INVESTIGATION ON NOZZLE THROAT EROSION IN HYBRID ROCKET MOTOR DUE TO NOZZLE EXPANSION RATIO

Mohd Aizat Iz'aan Mohd Ali [1], Muhammad Farhan Razali [1], Muhammad Hanafi Azami [1,*] and Ahmad Hussein Abdul Hamid [2]

1. Department of Mechanical and Aerospace Engineering, Kulliyyah of Engineering, International Islamic University Malaysia, Gombak, Kuala Lumpur, Malaysia.
2. High Energy Material Research Laboratory (HEMREL), School of Mechanical Engineering, College of Engineering, University Teknologi MARA, Shah Alam, Selangot, Malaysia.

*Correspondence: hanafiazami@iium.edu.my

Abstract: Rocket nozzle is one of the core elements in rocket motors. Throughout the years, nozzle throat erosion in rocket motors has been heavily discussed by researchers, especially in the hybrid rocket motor due to a high amount of oxygen and unburned propellant in the combustion product. Generally, throat erosion occurs in the rocket nozzle throat where the flow experiences minimum area due to the dissipation of its material. The velocity of the hot gas in the nozzle increases throughout the converging-diverging section of the nozzle and such high speed at the throat area causes the throat erosion, which leads to enlarged nozzle throat area that consequently causes reduction in the motor performance. The purpose of studying the nozzle throat erosion is to have a closer reach to understanding of the nozzle throat erosion factors, behaviors and effects towards the efficiency of rocket propulsion. In this study, the primary focus is on the effects of the nozzle expansion ratio to the throat nozzle erosion. Based on the simulation results in ANSYS and theoretical calculations, it is found that the thrust decreases as the expansion ratio increases. Therefore, it is concluded that rate of nozzle erosion increases as expansion ratio increases, which is shown to be caused by high-speed velocity of the firing going through the small area of the nozzle throat.

Keywords: hybrid rocket motor; throat erosion; nozzle expansion ratio; rocket nozzle; ANSYS

1. Introduction

Hybrid rocket motor (HRM) is one type of chemical rocket motors that has been frequently looked at due to its advantages over other chemical rockets in terms of safety, low cost, restart capabilities and throttling abilities. These advantages and capabilities of HRM have attracted various amateur academic groups to continue its research [1]. Historically, developments of HRM can be detected as early as 1933 [2]. Recently, there have been studies related to the development of modern space transportation using HRM. This highlights that the progressive interest in HRM development, even among entities from the non-space-faring nations with various studies on untraditional combinations of hybrid propellant [3]. In general, HRM is considered as a combination of solid rocket motor (SRM) and liquid rocket engine (LRE). By comparison, HRM is designed to have both solid and liquid in its propulsion system while SRM and LRE respectively use only solid and liquid as their rocket fuel and oxidizer. In HRM, solid fuel is usually contained in a cylindrical form within the combustion chamber whereas the liquid oxidizer is separated and delivered to the combustion chamber through a single fluid system [4].

The interest over hybrid rocket engines has increased in recent years and various efforts have been aimed at researching these engines. In general, the presence of a solid component makes it possible to significantly simplify the design, making hybrid rocket engine as one of the most promising, powerful and simple rocket engine types. A hybrid rocket has fuel and oxidizer in different stages [5]. There are some main components in all HRMs. The first is the oxidizer tank. Though gaseous or liquid fuels and solid oxidizers might be utilized by HRMs, fuels are typically selected as the solid propellant as they are easily available and easier to handle than solid oxidizers. A key valve in hybrid rocket engines controls the oxidizer flow rate into the combustion chamber. Another main part is the combustion chamber of the traditional HRM. Dual functionality is provided by the combustion chamber in HRM. It houses the solid grain of fuel and also gives the propellants volume to mix and react. One end of the chamber for combustion contains the nozzle, where the combustion products are accelerated and exhausted out to produce thrust. Figure 1 shows the schematic view of a HRM.

