Comparison of Infrared and Background Oriented Schlieren Techniques for Air Flow Temperature Measurements

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ABSTRACT

Air flow temperature measurements for natural convection over a horizontal heated plate using Background Oriented Schlieren and two quantitative infrared imaging techniques are performed to compare the accuracy, spatial resolution and simplicity of implementation. The first infrared technique, which can be called infrared thermography of optically thin media, is based on observation of a distant screen with known temperature through the investigated air flow. Due to high sensitivity of modern infrared cameras, it is possible to measure changes in observed radiation associated with air flow temperature variations without addition of absorbing gas. This allows obtaining 2D temperature fields averaged along line-of-sight, analogous to quantitative schlieren or interferometry techniques, using only software supplied with infrared camera. The second technique, becoming increasingly popular in engineering practice, employs solid targets installed within the air flow and observed with infrared camera. Temperature distributions, obtained with both infrared techniques, are compared to each other, to measurements using Background Oriented Schlieren, to thermocouple measurements and to results of 2D and 3D numerical simulations. It is shown that solid target apparent temperature is affected by radiative heat exchange with the heated plate. Simultaneous use of three kinds of targets with special treatment is proposed to determine local values of reflected radiation contribution and to correct for this effect. Infrared thermography of optically thin media is shown to be simple and reliable non-intrusive technique for air flow temperature measurements, possessing high spatial resolution. However, its random error is increasing with transmissivity of the flow under study.

1. Infrared techniques for air flow temperature measurements

Quantitative measurements of air flow temperature fields are in demand in many research and engineering applications, including HVAC, high-speed aerodynamics, meteorology and heat transfer enhancement problems, just to name a few. Experimental techniques are required to be non-intrusive, accurate, possess low inertia and high spatial resolution, to be robust and easy-to-implement. Conventional approaches include interferometry, rainbow schlieren, laser-induced fluorescence. Also, temperature-sensitive particles are sometimes used. Recently, due to the progress in infrared (IR) camera sensitivity and spatial resolution, IR techniques of temperature
measurement became increasingly popular. Though in most cases temperature or the heat flux at
the surface of a solid wall is measured, as described in review by Carlomagno and Cardone
(2010), some techniques yielding 2D fields of air flow temperature have been proposed as well.
They can be classified into two groups. Techniques of the first group utilize IR thermography of
solid targets, meshes or screens, immersed within the air flow. This is similar to air temperature
measurement using thermocouples, but provides higher spatial resolution, much lower inertia
(since targets are made to be thermally thin) and common calibration for all detectors using the
IR camera software. Such measurements were recently performed by Porras-Amores et al (2013),
Karadeniz et al (2013), Lewandowski et al (2014). Besides being an intrusive technique, this
approach has two more drawbacks: due to radiation heat transfer with the ambient the real
temperature of targets differs from the air flow temperature and also, in contrast to
thermocouples, the real temperature of targets is unknown, since only the radiation power is
measured by IR camera. Total radiation received by the camera is the sum of radiation emitted
by the object, reflected emission of the ambient sources and radiation of the air between the
object and the camera:

\[ W_{\text{tot}} = \varepsilon \tau W_{\text{obj}} + (1 - \varepsilon) \tau W_{\text{refl}} + (1 - \tau) W_{\text{air}}. \]  

(1)

where \( \varepsilon \) and \( \tau \) are, respectively, object emissivity and air layer transmittance. The last term in
the right-hand side of (1) can be neglected, since \( \tau \) is close to 1. Hence, in order to determine
object temperature, one has to know the apparent reflected temperature, related to \( W_{\text{refl}} \). If
object emissivity is close to 1, the reflected radiation vanishes. However, this case corresponds to
maximum of temperature difference between the target and air, determined by heat balance of the

\[ h(T_{\text{target}} - T_{\text{air}}) = \varepsilon \sigma (T_{\text{refl}}^4 - T_{\text{target}}^4), \]  

(2)

where \( h \) is convective heat transfer coefficient and \( \sigma \) is Stefan-Boltzmann constant. Thus,
incompatible requirements for \( \varepsilon \) arise, as noticed by Marinetti et al (2015): it must be high to
minimize reflected radiation in (1) and it must be low to minimize temperature difference
between the target and air flow. In the present study this contradiction is avoided
simultaneously using three kinds of targets: black-painted copper plate, the same plate with only
half black-painted and the other half polished, and crumpled aluminum foil. The latter type of
targets is used to determine local apparent reflected temperature, whereas the other two are employed for air temperature measurements: they have similar heat balance equations (2), but the radiation term in right-hand side for completely black-painted target is twice in comparison with half-painted target. This allows one to find air flow temperature, with only assumption that targets of identical size, located close to each other, possess equal heat transfer coefficients and apparent reflected temperatures.

In IR techniques of the second group a distant uniform screen is observed through the air flow under study. In earlier studies by Gordge and Page (1993) and Narayanan et al (2003) various gases were added to the air flow to increase IR radiation absorption. However, in this case no quantitative data about temperature field can be obtained, since thermograms depend also on the unknown local concentration of the gas. Sensitivity of modern IR cameras allows to perform measurements without additional gas. Total radiation received by the camera is still described by (1), which can now be rearranged to express air flow emitted radiation in terms of reflected temperature of the ambient and the object (distant screen) temperature. If the screen and the ambient have the same temperature, all calculations can be performed by the software, provided with IR camera. One has only to specify $\varepsilon = 1$, $\tau_l = 1 - \tau$ as air layer transmittance and screen temperature as air temperature, and the software will produce path-integrated air temperature fields instead of screen temperature fields. This quantitative measurement technique will be referred to as IR thermography of optically thin media (IRTOTM). It should be noted that quantitative measurements are possible in medium IR wavelength range (2-5 µm) only, since in long IR wavelength range (8-13 µm) the absorption coefficient of water vapor, present in the air, is comparable with that of the air itself. Air transmittance $\tau$ can be found by in-situ comparison of IRTOTM air temperature values with a thermocouple readings.

