Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879

Investigation of Solid Propellant Rocket Motor Nozzle via CFD Simulation

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ARTICLE INFO

Article history:
Received 7 October 2019
Received in revised form 11 January 2020
Accepted 11 January 2020
Available online 30 March 2020

Keywords:
Solid propellant rocket motor; CFD; FEA

ABSTRACT

The current work predicts the combustion characteristics of a solid rocket motor especially the flow in the nozzle part. The simulation work is done using computational fluids dynamic (CFD) software. The volume mesh was built in one quarter of the nozzle to reduce time for calculation. The same nozzle is also created with different mesh sizes for grid dependency check. All the rocket parameter is obtained from the theoretical design of rocket motor based on basic nozzle design. The simulation result in CFD is compared to the theoretical calculations and it shows that the modelling of rocket nozzle results shows good agreement with the theoretical ones. Parametric study on the nozzle was conducted. The results show that the best nozzle configuration for the current design is when the throat length is set to 1mm.

1. Introduction

Solid propellant rocket motor is not a new technology. It has been around since the Chinese Empire invented the fireworks at around 2000BC [1, 2]. Nevertheless, it is not until 1950s that the ultimate progress on the technology was happening due to the space race between the US and the Russian. The invention of missiles also contributes to the development of this technology [3, 4].

Even though this technology is not new, the technology problem still remains. Most of the rocket motors are used only once. The hardware that remains, after all the propellant has been burned and the mission completed, such as nozzle and case, is not reusable. In very rare applications, such as the Shuttle solid booster, is the hardware recovered, cleaned, refurbished; reusability makes the design more complex [5-7].

Unlike some liquid propellant rocket engines, a solid propellant rocket motor and its key component cannot be operationally pre-tested, since the testing will cause the erosion of nozzle throat as well as agglomeration of propellant particles that will jeopardize the performance of the motor afterwards [8]. Therefore, this is where the computational fluid dynamics comes into use [9-

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https://doi.org/10.37934/arfmts.68.2.18

11]. It can be used to simulate the internal combustion characteristics and visualize the combustion flow as well as to predict the performance. By doing so, optimization of the motor performance can be done without having to build and test lots of real rocket motor. Thus, a major cost saving can be achieved. New technique which is the IR experimental approach has also been developed [12-15]. However, this approach is costly and require substantial time to be completed.

Therefore, the current work will focus on the CFD simulation of the internal nozzle flow. The nozzle design will be conducted by using SRM-EXCEL. Once the design has been completed, the CFD simulation is performed using Ansys-Fluent software.

2. Methodology

Computer simulation software is used to study the flow characteristics of the solid propellant rocket motor and this was done by using CFD software. The objective of the simulation is to focus on the study of flow in the nozzle part so that any important factor that contributes to total pressure, total temperature, static pressure, velocity distribution, Mach number in choked nozzle part and so forth.

2.1 Motor Sizing

For the basic design contain the choosing appropriate requirements and parameters. The rocket design parameters are selected by referring SRM-EXCEL it was used to get Data and Kn, Pressure, Performance and Output. Data input shown as Table 1.

Table 1
Data input

Input parameter	Value
Motor chamber diameter (inside)	56mm
Chamber length (inside)	300mm
Grain outer diameter	55mm
Core diameter	13mm
Grain length	250mm
Ratio of burning area K_{n_O}	1000

After input data in SRM-EXCEL will get following data and performance of rocket. Grain parameter output shown as Table 2.

Table 2
Grain output parameter

Output Parameter	Value
Grain volume	560774mm^3
Grain mass	0.996 kg
End burning area A_{beo}	4486mm^2
Total burning area A_{bo}	57893mm^2

The parameter output of nozzle data shown in Table 3

Table 3
Nozzle output parameter

Output Parameter	Value
Throat cross-section area A_{to}	58mm^2
Throat diameter D_{to}	8.586mm
March No. at nozzle exit M_{eo}	3.163

Parameter of the rocket chamber pressure and performance are as shown in Table 4.

Table 4
Calculation of the SRM performance

Parameter	Value
Total impulse	1138 N-sec
Maximum thrust	641 N
Average thrust	533N
Thrust time	2.132 sec
Motor classification	J

2.2 Propellant

Solid propellant combustion and spray out create impulse, different types of propellant have quite different performance and it is most dangerous part because of flammable and explosive. To improve project security, give up choosing the most common sugar-based propellant, because during mix process have to heat. The Potassium Nitrate/Epoxy Composite Propellant (RNX) propellant be our first choice, the RNX propellant possessing excellent physical and mechanical properties, have reasonable performance power, are non- hygroscopic, and are produced by a cold-casting technique [1].

