Heat Transfer Study of Obliquely Impinging Jet Cooling a Hot Surface by Using Green Spectrum based Temperature Sensitive Paint

Haricharan Pippari[1]*, Keesanth Singh Chandrasekaran[1] and Sathesh Mariappan[1]

1: Dept. of Aerospace Engineering, Indian Institute of Technology Kanpur, India

* Correspondent author: haricharan23@iitk.ac.in

Abstract

Jet impingement cooling is a highly efficient thermal management technique utilized in aerospace applications due to its superior heat transfer performance. This study focuses on using an in-house developed Temperature Sensitive Paint (TSP) with eosin Y, which has a peak emission in the green spectrum, to measure temperature distributions on a heated plate when subjected to a relatively cold jet. The plate, at 345 K, is cooled by a jet at ambient temperature (309 K) with varying impingement angles. Surface temperature data are acquired from the calibrated TSP through a CCD (Charge-Coupled Device) camera; calibration is performed using an IR (Infrared) camera. The surface temperature distribution over time is used to calculate the normalized heat flux (using an analytical inverse heat transfer technique) and Nusselt number, which are then analyzed to determine optimal cooling conditions, with findings comparable to previous studies.

Keyword: *Temperature Sensitive Paint, Green Spectrum, Impinging Jet, Heat Flux, Nusselt Number.*

1. Introduction

Material life depends on the environment in which it operates. In the aerospace industry, most of the materials in aircraft engines are subjected to high temperatures due to the flow field around them and hot gases from combustion. Cooling these materials enhances their life and performance. Jet impingement is the traditional approach for cooling hot surfaces. This method allows for precise temperature control, improves material durability and system efficiency, and often requires significantly less flow compared to traditional wall-parallel cooling methods [1]. The effectiveness of jet impingement is influenced by factors such as Reynolds number, impingement angle, jet-to-target distance, and the thermal properties of materials and fluids.

The concept of Temperature Sensitive Paint (TSP) began to take shape in the 1980s by Kolodner and Tyson [2-4], but significant research and development occurred in 1990s [5]. The current study is done on the TSP using eosin Y as luminophore. This TSP is successfully tested for aerodynamic and thermal analysis [6]. The main advantage of eosin Y as luminophore is that it has peak absorption and emission wavelength in green spectrum, so conventional (Nd-YAG) lasers and scientific cameras can be used for exciting and then capturing the variable intensities of TSP. Heat transfer study was done to check the ability of this TSP, in this research the temperature change with time is found using the TSP and analytical inverse heat transfer method is employed for respective boundary conditions to calculate the normalized heat flux and Nusselt number from the acquired temperature distribution. The results show the self-similar evolution of surface temperature and heat flux over time.

2. Measurement Technique

This section describes the experimental setup and equipment used for the experiment, along with the equations applied to calculate the normalized heat flux and Nusselt number. These calculations are essential for analyzing the impact of the impingement angle on cooling the hot plate with cold jet by finding the heat transfer fields on the surface of the plate.

2.1 Experimental setup

The TSP has been illuminated continuously using high power green LED (IL-106G, HARDSOFT Microprocessor Systems, Kraków, Poland). A 12-bit IMPERX CCD camera of resolution 3312 x 2488 pixels with 35 mm focal length and attached optical filter is used to capture the TSP images. For eosin Y the peak excitation is at 523 nm and peak emission is at 555 nm, so to excite the TSP 525 ± 12.5 nm band pass optical filter is attached to the LED and 545 nm long pass filter is attached to the CCD Camera. This data is based on the spectroscopic study performed by Chandrasekaran K.S. [6].

