Chapter VI

LIQUID CRYSTAL THERMOGRAPHY ON THE FLUID SOLID INTERFACE OF ROTATING SYSTEMS

TEST CASE : HEAT TRANSFER TO A FREE ROTATING DISK

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Summary
List of Symbols
VI . 1 Introduction
VI . 2 Apparatus and Experimental Procedures
Rotating Disk
Liquid Crystal Coating and Hue Capturing
Infrared Point Sensor

VI . 3 Experimental Results and Discussion
Experimental Strategy
Implementation of Infrared Point Sensor Measurements in the Rotating Frame
Evaluation of Mechanical and Thermal Effects Influencing the Liquid Crystal Layer
Liquid Crystal Hue Response at Different Rotational Speeds
Adiabatic Disk Temperature Rise form Liquid Crystal Measurements
Comparison with Free Disk Heat Transfer Theory
Influence of Added Stroboscope Illumination on Liquid Crystal Hue

VI . 4 Experimental Uncertainty
VI . 5 Conclusions
References

Summary

Liquid crystal thermography is an effective method widely employed in transient and steady-state heat transfer experiments with excellent spatial resolution and good accuracy. Most of the past studies in liquid crystal thermography deal with stationary conditions. The main objective of the present investigation is to determine the influence of rotation on the color response of encapsulated liquid crystals attached to a flat rotating surface. A general methodology developed for the application of liquid crystals in rotating systems is described for the first time. The investigation is performed for a rotational speed range from 0 to 7500 rpm using two different liquid crystal coatings displaying red at 30 ^{o} and 45 ^{o} C, under stationary conditions. The color display bandwidth of the two crystals is approximately 1 ^{o} C. Local liquid crystal color on the surface of a rotating disk is correlated with local temperature as measured by a non-intrusive infrared point sensor at various rotational speeds. An immediate observation from the present study is that the color response (hue) of encapsulated liquid crystals is not altered by neither the centrifugal acceleration of the rotating environment nor the aerodynamic friction force at the rotating disk-air interface. It is concluded that a conventional hue versus temperature calibration obtained under stationary conditions is valid for a wide rotational speed range (0-7500 rpm). Present investigation also shows that when a stroboscope light is introduced, the perceived color information (hue) is not altered due to additional periodic illumination. A complete and general experimental methodology including rotating surfaces with non-axisymmetric temperature distributions is presented. Results from the current liquid crystal technique agree well with the theoretical temperature rise of a free rotating disk as predicted by an analytical method.

List of Symbols

b , D	=	disk outer diameter
C	=	specific heat of air
ds	=	differential circumferential distance = $r.d\theta$

dr = differential radial length
IR = infrared
k = thermal conductivity
r = local radius on the disk surface
rpm = rotations per minute
R = disk outer radius , D/2
Re = Reynolds number = $\Omega.r^2/\nu$
R30C1W = encapsulated thermochromic liquid crystal displaying red at 30 º C under stationary conditions, color bandwidth is 1 º C
Re = Reynolds number
σ = relative shift of temperature of appearance for a given hue value
T = temperature
TC = thermocouple
V = flow velocity
z = coordinate direction normal to the disk
θ = circumferential position, (positive in counter clockwise direction)
δ = shear layer thickness of disk boundary layer
ϕ = angle between aerodynamic shear stress and tangential direction
ρ = density
ν = kinematic viscosity = μ/ρ
σ = mechanical stress in solid material
τ = shear stress
λ = wavelength of the light selectively reflected from the liquid crystal surface
μ = absolute viscosity
Ω = angular speed

subscripts

aw = adiabatic wall
al = Aluminum
c = centrifugal
lc = liquid crystal
o = aerodynamic wall friction related
p = at constant pressure
tc = thermocouple
x,y,z = Cartesian coordinates
∞ = ambient quantity
θ,z = circumferential component at a given z position
r,z = radial component at a given z position

VI . 1 Introduction

Liquid crystal temperature indicators are widely used in convection heat transfer studies due to their excellent spatial resolution and accuracy. The heat transfer characteristics of liquid crystal coated rotating surfaces can be easily observed from a stationary frame of reference. Temperature/heat transfer measurement methods based on the calibration of liquid crystal hue in function of local temperature have been developed in the past , Kim (1991), Camci et al.(1992), Camci et al.(1993), Wiedner and Camci (1993.a and 1993.b), Wilson, Syson and Owen (1993), Farina, Hacker, Moffat and Eaton (1993), Rizzo and Camci (1994). When the liquid crystal coated heat transfer surface is illuminated by white light, a selective reflection of a specific wavelength occurs in the helical structure of the liquid crystal. This can be explained by the "interference of light reflected from the helical layers so that the optical wavelength in the material actually equals the helical pitch", Jones et al. (1992), Collings (1990), de Gennes (1974). The pitch of the crystal helix is very sensitive to temperature and hence the selectively reflected color may be used to indicate temperature. Most of the past work in liquid crystal thermography are reported under stationary conditions. There are limited number of measurements obtained from the rotating frame of thermal systems, mainly for rotating machinery applications. However, a quantitative investigation of hue response to temperature in the rotating environment does not exist.

One of the first studies using liquid crystal temperature indicators in the rotating frame of reference is described in Metzger, Bunker and Bosch (1991). A disk (D=0.2032 m) rotating at speeds up to 10,000 rpm has been sprayed directly by encapsulated liquid crystals. Although this study contains extremely detailed Nusselt number distributions with jet impingement onto a plane smooth disk, it is assumed that the rotation does not influence the color response of the liquid crystals. The centrifugal acceleration at the outer diameter of this disk (111,162 m/s^2) is close to the maximum value achieved in the present experiments, (89,968 m/s^2). These two centrifugal acceleration values fall into the same range as defined by actual rotating disk configurations used in gas turbines.

An experimental investigation of heat transfer coefficients in a spanwise rotating channel (D=1.16 m) with two opposite rib-roughened walls is reported by Taslim, Rahman and Spring (1991). Encapsulated liquid crystal coated polyester sheets are photographed in the rotating coolant passage surface by using a 35 mm still image camera. Steady-state heat transfer experiments are performed by using an etched foil heater with a liquid crystal coated polyester sheet as temperature indicator at a rotational speed of 250 rpm. The absolute level of the maximum centrifugal acceleration is only about 392 m/s^2 which may be considered extremely low compared to the present study.

An application of liquid crystal thermography in the rotor of a large-scale low-speed turbine research rig is described by Blair, Wagner and Steuber (1991). A mixture of 8 liquid crystal slurries, each having a 1 ^{o} C color bandwidth has been used in a steady state heat transfer experiment performed in the rotating frame. This paper contains the results of the first investigation claiming that there is a temperature measurement bias in liquid crystal thermography when encapsulated crystals are implemented in a rotational environment. It is reported that there is a + 2 ^{o} C temperature shift at 400 rpm when compared to stationary calibration of the liquid crystal. They attribute this deterministic rotational speed dependent shift to a combination of mechanical and aerodynamic stresses present in the liquid crystal/black paint coating when the rig is rotating. It is clearly reported in this paper that the observed temperature bias is corrected during the data reduction.

Another application of liquid crystal thermography in a rotating coolant passage is presented by Blair, Wagner and Steuber (1991). They report a +3 to +4 ^{o} C difference between the liquid crystal measurement and thin foil thermocouple measurement at 525 rpm, in a rotor cooling channel attached to a rotating arm , (D=1.83 m).The centrifugal acceleration experienced in this experiment (2,768 m/s^2) can be considered as medium level. Blair et al.(1991) conclude that a more complete analysis of this phenomenon is necessary to permit the full implementation of liquid crystal thermography in the rotating frame.

Wilson, Syson and Owen (1993) describe the recent efforts made in the use of an image processing based liquid crystal technique applied to rotating disk systems representing those found in gas turbine engines. They report that their eventual goal is to develop a liquid crystal based heat transfer measurement system on rotating disks. No further information is provided for the influence of rotation on the liquid crystal color response.

The current study has been initiated to address serious concerns about the accuracy of the liquid crystal color calibrations in the rotating environment. The main objective of the present investigation is to quantify the influence of the strong centrifugal acceleration field on the color calibration of encapsulated liquid crystals used in rotating disk experiments. A complete experimental methodology to correlate liquid crystal hue with local temperature as measured by a non-intrusive infrared point-sensor is described in detail.

VI . 2 Apparatus and Experimental Procedures

VI.2.1 ***<u>Rotating Disk</u>*** : The metallic rotating disk having a maximum rotational capability of 7500 rpm is shown in Figure 6. 1.a . The Aluminum disk (ρ_{al}=2707 kg/m^3) has an outer diameter of D=0.3048 m with a uniform axial thickness of δ_{al}=3.175x10^{-3} m. The disk rim is directly connected to the an AC electric motor (115 V , 60 Hz) via an aluminum flange. The rotational speed of the motor is controlled between 0 and 7500 rpm by an AC Variac. The disk assembly is housed in a steel protective cover. The thermocouple lead out wires are passed through a hollow flange and a flexible coupling that is connected to the rotor of the mercury slip-ring device. Although the setup initially included the slip-ring device for rotating thermocouple measurements, the current study uses a non-intrusive infrared point-sensor as local temperature reference. Figure 6.1.b shows the forces acting on a differential fluid element clinging to the rotating disk surface.

VI.2.2 ***<u>Liquid Crystal Coating and Hue Capturing</u>*** : The rotating disk has been coated with black paint and subsequently with an encapsulated liquid crystal material having a narrow color bandwidth of 1^{o} C. Two different liquid crystals with different temperature color play zones are evaluated individually. The first coat R30C1W manufactured by Hallcrest Inc. was sprayed in a 50 % slurry and 50% distilled water mixture (volumetric), using an air brush after the application of an extremely thin black paint on the aluminum disk surface. The resulting approximate thickness of the black paint/liquid crystal layer is about 35-45 µm. After the completion of the tests with this crystal, R45C1W have been subsequently evaluated. The hue determination via a color image processing system at a reference point on the rotating disk is made simultaneously with the actual temperature measurement from the non-intrusive infrared point-sensor. The infrared sensor is positioned in the stationary frame. The temperature output from the infrared sensor is displayed in the video image containing the liquid crystal colors and continuously recorded on a video tape. During the data reduction , individual images are processed frame by frame to obtain hue and local temperature (infrared sensor) pairs. The hardware including the 24 bit color image processor, video decoder/encoder and an array processor to accelerate image intensive operations and the color model based on Hue, Saturation , Intensity attributes are discussed in detail in Camci et al. (1992). The hue versus temperature calibrations are repeated at ten selected rotational speeds between 0 and 7500 rpm.

VI.2.3 ***Infrared Point-Sensor*** : The current study uses an infrared point-sensor for non-intrusive local temperature measurements on the flat surface of the rotating disk. The local infrared temperature measurement from a circular spot having a diameter of 2.54 mm is used to construct hue versus temperature curves of the liquid crystal layer. The specific infrared sensor (Raytek Thermalert ET3LT) consists of a thin film thermopile detector along with a spectral filter. A lens system designed to transmit infrared energy is used to focus the energy onto the detector. Stray radiation from sources both inside and outside the sensor is eliminated using special baffling techniques. The output from the IR detector and an ambient temperature sensor are summed and then digitized to a 12 bit level. After linearization, the 12 bit signal is fed to a digital-to analog converter followed by a sample and hold circuit and an output amplifier.

