Calculation Aerodynamic Heating to A Stagnation Point of A High Speed 2-D Cylindrical Nose for Protection the Mechatronics System and Structure

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Abstract: The flow field and temperature distribution of high-speed aerodynamic heating at stagnation point. The heat transfer through a thin, a thick or composite wall were analyzed in the present study. Convection coefficients and heat fluxes due to aerodynamic heating on critical surfaces of hypersonic vehicle are obtained analytically. The applicability of recovery temperature for stagnation regions is discussed. Convection coefficient for the curvature forward stagnation region is obtained directly from 2-D stagnation region correlation. This paper shows and application of Crank-Nicolson scheme to solve numerically transient heat conduction problem conjugate with high stagnation point heating problem. The results show good agreement with a known lumped system method solution for a thin wall. The present method of solution can be extended to solve three dimensional heat conduction problems in multi-layer composite bodies as well.

Key words: Stagnation point, Aerodynamic Heating, Lumped System, Composite wall.

1. Introduction

Aerodynamic heating is the heating of a solid body produced by the passage of fluid (such as air) over the body. The heating is caused by friction and by compression processes, significant chiefly at high speeds. Experiments on aerodynamic heating are done in a shock tube in which a shock is made to travel by rupturing of a diaphragm separating of high pressure and low pressure side. This helps in checking the effect of adverse increases in temperature on different materials, and to check whether there is some reaction on it. Even aerodynamic heating is a topic of great concern in re-entry vehicles where, due to great friction at high velocity, there's heating at the surface. To prevent which these vehicles are given blunt shapes to produce bow shock. As a result most of the heat is dissipated to surrounding air.

For practical aerodynamic heating problems had been developed for years. The purpose of this paper select a simple but useful ways to deal with the stagnation point heat transfer on a cylindrical body with different kinds of wall thickness or layers and consider heat transfer to the body for different types of conduction ways. There are two ways for comparison are present in the paper which named (1) lumped system for shin shell, and (2) finite difference calculation for thin and thick shell and determined the best ways for realistic using. For early predict the aerodynamic heating problems, usually simplify the heat conduction model to a lump system model [1] [2] for a thin wall let the Biot number less than 0.1, so the lumped thermal model is applicable. However, for most of real condition the wall is not thin and Biot number greater than 0.1, then the lumped system is not useful for that conditions. We need to choose another ways to calculate these kinds of problems. In this study, have choice the numerical calculation method based on finite difference [3] to approximate it, above all for composite wall or two layers problems [4-6]. The ascent peak stagnation point and wing leading-edge equilibrium wall temperatures of hypersonic trans-atmospheric vehicles are about 3000K to 4000 K, respectively [7]. Aero-thermal environments for the design of

X-34 were generated from conservative approach, based solely on engineering methods applied to critical areas [8,9]. Approximate analyses have used to estimate the stagnation-point heat flux [10]. Study of the influence of nose bluntness on heating levels for simple geometries corroborated that blunting reduces laminar heat transfer to the hypersonic vehicle [11]. An overview revealed that to compute the surface temperature accurately, it is necessary to describe the convection mechanisms [12]. Based on the survey, it is found that convection correlations are available for axisymmetric and 2-D stagnation regions [13,14].

Recently, Gui et al. [15] had studied numerical investigation on drag and heat-transfer reduction using 2-D planar and axisymmetrical forward facing jet. Monti [16] and Periklis [17] had studied reentry aerothermodynamics of atmospheric entry vehicles. Recently, there are some related studies for the aerodynamic heat transfer problems by Siavash et al. [18-25]. This paper is mainly dealing with the Aerodynamic heating problem more realistic application to a real condition. The paper have predict the temperature distribution in the high speed flying cylindrical body nose tip as a function of time and to predict the temperature by a set of trajectory data. Due to the different types of wall conditions so that choice different kinds numerical methods for approximations are presented.

2. Theoretical Analysis

This investigation is concerned with the temperature distribution in a high-speed flying body with cylindrical nose tip. The main purpose of this investigation is to predict the response of the heat transfer on the stagnation point of the sphere's shell wall during a period 40 seconds.

