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Hot Air Gun Identification by Inverse Heat Transfer

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The aim of this paper is to identify the unknown properties of an industrial hot air gun using inverse heat transfer approach. A combination of experiments and numerical analyses is used to define the convection coefficient and the produced temperature of this device. A numerical solver is developed by employment of a straightforward and powerful inverse heat transfer method: "The conjugate gradient method for parameter estimation". The variation of temperature versus time in a fixed point of a steel-304 rod is sensed by a thermocouple and is given as an input to the numerical solver. The produced temperature of the hot air gun and the variation of convection heat transfer coefficient of this device as a function of distance between gun and rod are estimated in this research. Two non-dimensional distances between hot air gun and head of rod, H/D, are considered in this research: 2 and 6. These distances are chosen based on the hot jet potential core, the former is inside the potential core and the latter is outside it. The identifications of this gun are used in the process of determining unknown thermal properties of insulating and ablative materials, which are essential components of ablative heat shields, by inverse heat transfer methods.

Keywords: Inverse Heat Transfer, Conjugate Gradient Method, Forced Convection, Thermal Properties, Numerical Analysis

Nomenclature

h	convection coefficient
k	conduction coefficient
T	temperature
t	Time
x	longitudinal coordinate

Introduction

An inverse heat transfer approach plays an important role in determination of properties of unknown materials and heat transfer coefficients in complex problems. Using the inverse heat transfer methods can be a useful way to obtain desirable results when accurate information does not exist about thermo-physical or thermo-chemical properties of ablative materials, thermal properties of modern complex materials in diverse directions, and surface heat flux that is resulted from different heat transfer ways (conduction, convection, and radiation). Many researchers devoted time to present complete inverse heat transfer methods and to clarify the necessary accurate measurement ways, like the published books of Ozisik and Orlande [1] and Beck et al. [2]. In addition, many attempts have been carried out to improve the numerical algorithms of inverse methods, such as the papers written by Beck [3], Weber [4], Battaglia et al. [5], and Beck et al. [6].

Employment of advanced inverse heat transfer methods accompanied by modern computational techniques and tools for the estimation of unknown parameters in complicated fluid mechanics problems are subjects of various research papers. For example, Huang and Yan [7] calculated temperature-dependent thermal properties by conjugate gradient method, Huang and Wang [8] estimated the surface heat flux in three-dimensional problems with the same method, and Molavi et al. presented their efforts to estimate the essential thermo-physical and thermo-chemical properties in ablation phenomenon in these three papers [9-11]. Furthermore, Yang et al. [12] used inverse solution to estimate time-dependent heat flux of a system composed of a multi-layer composite strip and semi-infinite foundation. Bahramian and Kokabi [13],

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similarly, used the inverse solution accompanied by experiment to determine the ablation characteristics of layered silicate nano-composite.

In this paper, the unknown thermal properties of a hot air gun that impinges on hot air jet perpendicularly upon a steelrod, the sides of which are insulated, are estimated by the inverse solution. Two different distances between hot air gun and rod surface are considered for determining variation of convective coefficient versus distance. These distances are chosen based on the circular jet potential core, and they are non-dimensional with respect to the hot air gun inlet diameter. H/D =2 and 6 are distances inside and outside the hot jet potential core, respectively. The produced temperature of this gun is another unknown parameter that is defined in this paper. The conjugate gradient method for parameter estimation is employed as an inverse algorithm for estimation of these unknowns. The numerical algorithm, solver validation, and experimental procedure that are used in this research are explained in the next three subsections, respectively, and the results are presented in the last section.

Numerical Algorithm

An iterative and one of the most efficient techniques among inverse heat transfer methods is chosen to estimate the unknown hot air gun properties in this study. "The conjugate gradient method for parameter estimation" is used as a base for the development of one-dimensional numerical solver. Heat transfer equation accompanied by suitable boundary and initial conditions govern the flow and solid behavior in this research. The governing equation and conditions are presented below.

$$\begin{aligned} &\rho C_p \frac{\partial T}{\partial t} = k\frac{\partial^2 T}{\partial x^2} && 0 < x < l, 0 < t \le t_f \\ &T = T_{in} && 0 < x < l, t = 0 \\ &T = T_l && x = l, 0 < t \le t_f \\ &h(T_{gun} - T_{surface}) = -k\frac{\partial T}{\partial x} && x = 0, t \ge 0 \end{aligned} \tag{1}$$

The convective coefficient, h, and T_{gun} are two unknown parameters in this inverse problem. Actually, in a direct problem, "h" and the produced temperature of the gun are the known, and temperature distribution along the rod or temperature variation in a fixed point versus time is the unknown function. However, in this inverse problem, the variation of temperature versus time in a fixed point of the rod is measured experimentally, and the convective coefficient and produced temperature should be defined based on this variation.

