The 2016 World Congress on
The 2016 Structures Congress (Structures16)
Jeju Island, Korea, August 28-September 1, 2016

Code development for reentry space debris survivability estimation under surface catalytic effect

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ABSTRACT

Survivability and trajectory estimation of reentry space debris have been carried out over the past few decades. ORSAT(Object Reentry Survival Analysis Tool) program by NASA and SCARAB(Spacecraft Atmospheric Reentry and Aerothermal Breakup) program by ESA are representatives of the reentry space debris analysis program. However, in the aerodynamic heating calculation, they use Fay and Riddell's formula which has several assumptions such that equilibrium boundary layer and surface of the object is super-catalytic. In this paper, Goulard formula is used to calculate non-equilibrium aerodynamic heating and to compare super-catalytic effect with non-catalytic effect. Also, it is shown that surface catalytic effect is important.

1. INTRODUCTION

Survivability and hazard analysis of reentry space debris has been conducted by many research centers worldwide including NASA in the past decade (Lips 2005). Korea has also developed a keen interest in space debris because space debris have threatened survivability of Korean satellites such as Science and Technology Satellite-3. Space debris orbiting the Earth begin to fall towards the Earth in a few years or in less than a few decades. Most space debris undergo ablation or melting due to aerodynamic heating and are burned up in the atmosphere. However, surviving space debris collide on the Earth, damaging ground as well as people. Therefore, it is important to develop a code that analyzes survivability and trajectory of space debris.

Several space agencies and research centers have their own reentry analysis tools. NASA's ORSAT and ESA's SCARAB are the representative reentry space debris analysis codes(Lips 2005). Although they use different methods for trajectory calculation and heat rate calculation, both codes have shown agreement under same conditions(Lips 2005). KARI's SAPAR also has its own developed code based on ORSAT(Sim 2010). However, despite their good performance, all conventional codes still need to improve for heat calculation, ablation, and breakup process. In aerodynamic heat

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calculation, they use Fay and Riddell formula which has several assumptions that the surface of the object is super-catalytic and the boundary layer is in equilibrium state (Sim 2010). These assumptions can produce a wrong result in the prediction of small reentry space debris' ablation process. In this study, a reentry analysis program has been developed and verified with the results of ORSAT and SAPAR. Also, Goulard formula is used to calculate non-equilibrium aerodynamic heating and to compare super-catalytic with non-catalytic assumption.

2. REENTRY ANALYSIS PROGRAM MODULES

In this paper, reentry analysis code was developed by using ORSAT's and SAPAR's methods. It is composed of five modules such as trajectory module, aerodynamics module, aerothermodynamics module, thermal module, and ablation module. These modules interact with each other to estimate survivability and trajectory of space debris (Sim 2010). Fig. 1 shows the schematic program modules.

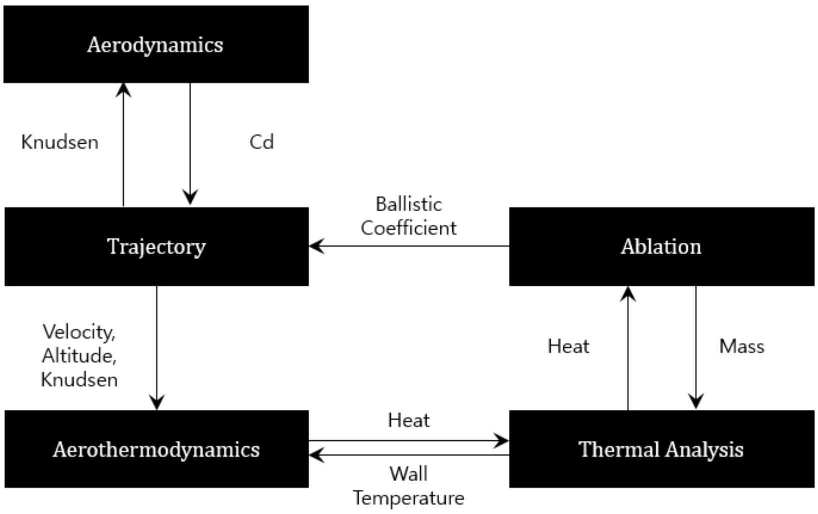

Fig. 1 Schematic program modules[Sim 2010]

Trajectory module which can be mathematically described by Newton's equation of motion simulates a three degree-of-freedom trajectory by assuming an object as a mass point. Only two forces, gravity and aerodynamic force, are considered.

