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Aero-thermal analysis of shielded fine wire thermocouple probes

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ABSTRACT

Thermocouple probes for high accuracy gas temperature measurements require specific designs optimized for the application of interest and precise characterization of the uncertainty. In the present investigation a numerical procedure is proposed that outperforms previous experimental approaches to analyze the thermocouple response and the different sources of temperature error. The results presented from conjugate heat transfer simulations on different shielded thermocouples, provide information of the influence of the design parameters on the different error sources. These outcomes should help experimentalists to better design future instrumentation.

1. Introduction

In aeroengine component testing [1–3] high fidelity in the total temperature is needed. In the present investigation numerical simulations were performed to study the steady and unsteady heat balances within a temperature probe and to evaluate both the temperature field during a transient and at equilibrium conditions.

Multiple attempts to provide correction factors for standard thermocouple designs were found in the literature [4–8]. The experimental evaluation of the time response has been a continuous subject of interest in which both internal and external heating techniques have been applied. Internal heating consists on heating electrically either with a continuous or pulsating DC current [9] or with AC current [10]. The time constant was deduced from the thermocouple temperature decay after the removal of the DC/AC overheating current. However the internal heating offers several disadvantages [11] such as Peltier effects and non-uniform temperature distributions over the sensor. In turn, the external heating includes a wide array of possibilities: oscillating temperature jet created by a the wake of 4a heated wire [12]; laser beam [11]; cold air jets impulses [13]; rotating wheel chopping hot and cold tubes [14]; fast displacement of probes to regions of different temperature [15]; fast displacement of probes to a rocket plume [16]. In addition to dynamic characterizations, overall recovery factors were traditionally experimentally determined as an indicator of the temperature error of a thermocouple. Such global recovery factors accounted for the total effect of radiation, conduction and convection on the probe for a given flow environment. The variability of the heat fluxes balance within the probe with the environment and probe design, required each thermocouple to be carefully designed and calibrated for the required application. However, exact corrections from experimental calibrations were impractical. Furthermore, not only the testing flow conditions but also the thermal interactions between the probe and the test bench required to be duplicated in the calibration set-up. The precision to reproduce and to characterize the calibration environment determined the accuracy of the corrections.

Zeisberger [17] applied one dimensional heat transfer calculations to analyze the influence of the steady temperature errors for different geometrical parameters of a kiel thermocouple. The current conjugate numerical characterization of shielded thermocouple probes performed the coupled fluid convection and solid conduction. The developed numerical methodology allowed understanding and quantifying the influence of the design parameters, essential to achieve a good design for precise gas temperature measurements. Adiabatic recovery factors, conduction error estimations and response times were determined for a shielded probe with different values of thermocouple wire diameter, wire materials and boundary conditions at the thermocouple wire support. The presented numerical approach may be coupled with optimizers to design the best probe for any specific application. This procedure is superior to current experimental design practices

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Nomenclature

d	diameter, m
h	convective heat transfer coefficient, W m^{-2} K^{-1}
k	thermal conductivity, W m^{-1} K^{-1}
l	wire length (junction to support), m
l_c	$\sqrt{k_w d_w / 4h}$ reference wire lenght, m
r_a	adiabatic recovery factor
t	time, s
x	axial coordinate (flow direction), m
y	normal coordinate (wire direction), m
z	lateral coordinate, m
y^+	nondimensional distance from the wall to the first grid point
C_p	heat capacity at constant pressure, J Kg^{-1} K^{-1}
P	pressure, Pa
S	transversal area, m^2
T	Temperature, K
V_j	junction volume, m^3
V	velocity, m s^{-1}
Z	overall recovery factor
Z_a	overall adiabatic recovery factor
ρ	density, Kg m^{-3}
τ	characteristic time constant, s
Nu	Nusselt number based on wire diameter
Re	Reynolds number based on wire diameter
AD	Adiabatic
CHT	conjugate heat transfer
ISO	Isothermal
Subscript	
j	junction
ad	adiabatic
f	final
g	gas
i	initial
int	conditions upstream of the junction within the shield
m	average
s	static conditions
sp	support
w	wire
0	total conditions
∞	free stream conditions

based on limited measurement access to the miniaturized probe. Moreover, this method is appropriate to analyze conditions difficult to be evaluated experimentally (combustion, hypersonic, accident testing).

2. Thermocouple probe design

2.1. Application

Total flow temperature measurements were to be performed in transient conditions in transonic wind tunnels at the von Karman Institute for Fluid Dynamics, such as [1] and [2]. The inlet flow temperature decayed approximately 15 °C from ambient conditions. Flow temperature traverses were to be recorded along test sections of about 0.01 m^2 transversal area. Hence, high-frequency response of the thermocouple probes was required in order to carry out fast traverses. The utilization of probe rakes allowed maximizing the measurement locations during a test. Precise characterization of the probe response was necessary to synchronize all readings, as well as to accurately analyze the engine component performances. Thin wire thermocouples were more suitable to fit the requirements of this application, than other kind of total temperature probes [18].

2.2. Pre-existent design rules

The temperature of a thermocouple junction is the result of the energy balance including the convective heat flux between the junction and the surrounding gas, radiation to the walls, and conductive flux to the wire. The measured temperature would be equal to the total flow gas temperature in the absence of radiative heat fluxes, conductive flux to the thermocouple support and dissipation of kinetic energy in the boundary layer.

General design rules reported in the literature [19,20], as well as design recommendations for particular applications based on comparative analysis of different probe configurations [4,5,21,22], provide advice to reduce the temperature error sources on new designs. A shield is recommended in order to decrease the error caused by the transformation of kinetic energy into thermal energy in the boundary layer around the junction (often called velocity error). The shield also provides structural resistance in high velocity flows and reduces radiation effects [23]. However, decreasing the velocity of the flow decreases the convective heat transfer, increasing the conduction error and the response time. Thus, the internal velocity must be kept as high as allowable. The internal velocity is function of the vent hole to inlet ratio. The junction position within the shield is a compromise between entrance flow effects, radiation shielding and convective heat transfer between the thermocouple and the shield. Recommended values are given by Rom and Kronzon [5] and Glawe et al. [4]. The wires within the shield can be placed parallel or perpendicular to the flow. In the first case, the length of the wires is limited to prevent wire bending. In the second, the length is limited by the shield diameter.

Conduction errors can be estimated from the one dimensional energy balance on a wire element. Integration along the wire considering symmetry boundary condition at the junction ($y = 0$), and isothermal temperature $T_w = T_{sp}$ at the support of the wire ($y = l$), results on a simplified solution for the wire temperature distribution [24]. At the position of the junction, the temperature is the given by Eq. (1). The assumptions of constant gas temperature T_0, and constant convection coefficient h required for the simplified integration along the wire, neglect the effect of the real flow temperature differences along it.

$$T_0 - T_j = \frac{T_0 - T_{sp}}{\cos h\left(l\sqrt{\dfrac{4h}{k_w d_w}}\right)} = \frac{T_0 - T_{sp}}{\cos h(l/l_c)} \tag{1}$$

Design rules derived from this simplified solution recommend to have high values of convective heat transfer coefficient (high velocities), high length to wire diameter ratios l/d_w, low conductivity wire materials k_w, and support temperatures T_{sp} close to gas temperatures. Petit et al. [12] suggest that the ratio l/l_c should not be smaller than 5.

The contribution of the error due to radiation is generally important at high flow temperatures. In the present transonic flow application both the flow and the test section walls remained at ±15 °C of the ambient temperature. Considering the most adverse