Implementation of the *"Invariant h"* Method in Liquid Crystal Thermometry Based Heat Transfer Research Including Film Cooling

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Abstract

This paper deals with the implementation of the recently developed "***invariant h method***" for the measurement of heat transfer coefficient h and its corresponding reference free stream temperature $T_{0\infty}$ in liquid crystal based convective heat transfer studies. The original "***invariant h method*** " previously described in a separate publication by Camci[1] requires the acquisition of a complete wall temperature history during a transient heat transfer experiment. However, many transient heat transfer facilities used today prefer a simpler approach in which only one (or a few points) temperature point at a selected time is recorded on the heat transfer surface. The success of this approach is mainly due to the unique property of liquid crystal coatings that color is displayed only in a pre-selected temperature bandwidth. Another reason for the popularity of this approach is the simplicity of the specific inverse solution of one-dimensional transient heat conduction equation that is based on constant $T_{0\infty}$ in time. In this approach, if one can deduce wall temperature from a liquid crystal coating at a user selected time, the heat transfer coefficient h can be calculated in a very time efficient procedure. The time consuming convolution integral type solution or a series summation based solution is reduced into a simple algebraic procedure using an exponential function and complimentary error function in non-dimensional time β. The current study explains the implementation of the "***the invariant h***" principle into liquid crystal based convective heat transfer research. The paper shows that the method is accurate and time efficient in performing h and $T_{0\infty}$ measurements in a simultaneous mode. The capability of obtaining an accurate $T_{0\infty}$ from the same experiment performed for obtaining h is extremely attractive in transient experiments. The new approach eliminates cumbersome and error prone temperature measurements at many streamwise locations in the free stream. The method is also applicable to film cooling research in which accurate measurements of adiabatic wall effectiveness η and film cooling heat transfer coefficient h_f is of interest. The method presented is capable of simultaneously determining (η and $\mathbf{h_f}$) pair by using only one film cooling experiment in contrary to the conventional multi-experiment approach in which multiple experiments for different non-dimensional coolant temperatures are executed.

Nomenclature

C_p	Specific heat at constant pressure
FACTOR	A multiplier used to vary free stream reference temperature
$FACTORxT_{o\infty}$	Suggested free stream reference temperature
k	Thermal conductivity for the semi-infinite wall
h	Heat transfer coefficient $h = q_w(t)/(T_{o\infty} - T_w(t))$
h_o	Heat transfer coefficient when there is no film cooling
h_f	Heat transfer coefficient for film cooling $h_f = q_w(t)/(T_{aw} - T_w(t))$
n	n th point in the $T_w(t)$ measurement
Nu	Local Nusselt number
Pr	Local molecular Prandtl number
$q_w(t)$	Measured wall heat flux $q_w(t) = h(T_{o\infty} - T_w(t)) = h_f(T_{aw} - T_w(t))$
Re	Local Reynolds Number
$\sqrt{\rho C_p k}$	Thermophysical triple product of the semi-infinite body
$\Delta\tau$	Time step for the acquisition of $T_w(t)$, $\Delta\tau$=0.1 seconds
$T_{o\infty}$	Reference free stream temperature
$\Delta T_{o\infty}$	Deviation from the actual free stream temperature ($T_{o\infty}$-$FACTORxT_{o\infty}$)
T_{aw}	Adiabatic wall temperature
T_i	Initial temperature of the transient experiment
Tu_∞	Free stream turbulence intensity
T_w	Wall temperature
t	Time
t_f	Final time of the transient experiment

Greek symbols

δ	Absolute error indicator
β	Non-dimensional time, $\beta = h\sqrt{t}/\sqrt{\rho C_p k}$
Γ	Normalized slope of h(t) $\Gamma=\{[h(t)-h(t-1)]/\ \Delta\tau\}/h(t_f)$
Θ	Non-dimensional coolant temperature, $\Theta = \dfrac{T_{o\infty} - T_{oc}}{T_{o\infty} - T_w}$
ρ	Density
η	Adiabatic wall effectiveness, $\eta = \dfrac{T_{o\infty} - T_{aw}}{T_{o\infty} - T_{oc}}$

