COMPRESSIBLE BOUNDARY LAYER HEAT FLUX MEASUREMENT USING EMBEDDED THERMOCOUPLES

Zhao xuejun1*, Ma yuanhong2, Xiao weizhong3*****
***China Academy of Aerospace Aerodynamics,**
**** China Academy of Aerospace Aerodynamics,**
*****China Academy of Aerospace Aerodynamics**

Keywords: *turbulence transition, thermocouples, hypersonic, heat flux*

Abstract

This paper proposes a temperature/heat flux measurements methodology to detect the flat plate compressible boundary layer turbulence transition. In the wind tunnel testing, we use the embedded thermocouples to measure temperature at the positioned points in the flat plate. The tests condition is Ma=5, and the total pressure is 1.0MPa. Then by inverse heat conduction problem analysis, we obtain surface temperature and heat flux of one dimension half space plate in time domain point of view. This approach does not require the specification of the imposed surface boundary condition. By the testing results, we give heat flux distribution on the flat plate with and without trips. And by comparing the testing results, we show transition effects got from the heat flux results.

1 Introduction

To understand thermo physical properties needs to measure accurately the temperature, heat flux. For some boundary conditions, such as smooth surface, it is not good to fix thermocouple on the surface. Also, for some very high temperature environment, it cannot work if the thermocouple is flush mounted on the surface. So the novel approaches are required to estimate the surface heat flux and temperature based on interior measurements. For the development of hypersonic vehicle, the ground simulation (ground test and CFD) techniques are very important. But the ground simulation techniques also show the insufficiency in the development of the vehicles, such as that the wind tunnel testing can not simulate all the similar parameters, and have some limitations in model size, Reynolds number, temperature and real gas effects. To meet the difference between the scale model and real vehicle, the testing vehicle became the research point in current days. The flight testing cost too much, so every experiments must be researched in detail, and must borrow from the ground testing techniques. Then the flight testing can success.

But the adverse environments preclude the use of surface instrumentation for several reasons. Firstly, surface sensor damage leading to bad results; secondly, surface sensors change the vehicle surface conditions; and lastly the intrusive nature of surface instrumentation that affects the desired measurement. Therefore, sensors must be embedded below the surface and one must use an inverse heat conduction technique to predict the surface condition. To measure the temperature and heat flux, infrared thermo graph, platinum thin film thermo resistant, thermocouple and so on is developed and used [1,2]. But all these technologies do not have enough measurement precision. Also normal heat flux evaluation is based on classical diffusion theory that uses Fourier's law for estimating the heat flux, qx'' irrespective of steady-state or transient conditions, and Fourier's law which is a constitutive relationship or particular law [3]. Sensor

development that uses Fourier's law, qx'', k, T/x and is normally limited to surface mounting (here, qx'' =heat flux in the x direction, T=temperature, k=thermal conductivity, and x=spatial variable).
To measure the surface heat flux using the in-depth thermocouples, there are many challenges associated with solving the inverse heat conduction problem. Inverse techniques must properly characterize the embedded sensor to account for these parameters and to avoid under-predicting and time delaying the surface thermal condition. Additionally, the accuracy of inverse techniques depends on accurate knowledge of the probe depth and thermophysical properties.
Kulish et al. gave the temperature and heat flux relationship based on Laplace's law [4]. In the Ref. [5], [6], Frankel. I.J. et al. gave the temperature and heat flux relationship based on Green's function.
In this paper, we design a flat plate to do the heat flux measurement experiment. The thermocouples are embedded under the flat plate surface. After the tests, we show the temperature and heat flux distribution along the flat plate central line to detect the transition.

2 One-dimensional Half-space

For the one-dimensional half-space condition, the normal space domain viewpoint to heat flux is based on:

- using a constitutive relationship (Fourier's law) for estimating the heat flux, q'' irrespective of

steady-state or transient conditions; and,

- using Fourier's law, as approximated by q'' ≈ k ΔT/Δx, for heat flux gauge development.

An alternative viewpoint for investigating transient problems lies in the implementation of a time-domain analysis. A time domain viewpoint to heat flux is based on:

- combining the general law (conservation of energy) and constitutive relationship (Fourier's law) to form an integral relationship1-4 between heat flux and temperature in the time variable.

The solution to the one-dimensional, half-space, transient heat conduction problem will be demonstrated by both Cosine and Sine transforms.

- Cosine transform solution assumes q''(0,t) is given.
- Sine transform solution assumes T(0,t) is given.

