Achieving Optimal Designs for High-Speed Blunt Body vehicles: A Multi-Objective Approach with an Efficient Aerothermodynamic Prediction Program

Hoonjung Yeo[1], *Kyu Hong Kim*[2]

Abstract

In this study, we have developed a rapid thermal aerodynamics analysis program as an alternative to Computational Fluid Dynamics (CFD) for performing fast analyses in the preliminary design step. This program utilizes empirical thermal aerodynamic correlation equations, allowing for efficient computations. We integrated thermal aerodynamics analysis program with a genetic algorithm to provide a design framework for multi-objective shape optimization of high speed vehicles, with objectives including maximizing payload capacity, minimizing total heat absorption, and minimizing ballistic coefficient. For shape optimization, thermal aerodynamic analysis was conducted based on the flow conditions obtained for the baseline configuration's flight trajectory.

Keywords : *Multi-objective optimization, High speed vehicle design, Genetic algorithm*

Nomenclature

A – Area
η_V – Volume efficiency
V – Volume
S – Surface area
m – mass
$\dot{Q}_{total}$ – Total heat absorbed
$\dot{q}$ – Heat flux
C_B – Ballistic coefficient
C_D – Drag coefficient

1. Introduction

The Computational Fluid Dynamics (CFD)-based thermal aerodynamic analysis method provides accurate results; however, it demands significant computational resources and time, making its application limited in the initial stages of design, particularly when iterative analyses are required for various flow conditions and geometries. In this study, we aim to develop a rapid thermal aerodynamics analysis program and extend it into a framework for multi-objective shape optimization of high speed vehicles. We intend to demonstrate its applicability in the preliminary design phase and establish a foundation for its use as a tool for designing high speed vehicles.

2. Aerothermodynamic Analysis Program

This research employed a rapid and efficient thermal aerodynamics analysis program developed for swift thermal analysis. The rapid thermal aerodynamics analysis program utilizes Cp correlations by Wells[1] for aerodynamic analysis, which is provide improved results compared to classical theoretical methods, particularly for blunt-cone body configurations where detached shock occurs. For thermal analysis, empirical formulas like Fay-Riddell stagnation heating model[2] were utilized, while various model equations were employed for off-stagnation analysis. In this manner, the utilization of various model-based analysis methods enables a significant reduction in analysis time. Furthermore, as it does

1 *Dep't of Aerospace Engineering, Seoul National University, Seoul, Republic of Korea, dudu98@snu.ac.kr*
2 *Dep't of Aerospace Engineering, Seoul National University, Seoul, Republic of Korea, aerocfd1@snu.ac.kr*

not necessitate complex preprocessing steps for shape modeling and grid generation, its usage is straightforward. Users can operate the program with just a few parameter inputs related to the geometry.

3. Multi-objective Design Optimization

3.1. Optimal design framework

To facilitate shape optimization, we integrated the previously developed rapid thermal aerodynamics analysis program with a genetic algorithm to establish a framework for multi-objective optimal design. For the implementation of multi-objective optimization, we utilized the DEAP open-source library[3] written in Python language.