Introduction

Liquid crystal thermography in heat transfer research has recently been used in a wide spectrum of forced convection experiments. Examples of transient and steady state thermography implemented into external and internal flow experiments with and without cooling can be found in Goldstein et al.[2,3,4], Jones et al.[5,6], Ireland and Jones[7], Cooper et al.[8] , Metzger,Bunker and Bosch[9], Vedula and Metzger[10] Hippensteele et al.[11,12,13], Arts[14], Ekkad and Han[15], Camci et al.[16,17,18,19], Kim[20], Blair [21,22,23,24], Wiedner and Camci[25,26], Rizzo and Camci[27] and Drost, Hoffs and Bolcs[28]. These are only a few examples selected from a large number of research publications existing in this area. The present paper describes an implementation of the recently developed "***invariant h***" method by Camci[1] into liquid crystal based heat transfer experiments performed in the transient mode. Figure 1 describes a typical application domain that may include film cooling arrangements and definitions used for adiabatic wall effectiveness η and film cooling heat transfer coefficient h_f. It is assumed that the heat transfer surface shown in Figure 1 is coated with thermographic liquid crystals.

The "***invariant h method***" as described in its most general form requires the acquisition of a complete wall temperature transient $T_w(t)$ in order to determine the heat transfer coefficient h and its corresponding reference free stream temperature $T_{o\infty}$. In many transient heat transfer rigs the local Reynolds number is prescribed to be constant by the design of the flow system. Hydrodynamic transients in the free stream are avoided by design. Once the free stream flow is started impulsively, the local Re number at a point in the free stream of the tunnel will remain constant in time. The only transient is the precisely monitored change in the wall temperature $T_w(t)$. The local convective heat transfer coefficient h is supposed to remain constant in time under constant free stream Re number conditions. By using this "***invariant h***" property, one can deduce the reference free stream gas temperature $T_{o\infty}$ simultaneously with h.

In its original form, the "***invariant h***" method can not be directly applied to liquid crystal thermography based research mainly because liquid crystal coatings measure temperature by exhibiting measurable color in a pre-determined bandwidth of temperature. Although one can mix a number of liquid crystal slurries in one batch to cover the complete range of temperatures encountered during a transient experiment, this is a very tedious process and not popular currently. Application of wide band crystals may result in the coverage of all temperatures contained in a typical transient. The discussion presented in this paper shows that the implementation of the "***invariant h***" method into a heat transfer system using liquid crystals is possible. The method can be used to eliminate cumbersome and error prone free stream reference temperatures during the measurement of the convective heat transfer coefficient h. The specific approach is extremely useful in experiments in which the free stream reference temperature is continuously modified in the streamwise direction. A good example of this feature is a serpentine type cooling passage used in gas turbine blades. In a transient experiment performed with an initially heated model, the air in the coolant passage will increase its free stream temperature as it moves from the entrance to the exit of the channel. A drop in free stream temperature in streamwise direction may also be observed in experiments with heated free stream flows because of thermal energy loss to the relatively cool model surfaces. Usually, the researchers either ignore this important variation or they perform separate free stream reference temperature measurements by inserting temperature probes into the free stream at many locations. The new method is a simple analytical procedure imbedded into the system that measures the convective heat transfer coefficient h when the heat transfer surfaces are coated with thermographic liquid crystals. An accurate free stream temperature level is reached, by forcing the local convective heat transfer coefficient h into a time-wise stationary status in a simple iterative process. The present paper discusses the details of the "**invariant h**" method that is applicable to "**single-shot**" transient heat transfer experiments.