RNX propellant is epoxy based composite propellant, the composition of RNX propellant is potassium nitrate 70%, epoxy 22% and ferric oxide 8%, because of epoxy, Epoxy plays a dual role, serving as fuel and binder. As a fuel, epoxy has good combustion characteristics, with a respectable energy content, and is a material that decomposes by pyrolysis upon heating. As a binder, epoxy has superb mechanical strength and toughness, good machinability, is safe to use, utilizes two-part curing and has low viscosity.

2.3 Case Dimensions and Material Selection Material selection
2.3.1 Material selection

For the material should light and strong also should withstand high temperature for a short period of time. Aluminum alloy 6061-T6 is chosen, the aluminum T6 temper 6061 has an ultimate tensile strength of at least 290 MPa and yield strength of at least 241 MPa.

2.3.2 Case wall thickness

The wall thickness was calculated by using equation below

$$t = \frac{pd}{2S_H} = \frac{16.548KPa*60cm}{2*290MPa} = 1.71 \tag{1}$$

2.3.3 Nozzle design

Ratio of Burning area / throat area Kn sizes the throat diameter and determines chamber pressure. Setting K_{n_o}=1000. Diameter of nozzle throat area was calculated via

$$A_t = \frac{A_{bo}}{k_n} = \frac{57893}{1000} = 58\ mm^2 \tag{2}$$

Meanwhile for Nozzle exit area was calculated using equation below

$$A_e = \frac{A_e}{A_t} A_t = 578.9\ mm^2 \tag{3}$$

The diameter of nozzle exit area was calculated by using equation below

$$D_e = \sqrt{\frac{4A_e}{\pi}} = 27.15\ mm \tag{4}$$

2.3.4 Nozzle design and CFD analysis

Shown as Figure 1 is the typical structure of nozzle, for the beta and alpha shown as Table 5.

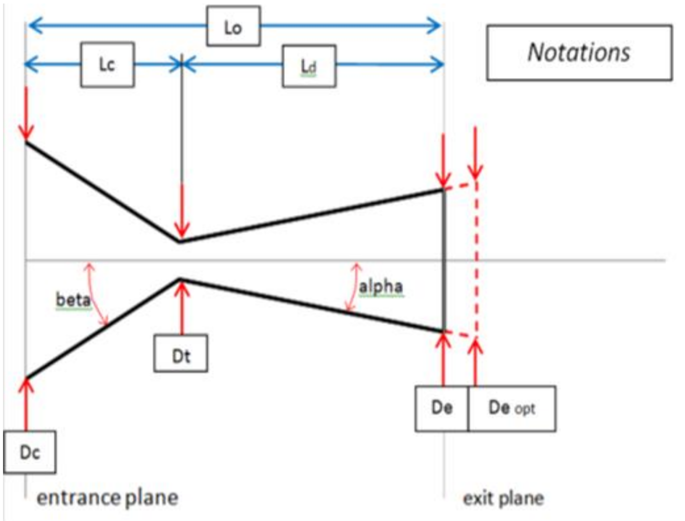


Fig. 1. Schematic of the nozzle

Table 5
Nozzle design data

beta	30.0	degrees	Nozzle convergence half-angle
alpha	12.0	degrees	Nozzle divergence half-angle
Dc	56	mm	Chamber inside diameter
Dt	8.586	mm	Nozzle throat diameter
De	27.15	mm	Nozzle exit diameter
Lc	32.5	mm	Convergence length
Ld	52.7	mm	Divergence length
Lo	85.2	mm	Overall length
-	6	mm	Throat length

The next step is using ANSYS fluent CFD software do 2-D flow simulation to study the performance of the nozzle and do the optimization, sketching data all from Table 5, and setting the nozzle throat length is 6mm.

For the sketching shown in Figure 2, the left side is the nozzle inlet and the right side is outlet, for the rest are walls separate the nozzle in several different areas to using different mesh size in different and can also improve the meshing quality, the meshing result shown as Figure 3.

