# NUMERICAL ANALYSIS OF FUEL REGRESSION RATE IN HYBRID ROCKET MOTOR WITH STAR SHAPE PORT FUEL GRAIN

Sabri M.E.E.[1], Togashi K.[2], Azami M.H.[1*]

[1]Department of Mechanical & Aerospace Engineering, Kulliyyah of Engineering, International Islamic University Malaysia
[2]Laboratory of Space Utilization Division of Mechanical and Space Engineering, Hokkaido University

**Article history**

Received: 2 June 2023

Received in revised form: 25 Dec 2023

Accepted: 26 Dec 2023

Published online: 29 Dec 2023

*Corresponding author: hanafiazami@iium.edu.my

**ABSTRACT**

Hybrid Rocket Motor (HRM) has a critical weakness that impacts performance: low regression rate. Due to this, extensive investigation has been done on the star-shaped port fuel grain to enhance the regression rate. Several simulations using Computational Fluid Dynamics (CFD) have been done on star-shaped port fuel grain under several initial conditions to study the impact on the regression rate using ANSYS Fluent software. The stars used have 5-, 6-, and 8-vertice. Paraffin wax and oxygen gas were selected as the fuel and oxidiser respectively. The regression rate of the 6-vertice star is the highest of the three types, and the 5-vertice star is the lowest. The results show that the corner's angle in the star shape affects the combustion temperature. The temperature in the corners is lower than in other parts of the star. The regression rate of the 6-vertice star is the greatest because it has the largest corner angle of 60 degrees, and the 5-vertice star has the smallest corner angle of 36 degrees.

***Keywords***: *Hybrid rocket, star, CFD, regression rate*

## 1.0 INTRODUCTION

Rocket propulsion comes in various shapes and sizes, classifications based on the rocket engine and propellant used. Liquid, solid, and hybrid rockets are the three basic types of rocket engines. The fuel and oxidiser are kept separate as fluids in a liquid rocket and then poured into the combustion chamber, where they burn. Solid rocket propellants are combined and placed in a sturdy container. This research will focus on Hybrid Rocket Motors (HRM) that combine solid fuel with a gas oxidiser. This rocket propulsion is gaining popularity because of its advantages over conventional liquid or solid rocket propulsion systems, such as low cost, ease of fuel management, durability, throttling capability, and environmental benefits.

The regression rate is one approach to assessing the performance of hybrid rockets for comparing propellants, designing a fuel grain, estimating HRM performance, and avoiding burn-throughs [1]. HRM is known for having a lower regression rate than liquid and solid rockets due to the combustion process in the boundary layer over the fuel surface, as seen in Fig. 1.

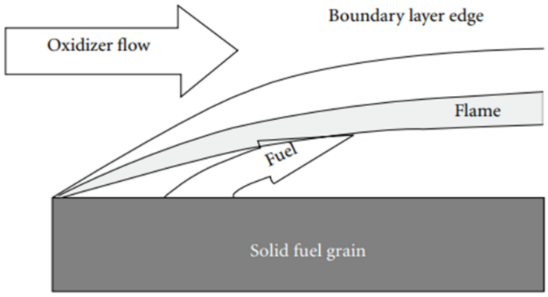



**Figure 1:** The hybrid rocket engine combustion [1].

The oxidiser is injected within the combustion chamber. After ignition, a reacting turbulent boundary layer develops over the solid fuel surface. The solid fuel pyrolyses and vaporises as it passes through the boundary layer. The oxidiser vapour diffuses toward the fuel vapour—a diffusion flame region forms in the boundary layer where the fuel-to-oxidiser stoichiometric conditions are achieved.

One of the ways to improve the regression rate is to change the fuel grain design to increase the fuel grain surface area in contact with the boundary layer [2]. According to research by Glaser et al., test firings on both forward- and backward-facing steps (FFS and BFS) enhanced the overall average regression rate by up to 48% and 53%, respectively, when compared to the classic cylindrical motor [3]. A layered helical structure also considerably increased the fuel grain's regression rate [4]. The innovative fuel grain's regression rate rose by 20% when compared to the single hole fuel grain at an oxidiser mass flow rate of 30 g/s. Fig. 2 shows different fuel grain geometry that can be used in HRM.

