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APPLICATION OF THE DECONVOLUTION METHODS FOR PROCESSING OF MEASUREMENT SIGNALS IN THE FAST PROCESSES

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Abstract. *In practice of experiment, one had to be faced with the distortions caused by measuring equipment, especially on a limit of its resolution. Sometimes not the equipment but the investigated process itself gives the grounds for distortion of the registered data, for example, at photography of quickly moving objects. Other examples of distortion of data are measurements of temperature and forces in wind tunnels. Problems of elimination of instrument function (or response function) of the device are most often reduced to the solution of the integral equations, usually, with convolution kernels. The solution of these equations is called problem of deconvolution. In present paper, methods and algorithms of the solution of some tasks, which appear at processing the signals obtained in aerodynamic experimental researches, are presented. The regularization algorithm of the solution of deconvolution problem, adapted to the level of experimental noise, is described. Results of numerical simulation of a task of temperature correction of thermocouples (temperature gages) lag at restrictions of temporary resolution of the thermocouples and short-term process are given.*

The numerical solution of a non-stationary problem of heat conductivity in two-dimensional statement for determination of average temperature of the thermocouples at three values of their diameter (d=50, 100, 200 microns) was performed. Within numerical modeling, the two-dimensional equations of heat conductivity by the relaxation method were solved. Experimental definition of instrument function of the thermocouples was carried in experiment with constant step thermal loading. The same type of thermal loading was used at numerical simulation. Direct comparison of the calculated and experimental data for the thermocouple with diameter of 50 microns shows that by means of calculation it is possible to receive the temperature step function close to the experimental one. Therefore, it is possible to estimate theoretical impulse response function of the thermocouple by differentiation of the calculated response function of the thermocouple to the step loading.

The calculation results agree well with the temperature measurements by the thermocouple of the same size obtained by its immersion in molten aluminum. Instrument function, defined from the real experiment with immersion of thermocouples in aluminum melt, appeared to be close to the function obtained theoretically.

1 INTRODUCTION

Ground-based and flight researches play an important role in creating new hypersonic vehicles. At hypersonic speeds, aerodynamic heating leads to extremely high heat flow and temperature on the outer surface of the machine and in the channel of the hypersonic propulsion air-jet engine [1]. A well-designed thermal protection system must maintain the integrity of the aircraft, preventing the thermal loads. Aerodynamic heating and aerodynamic resistance determine the choice of structural materials in the design of devices for hypersonic flight. Security, viability and stability are key considerations in achieving the goals of the flight. For their achievement, the knowledge of temperatures and heat flows for creation of effective thermal protection system [1, 2] is required.

Over the past decade, numerous experimental and numerical study of temperature and heat flow on aircraft elements were conducted to estimate and improve methods and models which are used for a prediction of operating conditions of the hypersonic vehicle [3-5].

Temperature measurement is important and therefore quite well studied direction in metrology. The application of traditional contact methods (thermocouples, resistance thermometers) [6, 7] and optical techniques [8] (Rayleigh scattering, pyrometers, laser-induced fluorescence, etc.) provides the acceptable accuracy of measurements. These methods have their advantages, disadvantages and limitations, and therefore are applied selectively in various conditions. Application of the contact methods for the measurement of high temperatures (more than 2000K) is limited to temperatures of melting and a high inertia of sensitive elements, resulting in a thermocouple condition to be far away from the stationary state. Optical methods, which allow to measure high temperatures, have limited access of optical diagnostics to the system [8, 9].

Implementation of optical temperature measurement in channel often becomes impossible for this reason. Research in high-speed wind tunnels with short operating time from 5 to 100 msec appears difficult solvable problem because of measuring system inertia [10]. The problem becomes especially actual when determining temperature fields inside the models channel [11].

Heat flow sensors and thermocouples based on them is one of the most widely used devices for temperature measurement in view of their simplicity, low price, simplicity of production and reliability and broad application. However, their applicability is not always possible due to the relatively low melting point and limited bandwidth of the sensor [6]. Therefore, in many applications, methods of compensation signal needed to establish the true temperature in small or extremely short measuring times. In this case, definition of the thermocouple time constant, which characterizes its inertia [10, 12], is required.