Figure 6.2 describes the orientation of the infrared point-sensor with respect to the reference calibration plate. The sensor head is required to be located at 76.2 mm (3 inches) normal to the measurement surface coated with a liquid crystal layer. The spectral response of the infrared sensor is between 8 microns to 14 microns. This character makes this sensor insensitive to the visible illumination lights used for liquid crystal hue determination . The plate has been illuminated by a 250 W incandescent light source located at a 1.5 m separation distance from the measurement spot. The light source has been oriented at 45 ^{o} angle measured from the plane of the disk. Possible infrared emissions from incandescent bulbs have been filtered out in front of the light source. The 80 millisecond response time of the IR sensor makes it ideal for the measurement of local rotating disk temperature during the hue versus temperature experiments. The emissivity of the liquid crystal covered surface has been determined using a calibrated thin foil thermocouple of K type . The thermocouple as shown in Figure 6.2 is mounted in the black paint layer of the Aluminum calibration plate that is identical to the rotating disk material . Although the current experimental procedure does not require an exact knowledge of the emissivity of the surface coated with liquid crystals, the emissivity has been determined (ε=0.96) using the calibrated thin foil thermocouple .

VI . 3 Experimental Results and Discussion

VI.3.1 Experimental Strategy : The current strategy is based on constructing a non-intrusive measurement scheme in order to quantify the changes in the color response of Chiral-Nematic encapsulated liquid crystals mounted on a rotating disk surface. Figure 6.2 shows the details of the Aluminum calibration plate which is coated with the same black paint and liquid crystal layer (R30C1W) as the rotating disk. A fast response thin foil thermocouple with an approximate thickness of 13 μm is imbedded in the surface coating before the liquid crystal layer is sprayed on the calibration plate. The size of the reference spot containing the thermocouple is about 2.54 mm. A non-intrusive measurement scheme can be constructed by performing simultaneous temperature measurements on the calibration plate using liquid crystals, an infrared point sensor and a thin foil thermocouple. The process described in this section provides the quantitative baseline calibrations for both the liquid crystal layer and the infrared sensor.

The reference plate is first heated up to a mean temperature of 60 ^{o} C slowly, without causing damage to the black paint and the crystal layer. As soon as the heat gun is removed from the reference spot location, a slow transient at an approximate cooling rate of 0.1 ^{o} C /minute is generated. During the transient, a color video camera records the liquid crystal color image, the voltage output of the infrared sensor that is focussed on the reference spot and the voltage output from the thin foil thermocouple that is imbedded in the reference spot location. Due to the extremely small thickness of the thermocouple junction and the crystal layer and large time scale of the thermal transient generated, one can reasonably assume that the local temperature measured by the thin-foil thermocouple is the same as the infrared sensor and the liquid crystal based temperature measurements.

Figure 6.3 provides the relationship between the local liquid crystal color (hue) and the local thermocouple based temperature measurement (T_{tc}) on the calibration plate. The linear portion of the hue versus temperature curve and the linear regression line fitted to measured data is given for the crystal designated as R30C1W. The hue versus temperature curve is highly repeatable on the stationary calibration plate as shown in Figure 6.3. Different symbols show individual hue versus temperature curves from different cooling transients. It should be noticed that color data hue can only be recorded when the reference spot temperature is around 30 ^{o} C because of the narrow band character of the liquid crystals selected. During a cooling transient, temperatures from 60 ^{o} C down to ambient level are experienced by the reference spot. However, distinct liquid crystal colors in the linear zone only appears around 30 ^{o} C in a 1 ^{o} C bandwidth. The reference spot color is either black or dark blue when the local temperature is outside the bandwidth of the liquid crystal.

Figure 6.4 shows the voltage output (V_{IR}) of the infrared point sensor plotted against the local thermocouple based measurement (T_{tc}) from the thin foil sensor on the reference calibration plate . It should be noted that the data presented in Figures 6.3 and 6.4 are simultaneously obtained from the slow cooling transient described in the previous paragraph. The linear relationship shown in Figure 6.4 is an accurate calibration of the infrared point sensor against a reference thermocouple including the emissivity influence of the liquid crystal coated surface. Figure 6.4 provides data over the complete cooling transient because an infrared sensor output is continuously available during the complete transient. The plus signs clustered around 30 ^{o}C (within ± 0.5 ^{o}C) shows the high resolution data obtained during the appearance of the meaningful liquid crystal colors . In order to correlate liquid crystal color (hue) with another non-intrusively obtained temperature measure (V_{IR}), a cross plot of the information provided in Figures 6.3 and 6.4 is presented in Figure 6.5. This approach provides the possibility of using two independent non-intrusive temperature measurement techniques simultaneously. This style is very effective for the measurements to be performed in the rotating frame of reference in rotating thermal systems. For example, a locally obtained liquid crystal color (HUE) can be quantified by using the infrared temperature measured at the same spot. In the present approach, the implementation of thermocouples and a signal transmission device such as a slip-ring and telemetry in the rotating frame of reference is completely eliminated. Installation of thermocouples underneath a liquid crystal layer with a finite thickness becomes a significant error source in high speed rotating machinery applications. It is the author's experience that, thermocouple measurement errors in a rotating system when combined with slip-ring related signal shifts may become very significant. This is especially true at high rotational speeds where high local heat flux values on rotating surfaces may create large temperature differentials between the liquid crystal layer and the thermocouple location underneath the coating. This temperature bias may be amplified by other thermal boundary conditions existing near the reference thermocouple. Most of these adverse effects may accumulate as rotational speed dependent temperature bias error. Since non-negligible bias errors have been observed during the initial phase of this investigation, the authors eliminated the use of a reference thermocouple sensor on the rotating disk surface in favor of an infrared temperature measurement system, located in the stationary frame.

VI.3.2 ***<u>Implementation of Infrared Point-Sensor Measurements in the Rotating Frame</u>*** **:** Although the liquid crystal calibration technique described in the previous paragraph shows excellent repeatability and good accuracy on the stationary calibration plate, its implementation on the rotating disk surface requires careful implementation. Figure 6.5 shows hue versus infrared temperature results from four individual cooling transients obtained on the rotating disk surface in addition to calibration plate results. The rotating disk as shown in Figure 6.1 is coated with an identical black paint/ liquid crystal layer. The hue versus infrared temperature relationship obtained on the stationary disk surface is compared with that of the calibration plate . The data from the disk surface at 0 rpm and the calibration plate show excellent agreement within the experimental uncertainty of hue capturing process and infrared measurement technique. This observation results in the conclusion that a totally non-intrusive liquid crystal technique and an infrared temperature measurement technique could be successfully used in a rotating frame of reference. However, an individual calibration of the infrared sensor and liquid crystal thermo-indicator on an equivalent stationary calibration plate as described in Figure 6.2 is essential. The process described in this paragraph eliminates the need for a reference thermocouple sensor on the rotating disk surface.

Current temperature measurements using the infrared sensor are capable of generating one measurement for every 80 milliseconds. During the experiments performed between 0 and 7500 rpm, the rotating disk is carefully heated at the disk centerline before a cooling transient. A heated impinging jet of air issued from a heat gun is the heating source for the rotating disk. The qualitative isothermal line visualization using liquid crystals shows that the isotherms on the disk surface are perfect circular lines especially when the disk is cooled by forced convection due to the rotation. There are almost no temperature gradients in the circumferential direction in this axisymmetric free disk problem**.** The circumferential uniformity of the temperature profile is also checked by freezing the image by using a stroboscope light source. This feature makes the infrared point-sensor an ideal instrument for time averaged temperature measurements in the rotating frame. At 5000 rpm, an infrared spot located at 0.135 m is expected to time average the infrared emissions (from the 2.54 mm spot) over 6 rotations of the disk. The time response of the video image processing system collecting the liquid crystal color data is about 30 frames/second. Therefore, it is expected that liquid crystal data will be averaged over 2.7 rotations of the disk by the image processor. During the non-intrusive measurements it is assumed that the emissivity of the liquid crystal/black paint layer does not change with rotational speed. It is a known fact that emissivity of an almost black surface is not influenced from how it moves with respect to a stationary reference frame. The emissivity is a strict function of the type of the surface material and its specific texture in the relatively narrow temperature band of the current experiments.

The non-intrusive infrared sensor described in the previous paragraph has been used to obtain temperature data in adiabatic disk experiments over a rotational speed range from 0 rpm to 7500 rpm. The shear layer thickness at 7500 rpm has been estimated as 4.5 mm at the infrared sensor spot location (r=0.135m). Thicker shear layer thickness is predicted for lower rotational speeds. Since a wide rotational speed range is used in this experiment, it is important to document the status of the shear layer at the measurement location. Figure 6.6 shows the correlation for the prediction of the onset of transition and fully turbulent shear layer over the disk , Kobayashi et al.(1980).The correlation indicates that the disk boundary layer will always be fully turbulent when the rotational speed is over 2500 rpm at the spot location. In order to compare the infrared sensor measurements with existing analytical models, the surface temperature rise on an adiabatic disk is plotted against the rotational speed as shown in Figure 6.7. Excellent agreement between the theory given by Owen (1971) and Chew (1985) and infrared point-sensor measurements above 2500 rpm is presented in Figure 6.7. The infrared sensor measurements on the present disk are underpredicted by the theory below 2500 rpm. This may be attributed to the fact that flow is expected to be transitional or laminar below 2500 rpm on a free disk experiment at r=0.135 m. The current non-intrusive infrared temperature measurement technique is in very good agreement with existing analytical model of temperature rise on an adiabatic rotating disk, for the fully turbulent flow zone.

VI.3.3 Evaluation of Mechanical and Thermal Effects Influencing the Liquid Crystal Layer

There are three factors which could influence to the liquid crystal color response under rotational flow conditions.

1. *The disk mechanical stresses associated with elastic deformations imposed by the rotation of the disk. The liquid crystal layer sprayed on the surface of the metallic disk may sense the stresses in the metallic disk as a surface force at the interaction surface.*

2. *Aerodynamic friction forces on the flow side of the liquid crystal layer due to the rotation of the disk in air.*

3. *The mechanical stress (including the radial and circumferential components) induced by centrifugal forces in the relatively thin and low density black paint/liquid crystal layer.*

Approximate Density of the Black Paint/Liquid Crystal Layer: An evaluation of mechanical stresses influencing the liquid crystal coating requires the knowledge of the density of a typical black paint/liquid crystal layer. For this purpose, an aluminum block in the form of a rectangular prism (0.125mx0.013mx0.03m) has been machined to obtain square cross section fins on its external surface. This process helps to increase the effective area of the prism for further liquid crystal coats. Multiple coats of liquid crystal layers have been sprayed and left to drying repeatedly. The volume change with respect to the uncoated block has been measured (~5 mL) in a glass jar filled with water. The accumulated liquid crystal mass has also been measured (0.408 gram mass) on an electronic scale accurate up to ±0.005 gram mass resolution. The resulting black paint/liquid crystal layer density was about ρ_{lc}=~81.6 kg/m^3. In a second experiment, the density has also been obtained by filling the initially known volume of a cylindrical cavity carefully machined into an aluminum block. The cavity has been sprayed and dried repeatedly until the whole cavity is filled with liquid crystal material. The air bubbles have been eliminated to the best possible extend during the filling process. The resulting density from this experiment was around ρ_{lc}=~84.7 kg/m^3. Since the geometrical shape of the cavity open surface is difficult to control in multiple coating experiments, it is suggested that the approximate density value of ρ_{lc}=~81.6 kg/m^3 from the previous experiment is adopted for the analysis presented in this paper. The uncertainty of the density measurement is estimated to be at least ±6 %. The measured density of the dry liquid crystal layer is very close to the values typical to Balsa wood (ρ=~100 kg/m^3). The measured ρ_{lc}=~81.6 kg/m^3 value is about 33 times smaller than the Aluminum disk density of ρ_{al}=~2707 kg/m^3.