Aerodynamic module calculates aerodynamic coefficients. The Earth atmosphere can be divided into three parts such as free molecular regime, transition regime, and continuum regime. Aerodynamic coefficients can be calculated in accordance with the three regimes.

Aerothermodynamics module evaluates heat flux from the hot wall condition. Net heat flux is composed of aerodynamic heating, oxidation, and re-radiation. While aerodynamic heating and oxidation increase heat flux, re-radiation decreases it.

Thermal module can calculate wall and inner temperature of an object from the evaluated heat flux in the aerothermodynamics module. At the melting point of the object, its temperature stays constant. An innermost node is assumed to be adiabatic

Ablation module uses the nodal thermal mass model for an object. If the heat flux from the aerothermodynamics module exceeds the heat of ablation for the outer layer of the object, the layer is assumed to melt away.

2.1 Module development of non-equilibrium heat calculation

NASA's ORSAT, ESA's SCARAB, and KARI's SAPAR are required to improve for heat calculation. Fay and Riddell formula uses super-catalytic assumption (Lips 2005). It is expressed as follows.

$$\dot{q}_{stagn} = \frac{110285}{\sqrt{R}}\left(\frac{\rho}{\rho_{sl}}\right)^{0.5}\left(\frac{V}{V_{cir}}\right)^{3.15} \quad (1)$$

Where, $\dot{q}_{stagn}$ is the stagnation heat flux, R is the radius of a sphere, ρ_{sl} is a sea level air density, and V_{cir} is an orbital velocity at 122km altitude. Super-catalytic assumption is that chemical reactions are catalyzed at an infinite at wall; it violates mass conservation and overestimates heat flux. In order to consider finite catalytic recombination rates at the wall, Goulard formula was used in this paper (Goulard 1958). It is expressed as follows.

$$\dot{q}_{stagn} = q_C + q_D \quad (2)$$

$$q_C = 0.47(2\beta\mu_{se}\rho_{se})^{1/2}\bar{\sigma}_w^{-2/3}\bar{h}_{se} \quad (3)$$

$$q_D = 0.47(2\beta\mu_{se}\rho_{se})^{1/2}Sc^{-2/3}h_R c_e \varphi \quad (4)$$

$$\text{where, } \varphi = \frac{1}{1+\frac{0.47Sc^{-\frac{2}{3}}(2\beta\mu_{se}\rho_{se})^{1/2}}{\rho_w k_w}} \quad (5)$$

Where, q_C is the conducted heat, q_D is the heat released by recombination at the wall, β is the stream velocity gradient, μ_{se} is the dynamic viscosity at the edge of boundary layer, ρ_{se} is the density at the edge of boundary layer, S_C is the Schmidt number, $\bar{\sigma}_w$ is the Prandtl number at the wall, $\bar{h}_{se}$ is the frozen enthalpy at the edge of boundary later, ρ_w is the density at the wall, and k_w is the catalytic reaction rate constant.

3. RESULTS

3.1 Code Validation

NASA's ORSAT, ESA's SCARAB, and KARI's SAPAR programs show such good agreement for simple shape objects with the same conditions for materials and sizes (Lips 2005). A reentry analysis program that has been developed in this study has also been verified with them. A simple sphere shape of four materials such as aluminum, titanium, graphite epoxy 1, and graphite epoxy 2 was used to analyze survivability.

