An Approach to Thermocouple Measurements That Reduces Uncertainties in High-Temperature Environments

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ABSTRACT: Obtaining accurate temperature measurements with thermocouples in flame environments is challenging due to the effects of radiative heat losses, as these losses are difficult to quantify. Efforts to minimize radiative losses by, for example, suction pyrometry often result in a significant sacrifice in spatial resolution. In this work, a new experimental methodology is presented that both minimizes the temperature correction and allows the remaining correction to be accurately quantified. The approach is based on increasing and controlling the convective heat transfer to the thermocouple junction, which is accomplished by spinning the thermocouple at high speed. The rotation yields a large and known convective velocity over the thermocouple. Heat transfer can then be modeled for the thermocouple, and a functional relationship between temperature and rotational speed can be found. Fitting this model to the data allows for an accurate temperature correction. To test the feasibility of the rotating thermocouple technique for temperature measurement in high-temperature gases, experiments were conducted over a range of rotational speeds in a controlled flame where the temperature was known. The measured thermocouple temperatures as a function of rotational speed closely match the theoretical temperatures, yielding a straightforward approach to highly accurate gas temperature measurement. The results also demonstrate limited perturbation to the flow field, even at high rotational speeds. Finally, a method of deconvolution is described that significantly enhances the spatial resolution of the technique, approaching that of a stationary thermocouple.

1. INTRODUCTION

Temperature measurements are ubiquitous in combustion systems. These measurements are useful in a wide range of applications, from laboratory-scale flames to large-scale boilers and furnaces. A variety of methods have been employed for making gas temperature measurements in flames. Broadly speaking, these methods can be classified into optical and probe-based measurements. Though optical approaches to gas temperature measurements provide some advantages over probe-based methods, they are often difficult to implement, can be costly and cumbersome, and are often not effective in particle-laden flames. Thus, probe-based measurements remain the method of choice for many combustion studies.

Among probe-based measurements, thermocouples have gained preeminence because they are inexpensive, robust, and easy to use. Fine-wire thermocouples have been extensively used for flame temperature measurements, and their use has been thoroughly described; unfortunately, these measurements require corrections due to radiative and conductive heat losses.1–6

For fine-wire thermocouples, conduction losses are negligible, and thus it is the radiation correction that presents the most difficult challenge to accurate measurement of gas temperatures. Radiation varies with the fourth power of temperature, so a sharp increase in radiative losses is observed with increasing gas temperature. At the temperatures typically encountered in flame environments the required correction resulting from these losses can be hundreds of degrees.7,8 While the common challenge in laboratory flames is to correct for cooling of the thermocouple due to radiation losses from the thermocouple to the environment, heating of the thermocouple can be significant in the cooler parts of large scale flames where the thermocouple is heated by radiation from hot surroundings such as furnace walls or from soot particle radiation.9

Correcting for radiation losses or gains is complicated by uncertainties in variables such as the convective heat transfer coefficient, the bead size, shape, and emissivity, and the temperature and emissivity of the surroundings. The presence of particles in the flow creates additional challenges. Many simple algebraic models have been developed to correct for radiation losses from the bead,7 and some have been validated using computational fluid dynamics models.9 Radiation gains due to radiation from the environment to the bead are system dependent, and thus no simple models are available for this correction.

One approach to radiation correction that has been extensively discussed is the use of multiple thermocouples (typically two) that are made of identical materials but of different diameters. In this way it is possible to extrapolate to zero diameter,10,11 In unsteady flows the accuracy of this technique is limited by the different time constants of the thermocouples, owing to their different diameters, providing no clear relationship between bead size and temperature, though several frequency-based compensation techniques have been

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suggested.11−14 Additionally, there is a dependence on the geometry and orientation of the thermocouples, which makes it difficult to implement the technique in practical combustion systems.

Perhaps the most widespread industrial approach to addressing the problem of radiation correction is the use of suction pyrometers, otherwise known as aspirated thermocouples, which are designed to minimize radiation losses.8,9,15,16 As the name suggests, suction pyrometers locally extract the combustion gases into a probe. The flow is accelerated within the probe so that when it passes over the thermocouple the convective heat transfer is high and controlled. This high convective heat transfer brings the thermocouple closer to the gas temperature.

