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Simulation and Numerical Characterization of Gaseous Oxygen Injector for ABS/GOX Hybrid Rocket Motor

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Abstract: *In the past decades, many research and experiment on hybrid rocket propulsion has grown rapidly. Such rocket propulsion is considered as green propulsion system as the exhaust products cause less harm to the environment. Unlike solid rocket and liquid rocket propulsion, hybrid rocket propulsion takes the advantage that the fuel is in solid form while the oxidizer is in liquid or gaseous form. Any leakage of the oxidizer piping system will not result in undesired combustion from mixing between the fuel and oxidizer since the fuel and oxidizer needed to be effectively mixed for possible combustion. In this paper, the primary design consideration of the hybrid rocket motor is presented. Commercially available 3D printing material, Acrylonitrile Butadiene Styrene (ABS), and gaseous oxygen were selected as the fuel and oxidizer, respectively. The operation and performance of the hybrid rocket are highly affected by oxidizer injection into the combustion chamber. A proper oxidizer injector design is very crucial to avoid combustion instability for better performance of the rocket motor to be achieved. In this paper, the expected pressure drop of the injector for the designed hybrid rocket motor is higher than 7.5 bar as well as high oxygen gas recirculation in the pre-combustion chamber section is desired. The design of the oxygen gas injector for the hybrid rocket motor is done by using numerical design approach considering multiple orifices injector, radial injector and pintle injector. The simulation to observe the flow characteristic of each injector is carried out by using Solidworks Computational Fluid Dynamic (CFD) Simulation software. The parametric analysis on the output of the simulation, mainly the pressure drop of each injector, is carried out in searching for the optimal injector geometry. A good injector must satisfy the fuel regression rate with sufficient oxidizer mass flux rate along the solid fuel grain. The simulated oxidizer flow pattern is shown, and characterization of each injector is discussed. According to the simulation's result, the multiple orifice axial injector has the highest pressure drop, 8.32 bar, among other two types for the same desired mass flow rate of 0.061 kg/s. On the other hand, the pintle injector can generate higher gas recirculation than axial injector while having the pressure drop of 6.25 bar, lower than the desired value of 7.5 bar. The pressure drop of radial injector stands in between axial and pintle injector, however this type of injector generates poor gas recirculation. Finally, according to the simulation result and analysis, the axial injector and radial injector are the potential designs to be selected for further study and develop for the designed hybrid rocket motor.*

Keywords: Hybrid rocket propulsion; Oxidizer injector; Axial injector; Radial injector; Pintle injector

1. INTRODUCTION

In the past decades, many researches regarding hybrid rocket propulsion have grown rapidly. Such rocket propulsion is considered as green propulsion system as the exhaust products cause less harm to the environment. There are two types of chemical rocket propulsion being used in launch vehicle nowadays. One type of them is solid rocket propulsion, in which the fuel and oxidizer are mixed and casted into solid grain with different configuration before being ignited for its operation. The operation of such rocket will stop when all the propellant is consumed. This means that any accidentally produced spark closed to the solid propellant will cause undesired ignition of propellant grain which is not a safe type of propulsion system. Another one is liquid rocket propulsion, in which the fuel and oxidizer are in the form of liquid stored different tanks. The two propellants are then fed into the combustion chamber then ignited to produce

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controllable explosion, generate hot exhaust gas, and propel the rocket. Since the propellants are in liquid form, an efficient and reliable feed system design is needed to feed the propellants into the combustion chamber for successful operation. This usually makes the design and setup of such propulsion system more complicate. Unlike solid rocket propulsion and liquid rocket, hybrid rocket takes the advantage that the fuel is in solid form while the oxidizer is in liquid form. For combustion, the fuel and oxidizer needed to be effectively mixed (vaporization, and atomization), so any leakage of the oxidizer piping system in the liquid form will not result undesired explosion. The hybrid rocket propulsion also has less complex piping work compared to liquid rocket as there is only one working fluid system present in this propulsion.

