6/27/94
E-8684

NASA Technical Memorandum 106541

Determination of a Transient Heat Transfer Property of Acrylic Using Thermochromic Liquid Crystals

James D. Heidmann
Lewis Research Center
Cleveland, Ohio

Prepared for the
32nd Aerospace Sciences Meeting
sponsored by the American Institute of Aeronautics and Astronautics
Reno, Nevada, January 10–13, 1994

National Aeronautics and
Space Administration

DETERMINATION OF A TRANSIENT HEAT TRANSFER PROPERTY OF ACRYLIC USING THERMOCHROMIC LIQUID CRYSTALS

James D. Heidmann
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

SUMMARY

An experiment was performed to determine a transient heat transfer property of acrylic. The experiment took advantage of the known analytical solution for heat conduction in a homogeneous semi-infinite solid with a constant surface heat flux. Thermochromic liquid crystals were used to measure the temperature nonintrusively. The relevant property in this experiment was the transient thermal conduction coefficient h_t, which is the square root of the product of density ρ, specific heat c_p, and thermal conductivity k (i.e., $\sqrt{\rho c_p k}$). A value of 595.6 $W\sqrt{s}/m^2K$ was obtained for h_t, with a standard deviation of 5.1 $W\sqrt{s}/m^2K$. Although there is no generally accepted value for h_t, a commonly used one is 580 $W\sqrt{s}/m^2K$, which is almost 3 percent less than the h_t value obtained in this experiment. Since these results were highly repeatable and since there is no definitive value for h_t, the new value is recommended for future use.

INTRODUCTION

Determining local heat transfer coefficients for solid surfaces in convective flows is important in many applications. At NASA Lewis Research Center, researchers have been performing experiments to measure local heat transfer coefficients at the wall surfaces in internal flows (ref. 1). In these experiments, such flows may occur in ducts, inlets, or nozzles, or at any surface where the gas temperature differs from the endwall temperature and, hence, causes heat transfer at the surface.

Traditionally, heat transfer coefficients at a solid surface are determined by placing a sufficient number of thermocouples on the surface of interest. Then, from a knowledge of the surface heat flux and temperature, heat transfer coefficients at the thermocouple locations can be calculated. This method gives no information, however, about points between the thermocouples. In addition, inserting thermocouples and their leads into the surface may cause errors in the measured values. Errors may arise from disruption of the flow field, thermal conduction along the thermocouple leads, and other factors.

In recent years, liquid crystals have emerged as an alternative to thermocouples. Liquid crystals are chemical substances whose color is a function of some physical property such as shear stress or temperature. Thermochromic liquid crystals are those affected by changes in temperature. If a solid surface is painted with a thin coat of these liquid crystals, the temperature of the surface can be measured nonintrusively through a color-temperature calibration. From a knowledge of the heat flux at the surface and the temperature at which a specific color appears, the heat transfer coefficients over the entire solid surface may be determined. Because yellow is usually the narrowest and most sharply defined color band, it is the color most often used for color-temperature calibration.

Many convective heat transfer test cells are fabricated out of acrylic. Acrylic is used because of its transparency, rigidity, good thermal properties, ease of machining, and low cost. In steady-state heat transfer experiments, the heat flux is typically produced by a thin-foil electric heater between an acrylic or insulated wall and a liquid crystal layer. However, for surfaces having compound-curvature (such as a spherical surface), a flat electric heater cannot be made to lie flat on the surface, so a transient liquid crystal technique (transient technique) is often employed (ref. 2). In such an experiment, the endwalls are heated (or cooled) to a specific uniform temperature prior to allowing air to flow through the test section. Then the air flow is started suddenly, and the endwalls (and hence the liquid crystal layer painted on them) begin to approach the air temperature. The location of the liquid crystal color at the surface is recorded over time. From this information, and a knowledge of the thermal properties of the endwall material, the distribution of the local heat transfer coefficient over the endwalls can be determined. For the transient technique, the important physical property is the transient thermal conduction coefficient h_t, which is defined as the square root of the product of density ρ, specific heat c_p, and thermal conductivity k. An h_t value of 580 $W\sqrt{s}/m^2K$ has commonly been used for acrylic at NASA Lewis Research Center. Although this value is believed, on the basis of previous results, to be fairly accurate, no definitive value has been obtained for the transient thermal conduction coefficient of acrylic.