Suction pyrometers, however, have important limitations. They rely on extremely high aspiration velocities, often on the order of 150 m/s, to minimize the value of the required correction. This requires suction flow rates on the order of 300 L/min, which results in extremely poor spatial resolution and large disturbances to the flow field. This high sampling volume can also mean that suction pyrometers are impossible to implement in smaller burners. The probes are also large and cumbersome, and can be expensive. Additionally, in particle-laden flows, clogging is a problem, as the molten ash can deposit on surfaces.17 Finally, the measurement may be affected by the orientation of the probe, and the probe has a very large time constant due to the shields,1 making the measurements slow and cumbersome. For example, even at an extremely high aspiration velocity of 250 m/s and an ambient temperature of 1600 °C, the probe can take up to 3 min to reach equilibrium temperature, and an estimated 1 min for a 100 °C increase in temperature.18

Blevins and Pitts8,17 showed that an aspiration velocity of as low as 5 m/s is usually a significant improvement over an open thermocouple measurement, but operation at this low velocity will result in high required corrections. For example, when the true gas temperature is 927 °C and the surroundings are at room temperature, the temperature measured with a 1.5 mm thermocouple will increase sharply from 450 to 730 °C when the aspiration velocity is increased to 5 m/s, but will not approach the true gas temperature until the aspiration velocity is increased to 200 m/s.8,11 illustrating the diminishing value in operating at higher aspiration velocities.

The present study seeks to introduce a new experimental methodology to minimize radiation and conduction losses and to avoid sacrificial determinations of temperature correction, and to do this without the level of sacrifice to spatial and temporal resolution that is inherent in aspiration thermocouple measurements. This is achieved by means of a high-speed rotating thermocouple (RTC), which ensures a high and quantifiable convective heat transfer, thereby minimizing the effects of radiation and conduction and ensuring an accurate correction. To the best of the authors’ knowledge, thermocouple rotation or translation have not been previously used to reduce the required radiation correction or to obtain accurate radiation corrections. A detailed description of the methodology and experimental system follows.

2. DESIGN CONSIDERATIONS

Figure 1a shows a thermocouple in a flow of hot gas in an enclosure. A simple steady-state heat balance for this thermocouple bead, as shown in Figure 1b, is given by

\[ \dot{Q}_{\text{conv}} + \dot{Q}_{\text{cond}} + \dot{Q}_{\text{rad}} = 0 \]  

(1)

[Diagram showing thermocouple in flowing gas and heat balance]

Convection can either heat or cool the bead, depending on whether the bead is cooler or hotter than the gas, respectively. The bead can lose heat by conduction through its wires, and gain or lose heat through radiative exchange with its surroundings. If the temperature of the surroundings, \( T_{\text{surf}} \), is lower than that of the thermocouple bead, \( T_b \), the net radiation heat transfer will be from the bead to the surroundings. In practice, the emissivities of the surroundings and the bead can be difficult to accurately predict. The emissivity of the surroundings is system-dependent, and in particle-laden flows, it can be particularly difficult to calculate, as it will depend on the temperatures and the emissivities of the particles throughout the entire flow field. In addition, the emissivity of the bead can change due to exposure to the flow, as it can undergo chemical changes or be coated with soot or ash.

The convective heat transfer can be expressed simply by Newton’s law of heating/cooling and is equal to the product of the temperature difference between the gas and the bead, the convective heat transfer coefficient, \( h \), and surface area, \( A_{\text{surf}} \). The conductive heat loss is directly proportional to the temperature gradient across the wire, given by \( \Delta T \), the cross-sectional area of the wire, \( A \), and the thermal conductivity of the thermocouple material, \( k_b \).

The net radiative heat flux entering or leaving the thermocouple depends on the temperatures of the thermocouple and the surroundings, the emissivity of the thermocouple, \( \varepsilon_b \), and the emissivity of the surroundings, \( \varepsilon_{\text{surf}} \). For illustrative purposes, we will assuming that the absorptivity and emissivity of the thermocouple are equal (Kirckoff’s law) and that the emissivity of the surroundings is unity. Using these assumptions and the above simplifications, eq 1 can be expanded and rewritten as

\[ h(T_g - T_b) + \varepsilon_b\sigma(T_b^4 - T_w^4) + \left( \frac{k_b A}{L A_{\text{surf}}} \right) \Delta T = 0 \]  

(2)

Rearranging eq 2, we get

\[ T_g = T_b + \varepsilon_b\sigma(T_b^4 - T_w^4) + \left( \frac{k_b A}{h L A_{\text{surf}}} \right) \Delta T \]  

(3)
The second term on the right side of eq 3 represents a correction or inaccuracy due to radiative and conductive heat losses. Increasing the value of the convective heat transfer coefficient, \( h \), minimizes the value of the correction. The value of \( h \) can be calculated from the Nusselt number, which is a function of the Reynolds number and Prandtl number. A generalized form for the Nusselt number is given by

\[
Nu_0 = C Re^m Pr^n = hD/k_g
\]  

(4)