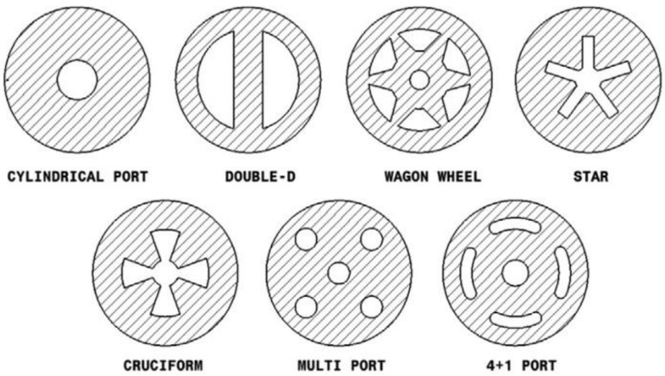



**Figure 2:** Various types of multi-port fuel grain geometries [2]

This study focuses on the star-shaped port fuel grain and its impact on the regression rate with varying initial temperature, pressure, and oxidiser mass flow rate. ANSYS Fluent is used in this study to simulate and observe the internal combustion of the HRM. This study aims to discover the relation between the initial oxidiser condition and regression rate and the relation between the shape of the fuel grain port and regression rate.

Previous works done shows that the average regression rates of the star and wagon wheel grains are much larger than that of the tube grain due to their lower hydraulic diameters [5,6]. This proves the performance improvement of HRMs with star grain. However, the stars used in both studies are different from this study as shown in Fig. 3 and 4.

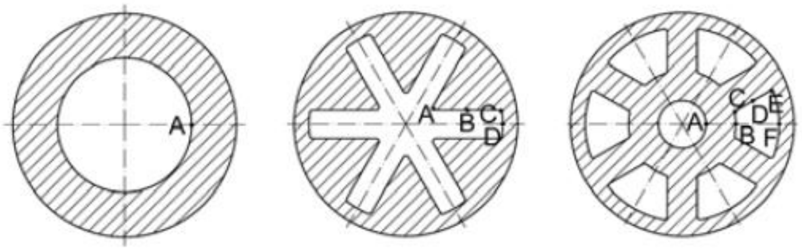



**Figure 3:** Cross sections of different fuel types [5]

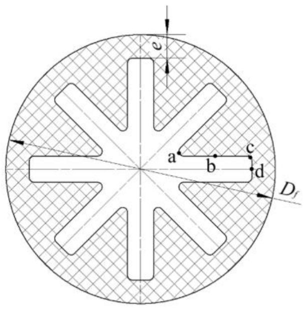



**Figure 4:** The cross section in the middle of star grain [6]

## 2.0 METHODOLOGY

### 2.1 Preliminary Assumptions

The assumptions of the calculation model used in ANSYS Fluent are as follows:

- Chemical reactions are not considered.
- Displacement of the fuel grain surface is not considered.
- The temperature of the fuel grain surface is fixed. Other surfaces are adiabatic.
- Radiative heat transfer is ignored.
- All of the wall heat flux is used for the decomposition of the fuel grain.
- The density of oxygen is constant.

### 2.2 Turbulence Model

The turbulence model used is Large Eddy Simulation (LES). In the LES model, large eddies are calculated directly, and small eddies whose scale is smaller than the mesh cell are modelled as stress. With finer mesh, the result will be replicable sufficiently; hence this model is commonly used for many industrial applications.

### 2.3 Calculation Model

The calculation model is shown in Fig. 5. The fuel grain port shape is set to 5-, 6- and 8-vertice stars, as shown in Fig. 6. The distance from the centre to the corner is 6.5 mm. Paraffin wax was chosen as the fuel, and oxygen gas as the oxidiser. Characteristics of paraffin and oxidiser are shown in Table 1 [7]. Thermal conductivity and viscosity of oxygen are fixed at 450 K.