The primary combustion mechanism of hybrid rocket relies on hot gas generation from the surface of solid fuel [1]. The combustion occurs very much like lighting a candle. An initial heat source is provided to ignite candle wax with oxygen in the atmospheric for flame generation and the flame continue if there is enough oxygen for the successful combustion. For hollow cylinder fuel grain, the simplified fuel regression rate law is

$$\dot{r} = a_o G_{ox}^{n} \qquad \text{(Eq. 1)}$$

where the coefficient a_o and regression exponent n are constant and determined empirically by the fuel and oxidizer choice. The value of a_o = 0.048 and n = 0.45 are taken for the design for low O/F shifting as suggested by [2]. The oxidizer mass flux G_{ox} is expressed as

$$G_{ox} = \frac{\dot{m}_{ox}}{\pi r^2} \qquad \text{(Eq. 2)}$$

where $\dot{m}_{ox}$ is the oxidizer mass flow rate. The (Eq. *1*) is established upon the assumption that neglecting the fuel mass generation rate.

Hybrid rocket combustion tends to generate pressure fluctuation if not meticulously designed. The pressure oscillation is observed to be remarkably close to the natural acoustic frequency of the combustion chamber. There are two basic types of instability: oxidizer feed system induced instability (non-acoustic), and flame holding instability (acoustic). The former mode of instability can be eliminated by the high pressure to the combustion chamber pressure while the later mode can be solved by the effective oxidizer injector design. Study suggested that hot gas recirculation zone at the front end of the solid fuel grain is desired [3]. Shirley M. Pedreira et al. [4] designed and performed experiments on orifice plat injector, radial injector, and swirl injector for gaseous oxygen polyethylene fuel cylindrical grains hybrid rocket. Their result showed that the orifice plate injector performed the best in term of discharge coefficient, while the same type injector and swirl injector yield best result in term of regression rate.

In this paper, the expected pressure drop of the injector for the designed hybrid rocket motor is higher than 7.5 bar as well as high oxygen gas recirculation in the pre-combustion chamber section is desired.

2. METHODOLOGY

2.1 Hybrid rocket motor configuration

The hybrid rocket motor is designed for static ground testing to achieved the desired maximum thrust level of 200 Newtons and operating chamber pressure of 15 bars. Commercially available 3D printing material, ABS, is selected as solid fuel of the rocket and pressurized gaseous oxygen as the oxidizer choice. The cylindrical 3D printed solid fuel grain has maximum diameter of 40 mm and port diameter of 15 mm. The grain length is 177.5 mm to favor the calculated oxidizer mass flow rate of 0.061 kg/s to achieve 2.5 initial oxidizer-to-fuel (O/F) mass ratio. A 20 mm long pre-combustion chamber is added to the forward section of the combustion chamber. The purpose of the pre-combustion chamber is to prevent the flame holding instability by allowing more space for the hot gas recirculation to formed. A post-chamber of the same length is also introduced at section between the solid fuel grain and rocket nozzle. The post-chamber will allow effective mixing of the burn fuel and oxidizer at the end of the solid fuel grain. A casted cement de Laval nozzle with expansion ratio of 2.89 is used to transform the high-pressure energy into thrust. Fig. 1. shows the section view of the designed hybrid rocket motor.

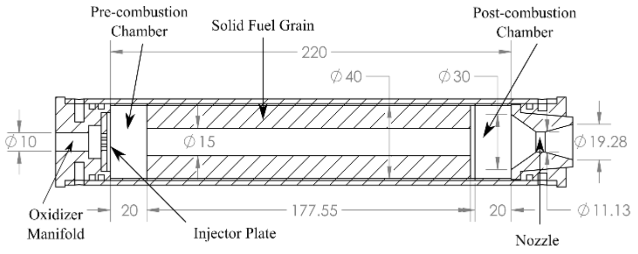

Fig. 1. Section view of hybrid rocket motor

2.2 Injector design

In this paper, 3 oxidizer injector designs are selected for the simulation and characterization. The multiple orifices axial injector plate and radial injector both consist of 5 2mm holes or orifices. The expected pressure drop of each injector is approximately higher than 7.5 bar to suppress the oxidizer feed system instability.