TRANSIENT TEST CASE FOR LIQUID CRYSTAL BASED HEAT TRANSFER METHOD

Figure 2 shows a transient temperature profile $T_w(t)$ that will generate a heat transfer coefficient of h=100 W/m^2K when the reference free stream temperature $T_{0\infty}$ is exactly at 302 °K. It is assumed that $T_{0\infty}$ remains constant in time and the local Reynolds number at the measurement location is invariant during the transient test. This is the same transient test environment used for the initial development of the "**invariant h**" method presented in Camci[1]. It is prescribed that the heat transfer model is kept at 283 °K initially. The model thickness is sufficiently thick so that the heat flow at the fluid solid interface can be assumed as one-dimensional. The thermo-pyhysical triple product for the plexiglass model material is about $\sqrt{\rho C_p k}$=569 W.(sec)$^{1/2}$/m^2. Under ideal conditions, the resulting heat transfer coefficient calculated from $h = q_w(t)/(T_{0\infty} - T_w(t))$ is shown in Figure 3. The time-wise variation of the heat transfer coefficient after the first three points is almost negligible when the transient is defined with a time step of $\Delta\tau$=0.1 seconds in a transient experiment lasting about 8 seconds. Under ideal conditions h in time is supposed to be invariant provided that the free stream hydrodynamic conditions are in a steady state, Camci[1]. It should be noted that only one T_w measurement at a user selected time is needed to calculate the corresponding h in a "single shot" experiment where the heat transfer coefficient can be calculated from equation 1. In this ideal approach (used only in the construction of the test case) the initial temperature T_i and the reference free stream temperature $T_{ref} = T_{0\infty}$ needs to be known before the computation of h. β is non-dimensional time defined as $\beta = h\sqrt{t}/\sqrt{\rho C_p k}$.

$$\frac{T_i - T_{w(t)}}{T_i - T_{0\infty}} = 1.0 - \exp(\beta^2).\mathrm{erfc}(\beta) \qquad (1)$$

LIQUID CRYSTAL BASED "Invariant h" METHOD

Heat Transfer Coefficients in Time from a Single-shot Method: The "invariant h" method described in Camci[1] consisted of a search algorithm in which a free stream reference temperature was suggested from an initial rough estimate. The method varied the suggested temperature by varying a parameter named FACTOR by small increments until the slope of the heat transfer distribution in time is minimized to a value of zero. In the previous method a very general convolution integral based heat flux determination algorithm was used. This type of calculation required the knowledge of wall temperature at each time point starting from the beginning of the transient experiment. This method is quite powerful when the free stream reference temperature has strong transients. However evaluating a convolution integral at each time point from a complete series of convolution integrals is numerically expensive and time consuming. The process also requires the acquisition of a complete time series of the wall temperature. This convolution integrals needed for the general method are given in Camci[1] as equations 2 and 3.

Since the liquid crystal thermography only provides surface temperature at only one pre-selected time during a transient experiment, it is impossible to use the general heat flux conversion relations based on a convolution integral. However, the evaluation of heat transfer coefficient from a simpler analytical model is possible when the free stream reference temperature is constant in time. An inverse solution to unsteady heat conduction equation at a fluid-solid interface for a semi-infinite substrate is a simple algebraic relationship as given in equation 1. This solution requires the knowledge of wall temperature at one time point. This equation forms the basis for many liquid crystal based measurements in transient facilities today. Figure 4 shows the distribution of heat transfer coefficient h in time for many suggested values of reference free stream temperature FACTOR*$T_{0\infty}$. In Figure 4, for each heat transfer coefficient calculation, only one wall temperature measurement was used in contrary to the convolution integral method used in Camci[1]. The immediate result from Figure 4 (using the simple algebraic equation 1) is that when the correct free stream reference temperature is suggested, the time-wise slope of h goes to zero and the correct level of h is reached. This is the same result obtained in Camci[1]. However, the process summarized in Figure 4 is very suitable for liquid crystal thermography because it requires the evaluation of the slope of heat transfer coefficient only at two or more time points.

