3-D Simulation of External Cooling of Aero-optical Side Window

Chun-Chi Li
Dept. of Mechatronic, Energy & Aerospace Engineering
Chung Cheng Institute of Technology, NDU
Dasi Township 335, Taoyuan County, Taiwan, ROC
e-mail: davidli560607@gmail.com

Yi-Chan Lin and Ming-Chun Hsieh
Master Program of Mechanical Engineering
Chung Cheng Institute of Technology, NDU
Dasi Township 335, Taoyuan County, Taiwan, ROC

***Abstract*— Under hypersonic flow environment, the aero-optical side window of optical guidance missile will trigger aero-thermodynamic effects causing high heat and cracks to optical windows which eventually leads to failure of optical windows. This study uses computational fluid dynamic as a tool to simulate hypersonic flow, optical side window cooling and jet flow design. Simulation results show that cooling effect with surface temperature less than 500K can be achieved when the external cooling jet flow reaches 0.125kg/s, thus meeting the needs of weight-bearing projectile. Since the optical side windows are located at leeward, greater angle of attack (AOA = 30) will result in a better cooling effect of the flow field under the condition with the present of AOA. Besides, the groove temperature for optical side window is similar to the temperature of cooling jet.**

Keywords- aero-optical side window; hypersonic flow; optical guidance missile; aero-thermodynamic effect; cooling

I. INTRODUCTION

Under hypersonic environment (Mach number > 5), the flow field surrounded the optical hood of optical guidance missile will generate real gas effects and interaction between shock wave and boundary layer. Furthermore, mutual interference of boundary layer and inviscid flow will cause air density, temperature and composition changes, and even the phenomenon of air molecules ionization. During the flight of high-speed aircraft with guidance system of optical imaging detection within the atmosphere, these previously mentioned effects will produce complex flow between the hood and air flow field causing heat, radiation, and image transmission interference to the optical imaging detection system, which result in target image offset, jittering and fuzziness. This effect is known as the aero-optical effects, shown in Fig. 1[1]. The dome of optical guidance missile generally composes of the hood body, optical window and the window cooling system, etc, shown in Fig. 2[2]. Under hypersonic flow environment, the aero-optical side window of optical guidance missile will trigger aero-thermodynamic effects causing high heat and cracks to optical windows which eventually leads to failure of optical windows. Therefore, it is necessary for the cooling system to reduce the surface temperature of optical window. The aero-optical window generally divided into mosaic optical window and planar optical side. This paper will focus on the planar optical side window. The optical side window is a flat sapphire optical window installed in the hood area of lateral surface, slightly below the surface of projectile, and its heat-resistant temperature is usually under 500K. This paper adopts computational fluid dynamics to study the external cooling characteristics of optical side window under different jet flow rates with flight speed of Mach 6, angle of attack from 0 to 30 degrees and 30 to 40 km altitude above sea level. In order to protect the optical side window from cracks which could cause failure, the optima cooling jet flow is expected to reduce the surface temperature of optical window to below 500K.

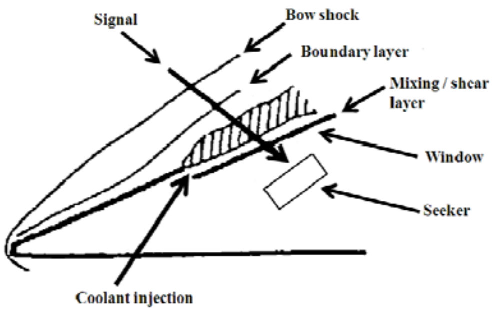

Fig. 1. Schematic diagram of aero-optical effects [1]

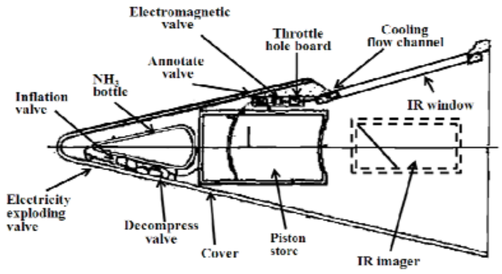

Fig. 2. Schematic diagram of external cooling [2]

