Correction of inertance of temperature sensing devices in high-speed flow

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Abstract. The influence of the thermocouple calibration method on the reconstruction of the real temperature in impulse wind tunnel with operation duration of up to 100 ms is presented. It is shown that in an impulse set-up allow obtaining a stepwise thermal load with long temperature plateau which enough to determination of instrumental function, necessary for temperature reconstruction. To this aim, the developed technique, based on the application of the solution of the convolution integral equation, was used. It was included the information on the instrumental function, which was obtained from the calibration measurements. In the deconvolution procedure, the signal was first smoothed by splines, the convolution kernel was extracted by the differentiation of smoothed function, and regularization was performed by Kaczmarz algorithm with relaxation parameter. A comparison is made of the temperature reconstruction in the regular mode of hot shot wind tunnel with two different methods for measuring the response of thermocouples to the temperature step: measurement behind the shock wave front and rapid immersion in aluminum melt. It is found that the use of the instrumental function obtained in a wind tunnel allows one to more reliably determine the position of the temperature maximum in real experiment, which corresponds to the physical structure of the flow.

1. Introduction
The development and research of hypersonic vehicle and scramjet engines as a propulsion for them has been carried out for many years. As a result of these studies, fundamental results were obtained and demonstration flights were carried out. They confirmed the possibility of implementing hypersonic flight in an atmosphere with an air-jet engine [1]. The basis for successful development future hypersonic technologies, along with numerical simulation, is to obtain reliable experimental data on the characteristics of the vehicle and its elements. At the initial stage of research, supersonic and hypersonic periodic-duration wind tunnels with an operation time of up to 10 minutes were used. Set up of this type made allowed simulating with reasonable accuracy the flow around a hypersonic aircraft and performances its propulsion [2].

To simulate real heat transfer processes, a higher level of heat fluxes and temperatures is required. Therefore, for these purposes short-time mode wind tunnels are used, such as shock and pulsed wind tunnels, expansion tubes, which allow raising the temperature level up to 5000 K [2, 3]. The peculiarity of such set up is that the operation time lies in the range of 2-3 ms up to 100 ms. Despite the intensive development of optical methods of thermal measurements, the main measurement techniques remain thermocouples of various types [4] due to their ease of application and reliability. At using thermocouple gauges in short duration set, it is necessary to solve the inertia (time lag of the response) problem of such gages.
There are various approaches to solving this problem. A brief review of possible approaches is given in [5]. In this study, as in a number of other works [6], it is indicated, the most attractive method is [5], based on the use of the integral convolution equation to describe the signal and its reconstruction. To implement this method, it is necessary to obtain the instrumental function of the measuring device that is to obtain the time dependence of the thermocouple response on a stepwise thermal load. Previously, the technique of quickly immersing temperature gages in an aluminum melt with a constant temperature was used for this purpose, which allowed obtaining an extended branch with a constant temperature. As a result, the maximum temperature was reconstructed, but the position of the temperature maxima was not determined correctly. A possible reason could be that when calibrating thermocouples, the temperature level was significantly lower than the actual temperature in the impulse wind tunnel and the heat transfer conditions differed from the conditions of real measurements in an aerodynamic experiment. Therefore, the aim of the present work was to determine the influence of the thermocouple calibration conditions and the accuracy of calculation of the instrumental function on the error of temperature reconstruction under conditions of high-speed processes in highly enthalpy wind tunnels. In addition, the aim was also to verify the applicability of the developed deconvolution method for the new thermocouples calibration.

2. Experiment technique
To perform thermocouples calibration, a high-enthalpy hot-shot wind tunnel IT-302M was used, which at Mach numbers from 5 to 10 has flow parameters close to flight conditions [7]. The peculiarity of this wind tunnel is that in regular operation with a constant Mach number the flow parameters (pressure, temperature, and Reynolds number) are significantly reduced. However, in a special mode of operation with the multiplier, the flow parameters can be kept constant for 80–120 ms. This property of the wind tunnel was used to calibrate the thermocouples and obtain the response of the thermocouple to a step temperature impact. Such dependences were obtained for the temperature range 1100–1620 K at Mach numbers 6 and 8. In the last case, it was possible to obtain a temperature plateau with duration of approximately 120 ms. To determine the temperature, we used the data of temperature measurement in first prechamber of impulse wind tunnel taking into account heat losses [7] and special measures were applied to ensure constant temperature along the plateau. Based on the obtained calibration dependence, an instrumental function was obtained, which was used to reconstruction the temperature, measured during the regular operation of the wind tunnel. During calibration and testing, it was used the same thermocouples, which were used at the previous stage of study, described in [5].