The constants \( C \), \( m \), and \( n \) vary for different thermocouple geometries, Reynolds numbers, and gas compositions. Solving eq 4 for \( h \) and plugging into eq 3 yields

\[
T_g = T_b + \frac{\epsilon_b \sigma (T_b^4 - T_w^4) + (k_g A/\text{LA}_{\text{surf}}) \Delta T}{C Re^m Pr^n (k_g/D)}
\]  

(5)

Equation 5 contains a number of terms that are difficult to accurately quantify in laboratory- and industrial-scale flames. The uncertainties in the emissivities of both the surroundings and the bead have already been discussed. The gas properties, such as the Prandtl number and \( k_g \), are dependent on temperature and composition, which are typically unknown. The Reynolds number is dependent on the local gas velocity over the thermocouple bead, \( V_g \), which is also typically unknown. Moreover, in a turbulent system, \( V_g \) fluctuates, further complicating interpretation since the heat balance becomes an unsteady problem and the thermal mass of the bead becomes important.

While inherent uncertainties in thermocouple measurement can exist (for example, from installation errors of the thermocouple, signal errors in the transmission wires, analog-to-digital (A/D) conversion, and conversion to temperature from voltage), these uncertainties are typically small for flame temperature measurements and can often be ignored.

Many of the challenges associated with thermocouple measurements in flames can be circumvented if the thermocouple is rotated at high speed, as will be explained below. The linear speed of the bead, \( V_{rel} \), is a function of the rotational speed, \( \omega \), and, if the rotational speed is fast enough that the surrounding gas velocity is small compared to \( V_{rel} \), then \( V_{rel} \), the total relative velocity between the bead and the gas, can be approximated by

\[
V_{rel} \approx \frac{2\pi \omega r}{60}
\]  

(6)

where \( r \) is the radius of the circular motion of the thermocouple, as shown in Figure 2. Here \( r \) is a design parameter and dictates how rotational speed translates into linear speed. This demonstrates one of the benefits of spinning the thermocouple: while the gas velocity over a thermocouple is typically unknown, spinning the thermocouple at sufficiently high speeds removes this uncertainty since the gas velocity over the thermocouple can be determined from the known rotational speed of the thermocouple.

Combining eqs 5 and 6, we obtain

\[
T_g - T_b = \frac{\epsilon_b \sigma (T_b^4 - T_w^4) + (k_g A/\text{LA}_{\text{surf}}) \Delta T}{C(2\pi D \rho/60 \mu \alpha)^m Pr^n (k_g/D)}
\]  

(7)

Equation 7 provides us with a functional relationship between the rotational speed, the diameter of the thermocouple, \( D_b \), and the correction. The denominator varies as \( \alpha^n \), indicating that as the rotational speed is increased, the magnitude of the correction is decreased. The exponent \( m \) is typically around 0.5. This demonstrates a second important benefit of spinning the thermocouple: the large relative velocity of the gas over the thermocouple leads to an increase in the convective heat transfer coefficient, which decreases the radiation and conduction corrections.

To gain an appreciation for the magnitude of the effect of spinning for realistic values of rotational speed and bead size, the following assumptions are made. A flame temperature of 1500 °C is used, and \( r \) is assumed to be 12 mm. The gas properties are evaluated at 1500 °C and are assumed for nitrogen since a large fraction of the combustion gas is typically nitrogen. The kinematic viscosity, \( \nu \), is taken to be 27.5 × 10^{-5} m^{2}/s, the thermal conductivity, \( k_g \), to be 0.09 W/m-K, and the Prandtl number to be 0.73. The temperature of the surroundings, \( T_s \), is taken to be 300 K. An emissivity of 0.1, that of uncoated platinum, is assumed for the thermocouple bead, and conduction losses are neglected.

In Figure 3, the normalized bead temperature, \( T_b^* \), defined as the ratio of the thermocouple bead temperature \( T_b \) to the true gas temperature \( T_g \) in °C, is plotted as a function of rotational speed.

\[
T_b^* = \frac{T_b}{T_g}
\]

(8)

Figure 3. Normalized temperature, which is the ratio of the thermocouple bead temperature, \( T_b^* \), to the true gas temperature, \( T_g \) (both in °C), plotted as a function of rotational speed.

