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TLC LITERATURE REVIEW (B)
HEAT TRANSFER AND FLOW VISUALIZATION STUDIES

This review was originally compiled during the late 1980s/early1990s. It is intended to be both an introduction and a guide. It contains references to some of the most important publications which pioneered the use of TLC products in flow visualization and heat transfer studies. It is not claimed to be an exhaustive study, and apologies are offered to authors whose work has not been included.

EARLY WORK

TLCs were first used in wind tunnel experiments by Klein (1, 2) in 1968, primarily to evaluate the feasibility of their use in determining the location of laminar and turbulent boundary layer transitions on aircraft models. Non-microencapsulated cholesteric LC mixtures were applied directly to the surface under study. At the appropriate conditions of free stream air temperature and velocity, the area of the model surface wetted with a turbulent boundary layer exhibited a different color to its laminar counterpart. The color difference resulted from the slightly higher adiabatic wall temperature associated with the turbulent flow. Although such qualitative information was readily available, attempts to obtain accurate quantitative data were unsuccessful due to the adverse effects that surface contamination, UV light and flow-induced shear stress produced on the unsealed liquid crystal mixtures.

In a follow-up study, Klein and Margozzi (3, 4) used the shear stress sensitivity of certain non-microencapsulated cholesteric LC mixtures in attempts to develop a technique for visually measuring shear stress. Although they found that it was possible to formulate cholesteric mixtures which were relatively sensitive to shear and insensitive to temperature, they found it difficult to accurately interpret the color signal produced, since the LC coating tended to flow and develop a rough texture in response to the shearing effects of the flow. It was concluded that while it appeared feasible to measure shear stress using non-microencapsulated cholesteric LC mixtures, much additional research would be needed to develop TLC mixtures that would exhibit high shear sensitivity, while at the same time maintaining low temperature, angle and pressure dependence. Since this study, significant advances have been made on the materials side and the availability of chiral nematic and combination TLC mixtures has enabled workers to overcome many of the problems encountered in the original study.

In an investigation similar in principle to that originally conducted by Klein (1, 2), McElderry (5) used microencapsulated TLC mixtures to determine boundary layer transitions on a flat plate placed in a supersonic air stream. The color displays produced were relatively independent of viewing angle and were not affected by the adverse sensitivity to shear and contamination experienced by Klein with unsealed TLC mixtures.

HEAT TRANSFER STUDIES: QUALITATIVE AND QUANTITATIVE

Other early studies of heat transfer and temperature field visualization using TLCs yielded only qualitative results, i.e. hot and cold regions were observed without regard to precise temperature levels (6-15). The first quantitative results were published by Cooper et al in 1974/5 (16, 17), who observed boundary layer transition and separation on a heated cylinder in cross-flow, and evaluated the variation of Nusselt number around the cylinder. More recently, quantitative as well as qualitative use of TLCs in flow visualization and heat transfer studies has become increasingly widespread (e.g. see refs 18-36, 65-71, 88-91, 97-99).

HEAT TRANSFER STUDIES: NEW TECHNIQUES - STEADY STATE AND TRANSIENT

New steady state techniques for measuring and mapping heat transfer coefficients using integral heater/TLC indicator combinations have recently been described (26, 28, 57). Heater uniformity, and the generation of uniform heat fluxes at the surface of interest were verified. The techniques have been evaluated, extended and improved by other workers (37, 38) where chiral nematic LC mixtures and different packaging arrangements have been used. Although the methods have wide general application in heat transfer studies (29, 39), they are particularly useful in the design and study of thermal performance of gas turbine components (38, 40). New transient techniques using microencapsulated chiral nematic TLC mixtures have been developed by Jones (51, 52) to measure local heat transfer coefficients in gas turbine blade geometries. The methods do, however, have far wider application potential. During the course of the work, the response of a film of microencapsulated chiral nematic to a rapidly increasingly surface temperature was assessed (53). Rates of increase in temperature of greater than 2000°C/sec were employed and experiments showed the delay between the time at which the surface reaches the steady state color display temperature, and the occurrence of the color display in the TLC film to be no more than a few milliseconds. This compares with values for thermal time constants of cholesteric mixtures which are of the order of hundreds of milliseconds (54, 55).