For calculating the surface temperature and heat transfer fields, an aluminum plate of 100 mm x 120mm x 4 mm is coated with the TSP of thickness 9 ± 0.6µm and basecoat of 7 ± 0.7µm. The plate is initially heated to 345 K using the heating pad for sufficiently large time such that there is an equal distribution of the temperature across the plate where ambient temperature is 309 K, the cold jet that is used for impingement is also of ambient temperature. The measurement of temperature fields is acquired for every 5 seconds using TSP images, which is pre calibrated for relating temperatures with emission intensities. The time varied temperature distributions are used to calculate the heat transfer fields, like heat flux and Nusselt number [7].

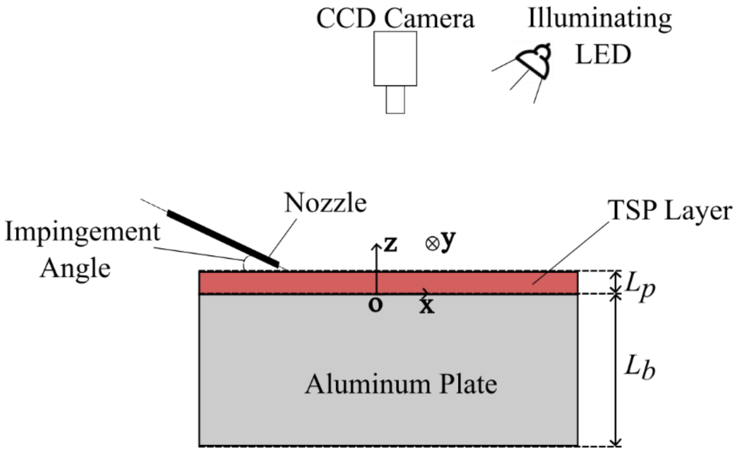

Fig. 1 Schematic Diagram

2.2 Heat flux and Nusselt number calculation

For a two-layer structure, the analytical inverse solution of the one-dimensional (1D) time-dependent heat conduction equation has been used in order to compute the heat flux from a time history of the surface temperature on a finite base thickness using TSP. The TSP layer on plat is prepared using the eosin Y as luminophore and polyurethane as binder, polyurethane has higher mass fraction compared to remaining components in TSP, therefore the thermal conductivity, density and specific heats of aluminum and polyurethane [8] are considered during heat flux calculation. Table. 1 shows the properties of these two materials, which are used in calculating analytical inverse heat transfer solution. For obtaining analytical solution, origin is taken at the interface of TSP and aluminum plate. Remaining sign conventions are shown in Fig. 1. Equation 1 is the analytical solution for calculating heat flux on the TSP layer which is defined by Liu et al. [9], where the discreate form of this equation is used for calculation of heat flux and the expression of $K(t)$ will be varying with the boundary conditions. Here k_p is thermal conductivity of polymer layer, $\theta = T - T_{in}$ at the polymer surface (T is the surface temperature and T_{in} is the initial temperature) and

$$q(t) = \frac{k_p}{\sqrt{a_p}} \int_0^t K(t-\tau) \frac{d\theta\left(\tau, L_p\right)}{d\tau}\, d\tau \tag{1}$$

$$K(t) = Re \int_0^{\infty} \frac{1}{\sqrt{s}} * \frac{g(s) * e^{2L_p \sqrt{\frac{s}{a_p}}} + 1}{g(s) * e^{2L_p \sqrt{\frac{s}{a_p}}} - 1}\, d\xi \tag{2}$$

$$g(s) = \frac{\bar{\varepsilon} f(s) + 1}{\bar{\varepsilon} + f(s)} \;;\; f(s) = e^{-2L_b \sqrt{\frac{s}{a_b}}} \;;\; \bar{\varepsilon} = \frac{\varepsilon - 1}{\varepsilon + 1} \;;\; \varepsilon = \sqrt{\frac{k_p \rho_p c_p}{k_b \rho_b c_b}} \;; \tag{3}$$

