ABSTRACT

The current work is the first in a series of investigations to develop a method for high-temperature thermometry of gaseous flows using thermocouple pairs with disparate convective properties to infer the contribution of radiation. Two thermocouples of deliberately dissimilar bead geometry are placed side-by-side in a flow while the two beads are heated by surface radiation. Their dissimilar responses to radiation cause a predictable divergence between the two temperature measurements.

The current approach improves upon others found in literature owing to its in-situ measurement for convection coefficients rather than dependence on empirical estimation. Each bead is deliberately overheated, and the time constant of the thermal decay back to equilibrium indicates the intensity of convection. Here, we perform this measurement in air while varying velocity, duration of overheat, and intensity of overheat. We compare the calculated temperature correction against the known air temperature.

Heat transfer through the probe wires to the ceramic probe support was found to have a strong effect on the correction, although corrected values were always closer to the actual gas temperature than the original uncorrected value. In conditions of mild radiation loading, the effect was sufficiently symmetric between the two beads to allow effective correction. All measurements indicated that if additional information about the probe body temperature was collected in addition to the thermocouple measurements, the correction could be improved significantly.

1 Introduction

1.1 Background

Following a flurry of research in the early twentieth century, it had become clear that certain persistent errors in thermocouple measurements of gas temperatures were due to heat transfer from radiation [1]. Radiation to or from the surroundings drove the thermocouple temperature away from the gas temperature by hundreds of Kelvin [2] [3, pp.263].

In high-temperature applications where radiation effects are believed relevant, it is common practice to place the thermocouple element in an environment where its surroundings can be relied upon to be at the same temperature as the surrounding gases. In the simplest cases, this is done by shielding the element with some vented material whose outer surface will tolerate radiation without severely affecting its inner temperature. In a more complex approach, a suction pyrometer is used to actively sample gases. Both of these approaches have implications on probe size and cost, leading some researchers to compensate for rather than minimize radiation error.

A clever design by Daniels [4] probably represents the first practical effort towards electrical radiation compensation. He used multiple probes of carefully chosen wire diameters to cancel the components of thermo-electric emf generated by incident radiation. While quite appropriate for the open air measurements for which his probe was intended, the cluster of probe elements formed a measurement region greater than one inch in size. In addition to forming a substantial disturbance to many flows of engineering relevance, the probe size proves a serious limitation.
since the compensation relies on all probe elements experiencing the same radiation and gas temperatures.

Around the same time, Bradley and Matthews were attempting an analytical method for correcting a single probe [5] for radiation when surroundings are assumed cool. More recent works applied to compartment fires have attempted to establish a correction by examining the difference between two probes of dissimilar size [6]. One experiment enhanced convection by deliberately moving the probe [7]. Arguably the strongest effort to characterizing heat transfer to these probes in recent years has been motivated by the desire to obtain high frequency measurements. To that end, substantial effort has been expended using the convection properties in a model for a thermocouple’s transient response [8–11]. Motivated by the study of turbulence in engines, these authors used the dynamic response of dissimilar thermocouples to reconstruct signal content at frequencies much faster than the beads themselves could respond.

All of these works leverage some kind of assumption with regard to the gas properties and probe emissivity in order to evaluate the thermal balance between radiation and convection. In the case of Daneils’s electrically compensated probe, the emissivity and gas properties are assumed unchanging [4]. The works of Heitor et. al. and Tagawa et. al. rely on correlations produced by Collins and Williams [12], Brohez et. al. and Krishnan use Whitaker’s correlations [13], and Krishnan also examined Hilpert’s [14] and Churchill and Bernstein’s [15] studies on spheres. Miles and Gouldin compare transient response data against several of these sources with favorable results for Collins and Williams.

The 1959 correlation by Collins and Williams seems to be the most practically conceived correlation for accurately predicting convection for wires in air treated here. It comes as little surprise, therefore, that so many engineering authors have adopted it. However, the corrections depend on accurate values for the sensor’s emissivity, and the kinematic viscosity, thermal conductivity, and bulk velocity of the surrounding gases. Even if the velocity is known, the gas and emissive properties present a substantial problem.

The emissivity of popular thermocouple materials have been studied by a number of authors. Examination of the emissivities of platinum thermocouples [16] [17, pp.9], and type K thermocouples [18, 19] reveal drastic inconsistencies. In the extreme case of Alumel, emissivities have even been reported from .012 to .98. Perhaps the best insight is derived from Harvey, Forrest, and Clark’s [18] comparison of type K materials at various levels of surface oxidation, revealing that in addition to the typical temperature dependencies authors report, these metals increase emissivity manyfold with increasing levels of oxidation.

