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Assessment of radiation correction methods for bare bead thermocouples in a combustion environment

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A B S T R A C T

The use of bare bead thermocouples for temperature measurement in combustion environments is widespread due to the low cost, robustness and ease of use of such a type of device. It is however well known that temperatures monitored with thermocouples can be significantly affected by radiation errors. This in turn implies to properly estimate the energy losses induced by this phenomenon so as to get a consistent estimate of the true temperature of the investigated medium. The present paper thus aims to rule on the relative efficiency of four different compensation techniques including the electrical compensation (EC), the reduced radiative error (RRE), the extrapolation and the multi-element ones. To do so, an original set of temperature measurements carried out in a fully characterized flat flame reactor has been acquired. The comparison of the above-listed correction approaches has moreover been supported by comprehensive sensitivity analyses dealing with the influence of parameters like the composition of the surrounding atmosphere, the local velocity, the Nusselt number correlation or the emissivity of the thermocouple junction on the predicted radiation corrections. The main conclusions drawn through this study coupling experimental approaches and theoretical calculations show that EC and RRE methods can lead to globally converging trends provided that some thermo-physical parameters integrated into the calculation of the RRE correction coefficient are correctly assessed. The extrapolation approach tends to predict radiation losses similar to those derived from the EC and RRE techniques while the multi-element strategy significantly diverges from the other ones probably due to its very important sensitivity to raw temperature values.

1. Introduction

The quantitative characterization of gas temperature in combustion environments is crucial in many applications insofar as such a parameter is required to monitor the efficiency of industrial combustion processes for instance as well as to derive heat fluxes or kinetic rate parameters from laboratory scale experiments [1]. The use of adapted experimental techniques is therefore of prior importance to get accurate and reliable data in such harsh atmospheres where high thermal gradients and temperature levels can be encountered. Among the different investigation tools available, optical diagnostics are of interest to characterize complex reacting media due to their non-intrusive character allowing disturbance to be avoided in the investigated flows. Such techniques being not within the scope of the present study, however, the reader will thus be referred to reviews from Eckbreth [2] or Khalid and Kontis [3] as examples for further details. That being said, it is worthy to note that the optical accesses needed for the implementation of such diagnostics can hardly be adapted in many industrial systems for feasibility reasons. Furthermore, the deposition of soot or ash is likely to obstruct the visualization windows thus preventing proper measurements to be operated. Optical diagnostics based on Raman and Rayleigh scattering or laser induced fluorescence [2] moreover imply the use of relatively constraining and complex laser emitter-receiver systems. In addition, when temperature profiles must be acquired under or in close proximity of the burning surface of condensed systems, optical diagnostics cannot be used anymore and other measurement devices should then be selected [4].

In this context, thermocouples represent the most widespread

Abbreviations: EC, electric compensation; emissiv., emissivity; FFB, flat flame burner; FFR, flat flame reactor; HAB, height above the burner; inv. method, investigated method; rel. dev., relative deviation; RRE, reduced radiation error; th, thermocouple.

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investigation tool especially due to their low cost, robustness, simple use and ease of installation [1,5]. It is moreover widely assumed that disturbances induced by the introduction of a micro-thermocouple in a flame can be considered as negligible especially when the flow velocity is quite low (Mach number less than 0.1 [6]). Such a hypothesis is nonetheless still subject to some discussions as illustrated in a recent work from Tereshchenko et al. who performed numerical and experimental analyses in a laminar methane flame leading to the conclusion that perturbations of the reacting flows evolving around thermocouples of a few ten of microns in diameter could be non-negligible especially in regions of high thermal gradient as well as in flame areas with high radical concentrations [4,7]. The use of thermocouples also implies to take into consideration that the temperature is measured at the weld of the probe and does not necessarily correspond to the real temperature of the surrounding gases. Obtained data can thus be significantly under-estimated due to inertia and energy loss issues. When temporal accuracy is expected, models based on the lumped capacitance hypothesis [8] allow correcting data from the internal behavior of the thermocouple as a first approach. Assessing temperature with a single sensor is often considered as insufficient however and two- or three-thermocouple investigation techniques are therefore often used to further correct temporal measurements. Such a topic being not directly addressed in the present work, information regarding these elaborated methodologies (described in Refs. [9–11] among others) will consequently not be further discussed in the following. As far as stationary temperature measurement is concerned, referring to the typical steady energy equation of a thermocouple placed into a combustion environment allows giving an overall comprehension of the measurement deviation that can be met. Basically, heat transfers depend on the contribution of convective exchanges induced by the local gaseous flows, thermal losses due to the radiation of the weld and conduction that can occur through the wires [1,6,8,12]. In addition, while platinum and its alloys are generally selected for the wires since they do not alter under oxidative atmospheres, such materials are likely to act as catalysts for exoergic chemical reactions at the bead surface like OH radical recombination which is especially prone to occur in premixed flame configuration [6]. Such an effect can therefore induce systematic errors in measured temperatures if not thoroughly taken into account. In a more general way, it can be considered according to [13] that a certain level of catalytic activity cannot be excluded when a thermocouple is introduced into a chemically non-equilibrium reactive flow.