In [12] a method based on the technique of the two thermocouples to evaluate the average time constants has been proposed. The method is based on mutual power spectra of temperature fluctuations. However, this method is very sensitive to measurement noise and does not allow receiving high accuracy that at determining of a time constant was approximately 25 %.

Measurement of pulsating temperatures in the combustion chambers and the propulsion is necessary to determine the entropy and noise in these systems. It is known that most of the thermocouples, suitable for use in such an unfavorable flow have response times considerably more than required in the working frequency range. The main problem of compensation is a measurement of the thermocouple response time, as the response depends on the environmental conditions in which thermocouples are located, and is defined by the convective and radiating components [13].

Previously developed methods for measuring the time constant are usually based on a quick immersion of thermocouple into the hot medium or switching of a gas flow from cold to hot. Mechanical methods are suitable only for time constants from 100 msec or more. However, for ‘fast’ thermocouple with a response of less than 10 msec mechanical methods of switching cannot usually be applied. Electrical heating methods also are not satisfactory, especially if the thermocouple is working near the limit of its working capacity. Therefore methods to determine the thermocouple time constant based on mutual power spectra processing [13] or solution of inverse problems [14] are developed.

Among several approaches to assessing the relationship of the time constants two basic assumptions were used: (1) the time constant is a function of the size of thermocouple based on empirical equations for the heat transfer coefficient of thin wires [15]; (2) the ratio of the time constants is defined as the ratio of the temperature derivatives, which is valid at equal temperatures of both thermocouples [16, 17]. The validity of such approaches in high-enthalpy flow and combustion remains uncertain, as the thermophysical properties can be changed in accordance with the conditions in the high-temperature region.

Serious problems in the process of temperature measurements arise in the study of fast processes in a short duration measurements, since in such cases it is necessary to take into account the inertia of the of time measurements. Such account inevitably leads to the necessity of solving inverse heat conduction problems [18], as well as to the problems of eliminating (correction) the impact of measuring system instrumental function. It should be noted that methods of inverse problems solution for processing signals of the dynamic weight and pressure measurements are used for a long time and more often than in the interpretation of thermocouple signals. For example, in [19, 20] the recovery of the temporal aerodynamic characteristics (pressure and forces) by solution of the convolution integral equation (deconvolution method) are described, usually by reducing the problem to a system of linear algebraic equations, or by solution of the problem in Fourier space [21].

In this regard a new modification of the method of two thermocouples was developed [13, 22], and the methods of deconvolution with parametric specification of the thermocouples instrumental functions in the space of the Laplace transform domain [23-25]. The resulting final integral equation containing the measured and actual flow temperature is solved using the original regularization parameter related to the grid in time [26]. This approach is further developed to take into account the dependence of the thermophysical properties of materials on the temperature, which leads to the nonlinear inverse problems of heat conduction, which are reduced by linearization to the known linear problems [27].

The analysis of known researches show that when interpreting the signals of temperature sensors and heat flow there is a trend towards more complex mathematical models, the transition from the time constant to the variable function of time.

The purpose of this paper is the following.

Study of the possibilities for improving the accuracy of temperature measurements over short time intervals, characteristic of fast running processes, particularly when tested in pulse wind tunnels.

Development of mathematical methods, algorithms and programs for improving the accuracy of temperatures and heat flows in the framework of modern methods for solving ill-posed inverse problems of gas dynamics.

Verification of methods and models for temperature and heat flow measurement, based on application of the method of two thermocouples and the method of a deconvolution.

2 FACILITY AND MEASUREMENTS

Experiments were performed at the hot-shot wind tunnel IT-302M [28] with arc heating in direct connect supersonic test mode. Such mode of investigation allows an effective use of the advantages of the hot-shot wind tunnel prechamber as a source of a high-enthalpy test gas (air).

The choice of the initial values of air pressure in the discharge chamber and the voltage of capacitors allowed obtaining the required flow temperature. This approach ensures not only the necessary Mach number but also the required pressure and temperature before the model entrance. High parameters may be reached due to the absence of technological problems related to the temperature strength of the sharp edges of the model and instrumentation. In addition, the setup has large quartz windows for flow visualization and optical measurements.