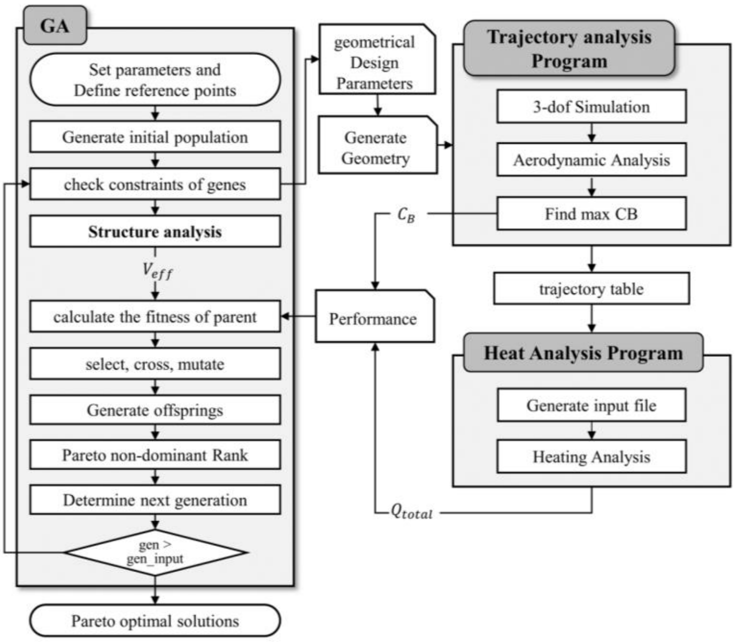

Fig 1. Optimal design framework

3.2. Design Problem Definition

A blunt-cone-flare type module[4] shape was chosen as the baseline. This basic module type is simple to manufacture due to its uncomplicated shape and has good aerodynamic stability, making it suitable for unmanned ballistic flight missions that do not require control[5].

The three objective functions for the optimal design are as follows:

$$maimize\ \eta_V = 6\sqrt{\pi}\frac{V}{S^{\frac{3}{2}}} \tag{1}$$

$$minimize\ \dot{Q}_{total} = A \times \int q_{net}^{\cdot}\, dt \tag{2}$$

$$minimize\ C_B = \frac{m}{C_d A} \tag{3}$$

The maximum lengths and angles of the cone-shaped body and flare sections are determined to account for the spatial constraints of the rocket upper stage fairing.

$$15 < \theta_1 < 25 \tag{4}$$

$$\theta_1 < \theta_2 < 40 \tag{5}$$

$$l_1 < 1m \tag{6}$$

$$l_2 < 1m \tag{7}$$

Maximum heat transfer rate limit for carbon phenolic, a common TPS material, is 1.2MW/m². Based on this, the minimum leading-edge radius of curvature was set as a constraint to ensure the structural integrity and thermal safety of the vehicle under the harshest expected conditions.

$$R_N > 0.1m \tag{8}$$

Space exploration modules are designed to carry out a variety of missions, including transporting cargo and conducting scientific experiments, which may include the return of samples. To facilitate these missions, it is essential to allocate space for mission equipment, such as payload and parachute canopy. Taking into account the volume of the payload space and the system structure, the minimum volume constraint for the interior of the module has been established as follows:

$$V > 0.3m^3 \tag{9}$$

3.3. Structure Analysis

The total surface area of the spacecraft is the sum of the areas calculated for the three previously identified sections(hemispherical nose, conical body, flare), as follows:

$$A_{total} = A_{nose} + A_{cone} + A_{flare}$$

$$V_{total} = V_{nose} + V_{cone} + V_{flare}$$

In this study, the mass of the vehicle was calculated by considering the weight of the structure, the weight of the payload, and the weight of the Thermal Protection System (TPS). The total mass of the vehicle can be calculated as follows:

$$m_{total} = m_{TPS,nose} + m_{TPS,body} + m_{structure} + m_{payload}$$

To estimate the weight of the Thermal Protection System (TPS), this study referenced the material properties of the TPS materials used in the baseline module[6,7]. For the nose, properties of carbon-phenolic were applied, while silica tiles were used for the remaining conical body and flare sections. The structural material of the vehicle was assumed to be aluminum alloy, and the weight of the payload and mission equipment was arbitrarily assumed to be 150kg.

3.4. Trajectory analysis

For the design of high speed vehicles, a wide range of flow conditions spanning high mach numbers must be considered. The flight trajectory of the vehicle was analyzed using the SAPAR[8] program. The SAPAR program conducts flight trajectory analysis through calculations based on the three-degree-of-freedom motion equations. The program's initial input values for the flight trajectory analysis were assumed as follows:

Table 1. Trajectory analysis program input

Input	Value
Initial altitude	120 km
Flight Path angle	-1 deg

The initial longitude and latitude were applied to ensure that the baseline shape could land in the mission target, with the values derived through a trial-and-error method. The angle of attack was set to 0 degrees to align with the freestream direction, assuming this configuration would ensure longitudinal stability. or each shape generated by the varying parameters, a new trajectory table is created. altitude and mach number tables generated for the flight trajectory were processed as inputs for the rapid thermal aerodynamics analysis program to calculate the free-stream flow conditions.