Physics: Finite width slabs (of width L) behave as half-spaces for small times, $t < t_{pen}$ (L)

Consider the heat equation in the half space:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t}(x,t) = \frac{\partial^2 T}{\partial x^2}(x,t), (x,t) \geq 0, \quad \text{............ (1)}$$

Subject to the initial condition, $T(x,0) = T_0 = 0$, and by using Fourier since or cosine transforms. We obtained the surface temperature and heat flux equation.

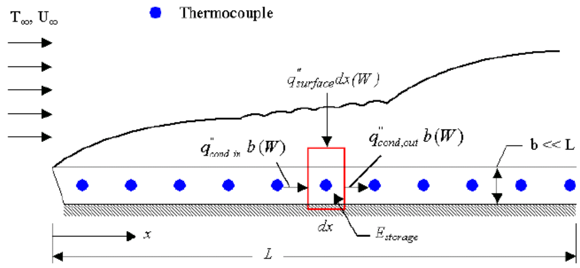


Figure 1. Thermocouples embedded in half-space

Temperature and integrate relationship:

$$T(x,t) = T_0 + \frac{1}{\sqrt{\pi \rho C k}} \int_{u=0}^{t} q''(x,u)\frac{du}{\sqrt{t-u}}, x,t \geq 0 \quad \text{............ (2)}$$

Through inverse analysis, obtain the heat flux equation :

$$q''(x,t) = \sqrt{\frac{\rho C k}{\pi}} \int_{u=0}^{t} \frac{\partial T}{\partial u}(x,u)\frac{du}{\sqrt{t-u}}, x,t \geq 0 \quad \text{............ (3)}$$

In the equation, the thermocouple is embedded at the position x= η to calculate temperature and heat flux. Here the surface temperature is $T(0,t)$ and the surface heat flux is $q'' = (0,t)$.
Digital filtering stabilizes the predictions in an accurate manner. The proposed Gauss filter, used in concert with DFT analysis for determining the cut-off frequency, is shown to display good numerical characteristics. Gauss filter produces continuous function that can be

differentiated without need for finite differences. However, analytic integration as shown will require quadratures. Analytic integration is available with a trick.

The process to do the calculation is as follows:

1) Obtained the temperature data from the thermocouple embedded in the flat plate;
2) Choose proper cut-off frequency f_c for the Gauss Filter calculation;

$$a_n = \sum_{k=0}^{N-1} T(t_k)\cos\left(\frac{2\pi nk}{N}\right), n = 0,1,\ldots,N-1,$$
$$b_n = \sum_{k=0}^{N-1} T(t_k)\sin\left(\frac{2\pi nk}{N}\right), n = 0,1,\ldots,N-1,$$
$$c_n = \sqrt{a_n^2 + b_n^2}$$

………….. (4)

3) Filter the temperature data, and then get the new temperature-time curve;
4) Taken Taylor series, and then get the surface temperature and heat flux.

The papers should be prepared, if possible, using the format like this document.

$$T(0,t) = T(\eta,t) + q''(\eta,t)\frac{\eta}{1!k} + \frac{\partial T}{\partial t}(\eta,t)\frac{\eta^2}{2!\alpha} + \frac{\partial q''}{\partial t}(\eta,t)\frac{\eta^3}{3!\alpha k} + \frac{\partial^2 T}{\partial t^2}(\eta,t)\frac{\eta^4}{4!\alpha^2} + \ldots$$

………… (5)

$$q''(0,t) = q''(\eta,t) + \frac{k}{\alpha}\frac{\partial T}{\partial t}(\eta,t)\frac{\eta}{1!} + \frac{1}{\alpha}\frac{\partial q''}{\partial t}(\eta,t)\frac{\eta^2}{2!} + \frac{k}{\alpha^2}\frac{\partial^2 T}{\partial t^2}(\eta,t)\frac{\eta^3}{3!} + \frac{1}{\alpha^2}\frac{\partial^2 q''}{\partial t^2}(\eta,t)\frac{\eta^4}{4!} + \ldots$$

………….. (6)

3 The Wind Tunnel and Model

3.1 The Hypersonic Wind Tunnel

The tests are carried out in FD-03 hypersonic wind tunnel in China Academy of Aerospace Aerodynamics (CAAA). This wind tunnel is transient, blow down, and free jet. The nozzle outlet is 170mm×170mm. The Mach number ranges from 5 to10. Every Mach number has a corresponding nozzle that can be changed to change the Mach numbers. Also there are two 300mm square optical glass windows on the test section side wall to view the schlieren flow field.

Data acquisition system uses DT9806 data acquisition board produced by American Data-Translation Company. This acquisition board has built-in CJC cold temperature compensate. It can acquire 7-channel thermocouple temperature data, and the acquisition frequency is 50K samples per second.