Mechanical Stresses in the Rotating Disk : The approximate magnitude of disk mechanical stresses induced by rotation are much greater (about 33 times) than expected mechanical stresses in the liquid crystal layer due to the corresponding aluminum to liquid crystal density ratio. To verify the influence of the disk mechanical stress on the liquid crystal layer, a simple tension test using a liquid crystal painted test coupon has been performed. The coupon has been instrumented with a thermocouple which was installed flush to the surface underneath the liquid crystal. A wide range of tensile stresses (from 0 to 5 times of total stresses corresponding to the disk rotating speed of 7500 rpm) have been applied. No liquid crystal color shift has been observed in these experiments when the coupon surface is kept at a prescribed temperature. This test clearly indicated that mechanical stresses in the substrate material alone cannot influence the color response of the liquid crystal coating.

Aerodynamic Wall Shear Stress : Another important force that may influence the liquid crystal layer is the aerodynamic wall friction force $\tau_o \cdot ds \cdot dr$ acting on the flow side of the liquid crystal layer, as described in Figure 6.1. This force can be predicted from existing solutions of the turbulent viscous pump problem for a free disk. A detailed treatment of this classical problem starting from von Kármán's (1921) problem definition is given in Dorfman (1963) and Owen and Rogers (1989). In the radial direction, the balance of the turbulent shear force applied to the area $dr \cdot ds$ and the centrifugal force acting on the fluid volume results in,

$$\tau_{r,o} = \tau_o \cdot \mathrm{Sin}\phi = \rho \cdot r \cdot \Omega^2 \cdot \delta \quad . \qquad (6.1)$$

According to Schlichting (1979), the shear stress component in the tangential direction ($\tau_{\theta,o} = \tau_o \cdot \mathrm{Cos}\phi$) can be borrowed from a model developed for a flat plate boundary layer using the 1/7 th power velocity profile. One may show from equation 6.1 that the shear layer thickness for turbulent flow over the free disk can be estimated as,

$$\delta = \sim 0.5261 \cdot r^{3/5} \cdot (\nu/\Omega)^{1/5} \quad . \qquad (6.2)$$

This solution assumes that ϕ angle does not change with radius. equation 6.2 is also consistent with the experimental results of Schmidt (1921), Kempf (1924), Dorfman (1963) and Glezer (1969).

From a mechanical point of view, the liquid crystal layer sees the aerodynamic wall shear stress as a reaction to the fluid friction at the flow surface. The tangential component of the aerodynamic wall shear stress can be calculated from,

$$| \tau_{\theta,o} | = 0.02668 \cdot \rho \cdot \Omega^2 \cdot b^2 \cdot (r/b)^{8/5} \cdot Re_\theta^{-1/5} = 0.02668 \cdot \rho^{4/5} \cdot \Omega^{9/5} \cdot r^{8/5} \cdot \mu^{1/5} \quad . \qquad (6.3)$$

The relationship between the radial and tangential component can be approximated as $|\tau_{r,o}| / |\tau_{\theta,o}| = 0.162$, Owen and Rogers (1989). The magnitude of the total aerodynamic shear stress vector is then,

$$|\tau_0| = [\tau_{\theta,0}{}^2 + \tau_{r,0}{}^2]^{1/2} = [\tau_{\theta,0}{}^2 + (0.162)^2 \cdot \tau_{\theta,0}{}^2]^{1/2} = 1.013 \cdot |\tau_{\theta,0}| \qquad (6.4)$$

The predicted magnitude of aerodynamic shear stress from equation 6.4 has the same order of magnitude of the mechanical stress estimate inside the liquid crystal/black paint layer.

VI.3.4 ***Liquid Crystal Hue Response at Different Rotational Speeds*** **:** In order to isolate the possible influence of rotation on the color response of liquid crystals a series of tests on the rotating disk assembly have been performed in a wide rotational speed range (0- 7500 rpm). The non-intrusive technique using narrow band liquid crystals and infrared point-sensor has been repeatedly used under identical conditions for many different rotational speeds at r=0.135 m. Figure 6.8 presents hue versus infrared sensor based temperature measurements obtained from three different experimental arrangements. The narrow band liquid crystal designated as R30C1W has been tested on the stationary calibration plate, the stationary disk and rotating disk at many different rotational speeds. The horizontal axis of Figure 6.8 can be easily converted from infrared sensor output voltage to local temperature by using the calibration curve given in Figure 6.4. An immediate observation from Figure 6.8 is that rotation does not have any significant influence on the color response of liquid crystals used on a rotating disk surface. A few hundred data points from many different rotational speeds always follow the same curve defining the hue versus temperature relation. The figure also includes results from repeatability tests. Some minimal scatter existing in the present data is within the reported uncertainty band of the hue capturing system and infrared measurement system.

Figure 6.9 includes similar hue versus infrared sensor based temperature measurements for a liquid crystal slurry designated as R45C1W. This material has also been provided by the same manufacturer for a color play bandwidth if 1 ^{o} C. Once again, a well defined hue versus temperature relation has been observed with very good repeatability for many rotational speed values between 0 and 7500 rpm. The data presented in Figure 6.9 also suggests that rotational effects on the surface of the disk do not influence the color response character of the liquid crystal thermo-indicator.

The data given in Figures 6.8 and 6.9 supports the initial estimates made for the order of magnitude of the mechanical stresses inside the thermo-indicator coating and the aerodynamic shear stress at the fluid solid interface of the disk. It seems that rotation induced aerodynamic shear stress when combined with internal mechanical stresses can not influence the physical process that causes specific color patterns appearing on the disk surface under certain local temperature conditions. The experimental observations made in this study and simple estimates of aerodynamic shear stress and mechanical stresses obtained under rotational conditions suggest that liquid crystal thermo-indicators are not influenced from rotational effects. The hue data clearly shows that there is no significant color shift due to rotation of the disk tested under realistic gas turbine conditions. However, it is the author's observation that systematic temperature shifts may be erroneously recorded when surface thermocouples are utilized (underneath the thermo-indicator coating) instead of a non-intrusive reference temperature measurement device such as the infrared point-sensor used in this study. Usually these systematic temperature shifts (erroneously recorded bias errors) are rotational speed dependent and may easily be accounted as a change in liquid crystal color calibration.

Past studies using liquid crystals in the stationary frame wind tunnel experiments always assumed that encapsulated liquid crystals are not influenced by aerodynamic wall shear stress. However, there is not a single reference in open literature including quantitative information on this problem. The present study quantitatively shows for the first time that liquid crystal hue can not be altered by imposing different levels of aerodynamic shear stress from the flow side. At a given radial position, every rotational speed setting imposes a different aerodynamic wall shear stress value on the thermo-indicator layer as predicted by equation 6.4. Figures 6.8 and 6.9 show no influence from aerodynamic wall shear stress on color response of liquid crystal layer in a wide range of aerodynamic shear stress magnitudes.

VI.3.5 ***<u>Adiabatic Disk Temperature Rise from Liquid Crystal Measurements</u>*** **:** Further investigations on the use of liquid crystal thermo-indicators have been carried out by using liquid crystals in a free disk heat transfer experiment. When the ambient temperature is reasonably uniform around a rotating free disk, the convective heating of the disk from the neighboring viscous region creates a specific radial temperature distribution. The adiabatic temperature rise is known to be a function of the disk rotational speed, the radial position on the disk and the specific heat of the fluid surrounding the disk. The liquid crystal based temperature measurements from the adiabatic disk experiments are shown in Figure 6.10. The rotating disk is brought to an adiabatic condition by running the disk at 6648 rpm for about an hour. The still air temperature is approximately T_∞=27.63 $^\circ$ C for the specific experiment. The liquid crystal colors falling into the linear range of the calibration shown in Figure 6.3 have been observed to exist over a 6 cm radial band starting from r=0.03m. Four other adiabatic disk experiments have also been performed at 6545, 6345, 5932 and 5488 rpm. The liquid crystal color band containing the colors in the linear range of the calibration move radially outward by decreasing rotational speed. It should be noted that the ambient temperature slightly decreases with decreasing rotational speed as shown in Figure 6.10. This slight change is because of the relatively small amount of heat dissipation to the still air, at reduced rotational speeds. If one continues to reduce the rotational speed from 5488 rpm level, for an approximate still air temperature of T_∞ =27.5 $^\circ$ C, the liquid crystal color band will not continue to appear on the disk surface. In this relatively low rotational speed range, the actual disk temperatures are well below the meaningful color play zone of the thermoindicator ($\pm$ 0.1 $^\circ$ C) around 30 $^\circ$ C. This observation shows the importance of the selection of the liquid crystal color play zone for a specific rotating disk heat transfer experiment. The specific location of the useful liquid crystal color band can be continuously adjusted by changing rotational speed or ambient temperature around the disk.

VI.3.6 ***<u>Comparison with Free Disk Heat Transfer Theory</u>*** **:** Figure 6.11 shows the comparison of liquid crystal based adiabatic disk temperature measurement using the calibrations presented in Figures 6.3, 6.4, 6.8, 6.9 and the theoretical prediction from Owen (1971). The adiabatic disk temperature is predicted as $T_{aw}=T_{\infty}+\Omega^2r^2/2C_p$ for 6345 rpm and 5488 rpm. Reasonably good agreement between the theory and the present liquid crystal measurements is shown in Figure 6.12. The data is presented from r=0.09 m to r=0.15 m on the rotating disk surface.

VI.3.7 ***<u>Influence of Added Stroboscope Illumination on Liquid Crystal Hue</u>*** **:** The current experiments described in this paper have been performed by generating a completely axisymmetric flow and heat transfer situation on the rotating disk surface. Because of the infrared measurement systems finite time response of 80 milliseconds, the measurement has been time averaged over 6 rotations of the disk at 0.135 m radius, at 5000 rpm. Time averaged character of infrared measurements is not an influencing factor as long as the flow and heat transfer parameters do not vary in circumferential direction. Rotating disk problems may have variations in axisymmetric direction in applications other than perfect free disk problem. For example, the existence of a bolt head or a step may cause a strong temperature distribution in both the radial and circumferential directions. When thermal non-uniformities in the circumferential direction and radial direction are introduced, freezing the liquid crystal image by using a stroboscope light can be extremely beneficial. A stationary visual image of the liquid crystal coated surface can provide an accurate two dimensional liquid crystal view of a highly three dimensional thermal field on a rotating surface.

Figure 6.12 compares the liquid crystal hue variation with respect to infrared sensor output without and with stroboscope light illumination at 3000 rpm. The stroboscope light has been used in these particular experiments in addition to the regular illumination lights as described in the previous paragraphs. The information provided in Figure 6.12 is from an axisymmetric free disk experiment, however the conclusions drawn from this experiment are valid for any non-axisymmetric surface heat transfer problem making use of liquid crystal thermo-indicators. The experimental data presented in Figure 6.12 clearly show that additional stroboscope light does not alter the hue versus temperature relationship in a rotating disk experiment. This observation can be explained with the insensitivity of hue measurements to variations in the intensity of additional illumination from the stroboscope. In general, captured hue value is not influenced from the strength of illumination, Camci et al. (1992). The infrared sensor used in the specific experiment is also not sensitive to visible light emitted from the stroboscope and the illumination system, because of its special spectral range in the infrared spectrum. The data in Figure 6.12 provides the conclusion that a stroboscope device can be directly used over a liquid crystal coated surface for the high resolution temperature mapping of non-axisymmetric disk problems. It has also been observed that slight variations in camera angle ($\pm 15\ ^{o}$) and slight camera zoom variations ($\pm$ 0.25 m) do not influence the results presented in Figure 6.12.

