Problems of heat flux measurement by means of IR camera under a pulse impact on a sample

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Abstract. A problem of temperature measurements under a pulse impact on a sample in a case of short-time wind tunnel experiments has been studied. Large errors in temperature definition of the sample wall leads to large errors in heat flux calculation, based on temperature change. The hypothesis on the reason of this error has been examined in the paper and the method of deconvolution has been proposed to improve heat flux calculation.

1. Introduction
Measurement of heat fluxes in various fields of science is an important and urgent task. There are different ways to measure heat fluxes: based on the temperature growth rate (for example, calorimetric sensors), by gradient heat flow sensors (ALTP, Germany [1]), by infrared radiation of the body, etc. The advantages of IR measurement technique are a panoramic view and the absence of the need to mount sensors in the sample. This method is used in many areas of science and, in particular, in aerodynamics. One of the important problems, which can be solved by means of IR camera measurements, is to define the transition position and to model it by numerical methods [2].

When measuring the heat fluxes of aerodynamic models using an IR camera, it is necessary to recover the heat flux from measurements of the surface temperature of the model, solving the inverse problem of heat distribution in a semi-infinite body. In this case, the surface temperature has to be measured with rather high accuracy.

Using the IR technique in an aerodynamic experiment and the well-known heat flux recovery algorithms, the authors faced the problem that the measured heat fluxes differ from the theoretical predictions and data from direct numerical simulation by a factor of 2-3. As it turned out, other researchers faced similar problems when measuring thermal fluxes with an IR camera (for example, at TsAGI [3]).

An analysis of the data obtained has shown that the problem consists exactly in measuring the surface temperature.

Experimental data were obtained in aerodynamic wind tunnel of pulsed or short-term action, where the run time and, consequently, the time of exposure to heat flux, ranged from several hundred to several tens of milliseconds. Under such conditions a large temperature gradient occurs deep into the model surface. In addition, infrared radiation is known to have a certain depth of penetration in a substance. That is, the imager perceives radiation not only from the surface of the sample, but also from a certain depth, showing not the surface temperature, but a certain average temperature at the depth of transparency. In an equilibrium situation or in the presence of small temperature gradients, a similar
error is absent or not significant. However, in the presence of large gradients, the surface temperature can be measured with a large error, which leads to an error in the determination of heat fluxes.

The paper discusses the hypothesis that the above mentioned effect leads to incorrect recovery of heat fluxes in an aerodynamic experiment, and also discusses methods for improving the accuracy of surface temperature measurement.

2. Experimental setup

The data obtained in the short-run tunnel “Transit-M”, the run time of which is about 200 ms, were analyzed. Experiments were carried out at Mach number \( M = 6 \) in a wide range of Reynolds numbers.

Flir infrared camera was used to measure surface temperature with a frame rate from 100 to 350 Hz and a matrix resolution of \( 320 \times 256 \). The recovery of heat fluxes from measured temperature fields was carried out using the Cook – Felderman algorithm [4].

In addition, the influence of the heating duration was studied on a special stand.

3. Results

3.1. Testing the hypothesis

The reason of wrong wall temperature measurements may be as follows. Under a pulse impact of heat flux on a sample a large temperature gradient arises in the sample. IR radiation can pass through a thin layer of material with some transmittance coefficient. This means that every layer of the sample radiates IR waves depending on the temperature of this layer. IR camera integrates these waves and according to the Planck's law (which is valid only for the equilibrium case) calculates temperature. However, it is not the temperature of the wall, but the averaged temperature at some depth. An indirect confirmation of this hypothesis is the fact that the longer the measurement takes place, the closer the heat flux is to that predicted by the theory, i.e. the longer is the measurement, the smaller is the gradient and the closer is the radiation to the equilibrium case.

To verify this assumption, the one-dimensional problem of heat propagation into a plate was solved numerically. The plate with a thickness of 500 μm was heated by a constant heat flux of \( 10^5 \text{ W/m}^2 \) for 10 ms.

For an unevenly heated plane-parallel plate, the spectral radiation intensity was calculated using the following formula:

\[
r_\lambda(T) = \frac{\alpha_\lambda k_\lambda}{(1 - e^{-k_\lambda d})} \int_0^d r^{bb}_\lambda(T(x)) e^{-k_\lambda x} dx,
\]

where \( \alpha \) is the emissivity factor, \( k \) is the absorption coefficient per unit length, \( d \) is the plate thickness, \( r^{bb}_\lambda \) is the black body radiation intensity (Planck's law), and sub index \( \lambda \) denotes dependence on wave length.

