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Implementation of a new thermal model and static calibration of a wedge-shaped hot-film probe in a constant-temperature mode

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ABSTRACT

Wedge-shaped hot-films are a promising alternative to hot-wires for supersonic free flow disturbance measurements if hot-wires cannot be used due to harsh flow conditions. Up to the present, wedge hot-films could not serve as quantitative tools because of an insufficient modelling of the substrate's influence on the thermal balance. The present paper shows a static calibration of a wedge-shaped hot-film sensor that is based on a combination of an analytical, a numerical and an experimental approach. The substrate's impact was analysed by the help of CFD simulations and modelled by a newly introduced substrate factor. The obtained sensitivities were discussed and qualitatively explained compared with standard hot-wires. A quantitative comparison of experimentally detected mass flux fluctuations proved the wedge hot-film data to match similar hot-wire results very well. The presented approach has the potential to upgrade hot-films of various shapes to tools for quantitative fluctuation measurements.

1. Introduction

Thermal anemometry is a well-established method for performing a fluctuation analysis in supersonic flows, for example in terms of modal analysis according to Kovásznay and Morkovin [1–3]. Many of the related experimental publications date back to the 1950s, 1960s and 1970s, but hot-wires and hot-films improved continuously and stayed a reliable tool for flow measurements. Good and conprehensive overviews are given by, among many others, Bruun [4], Comte-Bellot [5] and McKeon et al. [6]. Despite all this development, a huge share of these issues is still not fully understood. When continuing this research in 2015, Zhang and Duan [7] published DNS simulations about the sound radiated from the supersonic turbulent boundary layer on the inner wind tunnel walls. They successfully compared their results to the ones of Laufer [8] from 1964. Combining both approaches, thermal anemometry measurements can provide valuable constraints for related numerical simulations in return.

While hot-wires represent a standard tool [4], hot-films in general and wedge-shaped hot-films in particular are more robust sensors. Thus, they represent an alternative for harsh flow conditions that do not allow the use of hot-wires. Of course, flow particles hitting the sensor can damage hot-films as well and thereby change their characteristics.

Yet, their complex structure and the influence of the substrate material on the heat balance impose considerable difficulties. During the last decades, various researchers tried to model these relations analytically, but did not reach an applicable level. Among many others, the following publications deal with the listed issues: Bankoff and Rosler [9], Bellhouse and Schultz [10], Brison et al. [11], Freymuth [12], Nelson and Borgos [13], Seiner [14], Sheplak [15] and Sheplak et al. [16,17].

In contrast, the present study combined experimental data and extensive analytical modelling with modern CFD simulations of a wedge hot-film in a supersonic flow. This allowed to gain a sufficient insight that can facilitate quantitative disturbance measurements with the used wedge-shaped hot-film probe. It represents a great improvement compared with the state of the art, because up to the present wedge hot-films were considered as qualitative tools only [16]. In 1995, Sheplak et al. [16] suggested to perform such simulations that were not possible by then. Atak [18] and Li et al. [19] conducted similar simulations for hot-wires, but not with a complexity required for wedge hot-films.

The objective of the present study is to present the analytical, numerical and experimental elements of the modelling and calibration of the used wedge-shaped hot-film probe. This is outlined

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Nomenclature

A	$[\mathrm{m}^2]$ outer sensor surface
A	[–] offset of King's Law, 2d/ 3d separation
a	[–] exponent thermal conductivity
B	[–] gradient of King's Law, 2d/ 3d separation
b	[–] exponents dynamic viscosity
D	[m] sensor diameter
E	[V] output voltage
$f(\tau)$	[–] offset of King's Law, 2d/ 3d separation
$g(\tau)$	[–] gradient of King's Law, 2d/ 3d separation
h	$\left[\frac{\mathrm{W}}{\mathrm{m^2K}}\right]$ heat transfer coefficient
k	$\left[\frac{\mathrm{W}}{\mathrm{mK}}\right]$ thermal conductivity
L	$[\mathrm{V}^2]$ offset of King's Law, 2d/ 3d separation
l	[m] spanwise sensor length
M	[–] Mach number
N	$\left[\mathrm{V}^2/\left(\frac{\mathrm{kg}}{\mathrm{m^2s}}\right)^{n_{\rho u}}\right]$ gradient of King's Law, 2d separation
N	$\left[\mathrm{V}^2/\left(\left(\frac{\mathrm{kg}}{\mathrm{m^3}}\right)^{n_\rho}\left(\frac{\mathrm{m}}{\mathrm{s}}\right)^{n_u}\right)\right]$ gradient of King's Law, 3d separation
Nu	[–] Nusselt number
$n_\rho, n_u, n_{\rho u}$	[–] exponents King's Law
$\dot{Q}$	[W] heat flux
$\dot{q}$	$\left[\frac{\mathrm{W}}{\mathrm{m^2}}\right]$ heat flux density
q	[–] geometry factor
R	$[\Omega]$ ohmic resistance
Re_D	[–] Reynolds number based on D
Re_{unit}	$\left[\frac{1}{\mathrm{m}}\right]$ unit Reynolds number
$R_{x,y}$	[–] cross-correlation coefficient between the variables x and y
$S_\rho, S_u, S_{\rho u}, S_{T_0}$	[–] non-dimensional sensitivities
s	[m] substrate coordinate
T	[K] temperature
t	[s] time
x, y, z	[m] coordinates