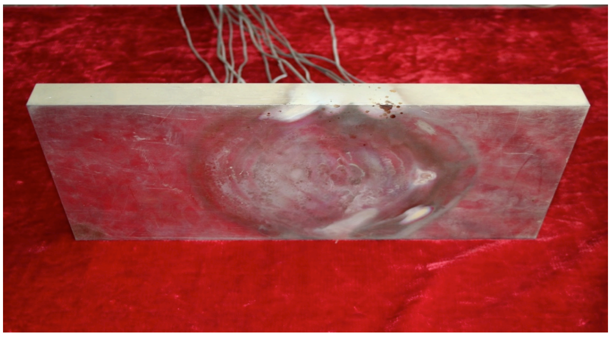
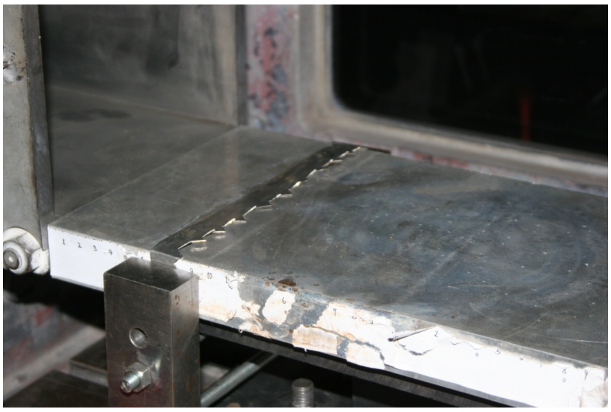
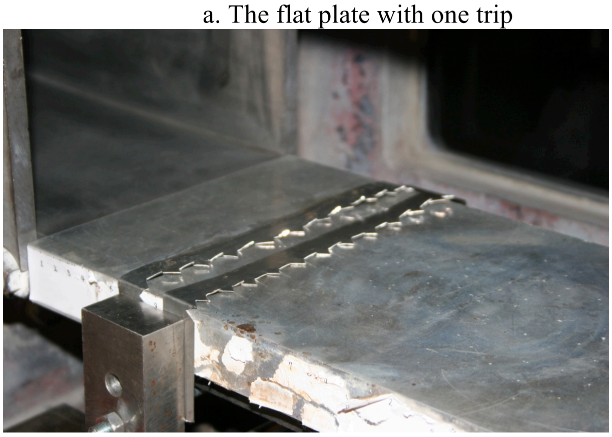


Figure 2. The aluminum flat plate



a. The flat plate with one trip



b. The flat plate with two trips

Figure 3. The flat plate fixed in the wind tunnel

3.2 The Model

The model used in the tests is an aluminum flat plate whose size is 400mm×170mm×30mm. The physics property is: density $2.7\times10^3 kg/m^3$; heat conduction coefficient 203W/m·K. And the thermocouple is wielded in the depth 15mm to the surface and the distance between two thermocouples is 15mm, and except the surface of the flat plate; the other walls of the flat plate are heat isolation.

We totally have 14 thermocouples, 13 of them are fixed in the middle of the flat plate, and 1 of them is fixed in the bottom. The reason of fixing the thermocouples like this is for comparing the surface temperature and heat flux from the thermocouples at different places.

The artificial trip is 0.5mm thick and 20mm width. And the teeth width is 5mm, and with the angle of attack is 30 degree. The artificial trip is fixed at the position on the flat plate 80mm to the leading edge.

4 The Experiment Results

To do the compressible boundary layer testing, we choose the test condition at Mach number 5, and the stagnation temperature is 473K, and the stagnation pressure is 1.0Mpa. The ambient temperature is 273.16K.

We run the tests for about 200 seconds. From 0-50 seconds, we adjust the parameters of the flow, stagnation temperature and stagnation temperature, until the flow stagnation temperature is almost constant. Then after 50 seconds, increasing with the time, the temperature of the flat plate increased. And after 150 seconds, the flat plate temperature is constant and we ended the test.

After one test, we have to wait until the temperature of the flat plate fall down to the ambient temperature. Then we can keep the initial condition of each test would be the same. Only by this, we can obtain the same results of every test.

Fig. 4 shows the raw data of the thermocouples measured directly in the thermocouple calibration tests. From the figure we can tell that the noise signal is much bigger. Then if we use this curve to do the calculation, the error must be big. So, we use Gauss filter to deal with the raw data, and then we obtained the temperature curve in the Fig. 5 which is much smoother than the raw data temperature curve in Fig. 4.