The IR camera perceives incoming radiation in a range of \( \lambda_1 - \lambda_2 \) as a gray body radiation with intensity equal to

\[
R(T) = \alpha_\lambda \int_{\lambda_1}^{\lambda_2} r^{bb}_\lambda \, d\lambda
\]

Using the formulas (1) and (2), and knowing the temperature distribution in the body one can calculate IR camera signal and "measured" temperature. In the absence of temperature gradient in the plate, the spectral intensity (1) must coincide with the intensity for the absolutely black body. Consequently, the temperature "measured" by the camera must coincide with the true temperature of the body surface. The calculation for this case with high accuracy shows that the temperature difference is absent.

In the presence of a temperature gradient deep into the plate created by a constant heat flux, the difference between real and the "measured" surface temperature can be significant as can be seen from Fig. 1 and Fig. 2.
So, it is seen that the IR camera gives wrong values of surface temperature in the presence of temperature gradient deep inside the body and the heat flux calculated from these data is also wrong.

3.2. Method of deconvolution
The behavior of the wall temperature reminds a time lag behavior in processes with heat inertia, similar to temperature measurements by means of thermocouple in high-enthalpy wind tunnels with short and super-short duration of operation. Such test conditions impose special requirements on the measurement techniques since it is necessary to consider a time lag of the response of measurement system. For processing the received experimental data and restoring the actual temperature, a method of deconvolution may be used [5]. This procedure of stagnation temperature restoration is based on the usage of convolution integral equation solution. Such procedure is called deconvolution. This approach implies the need for information on the transfer function, which should be obtained on the basis of calibration measurements of temperature step for thermocouples.

Figure 1. True surface temperature and temperature calculated for IR camera signal

Figure 2. Difference between true surface and “measured” surface temperatures

In the case of time invariant distortion, the signal $f$ can be expressed as:

$$f(t) = \int g(t')R(t-t')dt'$$

where $g(t')$ is the unknown function (true signal), and $R$ is the known kernel of the integral equation describing the instrumental response to the impulse action ($\delta$-function).

The standard approach to the solution of convolution is to use the relationship between Fourier transforms of these functions:

$$\tilde{f}(\omega) = \tilde{g}(\omega)\tilde{R}(\omega)$$

where the Fourier transform of the unknown function $\tilde{g}(\omega)$ is obtained by a simple algebraic transformation. However, this approach is sensitive to the random experimental noise and its regularization requires special procedures. The simplest regularization of convolution equation is as follows:

$$g(t) = F^{-1}\left(\tilde{f}(\omega)\frac{\tilde{R}^*(\omega)}{\tilde{R}(\omega)\tilde{R}^*(\omega)+\text{const}}\right)$$

Here $F^{-1}$ is the operator of inverse Fourier transform, symbol $^*$ denotes complex conjugation, regularization parameter $\text{const}$ is selected empirically.

To determine the apparatus function $R$ a step function can be taken as $g(t)$, then differentiating the measured function $f(t)$ one can obtain $R$ (see equation 3).
To create a heat flux step function a laser radiation was taken as a source of constant heat flux. The heat flux \( f(t) \) calculated from the experimental data is shown in Fig. 3. It is clearly seen the heat flux does not jump like in the step function but rapidly grows and then slowly reaches the constant value. Thus if the measured time is more than 0.5 sec one can obtain heat flux with minimum deviation from the real heat flux. However, if it is 0.1 sec or less than the error will be very large, which confirms the correctness of previous findings.

The derivative of the measured signal, that is \( R(t) \), is shown in Fig. 4. Applying the above described procedure (equation 4) we can restore the true signal (Fig. 5). However, the inverse Fourier transform gives very large oscillations in the vicinity of the signal jump in the step function. So regularization must be applied. Applying equation 5 the oscillations become much smaller (Fig. 5), but still exist. Nevertheless the result is much better than the heat flux recovered without taking into account the instrumental function \( R(t) \).

More complicated regularizations may be used to reduce oscillations, for example the Tikhonov regularization, where instead of \( \text{const} \) in Eq. 5 an expression \( \text{const} \ast \omega^2 \) is used.

Figure 3. Calculated heat flux based on surface temperature change after switching on laser radiation  
Figure 4. The apparatus function \( R \) calculated based on measured signal  
Figure 5. Measured heat flux and improved heat flux after applying the method of deconvolution
Conclusion
It has been shown that surface temperature gradient of a sample can strongly affect IR camera calculation of the temperature. That leads to a large error in heat flux computation based on the surface temperature measurement.

The deconvolution method has been applied to reduce the error of heat flux definition. It is shown that this method can significantly improve heat flux measurements.

Acknowledgments
The work was partly carried out within the framework of the Basic Scientific Research Program of the State Academies of Sciences for 2013–2020 (project AAAA-A17-117030610126-4). The experiments were carried out using the equipment of the Joint Access Center “Mechanics” (ITAM SB RAS). The work was partly supported by the Russian Foundation for Basic Research (grant No. 18-01-00536).

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