Technical Study on Transient Measurement of Nusselt Number in Convective Heat Transfer Using Thermochromic Liquid Crystals

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Abstract

Thermochromic liquid crystal is a type of cholesteric liquid crystal that exhibits significant optical rotation effect and possesses high sensitivity to temperature variations, making it widely applied in surface temperature measurements of objects. In experimental studies of flow and heat transfer, it is often necessary to investigate the heat transfer distribution over the entire internal surface of a channel. Utilizing transient liquid crystal to measure the temperature field on channel surfaces and subsequently deriving the surface heat transfer coefficient distribution and Nusselt number has become a trend in research on gas turbine blade cooling. This paper establishes a wind tunnel and test system based on transient liquid crystal experimental technology, employs the HSV color model to describe colors, and obtains a color-temperature relationship after calibration. Transient liquid crystal experiments are conducted, the transient heat conduction process is solved using semi-infinite heat conduction theory, the Nusselt number distribution contour map and average Nusselt number on the internal channel walls are obtained, and these results are compared with theoretical calculations, showing good agreement.

Full Text

Research on Transient Measurement of Nusselt Number in Flow Heat Transfer Using Thermochromic Liquid Crystal Technique*

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Abstract: Thermochromic liquid crystal is a type of cholesteric liquid crystal that exhibits significant optical rotation effects and high sensitivity to temperature variations, making it widely applicable for surface temperature measurements. In experimental studies of flow and heat transfer, investigating the heat transfer distribution across entire internal channel surfaces is essential. Measuring surface temperature fields using transient liquid crystal techniques to derive heat transfer coefficient distributions and Nusselt numbers has become an established trend in gas turbine blade cooling research. This paper establishes a wind tunnel and test system based on transient liquid crystal experimental technology, employing the HSV color model for color characterization to obtain a color-temperature relationship through calibration. Transient liquid crystal experiments were conducted, and the transient heat conduction process was solved using semi-infinite heat conduction theory, yielding both contour maps of Nusselt number distribution and average Nusselt numbers for internal channel walls. Comparison with theoretical calculations shows good agreement.

Keywords: liquid crystal thermography; transient; Nusselt number; flow and heat transfer

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1 Introduction

The measurement of Nusselt number distribution is fundamental to experimental convection heat transfer research. Traditional methods require installing a limited number of measurement points on the test surface to determine local heat transfer coefficients, from which the overall surface heat transfer coefficient distribution and internal channel Nusselt number distribution are derived. For complex flow fields—such as internal flow channels with turbulence promoters and overflow, channels with turbulence promoters and directional changes, film cooling with jet injection, and impingement cooling with crossflow—the surface temperature variation patterns are extremely complex. Only comprehensive surface temperature field measurements can provide accurate and reliable data for thermal analysis. Additionally, many fundamental aerothermal studies require non-intrusive measurement techniques that do not alter test piece structures or flow field characteristics. These requirements are difficult to meet with conventional measurement methods.

Thermochromic liquid crystal thermography is an emerging non-contact temperature measurement technology capable of capturing complete surface temperature fields. In recent years, the development of transient liquid crystal measurement techniques has become a clear trend. The fundamental principle is that when airflow passes over a test model surface at a different temperature, the temperature variation at each surface point is closely related to the local heat transfer rate. By accurately recording the temperature history at each point on the test piece surface, the convective heat transfer coefficient can be calculated based on heat transfer theory, and subsequently the Nusselt number can be determined. Since this method does not require steady-state heat transfer conditions, experimental duration is significantly reduced.

This paper first introduces the experimental principles of transient liquid crystal testing, followed by a description of the experimental techniques and data processing methods. Test cases and comparisons with numerical calculations are then presented, concluding with a summary of the work.