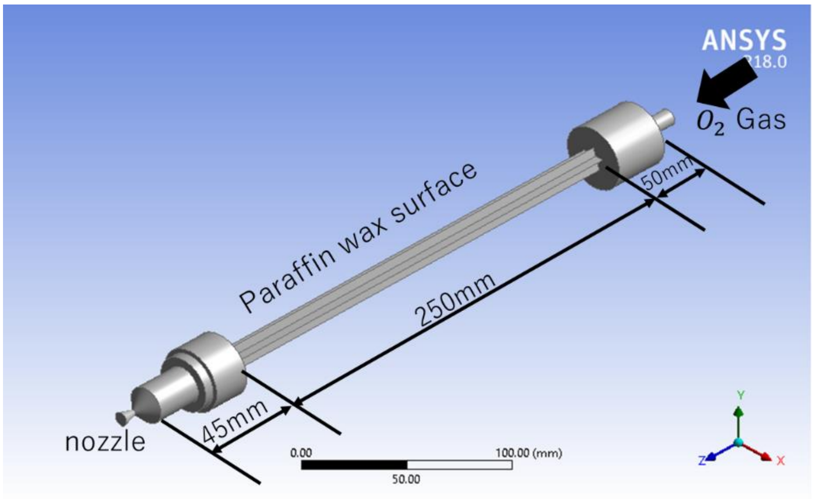



**Figure 5:** Calculation model

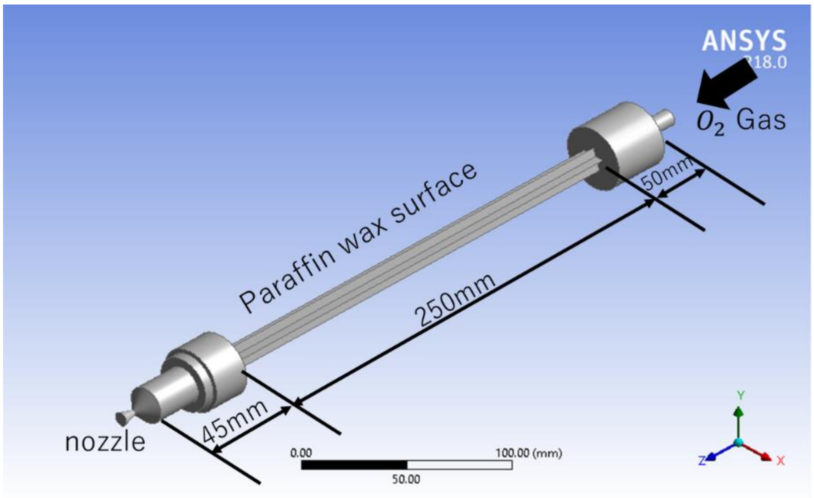



**Figure 6:** Shape of the fuel port grain

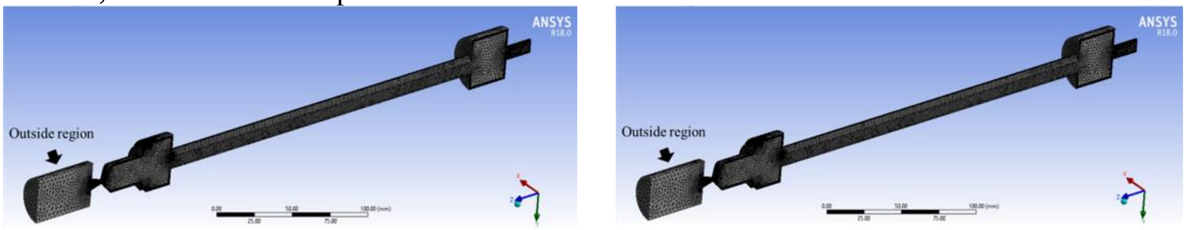
**Table 1:** Characteristics of paraffin and oxygen

| | Density [kg/m$^3$] | Specific Heat [J/kg.K] | Thermal Conductivity [W/m.K] | Viscosity [N.s/m$^2$] | Decomposition Heat [cal/kg] |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| **Paraffin** | 835 | 2800 | 0.21 | - | 850 |
| **Oxygen** | 1.299 | * | 0.0363 | $2.814\times10^{-5}$ | - |

* Depends on temperature

The outer region was set like in Figure 7 because it is difficult to predict the boundary condition of the nozzle outlet domain. The 5-vertice star mesh is cut into half to decrease calculation time, while 6- and 8-vertice stars are cut into quarters. The calculation is conducted for 1 sec, and each time step is 0.01 sec. The number of iterations is 20.




a) b)

**Figure 7:** a) 5-, b) 6- and 8-vertice star

### 2.4 Boundary Condition

The boundary condition is shown in Table 2. The simulations were conducted with variable initial pressure, temperature and mass flux. The boundary condition of the pre-chamber and sub-chamber is the wall and adiabatic. Paraffin temperature is fixed, 550K.