II. PROBLEMS AND METHODS

A. Governing Equation and Numerical Methods

The governing equations are the Reynolds averaged Navier-Stokes equations, the conservation can be expressed as follows

$$\frac{\partial U}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}+\frac{\partial H}{\partial z}=\frac{\partial F_v}{\partial x}+\frac{\partial G_v}{\partial y}+\frac{\partial H_v}{\partial z} \tag{1}$$

In solving equation (1), convection terms (F,G,H) are calculated by $AUSM^+$ scheme, while viscosity and diffusion flux terms (F_v,G_v,H_v) are calculated using the central difference method. Discrete space terms are to form a group of ordinary differential equations followed by time integration to obtain the numerical solution. Turbulence model adopted the Spalart-Allmars equation. The condition of inlet boundary and outlet boundary should be set at pressure-far-field condition and pressure-outlet condition, respectively. Besides, the cooling jet port is set to mass flow rates conditions. The projectile and optical window is set to no-slip and adiabatic conditions. Additionally, the real gas equation modified specific heat ratio is added.

B. 3-D Physical Model and Grid Configuration

In this paper, a simulation model of U.S. THAAD (terminal high altitude area defense) missile with missile body and the actual size of the optical window are adopted. There is no detailed size mentioned in literatures. With the scarce sources and data, various relevant articles and figures are gathered from the internet, journals and disclosure information. The estimation of the projection geometry size is displayed in Fig. 3-4[3-4].

Although optical window has long oval shape, this paper assumes the optical window to be rectangular for ease of modeling and prediction of flow field. According to the observation, it is known that the cooling jet hole is located at the bottom of leeward and its size is approximately half the height of leeward. Besides, the former configuration shows a groove tilt with a deep front and shallow end. Schematic model of missile is shown in Fig. 5.

The grid of three-dimensional optical window is sketched based on unstructured tetrahedron grids with a total grid number of approximately 100 million grids, as shown in Fig. 6.

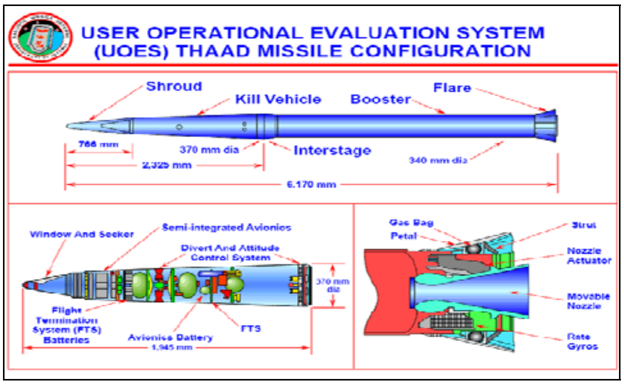

Fig. 3. THAAD missile configuration diagram [3]

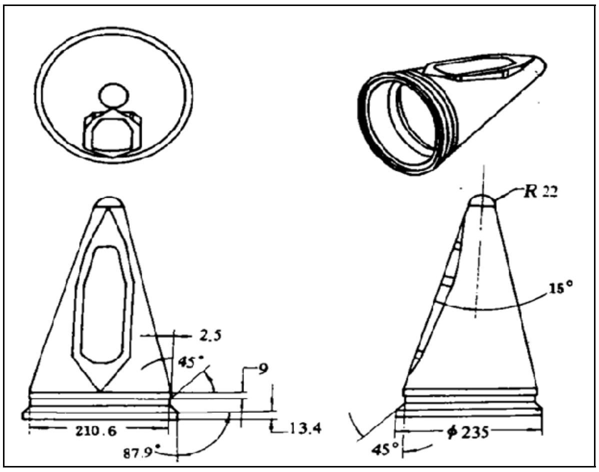

Fig. 4. THAAD missile optical hood geometry diagram [4]