2.1 Thermochromic Liquid Crystals and Image Processing Technology

The mesophase of crystals refers to the transitional state between solid and liquid phases. In this state, liquid crystals maintain anisotropic physical and chemical properties characteristic of solid crystalline molecules while exhibiting fluidity. The liquid crystals applied in heat transfer experiments typically refer to cholesteric liquid crystals, named after the liquid crystalline structures formed by certain cholesterol derivatives. These materials exhibit significant optical rotation, strong circular dichroism, and wavelength-selective reflection—the latter enabling visible color perception by the naked eye. Their high sensitivity to temperature changes makes them suitable for measuring surface temperature variations in experimental objects.

The temperature range over which thermochromic liquid crystals exhibit liquid crystalline behavior upon heating is known as the bandwidth, which varies considerably among different liquid crystal types. Experimental liquid crystals are categorized as narrow-band (color change range $< 1°C$) or wide-band ($> 5°C$). When temperature reaches the liquid crystal’ s color change range, the molecular arrangement transforms, producing visible light under illumination that sequentially progresses through red, green, and blue wavelengths. By capturing these color changes on the liquid crystal-coated surface with a high-definition camera and referencing calibration data, the surface temperature field can be determined. This temperature measurement can indirectly be used to determine local heat transfer coefficients.

Since thermochromic liquid crystals reflect different wavelengths of visible light at different temperatures, a mapping relationship exists between temperature and color: $RGB = f(T)$. By solving the inverse function of this relationship computationally, the temperature distribution across the test region can be obtained. Specifically, the liquid crystal-coated test piece is installed in the experimental channel and sealed. Gas temperature and flow rate are adjusted to induce temperature changes that alter the liquid crystal molecular arrangement, reflecting different colored visible light. The surface temperature field is then determined based on the color-temperature correspondence. Compared with traditional temperature measurement methods, this non-contact approach does not alter the flow field structure. Moreover, thermochromic liquid crystals are extremely sensitive to temperature changes, enabling quantitative measurement of two-dimensional temperature distributions in specific flow fields with high precision. Additionally, this method is more cost-effective than infrared thermography, and the reversible color change process allows for repeated use within a certain timeframe, offering significant cost advantages. These benefits have led to widespread application of thermochromic liquid crystal technology in heat transfer measurement.

In color space, multiple representation methods facilitate computer storage and analysis. The common RGB color space presents a broad color array through variations and superposition of three color channels (Red, Green, and Blue), making it one of the most widely used color models. Currently based on human color perception, the RGB model is primarily applied in electronic systems for image sensing and display. However, RGB is a device-dependent color model: different devices detect or reproduce given RGB values differently, as color elements (such as phosphors or dyes) and their responses to individual R, G, and B levels vary among manufacturers and even change over time within the same device. Consequently, RGB values are unsuitable as measurement standards.

The HSV color model is commonly employed in transient liquid crystal experiments. Created by A. R. Smith in 1978, HSV (also called the Hexcone Model) uses a three-dimensional polar coordinate system to describe color through three components: Hue (H), Saturation (S), and Value (V). As shown in [Figure 1: see original paper], Hue varies circumferentially from 0 to 360, Saturation varies radially from 0 to 1, and Value varies axially from 0 to 1. The HSV model provides more intuitive color representation and is unaffected by illumination intensity, making it ideal for transient liquid crystal experiments. In practice, the originally recorded RGB color space from cameras can be converted to the more intuitive HSV space using software to improve experimental accuracy.

[Figure 1: see original paper] RGB and HSV Color Spaces

2.2 Semi-Infinite Plate Assumption

As a non-contact measurement method, thermochromic liquid crystal thermography is primarily applied in heat transfer experiments to obtain temperature values on channel end walls for determining heat transfer coefficient distributions. Applications include both steady-state and transient temperature measurement. This study employs transient liquid crystal thermography, utilizing the principle of liquid crystal color change with temperature to solve for enhanced heat transfer coefficients on channel end walls by observing the step-change process of test piece surface temperature Tw(t) toward fluid temperature. Experimental control must ensure the liquid crystal completes a full color change cycle within an appropriate timeframe.