Twenty-four cases of a sphere shape were analyzed for survivability. The result was compared with SAPAR's. The calculated stagnation heat rate for spheres by ORSAT, SCARAB, SAPAR, and the present program can be seen in Fig. 2 and Fig. 3, respectively. There is good agreement with the peak values of spheres. Fig. 4 and Fig. 5 show demise altitude or impact mass for 24 cases, respectively.

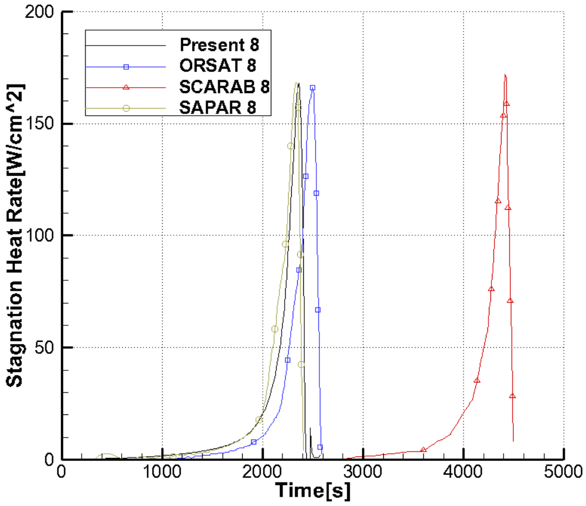

Fig. 2 Stagnation heat rate (case 8)

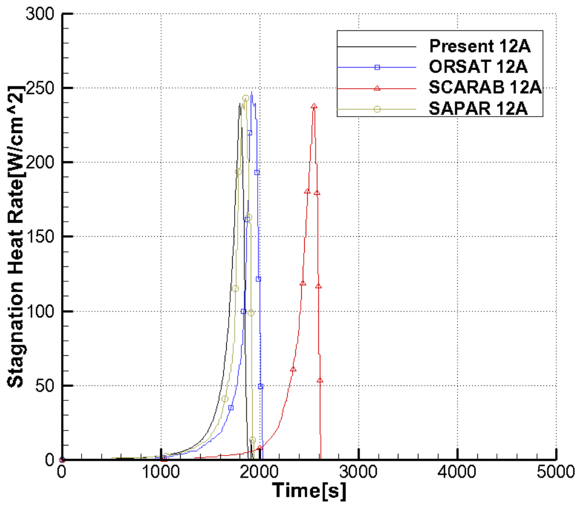

Fig. 3 Stagnation heat rate (case 12A)