The orifices axial injector plat consists of 5 small orifices; each has 2 mm in diameter. High velocity stream of gas along with high recirculation spanning zone can be generated by this injector [5]. The orifice configuration consists of one orifice located at the center of the 3 mm thick aluminum plate of 32 mm in diameter. Other 4 orifices circle around the center one at 3.5 mm distance measured from their center to the central one's.

The radial injector consists of the same number of orifice as the axial injectors. All orifices are positioned on an extrude surface and equally spaced by 72 degrees. This configuration allows the oxidizer to discharge into the pre-combustion chamber at 90 degrees relative to the inlet flow. Such configuration also produces a large vortex ring with clockwise rotation in proximity, although not directly adjacent, to the fuel grain forward face, according to Shirley M. Pedreira et al. [4]; Carmicino C. et al. [6].

The pintle injector is selected for simulation. Although such type of injector is commonly used for application that requires the mixing between two different fluids, the oxidizer stream generated by this type of injector should give the idea and its behavior exploration in hybrid rocket application.

Fig. 2, 3 and 4. present the engineering drawing and CAD model of each injector type.

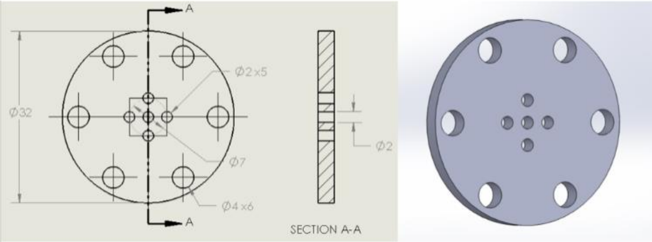

Fig. 2. Engineering drawing and CAD model of axial injector plate

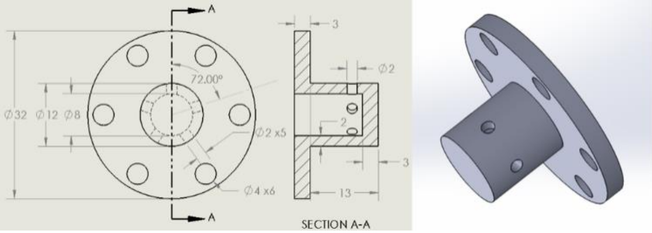

Fig. 3. Engineering drawing and CAD model of radial injector

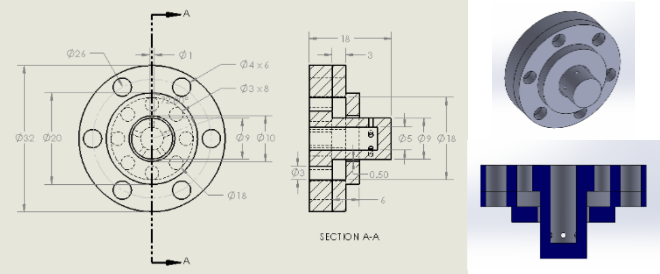

Fig. 4. Engineering drawing and CAD model of pintle injector assembly

The discharge coefficient C_d of each injector was calculated from the pressure and mass density data obtained from the simulation into (Eq. 3)

$$C_d = \frac{\dot{m}_{ox}}{A_{inj}\sqrt{2\rho_{ox}\Delta p}} \quad \text{(Eq. 3)}$$

where:

$\dot{m}_{ox}$ is the oxygen mass flow rate [kg/s],
A_{inj} is total injector fluid discharge area [m^2],
ρ_{ox} is oxygen mass density corresponding to injection pressure [kg/m^3] and
Δp is pressure drop across the injector [pa].

2.3 Numerical simulation

This section focus on the data preparation of input data for the numerical simulation of injector flow in SolidWorks software.