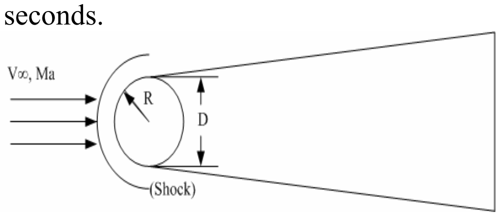

Figure.1 A schematic diagram of high speed aerodynamic heating at stagnation point

A schematic diagram of high-speed aerodynamic heating at stagnation point is presented in Figure 1 to illustrate the physical situation and the symbols of the parameters needed for the analysis. The following assumptions are in the analysis:

(1)Unsteady equilibrium flow
(2)The heat conduction is one dimensional
(3)The physical properties of each layer of the sphere nose tip are uniform and independent of temperature.
(4)The convective heat transfer coefficient is dependent on the surface temperatures
(5)The ambient air is transparent to thermal radiation.
(6)The trajectory data P，ρ，T，μ，Cp initially from the sea level temperature 288.3 K and all are idea gas.

Initially, the cylindrical nose has a uniform temperature equal to the ambient temperature but suddenly the surfaces are exposed to an incident time-varying heat flux, following the flying at high speed. Then the cylindrical body exchanges heat with the surrounding environment by convection and radiation. Following the trajectory conditions and calculation the skin friction temperature by Runge Kutta method for such case: A lumped thin shell wall thickness T_s =0.000762m, $\in$ = 0.3, σ =5.67×10^{-8}W/m^2.K^4, w=849kg/m^3, and trajectory data shown as figures 2-(a), 2-(b).Formulation the related problems and calculation processes are divided into two parts as follows:

2.1 For a lumped system (A thin wall)

The governing equation of the practical aerodynamic heating problems may be Expressed symbolically as follows:

Energy equation:

$$Q_{local}=q_{conv}-q_{rad} \tag{1}$$

or

$$\frac{dT_W}{dt}=\frac{h}{G}\left(T_{aw}-T_w\right)-\in\sigma T_w^{\ 4} \tag{2}$$

where

$$Q_{local}=cT_s w\left(\frac{dT_W}{dt}\right)$$

$\in$: Emissivity of the surface

σ :Stefan-Boltzman radiation

constant $\left(5.67\times10^{-8}\mathrm{W/m^2.K^4}\right)$

c : specific heat of skin $\left(\mathrm{Nm/kg.K}\right)$

T_s : skin thickness $\left(\mathrm{m}\right)$

w : specific weight of skin material $\left(\mathrm{kg/m^3}\right)$

T_w : outer surface skin temperature (k)

t : time(sec)

h : coefficient of heat transfer $\left(\mathrm{W/m^2.K}\right)$

T_{aw} : Adiabatic wall temperature

G : the heat absorption capacity of the skin $\left(G=c.t_s.w\right)$

From Equation (2) known that it is a non-linear unsteady energy equation could be solved by Runge Kutta method and the solving process as follows:

(3) Conduction heat transfer calculation: Finding the value T_W

$$\frac{dT_W}{dt}=F\left(h, T_W, q_{rad}, T_W-T_\infty\right) \quad (3)$$

From Equation (2) and (3) known that it is a non-linear unsteady energy equation could be solved by Runge-Kutta method or other numerical integration methods. The paper chooses time steps 0.5 sec to 1.0 sec and find a reasonable comparison result.

2.2 For a thick uniformed wall

$$\frac{dT_w}{dt}=\alpha\frac{\partial^2T_w}{\partial x^2} \quad (4)$$

Where α is the thermal diffusivity of the wall. The corresponding boundary conditions:

$$\frac{dT_w}{dx}=0 \quad \text{(for inner wall)}$$

$$-k\frac{dT_w}{dx}=h\left(T_w-T_\infty\right)-\in\sigma T_w^4$$

(for outer wall)

2.3 For a thick composite wall

$$\frac{dT_w}{dt}=\alpha_i\frac{\partial^2T_w}{\partial x^2} \quad (5)$$

Where is the thermal diffusivity of the layers, the corresponding boundary conditions:

$$\frac{dT_w}{dx}=0 \quad \text{(for inner wall)}$$

$$-k\frac{dT_w}{dx}=h\left(T_w-T_\infty\right)-\in\sigma T_w^4$$

(for outer wall)