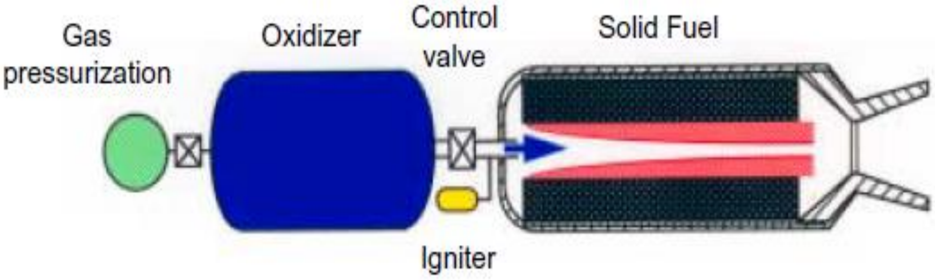


Figure 1: Illustration of a hybrid rocket system [6]

Nozzle is one of the main parts of a hybrid rocket. The propulsion and acceleration produced by a rocket happens during the firing through the nozzle. There are many types of nozzles that have been developed but the most common one is the converging-diverging (CD) nozzle. This nozzle essentially works based on the Newton's third law. In this case, the action-reaction of the rocket is produced when the hot gas leaves the combustion chamber and goes down to the smallest area of the nozzle, which is the throat. It is then expelled through the diverging section of the nozzle and, as a result, lifts the rocket upwards. Eventually, after the firing of the rocket, area around the throat section happens to experience erosion. Similarly, in the development of SRM, the nozzle throat erosion is one of the major challenges. In comparison, however, the nozzle throat erosion in HRM is significantly higher due to its distinctive feature of having greater concentration of oxygen, which affects the nozzle material behavior [7]-[8]. Subsequently, this leads to performance deterioration. Based on this realization, prediction of the throat erosion really helps in improving the development in rocket industries.

There are numerous factors that can contribute towards nozzle throat erosion. Among others, they include ratio of oxidizer to fuel (O/F), chamber pressure, fuel formulation, nozzle materials and nozzle throat parameter. Low O/F helps to reduce nozzle erosion rate since there are less free oxygen particles in the system. In addition, high chamber pressure also speeds up the nozzle erosion due to the existence of high mass flux at the nozzle throat [9]. The efficiency of rocket engine is partially dependent on the rate of nozzle material erosion caused by the flow of hot gas during the process. With the corrosion of the nozzle, the output and pressure of the rocket will decrease. For analyzing nozzle erosion, it has been demonstrated that the use of the model for classic equation of nozzle material erosion prediction has a strong agreement with experimental results [10].

This study is conducted to establish the effect of nozzle expansion ratio on throat nozzle erosion. To accomplish this, simulation modelling and analysis is performed on several CD nozzle designs with varying expansion ratio.

2. Methodology

One of the most common designs of CD nozzle is the conical nozzle. The conical nozzle has been often used in many rocket applications because of its simplicity and ease of construction [11]. Its design is not only simple but it also generates equal exit velocity to the one-dimensional value corresponding to the area ratio of nozzle throat and nozzle exit. In this study, five conical nozzle designs are considered and they are sketched and modelled in Solidworks software. It should be noted that these nozzle designs have similar length of the nozzle, inlet diameter, outlet diameter and also location of the throat to each other, which are set to 18 mm, 20 mm, 15 mm and 6 mm from the inlet of the nozzle, respectively. The only difference between these nozzle designs is their throat diameter that has been varied according to the expansion ratio. Basically, expansion ratio is the area ratio between exit area and throat area. In this study, the throat diameter is increased by 1 mm from 6 mm to 10 mm. Subsequently, the change made in the throat diameter will also change the half-angle of the nozzle design. This enables the simulation and analysis of nozzle throat erosion in optimal nozzle internal flow and abnormal conditions such as flow losses, which usually occurs when the value of half-angle exceeds 15°. All in all, the nozzle designs that are considered in this study are tabulated in Table 1.

Table 1: Expansion ratio and half-angle of the nozzle designs in this study

Throat Diameter (mm)	**Half-Angle (°)**	**Expansion Ratio**
10	11.77	2.25
9	14.04	2.78
8	16.26	3.52
7	18.43	4.59
6	20.56	6.25

For this study, the ANSYS Fluent software is utilized to simulate the flow in the nozzle and obtain resultant parameters from the analysis. In brief, the first step is to model the considered nozzle designs. The constructed drawing from Solidworks is imported into ANSYS as shown in Figure 2. If the import process is successful, the model is now ready to be meshed. In this study, the selected meshing method is the sweep method and the number of division is set to 100. Example meshed model of the nozzle is illustrated in Figure 3.