To prevent any energy loss that would directly impact the acquisition of accurate results, the diameter of the thermocouple weld and wires must be as small as possible to limit surface radiation and conduction (no loss being indeed possible from an ideal zero-dimension diameter thermocouple). Concerning the conduction losses occurring through the wires when they are exposed to a temperature gradient, they can be reduced using an adapted wire length as reported in a work from Heitor and Moreira [6] who especially recommended wire-length-to-diameter ratios greater than 200. Bradley and Matthews [14] suggested for their part a minimum length of 0.125 inch for S-type thermocouples having 0.0005-inch diameter wires. Eventually, a wire-to-cold length ratio higher than 10 has also been reported as a reference criterion in the general review from Shaddix [1]. Concerning the catalytic reactions which may induce extra energy transfers, they can be prevented by protecting the thermocouple with specific coatings. Different types of non-catalytic materials are listed in the review of Heitor and Moreira [6] including silica-based coatings [15], combination of yttrium and beryllium oxides [16] or alumina-based layers [17], the two last ones being more particularly recommended by the above-mentioned authors.

Thus, whilst conduction and catalytic losses can be avoided, radiation remains the most important source of error when measuring the temperature of hot gases. It has been shown for instance in an experimental work from Attya and Whitelaw that errors as high as 250 °C at a temperature level of 1400 °C could be made when performing measurements in a spray flame of kerosene with a 300-μm diameter thermocouple [18]. Different experimental solutions have therefore been developed to reduce the radiative exchange between thermocouples and their surroundings including the use of single- or double-shielded thermocouples as well as the implantation of aspiration techniques [19–22]. The dimensions of the thermocouples can become non-negligible in such cases, however, while aspiration of the gaseous streams can be very disruptive for the investigated reacting flows. Moreover, a fine resolution in space and time cannot be achieved with such devices [22] which are therefore mostly recommended for global temperature measurements. Alternatively, the use of bare bead thermocouples combined with a correct estimation of the radiation bias can be effective to determine the true local temperature when investigating combustion environments. To this aim, modeling procedures based on energy balances integrating the different thermal fluxes listed before [12,14,22] as well as electrical compensation [23–25] or multi-thermocouple methods [26–28] have been proposed.

Among these different approaches, the electrical compensation (EC) technique can lead to a very efficient correction of the thermocouple radiative losses even though it requires a rather significant equipment and relatively complex procedures to be followed [23–25]. Briefly, this method consists in imposing a high voltage alternating electrical current to the measurement probe which is first placed in a vacuum chamber. In this case, convective heat transfers are avoided thus leading to the equality between the energy provided to the thermocouple and the radiation losses. In a second step, the electrically-heated sensor is introduced into the combustion environment to be characterized where both convective and radiative effects are effective. A proper calibration of the radiation losses experienced by the thermocouple can then be operated through a comparison of the temperatures recorded under both vacuum and flame conditions (see Section 3.1 for more details concerning this methodology). Alternatively, Brohez et al. proposed a reduced radiative error (RRE) procedure involving the use of two thermocouples that offers a good compromise between experimental simplicity and efficient radiation correction [26]. The basis of Brohez et al.'s method relies on the fact that a constant RRE coefficient can be deduced from a simple steady-state heat transfer model (including convective and radiative contributions) applied to two bare bead thermocouples made of the same material but showing a diameter ratio comprised between 2 and 3. Temperatures recorded using the two thermocouples can then be corrected from radiation losses calculating this RRE coefficient that directly depends on the composition of the surrounding gaseous environment, on their local thermo-physical properties and on the velocity fields in the measurement region. All these parameters therefore need to be known or estimated prior to be able to assess any adjusted temperature (more information on this approach will be given in section 3.2). Other correction methods are more simply based on energy balances at the bead of the thermocouple. Knowing that an ideal zero-surface thermocouple undergoes no radiation loss as mentioned before, an extrapolation between results obtained with two thermocouples having different diameters allows estimating the true gas temperature [27,29]. Another similar and simple correction procedure can be made using the multi-element method proposed by De [28]. In this case, several thermocouples having different wire diameters are used to measure a given temperature while radiation losses are quantified using an