The experiments were carried out at the following conditions at the duct entrance: Mach numbers M_{en}=5-8, total temperature T_t=2000-3000K, static pressure P_{en}=8-50 kPa. Operation time of wind tunnel at these conditions was 80-120ms. Peculiarity of this wind tunnel is a decrease of flow parameter during operation time. Character of change of total pressure and total temperature are presented in Fig. 1 and 2. One can see that total pressure is drops more than in four times and total temperature decreases approximately by 40% during the wind tunnel operation.

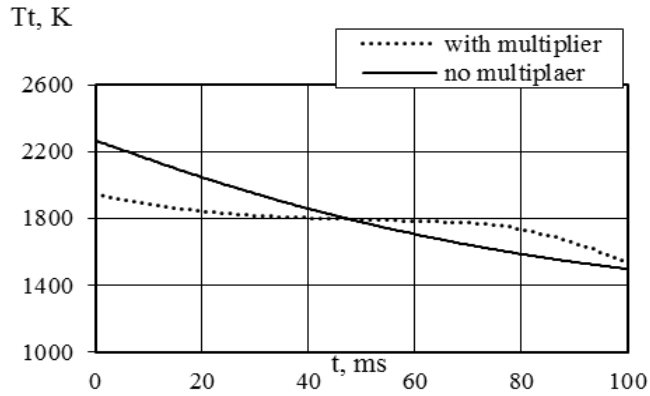

Figure 1: Time history of total temperature in free stream flow at Mach number 7.

Therefore some numbers of runs were carried out with the pressure multiplicator for maintenance of constant value of pressure and temperature as it can be seen in Figs. 1, 2 (point lines). This allows carrying out a measurement at fixed temperature (heat flux) of external flow. At the same time presented data demonstrate that real time of measurements does not exceed 50-60 ms even at Mach number of 7. At a decrease of Mach number, this time drops up to 20-25 ms.

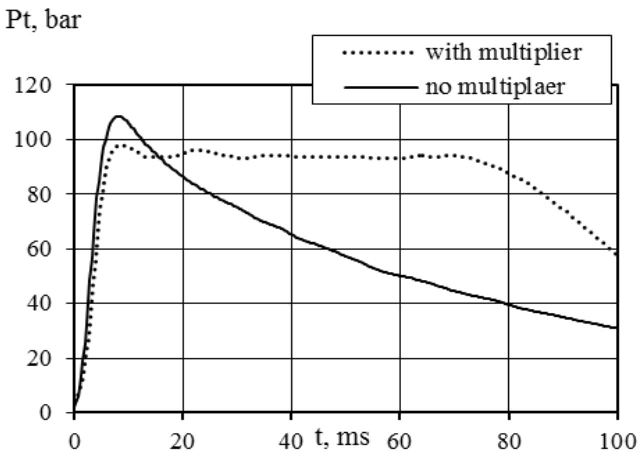

Figure 2: Time history of total pressure in free stream flow at Mach number 7.

The total temperature in the channel exit was measured by means of the rake consisting of 5 gas-flow hromel-alumel thermocouples with the sizes of measuring junction of 0.05, 0.1, 0.2 and 0.3 mm. The minimum sizes of thermo-junction are chosen for decrease of the response time at measurement under the conditions of short-time operation of wind tunnel. Thermocouples were installed in tubes made of stainless steel with external diameter 2.5 mm which functions as heat shield. The device construction (Fig. 3) was manufactured so that identical dynamic and thermal conditions were provided before the entrance in the each thermocouple channel.

During the tests, next parameters were measured: the total flow parameters in first and second prechambers; distributions of static pressure and heat flux in the model channel; Pitot pressure and temperature before model by different technique. This allows obtaining flow condition in the measuring region.

Figure 3: Device for installation of thermocouple sensors.

The typical form of a response of thermocouples with the various size thermojunction is presented in Figure 4 together with change of total temperature in free stream of a wind tunnel. It can be seen that the achievable maximum of temperature depends on the size of junction of thermocouple and lies in the range from 40 to 100 ms while the real maximum of temperature in wind tunnel operation section was reached approximately at 10th ms. In all cases, this maximum essentially was lower than total temperature in a free stream. Its value and time of achievement substantially depends on initial temperature in a free stream and rate of its reduction.

