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Gas temperature imaging using the heated grid technique with adaptive background correction

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Abstract

The “heated grid” technique can be used to measure fluid temperature distributions in gaseous flows. A wire is electrically heated and an infrared camera records images of its surface temperature distribution as it is exposed to the local fluid environment, providing a means to acquire spatial temperature profiles in a single image. This is relevant in the studies of coherent turbulent flow structures where spatial correlations have to be analyzed.

Careful calibration is necessary to separate the different thermo-physical effects affecting the wire temperature. The infrared signature of the wire is influenced by thermal radiation of the background, an error source which becomes particularly prominent if the overall scene varies after calibration. In this paper, we introduce a special background correction technique which represents a substantial improvement to the original heated grid technique.

1. Introduction

Infrared (IR) thermography (IRT) is an optical, usually nonintrusive measurement technique. Compared to probe based techniques, such as thermocouples, IRT provides much higher spatial resolution. It is therefore often used in situations where temperature distributions are of interest. Other quantities may be derived from these measurements, such as heat flow rates. These types of measurements are, however, limited to wall surface measurements.

Flow fields may be analyzed using IRT if molecules are present in the flow that either emit or absorb IR radiation (e.g. [1]). However, plain air, as used in many applications such as wind tunnels, does not meet this requirement. Therefore, to combine the large resolution of modern IRT cameras with the interest to measure flow features in air, some workarounds have been proposed.

By inserting a high emissivity mesh into the flow (e.g. Anderson et al. [2], Burch et al. [3]), IRT can be used to measure temperature distributions in flow fields. In the past, different materials, such as paper screens, have been used (e.g. Cehlin et al. [4]), but some of them are not well suited for hot gas flow measurements. In order to overcome these shortcomings, Neely [5] defined the mesh characteristics rendering a mesh resistant to high temperatures.

In order to measure temperature distributions transverse to the main flow direction, one has to be careful about blockage and/or the influence of the mesh on the flow characteristics. The need to reduce intrusivity leads to the idea to use heated wires. Organized in loops, the wires allow mapping of temperature distributions along lines (e.g. Gartenberg and Roberts [6]). Following this idea, Gallo et al. [7] presented and validated the heated grid technique by measuring temperature profiles in a free hot jet. However, the thermal radiation of the background, which can vary in space and time, influences the IR signature of the wires. This represents a considerable error source. A special background correction technique, coping with this problem, is presented in this paper.

2. Overview of the heated grid technique

The probe wire used in the experiment is a 0.4mm NiCr wire coated with a high emissivity paint. Applying electric power Q_{el} to the wire will cause it to dissipate this power according to Joule’s law and to heat up. The resulting local temperature of the wire T_w is then a function of the local cooling effect of the surrounding flow as well as the radiative heat loss. The convective cooling is characterized by two parameters, the local fluid temperature T_f and the local heat transfer coefficient h. In order to determine these two quantities, two measurements with the wire at two different heating levels are required under the assumption of a near-steady flow state.

An energy balance for the wire at two heating levels (in the following denoted with subscripts $(.)_1$ and $(.)_2$) gives the two following equations:

$$Q_{el,1} = h(T_{w,1} - T_f) + \sigma\varepsilon(T_{w,1}{}^4 - T_{amb}{}^4) \tag{1}$$

$$Q_{el,2} = h(T_{w,2} - T_f) + \sigma\varepsilon(T_{w,2}{}^4 - T_{amb}{}^4) \tag{2}$$

T_{amb} denotes an ambient temperature, which is the temperature of the laboratory. Combining Eqs. (1) and (2), one can solve for the h, which gives

http://dx.doi.org/10.21611/qirt.2014.067

$$h = \frac{Q_{el,1} - Q_{el,2} + \sigma\varepsilon(T_{w,2}{}^4 - T_{w,1}^4)}{T_{w,1} - T_{w,2}} \tag{3}$$

This expression is independent of the ambient temperature. Inserting this result in either one of the two energy balance equations, e.g. using Eq. (1), the local fluid temperature is obtained.

$$T_f = \frac{\sigma\varepsilon(T_{w,1}^4 - T_{amb}^4) - Q_{el,1}}{Q_{el,1} - Q_{el,2} + \sigma\varepsilon(T_{w,2}^4 - T_{w,1}^4)} \cdot (T_{w,1} - T_{w,2}) + T_{w,1} \tag{4}$$

In order to obtain the local wire temperature, it is necessary to relate the wire IR signature to the corresponding wire temperature T_w. In order to detect the wire in the IR camera image, it should be sufficiently hot, generating sufficient contrast with respect to the background. The wire can then be identified as a line of locally 'hottest' pixels. (It should be noted, however, that the wire can also be cooler than the background. The only requirement to be met is that there is sufficient contrast to identify the wire.)