VI . 4 Experimental Uncertainty

Stationary frame temperature measurements using the hue capturing method typically results in an overall uncertainty of less than $\pm 0.1\ ^{o}$C at about 30 ^{0}C provided that the hue values between 30 and 140 are used for data reduction purposes. This specific value requires a careful calibration of the reference thermocouple used in the construction of the hue versus temperature curve of liquid crystals. It is expected that the reference thermocouple is calibrated to an uncertainty of $\pm$0.05 ^{o}C around 30 ^{o}C. Other individual uncertainty contributors such as the illumination angle, model to illumination source distance, spatial distribution of liquid crystal color response and the repeatability of the hue capturing process are discussed in detail in Camci et al. (1992).

In the hue versus temperature charts presented in this paper the horizontal axis is infrared sensor output V_{IR} in Volts. A $\pm$ 0.020 Volts uncertainty over a nominal output value of 1.7966 Volts (at 30 ^{o}C) is estimated. This value corresponds to about $\pm$ 0.10 ^{o}C temperature measurement error on the infrared point-sensor. The repeatability of infrared based temperature measurements is estimated to be around $\pm$ 0.05 ^{0}C at 30 ^{0}C.

An additional uncertainty contributor may be the determination of the rotational speed that is monitored constantly by using an electronic rpm measuring device. This device uses the light reflections from a highly reflecting narrow strip on the disk surface. $\pm$ 5 rpm at a nominal speed of 2000 rpm is a standard estimate for this device.

It should also be remembered that even with the most precise liquid crystal coating procedures, uncertainties may be introduced when different coats of liquid crystal layers deposited at different times are compared for their hue response. The final uncertainty of the temperature measurements in the rotating frame using liquid crystal thermo-indicators is estimated as high as $\pm$0.30 C around 30 ^{o}C for all the experiments performed over a 4-month time period.

VI . 5 Conclusions

A liquid crystal thermography system in the rotating environment of a disk has been developed. Although a mercury slip ring and a thin foil reference thermocouple has been used in the initial phase of this study, the use of the thermocouple as a reference temperature sensor is eliminated to avoid the possible inclusion of rotational speed dependent temperature measurement errors.

A new experimental strategy is described using two simultaneous non-intrusive temperature measurements on the rotating disk surface. Liquid crystal hue can be effectively correlated against a carefully calibrated infrared point sensor output indicating local temperature.

An estimate of the centrifugal forces acting as body force in the liquid crystal layer requires the knowledge of the density of the liquid crystal coating. A new experiment has been designed for the first time for the approximate determination of the density of a typical dry liquid crystal coating , (ρ_{lc}=~81.6 kg/m^3).

It can be predicted that centrifugal acceleration of the disk creates non-negligible mechanical stress in the metallic disk. However, present static tensile experiments show that the metallic disk stress alone does not influence the color response of the liquid crystal layer.

The predicted magnitude of the aerodynamic friction stress is approximately the same order of magnitude as the mechanical stress acting inside the liquid crystal/black paint layer .

The experimental observations made in this study and simple estimates of aerodynamic shear stress and mechanical stresses obtained under rotational conditions suggest that liquid crystal thermo-indicators are not influenced from rotational effects within the rotational speed range of the current experiments (0-7500 rpm, r=0.135 m).

Although the current results are obtained from a circumferentially uniform free disk experiment, the specific method introduced is capable of performing well in situations where there are strong circumferential and radial temperature gradients . For this purpose, the use of a stroboscope is discussed. The current data shows that additional stroboscope light illumination does not influence the local liquid crystal based temperature measurements made on rotating disks.

Past studies using liquid crystals in the stationary frame wind tunnel experiments always assumed that encapsulated liquid crystals are not influenced by aerodynamic wall shear stress. However, there is not a single source of quantitative information on this frequently made assumption. The present study quantitatively shows for the first time that liquid crystal color response (hue) can not be altered by imposing different levels of aerodynamic shear stress from the flow side.

Only a stationary frame calibration of the liquid crystal layer is sufficient for a temperature measurement to be performed on a rotating disk. An identical stationary calibration plate using a reference thermocouple is an effective tool in documenting the hue response of a liquid crystal thermo-indicator.

The present methodology describes a complete, high resolution, non-intrusive and accurate temperature mapping technique on a rotating disk surface. The final uncertainty of the temperature measurements in the rotating frame using liquid crystal thermo-indicators is estimated as high as ±0.30 ^{0}C around 30 ^{o}C for all the experiments performed over a 4-month time period.

References

Blair, M.F., Wagner, J.H., Steuber, G.D., 1991, "New Applications of Liquid-Crystal Thermography in Rotating Turbomachinery Heat Transfer Research," ASME paper 91-GT-354.

Camci, C., Kim, K. and Hippensteele, S.A., 1992, "A New Hue Capturing Technique for the Quantitative Interpretation of Liquid Crystal Images Used in Convective Heat Transfer Studies," the Transactions of the ASME, *Journal of Turbomachinery*, Vol.114, No.4, pp.765-775.

Camci, C., Kim, K., Hippensteele, S.A. and Poinsatte, P.E., 1993, "Evaluation of a Hue Capturing Based Transient Liquid Crystal Method for High Resolution Mapping of Convective Heat Transfer on Curved Surfaces," the *Transactions of the ASME, Journal of Heat Transfer*, Vol.115, No.2 , pp.311-318.

Collings, P.J., 1990, "Liquid Crystals," *Princeton University*, Princeton, NJ.

deGennes, P.G., 1974, "The Physics of Liquid Crystals," *Clarendon Press*, Oxford, UK.

Dorfman, L.A., 1963, "Hydrodynamic Resistance and Heat Loss of Rotating Solids ," English translation, *Oliver&Boyd*, Edinburgh&London.

Farina, D.J., Hacker , J.M., Moffat, R.J. and Eaton, J., 1993 " Illuminant Invariant Calibration of Thermochromic Liquid Crystals," in ASME bound volume HTD-Vol.252, Visualization of Heat Transfer Processes.

Glezer, B., 1969, " Investigation of a Flow Between Rotating Disk and Stator," Energetica, No.3, *University Press*, Moscow.

Glezer, B., 1992, "Some Aspects of Industrial Gas Turbine Cooling Development," Proceedings of the 1992 International Symposium on Heat Transfer in Turbomachinery, organized by the International Center for Heat and Mass Transfer, Athens, Greece.

Jones, T.V., Wang, Z. and Ireland, P.T., 1992, "Liquid Crystal Techniques," Proceedings of the 1992 International Symposium on Heat Transfer in Turbomachinery, organized by the International Center for Heat and Mass Transfer, Athens, Greece.

Kármán, T. von, 1921, "Über laminare und Turbulente Reibung," Z. Agnew. Math. Mech., Vol.1, pp.233-252, (also English translation in NACA TM 1092).

Kempf, G., 1924, "Über Reibungswiderstand Rotierender Scheiben. Vorträge auf dem Gebiet der Hydro- und Aerodynamik, Innsbruck Congr. ; Berlin, pp.168.

Kim, K., 1991, " A New Hue Capturing Technique for the Quantitative Interpretation of Liquid Crystal Images Used in Convective Heat Transfer Studies," Ph.D. Thesis, The Pennsylvania State University.

Kobayashi, R., Kohama, Y. and Takamadate, Ch., 1980, "Spiral Vortices in Boundary Layer Transition Regime on a Rotating Disk," *Acta Mech*., Vol.35, pp.71-82.

Metzger, D.E., Bunker, R.S., Bosch, G., 1991, "Transient Liquid Crystal Measurement of Local Heat Transfer on a Rotating Disk with Jet Impingement," the Transactions of the ASME , *Journal of Turbomachinery,* Vol.113, No.1, pp.52-59.

Owen J.M. and Rogers R.H. , 1989, "Flow and Heat Transfer in Rotating Disk Systems," Vol.1, Rotor-Stator Systems, Research Studies Press, Taunton, Somerset, England and *John Wiley and Sons.*

Rizzo, D and Camci, C., 1994, "The Effects of a Boundary Layer Fence on the Aerodynamic Flowfield and Endwall Heat Transfer in a 90 ^{o} Turning Square Duct," 1994 ASME Winter Annual Meeting, Session : Heat Transfer in Gas Turbines, Chicago.

Schlichting H., 1979, "Boundary Layer Theory," seventh edition, *McGraw Hill*, pp.102-107.

Schmidt, W. , 1921, "Ein einfaches Messverfahgren für Drehmomente," Z.VDI Vol.65, pp.441-444.

Taslim, M.E., Rahman, A. and Spring S.,D., 1991, "An Experimental Investigation of Heat Transfer Coefficients in a Spanwise Rotating Channel with Two Opposite Rib-Roughened Walls," the *Transactions of the ASME , Journal of Turbomachinery,* Vol.113, No.1, pp.75-82.

Wiedner, B., Camci, C., 1993.a, "Accurate Determination of Local Heat Flux on Steady State Heat Transfer Surfaces with Arbitrarily Specified External and Internal Boundaries," presented at the 1993 National Heat Transfer Congress, Atlanta, Georgia, ASME volume HTD-Vol.242, pp 21:31 .

Wiedner, B., Camci, C., 1993.b, "Passage Flow Structure and Its Influence on Endwall Heat Transfer in a 90 ^{o} Turbulent Duct Flow : Mean Flow and High Resolution Heat Transfer Experiments," ASME paper ASME-93-WA/HT-52, presented at the 1993 ASME Winter Annual Meeting, to be published in Journal of Turbomachinery.

Wilson, M., Syson, B.J. and Owen, J.M., 1993, " Image Processing Techniques Applied to Wide-band Thermochromic Liquid Crystals," Proceedings of the Eurotherm 32, Heat Transfer in Single Phase Flows, 5-7 July 1993, Oxford University.

