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Analytical inverse heat transfer method for temperature-sensitive-coating measurement on a finite base

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ABSTRACT

An analytical inverse heat transfer solution is given for calculating surface heat flux from temperature-sensitive coating measurements on a base with a finite thickness, which is particularly relevant to high enthalpy hypersonic wind tunnel experiments. This solution is validated through simulations for several time histories of the heat flux imposed on the surface of the base, focusing on the effects of the relevant parameters including the control parameter in the inverse Laplace transform, base thickness and convective heat transfer on the backside of the base. Further, this solution is used to extract the heat-flux fields from temperature-sensitive-paint images obtained on a flat surface of an aluminum base in a transonic obliquely impinging jet. The experimental data exhibit the self-similar evolution of the surface temperature and heat-flux fields. The Nusselt number distribution evaluated by using this analytical method is consistent with the previous results.

1. Introduction

Problems in heat transfer are important in the design of hypersonic vehicles, in which surface heat flux is the most important aerothermodynamic quantity. Global heat-flux measurements are critical to better understand complex flow phenomena such as transition, near-surface stationary vortices, and separation. In addition to conventional point-based techniques like thermocouples and thin-film sensors, global techniques for surface temperature measurements, such as temperature-sensitive paint (TSP), thermographic phosphors (TP), thermochromic liquid crystals (TLC), and infrared (IR) camera, have been developed to obtain high-resolution surface heat-flux fields in hypersonic wind tunnels.

TSP is a thin luminescent polymer layer whose emission is sensitive to temperature. Surface temperature fields can be measured by detecting the luminescent intensity of TSP-coated surfaces [1]. TSP has been used to determine quantitative global heat transfer in short-duration hypersonic wind tunnels [2–4].

TP and TLC are also temperature-sensitive coatings used for measuring surface temperature distributions. Similar to TSP, TP utilizes the thermal quenching of the luminescent emission from ceramic materials that are doped or activated with rare-earth elements [5]. In the form of insoluble powders, TP is usually applied to a surface of a body with specific high-temperature paint. Since a family of TPs can cover a temperature range of 273–1600 K, TPs are more suitable for measurements in high-enthalpy flows [6,7]. TLC is also applied to a surface, which selectively reflects light depending on the surface temperature. Hence, the dominant wavelength or hue of the reflected light varies monotonically with temperature over a relatively narrow temperature range of about 32–42 °C. TLCs have been used for heat transfer measurements in supersonic and hypersonic flows [8–10]. In contrast to temperature-sensitive coatings (TSP, TP and TLC), IR thermography directly relates the thermal radiation from a body to its surface temperature, which has also been used in hypersonic wind tunnels [11–13]. For metallic bodies with low emissivity, a thermally black coating with high emissivity is usually applied to the body surface to enhance the thermal radiation and signatures associated with flows.

In high-enthalpy hypersonic flows, surface heat flux generated by aerodynamic heating enters into the body, causing a rise of the surface temperature. In principle, from a time history of the surface temperature fields measured by using the above global techniques, the corresponding heat-flux fields could be determined by solving the inverse heat transfer problem for specific structures like semi-infinite bases [14,15]. The Cook-Felderman method is a

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Nomenclature

a	thermal diffucivity
c	specific heat
D	diameter of nozzle exit
h_c	convective heat transfer coefficient
H	nozzle-to-surface distance
k	thermal conductivity
I	luminescent intensity
L	polymer thickness
q_s	surface heat flux
$\hat{q}_s$	normalized surface heat flux
Q_s	Laplace transform of q_s
Re	real part of complex function
s	Laplace transform variable
t	time
T	temperature
T_{in}	initial temperature
$\boldsymbol{x}$	surface coordinate
y	coordinate in normal direction to surface

Greek symbols

δ	angle of contour segment
ε	$\sqrt{k_p\rho_p c_p/k_b\rho_b c_b}$
θ	temperature change from initial temperature
$\hat{\theta}$	normalized θ
Θ	Laplace transform of θ
ρ	density
ϕ	jet impingement angle

Subscripts

aw	adiabatic wall
b	base
p	polymer
ps	polymer surface
ref	reference
s	surface

popular one-dimensional (1D) inverse heat transfer method [16]. The inverse methods have been used for different techniques such as thermocouples [17], IR thermography [18], and general thermographic data [19].