The interested region of this simulation is the pre-combustion chamber where the oxidizer is discharged from the injector orifice and progress itself into the combustion chamber. The main observation of this simulation is the oxygen flow stream generated by each injector at pre-combustion chamber, that is why the number meshes in this region must be higher compare to others such as the fuel port passage and the post chamber (Fig. 5). The main desired output data of the simulation are the injection pressure and oxygen mass density correspond to the injection pressure. The combustion of the rocket is not included in this simulation due to the limited capability of SolidWorks software. Hence an environment pressure of 15 bar at 20ºC is defined at the outlet to mimic the chamber operating pressure. The boundary conditions are defined as the following:

Inlet boundary condition:

- Mass flow rate = 0.061 kg/s as required by the design calculation. The flow condition is defined as fully developed

Outlet boundary condition:

- Environmental pressure = 15 bar (15×10^5 Pa)
- Temperature = 20ºC (293.15K)

The specification processor system used for the calculation is shown in Table 1.

Table 1 Computer specification

Processors	Intel(R) Core(TM) i5-5200U CPU @ 2.20GHz
Memory	8106 MB / 134217727 MB
Operating system	Windows 10 (or higher) (Version 10.0.19042)
CAD version	SOLIDWORKS 2017 SP3.0
CPU speed	2201

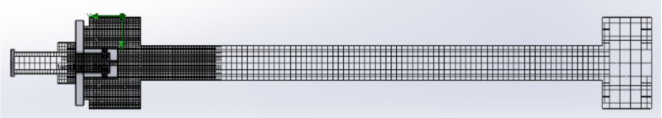

Fig. 5. Meshes of injector CAD model for SolidWorks CFD simulation of radial injector. The simulations of other injectors share the same mesh configuration

3. RESULTS AND DISCUSSION

3.1. Injector numerical characterization

The numerical calculation of the three injectors is carried out in SolidWorks Flow Simulation software by utilizing the steady-state solver. The main output data from the simulation and the corresponding discharge coefficient of each injector is and shown in Table 2.

From the simulation result the discharge coefficient of pintle injector is shown to be the highest, 0.77. The same injector type also found to have the lowest pressure drop. The axial injector has the lowest discharge confident of 0.44 while having the pressure drop highest among other injectors.

Fig. 9., Fig.10. and Fig. 11. show three dimensional view obtained from the simulation of the flow of oxygen gas at the pre-combustion chamber with axial injector, radial injector and pintle injector, respectively.

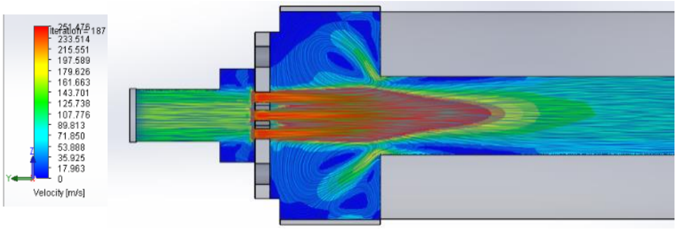

Fig. 6. Oxygen flow stream cut plot of velocity field of axial injector from the simulation

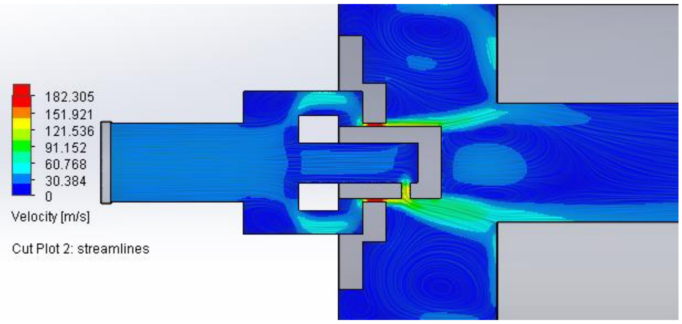

Fig. 7. Oxygen flow stream cut plot of velocity field of pintle injector from the simulation