**Table 2:** Boundary conditions

| | **Boundary Type** | **Temperature [K]** | **Initial Pressure [atm]** | **Mass Flux [kg/s]** |
|---|---|---|---|---|
| **Inlet** | Mass flow inlet | 800<br>900<br>1000 | 1<br>2<br>3 | 0.001<br>0.0015<br>0.002 |
| **Pre-Chamber** | Wall (adiabatic) | - | - | - |
| **Paraffin** | Wall (fixed temperature) | 550 | - | - |
| **Sub-Chamber** | Wall (adiabatic) | - | - | |
| **Outside** | Pressure outlet | 300 | 101,325 | - |

### 2.6 Regression Rate

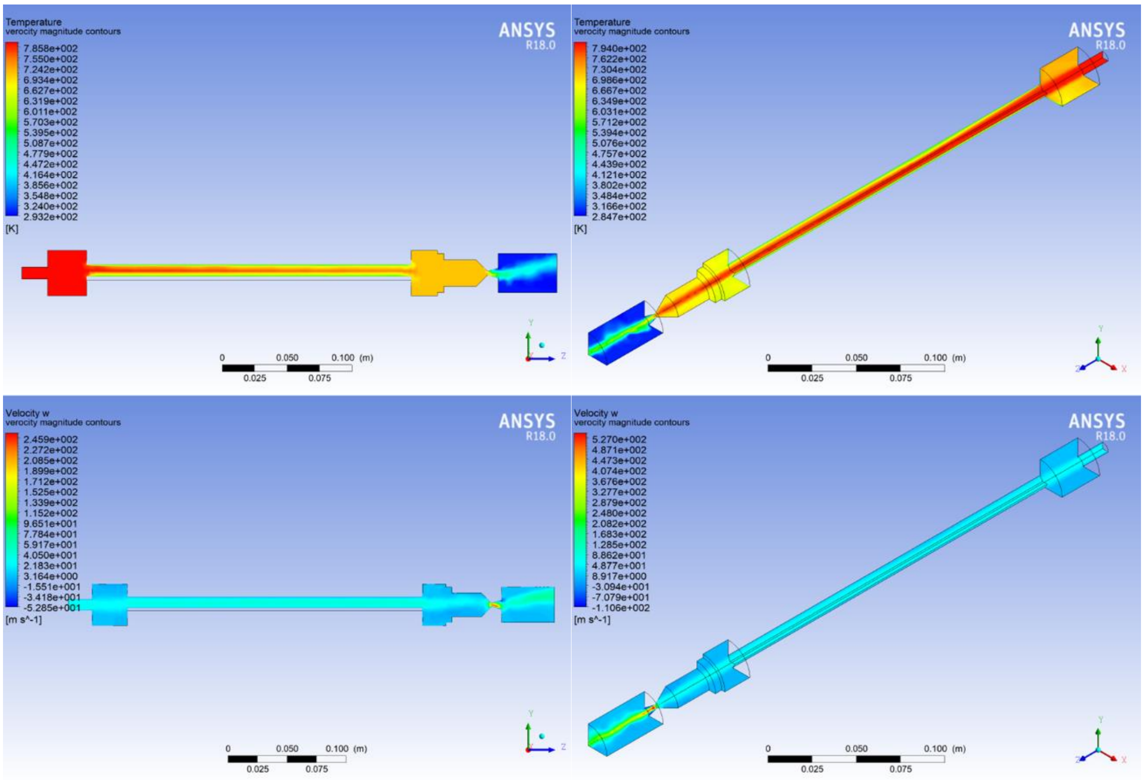
The regression rate in this study is calculated as follows:

$$\dot{r} = \frac{\dot{r}_{wall}}{\rho_{fuel} h_v} \tag{1}$$

where $\dot{r}_{wall}$ is wall heat flux from inside chamber to outside, $\rho_{fuel}$ is the fuel density, and $h_v$ is the decomposition heat of fuel. $\dot{r}_{wall}$ can be obtained from ANSYS Fluent as field function, named total surface heat flux.