The presence of water, carbon dioxide, and other important combustion products are certain obscure the gas properties downstream of the reaction zone. At comparable temperature and pressures, steam has a viscosity roughly half that of air [20, pp.146] [21, pp.59], and a Prandtl number near 0.9 [20, pp.148] to air’s 0.7. The problem is further complicated at sufficiently high temperatures, where gases can be made to dissociate [22], making heat transfer characteristics difficult to approximate accurately.

1.2 Approach

In the present work, no attempt is made to construct a probe with well behaved heat transfer characteristics, nor are a-priori assumptions made regarding the probe’s geometry, the gas composition, gas properties, or bulk velocity. Instead, the probe construction is simple and robust as opposed to the Y-supported butt-welded wires common to the studies cited above, and all attempts to approximate heat transfer characteristics theoretically are abandoned for an in-situ empirical approach.

When working with analytically compensated probes, we are bound to determine the convection coefficient between the probe elements and the gas. In the present work, we propose doing so by overheating the probes in-situ and observing the following relaxation. In this way, we relate parameters that can be reliably determined a-priori (like the probe’s thermal capacitance) to the convection coefficient in the experiment.

The present work is the first of a series of experimental efforts designed to support the method. Here, a pair of dissimilar thermocouples are driven from the ambient air temperature by momentary application of radiation. Observation of the beads’ transient responses allows us to deduce the beads’ convection coefficients, and observation of the beads’ steady state deviation from the ambient air temperature allows us to test the validity of the analytical correction. Future work will build upon knowledge gained in this controlled environment to optimize the probe, add a more practical method for in-situ overheating, and extend the method into a practical turbomachinery application. The reconstruction of the probes’ dynamic responses is not in the scope of the current investigation.

2 Formulation

When conduction along the leads is neglected, the heat transfer to a thermocouple bead can be modeled as

\[
m_c \frac{dT_i}{dt} = A_i h_i (T_g - T_i) + A_i \varepsilon_i (q_{\text{rad}} - \sigma T_i^4) .
\]

Here, \(m\), \(c\), and \(A\) are the mass, specific heat, and surface area of the bead. The heat transfer is characterized empirically by the convection coefficient, \(h\), and surface emissivity, \(\varepsilon\). The subscript, \(i\), indicates that a property is specific to a thermocouple among an array of thermocouples. The remaining temperatures are of the gas, \(T_g\), and radiation loading from the surround-
ings, \( q'_{\text{rad}} \), in power per unit area. The Boltzman constant, \( \sigma \), is \( 5.67 \times 10^{-8} \text{W m}^{-2} \text{K}^{-4} \).

### 2.1 Time Constant

In response to a small temperature perturbation, the thermocouple will relax back to its steady temperature, \( T_i \), with a time constant

\[
\tau_i = \frac{m_i c}{A_i (h_i + 4 \sigma \varepsilon T_i^3)}
\]  

Equation 2 can be derived by applying a small-amplitude perturbation analysis of equation 1.

Of course, the mass of the probe will be proportional to the bead volume. So, we define the effective thermal diameter of the probe based on a sphere that would have the same volume-to-area ratio

\[
D_i = 6 \frac{V_i}{A_i}
\]  

Writing the bead mass in terms of the volume and density, \( \rho \), produces an expression for \( \tau_i \) in terms of parameters that are all easily observed except \( h_i \).

\[
h_i = \frac{D_i \rho c}{6 \tau_i} - 4 \sigma \varepsilon T_i^3
\]  

Therefore, provided \( \tau_i \) can be measured, it is possible to obtain \( h_i \).

Table 1 shows values for \( \rho \) and \( c \) for some selected thermocouple materials. The ranges presented here reflect the variation in the properties over the temperatures at which the original authors studied the materials. The table presents approximate equivalent values for the weld by performing an average near the center of the valid temperature range; weighted by the mass of the metal in the constituent alloy.

In the current work, type K is used, but future studies are likely to involve type B. The type K effective thermal density \((\rho c)\) used in this study is 4.33MJ/Km\(^3\).