3. EXPERIMENTAL SECTION

A schematic of the system is shown in Figure 4. A hollow shaft made of 347 stainless steel is fitted with a platinum–platinum/rhodium 10%
(Type S) thermocouple. The dimensions of the shaft are 12.7 mm outer diameter, 3.18 mm inner diameter, and 165 mm length. The diameter of the thermocouple wire is 0.13 mm, and the diameter of the bead in these experiments is 0.20 mm. The wire diameter chosen represents an optimum, as it is significantly more robust than finer wire thermocouples while also being thin enough to minimize conduction losses. Tests were also conducted with a 0.05 mm diameter thermocouple, and stroboscopic measurements revealed that the thermocouple maintained its shape and did not deform while being spun. Nonetheless, wire wires of this size are not robust. Since the primary drawback of the larger wire size is the larger corrections due to radiation and conduction, which this work seeks to address, most experiments were conducted with the larger wire size of 0.13 mm diameter.

The thermocouple wire is housed inside an alumina ceramic tube. The wires protrude 14 mm from holes in the ceramic tubing and are bent at nearly right angles to the longitudinal axis of the shaft, thereby creating a radius of 14 mm. This radius represents somewhat of an optimum. A smaller radius would require a higher rotational speed to create the same velocity, while a larger radius represents a larger sampling area and reduced spatial resolution.

The shape of the thermocouple bead more closely resembled a cylinder than a sphere, though it was not perfectly cylindrical. As will be shown, with the RTC it is not necessary to know the exact shape of the thermocouple.

The shaft is mounted to an AC motor that is equipped with a variable speed control, and the rotational speed can be varied from 0 to 23 000 rpm. The rotational speed is measured using a noncontact laser tachometer. The low-voltage thermocouple signal is transmitted by a computer, where it is recorded in a temperature measurement system, for example in a furnace, these parts would need to be cooled to ensure that the temperatures of these components are never too high. In particular the stainless rod, which must protrude into the flame region and the premixed system, can be neglected here because the thermocouple was in the post-flame region and the premixed system was operated with a fuel-lean stoichiometry.

The RTC assembly was mounted such that the plane of rotation for the thermocouple was parallel to the surface of the flat-flame burner. In other words, the bead was a fixed height above the burner head during its rotation. However, the McKenna burner is not truly one-dimensional, as temperature gradients exist along the surface of the burner. To address this and ensure that the gas temperature along the path of the spinning thermocouple was nearly constant, a portion of the burner that displayed minimal temperature variations was identified and used. This is important because when the thermocouple rotates it traces out a circumference of 88 mm. For the region of the burner that was used, a temperature variation of 35 ± 5 °C was observed for the three flames that were used in this study. To obtain the average thermocouple temperature over this circumference, stationary temperature measurements were taken at 44 points along the circumference, with each measurement 2 mm apart, and the average of these measurements was computed. A radiation correction was then performed on this average temperature to yield the average gas temperature $T_{gas}$ along the path of the thermocouple bead.

Additionally, a control thermocouple was constructed of Pt 30% Rh–Pt 6% Rh (Type B) alloy, with 0.20 mm bead diameter. This thermocouple was placed in the flame at the same height as the RTC ±1 mm, but at a distance of 5 mm from the RTC at its closest location during rotation. This second thermocouple was used to evaluate the effect of flame perturbation caused by the high-speed rotation, and the data were recorded simultaneously with the RTC as part of the same experiment, also at a sampling rate of 2 Hz.

The stainless steel supporting rod and motor, shown in Figure 4, were not cooled in this experiment because the heat from the combustion products could be easily shielded from the rod and other components, so that the temperatures were never too high. In larger scale systems, for example in a furnace, these parts would need to be cooled to ensure that the temperatures of these components are never too high. In particular the stainless rod, which must protrude into the flame, would need to be shielded, e.g., with a water jacket, to keep it from warping.

The slip-ring bearings exhibited frictional heating. This heating led to predictable errors in the signal, which were on the order of 7 °C at 10 000 rpm, and virtually nonexistent below 5000 rpm. The error was corrected for by using a calibration.

4. RESULTS

Photographs of the RTC were taken at various rotational speeds and are shown in Figure 5. The photograph in Figure 5a was taken with an aperture setting larger than that for subsequent photographs to clearly illustrate the flat flame and the relative position of the RTC. The photographs in Figure 5b–d were taken with a smaller aperture setting to avoid saturation and clearly show differences in the brightness of the...
RTC with rotational speed. The increased brightness of the RTC at 7000 rpm over that at 3000 rpm is clearly visible.

To accurately quantify the dependence between the bead temperature and the rotational speed, separate flames were produced, each with a different equivalence ratio. The thermocouple was rotated at a range of rotational speeds between 0 and 10,000 rpm and allowed to come to steady state at each speed. The signal was averaged over 10 s to reduce noise, and these values are shown in Figure 6 along with a curve-fit of the data. The fluctuation in temperature at each speed was minimal, on the order of 1 °C. The fluctuation in temperature, along with other uncertainties, such as errors in the thermocouple calibration, are included in the error bars.