$$s = r\, e^{-i(\pi-\delta)} \;;\; r = \frac{\xi^2}{t} \tag{4}$$

The Equation 4 is used to transform the equation from Laplace domain to time domain for solving the discreate form of equation 1. Here k_p, ρ_p, c_p are thermal conductivity, density and specific heat of the TSP layer, k_b, ρ_b, c_b are thermal conductivity, density and specific heat of the aluminum plate and the control parameter δ is the constant angle that is obtained while performing the inverse Laplace transform by using contour integration method for eliminating the singularities during inversion. δ should be small for getting the accurate value, but cannot be zero, so from the reference [9], δ value is considered as $\pi/480$ for getting accurate results and ξ is the transformation variable, whose limits depends on the r which is changing for r_o to infinity and r_o tends to zero, therefore integration of ξ is performed from zero to infinity.

$$\hat{T} = \frac{T(x,t) - T_{ref}}{\max\,|T(x,t) - T_{ref}|} \tag{5}$$

$$\hat{q}_s(x,t) = \frac{q_s(x,t) - \; q_s(x_{ref}, t)}{\max\,|q_s(x,t)|} \tag{6}$$

$$Nu = \frac{hD}{k_f} \;;\; h = \frac{q_s(x,t)}{T(x,t) - T_{aw}} \;;\; \widehat{Nu} = \frac{Nu}{max(Nu)} \tag{7}$$

Normalization of heat flux and Nusselt number is done as given by equation 6 and equation 7, while calculating Nusselt number T_{aw} can be found by linearly fitting the heat flux with temperature data and find the value of temperature if heat flux is zero, but this value can be considered approximately equal to that of initial base temperature as given by [10].

Table. 1 Properties of Polyurethane and Aluminium

Properties	**Polyurethane**	**Aluminium**
Thermal Conductivity [k] (W/m K)	0.025	235
Density [ρ] (kg/m^3)	1260	2710
Specific heat [c] (J/Kg K)	1600	903

3. Results and Discussion

Experiments were carried out for two different impingement angles (α), 5°, 10° and 15°. Heat flux and Nusselt number were calculated using the temperature distribution at 5, 10, 15, and 20 s, respectively. The temperature is calculated using the calibrated TSP. Jet Reynolds number is maintained at 20000 for both the impingement angles. The TSP coated surface and aluminum base is heated to 345 K and the jet is at ambient temperature of 309 K. A comparative study of different angles of attack was conducted to find the optimal cooling conditions based on the heat transfer field data. The surface and centerline distributions of the heat transfer fields are shown in the figures below. Normalization can be done using different reference locations, but in this study, the jet impingement location is considered as the reference point for analyzing the relative distribution around the impingement point.

From Fig. 2, it is evident that the stagnation zone is non-circular and exhibits a sudden peak in normalized conductive heat flux as shown in Fig. 3(a) and 3(b). The stagnation point heat transfer can be calculated for different impingement angles and is observed that conductive heat flux is minimum at the stagnation point and increasing downstream the flow and also it can be observed that the stagnation point is moving upstream with increasing α.

From the plots of normalized Nusselt number shown in Fig. 3(c) and 3(d), downstream the jet the normalized value is higher for 5° and 15° compared to 10°. Therefore, for the given conditions cooling efficiency is higher for 5° and 15°. Time invariant solution is also observed for the normalized temperature difference and heat transfer fields as shown in the Fig. 4(a) and Fig. 4(b) respectively for α = 15° and this self-similarity is observed for all the heat transfer fields and for various α.