### 2.2 In Equilibrium

When a two-thermocouple probe is in thermal equilibrium, equation 1 becomes a system of algebraic equations that can be formed by considering each bead,

\[
0 = T_g - T_1 + \frac{\varepsilon_1}{h_1} (q''_{\text{rad}} - \sigma T_1^4)
\]

\[
0 = T_g - T_2 + \frac{\varepsilon_2}{h_2} (q''_{\text{rad}} - \sigma T_2^4)
\]

We refer to \( T_g \) as the corrected gas temperature. The voltages measured from the thermocouples provides a direct indication of their bead temperatures, \( T_1 \) and \( T_2 \), but due to radiation, they need not equal their surroundings. It is the purpose of this work to remove the effect of radiation loading, \( q''_{\text{rad}} \), and provide an approximation for \( T_g \) more accurate than if we simply trusted the thermocouples directly.

For this method to be applicable, there are a number of requirements

- The thermocouples must have sufficiently dissimilar convection coefficients to break the symmetry of equations 5 and 6.
- Convection coefficients and emissivities must be known with sufficient accuracy to render the correction useful.
- The two beads must be placed such that their effective radiation loading per unit area is the same.
- The frequency content of the temperature signal must be slower than the time constant of the slowest (largest) bead to apply a steady state assumption.

Provided these needs can be addressed by the probe design

<table>
<thead>
<tr>
<th>Component metal property values</th>
<th>Density</th>
<th>Specific Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>kg/m(^3)</td>
<td>J/kg/K</td>
</tr>
<tr>
<td>Alumel</td>
<td>8,600(^1)</td>
<td>504-573(^2)</td>
</tr>
<tr>
<td>Chromel-P</td>
<td>8,730(^1)</td>
<td>431-528(^2)</td>
</tr>
<tr>
<td>Platinum</td>
<td>21,450(^3)</td>
<td>131-166(^3)</td>
</tr>
<tr>
<td>Rhodium</td>
<td>12,414(^3)</td>
<td>247-339(^3)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Approximated bead values</th>
<th>Density</th>
<th>Specific Heat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Units</td>
<td>kg/m(^3)</td>
<td>J/kg/K</td>
</tr>
<tr>
<td>Type K</td>
<td>8,665</td>
<td>500</td>
</tr>
<tr>
<td>Type B</td>
<td>19,800</td>
<td>160</td>
</tr>
<tr>
<td>Type R</td>
<td>20,900</td>
<td>150</td>
</tr>
<tr>
<td>Type S</td>
<td>21,000</td>
<td>150</td>
</tr>
</tbody>
</table>

\(^1\)From the alloy data sheets \[23\]
\(^2\)At temperatures from 360 to 760K \[24\]
\(^3\)At temperatures from 300 to 1000K \[17\]
and placement, the gas temperature can be computed explicitly

\[ T_g = \frac{h_1T_1 - h_2T_2}{h_1 - h_2} + \frac{\sigma(T_1^4 - T_2^4)}{h_1 - h_2}. \]  

(7)

The relationship simplifies yet further if the two probe emissivities are similar enough to be assumed identical.

\[ T_g = \frac{h_1T_1 - h_2T_2}{h_1 - h_2} + \frac{\varepsilon\sigma(T_1^4 - T_2^4)}{h_1 - h_2}. \]  

(8)

### 2.3 Heat Transfer to the Wires

A wire of diameter, \( d \), and length \( L \), suspended in space from either end will be subject to a partial differential equation along its length, \( x \),

\[ \rho C \frac{dT}{dt} = k \frac{d^2T}{dx^2} + \frac{4h}{d}(T_g - T) + \frac{4\varepsilon}{d}(q_{rad}^T - \sigma T^4). \]  

(9)

Nondimensionalization of this equation reveals the length scale

\[ L = \sqrt{\frac{dk}{4h}}_{wire}. \]  

(10)

Wire lengths much longer than \( L \) will thermally isolate the bead from the probe, while wire lengths much shorter than \( L \) will place the two in excellent thermal communication. In this way, we may define a dimensionless parameter,

\[ \lambda = \sqrt{\frac{4L^2h}{dk}}_{wire}. \]  

(11)

which we use to quantify the beads’ isolation from the probe. It is important to distinguish \( h \) and \( k \) as the convection coefficient for the cylindrical wire and the conductivity of the metal respectively; lest they be mistaken for properties of the bead and air. We also note that \( h \) changes with the operating conditions, so that the probe does not have any intrinsic value for \( \lambda \).