In the experiment reported herein, an accurate determination of the h_t for acrylic was desired. Since the analytical solution for one-dimensional thermal conduction in a semi-infinite solid was known for constant surface heat flux, it was proposed that this situation could be approximated in the laboratory by using a liquid crystal to indicate the temperature at the solid surface.

THEORY

Figure 1 shows the case of one-dimensional heat conduction is a semi-infinite solid that is at uniform initial temperature and is subject to a constant heat flux boundary condition. Here the solid extends to infinity in all directions but one, and a uniform heat flux is imposed over the entire surface instantaneously. The temperature of the solid increases with time and decreases with distance from the surface. The analytical solution for this situation is well-known; it is given by Carslaw and Jaeger (ref. 3) as

$$T(x,t) - T_i = 2q_o'' \sqrt{\frac{t}{\pi \rho c_p k}} \exp\left(\frac{-x^2 \rho c_p}{4kt}\right) - \left(\frac{q_o'' x}{k}\right) \mathrm{erfc}\left[x \sqrt{\frac{\rho c_p}{4kt}}\right] \tag{1}$$

where t is the time from initiation of heat flux, x is the perpendicular distance from the surface, T_i is the initial temperature, q_o'' is the surface heat flux, and erfc denotes the complementary error function. The physical properties are those of the solid.

If we now restrict our attention to the surface (x = 0), equation (1) reduces to

$$T(t) - T_i = 2q_o'' \sqrt{\frac{t}{\pi \rho c_p k}} \tag{2}$$

or, by using the definition of h_t,

$$h_t = \frac{2q_o'' \sqrt{\frac{t}{\pi}}}{T(t) - T_i} \tag{3}$$

We now wish to apply this equation to the present experiment. If we know the initial temperature T_i of the solid, the heat flux q_o'', and the time t at which a particular temperature T(t) occurs at the surface, we can solve equation (3). A symmetrical sandwich composed of an electric heater between two thick pieces of acrylic (fig. 2) can be assembled. Since the sandwich is symmetrical, we can accurately determine the heat flux in each direction. If q_o'' is the heat flux in each direction, then the heater sheet actually produces a total heat flux of $2q_o''$. Since we know that the total heat flux produced by a rectangular electric heater is EI/LW (where E is the voltage across the heater, I is the current through the heater, L is the length of the heater sheet, and W is the width of the heater sheet), we can substitute this into equation (3) to arrive at the desired relation:

$$h_t = \frac{\frac{EI}{LW}\sqrt{\frac{t}{\pi}}}{T(t) - T_i} \tag{4}$$

TEST APPARATUS

The test apparatus is shown in figure 3. It has an electrical circuit that consists of a 50-A, 15-V power supply connected to a rectangular Inconel foil sheet with a 0.001-Ω shunt in series. When it was switched on, the power supply provided full test current practically instantaneously. This condition is necessary when a semi-infinite medium analytical solution is being used. The electrical connections were made via copper busbars that were spot-welded to opposite edges of the heater sheet. The sheet's length between weld lines was 15.95 cm, its width parallel to the weld lines was 15.14 cm, and its thickness was 0.025 mm. An Inconel sheet was chosen because it has a relatively uniform electrical resistivity that is constant despite changes in temperature. To provide a good contrast for viewing the liquid crystal color change, each side of the Inconel sheet was sprayed with a thin coating of flat black paint. An air-powered atomizer was used to ensure the evenness of the coating.

Although various types of thermochromic liquid crystals are available for measuring temperature, chiral nematic liquid crystals were chosen for this experiment because of their rapid response time. A thin layer of microencapsulated liquid crystals in a water base was sprayed over the black paint on both sides of the heater. Again, the atomizer was used to achieve a uniform coating. The water evaporated after a few minutes, leaving a very thin residue of microencapsulated liquid crystals. (The capsules are very small, on the order of a few micrometers in diameter.) The encapsulated liquid crystals were used because the properties of unencapsulated crystals can change when the crystals are exposed to air. Unencapsulated crystals can also exhibit an angle-dependence error due to the lighting. The chiral nematic crystals turned yellow at 28.2 °C; this temperature was calibrated by using a thin foil thermocouple permanently inserted into the test section. This same thermocouple also measured the initial temperature of the test section before a test run, thereby ensuring consistency of the temperature measurement. The thermocouple was read with a portable thermocouple meter.