B.C For interfaces

$$K_i\frac{\partial T_w{}^i}{\partial x}=K_{i+1}\frac{\partial T_w{}^{i+1}}{\partial x}$$

$$T^i=T^{i+1}$$

2.4 Convection heat transfer calculation

For the purpose of finding the coefficient of heat transfer (h) value of this problem, the influence of the wall directly heat transfer results first important factor is due to the high-speed stagnation fluid heating phenomena. Because the stagnation point mostly near to a laminar flow and specify to a boundary layer problem. Through a self-similar solution to the governing boundary for the stagnation point case become respectively [26-27]

$$\left(Cf''\right)'+ff''=\left(f'\right)^2-g \quad (6)$$

$$\left(\frac{C}{P_r}g'\right)'+fg'=0 \quad (7)$$

With boundary conditions

$$f\left(0\right)=0, \; f'\left(0\right)=0, \quad g\left(0\right)=g_w$$

Equation (6) and (7) are the governing equation for a compressible stagnation point boundary layer, Numerical solutions to them can be obtained by the shooting technique, for simply state the result of solving equation (6) and (7), correlated in the following expression obtained from Ref [28] in cylindrical nose

$$q_w=0.57P_r^{-0.6}\left(\rho_e\mu_e\right)^{\frac{1}{2}}\sqrt{\frac{du_e}{dx}}\left(h_{aw}-h_w\right) \quad (8)$$

Equation (8) is a result for aerodynamic heating to a stagnation point on a blunt cylindrical body, the paper choosing calculation formula is reference to it.

2.5 Radiation heat transfer calculation:

Finding the value of radiation heat transfer rate q_{rad} can be formulate as following

$$q_{rad}=\in\sigma T_w{}^4 \quad (9)$$

3. Numerical Technique

3.1 For lump system—A thin wall

The solution procedure for equation (2) is solved numerically by a Runge-Kutta method with respect to the initial and boundary layer properties according to the trajectory real flying conditions.

3.2 For thin and thick wall

The solution procedure for equations (4) and (5) are solved numerically by a finite difference Crank-Nicolson technique with respect to the initial and boundary conditions outlined previously. 8 non-uniformly distributed grid points were used in the thin wall, 8 to 16 non-uniformly distributed grid points were used in the thick wall, and the time steps in the final calculations were 0.5 seconds for economy calculate choice. These non-linear ordinary differential equations have discretized by a second-order accurate central difference method, and a computer program has developed to solve these equations.

3.3Calculation steps of the entire system

1. Calculate thermodynamic fluid properties from the wall temperature and free-stream temperature according to the trajectory calculation results.
2. Calculate the convective heat transfer for the stagnation point.
3. Solve the heat-conduction equation of the wall at the stagnation point with the local convective heat-transfer coefficient by different methods.

4. Discussion and Results

The purpose of this investigation is to predict the response of the heat transfer on the stagnation point of the sphere's shell wall during a period 40 seconds, flying with the high -speed Mach numbers up to 10. A schematic diagram of high-speed aerodynamic heating at stagnation point presented in figure 1 to illustrate the physical situation and the symbols of the parameters needed for the analysis. The figures 2-(a) and 2-(b) are the simulation trajectory in this study. Figure 3 depicts the surface temperatures of a thin wall that calculated by (a) lumped system methods (b) finite difference methods and find out that the results are almost closely with each other. Figure 3 get a very nice comparison between the two different types model for a thin wall (T_s=0.000762m). Usually simplify the heat conduction model to a lumped system model for a thin wall let the Biot number less than 0.1, so the lumped thermal model is applicable.