### 3 Experiment

The purpose of the experiment is to create a controlled environment to first calibrate the characteristics of each of the beads of the two-bead probe, and then test the two-bead probe method. The beads, placed in a flow of known temperature and velocity, are subjected to a radiative heat source in the form of one or two heat lamps. In all cases the initial conditions are collected before the heat source is applied. When the heat source is suddenly removed, the bead temperatures decay back to the initial conditions. The response of the beads to this heat perturbation across a range of convective cooling flows allows characterization of the bead thermal behavior. The thermocouples’ response to deliberate radiation loading is used to assess the correction’s potential for application in a high temperature environment.

#### 3.1 Apparatus

The apparatus is fed by compressed air, dried to a dew point of 3°C. Flow through the experiment was controlled with a metering valve and characterized by measuring the mass flow rate with a thermal mass flow meter. Air flow is conditioned in a low-velocity chamber filled with small beads, evened by multiple orifice plates, rendered irrotational by a honeycomb, and further evened by two fine mesh screens. Finally, a converging section minimizes boundary layer effects before delivering the conditioned flow to the test section shown in Figure 1. The temperature of the flow just upstream of the test section is measured with a Type K thermocouple. The test section is essentially a free turbulent jet, thus the test section containing the probe exists at ambient pressure.

The probe is positioned in the centerline of the flow with the two beads side-by-side (perpendicular to the flow) as shown in the test section setup, Figure 2. This probe location allows ample optical access for the application of radiation loading. Flow rate, flow temperature, and ambient pressure were monitored and collected continuously throughout each experiment in addition to the probe’s two bead temperatures.

#### 3.2 Probe Construction

The current probe body was constructed using a 3.175mm diameter, four-hole ceramic rod. Two separate Type K thermocouples were built with deliberately dissimilar geometries. The larger bead was made from 0.254mm wire and a resulting bead of approximately 1.0mm; the smaller bead was made with 0.127mm wire and a resulting bead of approximately 0.37mm. The two beads were secured within the ceramic rod and wired into a double bracket composed of two standard Type K thermocouple connections. The complete probe is shown in Figure 3 and a detail of the actual thermocouple bead end of the probe is shown in Figure 4.

### 4 Analysis and Results

#### 4.1 Calculating Time Constant

The time constant of each bead was assessed in each test by the linear decline of the thermocouple temperature on a semi-log plot. The raw mV voltages were cleaned by a 95.2ms rolling
average. Because an offset frustrates attempts to put a curve fit on an exponential decay, the thermocouple measurements were subtracted by the average of their first two seconds of data.

Windows over which decays were to be found were identified by scanning for a falling edge at half the peak voltage. The window began at the point at which bead 2 (the larger of the two) reached 95% of the local maximum. The window for each bead was terminated when the voltage declined below 25% of the local peak or 4 times the noise floor; which ever came first. Figure 5 shows a single test condition with multiple decays.

The time constant was assessed by linear regression of the log of the voltage. All data have $R^2$ values better than 0.999. For any test with multiple decays, each time constant measured was recorded, but their average was reported for the test.

At air velocities between 3.2 and 16 m/s, the smaller (.37mm) bead exhibited time constants from 0.28s to 0.72s and the larger (1mm) bead ranged from 0.99 to 2.4s. Convection coefficients were calculated from equation 4 by neglecting radiation. Values ranged roughly from 300 to 1000 W/m$^2$/K.

### 4.2 Performing the Correction

In the current experiment, the probes are kept at a temperature sufficiently low to ensure that emission is irrelevant, even when radiant heat is imposed deliberately. Therefore, equation 8 can be further simplified to

$$T_g = \frac{h_1 T_1 - h_2 T_2}{h_1 - h_2}. \quad (12)$$

At higher probe temperatures, equation 8 should be used.

Because small disagreements in the bead calibrations can be misinterpreted as radiation error, it will improve the quality of the correction if any offsets are removed so that they are in agreement in the absence of radiation. In the measurements presented here, data were adjusted by about .4 degrees Celsius to correct for a disagreement between the beads.

Figure 6 presents an example correction. The figure shows the corrected gas temperature and beads in initial agreement at the actual air temperature, $T_{air}$. The sudden rise and divergence in the thermocouples' temperatures occurs when the radiation is imposed several seconds into the test. The blue curve is the bead-1 (.37mm diameter) temperature, and the red curve is the bead-2 (1mm diameter) temperature. The black curve is $T_g$ from equation 12, computed from the time constants observed in the same plot. The actual air temperature is unchanged by the application
FIGURE 4. A picture of the two Type K beads at the end of the 3.175mm four-hole ceramic two-bead probe. The large and small beads are approximately 1mm and 0.35mm, respectively.