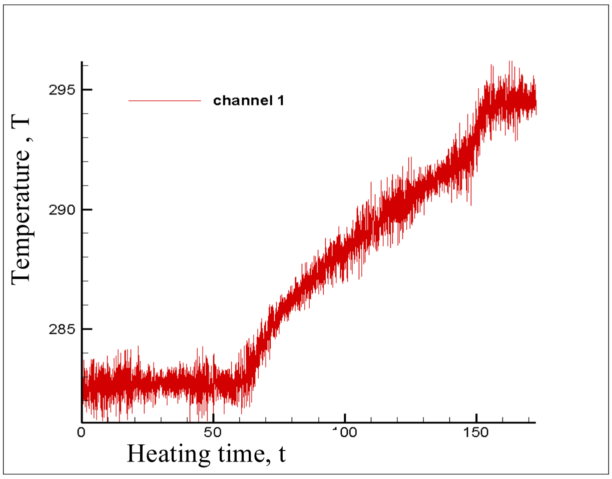


Figure 4. The raw data of the thermocouple

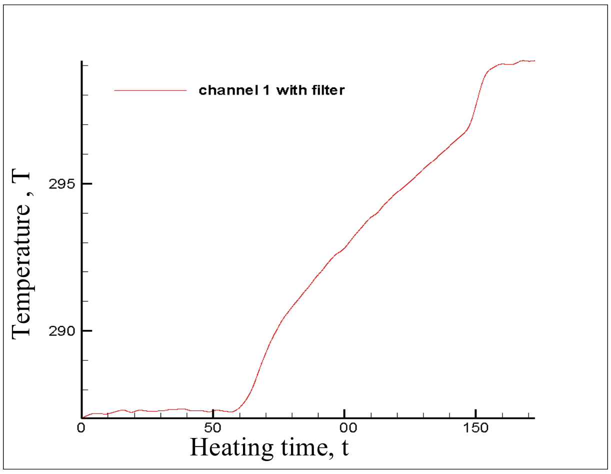


Figure 5. The filter data of the thermocouple

Fig.6 shows the schlieren photo of the flat plate with artificial trips. From the photo, we can see clealy the shock wave induced by the trips. Also we can see the flow field induced by the trips.

Fig. 7-9 shows the surface heat flux distribution got from the embbed thermocouples along the flat plate central line. Along the hypersonic flow direction, the thermocouples number is from 1 to 13. Then after the flow is stable at the set condition, we get the heat flux of the flat plate central line. From the heat flux distribution, we may conclud that the transition location is at number 5 thermoucople position. But obviously we do not have engough data to prove that.

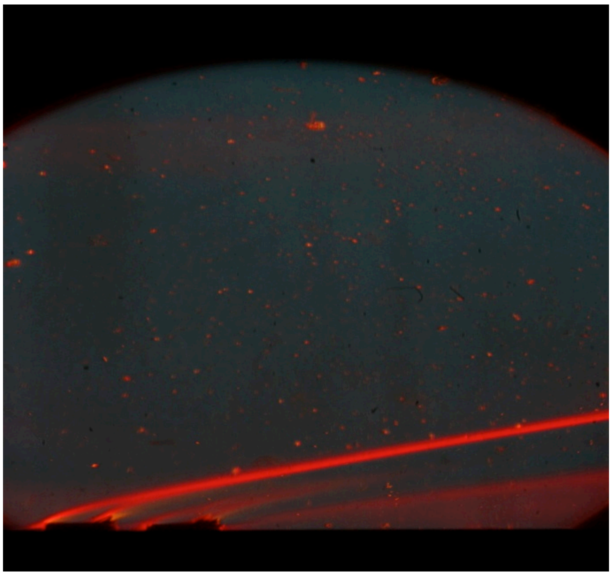


Figure 6. Schlieren photo of the flat plate with artificial trips

So we set one trip at the positon 6cm to the plate leading edge to change the flow field on the flat plate. Then we get the heat flux distribution showed in Fig.8. From the figure, we can see that the value of the heat flux with one trip is much bigger than that without trip. And alone the flat plate, the heat flux increases. So we can say the flow field on the flat plate was totally turbulence.

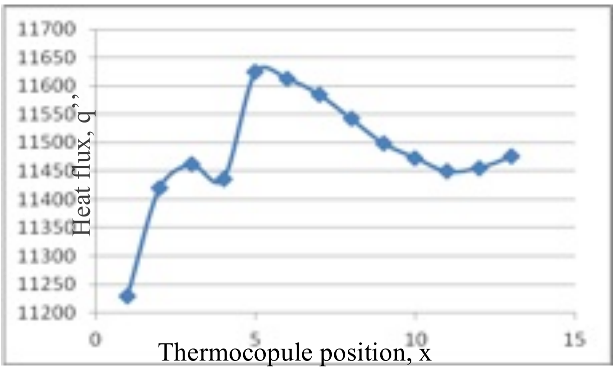


Figure 7. Surface heatflux distribution

without artificial trips

Then we set the second trip downstream 1cm to the first one. After the tests, we get the heat flux distribution in the Fig.9. It can be drawn that the heat flux regularity is the same to that in Fig.8, but the value is bigger. So it is clear that the flow field is also turbulence on the flat plate. And the turbulence flow field caused by two artificial trips is stronger.