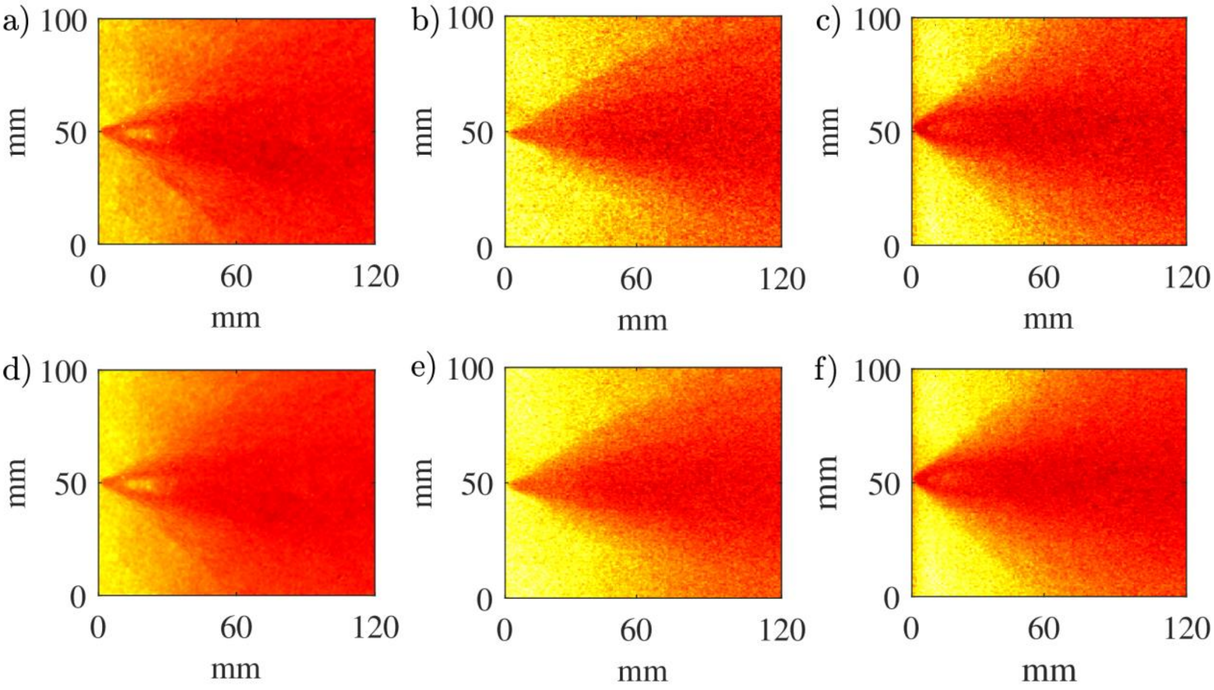

Fig. 2 Normalized heat flux values at 15 s for α = (a) 5°, (b) 10°, (c) 15° and at 20 s for α = (d) 5°, (e) 10°, (f)15°.