3.5. Heating analysis

The thermal analysis module of the rapid aerothermal analysis program includes ten subroutines for deriving heat transfer coefficients for simple shapes. Each subroutine is called based on the thermal analysis model option entered by the user. Users can assume the vehicle at specific points as simple shapes and select the appropriate thermophysical model options for each shape to derive heat transfer rates.

The vehicle configuration applied in this study consists of a nose, cone, and flare. The nose can be simplified to a hemisphere, the conical body to a cone with a half-angle of $\theta 1$, and the flare to a cone with a half-angle of $\theta 2$. Therefore, to determine the stagnation point of the nose, we applied the Fay-Riddell correlation[2]. For off-stagnation points on the nose, we used Lee's correlation[9] for a hemispherical nose. Finally, for the cone and flare, we applied Eckert's flat plate relation with a Mangler factor[10] to account for the curvature effect.

The heat transfer rates calculated from empirical formulas for each part are integrated over the area of that part as shown in the equation below. This calculation is performed for all points along the flight trajectory. By summing these amounts over the flight time, the total accumulated heat load on the vehicle is derived.

$$\mathrm{Q}_{\mathrm{total}} = Q_{nose} + Q_{cone} + Q_{flare}$$

$$= A_{nose} \int \ddot{q}_{nose}\, dt + A_{cone} \int \ddot{q}_{cone}\, dt + A_{flare} \int \ddot{q}_{flare}\, dt$$

4. Results and Discussion

The pareto-optimal solutions as shown in Fig. **2** From the Pareto front solutions, five preliminary shapes were selected**.**

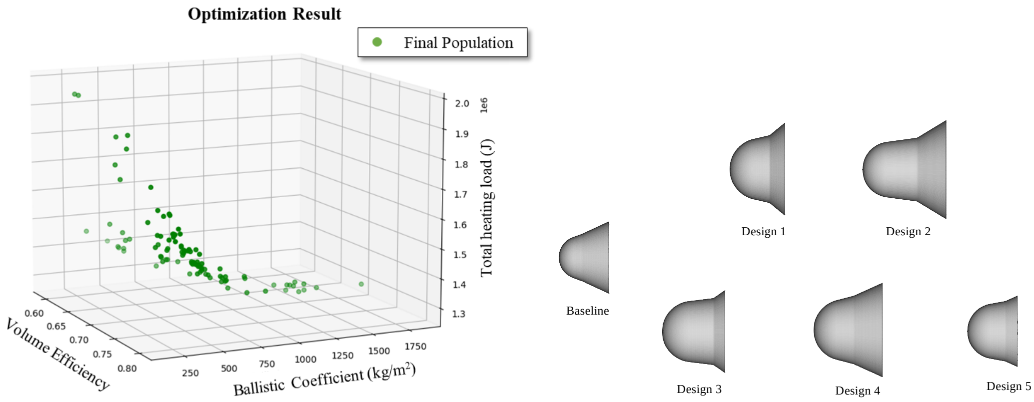

Fig 2. Pareto front of optimal solutions

Figure 3 shows the stagnation point heat transfer during flight of the five proposed shapes. All five proposed designs have a greater radius of curvature at the leading edge than the baseline to reduce heat transfer and the results can be seen again in Figure 3. Design 1, which has the smallest ballistic coefficient of the five shapes, decelerates the fastest, resulting in the lowest value of peak heating at low altitude.