Next, the painted heater sheet was placed between two identical acrylic sheets with the same surface dimensions as the heater. The thermocouple was centered on one side of the rectangular heater, between the crystal layer and the acrylic. Although the sheets were available in thicknesses less than 2.54 cm, the 2.54-cm pieces were chosen for this experiment for two reasons: first, the thicker piece was more rigid, which permitted the test section to be more evenly clamped; and second, the thicker piece more closely approximated the desired semi-infinite solid. Calculations showed that the amount of heat which penetrated through the entire 2.54-cm thickness of the acrylic during the typical test time of 1 to 2 min was negligible. The entire test section was clamped tightly with C-clamps at about 3.5 cm in diagonally from each corner. This clamping arrangement minimized any contact resistance in the test section while leaving the center of the test section unobstructed for viewing the color change in the liquid crystal.

A video camera was placed on each side of the test section to record the liquid crystal color change during the experiment. Both sides were viewed to ensure that the heat flow and color change were symmetric. The video signals from the cameras were input through time-date generators, which imposed on-screen timers on them, and then they were recorded on S-VHS video tape. To be consistent with the test procedure, the yellow color of the liquid crystal was calibrated by using the monitor picture. Two fluorescent lamps, one on either side of the test section, provided lighting. Fluorescent lamps were chosen because of their white light and relatively cool operating temperature. If hot lamps had been used, they might have increased the temperature of the test section during a test run.

Two digital multimeters measured the current and voltage across the heater. One meter was connected across the heater busbars to measure the voltage directly. The other was connected across the 0.001-Ω shunt to measure the voltage across the shunt, and hence, the current through the circuit. The voltage and current resolutions were 0.001 V and 0.01 A, respectively.

TEST PROCEDURE

The analytical solution for one-dimensional heat conduction in a semi-infinite solid assumes a uniform initial temperature in the solid; therefore, the first step in performing a test was to allow the test section to become isothermal. This isothermal condition was achieved by wrapping the entire test section in several layers of insulation and allowing it to sit overnight. For this reason, no more than one test run could be performed on a given day. Although the air temperature in the laboratory may have fluctuated slightly throughout the day, it was determined that the test section reached the mean temperature of the laboratory and that the effects of temperature differences between the air and the test section during the relatively short test time were negligible.

The monitor, VCR's, camera, multimeters, digital thermocouple meter, and fluorescent lights were turned on as the test section was unwrapped. The initial temperature of the test section was recorded as the cameras automatically focused on the heater surface. The VCR's were then placed in record mode. The power supply to the heaters and the time-date generators were turned on simultaneously, to accurately mark the initiation of the heating. The on-screen timer allowed direct determination of test times via frame-by-frame inspection of the video tapes. As the test section increased in temperature, the liquid crystal progressed through the color spectrum, including the yellow color band, and returned to a colorless state. The current and voltage across the heater during the test run were recorded. After the test run, the equipment was turned off, and the test section was rewrapped and allowed to sit overnight in anticipation of another test run. The video tapes were then inspected frame-by-frame to determine when the maximum yellow color occurred. Although there was some variation in color due to lateral conduction, especially near the edges, the center portion of the test section changed color in a very uniform manner. In addition, both videos showed the yellow occurred at the same time, thereby verifying test section symmetry.

RESULTS AND DISCUSSION

Nine tests were run to ensure repeatability of the data. The electric current used was nominally 20 A for each test run. This resulted in a constant voltage by the power supply across the heater of approximately 0.9 V. Since the current through the circuit decreased slightly as the temperature and electrical resistance of the Inconel foil increased, a mean value was used for the current. Each test run was performed on a different day, so the initial temperature of the test section also varied. This caused a greater variation in the test run times. However, as long as the acrylic is initially at a constant temperature, equations (1) to (4) hold, provided the initial temperature is below the temperature at which the liquid crystal turns yellow. Errors can arise if initial temperatures are very low, because the time required to reach the temperature at which the crystal turns yellow would be quite lengthy. In such a case, too much heat would have penetrated completely through the acrylic pieces, thereby violating the assumption of a semi-infinite solid. However, it was determined from equation (1) that less than 1 percent of the total heat flux penetrated to a depth of 2.54 cm during even the longest test times of this experiment. Thus, in the normal direction, the assumption of a semi-infinite solid is valid. In the transverse direction, it is also valid, because the exposed surfaces of the acrylic pieces normal to the heater plane may be considered insulated.