2. Background Oriented Schlieren

In Background Oriented Schlieren (BOS) technique (see the recent review by Raffel (2015)) refractive index variations in gas or liquid flow are measured by digital comparison of two photographs of the same background pattern, taken through medium with constant refractive index and through the flow under investigation. Cross-correlation interrogation, adopted from PIV, is usually used to find the displacement field, which is proportional to path-integrated refractive index gradient. Then, solving Poisson equation or just the first-order equations system (in least-squares sense, because it is overdetermined) with appropriate boundary conditions one can receive the refractive index field. In gases it is related to density by Gladstone-Dale relation.
In liquids one has to use Lorentz-Lorenz formula and empirical equation of state with some flow model (e.g. with constant pressure assumption, valid for convective flows) to obtain density and temperature fields. As shown by Vinnichenko et al (2014), BOS provides accurate measurements of temperature variations, as long as the flow is close to 2D. BOS sensitivity is determined by the refractive index temperature derivative and background-to-flow distance. In gases \( \frac{dn}{dT} \) is two orders of magnitude lower than in liquids, hence large background-to-flow distances have to be used to measure small refractive index gradients in air convection flows.

3. Experimental procedure

The performance of both IR techniques and BOS was evaluated for air convection over a heated horizontal latten plate 15×30×1 cm with temperature varying from 80°C to 140°C in different experimental runs. Special care was taken to eliminate spurious air flows in the room, which affected natural convection flow in preliminary experiments. A frame with three columns of targets was located near the flow centerline. IR thermography using solid targets, IRTOTM and BOS measurements were performed in separate experiments under the same conditions. BOS background was composed of randomly positioned black square dots with size corresponding to 3 pix in the final image. Black-painted plywood screen was imaged in IRTOTM. Background-to-flow distance in BOS measurements was varied from 107 cm for 80°C to 65 cm for 140°C, providing maximal displacement about 12 pix. The results were compared to thermocouple measurements (also installed along the centerline) and results of 2D and 3D numerical simulations, performed using the original code and OpenFOAM, respectively. Since the flow is becoming turbulent in this range of Rayleigh numbers (1.8-2.7·10^7) and temperature fluctuations according to thermocouple readings can be as large as 5 K, only time-averaged temperature fields will be discussed. FLIR SC7700-M IR camera, operating in wavelength range 3.7--4.8 µm with image resolution 640×512 was used for IR imaging.

4. Results and discussion

Comparison of time-averaged 2D temperature fields in vertical plane, obtained with IRTOTM, BOS, 2D and 3D numerical simulations, is shown in Fig. 1. Temperature field from 3D simulations was also averaged along line-of-sight of BOS and IRTOTM cameras.
Time-averaging employed 150 snapshots taken at 0.5 Hz in BOS measurements and 1500 snapshots taken at 25 Hz in IRTOTM. Slight overestimation of air temperature far from the plate in IRTOTM is due to inaccuracy of specified transmittance value. \( \tau_i = 1 - \tau \) is 0.02 only, hence the error of IR temperature measurement is strongly amplified in IRTOTM, as the measured air emitted radiation term is much smaller than other terms in (1). Nevertheless, the obtained temperature field is quite similar to BOS result and results of simulations. This is confirmed by temperature distributions along the flow centerline, presented in Fig. 2. All experimental data lie within or close to the interval between 2D and 3D simulations. BOS does not resolve the lower layer about 1 mm from the plate surface because of perspective effect and finite interrogation window size. IRTOTM seems to have better resolution near the plate, despite lower resolution of IR camera. Scatter of IRTOTM points reflects the increase of random error in IRTOTM measurements in comparison to conventional IR thermography. Apparent reflected temperature is strongly dependent on height, since the main contributor to reflected radiation term is the heated plate and the solid angle decreases with height. Height dependencies of \( T_{ref} \), measured using crumpled aluminum foil targets, are shown in Fig. 3. The requirement to know the
apparent reflected temperature values at different locations in the flow makes IR thermography using solid targets much more complicated. As can be seen from the scatter in Fig. 3, the accuracy of $T_{refl}$ determination using crumpled aluminum foil targets is low. However, at relatively low temperatures, as in the present study, reflected radiation has moderate influence on measured air temperature fields.

![Fig. 2 Air temperature along the flow centerline as function of height. Plate temperature is 80°C.](image-url)
Finally, it can be concluded that IRTOTM technique, proposed in the present study, and BOS can be used for quantitative measurements of air temperature in convective flows. BOS lacks sensitivity and does not resolve thin thermal layer close to the solid wall. IRTOTM has higher sensitivity, but larger random error. IR thermography using solid targets, besides being an intrusive technique, suffers from the influence of reflected radiation from the ambient, which can be different at different locations in the flow. This issue can be resolved performing simultaneous measurements with three types of targets, but the procedure becomes more complicated. Generally, IRTOTM can be recommended as the first-choice measurement method because of simplicity of experimental procedure and post-processing. The accuracy and spatial resolution of BOS and IRTOTM, at least for time-averaged fields, are sufficient for direct comparison with numerical simulations using various computational models.
References