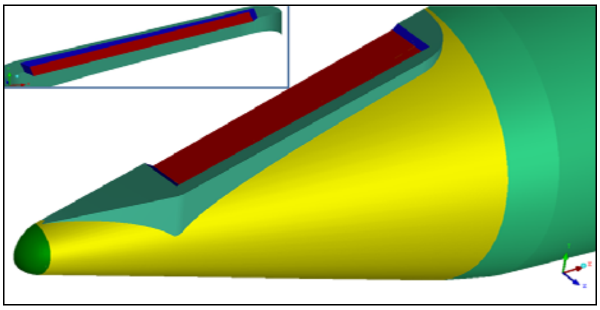

Fig. 6. THAAD guidance section model diagram

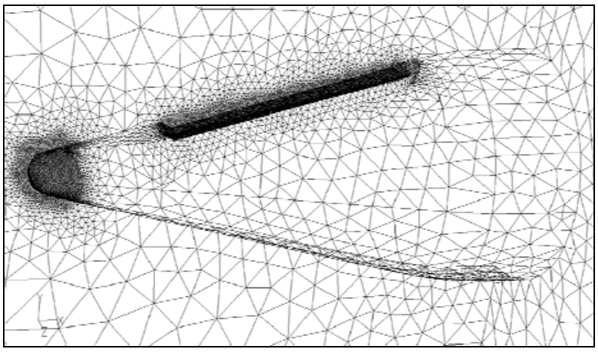

Fig. 6. 3-D THAAD optical window grid diagram

C. Research Matrix

This model of the optical window is named Model A. The external cooling jet flow is divided into five categories according to their spray flow rates (J) including 0 (kg/s), 0.1 (kg/s), 0.125 (kg/s), 0.15 (kg/s) and 0.175 (kg/s). Table 1 indicates the research matrix.

TABLE I. RESEARCH MATRIX

Research Matrix	
Model name	***Jet flow rate (kg/s)***
2D_A_0	0
2D_A_1	0.1
2D_A_2	0.125
2D_A_3	0.150
3D_A_0	0
3D_A_1	0.1
3D_A_2	0.125
3D_A_3	0.150

III. RESULTS AND DISCUSSION

A. Numerical Code Validation

In order to verify the feasibility of numerical programs, this paper compares the experimental and theoretical solution with the three-dimensional blunt body suggested by Rakich & Cleary [5] shown in Fig. 7-9. Under the simulation conditions with Mach number = 10.6, simulation results show that the cone at different azimuthal angel 0° , 90°, 180° has suggested very good agreement for surface pressure values. Therefore, it is indicated that this program can be adopted for hypersonic flow simulation.