Comparison of the Single-shot Method with the General Method Based on Convolution Integrals: Figure 5 presents the local slope of the convective heat transfer coefficient in function of time in a liquid crystal based experiment for various suggected values of FACTOR. The local slope of h is defined as follows.

$$\text{Local slope of } h = \{h(t)-h(t-1)\}/\Delta\tau \qquad (2)$$

When the free stream temperature is constant in time both the more general convolution integral method and more specific algebraic relation given in Equation 1 needs to produce the same result. The solid lines in Figure 5 are the results from the more general method in which the complete time history of the wall temperature is considered. Discrete symbols are the results from single-shot experiments using equation 1. The symbol at each time point is calculated from the single wall temperature measurement using equation 1. After t=2 seconds, the two methods merge to a unique solution. This comparison was used in the construction of the liquid crystal based methods in order to cross check the simple conversion scheme described in equation 1.

Evaluation of the Slope of Heat Transfer Coefficient at Seven pre-selected Time Points: The main goal in the construction of the liquid crystal based method is to obtain the time wise slope of the heat transfer coefficient at two discrete points in time so that the liquid crystal thermography can be applied by using either a mixture of two narrow band crystals or a wide band crystal that will yield at least two temperature measurements at a selected point on the surface. If one uses a hue based liquid crystal method, it is possible to obtain many hues/wall temperatures at different times at a selected point. In order the check the possibility of finding slope from small number of points, experiments at seven selected time points were executed. Figure 6 shows the seven time points as indicated by t_L. In each experiment, one of the seven t_L values has been taken as the lower limit of the experiment and the upper limit has always been fixed to t_U=7.145 seconds. Figure 6 also presents the corresponding wall temperature values corresponding to selected times on the generic transient created for our experiments. One can always choose seven different time intervals between t_L and t_U in order to monitor the slope of heat transfer coefficient. The number of questions to be answered in this effort are many. Is it sufficient to obtain the slope at the end of the experiment between points 1 and t_U=7.145 seconds

? What if one uses a large time interval between point 7 and t_U=7.145 seconds ? is the determination of the slope insensitive to the choice of the two specific time points in Figure 6 ? Clear answers to these questions are given in Figures 7,8,9 and 10.

Heat Transfer Coefficient versus Slope : Suggested reference free stream temperature FACTOR*$T_{0\infty}$ in function of local slope of h defined in equation 2 is shown in Figure 7. Seven individual symbols in Figure 7 are used for each one of the seven time intervals defined between t_L and t_U in Figure 6. All seven curves shown in Figure 7 pass through a zero slope only when FACTOR is suggested as 1.0. When the local slope is zero the vertical axis reads the correct free stream reference temperature. Figure 8 shows the resulting heat transfer coefficient h in function of normalized slope defined as Γ.

$$\Gamma=\{[h(t)-h(t-1)]/\ \Delta\tau\}/h(t_f) \tag{3}$$

h versus Γ curves are calculated at the last 5 points just before t_U=7.145 seconds. The normalization by $h(t_f)$ as suggested by equation 3 results in a highly linear variation of the resulting h when plotted against Γ. Plus signs are the results from equation 1. The solid lines are obtained from the more general convolution integral method as described in Camci[1]. Open circular symbols show the starting and final values of FACTOR during the trials suggested in this method. When FACTOR goes from 0.97 to 1.03 the resulting heat transfer coefficients go from a high erroneous value of 400 to a low value of 50. Of course the correct heat transfer coefficient of 100 W/m^{2}K shows up when the free stream reference temperature is correctly suggested at FACTOR=1.0. This point also corresponds to where Γ goes to zero. The results are very similar to the general "invariant h" method described in Camci[1].