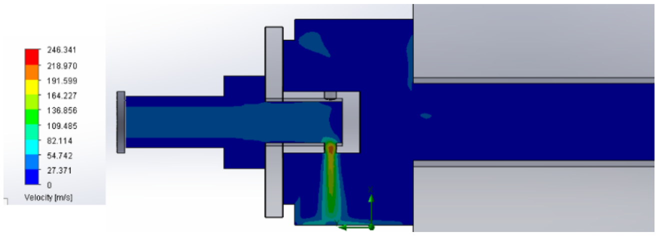

Fig. 8. Oxygen flow stream cut plot of velocity field of radial injector from the simulation

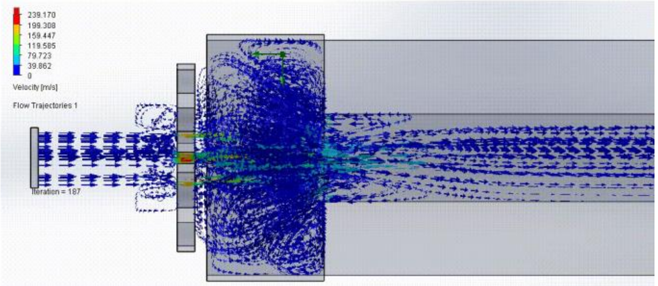

Fig. 9. Oxygen velocity trajectory view of axial injector obtained from the simulation

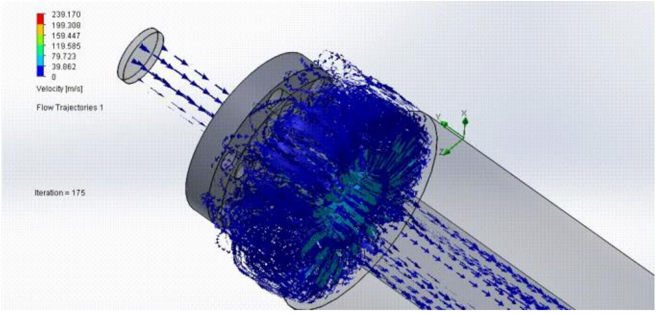

Fig.10. Oxygen velocity trajectory view of radial injector obtained from the simulation

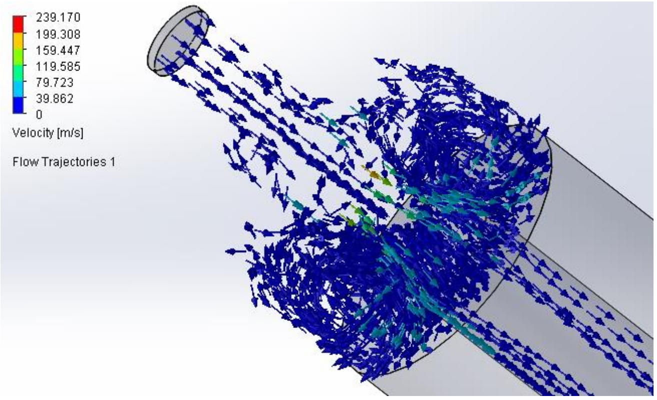

Fig. 11. Oxygen velocity trajectory view of pintle injector obtained from the simulation

According to the pressure drop Δp obtained from the simulation in Table 2., it can be seen that the pressure drop of the axial injector is 8.32 bar, the highest among the other two types of injector. This can imply that by utilize axial injector, the feed-system-coupled instability as state in section I, may effectively be suppressed. Although, such high pressure drop is preferred, the consequence of using this type of injector is the increase of the oxidizer tank storage pressure that affect the initial mass of the propulsion system as thicker and heavier tank is needed.