LIST OF FIGURES (CAPTIONS)

Fig. 6.1.a
Experimental setup

Fig. 6.1.b
Rotating disk geometry and the forces acting on the fluid element clinging to the disk

Fig. 6.2
Reference calibration plate and the orientation of the infrared point sensor

Fig. 6.3
Baseline calibration on the reference calibration plate,
Liquid crystal hue versus temperature measured by the thermocouple

Fig. 6.4
Infrared sensor calibration using the
reference thermocouple on the calibration plate

Fig. 6.5
Comparison of reference calibration plate and stationary disk hue calibrations using the infrared point sensor

Fig. 6.6
Predicted onset of instability point and the transitional zone near the rotating free disk

Fig. 6.7
Adiabatic disk temperature measurements using the
infrared point sensor and comparison with theory

Fig. 6.8
Influence of rotation on color response of encapsulated Chiral-Nematic liquid crystals,
hue versus infrared sensor raw output at various rotational speeds, R30C1W,
calibration plate and stationary disk results included

Fig. 6.9
Influence of rotation on color response of encapsulated Chiral-Nematic liquid crystals,
hue versus infrared sensor raw output at various rotational speeds, R45C1W compared to R30C1W, calibration plate and stationary disk results included.
(Hue versus temperature data is also included)

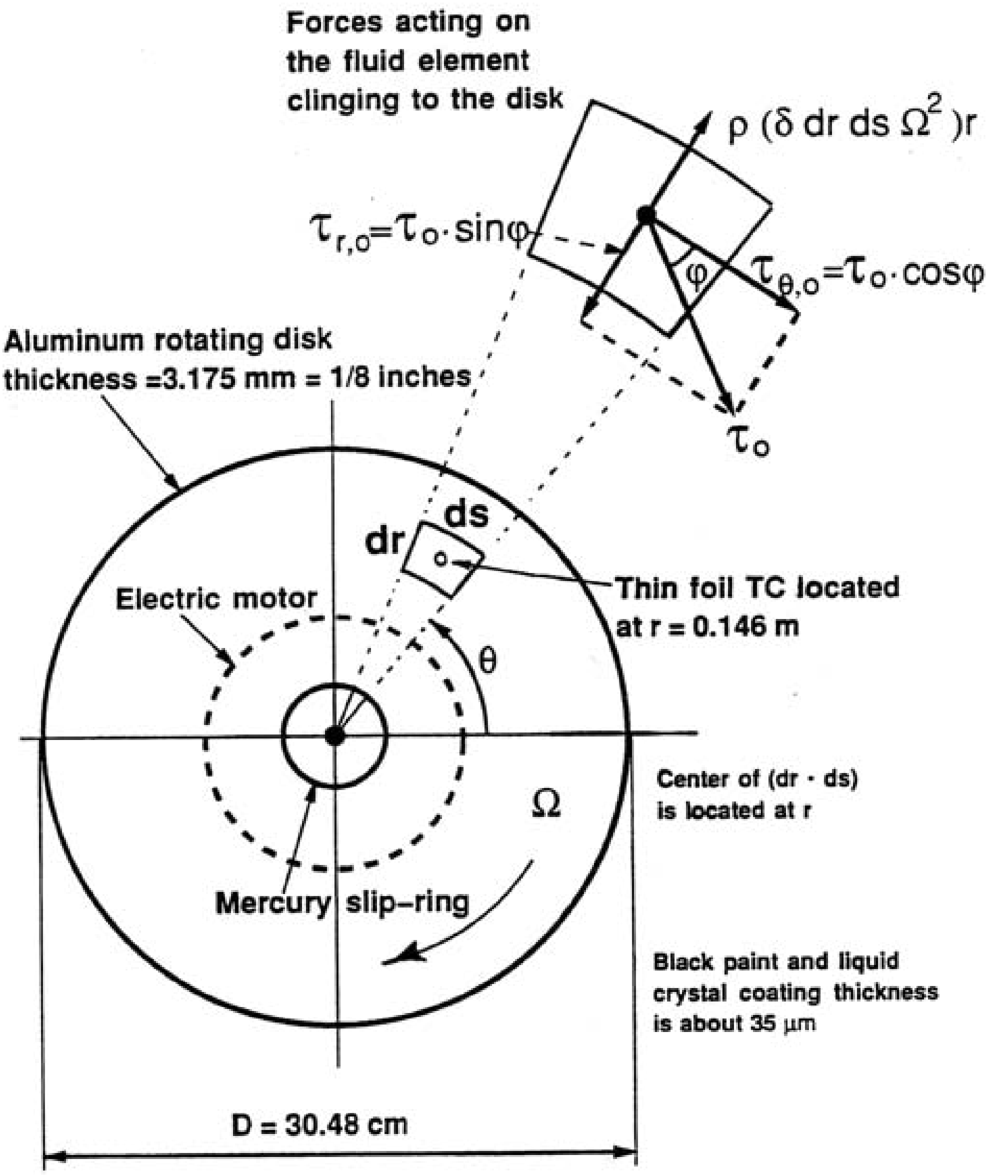
Fig. 6.10

Adiabatic wall temperature measurements on the rotating disk surface using the current liquid crystal technique, radial profiles for various rotational speeds

Fig. 6.11
Comparison of theoretical predictions of adiabatic wall temperature rise on a free rotating disk with the measured data from the current liquid crystal technique

Fig. 6.12
Influence of stroboscope light intensity, camera position and zoom level on color response of liquid crystals applied to a rotating disk surface at 3000 rpm

Fig. 6.1.a
Experimental setup



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Rotating disk geometry and the forces acting on the fluid element clinging to the disk

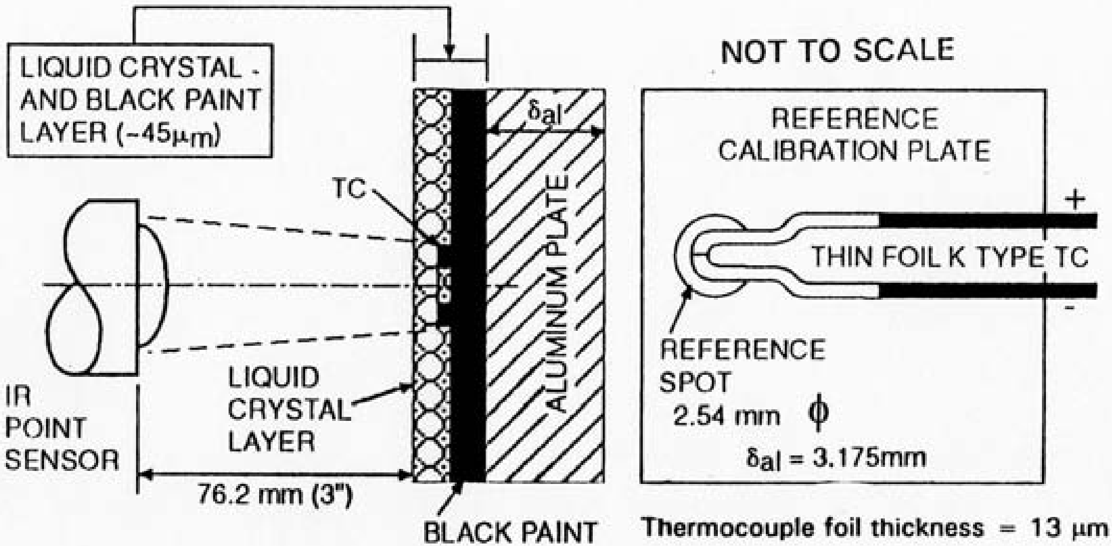

Fig. 6.2
Reference calibration plate and the orientation of the infrared point sensor

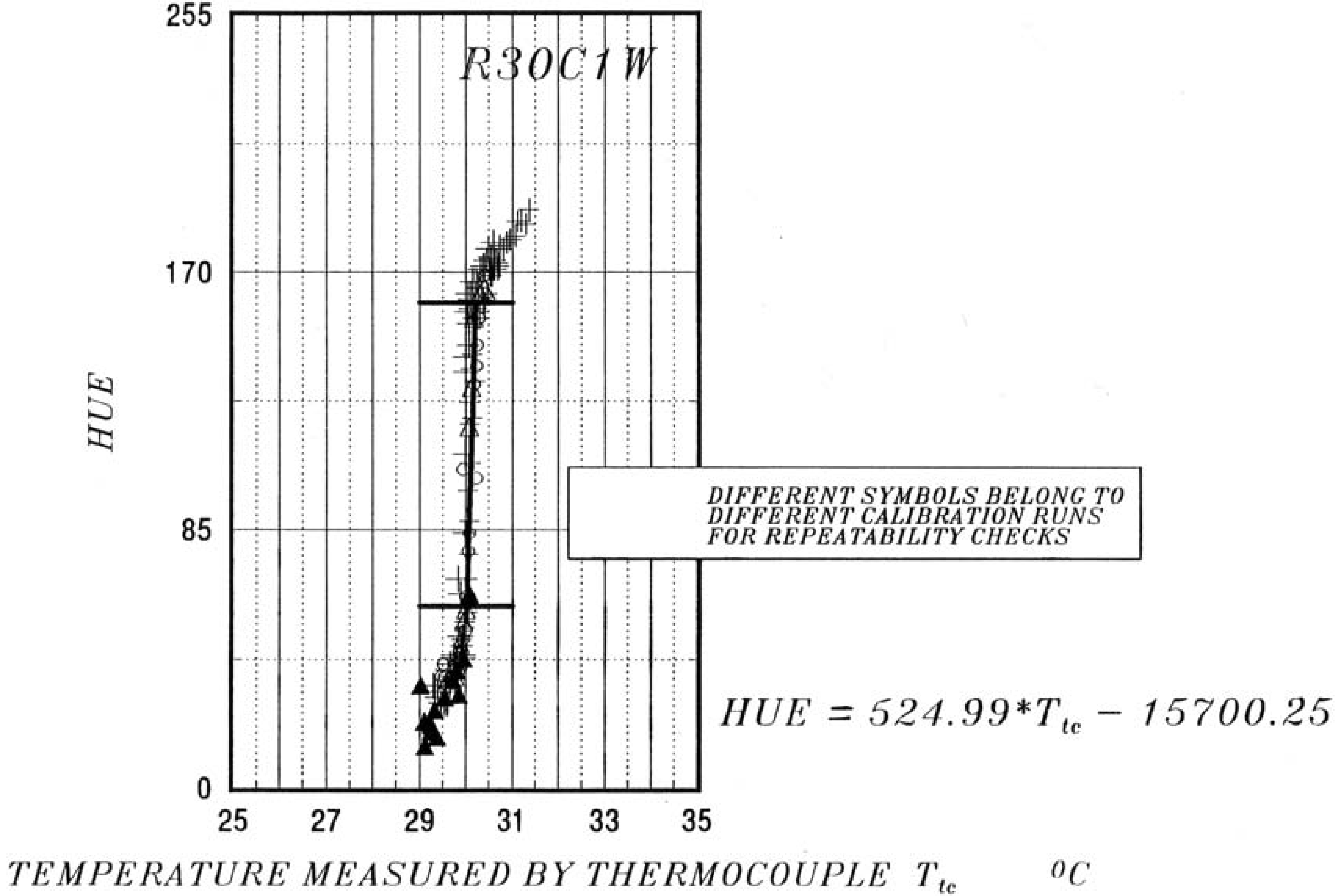

Fig. 6.3
Baseline calibration on the reference calibration plate,
Liquid crystal hue versus temperature measured by the thermocouple