The test piece uses an acrylic plate, offering advantages of good light transmission, aesthetic flatness, and long service life. The transient experiment is based on one-dimensional unsteady heat conduction theory for a semi-infinite plate.

The heat conduction schematic is shown in [Figure 2: see original paper]. The transient experiment is based on the Fourier one-dimensional heat conduction equation:

“#$” %# = “$

Boundary conditions: = 0, (, 0) = (2) = 0, − “$ = (4 − 5) (3) → ∞ ， (, 0) = 1 (4) 1：实验件 t=0 时刻的温度； 4：气体来流温度； 5：壁面温度。

经 Fourier 变换，一维半无限大平板微分方程的解为：89: ;9: = 1 − exp(A)) (H) (5)

The target plate’ s initial temperature can be measured using thermocouples; represents the fluid temperature during testing, recorded in real-time and output to corresponding Excel files; is obtained by inverse solution based on captured liquid crystal color change information on the target plate surface. represents the target plate material properties, characterizing thermal conductivity, density, and specific heat capacity, respectively.

In actual testing, heating by the gas flow exhibits some delay, making ideal step changes difficult to achieve. Applying Duhamel’ s principle of homogenization:

− = 1 − exp(K#LM)9)NO) (KHLM)9)NO)

Where: : Initial temperature of the acrylic plate : Thermal diffusivity of the test piece : Convective heat transfer coefficient at the wall : Heating time of the air

The solution in Equation 6 is based on the semi-infinite plate conduction assumption. This assumption requires that the heated air thermal flux does not penetrate through the target plate, meaning the deepest portion of the plate can still be considered at temperature , and thermal disturbance effects remain confined to the plate surface. Therefore, to ensure stable and clear liquid crystal color change images over a sufficiently long time period for subsequent data processing, test plates must be made of low thermal diffusivity materials. The acrylic plate used in experiments has low thermal diffusivity while offering high strength, good light transmission, and easy observation, making it well-suited for experimental conditions. Specifically, when the target plate thickness satisfies W = / A < 0.25, the applicability condition for one-dimensional semi-infinite plate theory is met.

Using Equation 6, the convective heat transfer coefficient can be solved, and subsequently the Nusselt number for the channel end wall can be determined. The Nusselt number is a dimensionless parameter representing convective heat transfer intensity, defined as the ratio of convective to conductive heat transfer across the boundary layer. Based on the definition:

= K ‘

Where D is the hydraulic diameter of the channel inlet, calculated as four times the channel cross-sectional area divided by the perimeter; is the thermal conductivity of the stationary fluid in W/(m · K).

2.3 Liquid Crystal Calibration Experiment

Prior to conducting transient liquid crystal experiments, calibration of the liquid crystals is required. The transient experiments employ narrow-band liquid crystals with a bandwidth of 1°C. To obtain clear color change images, specialized black paint is used as a base coating during calibration. As shown in [Figure 3: see original paper], the calibration experiment uses a smooth copper plate with excellent thermal conductivity as the calibration substrate, ensuring the liquid crystal color transition temperature matches the actual thermocouple measurement temperature. Before spraying, the copper surface must be clean and smooth. A water-soluble black paint is first applied uniformly, and after thorough drying, the prepared thermochromic liquid crystal is evenly sprayed onto the black-painted surface. Following liquid crystal application, a hair dryer is used for quality inspection to observe surface noise, color change brightness, and uniformity. After 6-8 hours of natural drying, the calibration experiment can commence.