FIGURE 5. An example experimental measurement produced with a lamp producing overheat. Blue data are from the small bead, and red data are from the large bead.

FIGURE 6. Corrected temperature with long-duration single lamp heating and with air velocity 15m/s. All temperatures are initially at the air temperature, and loading is applied about 5 seconds into the test.

FIGURE 7. Corrected temperature with long-duration single lamp heating and with air velocity 3.5m/s.

of radiation, so comparison of the black curve ($T_g$) against its value before the application of radiation gives an excellent indication of the correction’s success.

We see confirmation that there is a substantial difference between beads’ response to radiation, and that the correction converges quite close to the actual air temperature once the initial dynamics have decayed.

4.3 Quantifying Error

Figure 7 shows a test with a single lamp at relatively low air velocity. The gas temperature has been under-corrected in this case, and there is also a slow background rise in the large bead (red) temperature that would seem to suggest tertiary heating (neither lamp nor air).

The severity of the phenomenon can be exaggerated by deliberately increasing the radiation loading. Figure 8 shows a test with two lamps applied to the probe, resulting an an over-correction and a more noticeable background rise in the large bead (2) temperature.

Of course, the model on which the correction is predicated assumes that only radiation and convection play a role in the
bead temperatures. However, in the name of developing a post-processing method that can be applied to a ruggedly constructed probe, we have tolerated lead lengths that are quite short (about 4mm).

Because the bead diameter and wire diameters are scaled similarly, errors induced by conduction seem to affect the beads somewhat symmetrically. Figure 9 shows the convection coefficient of the two beads compared while performing the above experiment with long (more than 20s) and short (roughly 5s or shorter) durations; with one and two heat lamps focused on the probe; and with air velocities between 3.2m/s and 16m/s. The level of bead-to-bead consistency across the range of conditions measured encourages the conclusion that both beads are subjected to the same thermal processes.

To quantify the thermal isolation between the beads and the probe body, we estimate $\lambda$ (equation 11) by approximating the convection coefficient for the wires as that of a cylinder. Hilpert’s correlation for a cylinder in air of these Reynolds numbers predicts

$$h_{\text{wire}} = 0.6064 \frac{k_{\text{air}}}{d} \left( \frac{ud}{v_{\text{air}}} \right)^{0.466}$$  \hspace{1cm} (13)

Our approach for estimating the properties of air are described in section 4.4 below.

When we compute a value for $\lambda$, we will consider the worst (smallest) case, which is represented by the large diameter wire and the most conductive of the two metals. The larger bead is constructed from $d = 0.254$mm diameter wire, and between alumel and chromel, the higher conductivity is about $k = 300$W/m·K. We approximate the free hanging lead length to be about $L = 4$mm. Values range from about 0.55 to 0.83, confirming that the beads are not well isolated from the probe holder.

Since the small bead temperature represents the best measurement available without a correction, a fractional error for each test can be determined by comparing the error in $T_1$ to the error in the corrected gas temperature, $T_{g}$. The actual air temperature, $T_{\text{air}}$, is obtained from the stable thermocouple measurements in the seconds prior to the application of the radiation.

$$\text{error} = \frac{T_{g} - T_{\text{air}}}{T_{1} - T_{\text{air}}}$$  \hspace{1cm} (14)

Figure 10 shows the resulting fractional correction error for all long duration tests versus $\lambda$. In all tests, the temperature values were averaged for roughly one second immediately prior to the end of overheating.

At low radiation loading, the result shows between 50% to 75% reduction in radiation error at low $\lambda$ that steadily improves as the flow rate increases $\lambda$. Heavy radiation loading, on the other hand, produces substantial over-correction at low $\lambda$, which improves somewhat but never vanishes at higher $\lambda$. Figure 9 shows a mildly asymmetrical effect from radiation intensity that would seem to be to blame for the reduced performance in high loading cases.

Observe that the denominator of equation 12 depends on the difference between $h$ values, which may only be one or two hundred W/m²·K. Fractional errors in differences of $h$ may be three or four times their the fractional errors of $h$.

In all tests conducted, the correction was more accurate than the uncorrected measurements. Tests with a single lamp show reduction in error (relative to the smaller bead) of 50% to 75% for
the worst cases, and better than 95% for the best cases. While the duration of a test seems to have little impact when the radiation loading is light, shorter tests show a significant improvement. The worst tests with dual lamps show 100% over-correction at low flows with improvements at intermediate flows.