## 3.0 RESULTS AND DISCUSSION

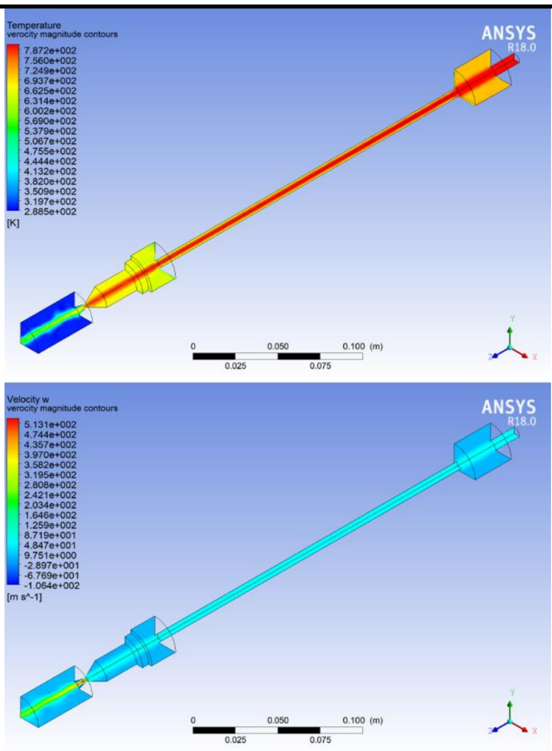
Fig. 8 shows the calculation results of 5-, 6-, and 8-vertice stars at 800 K, 1 atm, and 0.001 kg/s.




a) b)

PERINTIS eJournal

*PERINTIS eJournal*, 2023, Vol. 13, No. 2, pp. 9-18




c)

**Figure 8:** a) 5-, b) 6-, and c) 8-vertice stars at 800 K, 1 atm, 0.001 kg/s

Figures 9 and 10 are the graphs of the average regression rate versus flow rate in each shape, initial pressure, and temperature, respectively. At every condition, the regression rate increases with increasing mass flow rate. The average regression rate of the 6-vertice star is the highest at all initial pressure and temperature values, while the 5-vertice star is the lowest.