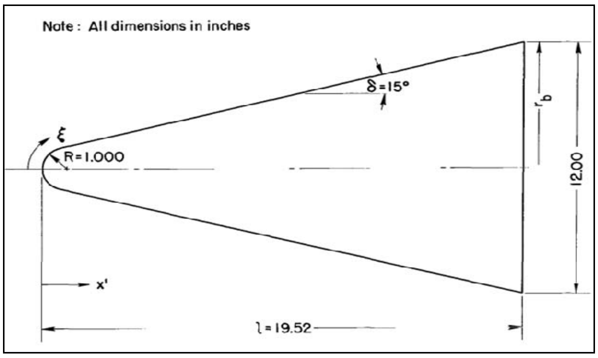

Fig. 7. 3-D blunt body configuration diagram

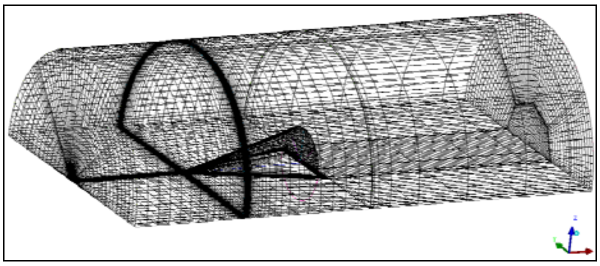

Fig. 8. 3-D blunt body grid diagram

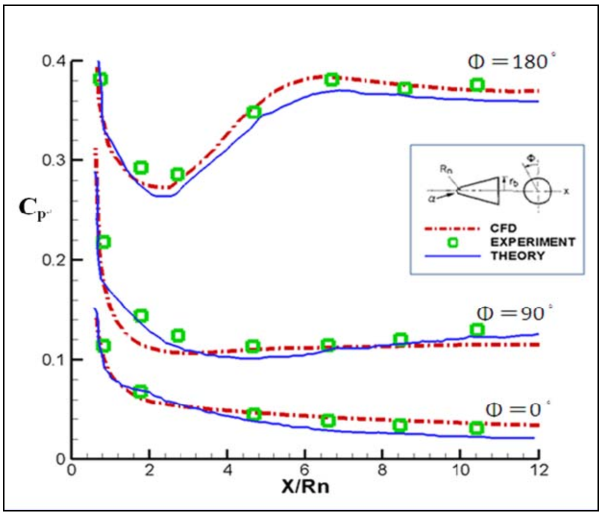

Fig. 9. Comparison the C_p values of computation with the experimental and theory of Rakich & Cleary.

B. External Film Cooling

When there is no cooling jet flow, the flow field temperature on the surface of optical window will reach approximately 1600K. High temperature and dynamic effects from the heat will cause failure to optical window, as shown in Fig. 10-11. When the external cooling jet flow is 0.1 kg/s, the optical window surface temperature is still higher than 500K. This is because the amount of coverage for cooling effect from the thin jet is less than the surface of optical window, as shown in Fig. However, surface temperature for optical window reduces to 480K and 450K when the jet flows are increased to 0.125 kg/s and 0.15 kg/s, as shown in Fig. 12-13. By considering the missile payload and exercise flexibility, the optimal cooling jet flow rate is achieved at 0.125 kg/s.

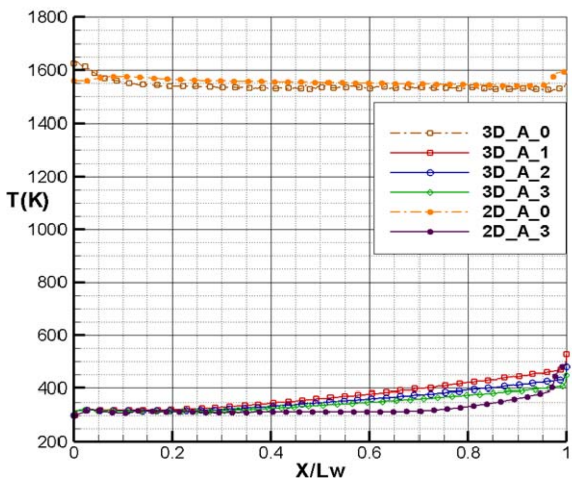

Fig. 10. Optical window position (dimensionless) and temperature plots

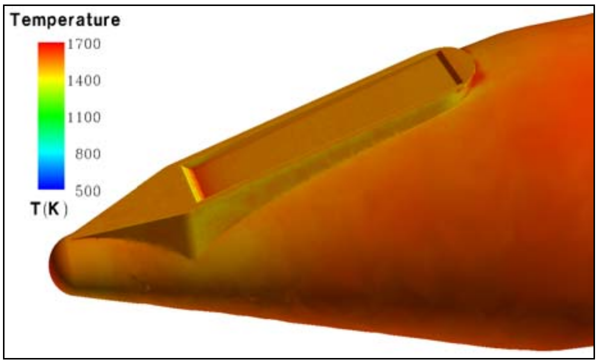

Fig. 11. Optical window temperature contour without jet cooling.

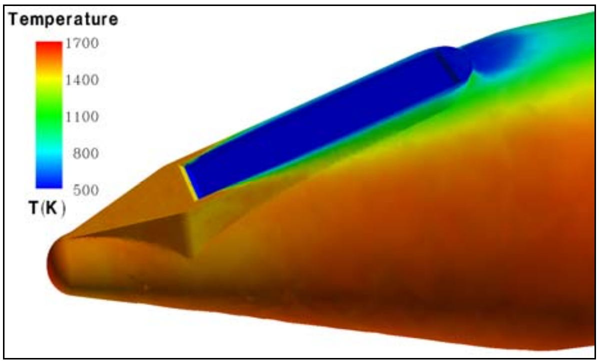

Fig. 12. Optical window temperature contour with jet flow =0.125 kg/s.