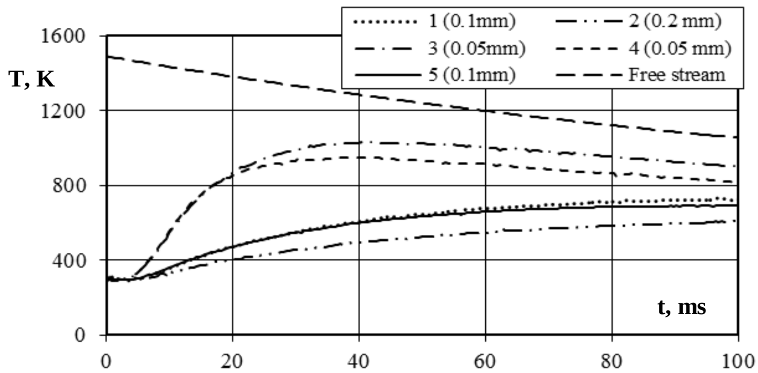

Figure 4: Measurement of total temperature in operation section of wind tunnel.

This data shows that all used thermocouples have a time delay of different duration. This data demonstrates also that measurement by thermocouples of the identical size, but they, nevertheless, does not always coincide owing to a deviation of the thermocouple junction size from the nominal value.

3 DECONVOLUTION METHOD

For processing the received experimental data and restoration of actual temperature, a deconvolution approach has been used. This procedure of stagnation temperature restoration is based on the usage of convolution integral equation solution. Such procedure is called deconvolution [29]. This approach implies the need for information on the transfer function, which should be obtained based on calibration measurements of temperature step for thermocouples with the various size of junction.

Often in diagnostic experimental practice one can face with distortions caused by the measuring apparatus, especially working at the limit of its resolution. For example, the resolution of flow images are limited by so-called point spread function (PSF), arising due to diffraction effects on the receiving aperture, as well as various types of aberrations. Sometimes it is not the equipment, but the process under study itself gives rise to distortion of the recorded data, for example, when photographing fast-moving particles with insufficient temporal resolution. Another example of a data corruption is temperature and balance measurements in wind tunnels. Problems of the apparatus functions corrections are usually reduced to the solution of integral equations, most often of convolution type. Treatment of these equations and their solution are called deconvolution problem.

In general, the integral equation for linear distortions can be written as:

$$f(x) = \int g(x')K(x,x')dx' \tag{1}$$

Here, the vector x may include spatial variables as well as others - time, radiation frequency, etc.; $f(x)$ is the measured signal, $g(x)$ - unknown function, $K(x,x')$ - known kernel of the integral equation describing the instrumental response to the impulse action (δ-function). In the case of time invariant distortion equation (1) simplifies to

$$f(x) = \int g(x')K(x-x')dx' \tag{2}$$

the kernel of which now depends only on the difference of the arguments. Equation (6) is called the convolution equation. This equation describes the optical image blur due to subject movement (or recording device) as well as the problem of reconstruction of signals from sensors that have lag time [19]. Solution of integral equations of the first kind of the form (1), (2) refers to the number of ill-posed problems and requires the development of special regularization methods [8, 30-32].

The standard approach to the solution of convolution is to use the known relationship between Fourier transforms of three functions in equation (2):

$$\tilde{f}(\nu) = \tilde{g}(\nu)\tilde{K}(\nu), \tag{3}$$

where the Fourier transform of the unknown function $\tilde{g}(\nu)$ is obtained by a simple algebraic transformation However, this approach is strongly susceptible to the random experimental noise and its regularization requires special procedures, to suppress high frequency noise components. Formula for the Tikhonov regularization of convolution equation is as follows:

$$g_\alpha(x) = F^{-1}\left(\tilde{f}(\nu)\frac{\tilde{K}^*(\nu)}{\tilde{K}(\nu)\tilde{K}^*(\nu)+\alpha\nu^2}\right). \tag{4}$$

Here F^{-1} – operator of inverse Fourier transform, symbol * is complex conjugation, regularization parameter α is restored from the equality of the residual norm to the norm of noise η^2 (residual criterion):

$$\left\|\tilde{f}(\nu) - \tilde{g}_\alpha(\nu)\tilde{K}(\nu)\right\|^2 = \eta^2.$$

Particular attention is paid to the so-called algebraic reconstruction technique (ART), allowing to find the solution of large systems of linear algebraic equations (SLAE) by iterations, including a highly underdetermined SLAE, using a priori information at each iteration step. The system of linear algebraic equations corresponding to the integral equation (1) is obtained by its discretization:

$$f = Kg, \tag{5}$$

where f and g are vectors, and K is matrix.