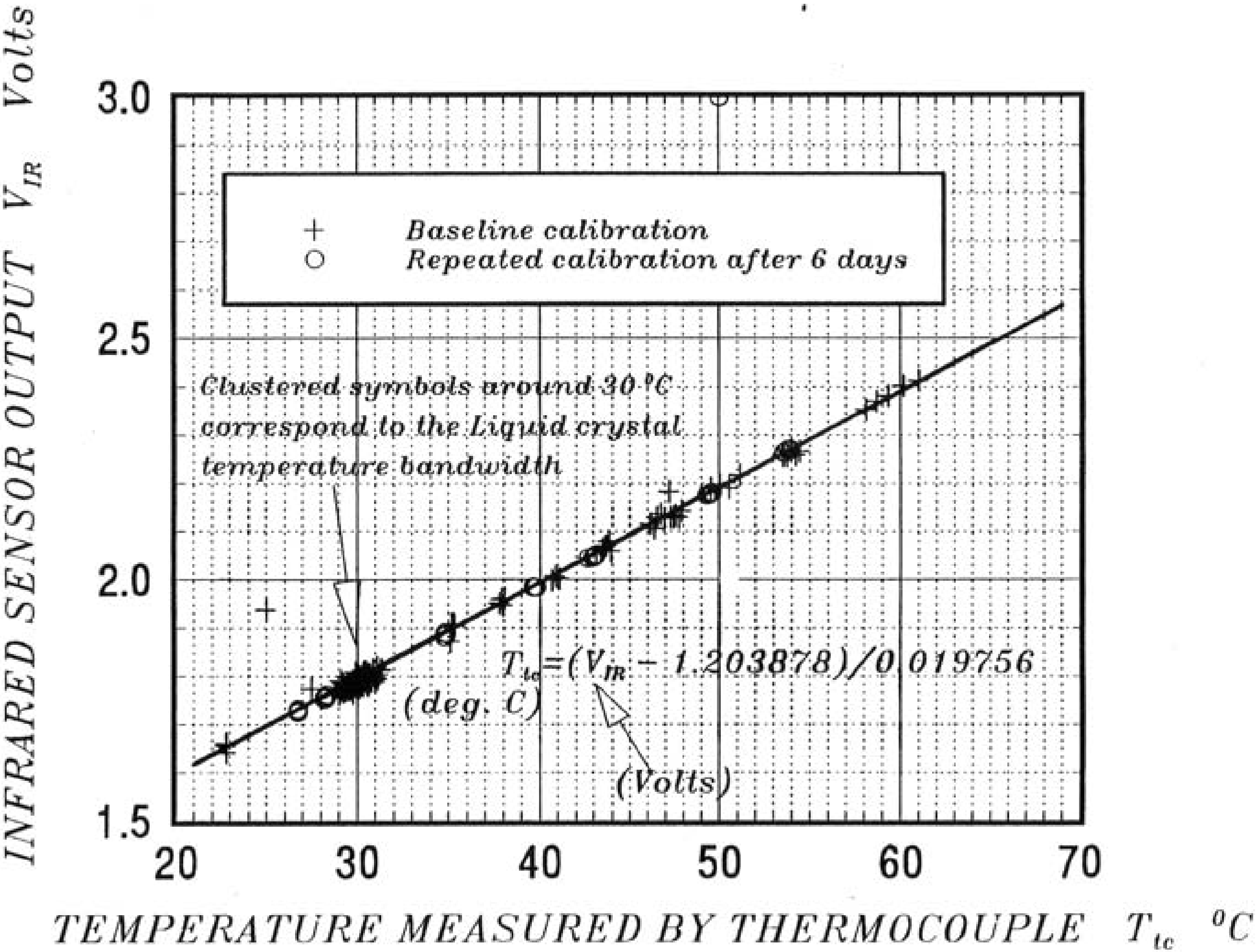

Fig. 6.4

Infrared sensor calibration using the reference thermocouple on the calibration plate

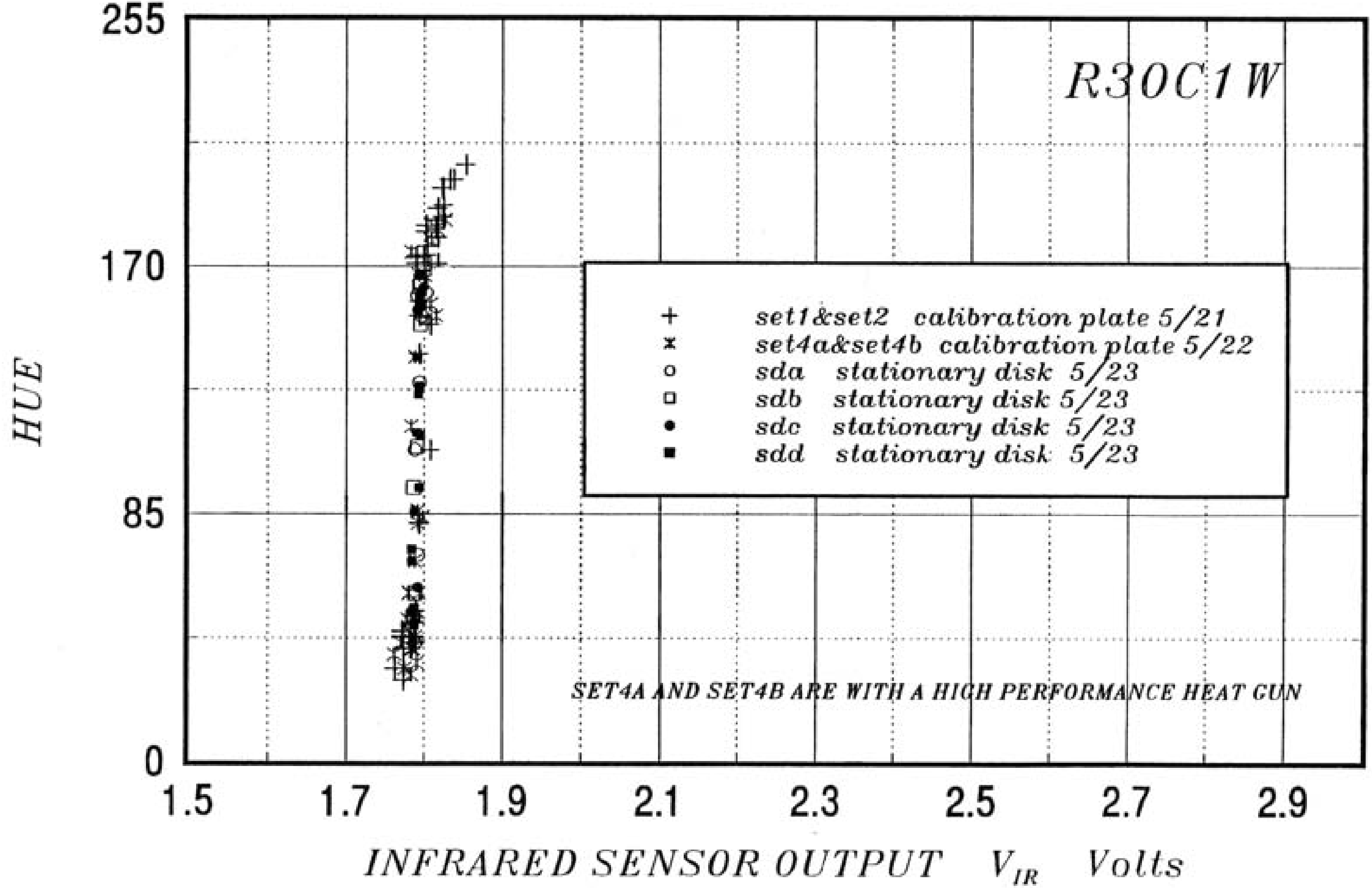

Fig. 6.5
Comparison of reference calibration plate and stationary disk hue calibrations using the infrared point sensor

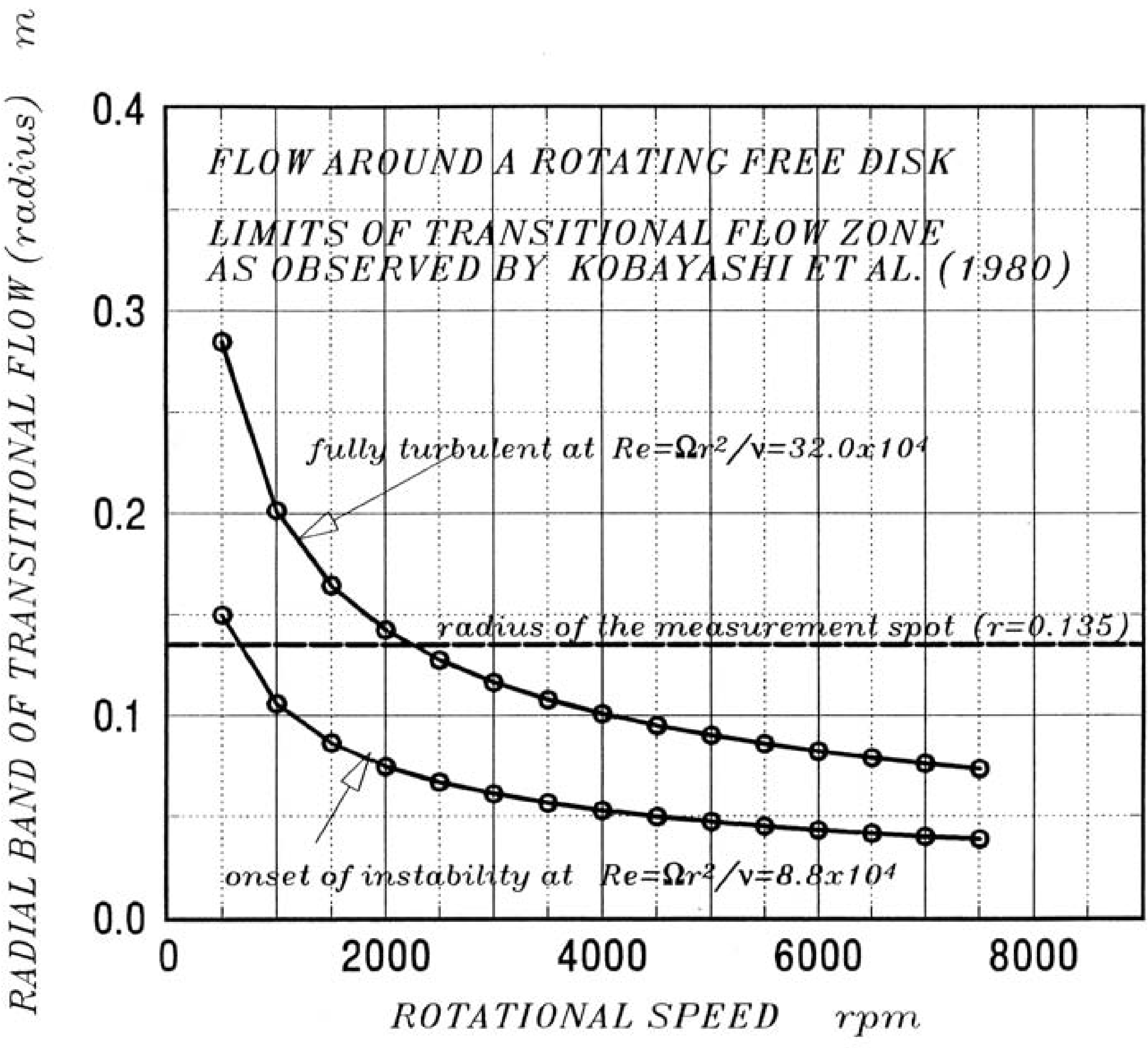

Fig. 6.6

Predicted onset of instability point and the transitional zone near the rotating free disk