An important goal of this work is to validate the RTC technique, and to do this the gas temperature was obtained for a stationary thermocouple. For this particular burner, the gas velocity can be accurately predicted, because the burner mass flow rate is known and the flow rate exiting the burner is nearly uniform. Thus, a rather accurate temperature correction can be made for the stationary thermocouple, and this radiation-corrected temperature is a reference gas temperature, \( T_g^{\text{ref}} \), that can be compared to the curve-fitted gas temperature for the RTC, \( T_g^{\text{RTC}} \). In Figure 6, \( T_g^{\text{ref}} \) is shown as the horizontal dashed line.

To obtain the gas temperatures from the curves, no assumptions were needed as to the thermocouple shape and geometry. The gas properties are assumed to be those of air at 1350, 1300, and 1240 °C, respectively; \( r/L \), the inverse aspect ratio, was measured to be \( \sim 0.005 \); and the emissivity of the thermocouple bead is assumed to be 0.1, that of uncoated platinum. The data were fitted to the general form for the Nusselt number given in eq 4, and yielded the following values for the fitting constants: \( C = 0.6, m = n = 0.5 \), and \( Pr = 0.69 \), which are consistent with values reported in the literature. The quality of the fit is illustrated by \( r^2 \) values of 0.99, 0.99, and 0.95, respectively, for the three data sets. It is important to note that the values for \( C \), \( m \), and \( n \) obtained represent actual experimentally obtained constants and are thus more accurate than just pulling these values from the literature for idealized systems (e.g., by assuming spherical or cylindrical bead shapes).

For the RTCs the relative velocity of the gas over the thermocouple bead was obtained from rotational speed, neglecting the actual gas velocity since it was small compared to rotational velocity.
to the velocity of the bead, except at lower rotational speeds (<3000 rpm). Conduction losses are negligible here because of the high aspect ratio of the thermocouple wire. The gas temperatures obtained from curve-fitting the RTC data, \(T_{g,RTC}\), at the three different equivalence ratios (1, 0.85, 0.7), are within 7, 17, and 1 °C, respectively, of the values obtained from the radiation-corrected stationary thermocouple data \(T_{g,ref}\). These results are summarized in Table 1.

<table>
<thead>
<tr>
<th>(\Phi)</th>
<th>(T_{g,ref} (°C)^{a})</th>
<th>(T_{g,RTC} (°C)^{b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>1347</td>
<td>1340</td>
</tr>
<tr>
<td>0.85</td>
<td>1301</td>
<td>1284</td>
</tr>
<tr>
<td>0.70</td>
<td>1234</td>
<td>1235</td>
</tr>
</tbody>
</table>

\(^{a}\)Obtained from radiation correction to stationary thermocouple measurement. \(^{b}\)Obtained by curve-fitting RTC data.

Table 1. Radiation-Corrected Gas Temperatures and Gas Temperatures Predicted with RTC

5. DISCUSSION

**Validity of the Technique.** The result shown in Figure 5 demonstrate the dynamics of the RTC: increasing rotational speed yields an increase in bead temperature due to the increase in convective heat transfer and thus reduction in radiation correction. Increasing convection to reduce the radiation correction is analogous to what is done in a suction pyrometer. However, if the technique simply relied on high convection, then the accuracy would be severely limited, as even at rotational speeds as high as 10 000 rpm the corrections vary in space along the path of the thermocouple. If the RTC were allowed to reach steady state at each angle \(\theta\) along the circumference, then it would measure the temperature \(T_{b,\theta}\) (\(\omega = 0\)). This is represented by the solid curve in Figure 7b. When \(\omega\) is greater than zero, the RTC temperature lags behind the stationary temperature due to the thermal mass of the thermocouple bead and the resulting time constant of the RTC. This flattens the \(T_{b}\) curve, the extent (0.13 mm), and at rotational speeds of 10 000 rpm, the Reynolds number is around 30, resulting in a relatively thin boundary layer and a small flow perturbation.

More saliently, the high-speed rotation controls and defines the local velocity, and therefore the local convective heat transfer coefficient can be accurately predicted. The minimal number of assumptions that are required to yield good curve fits suggests the ability to accurately predict gas temperature with low uncertainty. The value of gas temperature predicted by the RTC is within 17 °C of \(T_{g,ref}\). Additionally, the values of the fitting parameters correspond very well to values reported in the literature, and this serves as further validation of the fitting technique. It is highly likely that the curve-fitted value is, in fact, more accurate than \(T_{g,ref}\) since \(T_{g,ref}\) was obtained from a radiation correction that required an assumption about bead shape and the functional form of the Nusselt number correlation. Moreover, this accuracy is virtually impossible to attain with a suction pyrometer because the flow rates do not approach infinity, the gas sample volume is large, and the measurement times are long.

