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P17 Use of a Laser-Induced Fluorescence Thermal Imaging System for Film Cooling Heat Transfer Measurement

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Abstract

This paper describes a novel approach based on fluorescence imaging of thermographic phosphor that enables the simultaneous determination of both local film effectiveness and local heat transfer on a film-cooled surface. The film cooling model demonstrated consists of a single row of three discrete holes on a flat plate. The transient temperature measurement relies on the temperature-sensitive fluorescent properties of europium-doped lanthanum oxysulfide ($\text{La}_2\text{O}_2\text{S:Eu}^{+3}$) thermographic phosphor. A series of full-field surface temperatures, mainstream temperatures, and coolant film temperatures were acquired during the heating of a test surface. These temperatures are used to calculate the heat transfer coefficients and the film effectiveness simultaneously. Because of the superior spatial resolution capability for the heat transfer data reduced from these temperature frames, the laser-induced fluorescence (LIF) imaging system, the present study observes the detailed heat transfer characteristics over a film-protected surface. The trend of the results agrees with those obtained using other conventional thermal methods, as well as the

liquid crystal imaging technique. One major advantage of this technique is the capability to record a large number of temperature frames over a given testing period. This offers multiple-sample consistency.

Nomenclature

d	Injection hole diameter.
G	Mass velocity = ρV .
h	Heat transfer coefficient in $q = h(T_f - T_w)$.
h_m	Heat transfer coefficient in $q = h_m(T_m - T_w)$.
h_0	Heat transfer coefficient without injection.
k	Thermal conductivity.
M	Blowing ratio = $\rho_f V_f / \rho_m V_m$.
Nu	Nusselt number.
Pr	Prandtl number.
q	Heat flux.
Re	Reynolds number.
t	Time.

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T_i	Initial temperature.
T_f	Coolant temperature.
T_m	Mainstream temperature.
T_r	Reference temperature.
$T_w(t)$	Wall temperature at time t .
V_f	Coolant velocity.
V_m	Mainstream velocity.
α	Thermal diffusivity.
η	Effectiveness = $(T_r - T_m)/(T_f - T_m)$.
ρ_f	Density of mainstream.
ρ_m	Density of cooling film.
τ_j	Time step.
θ	Dimensionless temperature = $(T_f - T_m)/(T_w - T_m)$.

Introduction

This study examines the heat transfer characteristics of film cooling through a single row of discrete injection holes on flat surface, using a laser-induced fluorescence (LIF) thermal imaging system based on a thermographic phosphor. Film cooling is one of the most effective means for thermal control of gas turbine components subjected to intensive heat load. While research concerning film cooling has been very active for several decades, most of the studies were performed under near room temperature conditions. This is largely attributable to the limited thermal measurement capabilities in a high-temperature environment. As a result, many important effects pertaining

to large temperature differential in the system, such as the coolant-to-gas thermal property variations, are unable to be explored effectively. With a proper choice of the phosphor material, the measurement approach present in this paper can be extended to high temperature applications.

Certain thermographic phosphors whose fluorescence intensity and/or lifetime are temperature sensitive have been successfully used for surface temperature measurement. Goss and Smith (1986) determined local surface temperatures during the combustion of the test specimen using the ratio of two emission lines of dysprosium-doped yttrium aluminum garnet (YAG:Dy³⁺) crystals embedded in a thermal-setting plastic. Lutz et. al. (1988) and Noel et. al. (1990) used the approach based on the fluorescence lifetime sensitivity of certain rare-earth phosphors for temperature measurements on a heated turbine disk and on a first-stage stator vane in an operating turbine engine, respectively. While previous studies involved primarily discrete-point measurements, Chyu and Bizzak (1993, 1994) recently reported a detailed two-dimensional surface temperature measurement using an approach combining the thermal sensitivity of emission intensity and decay time. The particular thermographic phosphor they used is europium-doped lanthanum oxysulfide (La₂O₂S:Eu³⁺).

The present study was based on the approach by Chyu and Bizzak (1993, 1994), in conjunction with a transient measurement technique, to simultaneously determine the film effectiveness and heat transfer coefficient. The particular LIF system used here exploits the temperature sensitivity of both the fluorescence intensity and the lifetime of certain emission lines. Fluorescent images of the temperature sensitive 512-nm triplet, along with that of the relatively temperature-insensitive 620-nm emission line, are acquired.

