating shear, since, for a pipe with smooth walls and
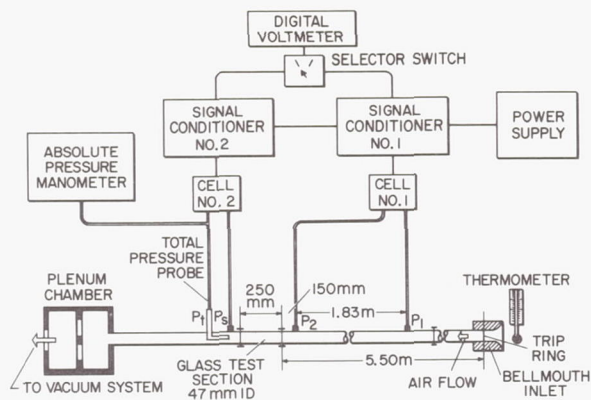
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Figure 5.- Schematic arrangement of the pipe-flow experiment.

steady turbulent flow, the static pressure drop in a given length becomes constant and is given by

$$\Delta p = \tau_0 \frac{4L}{D}$$

where Δp is the pressure drop over a length L in a pipe of inside diameter D, and τ_0 is the local value of shear. Therefore, the shear can be calculated directly from the static pressure drop in the pipe.

In this experiment, a long glass pipe, 47-mm inside diameter, with a 250-mm-long removable test section was connected to a large vacuum system. With part of the test section internally coated with a liquid crystal mixture, the color changes and behavior of the coating could be observed from the outside against a black background painted externally on the opposite side of the test section.

From test-section measurements of the dynamic and the total pressure at various radii, and the total temperature near the pipe inlet, it was possible to calculate the Mach number, Reynolds number, and velocity distributions across the pipe. Further, the local skin friction could be computed from the static pressure drop over a known length in the fully turbulent flow region. Optical measurements of the liquid crystals could be made with the apparatus described earlier (see fig. 2).

While this pipe-flow experiment was designed for the calibration of shear-sensitive liquid crystals, so far it has been mainly employed to observe the behavior of these substances in a wind-tunnel environment.

MEASUREMENTS AND RESULTS

A search was made for a liquid crystal material that would exhibit a significant variation in wavelength of maximum scattering due to shear, relative to the variation due to temperature, pressure, and angle of viewing. The field was finally narrowed to mixtures of four components: cholesteryl nonanoate, cholesteryl chloride, cholesteryl benzoate, and cholesteryl oleyl carbonate. The static calibration curves in figure 6 show the temperature dependence of the wavelength of maximum scattering at $\alpha = 0°$ and $p = 760$ torr for three liquid crystal mixtures. The proportions of the four-component
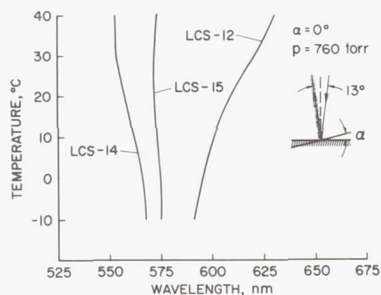

Figure 6.- Static temperature calibration curves of LCS-12, LCS-14, and LCS-15.

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mixtures, LCS-12, LCS-14, and LCS-15, are given in table I.

TABLE I.- PROPORTIONS OF LIQUID CRYSTAL MIXTURES

LCS-12, percent	LCS-14, percent	LCS-15, percent	Components
60.00	60.00	60.00	Cholesteryl nonanoate
30.00	25.00	26.75	Cholesteryl chloride
5.00	10.00	8.25	Cholesteryl benzoate
5.00	5.00	5.00	Cholesteryl oleyl carbonate

Maintaining constant the percentage of cholesteryl nonanoate and cholesteryl oleyl carbonate made it possible to interpret the effects of varying proportions of cholesteryl chloride and cholesteryl benzoate. It was known beforehand that the wavelength of scattered light from cholesteryl nonanoate/cholesteryl chloride mixtures is independent of temperature over large temperature spans (ref. 4). Measurements on a mixture of cholesteryl nonanoate, cholesteryl chloride, and cholesteryl oleyl carbonate[2] showed that the addition of the latter component, besides lowering the melting point, had the effect of maintaining the calibration line straight while giving it a positive slope. With reference to figure 6, experience showed that an increasing percentage of cholesteryl chloride mainly shifts the curve toward the red end of the spectrum, while an increasing percentage of cholesteryl benzoate rotates the curve in a counterclockwise direction. Curvatures and inflections in the graph of figure 6 are not easy to interpret with the available data. They could be due to the mixture of the main components or to impurities.