The algorithm ART is based on an additive correction of the solution at each step, using the solution in the previous step by the following formula [33]:

$$g_j^{k+1} = g_j^k + \lambda \frac{f_{i(k)} - \sum_j a_{i(k)j} g_j}{\sum_j a_{i(k)j}^2}, i(k) = k \cdot mod(M) + 1. \quad (6)$$

Here k is the iteration number, λ – relaxation parameter, g - restored signal from the measured signal f, a_{ij} – an element of the matrix K, approximating the PSF function (kernel of the convolution equation), M – number of the matrix K rows, $j=1,..., N$, $i=1, ..., M$. Iterative process is stopped by the residual criterion [30] or by achieving a minimum residual norm.

Since inverse problems are very sensitive to the measurement noise, the measured signals f are filtered by smoothing splines.

4 NUMERICAL SIMULATIONS

For calibration, we used the method of rapid drop of thermocouple in the melt aluminum to make a temperature step in the signal of the thermocouple.

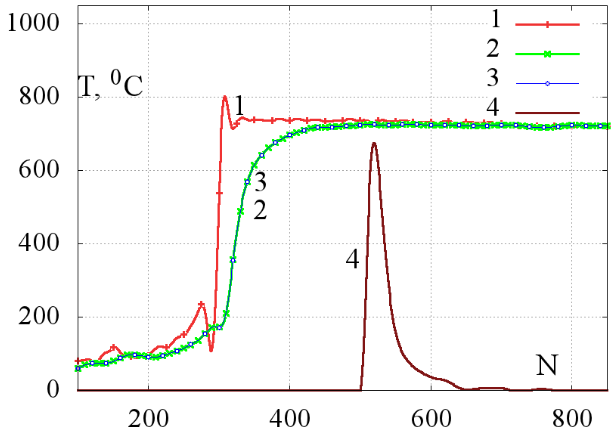

Figure 5: Reconstruction of the thermocouple PSF from the temperature step.

Figure 5 shows the smoothed experimental curve of the thermocouple (green line (2), noise estimation - 2%), and its transfer function, PSF (brown (4)), obtained by differentiating. In this section, ***N*** is a number of the time grid point. Use this function as a kernel of the integral equation allows to solve this equation for the true values of the temperature (red curve (1)). Technical features of the introduction of the thermocouple into the melt led to some transition process when jumping from room temperature to melt temperature. To improve initial part of the curve, it was partly approximated by a straight line with a continuation to zero. Consequently, the reconstruction before the start of the real temperature jump is not enough reliable, the step itself is restored with good accuracy.

Figures 6-7 demonstrate developed algorithm properties in numerical simulations of temperature step reconstruction. Here we investigate influence of the experimental noise on resulting reconstruction and spline smoothing of the noise. PSF of the thermocouple was taken from the real experiment (Figure 5). In Figures 6-8 black curves (3) are exact model temperature functions, green curves (2) present ‘measured’ temperatures, red ones (1) are reconstructed solutions of the equation (6). Also blue curves (4) show which ‘measured’ temperature would be like with reconstructed temperature (results of direct problem solutions) and brown curves (5) represent model PSF close to the experimental one.

The initial portion of the reconstructed step contains a small splash, similar to the Gibbs phenomenon, often displayed in problems of signal processing. In our numerical simulation, it was verified that this effect does arise for the stepwise model temperature distribution using real thermocouple transfer function. Figure 6 shows the ‘measured’ model temperature curve (arbitrary units, green curve) to which was added a random Gaussian noise of 2%, and the resulted reconstruction without smoothing (red curve). In reconstruction noticeable strong fluctuations around the exact model step (blue curve) aroused, errors level RMS=10.7%.