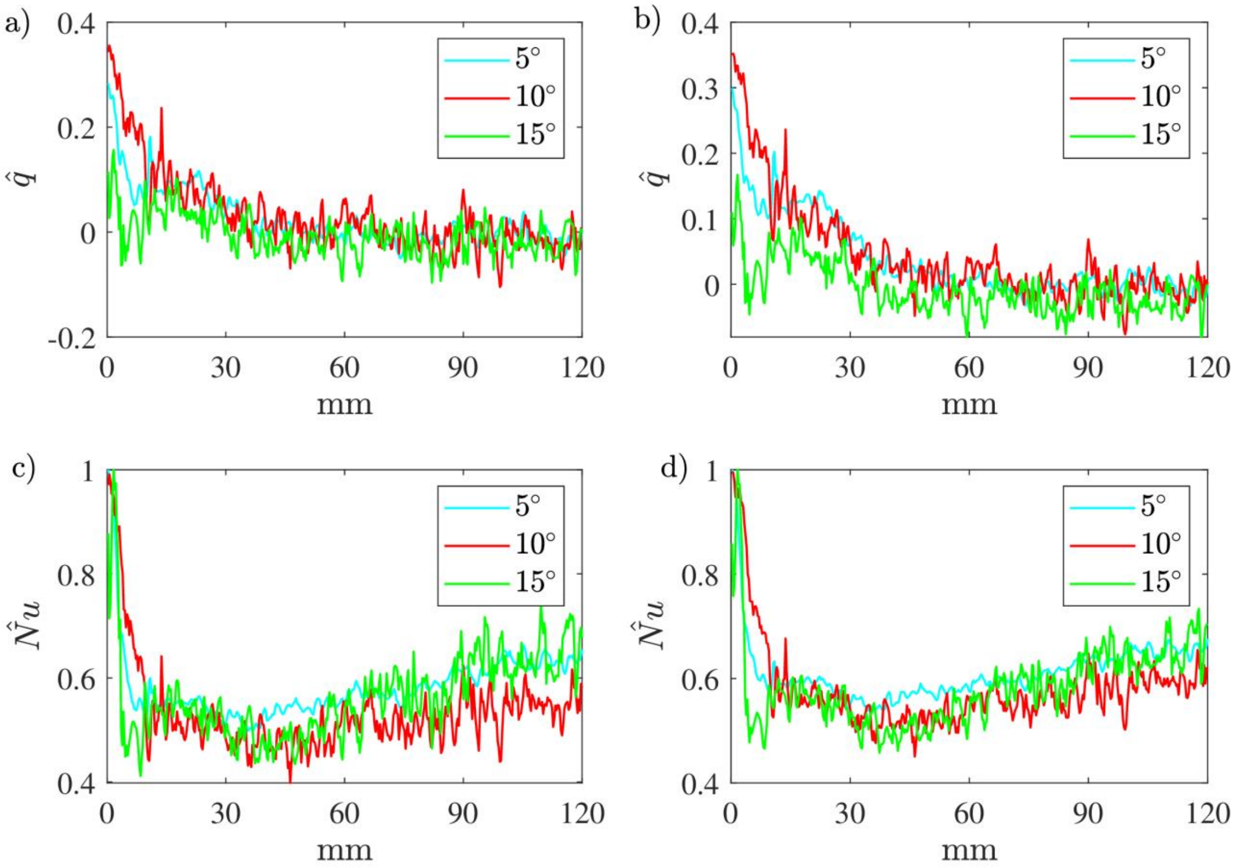

Fig. 3 Normalized heat flux along the centerline at (a) 15 s, (b) 20 s and normalized Nusselt number along the centerline at (c) 15 s, (d) 20 s.

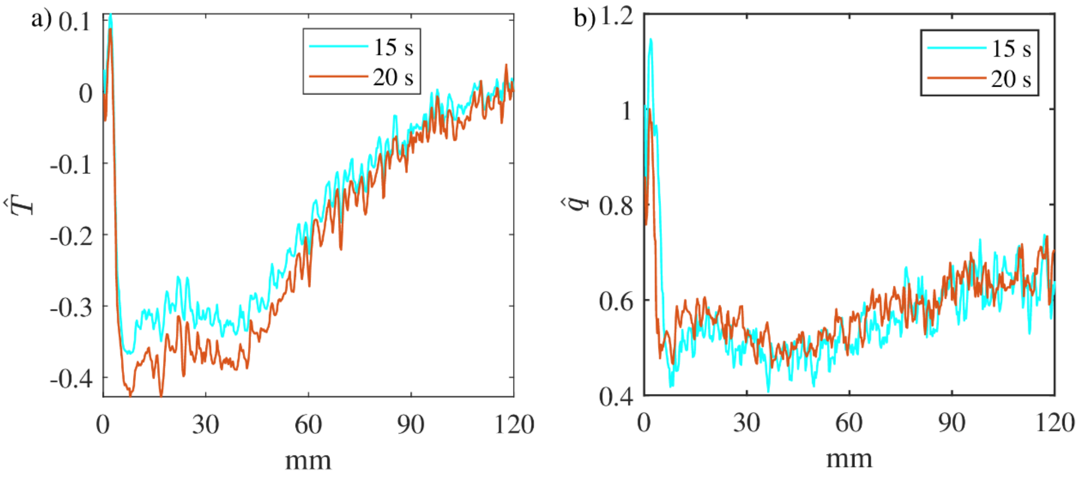

Fig. 4 Normalized values of (a) Temperature (b) Heat flux at α = 15° at 15 s and 20 s.