FLOW VISUALIZATION IN FLUIDS

TLCs have been used in fluids as well as air. Temperature distributions have been visualized using the materials in the unsealed (neat) and microencapsulated forms as both tracer particles in flow field studies, and as surface coatings (41-46, 71-74, 92-96). The studies include flow visualization of a re-circulating flow using 0.02% doping of water with TLC microcapsules (42) and simultaneous measurement of temperature and velocity field in thermal convective flows with unsealed TLC being dispersed directly into the flow medium (45). The background theory for the measurement of color recorded by cine photography has been reviewed and applied in the color/temperature calibration of temperature-sensitive liquid crystal tracer particles (76). In addition, coatings containing microencapsulated TLC mixtures, and TLC coated polyester sheets, insensitive to the effects of shear stress, have been used to obtain quantitative surface temperature measurements on water tunnel models (43, 75) and shear-sensitive unsealed TLC mixtures have been used successfully in hydrodynamic flow visualization on surfaces producing high resolution observations of both steady and unsteady boundary layer separation and transition characteristics (44)

SURFACE FLOW VISUALIZATION USING SHEAR-SENSITIVE TLC MIXTURES

The visualization of laminar to turbulent boundary layer transitions plays an important role in flight and wind tunnel aerodynamic testing of aircraft wing and body surfaces. Following the early example set by Klein and Margozzi (3,4), Holmes and co-workers at NASA have developed new techniques for visualizing transitions using shear-sensitive TLC mixtures (e.g. 47-50). In these methods, unsealed TLC mixtures were applied to the test surface, and air flow over the surface produced shear stress that induced a color change between high shear turbulent flow and low shear laminar flow regions. Although other earlier studies in which the shear was also applied perpendicular to the helical axis of the unsealed TLC mixture have also been undertaken (81-84), it has been the work of Holmes et al. which has pioneered the use of shear-sensitive TLC mixtures as a qualitative diagnostic tool for flow visualization. The use of TLCs overcomes some of the limitations of sublimating chemicals and oil flow techniques and provides transition visualization capability throughout almost the entire altitude and speed ranges of virtually all subsonic aircraft flight envelopes. The methods are also widely applicable for supersonic transition in flight and for general use in wind tunnel research over wide subsonic and supersonic speed ranges. Reda has demonstrated the dynamic capability of shear-sensitive liquid crystals on an oscillating airfoil (87,100) and found that the TLC response was fast enough to trace 1 Hz oscillations. Reda has also investigated the use of the materials at hypersonic speeds (101). An improved method for visualizing flow has been proposed by Jones, McDonnell and Bonnett (64) which utilizes a shear induced texture change from the uncolored (non-reflecting) focal -conic texture to the colored Planar (Grandjean) texture. This work is also the subject of a UK patent application (80). These novel experimental techniques together with the availability of new and improved TLC formulations have led to much interest in this area of research in particular, and the use of shear-sensitive liquid crystals has now become an established technique for diagnostic flow visualization. The technique has been demonstrated to illustrate laminar boundary layer transitions, laminar bubbles, shocks and separation in flight and wind tunnel environments (102). The validity of the technique has been evaluated by most authors (102) and transition locations indicated by shear-sensitive TLCs have been confirmed using other techniques including sublimation chemicals, hot film transducers and pressure rakes (102, 103). Steps are currently being taken to resolve the few issues that remain from the TLC viewpoint in order that the technique may be developed to its full potential and facilitate its widespread use throughout the aerodynamic testing community.

MISCELLANEOUS

In another novel study, the analogy between heat transfer and skin friction within the laminar sublayer of a turbulent boundary layer has been used as the basis for the development of a liquid crystal/skin friction measurement device (56). This can also be used to indicate boundary layer transition and separation, and should be applicable to flows with strong pressure gradients.

JAPANESE STUDIES

Following the leads set by workers like Kasagi, Kimura and Akino (e.g. 31, 77, 78, 85, 86) and the general high level of interest in experimental techniques utilizing TLC products, Japanese work in all areas has grown significantly, evidenced by the increasing number of publications (e.g. 68-73, 79, 95-97).

NOTES

Since this review was originally compiled, publications covering the use of TLC products in heat transfer, flow visualization and related research have continued to appear in the open and patent literature and will continue to do so in the future. Much of the pioneering work that has been undertaken to date was classified and is unlikely to appear in print, at least for the foreseeable future. Nevertheless, TLC products have become established as invaluable tools in allowing the rapid accumulation of experimental data that would otherwise be unobtainable or require long periods of time to compile.

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