**Spatial Resolution.** The improvement in spatial resolution of the RTC over the suction pyrometer represents a significant advantage of the technique. Furthermore, to increase the accuracy of \(T_{g,RTC}\) the rotational speed can be increased, but when this is done the circumference over which the RTC averages the temperature (i.e., the spatial resolution) does not change. This means that there is no trade-off between accuracy and spatial resolution in the RTC. This is not the case with the suction pyrometer: the accuracy of the measurement increases with the amount of gas aspirated into the suction pyrometer, but the spatial resolution is worse. Suction pyrometer velocities can be as high as 200 m/s, leading to poor spatial resolution.

**Averaging over the Circumference Traced Out by the Rotating Thermocouple Bead.** The RTC measures an average temperature in space and time. Figure 7a shows the circle traced out by an RTC with a rotational radius \(r\) rotating at a speed \(\omega\) in an arbitrary stationary temperature field. An illustration of the instantaneous temperature of the bead is shown in Figure 7b. The temperature field is shown to be varying in space along the path of the thermocouple. If the RTC were allowed to reach steady state at each angle \(\theta\) along the circumference, then it would measure the temperature distribution \(T_{b,\theta}\) (\(\omega = 0\)). This is represented by the solid curve in Figure 7b. When \(\omega\) is greater than zero, the RTC temperature lags behind the stationary temperature due to the thermal mass of the thermocouple bead and the resulting time constant of the RTC. This flattens the \(T_{b}\) curve, the extent

![Figure 8. Schematic of deconvolution operation. The coordinates \(x_1\) and \(y_1\) represent arbitrary points in a 2-D plane with a temperature distribution \(f(x_1,y_1)\). The rotation of the thermocouple results in a circularly swept region, represented by the circles, and a measured temperature \(g(x_1,y_1)\).](Image 376x636 to 495x740)
to which is dictated by the time constant, \( \tau_b \), at a given \( \omega \). As \( \omega \) is increased, \( T_{b,\theta}(\omega) \) further flattens out, as shown in Figure 7b by curves \( T_{b,\theta}(\omega_1) \) and \( T_{b,\theta}(\omega_2) \).

Table 2 shows the relative magnitude of the RTC time constant, \( \tau_b \), and the time taken to traverse the circle at two rotational speeds of interest, for a range of bead diameters. It is apparent that at rotational speeds of 5000 and 10 000 rpm, \( \tau_b \) is much longer than the time it takes to traverse the circumference one time, and thus, at sufficiently high rotational speeds, the measured bead temperature is the average temperature across the circumference.

If the temperature field that the RTC is spinning in experiences a change on a time scale that is significantly longer than \( \tau_b \) then it can completely capture this change, as a normal nonrotational thermocouple would. Similarly, if the temperature field changes on a time scale that is significantly shorter than \( \tau_b \), then the RTC would not be able to capture these changes. If the change were on the order of the time-constant of the thermocouple, then the rotation would average the measurement in both space and time.

**Deconvolution To Improve Spatial Resolution.** We have shown that the RTC measures an averaged temperature \( T_{b,\theta} \) for practical rotational speeds and RTC time constants. Thus, the spatial resolution of a single RTC measurement is dictated by the region that is swept out by the RTC. However, when the RTC is traversed across a given temperature field the actual temperature field is contained within the convolved temperature field. Thus, deconvolution of this field can yield an increase in spatial accuracy. Below we construct a methodology by which the RTC measurements in a temperature field can be deconvolved to yield spatial resolution approaching that of the diameter of the thermocouple bead.

We consider the RTC as a system, the original temperature field as the input of the system, and the measured temperature field as the output of the system. The RTC system is described by its impulse function, which is defined as the output of the system with the input being a Dirac delta function at the origin of the space. We denote the impulse function of the RTC system as \( h \), the original temperature field as \( f \), and the measured temperature field as \( g \). These are illustrated in Figure 8. Then, according to the theory from ref 25, we have

\[
g = f \ast h
\]

where the asterisk denotes the operation of convolution. In order to determine the original temperature distribution \( f \) from the measured distribution \( g \), we need to solve an inverse problem of eq 9, or in other words a deconvolution problem.