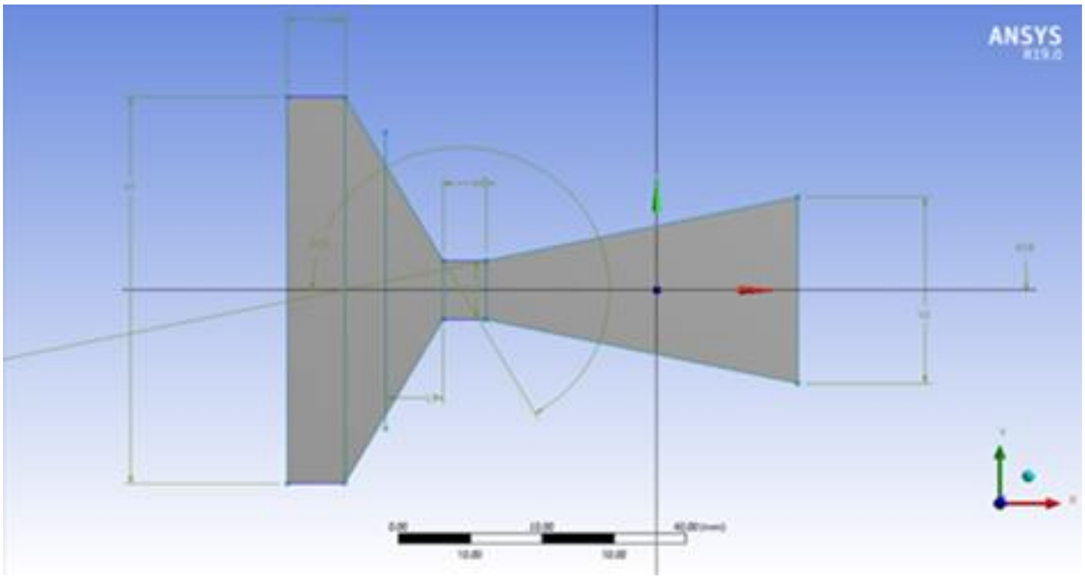


Fig. 2. Nozzle sketching

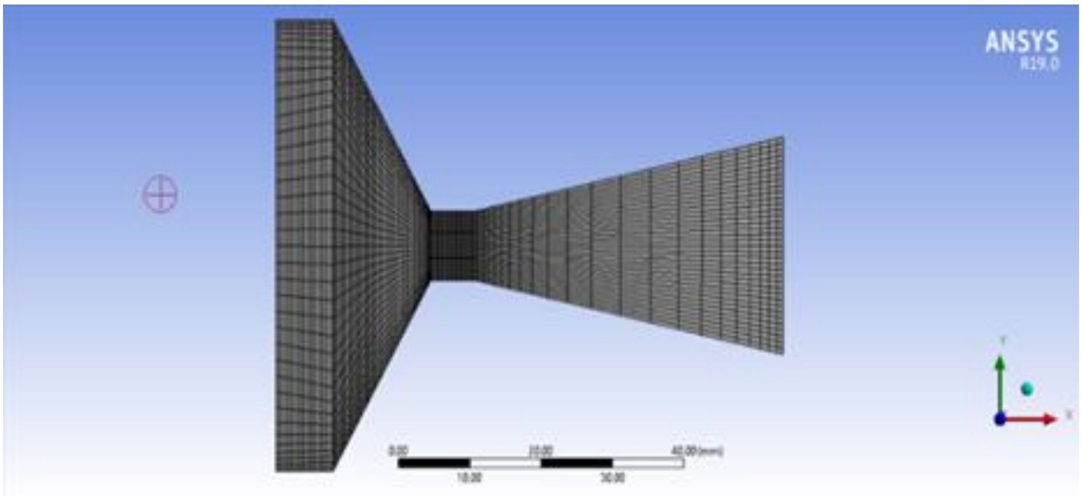


Fig. 3. Nozzle meshing

3. Results

In the fluent setup, the material was set as an ideal- gas. The boundary condition of inlet was set to be Pressure-inlet and the total pressure set to 7.89MPa. For the outlet, it was set to be Pressure-outlet and the gauge pressure was set to 0 Pa. Figures 4 and 5 show the contour of pressure and the Mach number respectively. Generally a typical flow phenomenon can be observed where low speed high pressure gas through the nozzle are transferred to the high speed low pressure gas. Meanwhile Figure 6 shows the plot of the velocity magnitude across the nozzle. It is clearly be seen that the gas was accelerated when it passed through the nozzle throat area in which the magnitude is about

1000m/s. This magnitude is equivalent to the speed of sound and therefore it is a choke condition. It is observed also that the maximum Mach number at the exit region was about 2.8 while from the gas dynamics calculation the exit Mach number was 3.16 (see Table 2). The difference is about 11% and therefore it is acceptable. From the contours, it can be seen that the throat area is the discontinuity area. By hypothesize that the throat area can influence the exit Mach number, the following results will show the effects of the various throat area lengths.