An Arbitrary Selection of Time Interval does not Influence the Process: Fig.9 shows the heat transfer coefficient versus the normalized slope Γ distribution obtained from seven time pairs defined in Figure 6. The seven time pairs are obtained when the points from t_1 through t_7 are coupled with the time of the upper limit t_U=7.145 seconds. Each symbol in Figure 9 is used once for the slope evaluated at the lower time limit t_L and once for the upper limit t_U. For instance the solid triangles form two approximate lines crossing exactly at Γ=0 point that is called as the target point. It is very interesting to note that normalized slope lines evaluated at the lower and upper limits of a selected time interval between t_L and t_L form slightly different boundaries on Fig.9. However the slope lines belonging to t_U and t_L always cross-sect at Γ=0 point. The seven sets of cross-secting lines in Figure 9 suggest that normalized slope Γ can be evaluated at any time point during the transient experiment. The choice of evaluation time or $\Delta\tau$ does not influence the iterative process that will provide the correct heat transfer coefficient h and reference free stream temperature $T_{ref} = T_{0\infty}$. Figure 10 shows a close-up view of Figure 9 near the region where the slope of the heat transfer coefficient is minimized around the correct heat transfer coefficient point. The value of the suggested free stream temperature that returns Γ=0 during the iterative process can be taken as the correct free stream reference temperature for this problem. All of the curves resulting during the iteration are almost linear and all of them cross sect at Γ=0 point that marks the correct h on the vertical scale.

Liquid Crystal based "Invariant h" method: Figure 12 suggests a complete procedure for finding the correct heat transfer coefficient h and its corresponding free stream reference temperature $T_{ref} = T_{o\infty}$. The specific method is suitable for use on liquid crystal coated surfaces. In contrary to the general method, this approach does not require the complete history of wall temperature. There are two possible implementations. One can use a wide-band thermochromic liquid crystal coating providing two distinct hue values at two sufficiently separate wall temperatures T_{wL} and T_{wU} at times t_L and t_U. The normalized slope of the heat transfer coefficient can be calculated from $\Gamma = (h_U - h_L)/(\Delta\tau)/h_U$. In the second approach one can mix two narrow band crystals that are responding around T_{wL} and T_{wU}. The user needs to make sure that the blue color zone of T_{wL} and the red zone of T_{wU} do not get mixed by the proper specification of the two crystals that will be mixed in a slurry.

The process starts with a rough estimate of the free stream reference temperature. The specific liquid crystal hue value corresponding to T_{wL} is recorded at t_L. Since the initial temperature and thermo-physical triple product of the substrate material is known, corresponding h_L can be calculated from equation 1. The liquid crystal hue corresponding to T_{wU} shows up at $t=t_U$ at a later time at the same measurement point. The heat transfer coefficient h_U can be calculated at $t=t_U$ using the same technique used for h_L. The numerical value of the normalized slope $\Gamma = (h_U - h_L)/(\Delta\tau)/h_U$ is an indication of the error made in the determination of the heat transfer coefficient. The value of the suggested free stream temperature is incrementally altered in such a way that the magnitude of Γ is reduced in the next iteration. This process is repeated until a sufficiently small Γ value near zero is obtained. Detection of a change of sign in Γ is another indication of the fact that a correct free stream reference temperature is achieved. Near $\Gamma=0$ our model suggests that the heat transfer coefficient h_L and h_U numerically merge into each other as clearly shown in Figure 10.

The Implementation of the "Invariant h" Method in Film Cooling Research: For the case of discrete hole film cooling or tangential slot injection the heat transfer problem is considered to be a three temperature problem. The heat transfer coefficient defined between the hot gas side temperature $T_{o\infty}$ and the wall is not anymore independent of thermal boundary conditions.

$$h = q_w(t)/(T_{o\infty} - T_w(t)) \tag{4}$$

A better heat transfer coefficient that is independent of thermal boundary conditions for this case is defined between the adiabatic temperature of the coolant region existing between the free stream boundary layer and the wall.