Another factor from the simulation result to look at is the turbulence generation of each injector at the pre-combustion chamber. The turbulence in this particular section of the hybrid rocket motor is highly contribute to the flame holding instability inside the combustion chamber. Slight delay of the combustion between the gaseous oxidizer and solid fuel cause the flame to move back and forth inside the combustion chamber if the pressure at the pre-combustion chamber is not high enough. The high pressure zone can be generated by gas recirculation zone created by the injector. The velocity contour plot of each injector in shown in Fig. 6, 7. and 8. It is shown that the gas recirculation of pintle injector is much higher than axial injector. The pintle injector generate its turbulence from the impinging velocity of axial and radial stream of gas right before reaching the surface of the solid fuel. The radial injector generates its turbulence when the axial gas stream hit the surface of the solid fuel causing the gas recirculation. Although the recirculation is created, the process may allow the contact area between the oxygen gas and the solid fuel to be combustion undesirably.

On the other hand, the pressure drop and discharge coefficient of the radial injector stands in between axial and pintle injector. These results can make this type of injector be very useful in suppressing the stability cause by the feed system, however, the gas stream exits the orifice and injects directly onto the wall of the pre-combustion chamber. In this case, potential hotspot may be generated and cause the rocket motor to fail by the burn throw of the combustion chamber.

Table 2 Result C_d obtained from the simulation as the basis of oxygen mass flow rate

Injector Type	$\dot{m}_{ox}$ [kg/s]	p_{inj} [bar]	ρ_{ox} [kg/m^3]	p_c [bar]	ΔP [bar]	C_d
Axial Injector	0.061	22.8	29.93	14.48	8.32	0.44
Radial Injector	0.061	22.4	29.53	15.25	7.15	0.48
Pintle Injector	0.061	21.07	27.65	14.82	6.25	0.77

4. CONCLUSIONS

In this paper, the primary design consideration of the hybrid rocket motor is presented. Commercially available 3D printing material, Acrylonitrile Butadiene Styrene (ABS), and gaseous oxygen were selected as the fuel and oxidizer, respectively. Therefore, combustion parameters can be specified. The design specifications of important components of the hybrid rocket motors such as combustion chamber, pre-combustion chamber, post-combustion chamber, solid grain and nozzle are discussed. Different oxidizer injectors such as multiple orifices injector, radial injector and pintle injector are designed and analyzed by numerical approach in Solidworks Computational Fluid Dynamic (CFD) Simulation. The results of simulated oxidizer flow patterns are shown and discussed. The pressure drop of multiple orifices axial injector is found to be 8.32 bar, higher than the 7.5 bar threshold of Δp while redial injector has Δp of 7.15 bar slightly lower than the desired Δp. The pintle injector is found to have the lowest pressure drop at about 6.25 bar. From turbulence generation perspective, the pintle injector can generate very high oxygen gas recirculation in the pre-combustion chamber section among the other two injectors, while radial injectors is shown to generate poor gas recirculation. From the simulation result, the axial injector has the highest pressure drop which is preferred for feed-system-coupled instability. The pintle injector generates the highest turbulence in the pre-combustion chamber which is preferred for flame holding instability.

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REFERENCES

[1] Cantwell, B. (2010). Aircraft and rocket propulsion. AA283 course.

[2] Spurrier, Z. S. (2016). Throttleable gox/abs launch assist hybrid rocket motor for small scale air launch platform.

[3] Sutton, G. P., & Biblarz, O. (2016). Rocket propulsion elements. John Wiley.

[4] Pedreira, S. M., Dutra, R. C., Oliveira, J. I., Gonçalves, R. F., Rocha, R. J., & Rocco, J. A. (2019). Performance analysis of injectors for a hybrid propulsion system. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*, *41*(1), 47.

[5] T.A. Boardman, D.H. Brinton, R.L. Carpenter, T.F. Zoladz, An experimental investigation of pressure oscillations and their suppression in subscale hybrid rocket motors, AIAA Paper 95-2689, July 1995.

[6] Carmicino, C., & Sorge, A. R. (2007). Performance comparison between two different injector configurations in a hybrid rocket. *Aerospace Science and Technology*, *11*(1), 61-67.