Since the liquid crystal color change was much more vivid near the center of the test section than near the edges, this indicated a reduction in liquid crystal near the edges. The likely explanation for this is that the test section was more tightly clamped near the edges, which caused the liquid crystal to be "squeezed" away from the clamps. This phenomenon raises a question about whether the heat flow in the test section can be considered one-dimensional. There is a thermal contact resistance between the acrylic and the liquid crystal film. This resistance need not be zero for one-dimensional heat flow, but it must be constant over the region of interest. The fact that the color change was nearly uniform over the center portion of the test section indicates that any thermal contact resistance between the acrylic and the liquid crystal film was constant in this region.

Table I shows the values of initial temperature, voltage, current, time, and transient thermal conduction coefficient for the nine test runs. The values of h_t were computed from equation (4). Note that the results of the runs are repeatable, as evidenced by the standard deviation of less than 1 percent of the mean value.

Table I shows that the average value of h_t found experimentally is 595.6 $W\sqrt{s}/m^2K$, compared to the commonly used value of 580 $W\sqrt{s}/m^2K$. The new value is greater than the old value by more than three experimental standard deviations; this indicates that the difference is not due to random experimental error. It is possible that fixed experimental error could cause this difference. However, since the old value was not based on definitive experimental evidence, and any fixed errors have been minimized and accounted for, the new value is recommended for future use.

SUMMARY OF RESULTS

A transient technique has been used to determine the transient thermal conduction coefficient for acrylic. This coefficient is required for reduction of transient heat transfer data taken with acrylic endwalls. The technique takes advantage of the optical transparency of acrylic to measure temperatures nonintrusively by using thermochromic liquid crystals.

A value of 595.6 $W\sqrt{s}/m^2K$ was measured experimentally with a standard deviation only 5.1 $W\sqrt{s}/m^2K$, or less than 1 percent. Because of the consistency of these data and the lack of definitive data for the previously used values, the use of the new value is recommended for reducing the data from transient heat transfer experiments with acrylic endwalls.

The technique is also recommended for future use in measuring the transient thermal conduction coefficient for other optically transparent solids. A similar technique could be applied for opaque solids by using a thermocouple instead of liquid crystals to indicate temperature. In this case, however, the nonintrusive nature of the experiment would be lost.

REFERENCES

1. Hippensteele, S.A.; Russell, L.M.; and Stepka, F.S.: Evaluation of a Method for Heat Transfer Measurements and Thermal Visualization Using a Composite of a Heater Element and Liquid Crystals. NASA TM–81639, 1981.

2. Jones, T.V.; and Hippensteele, S.A.: High-Resolution Heat Transfer Coefficient Maps Applicable to Compound-Curve Surfaces Using Liquid Crystals in a Transient Wind Tunnel. NASA TM–89855, 1988.

3. Carslaw, H.S.; and Jaeger, J.C.: Conduction of Heat in Solids. Second ed., Oxford University Press, London, 1959.

TABLE I.—DATA AND RESULTS

Run	Initial temperature, T_i, °C	Voltage, V, V	Current, I, A	Time, t, s	Transient thermal conduction coefficient, h_t, $W\sqrt{s}/m^2K$
1	21.4	0.917	20.13	89.0	597.9
2	21.4	.832	18.24	133.0	601.7
3	21.4	.846	18.57	119.0	588.4
4	22.6	.842	18.48	84.0	591.1
5	22.1	.840	18.44	104.0	595.8
6	22.1	.919	20.18	72.5	601.0
7	22.7	.918	20.15	60.3	601.1
8	21.8	.913	20.04	80.0	593.3
9	20.7	.910	19.98	111.0	590.2
Average					595.6
Standard deviation					5.1