$$h_f = q_w(t)/(T_{aw} - T_w(t)) \tag{5}$$

The adiabatic temperature of the coolant fluid in the immediate vicinity of the wall is the true reference gas temperature of this problem. For many different coolant temperatures the value of h_f is unique. This h_f value is a true indicator of the hydrodynamic status of the coolant film only. By using the definitions of the non-dimensional coolant temperature $\Theta = \frac{T_{o\infty} - T_{oc}}{T_{o\infty} - T_w}$ and the adiabatic wall effectiveness $\eta = \frac{T_{o\infty} - T_{aw}}{T_{o\infty} - T_{oc}}$ one can show that,

$$h = h_f \cdot (1 - \eta \cdot \Theta) \tag{6}$$

Equation 6 clearly shows that the conventional heat transfer coefficient h is linearly dependent on non-dimensional coolant temperature Θ for a prescribed adiabatic wall effectiveness value of η. This linear dependency is clearly shown in Figure 1.

The liquid crystal based "invariant h" method is equally applicable to a film cooling case in which the free stream reference temperature is T_{aw} and the associated heat transfer coefficient is h_f. The method described in this paper has the capability of simultaneously determining the adiabatic wall effectiveness $\eta = \frac{T_{o\infty} - T_{aw}}{T_{o\infty} - T_{oc}}$ and h_f in one single film cooling experiments. Previously this effort required either running film cooling experiments at multiple coolant temperature levels for the same blowing rate. Another approach was to vary the wall temperature a few times for a fixed coolant temperature operation at a selected blowing rate. The "invariant h" method eliminates the need to run multiple experiments that are costly and time consuming. $T_{o\infty}$ value that is now a temperature level belonging to the hot gas side fluid can easily be obtained in an experiment without any film injection. The corresponding heat transfer coefficient for this case is denoted as h_o.

Figure 12 shows the relative error contribution from the measurement errors that may occur in the determination of T_{aw} in a typical film cooling problem. The analysis presents results for a hypothetical film cooling effectiveness level of η=0.7. It is also assumed that the free stream gas temperature $T_{o\infty}$ and coolant temperature T_{oc} can be measured with an uncertainty of ± 0.2 °K.. For this case, when the adiabatic wall temperature T_{aw} is measured within 0.1 °K, the error on the adiabatic effectiveness is about 0.5 %. When the error on adiabatic wall temperature is increased to 1.0 °K, the relative error on adiabatic effectiveness is about 3 %. When the error on free stream gas temperature, coolant temperature and adiabatic wall temperature are all the same at ± 3 °K, the relative error on the adiabatic wall effectiveness η is about 13 %. Figure 12 shows the potential improvements that can be obtained in film cooling heat transfer research by using the new "**Invariant h**" method specifically developed for liquid crystal based heat transfer measurements

Conclusions

This paper describes a new approach to obtain the heat transfer coefficients and their corresponding free stream reference temperatures from a liquid crystal covered surface. The general "Invariant h" method recently described by Camci[1] is modified for the specific properties of liquid crystal based wall temperature and heat transfer measurements in transient experiments. The modified method is extremely powerful in determining the free stream reference temperature and heat transfer coefficient simultaneously. The time invariant nature of the heat transfer coefficient in a transient heat transfer experiment is used as an additional flow property. This extra flow property which has never been utilized in the past results in an extremely time efficient and less costly method named as "invariant h" method. The specific paper explains the implementation of this method on liquid crystal coated surfaces in detail. The new method can also be used in film cooling problems in which the reference flow temperature is the adiabatic wall temperature (or adiabatic effectiveness η) of the coolant film and the heat transfer coefficient of the coolant film h_f. The new approach is capable of measuring adiabatic wall temperature T_{aw} and h_f accurately from just one experiment executed at a user selected coolant temperature. The potential improvements in reducing the errors made in the determination of the adiabatic wall temperature of a typical cooling film case are presented in detail.

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