Because the wire image may be larger than a single pixel and may not be perfectly aligned with the camera's pixel grid, the wire signature may extend over neighbouring pixels as well. The total signal can still be captured by summing up the hottest pixel and its neighbours perpendicular to the wire. Denoting the pixel identified as the locally hottest pixel with I_{max}, the sum is given by

$$S = I_{\max-1} + I_{\max} + I_{\max+1} \tag{5}$$

Figure 1 illustrates this summing process of pixels containing the wire. This integral wire signature can be correlated to the temperature of the wire, which is measured separately during calibration with an independent technique, e.g. with thermocouples. The correlating function is subsequently used to calculate the wire temperature from an IR image. This standard calibration technique was presented in [7].

However, the procedure becomes unreliable when calibration and subsequent measurements are performed with different thermal background signatures. The reason is that the background radiation is part of the signal used in finding the wire temperature correlation. To solve this problem, an extension to the heated grid technique has been suggested [8] and will be outlined here.

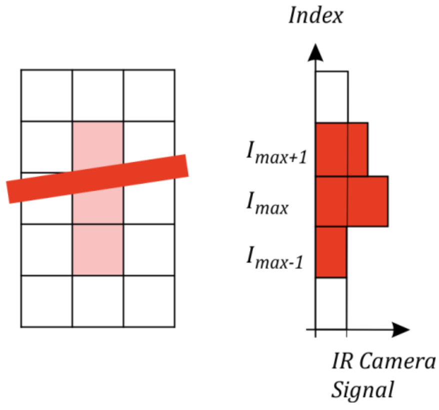

Fig. 1. *Summation over 3 pixels. I_{max} denotes the maximum intensity pixel.*

3. Adaptive background correction for the heated grid technique

3.1. Background subtraction

The summation over pixels recording the image of the wire and its immediate neighbourhood is necessary to acquire the total signal independent of alignment issues. But this will lead to problems, when the background changes between calibration and measurement. To eliminate the background falsely contributing to the wire signal to be evaluated, the background should be subtracted.

http://dx.doi.org/10.21611/qirt.2014.067

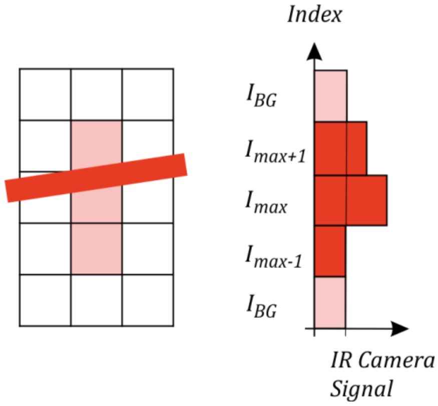

Fig. 2. *Location of the pixels used to estimate the background signal I_{BG}.*

Pixels that are known not to show the wire can provide an estimate of the background signal. In a simplified model, a locally constant background signature I_{BG} is assumed. A reasonable estimate for I_{BG} is obtained as the average of two background pixels lying close to the wire, but nevertheless sufficiently far away. Figure 2 shows the location of these pixels. (If the characteristics of the background are known also more complex models could be employed). The background estimate obtained in this way can then be used to effectively remove the background contribution I_{BG} from the sum S over the pixels with a wire contribution and obtain a signal I_w that depends only on the wire temperature. Eq. (5) can be rewritten in terms of the different contributing signals as

$$S = I_{\max-1} + I_{\max} + I_{\max+1} = \kappa \cdot I_w + (3-\kappa) \cdot I_{BG} \qquad (6)$$

κ is the ratio of projected wire diameter and the pixel size ("fill factor"), i.e. it indicates how much of a camera pixel is covered by the wire image. κ is a geometric quantity and depends on the distance between camera and wire and the lens used. Its value can be determined in a second calibration step explained in the following.