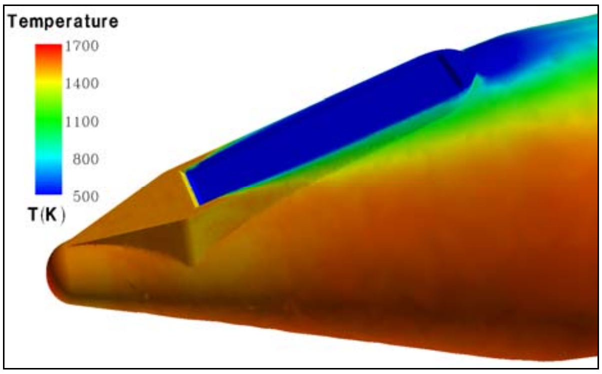

Fig. 13. Optical window temperature contour with jet flow =0.15 kg/s

C. *Attack Angle Eeffect*

This section discusses the change of the cooling jet with AOA = 10 °, 20 °, 30 ° and jet flow rate=0.125 kg/s Comparison for different AOA (angle of attack) is made. Based on the simulation results, the cooling jet is not affected by the angle of attack changes the area covered by the optical window, as shown in Fig. 14-16. In addition, the flow field comparison of optical window surface temperature at AOA = 0 °, 10 °, 20 °, 30 ° is displayed in Fig. 17-18. As the angle of attack increases, the surface temperature of optical window of the flow field becomes closer to the cooling jet temperature.