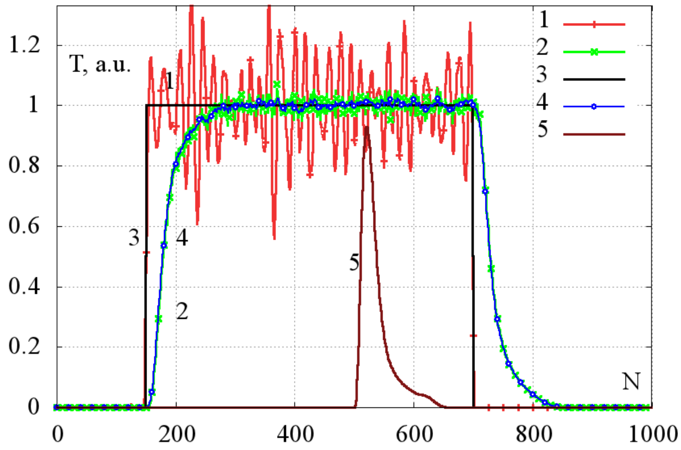

Figure 6: Temperature step reconstruction with experimental PSF, without smoothing, RMS=10.7%.

Figure 7 shows recovery of the model temperature step with the experimental noise (2%) in the thermocouple signal, when it is smoothed by regularized splines. Total step reconstruction error (RMS) was 4.65%.

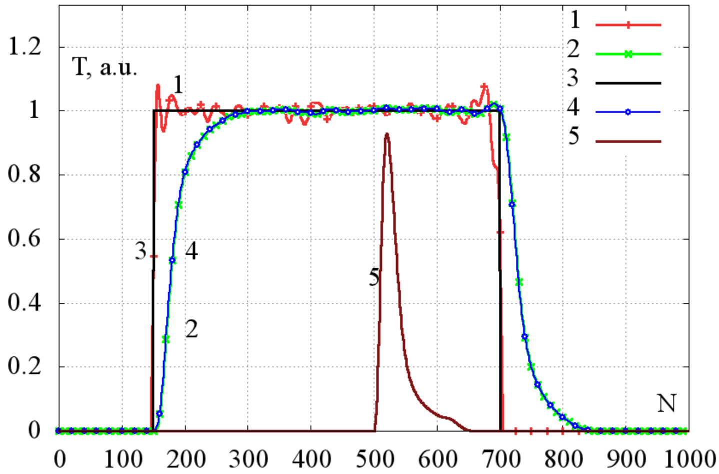

Figure 7: Temperature step reconstruction with experimental PSF; noisy data (2%), with spline smoothing, RMS=4.65%.

Qualitatively another case is presented in Figure 8. Here there is decreasing temperature function with noise level 2%. Here data with noise gave RMS=2.64% (a) after 140 iterations, while signal smoothing gives error much less, RMS=0.3% (b).

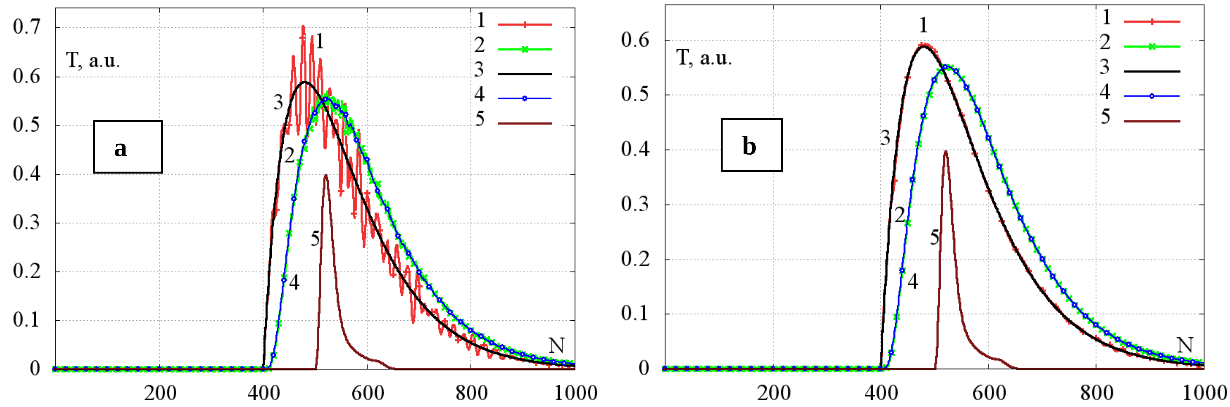

Figure 8: Temperature splash reconstruction with experimental PSF; noisy data (2%); a) without noise smoothing, RMS=2.64%; b) with spline smoothing, RMS=0.3%.

