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Conjugate heat transfer simulations of a thermocouple sensor in a low temperature nitrogen gas ambient

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ABSTRACT

An unsteady, three-dimensional numerical simulation model is developed to investigate conjugate heat transfer effects from a low temperature nitrogen gas ambient to a thermocouple of diameter ranging between 10 and 100 μm. The response of the thermocouple to a sudden temperature jump of the ambient gas has been investigated. Results include the calculated time constant of the thermocouple, temperature distributions in the gas and the solid and velocity distributions in the gas as a function of the ambient conditions. The wire size is clearly the most important factor, while the ambient temperature and velocity also significantly affect the response time. Comparison with an experiment shows good agreement.

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1. Introduction

Large and fast temperature changes in gases are frequently encountered in several configurations, such as internal combustion engines[1], regenerators[2] and during flight[3]. The ability of the current equipment to achieve accurate measurement in a short response time may be crucial for the control of such processes. In the field of vacuum metrology, the commonly used static expansion method[4–6] consists of one or more expansion stages of a gas. It is well known that this leads to a decrease of temperature in the high pressure vessel, which may cause significant inaccuracies in the calculation of the gas pressure if not taken into account. This effect becomes even more important when the process is dynamic and a method to measure fast temperature changes is required.

The deviation of the gas temperature from room temperature in static expansions has so far been estimated by experiments with significant success[7]. However, since the response time of the instrumentation becomes comparable to the time scale of the expansion, sensors may lag behind the true gas temperature. Thermocouple sensors are the most appropriate for this type of fast measurement, as it has been seen in other applications[8,9], due to their low heat capacity. The wire diameter may be as small as 10 μm and is usually wrapped in a coil. Previous studies on this configuration, however, either do not provide a lot of information regarding the expected response time, or only apply for a particular geometry and certain velocity directions.

Conjugate heat transfer formulations are used to describe processes of heat transfer between solids and their surrounding fluids due to their mutual thermal interaction. Even though the methodology is not new[10], it is only in the last decades that it became more popular due to the increase in computational power and improved techniques, leading to a plethora of relevant works[11–18]. Such simulations have been used successfully in the past to model microchannel heat transfer for the cooling of microelectronic products[11], heat exchangers[12,14,15,17], as well as for the quantification of the measurement bias of thermocouples in fire environments[14,15] and hot wire anemometers in the proximity of walls[13]. Thermocouples were also recently investigated[18] through conjugate heat transfer simulations but for shielded sensors and for higher flow velocities and temperatures than the ones considered here.

In the current study, the conjugate heat transfer approach is employed for the characterization of a thermocouple in terms of its expected response time. Such a sensor is used in the dynamic vacuum expansion experimental facility of PTB[19]. Heat transfer from the wire to the nitrogen ambient is considered on the basis of a numerical solver. The evolution of the whole flow field is investigated, including the possibility of the ambient gas movement. Some non-trivial geometrical characteristics are taken into account, contributing to the reduction of the overall uncertainty. The results were obtained using the OpenFOAM® computational platform[20].

The structure of the paper is as follows: at first, the problem is described in detail and the physical parameters are given in Section 2. The derivation of a simplified model which approaches

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the behavior of the current physical system is given in Section 3. The descriptions of the formulation and numerical solution are given in Section 4. Finally, results are presented in Section 5 and the main conclusions extracted from this work are summarized in the final section.

2. Definition of temperature jump problem and physical assumptions

A thermocouple, consisting of two wires of diameter d, is placed inside a nitrogen ambient with a specified pressure p_a, temperature T_a and velocity $\boldsymbol{U}_a$ (Fig. 1). Wire materials were chosen according to the thermocouples used in practice. In particular, type-T (copper-constantan) thermocouples were considered for the most part of this study, but indicative results for a type-K thermocouple (chromel–alumel) are presented as well. Both wires are initially at T_s ($t = 0$) = 293.15 K. The ends of the two wires are welded together to form a thermocouple and no insulation is present around them. The ambient temperature is instantaneously changed from 293.15 K to a value lower than the wire temperature. In this work, the temperature jump is typically 100 K (i.e. $T_a = T_g$ ($t = 0$) = 193.15 K), chosen according to the expected temperature values in applications for our vacuum expansions.

In order to design a three-dimensional model, the geometrical characteristics were expressed as multiples of the diameter d. The dimensions of the nitrogen ambient environment have been selected large enough, such that the imposition of the ambient conditions at the boundary would be justified. The z-dimension was in most cases also reduced in half by taking advantage of the symmetry, except when otherwise noted. An angle $\theta = 6°$ has been selected between the two wires.