4. Conclusion and Future work

The surface temperature fields over time on a heated aluminum base with finite thickness, exposed to an oblique impinged relatively cold jet, were measured using TSP. The heat flux fields were then determined through an analytical inverse heat transfer solution, Heat flux and Nusselt number data are calculated. These results help in concluding that this in-house made TSP is capable in calculating heat transfer and it not only demonstrate the viability of this solution but also uncover new physical phenomena, such as the self-similar evolution of surface temperature and heat flux fields within the flow. This analysis also help in determining the location of the non-circular stagnation point for various impingement angles. The better cooling configuration can be determined from the date acquired and can be applied in real life applications based on the requirement and design constraints.

In future this work can be extended to higher jet velocity and different nozzle designs, and can also explore the integration of TSPs with other sensors to provide a more comprehensive understanding of the cooling process and perform on-site calibration.

5. Acknowledgments

The support from the Indian Space & Research Organisation (Grant Number STC/AE/2020197) and the Science & Engineering Research Board (Grant Number CRG/2019/000500) is greatly appreciated. The authors are grateful to Dr. Alakesh Chandra Mandal from the Indian Institute of Technology Kanpur for providing LED.

References

[1] Zukerman N. and Lior N., “Jet impingement heat transfer: physics, correlations, and numerical modeling”, *Advances in Heat Transfer*, Vol. 39, No. 6, (2006), pp 565-631

[2] Kolodner P. and Tyson., “Microscope fluorescent imaging of surface temperature profiles with 0.01 C resolution”, *Applied Physics Letter,* Vol. 40, No. 9, (1982), pp 782-784.

[3] Kolodner P. and Tyson., “Remote thermal imaging with 0.7micron spatial resolution using temperature dependent fluorescent thin films”, *Applied Physics Letter,* Vol. 42, No. 1, (1983), pp 117-119.

[4] Kolodner P. and Tyson., “Non-contact surface temperature measurement during reactive-ion etching using fluorescent polymer films”, *Applied Physics Letter,* Vol. 42, No. 8, (1983), pp 749-751.

[5] Campbell, Liu T. and Sullivan J.P., “Temperature sensitive fluorescent paint systems”, *25th Plasmadynamics and Lasers Conference*, Colorado Springs, CO, U.S.A, 94-2483, (1994), pp 1-19.

[6] Chandrasekaran K.S., Mariappan S., Das D. and Singh A., “Development of a new class of temperature-sensitive paints operating in the green spectrum of light for aerodynamic flow applications”, *Measurement Science and Technology*, Vol. 35, No. 8, (2024), pp 1-12.

[7] Lang W., Gardner A. D., Mariappan S., Klein C. and Raffel M., “Boundary-layer transition on a rotor blade measured by temperature-sensitive paint, thermal imaging and image derotation”, *Experiments in* fluids, Vol. 56, No. 118, (2015), pp 1–14.

[8] https://www.bergerpaints.com/products/wood-finishes/imperia-and-imperia-grande-clear

[9] Liu T., Montefort J., Stanfield S., Palluconi S., Crafton J. and Cai Z., "Analytical inverse heat transfer method for temperature-sensitive-coating measurement on a finite base", *International Journal of Heat and Mass Transfer*, Vol. 118, No. 56, (2018), pp 651-662.

[10] Liu T., Montefort J., Stanfield S., Palluconi S. and Crafton J., "Self-similarity of surface heat transfer fields on a pre-heated rectangular plate in an obliquely impinging sonic jet", *International journal of Heat and Mass Transfer*, Vol. 147, No. 14, (2020), pp 1-16.