(a) Calibration experiment schematic (b) Copper plate color change image [Figure 3: see original paper] Liquid crystal calibration experiment schematic

The calibration experiment utilizes seven temperature measurement holes at the center of the copper plate' s back surface, spaced 25 mm apart. A heating film is tightly attached to the back surface, with thermocouples inserted through the film into three of these holes and sealed with thermally conductive silicone to minimize contact resistance, then secured with tape to prevent detachment. The experimental procedure is as follows:

(1) Install the prepared calibration plate on the test stand, connect the heating circuit, and verify normal surface color change;
(2) Adjust power supply to stabilize thermocouple temperature, record the temperature and calibration images, repeating this step 30-50 times until the liquid crystal color change is complete;
(3) Plot calibration curves based on video data and Excel temperature data, implemented through Matlab programming. The program converts RGB data from the 3CCD camera to HSV hue values, using instantaneous temperatures from thermocouples as independent variables and HSV hue data as dependent variables to obtain the final calibration curve. As shown in [Figure 4: see original paper], the Hue-T curve exhibits distinct hue variations near the color transition temperature, with the most significant change occurring around 35.2°C-35.7°C, which is selected as the calibration region.

[Figure 4: see original paper] Liquid crystal calibration result curve

Excessive liquid crystal coating thickness causes surface non-uniformity, affecting heat transfer and yielding unrealistic results, while insufficient thickness fails to produce adequate color change, impacting photographic accuracy and subsequent data processing. Therefore, liquid crystal quantity must be configured based on target plate size. According to Rao et al., optimal color change effects are achieved at a liquid crystal thickness of 17 µm. The transient liquid crystal suspension used in experiments (LCR Hallcrest SPN-100/R35C1W) has a concentration of 10%, allowing calculation of the required volume for a 17 µm thickness.

The extracted liquid crystal is mixed with water at a 1:1 volume ratio and stirred with a magnetic stirrer for 30-60 minutes. The suspension with crushed large particles is then filtered through a sand core funnel with continuous agitation to prevent sedimentation and clogging. Filtration typically requires 1-2 hours for complete processing before transfer to a prepared container.

The test target plate is cleaned with alcohol, dried, and then coated. The experiment requires an air compressor and liquid crystal spray gun. Air pressure is compressed to 60 psi, and nozzle functionality is verified. After loading the liquid crystal, the nozzle airflow is adjusted to prevent excessive spray causing noise or insufficient spray allowing large particles to clog the nozzle. During spraying, the surface is continuously monitored for large particles, and a hair dryer is used to check color change uniformity. Nozzle condition must be rechecked after each liquid crystal refill, maintaining consistent spray volume. Additionally, when pressure drops below 30 psi, the compressor must be restarted to prevent gun clogging and uneven coating. After 1-2 hours of natural drying, black paint is applied.

During black paint spraying, the thin layer at the nozzle dries easily, so prolonged inflation should be avoided to prevent clogging. Severe clogging requires nozzle cleaning with water before continuing. Concentrated spraying on one area must be avoided as it can cause localized overwetting and damage the liquid crystal layer, necessitating complete re-spraying if color change effects are compromised. After complete coating, the surface is sealed with plastic film to prevent dust contamination and allowed to dry naturally.

3.1 Experimental Apparatus

The transient liquid crystal experimental apparatus for this study is shown in [Figure 5: see original paper]. Air is drawn into the channel through a circular arc collector by a vortex air pump, then develops uniformly and passes through a vortex flowmeter to determine the actual flow rate within the experimental channel. Before entering the test section, the airflow passes through a laboratory-designed mesh heater to achieve appropriate temperature, then enters the test section through a converging channel. Three pressure measurement holes and three temperature measurement holes are arranged at the test section inlet, with nine pressure and nine temperature holes at the outlet to monitor real-time airflow temperatures, with data acquired through a data acquisition card into a computer. To ensure flow uniformity, a uniform turning section and a 0.125 m^3 pressure stabilization tank are installed downstream, with final exhaust through a blower.