If P is assigned as an unknown parameters vector with N components ($P_j = P_1, P_2, ..., P_N$), the objective of the chosen algorithm is to minimize the ordinary least squares norm which is defined below:

$$S(P) = [Y - T(P)]^T [Y - T(P)] \tag{2}$$

Where Y is the vector of time variation of measured temperature in a fixed point of the rod, and T(P) is the calculated temperature variation versus time in a specified fixed point by solver based on the unknowns estimation. The iterative procedure of the conjugate gradient method for the minimization of the above norm S (P) is given by [1]:

$$P^{k+1} = P^k - \beta^k d^k \tag{3}$$

Where β^k is the search step size, d^k is the direction of descent, and the superscript k is the number of iterations. The direction of descent is a conjugation of the gradient direction, $\nabla S(P^k)$, and the direction of descent of the previous iteration, d^{k+1}. It is given as [1]:

$$d^k = \nabla S(P^k) + \gamma^k d^{k-1} \tag{4}$$

The Polak-Ribiereexpression is used for determination of conjugation coefficient γ^k.

$$\gamma^k = \frac{\sum_{j=1}^{N}\left\{[\nabla S(P^k)]_j [\nabla S(P^k) - \nabla S(P^{k-1})]_j\right\}}{\sum_{j=1}^{N}[\nabla S(P^{k-1})]_j^2} \tag{5}$$

The above equation is for k=1, 2, and for k=0, γ^k=0.Here, $[\nabla S(P^k)]_j$ is the j[th] component of the gradient direction evaluated at iteration k. The expression for the gradient direction is obtained by differentiating equation (2) with respect to the unknown parameter vector P, the result is [1]:

$$\nabla S(P^k) = -2(J^k)^T [Y - T(P^k)] \tag{6}$$

where J^k is the sensitivity matrix that is defined by the following equation.

$$J(P) = \left[\frac{\partial T^T(P)}{\partial P}\right]^T = \begin{bmatrix} \frac{\partial T_1}{\partial P_1} & \frac{\partial T_1}{\partial P_2} & \frac{\partial T_1}{\partial P_3} & \cdots & \frac{\partial T_1}{\partial P_N} \\ \frac{\partial T_2}{\partial P_1} & \frac{\partial T_2}{\partial P_2} & \frac{\partial T_2}{\partial P_3} & \cdots & \frac{\partial T_2}{\partial P_N} \\ \vdots & \vdots & \vdots & & \vdots \\ \frac{\partial T_I}{\partial P_1} & \frac{\partial T_I}{\partial P_2} & \frac{\partial T_I}{\partial P_3} & \cdots & \frac{\partial T_I}{\partial P_N} \end{bmatrix} \tag{7}$$

Where:
N: total number of unknown parameters
I: total number of measurements

The second step size, β^k, appearing in equation (3) is obtained by minimizing the function $S(P^{k+1})$ with respect to β^k. The final expression after some mathematical operations is:

$$\beta^k = \frac{\sum_{i=1}^{I}\left[\left(\frac{\partial T_i}{\partial P^k}\right)^T d^k\right][T_i(P^k) - Y_i]}{\sum_{i=1}^{I}\left[\left(\frac{\partial T_i}{\partial P^k}\right)^T d^k\right]^2} \tag{8}$$

where

$$\left(\frac{\partial T_i}{\partial P^k}\right)^T = \left[\frac{\partial T_i}{\partial P_1^k} \quad \frac{\partial T_i}{\partial P_2^k} \quad \cdots \quad \frac{\partial T_i}{\partial P_N^k}\right] \quad \text{or} \tag{9}$$

$$\beta^k = \frac{[J^k d^k]^T [T(P^k) - Y]}{[J^k d^k]^T [J^k d^k]} \quad (10)$$

Ozisik [1] introduced three techniques for computation of sensitivity matrix coefficient, but in this research, the finite difference approximation approach is used. Each component of the sensitivity matrix can be defined by implementation of the following forward difference:

$$J_{ij} = \frac{T_i(P_1, P_2, \dots, P_j + \varepsilon P_j, \dots, P_N) - T_i(P_1, P_2, \dots, P_j, \dots, P_N)}{\varepsilon P_j} \quad (11)$$

where $\varepsilon \approx 10^{-5}$ or 10^{-6}.