While retaining the wire at a constant temperature, i.e. constant I_w, two images with different background radiations I_{BG} are recorded, giving:

$$S_1 = \kappa \cdot I_w + (3-\kappa) \cdot I_{BG,1} \qquad (7)$$

$$S_2 = \kappa \cdot I_w + (3-\kappa) \cdot I_{BG,2} \qquad (8)$$

The two sums can be subtracted to eliminate the wire contribution, while the ratio κ still appears in the equation. Since the two background signals are known, κ can be calculated, yielding:

$$\kappa = 3 - \frac{S_2 - S_1}{I_{BG,2} - I_{BG,1}} \qquad (9)$$

. With κ known, the wire signal I_w can finally be extracted from the measurements taken during the original temperature calibration, as can be seen in Eq. (10).

$$I_w = \frac{S}{\kappa} - \left[\frac{3}{\kappa} - 1\right] \cdot I_{BG} \qquad (10)$$

Correlating this wire signal to wire temperature yields a function generally valid independent of the background. This allows measurements in situations where the background temperature changes over time.

3.2. Fill factor κ as distance dependent quantity

As mentioned in the previous section, κ depends on the distances between camera, wire and the lens used while acquiring images. It is the ratio of projected image on the camera sensor to pixel size of the sensor. Using the thin lens formula from geometric optics, found e.g. in [9], the relationship between wire diameter and projected wire diameter can be given as:

http://dx.doi.org/10.21611/qirt.2014.067

$$\frac{D_p}{f} = \frac{D_w}{d - f} \tag{11}$$

D_w denotes the true wire diameter, D_p its projection on the camera sensor, d the distance between lens and wire and f the focal length of the lens. The 'pixel fill factor' κ is the ratio of D_p and the pixel size Δp, which is camera specific. With all values being constant except the distance d, κ can be written as:

$$\kappa = \frac{D_p}{\Delta p} = \frac{f \cdot \frac{D_w}{d-f}}{\Delta p} = \frac{C}{d-f} \tag{12}$$

With a value κ_0 known at a distance d_0 from calibration measurements, the value of κ can be calculated at arbitrary distances d with the following expression:

$$\kappa = \kappa_0 \cdot \frac{d_0 - f}{d - f} \tag{13}$$

This further generalization of the heated grid technique removes the constraint to perform the calibration at the same distance between camera and wire as used during measurements.

4. Results

The infrared camera used for all measurements presented in this paper is a CEDIP Jade III camera. It is sensitive in the 3 µm to 5 µm range. The raw images sent by the camera are preprocessed on a computer. Non-uniformity correction is applied and bad pixels are replaced.

In order to find the value of κ for a given wire and distance, a hot plate is placed behind the wire as a variable background. The temperature of the hot plate is held constant by a controller.

Figure 3 shows the measured wire signal I_w plotted against the measured background signal I_{BG}. The wire is not heated electrically, but is in thermal equilibrium with the surrounding laboratory having an almost constant temperature. It can be seen, that the recovered wire signal stays almost constant and does not depend on the background radiation from the hot plate.

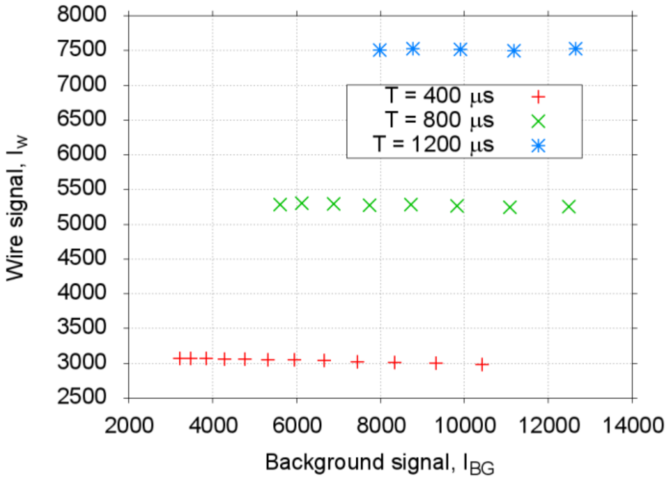

Fig. 3. *Wire signals I_w obtained at different background levels I_{BG}.*

In Figure 3 the results are shown for three different integration times of the camera. The lowest values of each wire signal series represent the signal recorded at ambient temperature. The upper boundary represents the saturation limit of the camera.