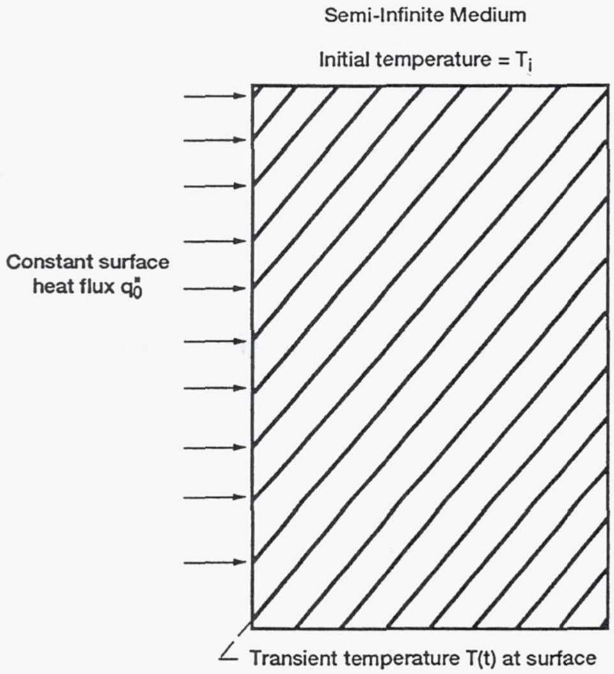

Figure 1.—Heat conduction in a semi-infinite solid.

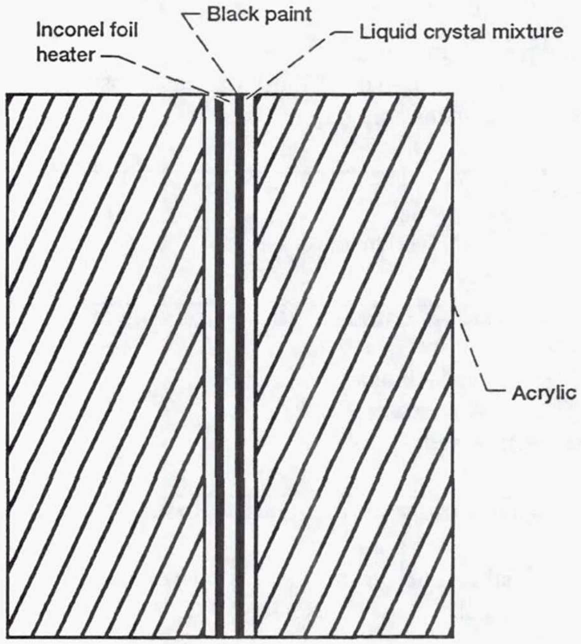

Figure 2.—Experimental test section.