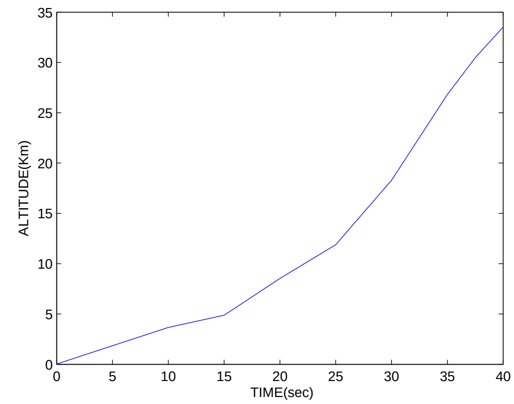

Figure 2-(a). Trajectory data for Time (sec) vs. Altitude (km)

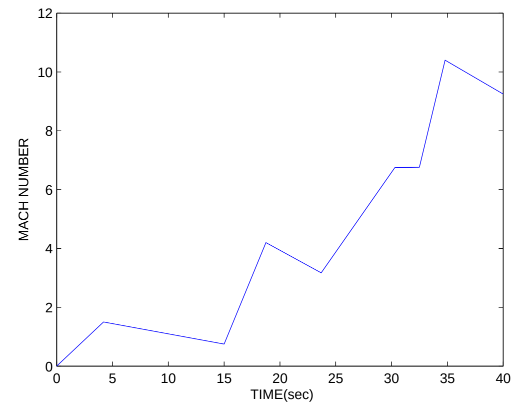

Figure 2-(b). Trajectory data for Time (sec) vs. Mach Number

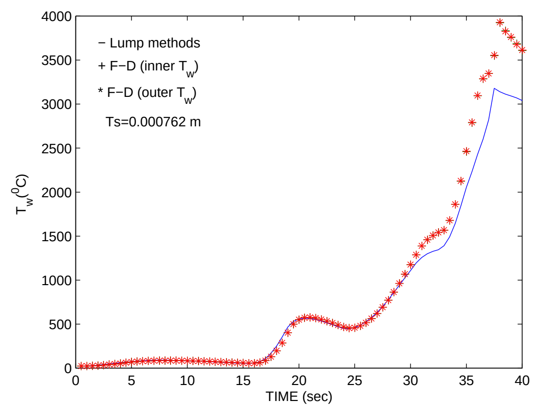

Figure 3. Comparison of two conduction theories for Lump method vs. F-D method

The thin wall temperature up to 4000^0C just in a short period of time for forty seconds.

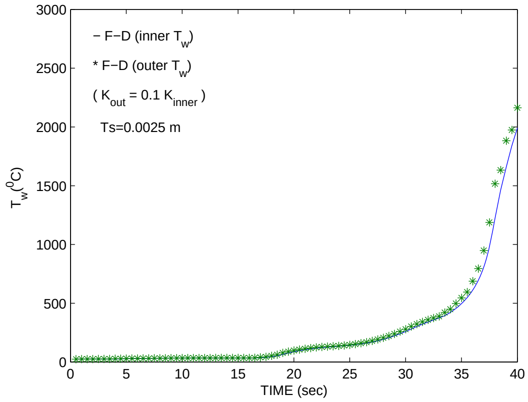

Figure 4. Two layers composite thin wall for different K values

Figure (4) depicts two layers composite wall inner and outer wall temperature distribution(T_s =0.0025m). Where the outer layer conductivity constant $K_{out} = 0.1K_{inner}$, so produce a significance adiabatic effect , and let the outer wall temperature increase but the inner wall temperature decrease. The whole range temperature at the wall is also decreased to 2/3 ratio value of the original single layer wall temperature. The thin wall temperature up to 2000^0C just in a short period of time forty seconds.

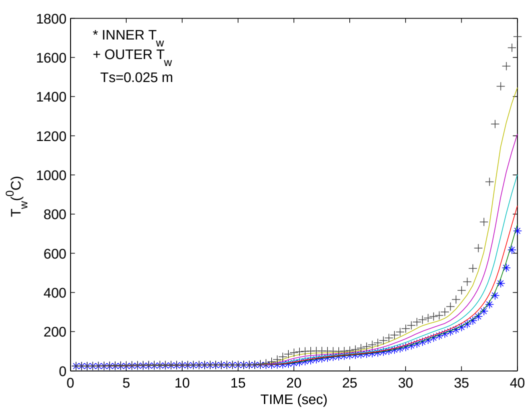

Figure 5. Uniform one layer thick wall conduction phenomenon

Figure 5 and Figure 6 depict the surface temperature of a thick wall (T_s =0.025m). which calculated by only Finite Difference method, From figure 5 find out that there are difference for the inner or outer wall temperature, Because the wall is thick enough. However, if the wall for different materials composite wall $K_{out} = 0.1K_{inner}$, it will be produce an obviously different result from figure 6.