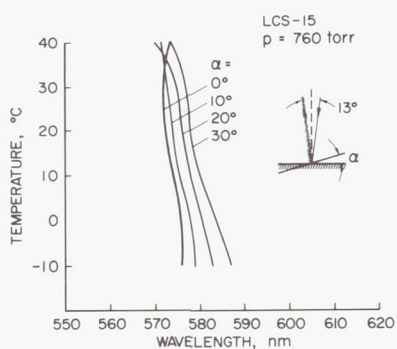Temperature calibration curves for LCS-15, the most temperature insensitive of the three mixtures, are shown in figure 7, which has an expanded abscissa scale. The curves correspond to $p = 760$ torr and $\alpha = 0°$, $10°$, $20°$, and $30°$. From the graph of figure 7, it is clear that the wavelength of maximum scattering depends on α. As α increases, the curve shifts toward the red end of the spectrum and becomes somewhat more dependent on temperature. It is desirable to have a liquid crystal mixture in which the influence of α is small so that the technique will be applicable to surfaces of large curvature.

Figure 7.- Static temperature calibration curves of LCS-15.

[2]Supplied to the authors by J. L. Fergason of the Liquid Crystal Institute in Kent, Ohio.

Separate measurements were also made at p = 380 and 10 torr. The curves of temperature versus wavelength for the three values of pressure at α constant revealed that the effect of pressure can be considered negligible by comparison with the effect of α. The greatest spread was consistently observed at temperatures above 20° C, and showed a maximum spread in wavelength of 4 nm.

It must be mentioned at this stage that all static calibration measurements were made after the liquid crystal coating had been "alined." This meant blowing air on it, at a shallow angle of incidence but in any direction, prior to taking measurements. Failure to do so would usually result in double peaks of the wavelength of maximum scattering and large and inconsistent deviations in the angle dependency. This "alining" will occur, of course, automatically in a shear calibration or wind-tunnel experiment.

The calibration curve of LCS-15 with shear is shown in figure 8. From 0 to about 3 g/cm^2 of shear, the liquid crystal mixture gives a 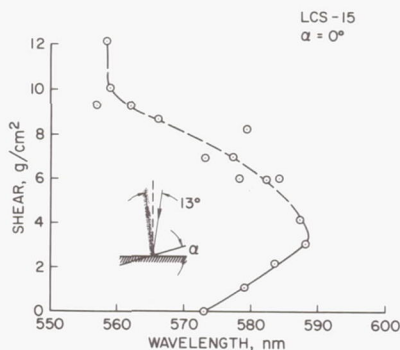change in peak indication from green to yellow. With increasing shear up to around 10 g/cm^2, the curve folds over and the peak indication returns toward the blue end of the spectrum. Above 10 g/cm^2, a saturation takes place and no further change in wavelength can be detected. For LCS-15, strong single peaks in the wavelength of maximum scattering were observed where the curve has a positive slope. In the region of negative slope and beyond, peaks were difficult to detect, repeatability was poor, and pen recordings revealed the appearance of multiple peaks. The uncertainty in the definition of the calibration curve for shear above 3 g/cm^2 is not detrimental since in most wind-tunnel tests the shear will be less than 3 g/cm^2.

Figure 8.- Calibration curve of LCS-15 with shear.

Calibration tests using LCS-12 gave a curve shifted on the shear scale and with different slopes, suggesting that liquid crystal mixtures could be modified to obtain other sensitivities and ranges on the shear scale.

In this investigation, no measurements were made to determine the effects of temperature and angle of illumination and viewing on the response of the liquid crystals while subjected to shear. Force measurements remained steady during each run, and proved to be repeatable and independent of the thickness of the liquid crystal layer.

The static temperature and angle calibration curves (fig. 7) and the shear calibration curve (fig. 8) for LCS-15 indicate the importance of obtaining liquid crystal mixtures that minimize the variations due to angle and temperature relative to shear sensitivity.

The pipe-flow experiment provided a useful tool for the observation of shear-sensitive liquid crystals under aerodynamic testing conditions. Preliminary qualitative tests were made with LCS-12 instead of LCS-15, since it showed greater sensitivity in the shear range obtainable from this apparatus.

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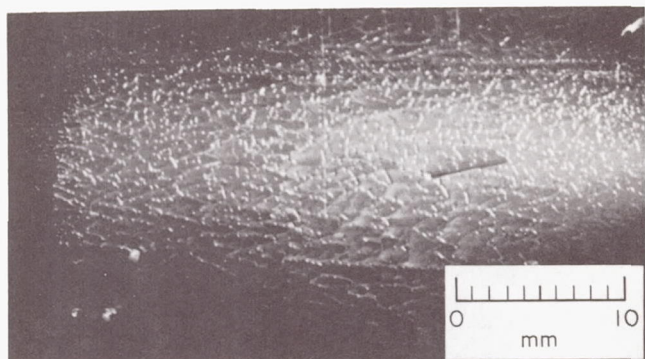
(a) Thin coating of LCS-12.
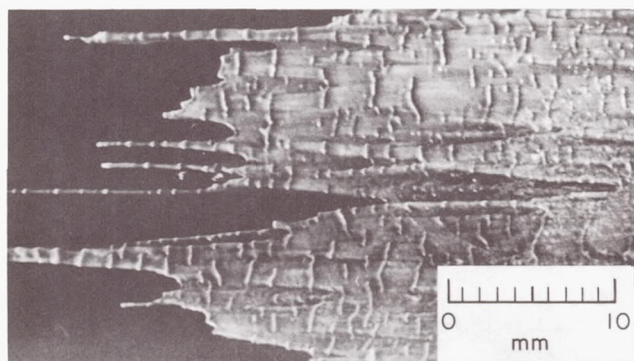
(b) Thicker coating of LCS-12.