We can see good quality of the reconstruction observed in the initial part of the decreasing signal, but in the wings of the distribution reconstruction quality is not so good.

5 EXPERIMENTAL RESULTS

To perform comparative measurements from a variety of sources, it is necessary to estimate the error for each type of sensor. Usually two main sources of errors for the thermocouples are identified. Firstly, it is an error of a signal conversion (voltage) to the temperature because of use standard translation tables which errors may reach 1.7% change in temperature, which correspond directly to errors in the heat flow for the same 1.7%. Secondly, the accuracy of the thermophysical properties of the materials of the thermocouple junction can cause errors up to 8% of the heat flux [23, 34]. Since the same type of sensors is used, the physical error sources are the same, but the values are different. For the evaluation of measurement errors calibration of all of sensors was carried out in all estimated range of measurements. The weighted average difference between the calibration point and the calibration curve was used as an error in the temperature measurement. The error from the voltage conversion in the temperature is found to be no more than 0.2% and an error of thermophysical properties reached 5.7%.

One of the method of stagnation temperature restoration is based on the results of the solution convolution integral equation (deconvolution). This requires information on the transfer function, which can be obtained on the basis of determination of the temperature calibration step (Figure 9).

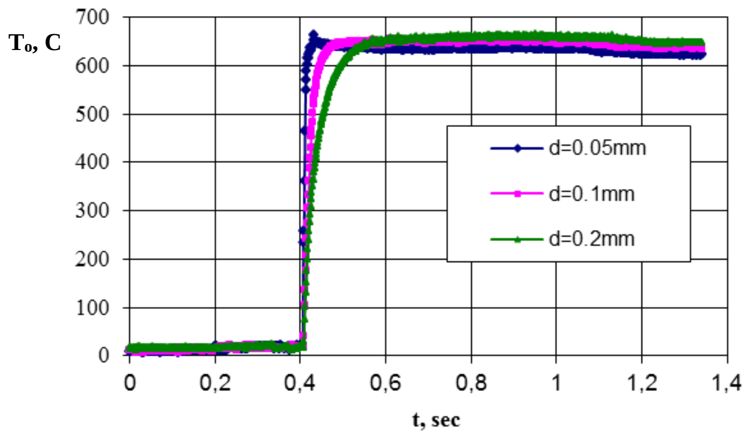

Figure 9: Thermocouples response at fast immersion in molten aluminium.

In this case, the transfer function is obtained by differentiating the response of the measuring system on the step. To get a step signal thermocouple was immersed fast in the molten aluminum (99%). The special device for simultaneous input of three thermocouples was for this purpose used.

Figure 9 shows the step responses for the thermocouples of different size, which depends on the size of the thermocouple junction. The temperature of molten aluminum (643°C) was measured with an average error of no more than 1.54% for the entire time span, which is typical within the range of preliminary calibration of thermocouples.

For processing of the obtained experimental data and to implement reconstruction of real temperature of flow in impulse wind tunnel, two different approaches, described above, have been employed. The first method of signal processing is based on use of readings of two thermocouples with diameters of 0.1 mm and 0.2 mm, and the data on change of Reynolds number during an mode of operation of a impulse wind tunnel. The results obtained have shown in Figure 10.

One can see that initial temperature (without correction) was lower than theoretical value and maximum was reached at 55 ms and 90 ms. These moments are close to finish of operation of wind tunnel.

Application of developed technique of two thermocouples allows with sufficient accuracy to define total temperature in wind tunnel at short-duration action. Results of reconstruction of total temperature by means of this technique are presented in Figure 10 (red line). Maximal temperature is reached approximately at 27 ms and it is close to theoretical value. At the same time, one should notice that restored temperature remains a little bit lower than theoretical value. Nevertheless, results obtained confirmed possibility of determination of maximal temperature and applicability of such approach for a wide class of the tasks in view of simplicity and accessibility.