The thermal properties of the two solids (density ρ_s, heat capacity $C_{p,s}$ and heat conductivity k_s) do not change more than 10% within the chosen temperature range of 193.15–293.15 K[21,22]. They are assumed to be uniform, isotropic and constant. On the other hand, the thermophysical properties of nitrogen are highly affected[23] and are therefore given here as polynomials of temperature. Even though the temperature drop is relatively large, no phase change takes place in this range. On the other hand, the physical properties of nitrogen are practically independent of pressure within the range of our interest (0.1–1 bar) with less than 0.41% deviation for $C_{p,g}$, μ, k_g and therefore also the Prandtl number Pr. A constant value of 0.72 has been assigned for the Prandtl number of nitrogen. It has been confirmed through simulations that the influence of pressure on the time constant is very weak within this range.

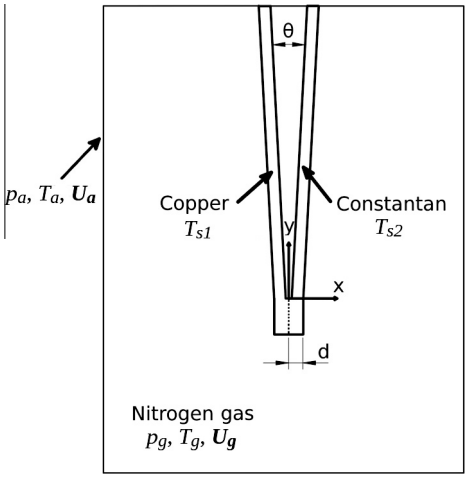

Fig. 1. Geometry of the solid and flow domains. The z-direction is pointed towards the reader. Typically $\theta \approx 6^{\circ}$.

The exact value of the heat transfer coefficient h is generally not known for this configuration. A complete numerical simulation is beneficial since the ambient gas motion and conditions, as well as the precise wire geometry can be taken into account. The Reynolds number was less than 7 as defined by the wire diameter and due to the low velocities. Therefore, turbulence is not included in the system of equations. Our conditions correspond to the regime of low Peclet, where the contributions of advection and diffusion are comparable and simulations are usually required. The maximum Knudsen number for the cases shown below is 0.0051 as defined according to the wire diameter; thus, the flow remains within the viscous regime and no-slip boundary conditions may be applied on the wire walls. The contribution of natural convection effects is negligible, since the Grashof number, expressing the ratio of buoyancy to viscous forces, is less than 10^{-3}. Finally, thermal radiation has been found to have an effect significantly smaller than 1% and has therefore not been included in our formulation.

3. Model derivation

It is often useful to define a simplified model fitting the results, since it may be employed to examine the influence of small changes in our system without performing more simulations. The model used here to fit the results of the temperature evolution is very similar to the well-known Newton's law of cooling. The derivation is based on the assumption that the temperature of both wires is uniform and equal. This is justified by the large values of heat conductivity for the solids and confirmed by simulation results (within 1 K). Furthermore, as noted before, the wire properties remain practically constant within our range of interest for the temperature.

Considering the two wires, the energy equilibrium is:

$$(\rho_{s1}V_{s1}C_{p,s1} + \rho_{s2}V_{s2}C_{p,s2})\frac{dT_s}{dt} = -h(A_{s1} + A_{s2})(T_s(t) - T_a) \tag{1}$$

where ρ_{si}, V_i and $C_{p,i}$ with i = 1,2 are the density, volume and thermal capacity of each material. The symbol A_i denotes the solid surface in contact with nitrogen and h is the heat transfer coefficient. In order to derive a simplified model, we assume that the heat transfer coefficient h is the same for both materials and constant throughout the duration of the flow. By rearranging the terms and integrating, we obtain

$$T_s(t) = T_a + (T_s(0) - T_a)\exp\left[-\frac{h(A_{s1} + A_{s2})}{\rho_{s1}V_{s1}C_{p,s1} + \rho_{s2}V_{s2}C_{p,s2}}t\right] \tag{2}$$

or simply

$$T_s(t) = T_a + (T_s(0) - T_a)\exp\left[-\frac{t}{\tau}\right] \tag{3}$$

where $\tau = 1 / (h\,C)$ is the time constant and the term

$$C = \frac{(A_{s1} + A_{s2})}{\rho_{s1}V_{s1}C_{p,s1} + \rho_{s2}V_{s2}C_{p,s2}} \tag{4}$$

is constant throughout the simulation. In particular, for a type-T thermocouple we may simplify $C \approx 4 \times 10^{-6}/(3d)[s^2K/kg]$ and for a type-K thermocouple $C \approx 9 \times 10^{-6}/(8d)[s^2K/kg]$.Then, we can obtain τ by fitting the simulation data to this expression. The response time can finally be defined as a multiple of the time constant τ.

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