So comparing the above three kind of flow field, we can draw that the embbed thermocouple can detect the difference of the flow field. And from the testing results, it can be drawn that embedded thermocouples can detect the surface heat flux very well.

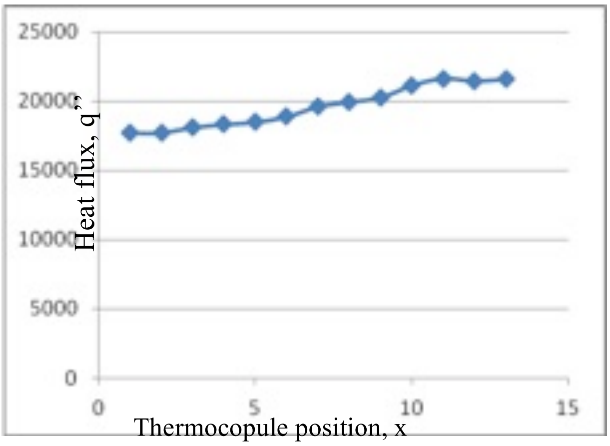


Figure 8. Surface heatflux distribution

With one artificial trip

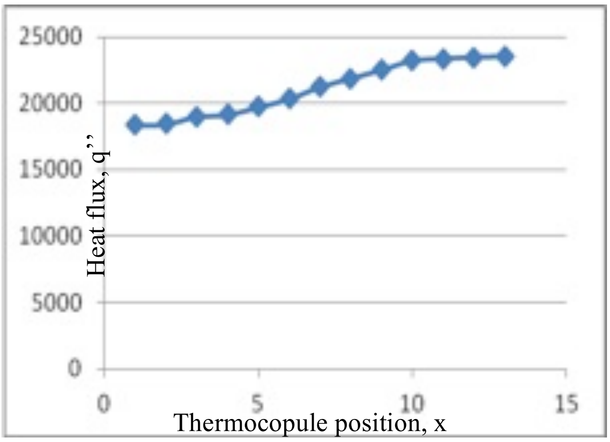


Figure 9. Surface heat flux distribution

With Two artificial trips

5 Conclusions

To measure the surface temperature, we introduce the embedded thermocouple. Comparing to the normal method, the differences are between a spatial (or space domain) and temporal (or time domain) viewpoints to heat flux. Based on the preliminary numerical results and testing results, this approach represents a new methodology for estimating thermal diffusivity to heat flux.

From the tests, these results are highly suggestive for developing alternative regularization schemes and parameters. These results indicate that digital filtering is important for stabilizing predictions. These results indicate that new sensor development based on time derivatives should be initiated.
Comparing the testing results of with artificial trip and without one, the new approach can detect the turbulence effects without destroy flat plat surface condition.

References

[1] R. Harris, T. Hogan, et al. Heat Transfer and Electric Current Flow in a Thermo-electric couple. *44th AIAA Aerospace Sciences Meeting and Exhibit Reno*, Nevada, January 2006.
[2] Jose A. Santos, Robin A. S. Beck, et al. Thermal Modeling of In-depth Thermocouple Response in Ablative Heat Shield Materials. *26th AIAA Aerodynamic Measurement Technology and Ground Testing Conference*.
[3] William J. Rothschild, Debra A. Boyd, et al. Shuttle Derived Launch Vehicle Concepts. *Space 2005*, Long Beach, California, September 2005.
[4] Kulishi, V. V. and Lage, J.L. Fractional Diffusion Solutions for Transient Local Temperature and Heat Flux. *Journal of Heat Transfer*, Vol. 122, No. 2, 2000.
[5] J.I. Frankel, M. Keyhani, et al. Rate-Based Sensing Concepts for Heat Flux and Property Estimation, and, Transition Detection. *16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference*, 2009.
[6] Frankel, J.I. Generalizing the Method o Kulish to One-Dimensional Unsteady Heat Conducting Slabs. *Journal of Thermophysics and Heat Transfer*, Vol: 20, No. 4. 2006.

Contact Author Email Address

zhaoyanziqi@yahoo.com

Copyright Statement