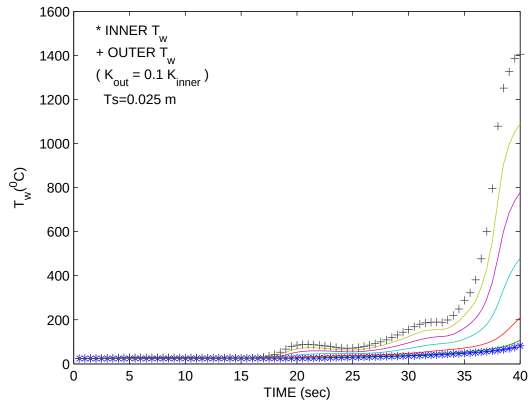

Figure 6. Composite two layers thick wallconduction phenomenon for different K values

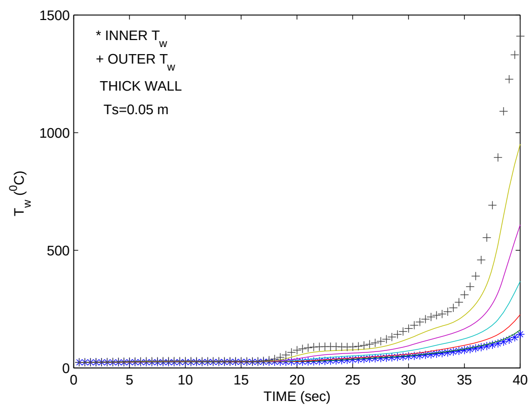

Figure 7. Uniform thick two layers thick wall conduction phenomenon

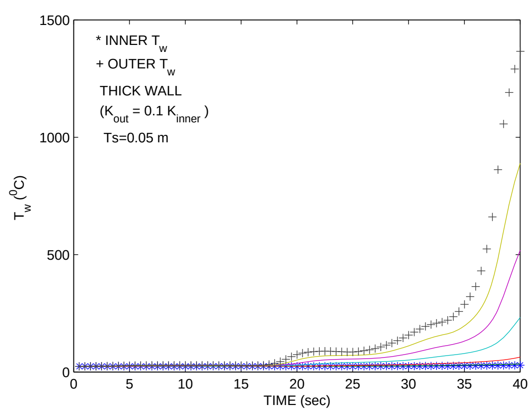

Figure 8. Composite two layers thick wall conduction phenomenon for different K values

Figure 7 and figure 8 have the same types and results as figure 5 and figure 6. The only difference between them is the wall in which is not thin but a thicker wall (T_s =0.05m). The lump system method is no more suites to that condition again. On the other hand, for a thicker wall may find out that the temperature distribution from outer to inner have significance difference, So that it could not use a simple lump system method to approach it. The contribution in this study are presented a practical aerodynamic heating problem of stagnation point at high speed flying analysis works for different kinds of wall conditions. It is a conjugate heat transfer problem in the solving problem that included convection, conduction, and radiation by different physical modules and numerical methods.

5. Conclusion

A practical aerodynamic heating problem of stagnation point at high speed flying analysis works for different kinds of wall conditions has been studied in this paper. It is a conjugate heat transfer problem in the solving problem that included convection, conduction, and radiation. The conduction area is included lump system, composite wall. Therefore, in this study has choice numerical methods to solve the problems and get some required results. The paper has applied a fundamental principle from the early research jobs and extended to the recently pertinent papers about the more complexes heat conduction at thick and composite wall conditions. From the results and discussions, get a reasonable analysis results. On the other hand, there are many interest topics can be study in the future, such as the flying body temperature predict, the flying wing temperature predict or some other different configurations designing jobs.