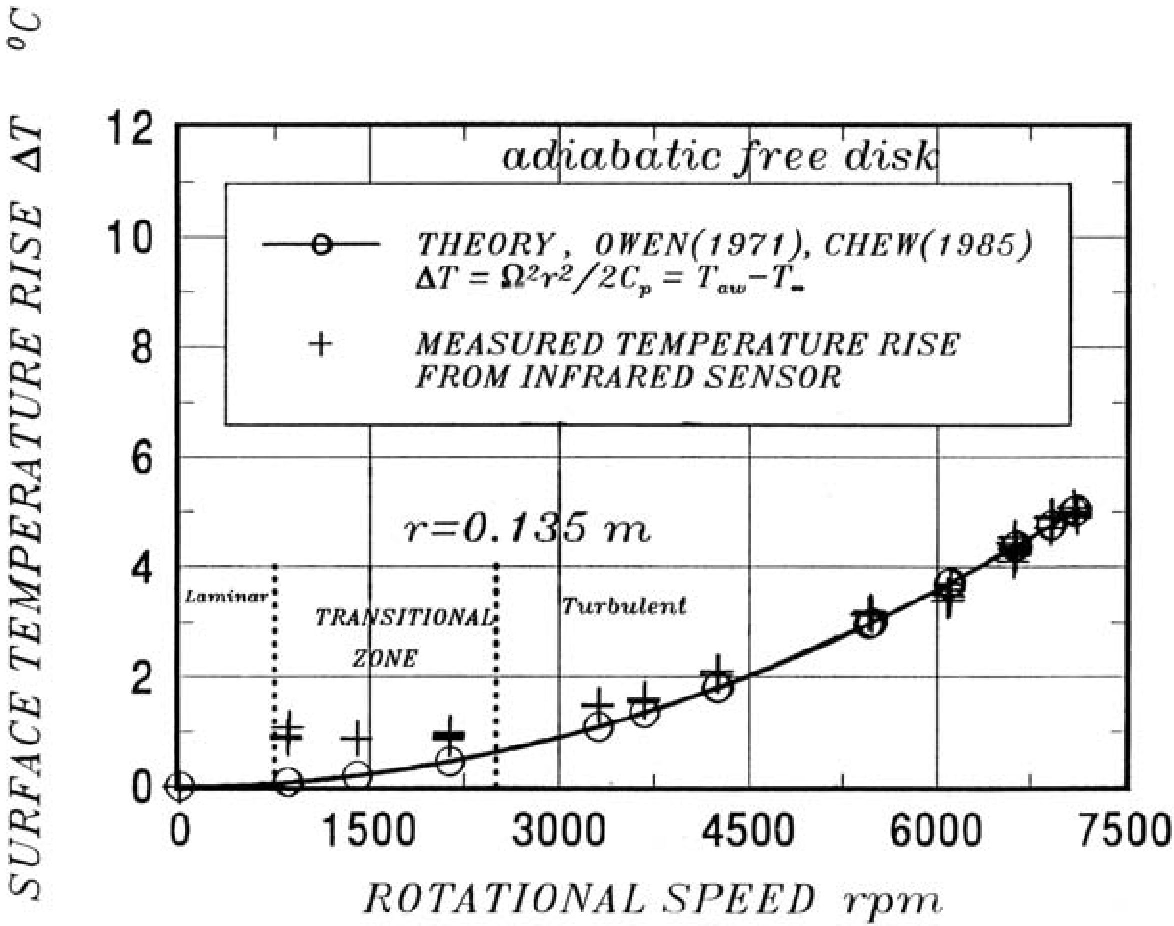

Fig. 6.7

Adiabatic disk temperature measurements using the infrared point sensor and comparison with theory

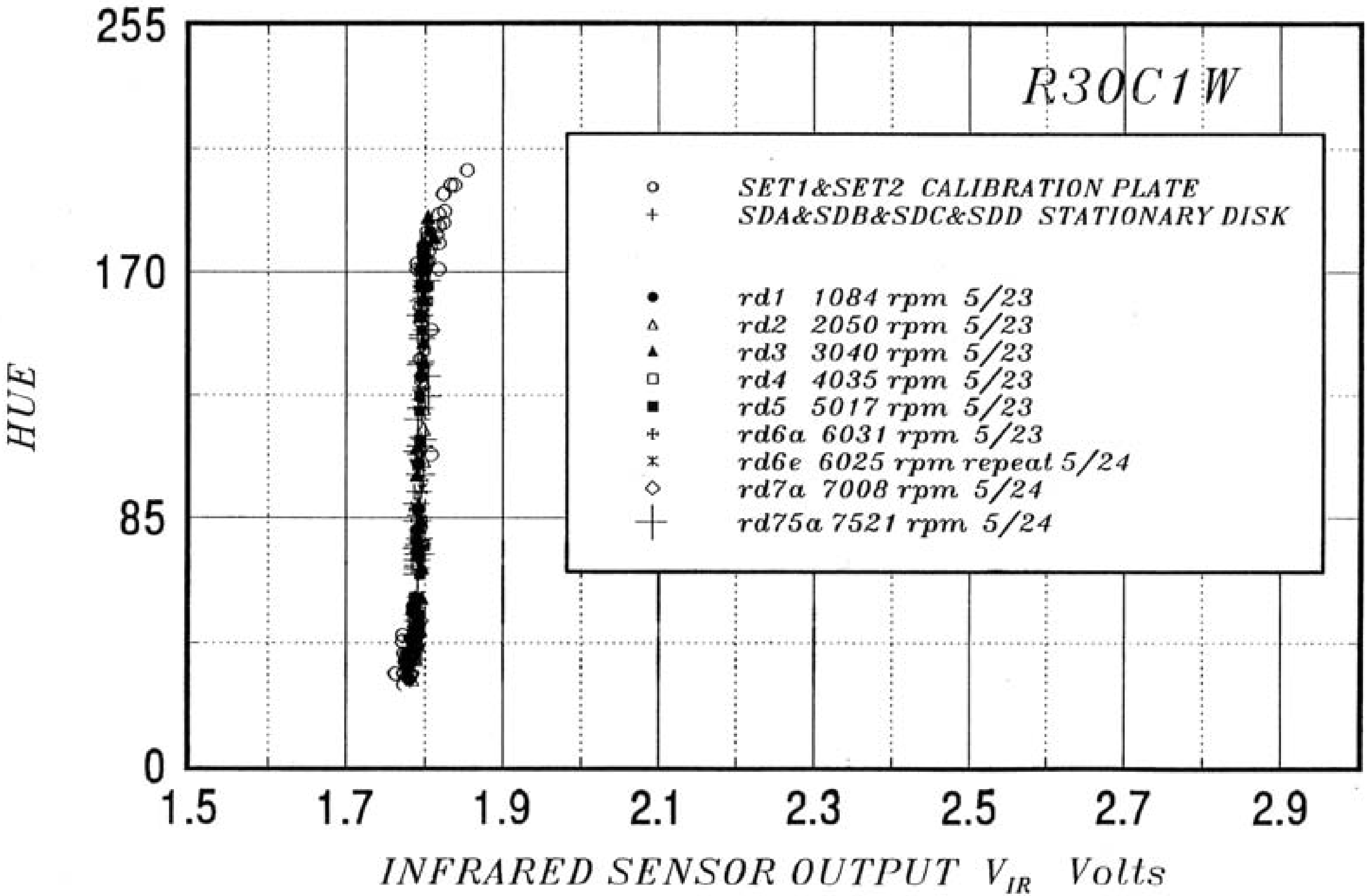

Fig. 6.8
Influence of rotation on color response of encapsulated Chiral-Nematic liquid crystals, hue versus infrared sensor raw output at various rotational speeds, R30C1W, calibration plate and stationary disk results included

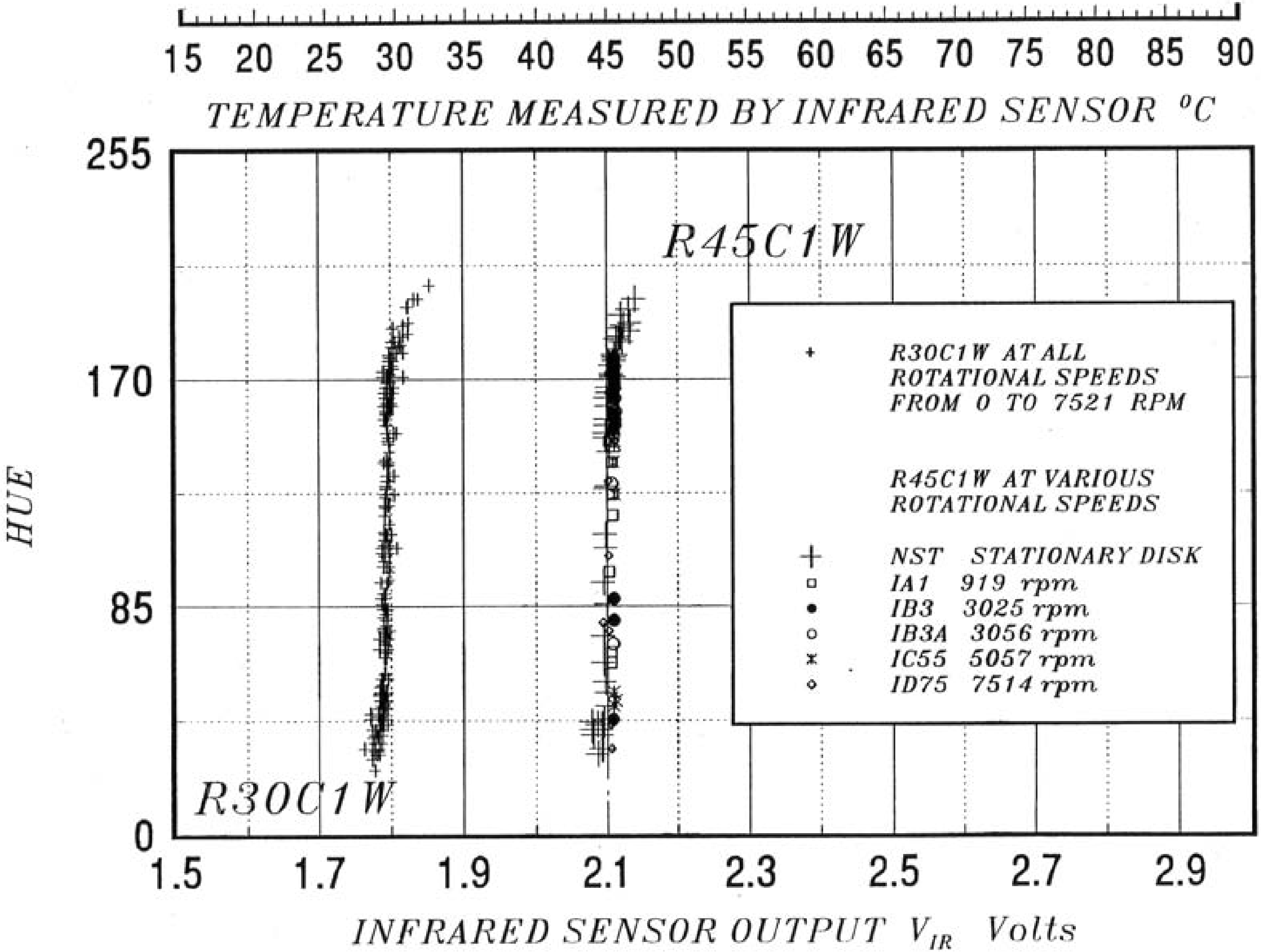

Fig. 6.9
Influence of rotation on color response of encapsulated Chiral-Nematic liquid crystals, hue versus infrared sensor raw output at various rotational speeds, R45C1W compared to R30C1W, calibration plate and stationary disk results included.