Figure 4 shows the wire signal recovered from a measurement where the thermal background is modulated by a stripe pattern alternating between high and low brightness regions. In this case the wire is heated by a hot jet, which makes it well visible in the left part of figure 4. The sum S, the estimated background contribution I_{BG} and the resulting

http://dx.doi.org/10.21611/qirt.2014.067

wire signal I_w are shown in the right part of figure 4. As can be seen, the wire signal shows no dependency on the change in background radiation following the correction step.

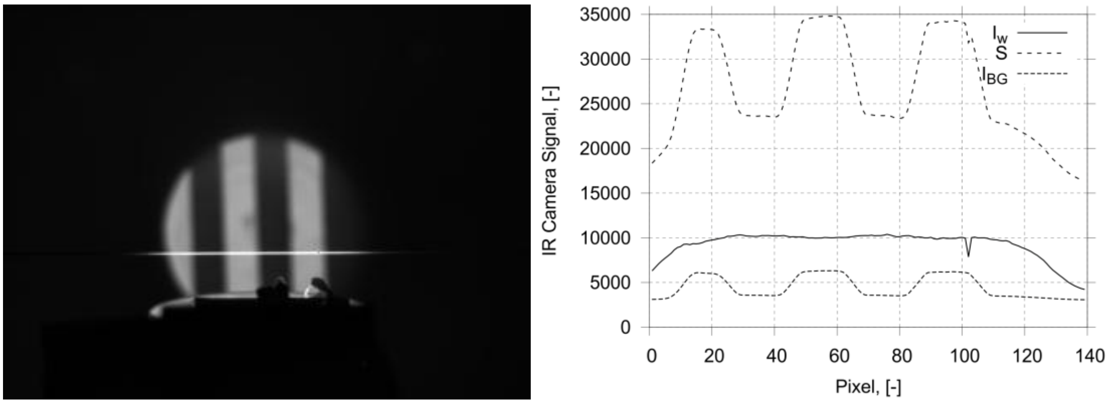

Fig. 4. *Original IR image (left) and the wire signal I_w recovered from it (right).*

Figure 5 finally shows three measurements where the distance between camera and wire is changed. For every distance, two images with different background temperatures are recorded. Thus the value of κ can be determined from the image pair at every distance. Taking then the first value of κ (1.325 [-] at 0.5 [m]) as reference, the values of κ are extrapolated for the other distances using Eq. (13). It can be seen that the calculated values of κ fit well with the values obtained evaluating the IR images.

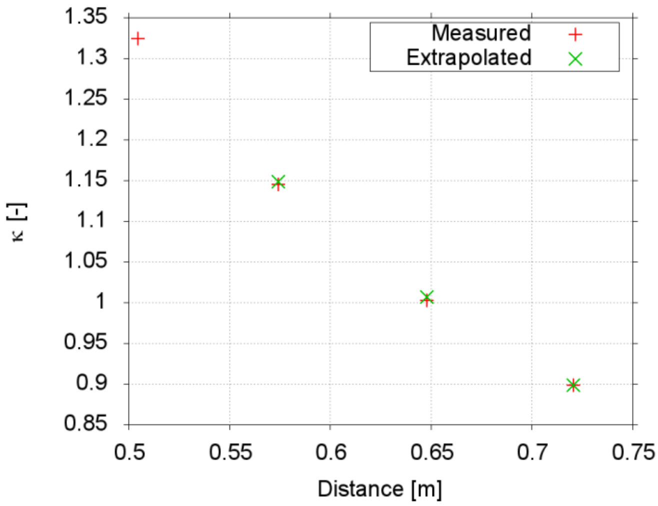

Fig. 5. *Values of κ plotted against distance.*

5. Conclusions

An improvement to the heated grid technique has been presented. It renders the measurements independent of the background and allows for different measurement distances. This reduces the calibration effort, because conditions during calibration can differ from those met during subsequent measurements. The presented results demonstrate that subtraction of the background enables proper measurements of the wire signal. They further show that the distance can be varied after calibration without affecting the results.

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