Assume the radius of an RTC to be \( r \). Suppose that the investigated temperature field is on a two-dimensional plane. For any point \((x_i,y_i)\) on the two-dimensional plane, we denote the original temperature as \( f(x_i,y_i) \) and the measured temperature of the RTC as \( g(x_i,y_i) \). Thus, \( g(x_i,y_i) \) is the average of \( f(x,y) \), where \((x,y)\) is \( r \) away from \((x_i,y_i)\), or in other words the average temperature on the circle centered at \((x_i,y_i)\) with radius \( r \). As the RTC sweeps across the two-dimensional plane, as represented by the dotted circles in Figure 8, we record the circle average as our measured temperature at the center of the circle.

Since the temperature field is continuous, the average along a circle is in fact an integral in mathematics, which makes the inverse problem intractable to solve. For convenience, we approximate the temperature field as a discrete grid with each block in the grid taking as its value the average temperature over the area it covers. (Note that the size of a block determines the resolution of the discretization.) Then, we can replace the original coordinates of a point \((x,y)\) with a two-dimensional integer block index \((m,n)\), which makes the temperature distribution appear in the format of a matrix. Also, the measured temperature at a block \((m_n)\) is approximated as the average temperature over blocks that are intersected by the circle centered at the center of the block \((m_n)\) with radius \( r \). Since the temperature field is discretized, the number of intersected blocks is finite, and thus the average is simply an arithmetic average, instead of an integral. Let \( N \) be the number of intersected blocks, then the impulse function of the RTC system can be approximated as a matrix where those intersected

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**Figure 9.** Results of deconvolution simulation: (a) original temperature distribution, (b) measured temperature distribution from the RTC measurement, (c) deconvolved temperature distribution, and (d) distribution of error, in °C, after deconvolution operation.
### Table 3. Summary of Advantages and Disadvantages of Various Thermocouple Measurements of Flame Temperature

<table>
<thead>
<tr>
<th></th>
<th>fine-wire thermocouple</th>
<th>suction pyrometer</th>
<th>high-speed RTC</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td>high</td>
<td>moderate</td>
<td>very high</td>
</tr>
<tr>
<td>Minimizes radiation losses, though they may still be present.</td>
<td></td>
<td>Inaccuracies of hundreds of °C can persist, even with high-speed aspiration.</td>
<td>Can fit data to theory to get true gas temperature.</td>
</tr>
<tr>
<td><strong>Spatial Resolution</strong></td>
<td>very high</td>
<td>poor</td>
<td>high</td>
</tr>
<tr>
<td>Limit of resolution is surface area of fine-wire thermocouple, on the order of $10^{-9}$ m$^2$.</td>
<td></td>
<td>Can be on the order of 1 m$^2$; significant trade-off between increased accuracy and spatial resolution.</td>
<td>Can deconvolve measurements to achieve spatial resolution approaching that of stationary thermocouple. No trade-off between accuracy and spatial resolution.</td>
</tr>
<tr>
<td><strong>Temporal Resolution</strong></td>
<td>extremely high</td>
<td>very poor</td>
<td>high</td>
</tr>
<tr>
<td>Owing to small mass of thermocouple; time constant on the order of 50–100 ms.</td>
<td></td>
<td>Due to presence of shields; time constant on the order of minutes.</td>
<td>Time constant is higher than that of fine-wire thermocouple, but RTC also averages over space and time, so temporal resolution is not as high as that of fine-wire thermocouple.</td>
</tr>
<tr>
<td><strong>Mechanical Integrity</strong></td>
<td>very poor</td>
<td>moderate to high</td>
<td></td>
</tr>
<tr>
<td>Extremely fragile.</td>
<td></td>
<td>Due to presence of shields.</td>
<td>Thermocouple wire diameter is larger than that of a fine-wire thermocouple and can be shielded, but not completely enclosed like suction pyrometer.</td>
</tr>
<tr>
<td><strong>Time To Take Measurement</strong></td>
<td>very low</td>
<td>very high</td>
<td>very low</td>
</tr>
<tr>
<td>Due to presence of shield.</td>
<td></td>
<td>Due to presence of shield.</td>
<td></td>
</tr>
<tr>
<td><strong>Maintenance</strong></td>
<td>very high</td>
<td>anticipated to be low</td>
<td></td>
</tr>
<tr>
<td>Fragility causes frequent breakage, particularly in particle-laden flows.</td>
<td></td>
<td>Due to clogging.</td>
<td></td>
</tr>
</tbody>
</table>
blocks or elements take the value of $1/N$ and the others take the value of 0.

After discretization, $f$, $g$, and $h$ all become two-dimensional matrices. Considering the structural similarity between a matrix and an image, we apply to our problem a deconvolution algorithm developed for image recovery. Deconvolution is frequently used in image recovery, and some popular deconvolution algorithms are introduced in ref 26. We solve our problem using the constrained least-squares (regularized) filtering algorithm, which has a corresponding built-in function named “deconvreg” in MATLAB (The Mathworks, Natick MA).