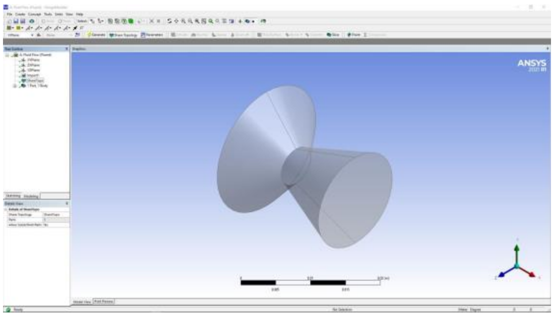


Figure 2: Imported nozzle model into ANSYS

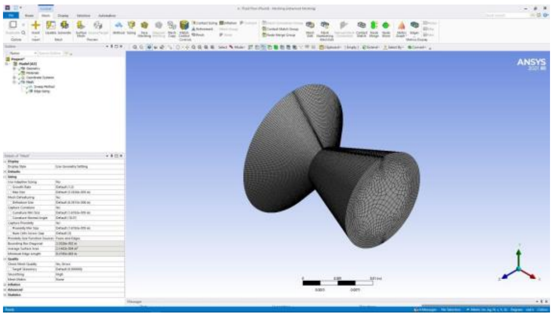


Figure 3: Meshed nozzle model in ANSYS

For the simulation analysis, density-based setup has been selected for high speed compressible flow simulation. Furthermore, the models are analyzed with energy turned on and the viscous model used is k-epsilon. In addition, the temperature, velocity and pressure of the simulated flow conditions for the analysis are set to be 500 K, 110 m/s and 3 atm (303,975 Pa), respectively. The hybrid initialization is used and the number of iterations is set to 500. For this study, the calculated primary outputs are exit pressure and velocity of the inlet. These pre-setup and post-setup are shown in Figure 4 and Figure 5, respectively. Moreover, the settings for the simulation outputs are set such that the pressure and velocity of the flow in the nozzle are presented in contour plots as illustrated in Figure 6.

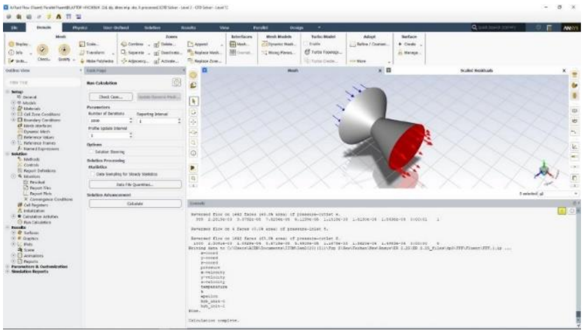


Figure 4: Pre-setup in ANSYS

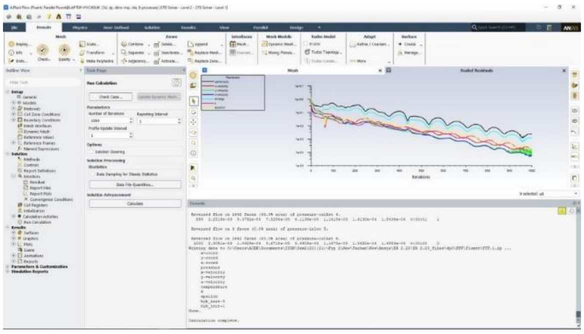
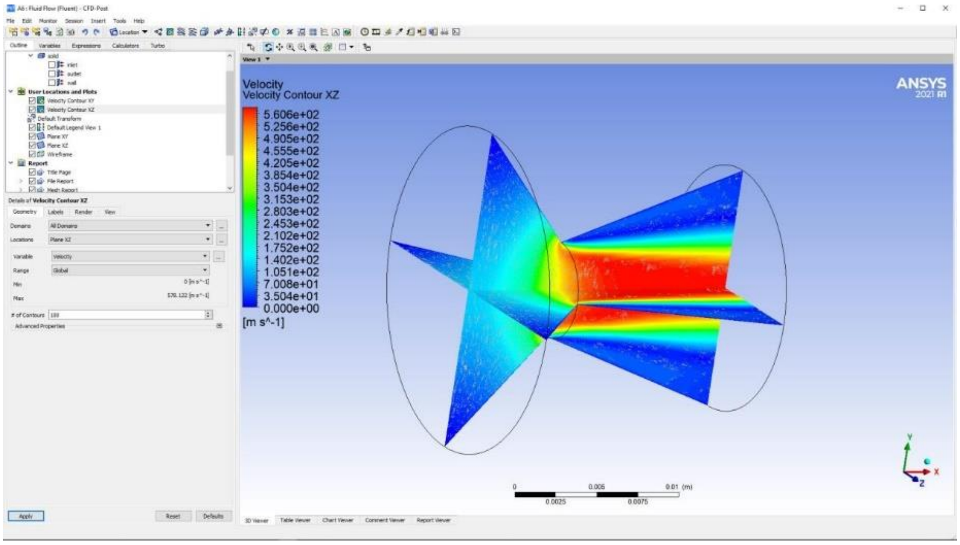