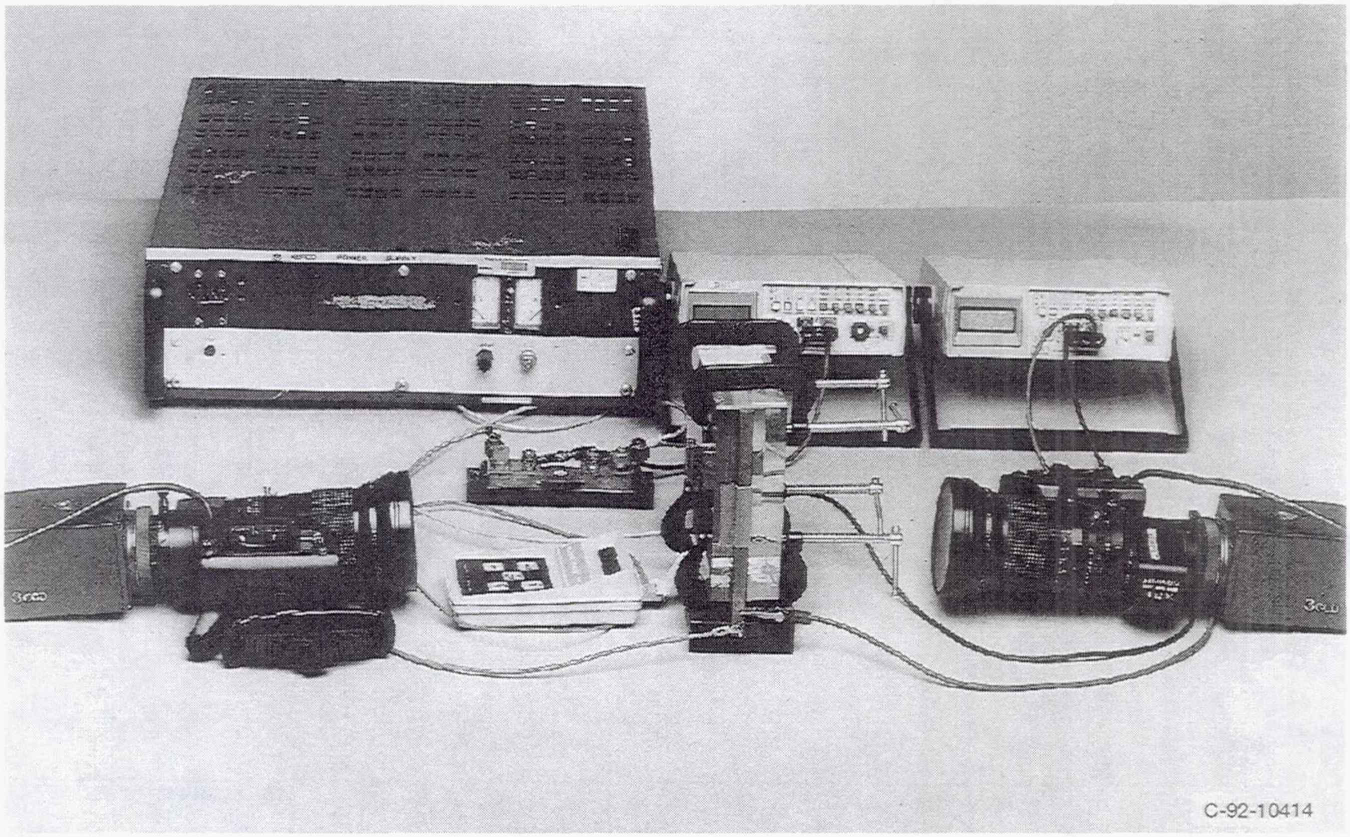

Figure 3.—Experimental apparatus.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)	**2. REPORT DATE** May 1994	**3. REPORT TYPE AND DATES COVERED** Technical Memorandum

4. TITLE AND SUBTITLE

Determination of a Transient Heat Transfer Property of Acrylic Using Thermochromic Liquid Crystals

5. FUNDING NUMBERS

WU–505–62–10

6. AUTHOR(S)

James D. Heidmann

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–8684

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–106541

11. SUPPLEMENTARY NOTES

Prepared for the 32nd Aerospace Sciences Meeting sponsored by the American Institute of Aeronautics and Astronautics, Reno, Nevada, January 10–13, 1994. Responsible person, James D. Heidmann, organization code 2760, (216) 433–3604.

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Category 07

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

An experiment was performed to determine a transient heat transfer property of acrylic. The experiment took advantage of the known analytical solution for heat conduction in a homogeneous semi-infinite solid with a constant surface heat flux. Thermochromic liquid crystals were used to measure the temperature nonintrusively. The relevant property in this experiment was the transient thermal conduction coefficient h_t, which is the square root of the product of density ρ, specific heat c_p, and thermal conductivity k (i.e., $\sqrt{\rho c_p k}$). A value of 595.6 $\mathrm{W}\sqrt{\mathrm{s/m^2K}}$ was obtained for h_t, with a standard deviation of 5.1 $\mathrm{W}\sqrt{\mathrm{s/m^2K}}$. Although there is no generally accepted value for h_t, a commonly used one is 580 $\mathrm{W}\sqrt{\mathrm{s/m^2K}}$, which is almost 3 percent less than the h_t value obtained in this experiment. Since these results were highly repeatable and since there is no definitive value for h_t, the new value is recommended for future use.

14. SUBJECT TERMS

Heat transfer; Liquid crystals; Plexiglas

15. NUMBER OF PAGES

9

16. PRICE CODE

A02

17. SECURITY CLASSIFICATION OF REPORT Unclassified	**18. SECURITY CLASSIFICATION OF THIS PAGE** Unclassified	**19. SECURITY CLASSIFICATION OF ABSTRACT** Unclassified	**20. LIMITATION OF ABSTRACT**

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18
298-102