Nomenclature:

c : specific heat of wall $(\mathrm{Nm/kg.K})$

c_p : specific heat at constant pressure $(\mathrm{Nm/kg.K})$

C_f :skin friction coefficient

f : dimensionless velocity at the wall for heat convection.

f' : first order dimensionless velocity gradient at the wall for heat convection.

f'' : second order dimensionless velocity gradient at the wall for heat convection.

g : dimensionless temperature at the wall for heat convection.

g' : first order dimensionless temperature gradient at the wall for heat convection.

G : the heat absorption capacity of the skin $(G=c.t_s.w)$

h : coefficient of heat transfer $(\mathrm{W/m^2.K})$

K: conductivity of the fluid $(\mathrm{W/m.K})$

k: conductivity of the fluid $(\mathrm{W/m.K})$

P : pressure.

Pr: Prandtl number.

q_{conv} : convective heat transfer rate at the wall. $(\mathrm{W/m^2})$

q_{rad} : radiation heat transfer rate at the wall. $(\mathrm{W/m^2})$

q_w : heat transfer rate at the wall. $(\mathrm{W/m^2})$

Q_{local} : local heat transfer rate at the wall. $(\mathrm{W/m^2})$

t : time(sec)

T_s : skin thickness (m)

T_w : outer surface skin temperature (k)

T_{aw} : adiabatic wall temperature(k)

T_e : flow temperature at the outer edge of the boundary layer. (k)

T_∞ : constant ambient temperature. (k)

u :velocity components in the x directions.(m/s)

w :specific weight of skin material $(\mathrm{kg/m^3})$

x : horizontal coordinate.

Greek symbols:

α : the thermal diffusivity of the wall. $(\mathrm{m^2/s})$

ρ: density of the air. $(\mathrm{kg/m^3})$

$\in$: Emissivity of the surface

σ : Stefan-Boltzman radiation constant $(5.67\times10^{-8}\mathrm{W/m^2.K^4})$

Subscripts

aw : adiabatic wall

e : flow properties at the outer edge of the boundary layer.

stag : stagnation region

0: stagnation value

∞: free-stream value

References:

[1] Lo, Hsu., Determination of Transient Skin Temperature of Conical Bodies During Short Time, High Speed Flight, NACA TN 1725, (1948).

[2] Truitt, R.W .and Anderson , A. K. , JR. Determination of Transient Skin Temperature of at the Stagnation Point of a Hemi cylindrical Nose., Virginia Academy of Science, Engineering Section Meeting , May 10 , (1957) .

[3] Joe D. Hoffman, Numerical Methods for Engineers and Scientists ", McGraw Hill , Inc., (1992) .

[4] A. L. Crosbie and R. Viskanta, Int. J. Heat Mass Transfer vol 11, pp 305 (1968).

[5] P.S Ghoshdastidar and A. Mukhopadhyay, Transient Heat Transfer From A Straight Composite Fin, Int. Comm. Heat Mass Transfer Vol 16,257-265(1989).

[6] M. D. Mikhailov and M.N. Ozisik, Int. J. Heat Mass Transfer, Vol 29, No.2 , 340,(1986).

[7] M.E. Tauber, G.P. Menees, H.G. Adelman, Aerothermodynamics of transatmospheric vehicles, AIAA J. Aircraft 24 (9), 594–602 (1987).

[8] H.D. Fuhrmann, J. Hildebrand, T. Lalicata, Aerothermodynamic overview, X-34, AIAA J. Spacecraft and Rockets 36 (2) ,153–159 (1999).

[9] K.E. Wurster, C.J. Riley, E.V. Zoby, Engineering aerothermal analysis for X-34 thermal protection system design, AIAA J. Spacecraft and Rockets 36 (2), 216–228 (1999).

[10] F. Rankins, D.J. Pines, Relative heat load comparison of vehicles flying hypersonic transatmospheric trajectories, AIAA J. Spacecraft and Rockets 37 (4), 491–498 (2000).

[11] E.V. Zoby, R.A. Thompson, flow field and vehicle parameter influence on hypersonic heat transfer and drag, AIAA J. Spacecraft and Rockets 27 (4), 361–368 (1990).