Gradient direction, conjugation coefficient, direction of descent, and second step size can be computed after computation of sensitivity coefficients. Finally, the unknown vector components are defined for the next iteration.

For the stopping criterion in this paper, “the discrepancy principle” is chosen. The iterative procedure is stopped when the following criterion is satisfied [1]:

$$S(P^{k+1}) < \varepsilon' \quad (12)$$

The value of tolerance ε' is chosen so that sufficiently stable solutions are obtained. If σ_i is the standard deviation of the measurement error at time t_i, and if the standard deviation of the measurement at any time is the same, $\sigma = \sigma_i$, the tolerance for stopping criterion can be defined as the following:

$$|Y(t_i) - T(x_{sensor}, t_i)| \approx \sigma_i \quad (13)$$

$$\varepsilon' = \sum_{i=1}^{I} \sigma_i^2 = I\sigma^2 \quad (14)$$

The summary of this algorithm can be explained as:

- Assume P^k
- Solve the governing equation to find $T_i(P^k)$
- Compute the sensitivity $\frac{\partial T_i}{\partial P^k}$
- Calculate P^{k+1}
- Check the criteria of the convergence

In the next section, the validation process of the developed solver is presented.

Solver Validation

To validate the accuracy of the chosen method, many test cases are examined before the experiments. In all test cases, the variation of temperature on a fixed position of the rod is considered as an input for the numerical solver.

First, an implicit second order finite difference solver calculates the variation of temperature versus time at the specified position for the imaginary sensor. In this step, the convection coefficient, the produced maximum temperature of the hot air gun, and the rod thermal properties are known, and the purpose is to calculate the distribution of temperature. Then, in the next step, this temperature variation—which is obtained from the numerical simulation—at a fixed point is given as the measured temperature to the solver for estimation of unknown parameters, convection coefficient and maximum produced temperature by the hot air gun. In order to check the validity of the solver on the broad interval of temperature, numerous convection coefficients and produced maximum temperature with different magnitudes are considered as unknowns. Some results of the numerical solver are tabulated below in Table1, and it should be mentioned that all approximations are completely reasonable.

In addition, to the broad range of convection coefficients and the produced maximum temperature, measurement period—which is defined as the time interval between two sequence measurements—and the measurement oscillations or errors should be checked in numerical solver results. In this study, two measurement period ways are considered for validation of the numerical solver approximations. First, the period of measurement is set equal to the time step of the temperature distribution solver, and second, measurement period is set longer than the simulation time step.

Table 1 presents the approximation results of some test cases that are considered for validation. The length of the rod is 10 centimeters; simulation time, t_f is 100 s; and 200 nodes divided the bar. The temperature of all nodes is set to 300Kelvin degrees at initial time, the measurement is considered errorless, it means $\sigma = 0.001$, and the temperature at the end of the bar is set to 273 degrees of Kelvin.

Table 1. Obtained results of numerical solver in various test cases

Convection Coefficient ($W/m^2 K$)	Approximated convection coefficient by solver ($W/m^2 K$)	Initial guess of convection coefficient ($W/m^2 K$)	Produced maximum temperature by hot air gun (K)	Approximated produced temperature by solver (K)	Initial guess of produced temperature (K)	Measurement time interval (s)	Sensor position from the head of the bar (m)
1000	1000.05	1200	500	499.989	600	Equal, 0.5	0.025
3000	2999.98	800	380	380.000	310	Equal, 0.1	0.005
1000	1009.43	400	350	349.591	310	Equal, 0.5	0.05
1000	999.852	500	400	400.008	600	Simulation =0.01 Measurement=2	0.025
500	499.372	350	500	500.217	350	Simulation =0.01 Measurement=5	0.01

Figure 1 depicts three input temperature data of the solver for estimation of unknown parameters. Case I and II contain oscillation and errors on imaginary measurements, the aim of this test is to check the flexibility of numerical solver in estimation of unknown parameters when the measurements are faced with dominated errors. The approximated results are presented in table 2. It should be mentioned that the convective coefficient and produced temperature of hot air gun are considered 1500 W/m^2 K and 800 K, respectively. The initial guess for the convective coefficient is 800 W/m^2 K and for the produced temperature by gun is 500 K. The imaginary sensor is located at the 0.0075 m from the head of the rod, and measurement time interval is 1 s.