Figure 5: Post-setup in ANSYS



Domains: All Domains
Locations: Plane XZ
Variable: Velocity
Range: Global
Min: 0 [m s^-1]
Max: 576.122 [m s^-1]
# of Contours: 100

Figure 6: Simulation analysis output in ANSYS

After the simulation analysis has been completed in ANSYS, the investigation on throat erosion is proceeded using the calculation method. Throat erosion is studied based on comparison of initial throat nozzle diameter and final throat nozzle diameter after burning. Equation 1 is applied to determine the throat nozzle diameter, D_t where the nozzle throat area, A_t is given by Equation 2.

$$D_t = \sqrt{4A_t} \tag{1}$$

$$A_t = \frac{F}{\gamma \cdot \varsigma_F C_F \cdot P_c} \tag{2}$$

Moreover, the thrust can be derived by using the rocket thrust equation as presented by Equation 3 and the maximum mass flow rate is given by Equation 4. After the calculation is completed, the thrust versus half-angle graph is plotted for better observation and explanation on the nozzle throat erosion behavior. These results help in concluding this study of the nozzle throat erosion.

$$F = \dot{m} v_e + (p_e - p_0) A_e \tag{3}$$

$$\dot{m} = \frac{A p_t}{\sqrt{T_t}} \sqrt{\frac{\gamma}{R}} \left(\frac{\gamma+1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \tag{4}$$

3. Results and Discussion

From Figure 7, it can be seen that the velocity near the throat area for all nozzles is in the range of 600 m/s to 700 m/s. The sturdy pattern of the thrust can also be observed in the contour velocity of the nozzles with expansion ratio 2.25 and 2.78 in Figure 8. Meanwhile, the nozzles with expansion ratio of 3.52, 4.59 and 6.25 show a little bend in the flow. Nonetheless, despite this flow behavior, the nozzles with expansion ratio of 4.59 and 6.25 have high maximum velocity of about 800 m/s, which is observed in Figure 9. Corresponding to Figure 10, the pressure of nozzles with expansion ratio of 4.59 and 6.25 is the highest among the lower expansion ratio nozzles, which explains the higher velocity of the highest expansion ratio nozzle.

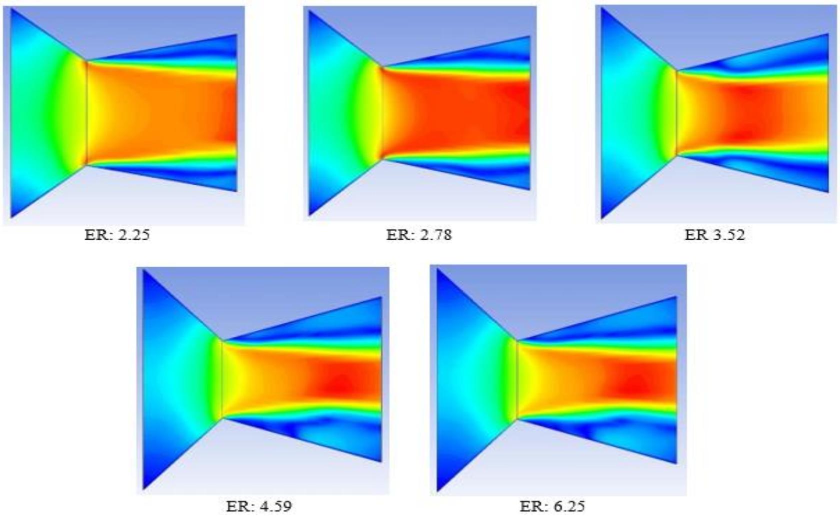


Figure 7: Velocity contour for nozzle designs with different expansion ratio (ER)