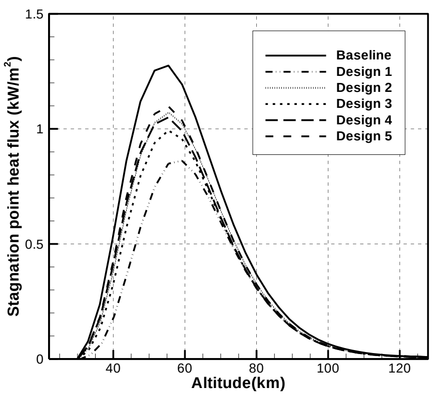

Fig 3. Stagnation heating of proposed designs and baseline during flight

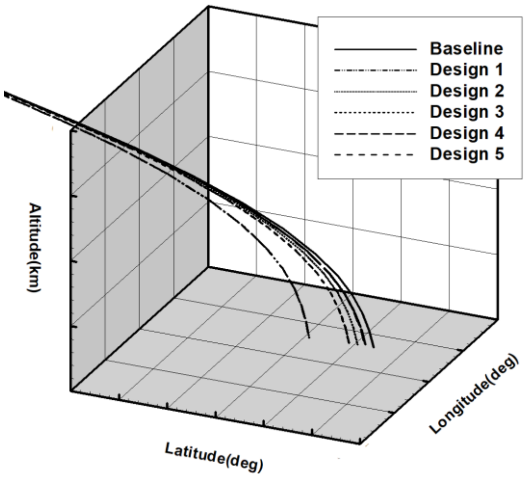

Fig 4. Flight trajectory of proposed designs and baseline

To verify that the five proposed design geometries reliably reach the mission arrival point, the derived trajectories are compared in Figure 4. All proposed designs have lower ballistic coefficients compared to the baseline geometry, indicating that they have sufficient deceleration at high altitudes, resulting in a reduced range compared to the baseline geometry.

Design 1 landed 63 km away from the baseline arrival point, but was able to enter the middle of the mission target area. Similarly, there were some differences in the flight trajectories of the other proposed geometries, but all five geometries were found to be stable within a few kilometers.

Conclusion

In this study, a rapid thermo-aerodynamic analysis program is developed as an alternative to computational fluid dynamics (CFD) to perform rapid analysis in the early design phase. The program uses empirical thermo-aerodynamic correlation equations to enable fast computation. By integrating the thermo-aerodynamic analysis program with a genetic algorithm, we present a design framework for multi-objective geometry optimization of high-speed vehicles with the goals of maximizing payload, minimizing total heat absorption, and minimizing ballistic coefficient. The trajectory is analyzed using the SAPAR program, which computes the 3DOF equations of motion, and the total heat absorption is calculated using a high-speed thermo-aerodynamic analysis program. The multi-objective optimal design framework is integrated and built in a Python environment using the NSGA-II method from the DEAP library. Optimization was performed for 100 objects over 20 generations and a Pareto front solution was obtained. Five proposed geometries were selected and their stagnation point heat transfer during flight was compared, and the maximum heat transfer was lower than the existing geometry, and the improved geometry was obtained while landing stably at the destination.

Acknowledgement

This work was supported by the Agency For Defense Development by the Korean Government (UE213016SD)

References

1. Wells, P.,P. Thornley: Blunt cone pressure correlations for supersonic and hypersonic flow. 14th applied Aerodynamics Conference. 2447 (1996)
2. Fay,J.A., Riddell. F. R.: Theory of Stagnation Point Heat Transfer in Dissociated Air. J.Aeronaut. Sci., 25.2, 73-85 (1958)
3. Deb, K., Jain, H.: An Evolutionary Many-Objective Optimization Algorithm Using Reference-Point-Based Nondominated Sorting Approach, Part I: Solving Problems With Box Constraints, IEEE Transactions on Evolutionary. Computation. 18(4), 577-601 (2013)
4. Mehta, R. C.: Numerical simulation of supersonic flow past reentry capsules. Shock Waves 15.1, 31-41 (2006)
5. Adami, A., Nosratollahi, M., Mortazavi, M., Hosseini, M.: Multidisciplinary design optimization of a manned reentry mission considering trajectory and aerodynamic configuration. RAST 2011.IEEE.598-603(2011)
6. Narayana Murty, S. V. S., S. C. Sharma.:Materials for Indian Space Program: An Overview. Journal of the Indian Institute of Science,1-47 (2022):
7. Nakamura, T., Kamimura, Y., Igawa, H., Morino, Y.: Inverse analysis for transient thermal load identification and application to aerodynamic heating on atmospheric reentry capsule. Aerospace Science and Technology, 38, 48-55 (2014).
8. Sim, H. S., Kim, K. H.: Reentry Survival Analysis of Tumbling Metallic Hollow Cylinder. Advances in Space Research, 48.5, 914-922 (2011)
9. Lees, L.: Laminar heat transfer over blunt-nosed bodies at hypersonic flight speeds. Journal of Jet Propulsion. 26(4), 259-269 (1956).

10. Engel, C. D.,Praharaj, S. C.:MINIVER upgrade for the AVID system. Volume 1: LANMIN user's manual .No. NASA-CR-172212 (1983).