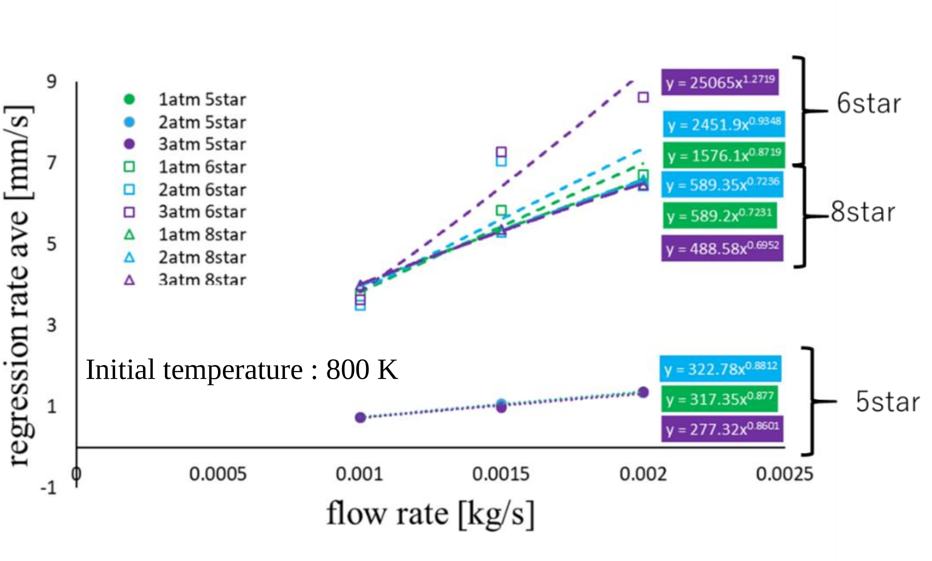



**Figure 9:** Regression rate vs mass flow rate in each shape and initial pressure

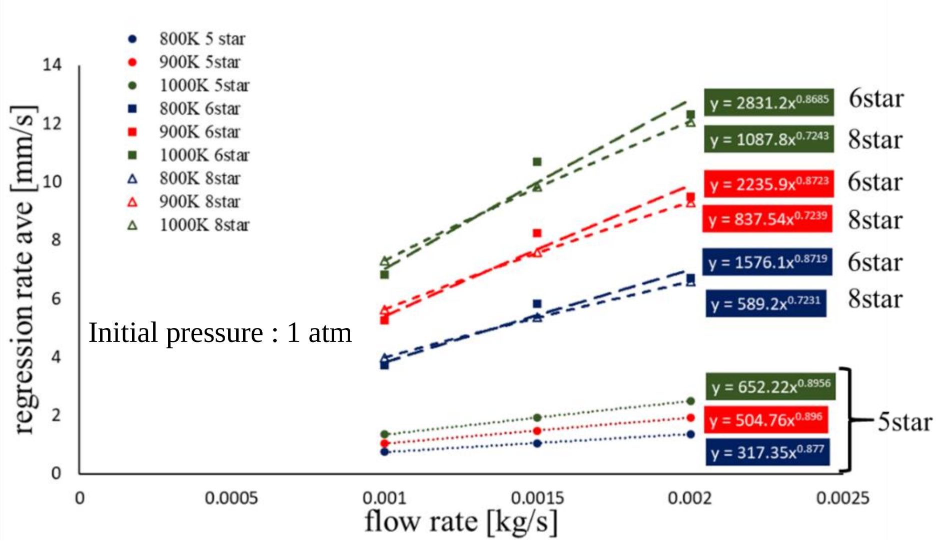



**Figure 10:** Regression rate vs mass flow rate in each shape and temperature

The reason why the 6-vertice star has the highest regression rate is due to the corner angle. Figure 11 shows the star-shaped port's cross-section and temperature distribution. The corner angle in the 5-vertice star is the smallest, and the biggest is in the 6-vertice star at 60 degrees. Fig. 11 shows a more significant distribution of lower temperature area in the corner of the 5-vertice star compared to the 6- and 8-vertice star. These results match the study done by Tian et al. [8]. In Figure 12, A and C are located at the corners and have lower temperatures compared to other points along the surface.