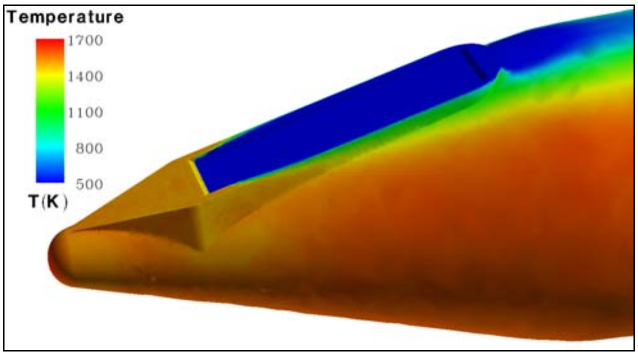

Fig. 14. Optical window temperature contour of AOA=10 with jet flow =0.125 kg/s

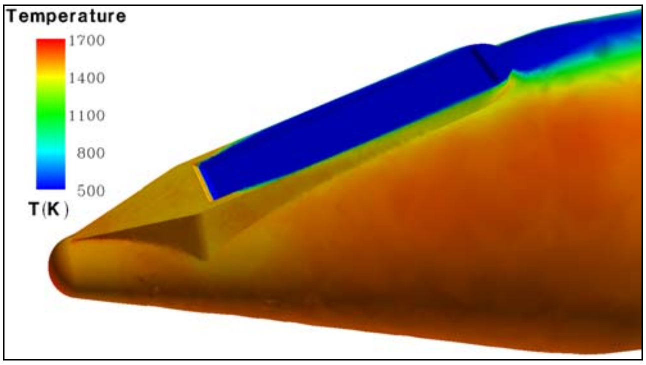

Fig. 15. Optical window temperature contour of AOA=20 with jet flow =0.125 kg/s

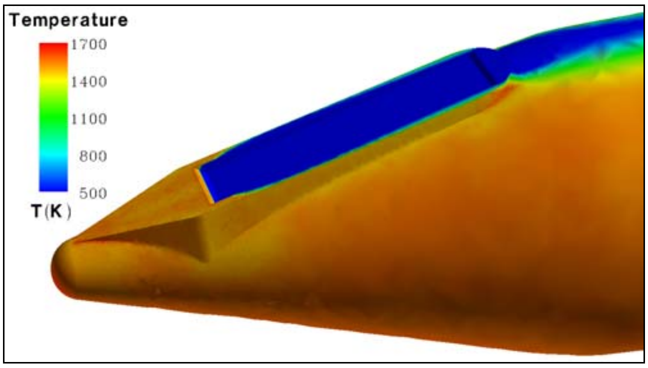

Fig. 16. Optical window temperature contour of AOA=30 with jet flow =0.125 kg/s

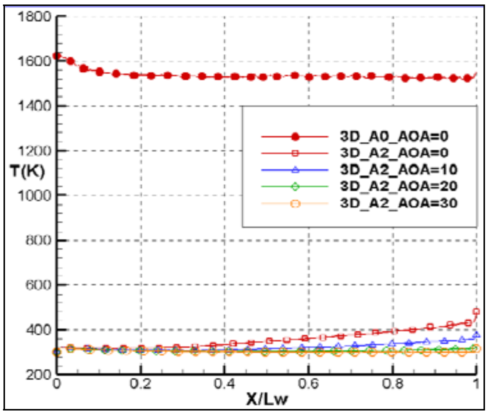

Fig. 17. Comparison of optical window position (dimensionless) and temperature plots of different angles of attack with different jet flow rates

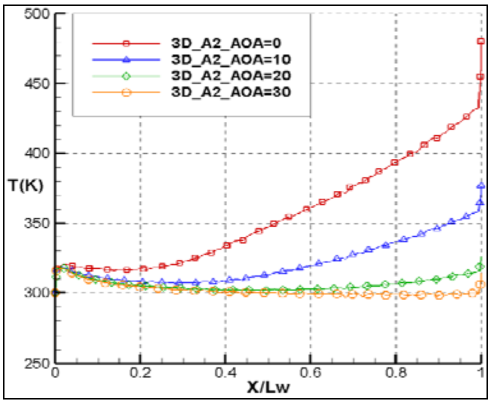

Fig. 18. Comparison of optical window position (dimensionless) and temperature plots of different angles of attack with jet flow rate=0.125 kg/s

IV. CONCLUSIONS

For the cooling of optical window, the cooling gas contains air temperature at 300K. It can be simulated in relevant traffic leading to different spray cooling effects with different optical window. In addition, the optical window surface temperature is proportional to the flow field Mach number; the greater the Mach number, the higher the surface temperature of the optical window, especially in the absence of cooling jet. For instance, the optical window surface temperature rises up to approximately 1600K with Mach number M = 6. However, cooling jet is utilized to cool the surface of optical windows. When the cooling jet flow reaches 0.125kg/s, cooling effect with surface temperature less than 500K can be achieved, thus meeting the needs of weight-bearing projectile.

With the present of angle of attack, the optical window in leeward has better cooling effect of flow field with a greater angle of attack (AOA = 30). Furthermore, the groove temperature of the optical window approximates to the temperature of cooling jet.

ACKNOWLEDGMENT

The author would like to thank the National Science Council of the Republic of China for financially supporting this research under Contract No. NSC 99-2221-E-606-004.

REFERENCES

[1] X. Y. Yang, C. H. Liu, Y. Q. Gu, "Design of Hypersonic Vehicle Infrared Cooling Dome," Infrared and Laser Engineering, vol. 33, no. 6, pp. 576-579, Dec. 2004.

[2] J. A. Majeski, and H. W. Morris, " An Experimental and Computational Investigation of Film Cooling Effect on an Interceptor Forebody of Mach 10," AIAA 90-0622, Reno, NV, 1990.

[3] http://www.fas.org/spp/starwars/program/38112.pdf

[4] Q. Z. Li, "Analysis on IR Homing Technique of THAAD System Intercept Missile in US," Infrared and Laser Engineering, vol. 27, no. 2, pp. 25-28, Apr. 1998.

[5] J.V. Rakich, and J. W. Cleary, "Theoretical and Experimental Study of Supersonic Steady Flow Around Inclined Bodies of Revolution," Journal of Spacecraft and Rockets, vol. 8, no. 3, pp. 511-518, Mar. 1970.