The ratio of the integrated intensities of these two emissions, which can be accurately correlated to temperature and intensity data from a reference isothermal surface image, permits the determination of temperatures at several discrete locations on the test surface.

To evaluate the capability of the LIF system in measuring the transient characters of three-temperature heat convection case, film cooling through a single row of injection holes is selected for the demonstration. Both the local film effectiveness, η , and local heat transfer coefficients, h , are determined simultaneously using the temperature measurements of a single test. The results are then compared with those obtained from other methods to allow assessment of the measurement capabilities of the LIF thermal imaging system.

Three-Temperature System

In case of general two-temperature force convection situation, the local surface heat flux is expressed as

$$q = h_0(T_m - T_w) \quad (1)$$

where T_w and T_m are the wall temperature and the mainstream temperature, respectively, and h is the convective heat transfer coefficient. The heat transfer coefficient, h_0 , is usually considered as a function of primarily aerodynamic character of the flowfield. For a given flowfield, h is, therefore, a constant locally and can be determined by measuring q together with T_w and T_m .

In a film cooling system, temperature of the coolant injected from a cooling hole or a slot emerges as a third temperature that also control the heat transfer process in the system. Hence a system as such is termed three-temperature problem. One way to relate the

surface heat transfer (q) and a heat coefficient, h_m , is

$$q = h_m(T_m - T_w) \quad (2)$$

Although the expression is somewhat convenient in nature and bears great similarity to Equation (1), h_m is not a constant quantity as h_0 is, since the temperature difference between the mainstream and the wall, $T_m - T_w$, is not a true driving potential of heat transfer. An alternative way to express the surface heat flux is

$$q = h(T_r - T_w) \quad (3)$$

where T_r is the reference temperature, and $T_r - T_w$ represents the true driving potential for maintaining h_0 as a constant, and is actually an unknown. It can be considered as the mixing temperature of two interacting streams just above the surface. To find the unknown T_r in terms of known quantities T_m and T_f (the temperature of mainstream and coolant film, respectively), a dimensionless temperature is defined as film cooling effectiveness (η)

$$\eta = (T_r - T_m) / (T_f - T_m) \quad (4)$$

Thus,

$$T_r = \eta T_f + (1 - \eta) T_m \quad (5)$$

Applying the analytical result of a semi-infinite solid whose surface is suddenly subjected to a step change in ambient temperature, that is

$$\frac{T_w - T_i}{T_r - T_i} = 1 - \exp\left(-\frac{h^2 \alpha \cdot t}{k^2}\right) \operatorname{erfc}\left(\frac{h \sqrt{\alpha \cdot t}}{k}\right) \quad (6)$$

Replacing T_r in Equation (5) by Equation (4), the relationship of T_w , T_i , T_m , and T_f can be

expressed as the following equation, with two unknowns, h and η .

$$T_w - T_i = [1 - \exp(-\frac{h^2 \alpha \cdot t}{k^2}) \operatorname{erfc}(\frac{h \sqrt{\alpha \cdot t}}{k})] * \quad (7)$$

$$[\eta T_f + (1 - \eta) T_m - T_i]$$

In a real experiment, either T_m or T_f may not be a true step function, hence, by Duhamel's theorem, the temperatures are represented as a series of superimposed time step changes. Equation (7) can be written as

$$T_w - T_i = \sum_{j=1}^N U(t - \tau_j) [(1 - \eta) \Delta T_m + \Delta T_f] \quad (8)$$

where:

$$U(t - \tau_j) = 1 - \exp[-\frac{h^2}{k^2} \alpha (t - \tau_j)] \operatorname{erfc}[\frac{h}{k} \sqrt{\alpha (t - \tau_j)}] \quad (9)$$

To evaluate h and η , it is necessary to obtain two equations involving those two unknowns. The wall temperature data monitored by the laser-induced fluorescence (LIF) imaging system, in conjunction with the temperature history data of both coolant film and mainstream measured by thermocouples, yields several equation sets which allow simultaneous determination of h and η . One unique feature of the present LIF-based measurement approach is the capability of acquiring multiple solution sets (with different elapse-times) under a single transient test. These multiple solution sets can minimize the uncertainty of the calculated h and η .

Laser-Induced Fluorescence Imaging System

The LIF imaging system employed for the present study is shown schematically in Figure 1. The major elements of the system include (1) phosphor excitation laser, (2) fluorescence image detector, (3) image processing and control subsystem. While detailed description of the system has been given in earlier studies (Bizzak and Chyu, 1995 * use the scientific instrumentation paper), a brief discussion is given below.