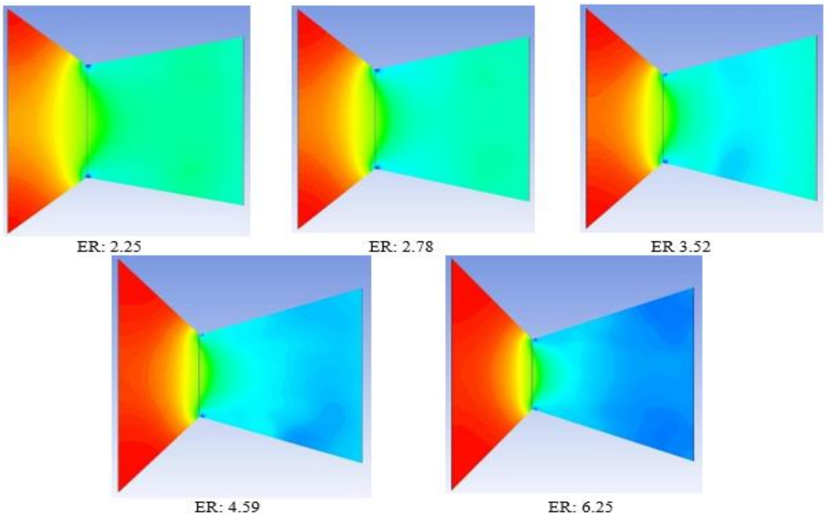


Figure 8: Pressure contour for nozzle designs with different expansion ratio (ER)

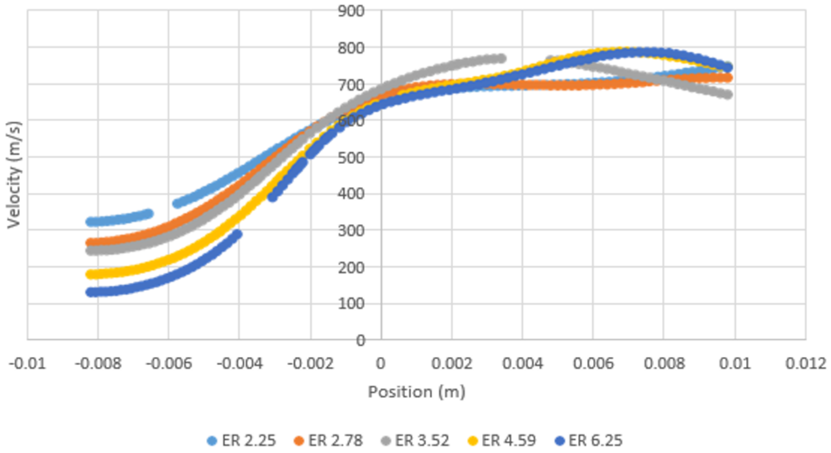


Figure 9: Velocity versus position for nozzle designs with different expansion ratio (ER)

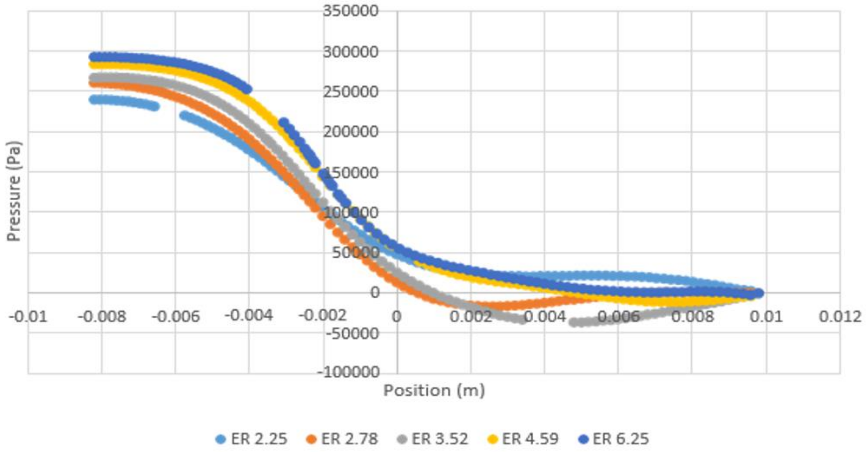


Figure 10: Pressure versus position for nozzle designs with different expansion ratio (ER)