Greek symbols

Δx	interval of quantity x
η	[–] recovery ratio
μ	$\left[\frac{\mathrm{kg}}{\mathrm{ms}}\right]$ dynamic viscosity
ρ	$\left[\frac{\mathrm{kg}}{\mathrm{m^3}}\right]$ density
ρu	$\left[\frac{\mathrm{kg}}{\mathrm{m^2s}}\right]$ mass flux
σ	[–] substrate factor
τ	[–] temperature overheat ratio

Subscripts

a	active bridge arm
film	film layer
fluid	fluid
hf	hot-film
hw	hot-wire
leads	cables, connectors, prongs
mod	σ-modified
rec	recovery conditions
subst	substrate
0	stagnation conditions
1	conditions upstream of shock

Superscripts

x'	fluctuating part of quantity x
$\bar{x}$	mean value of fluctuating quantity x
$\langle x' \rangle$	root mean square (rms) value of quantity x

more detailed in Krause [20]. The shown methods in general can serve as an instruction of how to model and calibrate hot-films of various shapes.

2. Materials and methods

2.1. Thermal anemometry

As outlined by Morkovin [3], a hot-wire is in general sensitive to perturbations of the density ρ, the velocity u and the stagnation temperature T_0.

$$\frac{E'}{\overline{E}} = S_\rho \frac{\rho'}{\overline{\rho}} + S_u \frac{u'}{\overline{u}} + S_{T_0} \frac{T_0'}{\overline{T}_0} \quad (1)$$

The apostrophe denotes the fluctuation part and the overbar the average. The anemometer's output voltage is: $E(t) = \overline{E} + E'(t)$. The non-dimensional sensitivities S_ρ, S_u and S_{T_0} are determined via logarithmic derivation.

$$S_\rho = \frac{\partial \ln(\overline{E})}{\partial \ln(\overline{\rho})}, \quad S_u = \frac{\partial \ln(\overline{E})}{\partial \ln(\overline{u})}, \quad S_{T_0} = \frac{\partial \ln(\overline{E})}{\partial \ln(\overline{T}_0)} \quad (2)$$

According to Morkovin [3], the sensitivities S_ρ and S_u become hardly distinguishable in a supersonic flow and turn into $S_{\rho u}$. Following Horstman and Rose [21], the approximation $S_\rho \approx S_u \approx S_{\rho u}$ holds only for a temperature overheat ratio of $\tau > 0.5$ and a diameter-based Reynolds number of $Re_D > 20$. τ, which the sensitivities are a function of, is defined as $\tau = (T_{hw} - T_{rec})/T_0$. T_{hw} is the hot-wire's temperature and T_{rec} the sensor's recovery temperature. Thus, the anemometer becomes sensitive to fluctuations of the mass flux (ρu) and T_0. The perturbation equation Eq. (1) simplifies to a 2-dimensional voltage separation, as listed by Kovásznay [1,2].

$$\frac{E'}{\overline{E}} = S_{\rho u} \frac{(\rho u)'}{(\overline{\rho u})} + S_{T_0} \frac{T_0'}{\overline{T}_0} \quad (3)$$

Analogous to Eq. (2), the sensitivity $S_{\rho u}$ is derived:

$$S_{\rho u} = \frac{\partial \ln(\overline{E})}{\partial \ln(\overline{\rho u})} \quad (4)$$

The present study revealed that the simplification $S_\rho \approx S_u \approx S_{\rho u}$ does not hold for the analysed wedge hot-film probe. The used sensor requires a 3-dimensional voltage separation according to Eq. (1).

The procedure of solving Eqs. (1) and (3) for the unknowns usually implies to square and time average the equations. That way, the fluctuating quantities are changed into their normalised rms values which are suitable for handling experimental data, compare [1–3]. Since this procedure is well described in the standard literature about thermal anemometry, it is outlined only very briefly in the present publication. The normalised rms value of the mass flux is exemplarily given in Eq. (5).

$$\langle(\rho u)'\rangle = \frac{\sqrt{\overline{(\rho u)'^2}}}{\overline{\rho u}} \quad (5)$$