Ultraviolet (UV) excitation of the phosphor coating of the test surface is provided by the tripled output (355 nm) of a ND:YAG pulsed laser. The tripled output from the laser is generated by passing the 1064-nm primary output through a harmonic generator, to obtain a beam of 355 nm wave-length light, along with residual components of the primary and first harmonic (532 nm). These undesired portions of the laser beam are then effectively separated and eliminated by a beam splitter assembly. The energy of the 355 nm output beam from the splitter, which is delivered over a 5 to 6 ns pulse, is approximately 75 mJ.

The critical element of the LEF thermal imaging system is the thin layer of europium-doped lanthanum oxysulfide ($\text{La}_2\text{O}_2\text{S:Eu}^{+3}$) phosphor that is applied to the test surface. When subjected to UV excitation, this phosphor fluoresces in the visible spectrum. The emission spectrum of this phosphor (as for other rare-earth doped phosphors) consists of a number of sharp emission lines, and certain of these lines exhibit a temperature sensitivity that is manifested in changes to both the fluorescence intensity and decay time. For

Figure 1. Apparatus Schematic

$\text{La}_2\text{O}_2\text{S:Eu}^{+3}$, the steady-state intensity of the 512 nm emission triplet decreases by a factor of 2.5 as temperature is increased from 20 to 60 C, while the lifetime of this temperature range decreases by an order of magnitude. Collection of the fluorescence signal during its decay permits a precise determination of temperature based on both of these sensitivities. However, since the initial fluorescence amplitude at a given surface location is dependent on both the excitation energy and phosphor coating density, use of the 512 nm fluorescence signal alone may be unable to yield

accurate two-dimensional thermometry. To compensate for these spatial variations in the signal, the intensity of the 512 nm emission triplet is ratioed to that of the 620 nm emission. The intensity of the latter emission (which is relatively immune to temperature) provides a reference signal whose intensity variation, due to spatial nonuniformity in excitation energy or phosphor density, is identical to that of the 512 nm emission. As a result, this intensity ratio can be accurately correlated to temperature regardless of the absolute magnitude of the local emissions.

The fluorescent image of both 512-nm and 610-nm lines over the test surface following excitation is collected by a 150 mm enlarger lens and split into equal length optical paths that are focused side-by-side onto an image intensified-CCD detector. One optical path passes through a 510 nm narrow bandpass filter, while the other is directed through a 620 nm bandpass and a neutral density filter. The neutral density filter is required to reduce the intensity of the 620 nm fluorescence signal to a level comparable to that of the 510 nm signal, because the intensity and lifetime of the 620 nm emission is considerably greater than that of the temperature sensitive 510 nm emission.

The major components of the imaging subsystem include a gate pulse generator, a detector controller, and a microcomputer for overall system control. Concurrent with laser excitation, the detector simultaneously records images of the surface at the emission-line wavelengths of interest. The timing and duration of image acquisition are controlled by the gate pulse generator, which issues a square-wave pulse that enables the image intensifier. The duration of this pulse defines the fluorescence signal integration period. The pulse generator in this study is set to issue a 40- μ s pulse approximately 280 ns in advance of laser firing. To prevent exposure of the detector during readout following image capture, the controller disables the pulse generator until image data have been read and stored to disk. Finally, a 80486 processor based computer provides overall system control and is used in image post-processing to calculate emission intensity ratio values which are then used in conjunction with the phosphor calibration to determine local surface temperatures.

Experimental Setup and Procedure

The apparatus for the film cooling tests is shown schematically in Figure 1. The test surface is part of the duct wall, with a constant area of rectangular cross-section; secondary flow is injected through a single row of three circular tubes with 30 degrees inclined angle ending flush to the test surface. Near the injection holes, a thin layer -- about 25 μ m -- of $\text{La}_2\text{O}_2\text{S:Eu}^{+3}$ is coated on top of the test surface. Since this layer is so thin and presents virtually no thermal resistance, the material properties of the test section (Plexiglas) are used to calculate the local heat transfer coefficient and film effectiveness, based on Equations (7) and (8). During the test run the laser beam is expanded using a cylindrical concave lense to excite the phosphor on the test surface emitting fluorescence. The shone area is about 10 mm in width over all the test surface, as shown in Figure 2.