In Figure 9, the velocity of the flow throughout the nozzle design is shown. In the converging part, velocity of the flow in all considered nozzle designs increases uniformly. As the flow reaches the nozzle throat, the flows experience linear velocity due to the constriction at the throat, which forces the flow to accelerate. Subsequently, once the flow exited the nozzle throat area, the velocity further increases. However, the loss of velocity can be seen near the end of the nozzle for flow in the nozzle designs with expansion ratio of 3.52, 4.59 and 6.25. On the other hand, the wall distribution of pressure inside the nozzles throughout the simulation is depicted by Figure 10. It can be observed that the pressure starts to decrease as the flow goes towards the rocket nozzle and the reduction is much steeper as it reaches the nozzle throat. Subsequently, pressure is low as the flow exits the nozzle throat. Pressure distribution is significantly steeper for nozzles with expansion ratio of 2.78 and 3.52. Additionally, Figure 10 also shows that the flow starts to separate for nozzle with expansion ratio of 2.25 at around 0.003 m.

From Figure 10, the flow experiences a pressure drop as the velocity increase at the nozzle throat and this phenomenon is commonly known as choked. The pressure near the nozzle exit is lower, hence resulting in a faster flow speed at the throat and it eventually reaches the speed of sound. All considered nozzle designs show sudden drop of pressure even when there is no increment of velocity. This happens due to demerit of the simulation design, which consists of a sharp turning at the throat, thus producing an oblique shock wave near the area. This behavior can be seen for the nozzles with expansion ratio of 3.52, 4.59 and 6.25. All these nozzle designs have half-angle value of more than the optimal value, which is around 11° to 15°. It can be concluded that the nozzle designs with expansion ratio of 2.25 and 2.78 have better performance.

Investigation of the nozzle throat erosion is computed using the data obtained from the simulation analysis. The mass flow rate, thrust coefficient and deduced throat area of each expansion ratio are then calculated. The final diameter values of the nozzle are obtained and differences between the initial and final diameter is tabulated in Table 2 and Table 3. It is observed that the final diameter of each nozzle design results in a percentage difference from 0.52% to 1.63% as the expansion ratio increases. This is taken to indicate that the thrust decreases as the expansion ratio increases, which further implies that the rate of nozzle erosion increases as the expansion ratio increases. One reason behind this occurrence is because of the high-speed velocity of the firing going through a small area of the nozzle throat.

Table 2: Calculated parameters

Expansion Ratio	**Mass Flow Rate (kg/s)**	**Thrust Coefficient**	**Exit Velocity (m/s)**	**Thrust (N)**	**Deduced Area (m^2)**
2.25	0.253	199.03	786.08	3165.87	7.94×10^{-5}
2.78	0.205	149.61	729.81	1928.45	6.46×10^{-5}
3.52	0.162	129.19	797.71	1315.93	5.13×10^{-5}
4.59	0.124	99.38	801.45	774.99	3.95×10^{-5}
6.25	0.091	73.88	811.04	423.33	2.92×10^{-5}

Table 3: Calculated values for throat erosion

Initial Diameter (mm)	**Final Diameter (mm)**	**Percentage Difference %**
10	10.05	0.52
9	9.07	0.76
8	8.08	1.02
7	7.09	1.31
6	6.09	1.63

4. Conclusion

Research and studies on HRM development are still blooming and garnering the attention of the educational and commercial or business sector due to its safety and also economical propulsion system. However, due to its properties, HRMs are unable to stray away from one of its major problems, which is throat nozzle erosion. This study is focusing on one of the factors of throat nozzle erosion, which is the nozzle expansion ratio. From the simulation done, it is found that the final diameter of each nozzle results in a percentage difference from 0.52% to 1.63% as the expansion ratio increases. The tabulated data of calculated values shows the decrease of thrust as expansion ratio increases. It can be concluded that the rate of erosion of the nozzle increases as the expansion ratio increases. One of the mitigations of throat erosion is to not design the throat area to be too small. Instead, a suitable dimension should be selected for the throat area. It should be noted that the results of the simulation may vary from reallife experiment, however it increases the possibilities to predict throat erosion numerically. Aside, the simulation will act as a guide for future experimental studies on throat erosion in HRMs.

Acknowledgement

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