Figure 9.- Surface roughness of liquid crystal coatings in pipe-flow experiments, flow from right to left.

LCS-12 was applied to the inside wall of the glass test section. All runs were made with a centerline Reynolds number of 5.08×10^5, and a centerline Mach number of 0.68, resulting in a skin friction of 0.55 g/cm^2. Photographs of resulting flow patterns are shown in figure 9, with the flow from right to left.

No good color indication was observed for very thin coatings, which was also the case with temperature-sensitive liquid crystal mixtures (ref. 1). Thin coatings displayed brilliant color when subjected to the aerodynamic shear forces in the turbulent boundary layer of the pipe; however, they tended to flow and develop a roughened surface (see fig. 9(a)). With a thick coating, transverse bars protruded from the liquid crystal surface and traveled downstream like propagating waves. This is illustrated in figure 9(b), in which the clean glass surface on the left is becoming coated by the flowing liquid crystals. Such surface roughness must be avoided for the measurement of skin friction in aerodynamic testing. These propagating waves were not observed with thick coatings of temperature-sensitive liquid crystals (refs. 1 and 2).

From still and motion pictures, as well as direct observation, the coating in figure 9(a) showed a fairly uniform color during the run. In a test using LCS-12 with a thin coating like that in figure 9(a), the color was seen to go from red to green during the change from static to maximum flow conditions. For LCS-12, the wavelength variation due to cooling is in the same direction and of significant magnitude relative to the observed change due to shear; therefore LCS-12 was not considered suitable for quantitative measurements.

Attempts to measure wavelengths using the pipe-flow experiment were not successful because of the unsteadiness of the scattered light signal, caused both by a change of intensity resulting from the motion in the roughened surface, and presumably by the fluctuations of the local turbulent skin friction value.

CONCLUDING REMARKS

The main contributions of this exploratory investigation on the measurement of skin friction by means of liquid crystals can be summarized as follows:

1. Experimental apparatus and instrumentation were devised for the quantitative calibration of the optical response of liquid crystal substances as a function of shear, temperature, pressure, and angle of viewing.

2. Proof was obtained that stable liquid crystal substances could be found and mixed in given proportions to provide a material with low sensitivity to temperature and good response to shear.

3. Static calibration results for a shear responsive but largely temperature-insensitive liquid crystal mixture showed that the wavelength of maximum scattering for this substance had practically no pressure dependence, and only a small dependence on the angle of viewing.

4. Shear calibration results suggested that shear-sensitive liquid crystal mixtures could be modified to obtain various degrees of sensitivity and cover different ranges on the shear scale.

5. Pipe-flow experiments revealed that, for the shear-sensitive liquid crystal mixtures tested, the coating thickness must be sufficiently thin to avoid surface roughness patterns when subjected to aerodynamic shear forces.

From the experience gained in this investigation, it is possible to point toward future research objectives for the development of a practical system for the measurement of local skin friction using shear-sensitive liquid crystal mixtures. These objectives are:

1. To obtain liquid crystal mixtures with low temperature, angle and pressure dependence; responsive over a large portion of the visible spectrum, in the shear ranges of interest in aerodynamic testing: 0 to 0.5 g/cm^2, 0.5 to 1.5 g/cm^2, and 1.5 to 2.5 g/cm^2.

2. To develop means for keeping the liquid crystal surface smooth when subjected to aerodynamic shear forces, and means for damping out oscillations in shear such as occur in turbulent boundary layers. Such results could per-haps be achieved if the liquid crystal surface were shielded with a tough, thin, and transparent film distributed over the surface in small separate pieces.

3. To develop an effective measuring system capable of detecting the wavelength of scattered light from liquid crystals over the surface of a model within a short period of time. Such a system could be based on a color television camera with appropriate filtering and a fast recording device.

Although a considerable amount of research and development would still be required before such a method can be practically implemented, the authors believe that shear-sensitive liquid crystal mixtures could offer a valuable new means for the measurement of local skin friction on the surface of wind-tunnel-tested models.

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