[12] A. Frendi, Accurate surface temperature prediction at high speeds, Numerical Heat Transfer; Part A: Applications 41 (5), 547–554 (2002).

[13] J.D. Anderson Jr., Hypersonic and High Temperature Gas Dynamics, McGraw-Hill, New York, (1989).

[14] R.W. Truitt, Fundamentals of Aerodynamic Heating, Ronald Press, NewYork, (1960).

[15] Gui, Ye-Wei; Wang, An-Ling; He, Li-Xin, Geng, Xiang-Ren, Numerical investigation on drag and heat-transfer reduction using 2-D planar and axisymmetrical forward facing jet ; Kongqi Donglixue Xuebao/Acta Aerodynamica Sinica, v 24, n 1, March, p 85-89 (2006)

[16] Monti, R., A low risk reentry: Looking backward to step forward; Paterna, Diego M. Source: Aerospace Science and Technology, v 10, n 2, March, p 156-167(2006).

[17] Periklis; Web-based computational investigation of aerothermodynamics of atmospheric entry vehicles Papadopoulos, Subrahmanyam, Prabhakar Source: Journal of Spacecraft and Rockets, v 43, n 6, November/December,p1184-1190 (2006).

[18] Siavash H. Sohrab, A Modified Theory of Turbulent Flow over a Flat Plate, Proceedings of the 5th IASME / WSEAS International Conference on Fluid Mechanics and Aerodynamics, Athens, Greece, August 25-27, 2007, 565-291

[19] Donatienne Portugaels, Jerome Anthoine, Domenico Olivari, Determination of Aerodynamic Force Coefficients of Octagonal Lighting Columns from Wind Tunnel Experiments, Proceedings of the 5th IASME / WSEAS International Conference on Fluid Mechanics and Aerodynamics, Athens, Greece, August 25-27, 2007, 565-375

[20] M. Malerba, M. Argento, A. Salviuolo, G. L. Rossi , An Approach for Numerical Validation of Aerodynamic Effects through Thermography, Proceedings of the 5th IASME / WSEAS International Conference on Fluid Mechanics and Aerodynamics, Athens, Greece, August 25-27, 2007, 565-191

[21]Abbas Mansoori, Mohammad Reza Bazargan-Lari, Evaluation of Turbulent Models in Sudden Expansion Analysis at High Reynolds Numbers, Proceedings of the 5th IASME / WSEAS International Conference on Fluid Mechanics and Aerodynamics, Athens, Greece, August 25-27, 2007, 565-124

[22]Ahmad Reza Bahramian, Mehrdad Kokabi, Mohammad Hossein Navid

Famili and Mohammad Hossein Beheshty, High temperature ablation of kaolinite layered silicate/phenolic resin/asbestos cloth nanocomposite Journal of Hazardous Materials, Volume 150, Issue 1, 15 January 2008, Pages 136-145

[23] Roxan Cayzac, Christophe Grignon and Eric Carette, Navier–Stokes computation of heat transfer and aero-heating modeling for supersonic projectiles Aerospace Science and Technology, Volume 10, Issue 5, July 2006, Pages 374-384

[24] Ahmad Reza Bahramian, Mehrdad Kokabi, Mohammad Hossein Navid Famili and Mohammad Hossein Beheshty, Ablation and thermal degradation behaviour of a composite based on resol type phenolic resin: Process modeling and experimental Polymer, Volume 47, Issue 10, 3 May 2006, Pages 3661-3673

[25] Laszlo Garbai, Szabolcs Mehes, New Analytical Solutions to Determine the Temperature Field in Unsteady Heat Conduction,WSEAS TRANSACTIONS on HEAT AND MASS TRANSFER Issue 7, Volume 1, July 2006,677-685

[26] Van Driest, E. R., Investigation of Laminar Boundary Layer in Compressible Fluids Using the Crocco Method, NACA TN 2579, January (1952).

[27] Cohen C. B., and E. Reshotko, Similar Solutions for the Compressible Laminar Boundary Layer With Heat Transfer and Pressure Gradient, NACA Report 1293, (1956).

[28] Van Driest, E. R., The Problem of Aerodynamic Heating, Aeronautical Engineering Review, 26-41, October (1956).