[Figure 5: see original paper] Experimental apparatus schematic

3.2 Experimental Procedure

A typical transient experiment proceeds as follows: (1) Preparatory work includes setting up the test rig, installing the black-painted and liquid crystal-coated test section, arranging thermocouples and pressure scanners, and ensuring proper sealing; (2) The experiment must be conducted in complete darkness, with the test section covered by black cloth containing reflective material, doors and windows closed to prevent convective disturbances, maintaining room temperature conditions; (3) LED light tubes are positioned above both sides of the test section as illumination sources, with positions adjusted based on real-time camera images to eliminate reflection effects; (4) The blower is activated and inlet flow is adjusted according to the vortex flowmeter; (5) The LabVIEW program and data acquisition system are initiated, camera white balance and frame rate parameters are adjusted, video recording begins synchronously, and the laboratory-designed mesh heater is activated; (6) As the test piece heats, the camera records the liquid crystal color change process, storing data in AVI format; (7) When the channel wall liquid crystal color change is fully developed, the mesh heater, camera, and data acquisition system are shut down; (8) Data processing involves exporting LabVIEW data to Excel and processing video data with Matlab to output Nusselt number distribution contours for the pin-fin channel and record the average Nu value.

3.3 Data Processing

This study employs Matlab software for data processing. First, color change images captured by the CCD camera are transferred to the computer, and useful segments are extracted based on heating indicator signals and maximum test time. PAL-format DV stores 25 frames per second, with frame count determining the time of each frame from zero. Each frame is then processed into a color distribution image described by the HSV model, extracting the Hue value for each color-developing point. Using the hue-temperature relationship, images are converted to temperature distributions. This processing is applied to each frame, yielding the wall temperature Tw and time t required to reach this temperature for every color-developing point on the test surface. Based on the airflow temperature variation recorded by the data acquisition system, the airflow temperature curve Tr(t) from zero to each color development point is obtained. Combining material properties , c, and initial temperature Ti, the heat transfer coefficient h is solved using Equation (6). If every point on the test surface undergoes color development, the entire surface heat transfer coefficient distribution can be obtained, and subsequently the Nusselt number.

4 Test Case Introduction

[Figure 6: see original paper] shows the Nusselt number distribution contours on the end wall from transient liquid crystal experiments and CFD calculations at Re = 60,000. The comparison reveals similar heat transfer distributions in the central spanwise region, with strong heat transfer zones forming at the leading edge of pin fins, where experimental results are significantly higher than computational predictions. Flow at the first pin-fin row is not fully developed, with the horseshoe vortex position biased toward the channel bottom. From the second row onward, the flow enters a fully developed region with good agreement between numerical and experimental results. Large heat transfer zones form at the second pin-fin row where impacted by airflow, while heat transfer becomes more moderate behind this region and at the front of the third pin-fin row due to lower spanwise flow velocities. Similar patterns occur in subsequent rows. Spanwise results show lower heat transfer trends near the channel bottom in both experimental and computational results, where low-velocity flow is evident.

(a) Exp. (b) CFD [Figure 6: see original paper] Experimental and numerical Nusselt number contours for channel end wall at Re = 60,000

[Figure 7: see original paper] presents the average Nusselt numbers for the target region from experiments and numerical calculations at four Reynolds numbers: 21,000, 39,000, 48,000, and 60,000. The computational and experimental values show good agreement, with maximum error not exceeding 12.7%.

[Figure 7: see original paper] Comparison of Nusselt numbers from transient experiments and numerical calculations

5 Conclusion

Thermochromic liquid crystal thermography enables convenient measurement of surface temperature fields in a non-contact manner that does not affect test piece structure or flow field characteristics. Using liquid crystal thermography and transient experimental techniques, end-wall Nusselt numbers were measured and compared with theoretical values, showing consistent results. The test method is accurate and reliable.

The Nusselt number measurement method based on liquid crystal thermography and transient experimental techniques offers short measurement times and high experimental efficiency. Under identical operating conditions, it requires less demanding air supply and heating equipment compared to steady-state experiments, representing an effective approach for heat transfer coefficient measurement.

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