Table 6 shows the results of the parametric study. Various throat area length were tested and the Mach number contours are displayed. The original length of the throat was set to 6 mm (see table 5). In the current work, the length was changed to several values which are 0.5mm, 1mm, 1.5mm, 2mm, 3mm, 4mm, and 8mm.

From Table 6, it can be seen that by shortening the throat length, the exit Mach number is increased. It is also observed that the length that produce the highest exit Mach number is 1mm. With this length, the exit Mach number was 2.807. It is also observed that by increasing the distribution of the velocity is similar to all throat length cases.

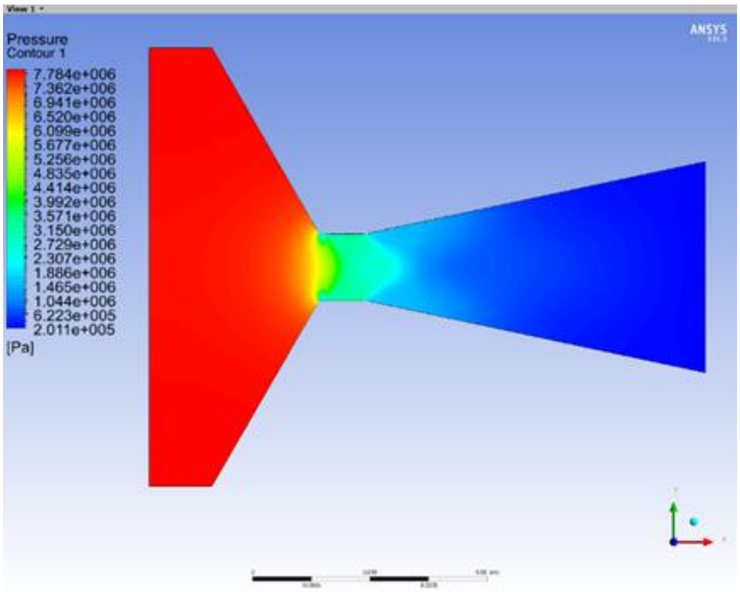


Fig. 4. Result of nozzle pressure

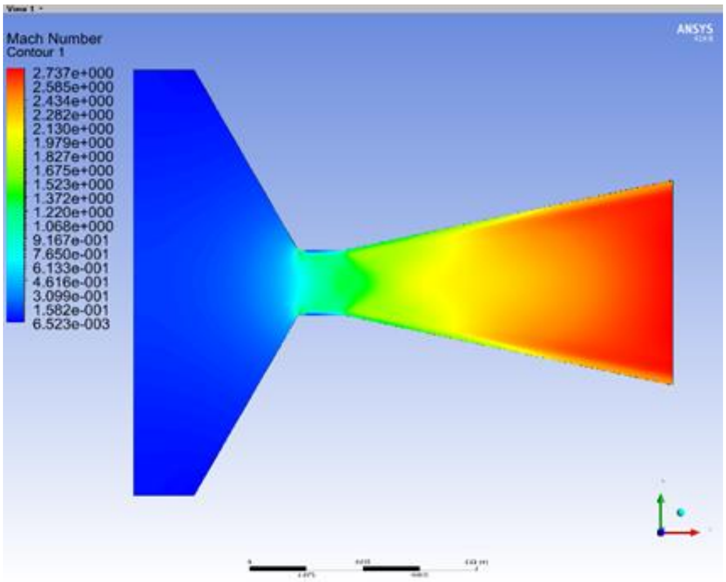


Fig. 5. Result of nozzle March number

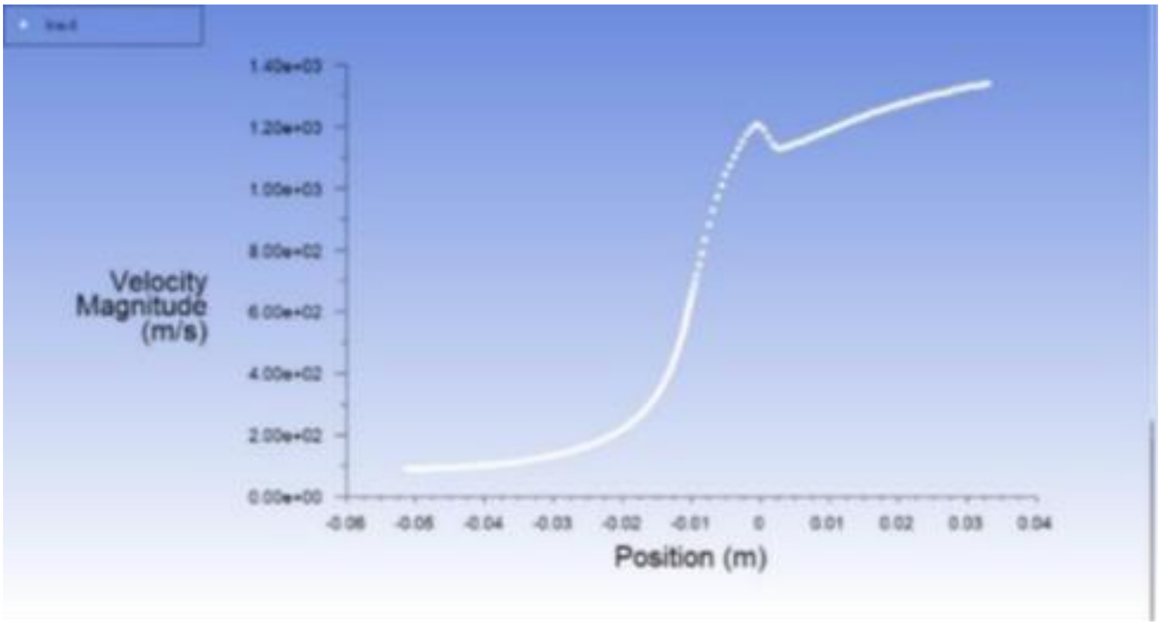
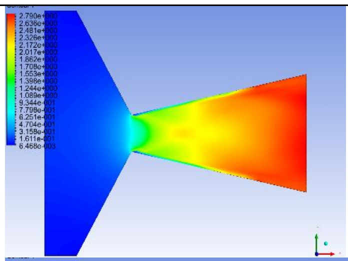