For TSP, TP, TLC and IR camera, a thin sensor layer plus a base coating with the relatively low thermal conductivity is applied on the surface of a metallic body. Sometimes, a white polymer base coating is applied for TSP and TP to enhance light scattering and improve the signal-to-noise ratio. The sensor layer is usually represented by a composite polymer layer, which itself would change the time history of the surface temperature. Therefore, the effect of the composite layer should be accounted for when determining heat flux. The analytical solution for heat-flux from temperature-sensitive-coating measurements was given by Liu et al. [20]. This solution included the effects of the polymer coating on a semi-infinite base. The corresponding numerical inverse heat transfer solution was given by Cai et al. [21] for materials with temperature-dependent thermal properties. Further, the deconvolution method was developed by Liu et al. [22] for correction of the lateral heat conduction effect. The methods described in [21–23] were used to determine heat flux from TSP measurements for a circular cone in a Mach-6 quiet tunnel [23].

Most inverse heat transfer methods have been developed based on the assumption of a semi-infinite base due to its simplicity of the boundary condition at infinity. However, since some models in aerothermodynamic experiments have finite wall thicknesses, these methods may lead to considerable errors, particularly when applied to models with thin shells. The work described in this paper focuses on the development of an analytical inverse heat transfer method for determining heat flux from surface temperature measurements using temperature-sensitive-coatings and IR thermography for finite base models in high enthalpy wind tunnels. First, we derive the analytical inverse heat transfer solution for a coating (typically a polymer coating) on a finite base by applying the Laplace transform to the heat diffusion equations with the suitable boundary and matching conditions, which clearly elucidates the effects of the coating and the base thickness (see Appendix A for the details of the derivations). Then, the solution is validated through simulations for the given time histories of heat flux imposed on the coating surface. The results from the simulations help in understanding how to select the control parameter in the inverse Laplace transform, and evaluate the effects of the wall thickness and heat transfer on the backside of the wall. Furthermore, as an example, the method developed is applied to TSP measurements in a transonic obliquely impinging jet. The results reveal some interesting heat transfer phenomena such as self-similar evolution of the surface temperature and heat-flux fields in this time-dependent process.

2. Analytical inverse solution

A new analytical inverse solution is presented here for a polymer layer on a base with a finite thickness (the detailed derivation of this solution is given Appendix A). As illustrated in Fig. 1, a polymer layer (or a sensor layer plus a basecoat) on a base with a finite thickness is considered. The thicknesses of the polymer layer and the base are L_p and L_b, respectively. The origin of the coordinate system is located at the interface between the polymer layer and the base. The positive y-coordinate points upward into the flow domain. The heat flux into the base is defined as a positive value. In Appendix A, a transient solution of the 1D time-dependent conjugated heat conduction equation is sought by using the Laplace transform for this geometrical configuration. In particular, an explicit relation is given between the heat flux $q_s(t)$ and the

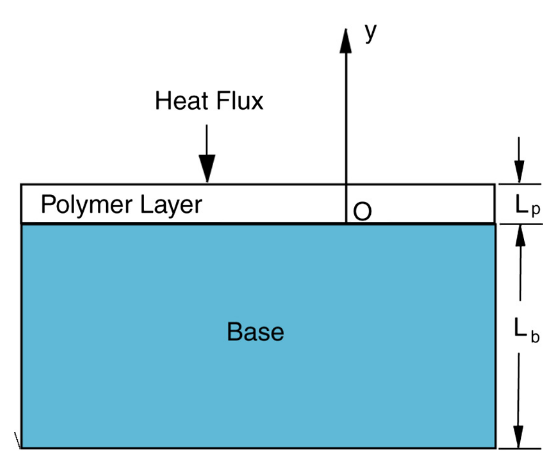

Fig. 1. A thin polymer layer on a base with a finite thickness and a coordinate system.