Figure 1 demonstrates the form of the temperature step, which is implemented in the hot shot wind tunnel at nominal temperature of 1500K. It should be noted two features of the initial dependence (line 1), which was obtained because of measurements in the first prechamber.
The first of them consists in the existence of a small in time region (6-8 ms) of temperature increase, the appearance of which is caused by wave processes during a discharge in the first prechamber and is limited by the duration of the filling of the second prechamber. The maximum temperature rise relative to the average level was not more than 1.6%. Second feature is the decrease in temperature at the end of calibration process after the 110th millisecond because of the pressure drop in the second prechamber at the end of the wind tunnel operation mode. These features are a consequence of the technological properties of the wind tunnel of this type, and they cannot be adjusted during the experiment. An analysis of the time temperature dependence indicates that the temperature pulsation in flow realized on the level of 3-5%. This is a consequence of the influence of the discharge in the first chamber and wave processes at the second prechamber filling. Since this form of the temperature step does not allow one to obtain an instrumental function suitable for the correct temperature recovery, the initial function was smoothed out. This made it possible to obtain temperature dependence with a constant temperature over the entire time range (line 2 in figure 1). The error in temperature deviation from the mean constant value did not exceed ±0.9% in the time interval between 2 and 110 milliseconds. The response of a thermocouple with a diameter of 50 microns to a step temperature effect (line 3) shows that the maximum temperature is reached only at the end of the operation mode of the wind tunnel. It was also revealed that the pulsations of the temperature, measured by means of the thermocouple, remain at about 3-5% that can create difficulties at determining the instrumental function.

3. Signal processing and method of deconvolution

Due to the inertia of thermocouples, the measured temperature depends not only on the current flow temperature, but also on its previous temperatures. Therefore, a special approach was taken to interpret the measured signal, namely, the convolution integral equation [8] was used to describe the relationship between the true temperature of the thermocouple and the measured one [7]. The problems of usage of the instrument hardware function are usually reduced to solving similar convolution equations [9]. Signal processing and solving these equations is called the deconvolution problem [10-12]. After discretization, the integral equation was written in the form of a system of linear algebraic equations (SLAE). Details of the used algorithm are described in the authors’ paper [5]. In summary, its essence is as follows. The unknown temperature distribution \( T(t) \) is restored from the solution of the integral equation (actually, we need to resolve the temperature differences \( E-E(0) \) and \( T-T(0) \), which we will denote by \( E \) and \( T \) below):

\[
E(t) = \int_0^T K(t - \tau) T(\tau) d\tau
\]  

(1)

where \( K(t) \) is the instrument function (in optics it is called the point spread function, PSF), and \( E(t) \) is the measured value of the thermocouple temperature after subtracting its initial temperature \( E(0) \). After discretization, this equation reduces to the matrix equation \( E = KT \), the solution of which is found by the Kachmarz iterative method [13]. In this case, the next \( (k + 1) \) iteration of the restored temperature distribution \( T \) is found as follows:

\[
T_n^{k+1} = T_n^k + \lambda K_{mn} (E_m - (KT)_m^k) / \sum_{j=1}^N |K_{mj}|^2 .
\]  

(2)

Here \( \lambda \) is a relaxation parameter, the matrix \( K \) has the dimension \( M \times N \), the rows of the matrix are handled according to the rule \( m = k \pmod{M} + 1 \), the stop criterion is the nondecreasing residual norm of the original equation (1).

To suppress instabilities inherent in the deconvolution procedure, smoothing splines and median filtering were used for experimentally measured signals, as well as regularization of the obtained SLAE. Figure 2 shows the thermocouple signal received in an impulse wind tunnel, here the temperature is shown in Kelvin and starts from a value of 274 K. The derivative of temperature is given in relative units, starting from zero.

An example of testing the obtained experimental PSF (curve 5) in a numerical experiment with a known distribution of model temperature (curve 3) is depicted in figure 3. After solving the direct
problem for these functions, the inverse problem (curve 1) was solved by the authors’ algorithm. For a random noise of 1%, the reconstruction error (RMS) was only 0.45%.

Figure 2. The part of the calibration signal of the thermocouple (K), together with its derivative representing the device function.

Figure 3. Verification the properties of a new instrumental function in a numerical experiment; random noise 1%, reconstruction error RMS = 0.45%. Here 1 is the reconstruction (solution of the inverse problem), 2 is the solution of the direct problem, the measured signal, 3 is the exact solution, 4 is the calculation of the direct problem for the solution found (pseudo signal), 5 is the PSF.

Figure 4 shows an example of the restoration of a calibration signal with this PSF, and the initial hypothesis assumed a stepwise behavior of the temperature curve towards the end of its rise. Although the initial portion on curve (1) shows the obvious influence of the Gibbs effect when processing high-gradient signals, the range of this curve from 30 to 100 ms can be considered conditionally constant on average.

Figure 4. Restoration of the calibration temperature step at the initial measurement part. Here 1 is the reconstruction (solution of the inverse problem), 2 is the measured signal, 3 is the calculation of the direct problem for the solution found (pseudo signal), 4 is the PSF.
Note that the found hardware calibration function (figure 1) turned out to be somewhat wider than when calibrating a thermocouple in an aluminum melt [5], apparently due to weaker heat transfer in the impulse wind tunnel. This circumstance complicates the deconvolution procedure [14] and requires further research on the algorithm for processing such a signal.

4. Summary
Studies in the impulse wind tunnel have shown that, in order to obtain an instrumental function, calibration of thermocouples under conditions close to the measurement conditions is preferable. To realize the temperature step and obtain the instrumental function with acceptable accuracy, an impulse wind tunnel with high flow parameters can be used.

In the framework of the proposed signal processing scheme and temperature reconstruction model, based on the deconvolution method, it was revealed that the use of the instrumentation function obtained in a pulsed wind tunnel makes it possible to more accurately determine the position of the temperature maximum at the real experiments, which corresponds with the physical structure of the flow.

An analysis of the simulation results indicates that the approaches based on processing signals using smoothing splines, median filtering, and an iterative deconvolution algorithm with regularization are universal and do not depend on the scheme and calibration conditions of thermocouples.

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