4.4 Dimensionless Behavior

The physical phenomena that impact the correction performance are even more readily observed by inspecting the dimensionless heat transfer characteristics of the beads. Figure 11 shows all tests’ Nusselt numbers plotted against Reynolds numbers in comparison with that of a sphere and cylinder. Triangles represent long heating duration while circles represent brief heating. Points with solid color represent experiments conducted with two lamps and empty points were conducted with a single lamp or a torch.

The Nusselt number was calculated from the convection coefficient computed from the measured time constants and the conductivity of air using Collins and Williams’ correlation [12] (valid up to 218 degrees Celsius).

\[ Nu_i = \frac{h_i D_i}{k} \]

\[ k(T) = 0.0241 \frac{W}{mK} \left( 1 + \frac{0.00317}{C} - \frac{2 \times 10^{-6}}{C^2} \right) T^2 \]

The Reynolds number was calculated using the kinematic viscosity for air, using Southerland’s equation as extolled by Montgomery [25].

\[ Re_i = \frac{U D_i \rho(T,p)}{\mu(T)} \]

\[ \mu = \mu_{ref} \frac{T_{ref} + T_S}{T + T_S} \left( \frac{T}{T_{ref}} \right)^{3/2} \]

\[ \rho = \frac{p}{RT} \]

For air, Montgomery recommended values \( \mu_{ref} = 1.8325 \times 10^{-5} \text{kg/m/s}, T_S = 120^\circ\text{C}, T_{ref} = 296.15\text{K}, R = 2871/\text{kg/K}. \)

Nusselt numbers for a cylinder (solid) and sphere (dashed) are calculated from the correlations of Hilpert [14] and Whitaker et al. [13] respectively.

The eye can identify several important patterns. The most obvious; the breadth of scatter is inconsistent with the linear behavior exhibited by the same data on Figure 9, and the rate of heat transfer out-paces what one would expect from a similarly sized cylinder or sphere. This is the most substantial evidence yet that there is a tertiary heat transfer process that affects both beads (almost) equally.

The second and more subtle trend; the larger bead (2) seems to form two distinct lines depending entirely on the duration but not the intensity of heating. The same trend is present in the smaller bead (1), but it seems weaker, and it is compounded by a sensitivity to the intensity of heating (number of lamps). This slight dissimilarity between their responses is the dark/light shift in slope from Figure 9.
These behaviors are completely consistent with thermal interaction with the probe holder. Heat lost through the wires to the massive probe body would artificially accelerate the thermal decay of the beads above that of the ideal cylinder or sphere. Furthermore, long duration heating would more effectively heat the probe body, slowing the rate of cooling through the leads, which we observe in Figure 11.

It may be added that buoyant effects (free convection) can be completely neglected. Collins and Williams found in their study of thermocouples, that when the cube of Reynolds number is in excess of the Grashof number, buoyancy effects are irrelevant [12]. The Grashof number, given in equation 20, uses acceleration due to gravity, \( g \), and fluid expansion coefficient, \( \beta \), to determine the impact of buoyant forces relative to viscosity.

\[
Gr = \frac{g \beta (T_i - T_e) D_i^3}{\nu^2}
\]  

Equation (20)

Not only are the lowest Reynolds numbers orders of magnitude stronger than buoyant effects, a close examination of the data presented here reveals no trend between \( Nu \) and \( Gr \).

5 Conclusions

The proposed steady-state radiation correction was tested in flows at ambient temperatures. Tests with mild radiation loading were corrected with a 50% to 95% reduction in error. Tests with heavy radiation loading showed poorer performance; overcorrected to as much as 100% of the original radiation error. The corrected gas temperature exhibited a time constant equivalent to the slowest of the two beads, which was on the order of 1 to 2 seconds.

Heat transfer through the probe wires to the ceramic probe support was found to have a strong, disruptive effect on evaluation of the convection coefficients. In conditions of mild radiation loading, the effect was sufficiently symmetric between the two beads to allow effective correction results. At ambient conditions (when emission from the probe is not important) this approach may prove satisfactory for a number of applications. At elevated temperatures, where the rate of convection must be considered in balance with radiation, numerical accuracy of the convection coefficients will be more important.

This presents two possible paths; (1) measurements employing this approach may resume the typical practice of employing long-lead probes, or (2) a third bead could be added in deliberate contact with the probe body, and the third measurement would allow the elimination of the third unknown; the probe holder temperature. The latter approach is attractive for probe simplicity and robustness, and will be the focus of the authors in future works.

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REFERENCES