Figure 9 shows the results of the deconvolution simulation. In Figure 9a, a temperature distribution is assumed between 20 and 1000 °C over a two-dimensional plane that is 100 mm × 100 mm. The plane is then discretized with each grid square measuring 1 mm × 1 mm. An RTC with rotational radius 10 mm, chosen for computational convenience, is then swept across the plane in both the x- and y-directions, with each new RTC measurement centered at the next grid point. This “measured” distribution, $g(x,y)$ is shown in Figure 9b. The deconvolution operation is then applied to the measured distribution in Figure 9b and yields a deconvolved temperature distribution, shown in Figure 9c and aimed to approximate the original temperature distribution in Figure 9a.

The deconvolved distribution is in excellent agreement with the original distribution. The RMS error of the deconvolved distribution is 0.37 °C, while the RMS error of the measured distribution is 24 °C. The distribution of this error for the deconvolved distribution is shown in Figure 9d.

Required Modifications for Use in Industrial Systems. This work represents a proof-of-concept for the RTC technique; however, in order to be viable for use in for industrial-scale, particle-laden flows, a number of design modifications are required. In order to obtain temperatures inside of a combustion chamber the probe would need to be cooled with, for example, a cooling jacket to protect the probe from the high-temperature environment. A cooled extension to support and move the probe would be required as well. Finally, in order to protect the RTC from excessive particles, a particle shield would be required. The particles, having a high Stokes number, would strike the shield, leaving a particle free region in the wake of the shield, while the gases would flow around the shield. The shield would need to be spaced sufficiently far from the thermocouple to ensure that the gas temperature is not affected by the presence of the shield. These discussions are summarized in Table 3.

6. CONCLUSIONS

In this work, the challenges associated with making accurate temperature measurements with thermocouples in radiating flame environments are summarized, as are the limitations of techniques currently in use. A rotating thermocouple method is presented that seeks to alleviate many of the inaccuracies that limit thermocouple temperature measurements. An experimental system was constructed to test the ability of a RTC to make accurate flame temperature measurements. Data collected between 0 and 10 000 rpm were fitted to a general functional form derived for the RTC, and the results demonstrate that the RTC can be used to obtain highly accurate gas temperatures. Gas temperatures measured with the RTC data were within ±17 °C of the temperatures measured by a radiation-corrected fine-wire thermocouple, well within the margin of error for such a measurement. Radiation-corrected fine-wire thermocouple measurements can be highly accurate, but they are subject to uncertainties associated with the local flow characteristics and the thermocouple shape. The RTC technique does not require this information, and obtains the unknown heat transfer parameters by fitting the data to the well-known functional form for the thermocouple temperature corrections, thus yielding high-temperature accuracy. The spatial resolution of the measurement, while significantly superior to that of a suction pyrometer, is not as good as that of a single fine-wire thermocouple, as there is spatial averaging associated with rotation at high speeds, dictated by the radius of rotation of the thermocouple. A deconvolution technique is presented in this work to yield significant improvements in spatial resolution, approaching, but inferior to, the resolution of a fine-wire thermocouple. The device can be used in large flames, but it can also be used in smaller flames, as low as 5 kW, which are too small for a suction pyrometer.

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The authors declare no competing financial interest.

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■ NOMENCLATURE

$A = \text{area (m}^2\text{)}$
$D = \text{diameter (m)}$
$h = \text{convective heat transfer coefficient (W/m}^2\text{-K)}$
RTC = \text{rotating thermocouple}$
$L = \text{length (m)}$
$Q = \text{heat flux (W)}$
$r = \text{radius (m)}$
$T = \text{temperature (}°\text{C)}$
$V = \text{velocity (m/s)}$
$\omega = \text{rotational speed (revolutions per min, rpm)}$
$\sigma = \text{Stefan–Boltzmann constant (5.67051 \times 10^{-8} W/m}^2\text{-K}^4)}$
$\varepsilon = \text{emissivity}$
$k = \text{thermal conductivity (W/m-K)}$
$\mu = \text{dynamic viscosity (kg/m-s)}$
$\rho = \text{density (kg/m}^3\text{)}$
$t = \text{time (s)}$
$\tau = \text{time constant (s)}$
$b = \text{bead (thermocouple bead)}$
$g = \text{gas}$
$s = \text{surface}$
$w = \text{wall}$
$\text{Dimensionless Numbers}$
$Bi = \text{Biot number}$
$Nu = \text{Nusselt number}$
$Pr = \text{Prandtl number}$
$Re = \text{Reynolds number}$
REFERENCES