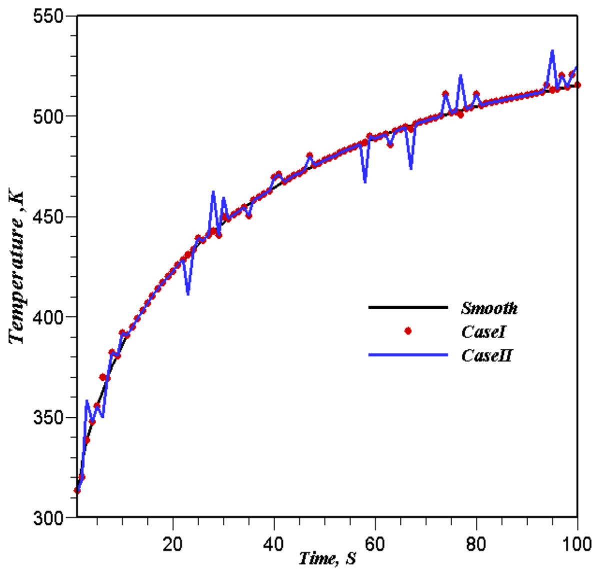

Fig. 1 Oscillatory imaginary measurements

Table 2. Obtained results from numerical solver in disturbed imaginary measurements

Approximated convection coefficient by solver (W/m^2 K)		Approximated produced temperature by solver (K)		σ	
Smooth	1499.99817	Smooth	800.00038	Smooth	0.0001
Case1	1505.08588	Case1	800.28533	Case1	0.1
Case2	1437.64301	Case2	815.87724	Case2	0.1

Experimental Procedure

For temperature variation measurement, the appropriate thermocouple is utilized in this study; it is joined to the trans-meter, and trans-meter, ampere-meter, and power supply are connected to each other in a series circuit. A steel-304 rod with the length 14.5 cm is chosen for this experiment. The side surface of the rod is insulated so that the measured data can be given as input to one-dimensional developed solver. The power supply is set to produce 15 V in this study.

When the temperature increases, the ampere-meter starts to show higher electric current (μA). Based on the trans-meter set-up, when it senses the 0 degree of Celsius, the ampere-meter shows the 4 μA, and when 300 degrees of Celsius is sensed, the ampere-meter should show 20 μA. In addition, the variation of temperature versus electric current is linear, so each micro ampere increase equals to 18.75 degrees of Celsius temperature rise. The thermocouples have been calibrated in a reference laboratory.

Figure 2 shows the experiment set up which is used in this research. The outlet diameter of hot air gun, the properties of which are unknown, is 2.3 cm and two different distances between hot air gun outlet and rod surface, H/D = 2 and 6, are set. The other side of the rod is connected with the ice in order to produce boundary condition at the fixed temperature of 273 K.

The electric current variation is recorded by a camera. Then the data is extracted in every three seconds. The measured temperature error is around 1.0 degree. Although the side surface of the rod is insulated, it is possible that heat transfers from the other directions rather than the only axis of the rod, and the heat transfer problem cannot be considered as one-dimensional. Therefore, in order to prevent any heat transfer from the side surface of the rod, a PTFE plate is pierced and is located in the head of the rod.

A start time is another important parameter; it takes some seconds for hot air gun to receive its steady condition. Hence, another plate is hold in front of the gun for some seconds in order to ensure the steady conditions of the hot air gun and it produces hot jet; then, the plate is moved, and the hot air jet impinges on the rod head.

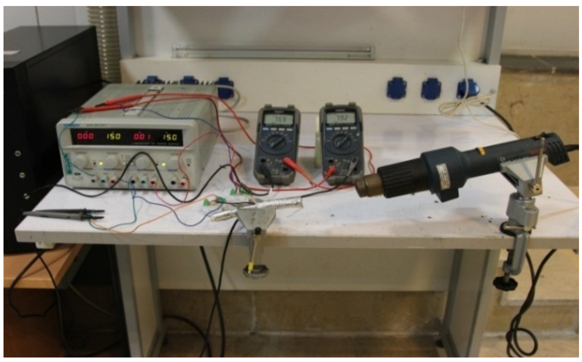

Fig 2. Experiment set up

Results and Discussion

The produced temperature of the hot air gun and the variation of convective coefficient versus distance between the gun outlet and the rod are the important parameters that are to be specified in this paper. Table 3 presents the estimated convective coefficient and the produced temperature of the hot air gun by the developed solver when the temperature variation measurements at two dimensionless distances between gun and rod are given as inputs to the solver. It should be mentioned that the temperature variation during 102 seconds is extracted from the measurements of the thermocouple that is located in 1cm distance from the head of the rod.