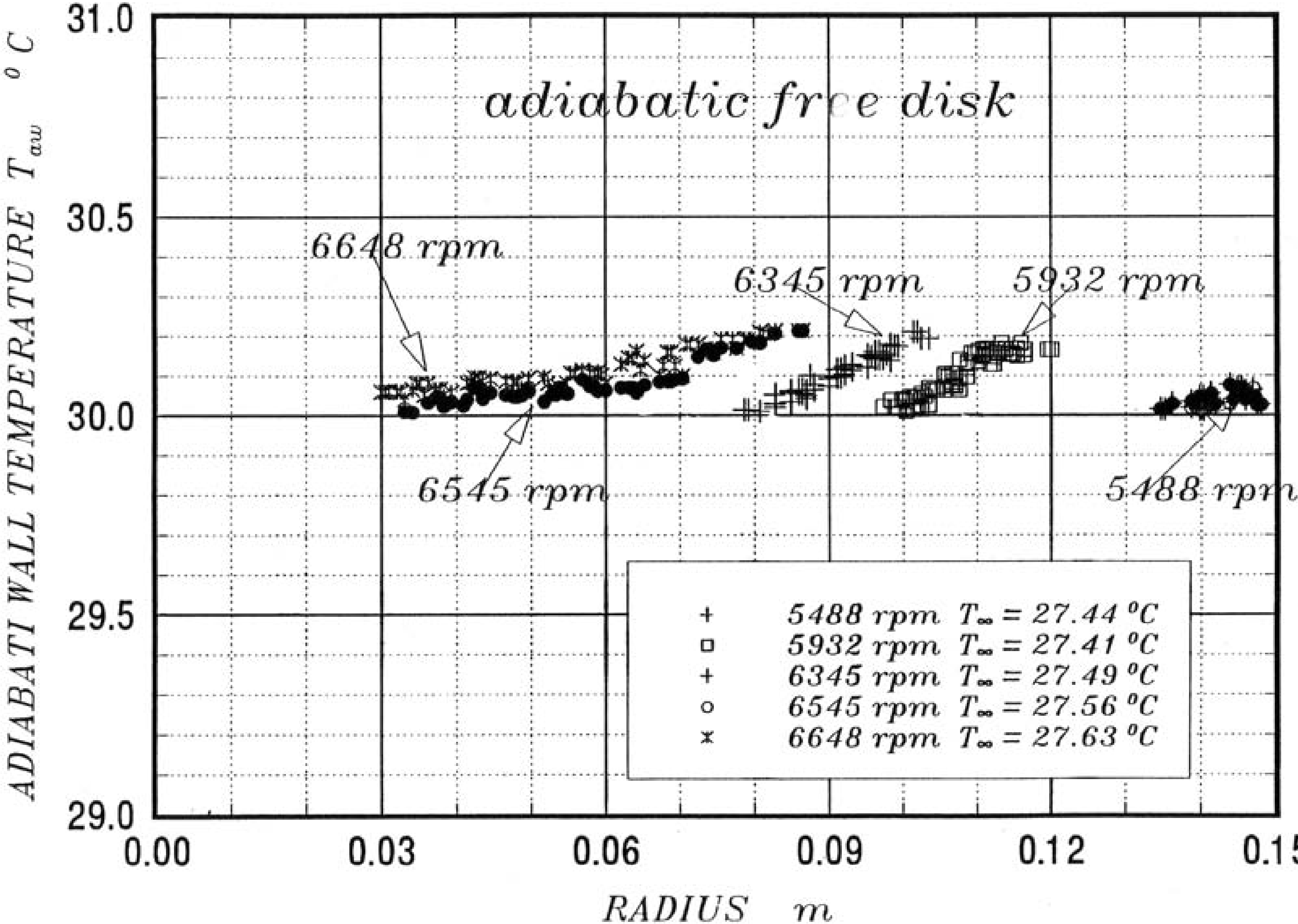

Fig. 6.10
Adiabatic wall temperature measurements on the rotating disk surface using the current liquid crystal technique, radial profiles for various rotational speeds

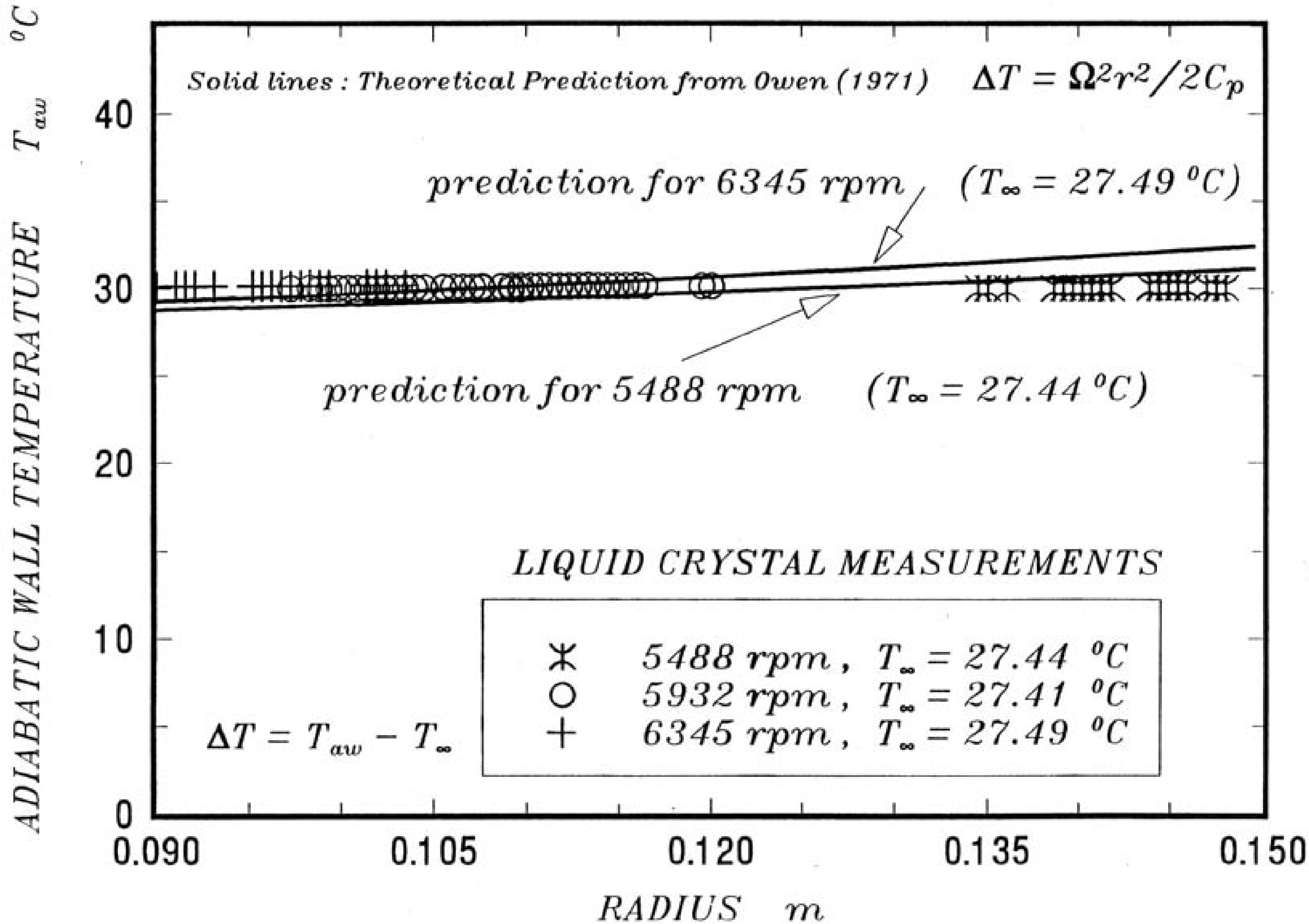

Fig. 6.11

Comparison of theoretical predictions of adiabatic wall temperature rise on a free rotating disk with the measured data from the current liquid crystal technique

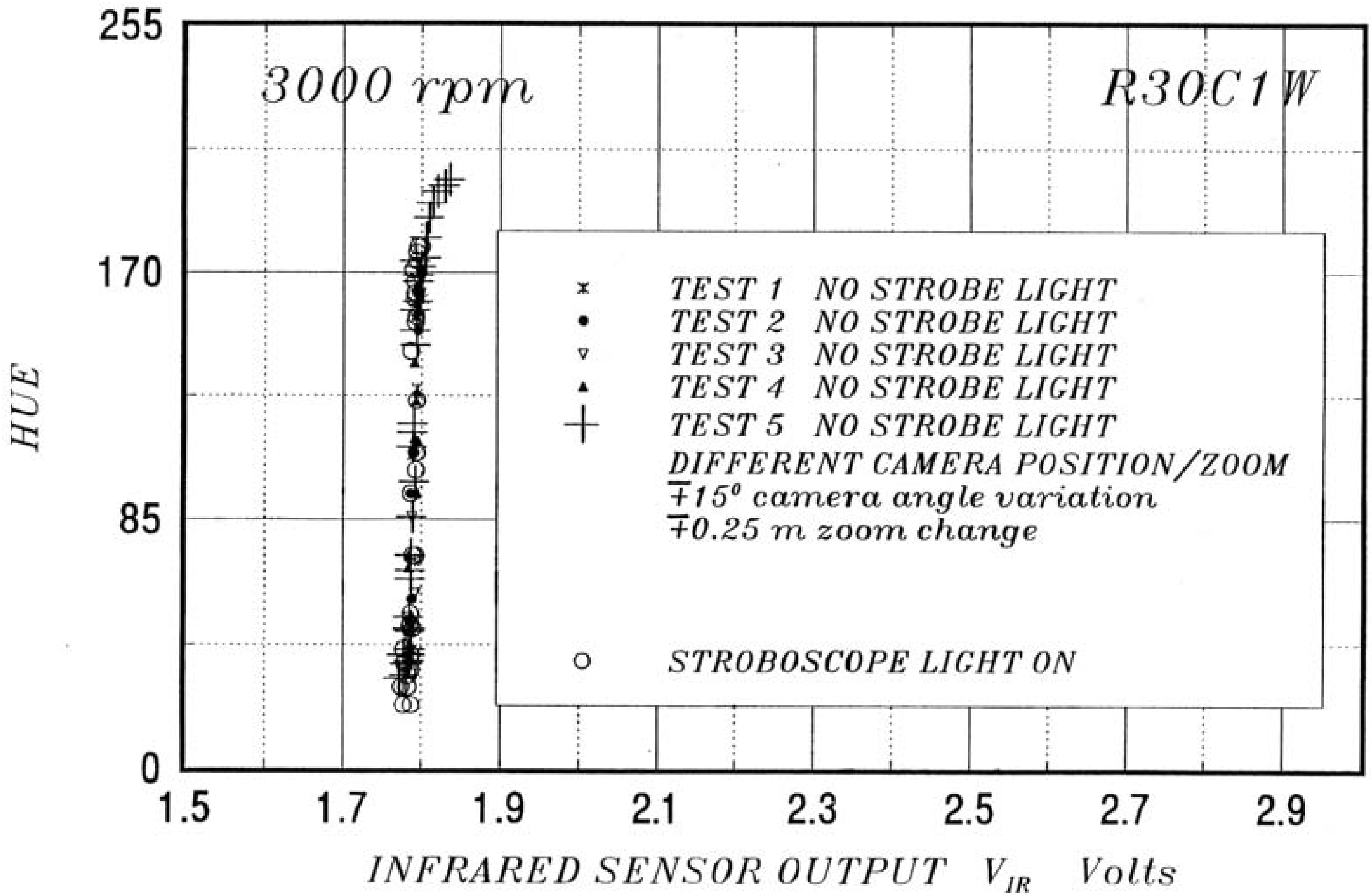

Fig. 6.12

Influence of stroboscope light intensity, camera position and zoom level on color response of liquid crystals applied to a rotating disk surface at 3000 rpm