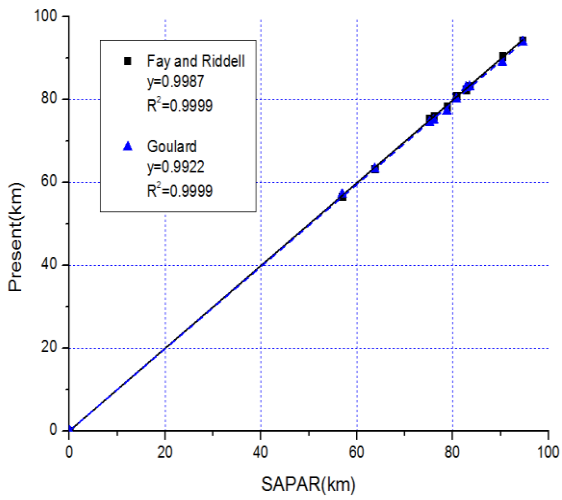

Fig. 4 Comparison of SAPAR and Present for demise altitude

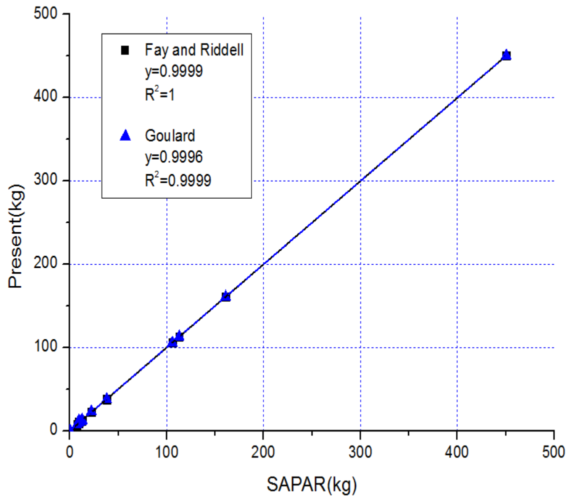

Fig. 5 Comparison of SAPAR and Present for impact mass

3.2 Surface Catalytic Effect

In order to examine a surface catalytic effect, super-catalytic and non-catalytic assumptions were used by using Goulard formula. Initial conditions are the same with the previous study in chapter 3.1. Fig. 6 and Fig. 7 show demise altitude or impact mass for 24 cases with two different assumptions, respectively.

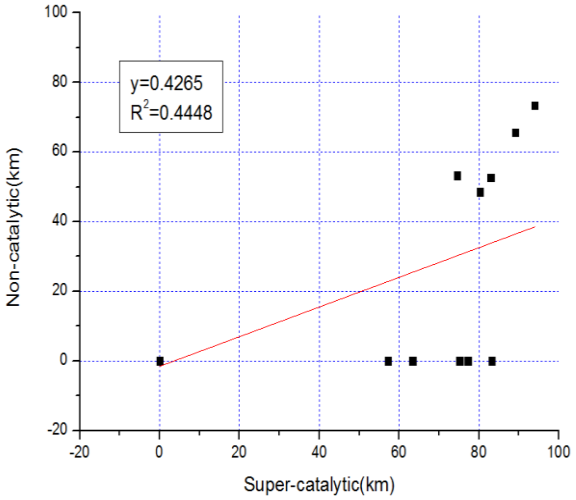

Fig. 6 Comparison of super-catalytic effect and non-catalytic effect for demise altitude

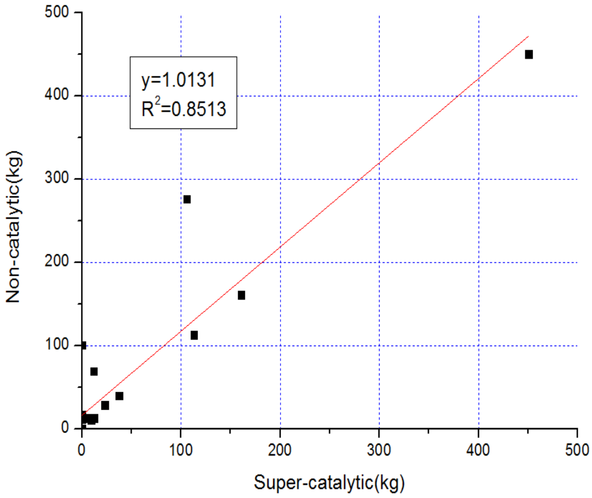

Fig. 7 Comparison of super-catalytic effect and non-catalytic effect for impact mass

4. CONCLUSIONS

A reentry analysis code for space debris was developed and used to analyze surface catalytic effect. It was validated by comparing its analysis results for space debris survivability to those from ORSAT, SCARAB, and SAPAR. However, the latter codes used Fay and Riddell formula which has super-catalytic assumption. This assumption overestimates heat rate because chemical reactions are catalyzed at an infinite at the wall. The real catalytic effect lies between super-catalytic and non-catalytic assumptions. Therefore, Goulard formula was used to compare the two assumptions. There was a big difference between results from the assumptions. It was shown that the catalytic effect on the wall is important.

ACKNOWLEDGMENTS

This work was supported by the National Research Foundation of Korea Grant, funded by the Korean government (NRF-2015R1C1A1A02036694).

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