Table 3. Estimated results from experiments

H/D	Convective Coefficient (W/m^2K)	Produced Temperature (K)
2	272	615
6	195	589

Figures 3 and 4 depict the comparison of measured and estimated temperature variation versus time in two dimensionless distance H/D 2 and 6, respectively. These figures prove the acceptable estimation of numerical solver. Circular jets potential cores usually are around 4-5 times greater than the outlet diameter. At the potential core region, the jet velocity is equal to the jet outlet velocity. As jet travels more distance, it expands, and its shear layers merge and pierce potential core, so jet velocity starts to diminish. It is reasonable to expect that the convective coefficient decreases when the distance between hot air gun and rod head increases because jet axis velocity has a direct effect on the stagnation point heat transfer.

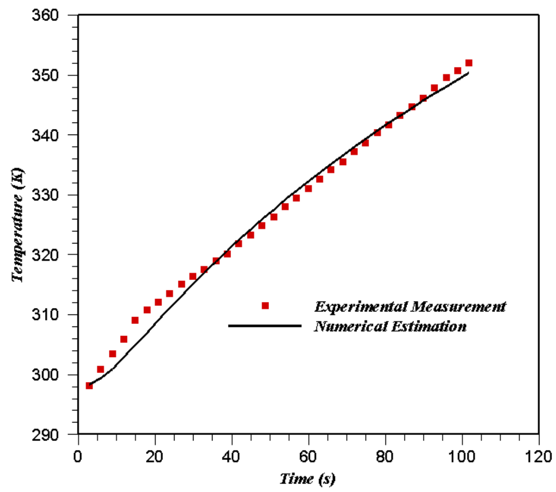

Fig 3. Comparison of measured and estimated temperature variation versus time for H/D=2

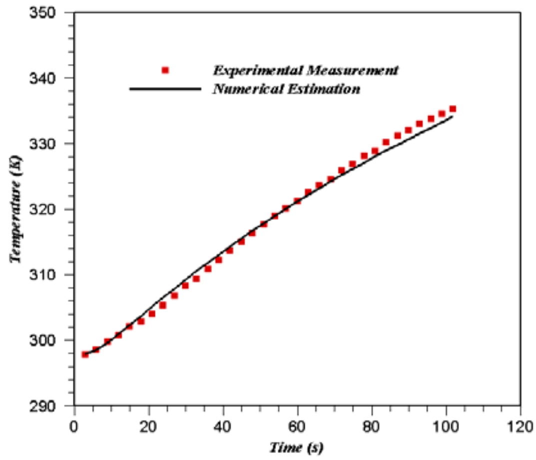

Fig 4. Comparison of measured and estimated temperature variation versus time for H/D=6

It is found that the average produced temperature of hot air gun is around 600 degrees of kelvin. If the produced temperature is given as a known variable to the solver, the only unkonwn parameter becomes convective coefficent.For these cases, the varition of convective coefficent versus dimensionless distance is presented in table 4.Therefore, by determination of this hot air gun properties, it is possible to use this device in the future tests for estimating unknown thermo-physical and thermo-chemical properties of ablative materials and insulations that are suitable for the usage in various critical parts of propulsion systems, heat shields, and spacecraft Thermal Protection System.

Table 4. Estimated convective coefficient for fixed produced temperature

H/D	Convective Coefficient (W/m^2K)	Produced Temperature (K)
2	288	600
6	191	600

Conclusion

The unknown properties of the hot air gun are determined by combination of numerical analyses and experimental measurments. In other words, the inverse heat transfer approach is used to estimate convection coefficent and maximum produced temperature of a hot air gun.The conjugate gradient method for parameter estimation is choesn as an inverse heat transfer technique for the numerical part, and measuremnts of temperature variation versus time in a fixed point of a steel-304 rod by a thermocouple belonging to the experimental section. The variation of convective coeffieceint versus two dimensionless distancesbetween hot air gun outlet and rod surface—inside and outside the hot jet potential core—is presented. The avarage produced temperature of this device is around 600 kelvin, and convective coefficient decreases when the jet leaves behind its potential core. This information can be useul for experimental analyses of thermal protection systems that are utilized in spacecraft or different parts of propulsion devices.

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