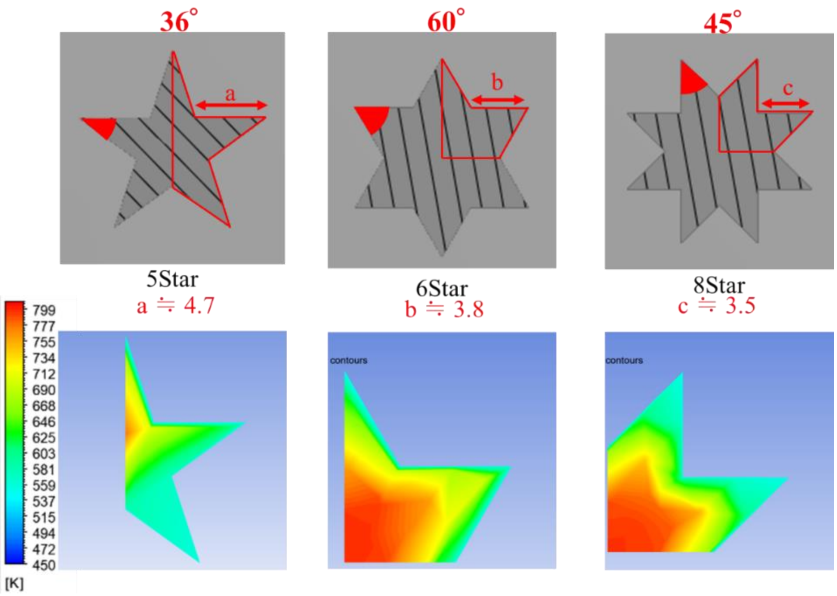



**Figure 11:** Cross section of fuel grain and temperature distribution in star-shaped port

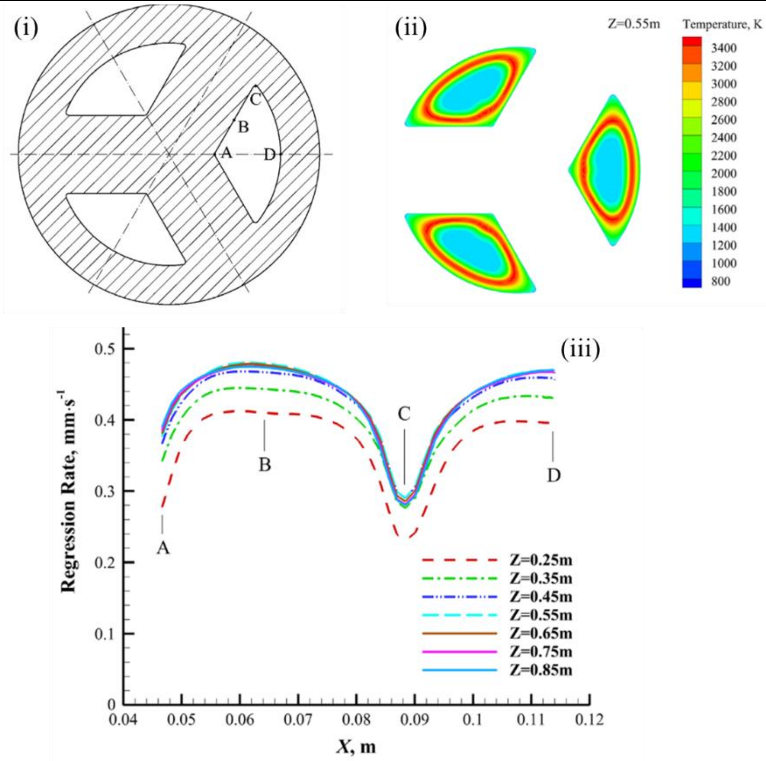



**Figure 12:** Temperature and regression rate at a cross-section in multi ports fuel grain [8]

## 4.0 CONCLUSION

The hybrid rocket has since appealed to many people as it is safe, low-cost, has throttling capabilities, and has more propellant range that can be used. The main disadvantage of this type of rocket is the low regression rate and the combustion inefficiency. Many approaches were taken to tackle this problem, and one of the methods was increasing the fuel grain surface area. Star-shaped port fuel grain usage and how they affect the hybrid rocket's regression rate was studied in this work.

5-, 6-, and 8-vertice star-shaped port fuel grain was used in this study with paraffin wax and oxygen gas as the fuel and oxidiser. The regression rate was obtained under several varying initial conditions. The regression rate increases with increasing mass flow rate. At every condition, the regression rate of the 6-vertice star is the greatest while the 5-vertice star is the smallest. The reason is due to the corner angle in the star. In the corner, the temperature is lower than in other parts of the star. Temperature decreases with decreasing angle of the corner. 6-vertice star has the largest corner angle of 60 degrees, while 5- and 8-vertice stars have 36- and 45-degrees angles, respectively.

The research shows that the area of combustion for a star-shaped fuel port depends on the angle at the vertice of the star. The larger the angle, the better the area of combustion, thus increasing the regression rate. Further improvements can be made to this study by prolonging the simulation time and increasing the number of iterations to improve the accuracy of the results.

**REFERENCES**

[1] Pastrone, D. (2012). Approaches to low fuel regression rate in hybrid rocket engines. *International Journal of Aerospace Engineering*.

[2] Pal, Y., Mahottamananda, S. N., Palateerdham, S. K., Subha, S., & Ingenito, A. (2021). Review on the regression rate-improvement techniques and mechanical performance of hybrid rocket fuels. *FirePhysChem*, 1(4), 272-282.

[3] Glaser, C., Gelain, R., Bertoldi, A., Hendrick, P., & Anthoine, J. (2022, June). Experimental investigation of stepped fuel grain geometries in hybrid rocket engines. In *EUCASS 3AF 2022*.

[4] Z. Wang, X. Lin, F. Li, and X. Yu. (2020). Combustion performance of a novel hybrid rocket fuel grain with a nested helical structure. Aerospace Science and Technology. 97, 105613.

[5] Xintian, L., Hui, T., & Guobiao, C. (2013). Numerical analysis of fuel regression rate distribution characteristics in hybrid rocket motors with different fuel types. *SCIENCE CHINA-TECHNOLOGICAL SCIENCES*, *56*(7), 1807-1817.

[6] Tian, H., Jiang, X., Lu, Y., Liang, Y., Zhu, H., & Cai, G. (2022). Numerical Investigation on Hybrid Rocket Motors with Star-Segmented Rotation Grain. *Aerospace,* 9(10), 585.

[7] Tian, H., Li, Y., & Zeng, P. (2014). Transient simulation of regression rate on thrust regulation process in hybrid rocket motor. *Chinese Journal of Aeronautics,* 27(6), 1343-1351.

[8] Tian, H., Li, X., Zeng, P., Yu, N., & Cai, G. (2014). Numerical and experimental studies of the hybrid rocket motor with multi-port fuel grain. Acta Astronautica, 96, 261-268.