Figure 2. Laser Excitation Area

The air supply is divided into two paths, mainstream and secondary injection. The desired volumetric flow rate is set using a regulator in conjunction with a Pitot tube in the mainstream, and using a rotameter in the coolant film path. Metered flows are then

heated using tubular heaters, with their temperatures monitored by thermocouples. The coolant-to-mainstream mass flux ratio is set to 0.2. The mainstream temperature in the range of 45 to 50 °C is reached within 40 seconds; the coolant temperature is kept at room temperature.

Prior to conducting the test, an isothermal fluorescent image (that is the fluorescent image of the test surface maintained in ambient air temperature) must be taken as a reference image for later use in data processing. A transient test is initiated by switching on the gate valve and routing the flow pass through the path of mainstream and coolant film. A PC-based data acquisition system is initiated at the same time to record the temperature history of both the mainstream and coolant film. Each fluorescent image is acquired after the initiation of flow, but before 100 seconds have elapsed. Each image frame represents the integrated fluorescent signal accumulation over 11 laser pulse -- or 1 second -- with the signal integration period following each pulse being 40 μ s. The time from the initiation of test to collection of the first image, and the time between the collection of each image is clocked using a stop watch.

Following acquisition of the raw fluorescent image data, the PC starts to execute an image processing program and calculate both the film effectiveness and heat transfer coefficient for 174 locations on the test surface. For each surface location, intensity data from a 5 x 5 pixel array (which corresponds to an area of 0.8 mm by 0.8 mm viewed from 1 m distance) are used to calculate local surface emission-line intensity ratios. These intensity ratios are then divided by the value of intensity ratio at the same surface location obtained from the isothermal reference image. These "corrected" intensity ratios may be converted

to temperature using a phosphor calibration curve. To permit direct determination of temperature however, the generic phosphor calibration data must be normalized by the value of the emission intensity ratio at the reference temperature. The temperature data for two different frames then serves as input to a software routine that implicitly solves Equations (7) and (8) for obtaining local heat transfer and local film effectiveness simultaneously. Since there are 11 data sets for different timeframes, the solution of h and η can use up to 55 combinations and produces much accurate results than those based on only single combination.

Results

Figures 3 and 4 give the contour plots of film effectiveness and heat transfer coefficient for the case of $M = 0.2$, respectively. The results shown here are those in the near wall region; i.e., $x/d < 5.2$. Due mainly to experimental difficulty, data of such nature have little been reported in the literature. As a typical case of film cooling with a low blowing ratio, both film effectiveness and heat transfer coefficient generally decrease toward downstream. Their magnitudes are higher along the injection axis directly behind the coolant holes and lower in the region between holes. There is no indication of the coolant liftoff that is often encountered in the cases with larger blowing ratios.

Figures 5 and 6 shows the distributions of the spanwise averaged film effectiveness and heat transfer coefficients, respectively. Reflecting the same phenomena shown in the contour plots, both figures reveal decreasing trend along the streamwise direction. Also present in the figures are some corresponding data available in the literature using different, while more conventional, measurement

Figure 3. Full Field h/h_0 Distribution

Figure 4. Full Field η Distribution

Figure 5. Center-Line Local Heat Transfer Distribution

techniques. The present results compare very favorably with those of earlier studies.

Figure 6. Center-Line Film Effectiveness Distribution

The uncertainties of the present data, based on the transient method suggested by Moffat (1985), are 0.76 percent for local heat transfer, and 2.2 percent for film effectiveness. This estimate encompasses the uncertainty in the calculation of these two parameters due to the measurement errors of initial temperature, wall temperature and mainstream temperature, the error in timing the initiation of working fluid and LIF system, and that of the thermal and mass properties for test surface. As for repeatability, the maximum deviation of heat transfer is 10 percent, the deviation of film effectiveness is 7 percent, occurring at the edges; the h and η value there is 28 and 0.59 respectively. Therefore this deviation represents an error of ± 2.8 in h and ± 0.04 in η .

Conclusions

Through the examination of the local heat transfer and effectiveness of cooling film injected from a single row of injection holes on flat surface, this study has demonstrated the efficacy of the LIF thermal imaging technique for transient two-dimensional surface temperature measurement, suitable for calculating

h and η simultaneously for a three-temperature heat convection situation. Based on these results, and the inherent advantages in temperature measurement, such as nonintrusive measurement and high spatial resolution capabilities, etc., the present system promises to be a powerful optical technique suitable for use in the studies of gas turbine heat transfer. The operational principle of the three-temperature system approach is readily applicable for high-temperature applications.

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