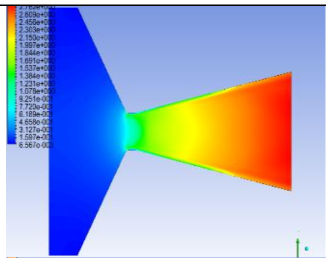
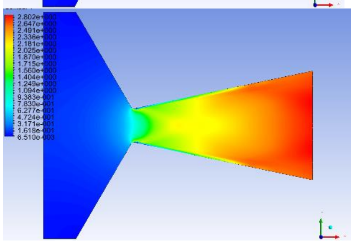
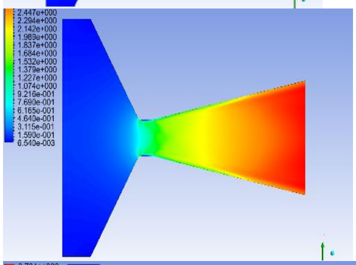
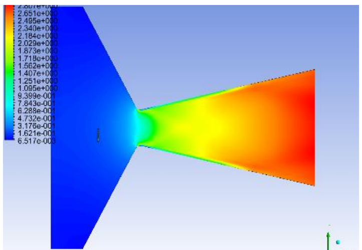
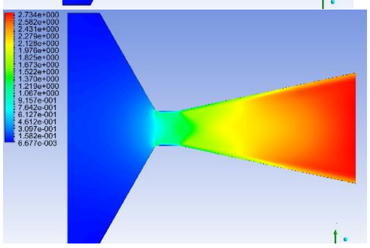
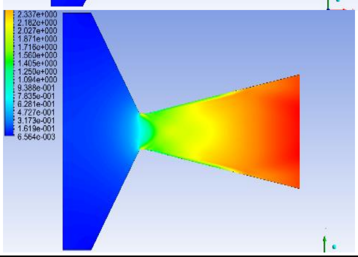
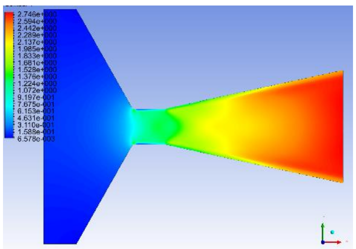


Fig. 6. The plot of the velocity magnitude

Table 6
Result of the parametric study

Length (mm)	Mach Number	Mach Contour	Length (mm)	Mach Number	Mach Contour
0.5	2.754		3	2.715	
1	2.807		4	2.752	
1.5	2.741		6	2.734	
2	2.738		8	2.746	

4. Conclusions

A simple rocket nozzle has been designed via basic compressible flow theory. The designed nozzle was tested using CFD simulations. It was found that nozzle throat length has significant impact on the throat Mach number. It was found that for the current design, the optimized nozzle throat length should be set at 1mm.

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