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A novel surface-integrated spray-on thermocouple for heat transfer measurements

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ABSTRACT

A novel manufacturing process for surface-integrated thermocouples is presented and its potential for heat transfer experiments is demonstrated. The presented manufacturing approach allows finely structured and reproducible thermocouples produced as part of the object under study. Therefore a fine channel is milled inside the investigated Perspex wall and gradually filled with conductive paints using spray cans of copper and nickel paint. High flexibility in adapting the sensor design to the requirements of a given experiment is offered by this approach as it involves only low-cost materials and standard manufacturing machinery. The paper details the characteristics and performance of such sensors, i.e. durability, reliability and operational range. Furthermore, an analytical, one-dimensional heat conduction model is used to describe the two layer arrangement of the sensor and underlying support substrate. For a step change in fluid temperature, this model in combination with a multipoint optimization procedure allows to determine the local heat transfer coefficient and the corresponding reference temperature. It is shown that this is possible without knowledge of the thermal properties of the sensor resulting in no additional calibration requirements. The obtained results are validated against measurements with thermochromic liquid crystals and commercial thermocouples. Deviations are within the uncertainty of the reference showing that the new device is competitive to state of the art techniques. Potential applications are seen for all kind of heat transfer experiments, especially when optical access for conventional techniques is restricted. Another possible field is the in-situ calibration of planar measurement techniques such as infrared thermography or thermochromic liquid crystals.

1. Introduction

Surface thermocouples are an important supplement to spatially resolved plane surface temperature measurement techniques like semi-invasive temperature-sensitive paints (TSPs), thermochromic liquid crystals (TLCs) or noninvasive techniques like infrared thermography (IRT) [1]. Examples for the use of surface thermocouples (STCs) include local temperature measurements in regions where an optical access is not feasible. In case of IRT further use of the STCs results from the application as an in-situ reference temperature measurement device. The detected radiation of the IRT system is not only influenced by the object of interest but, e.g., by the radiation of the surroundings, the transmittance of a window or the radiation of hot gas. Therefore, the STCs can increase the accuracy of the IRT system. Their importance for in-situ calibrations are outlined, for instance, in [2–4]. In addition STCs allow to derive local heat flux histories on basis of the time-resolved temperature measurements [5].

As an invasive measuring device, the main challenge in applying STCs is their installation especially in complex geometrical situations like turbine guide vanes or blades with highly curved surfaces [6,7]. Commercially available STCs consist of two metal legs made as thin film, often deposited on an additional flexible substrate. Among the aforementioned applications, it is difficult to implement such a device on a complex shaped object as the metal legs easily break when forced onto the curved surface. For thermocouples supplied on a support substrate, this is even more challenging as the entire substrate must follow the surface curvature. In addition, both configurations share the disadvantage that the device alters the surface of the object of interest and may negatively interfere with the surrounding flow field.

Instead it would be often desirable for the researchers to manufacture their own thermocouples deposited directly on the curved surface. Then the individual requirements of the intended application can be stronger reflected in the design of such custom solutions. Manufacturing processes like sputtering [8–11], thermal spraying [12–14], evaporation [15,16], printing [17] or painting [18] are suggested in literature for custom made surface thermocouples.

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Nomenclature

Acronyms

IRT	infrared thermography
STC	surface thermocouple
TLC	thermochromic liquid crystal
TSP	temperature-sensitive paint

Greek symbols

η	coordinate
ν	kinematic viscosity
ρ	density
σ	standard deviation
ξ	variable

Roman symbols

ΔT	quadratic deviation of temperature
$\dot{q}$	heat flux per area
Bi	Biot number ($Bi = hL_1/k_1$)
Re	Reynolds number ($Re_d = ud_h/\nu$)
c	specific heat capacity
d	diameter
h	heat transfer coefficient
k	thermal conductivity
L	layer thickness
N_I	number of individuals
N_P	number of populations
R	coefficient of determination
S	seebeck coefficient
T	temperature
T_{hold}	holding temperature
U	voltage
u	velocity

Subscripts

1D	one dimensional
A	clamping point amplifier
Cl	clamping point
Cond	conduction
Conv	convection
Cr	chrom
Cu	copper
h	hydraulic
i	TLC indication
m	measured
Ni	nickel
p	paint
ref	reference
S	surface
TC	thermocouple
th	theoretical
U	voltage
W	wall

Sputtering represents the state of the art for thin film thermocouples allowing film thicknesses and structures in the order of tenths of nanometers [9]. This results in a number of beneficial properties for different applications, but suffers from its complicated and costly manufacturing process. In addition the overall dimensions of the object of interest are restricted to the manufacturing space, especially with respect to the thickness of the object. For this reason, the thermocouples are mainly deposited on thin carrier foils with the aforementioned drawbacks that also holds for other sensing devices based on this manufacturing technology.

Thermal spraying offers the possibility to deposit fine structures in the order of 200 μm on the object of interest without the vacuum process of a sputtering machine. The principle of this manufacturing process bases on the deposition of melted metal in form of a spray. While a more universal approach compared to sputtering, thermal spraying is, however, not possible for polymer models due to the resulting thermal loads.

More recent developments involve conductive inks designed to improve inkjet printing of electronic circuits [19,20]. Such an approach was used by Duby et al. [17] to manufacture thick film thermocouples on a flexible substrate. Although a simple and cost-efficient process, it imposes the same restrictions with respect to multi-curved surfaces as outlined for the commercial thermocouples.

Rather than printing, conductive ink may be applied in a painting process using a brush or a ruling pen [18]. This removes the restriction regarding the curved surfaces, but implies a more elaborate process when multiple thermocouples are formed. In addition, metallo-organic inks used in literature (e.g. [21]) require a firing process for curing, which is suitable for ceramic substrates used in high temperature applications, but not for the polymer structures investigated here.

The approach presented here differs in such that acrylic conductive paints are used and deposited via common, everyday spray cans. The geometry of the thermocouple and its connection leads is formed by fine channels embedded into the object beforehand. These channels are filled with the paint while an overlap of both paints is restricted to the measuring tip. Paint outside of the channels is then removed which leaves the entire device completely integrated into the surface of the object.

Structuring the paint layers this way results in small and reproducible thermocouples. This is especially important when the design is extended from single to multiple sensors arranged in a large sensor matrix to cover the entire object. Here, spray deposition is beneficial as a homogeneous layer thickness is achievable for the entire object. Furthermore, it allows to manufacture the thermocouple directly on the object of interest even for complex geometries.

Conductive paints are commercially available from electromagnetic shielding applications. It will be shown that these paints offer an easy and cost-efficient solution for custom thermocouples. As these paints are acrylic-based, they dry at ambient temperatures and,therefore, allow the application on polymer structures.

Beside the adaptable manufacturing process, a key feature results from the integration of the sensor into the surface. Thus, the boundary layer flow field remains undistorted, which is an important difference to any form of attached sensors.

In this paper we describe the novel manufacturing process for these thermocouples in addition to the granted patent [22]. In a first step, we evaluate the manufactured thermocouple with respect to its response to temperature, its reliability and range of operation. In a second step, it is shown that the accurate knowledge of the surface temperature history allows to derive the local heat transfer coefficient h together with the reference temperature T_{ref} associated with the heat transfer process. With the presented approach, this is possible even without distinct knowledge of the thermal properties of the sensor material. The obtained results are verified by reference measurements using different types of TLCs and commercial thermocouples.