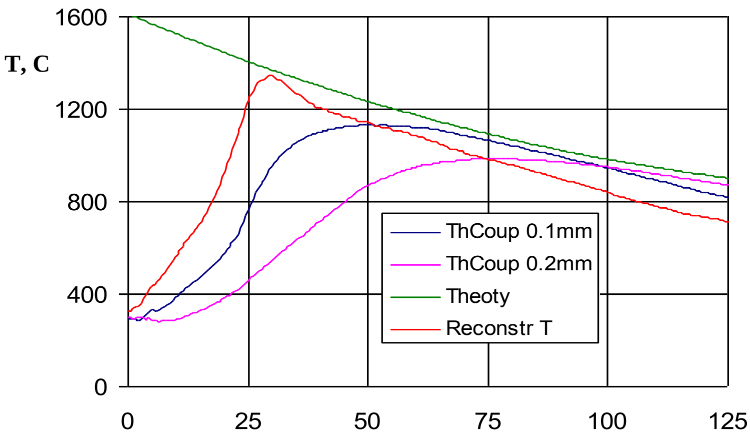

Figure 10: Total temperature reconstruction: method of two thermocouples

Second method of reconstruction allows to exclude errors denoted above. This method is based on deconvolution of integral equation. Kernel of this equation can be restored by differentiation of the experimental output response of thermocouple to the temperature step of input signal. For this purpose the information about the transfer function is necessary. This function has been obtained from results of measurements of a temperature step for two different diameters (Figure 11). In both cases, the same signals of thermocouples were used, which were used at the processing by means of technique of two thermocouples. Before deconvolution, experimental signal was smoothed by splines. Convolution kernels were chosen as decreasing exponents with a single unknown parameter, namely, half-width. During deconvolution the regularization procedure in the Fourier domain was employd. Half-width parameter searching was done by minimization of residual norm, and resulted in the next values: the first half-width was approximately 20 ms and the second one was 40 ms.

Curves of “ThCoup 0.1mm” and of “ThCoup 0.2mm” in Figure 11 coincide with temperature measurements by two thin thermocouples with diameters 0.1 and 0.2 mm, and curves of “Reconstr 0.1mm” and “Reconstr 0.2mm” are result of solution (deconvolution) of integral equation for curves 1 and 2. As opposed to previous method here were obtained two values of maximal temperatures, which correspond well to each other in magnitude but have different position depending on time.

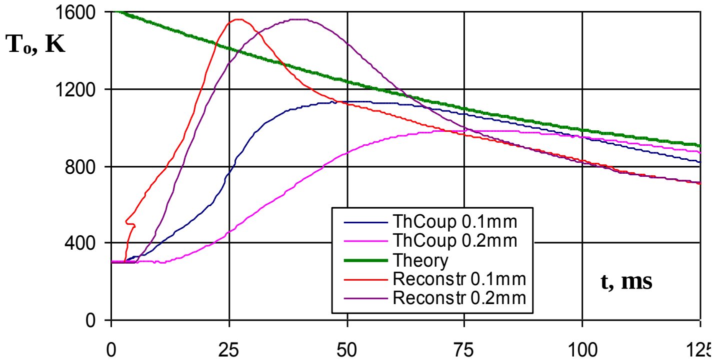

Figure 11: Total temperature reconstruction: deconvolution approach

One can see that application of deconvolution method allows determining the temperature, conformable to temperature of flow in wind tunnel better than method of two thermocouples. Apparently, best result was obtained at the use of thermocouple with smaller size (0.1 mm).

Error estimation of restoration procedure using the suggested approaches has shown that temperature can be recovered with the accuracy not worse than 8%.

6 CONCLUSIONS

The estimation of an error of definition of total temperature by means of the offered approaches has demonstrated that the temperature can be reconstructed with accuracy not worse than 8%.

An iterative reconstruction technique ART gives some promising results for the deconvolution problem, which take into account noise estimation for adaptive regularized cubic splines. The important effect is found. Results of true temperature reconstruction at solution of the integral equation strongly depend on noise level in a signal and quality of its smoothing. In addition, noise in point spread function, which in these numerical experiments has reached 10%, influences results weakly.

7 ACKNOWLEDGEMENTS

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