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Numerical study for the pre-burners of staged combustion cycle rocket engines

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Abstract

This study conducted numerical simulations of oxidizer-rich pre-burners for 100 tonf and 10 tonf class liquid rocket engines, both operating on a staged combustion cycle using liquid oxygen and kerosene as propellants. The pre-burners generate high-temperature oxidizer-rich gas to drive the turbopump, and then supply the gas to the main combustor. Using ANSYS Fluent, the analysis applied the SRK real-gas equation of state, a chemical equilibrium combustion model, and a PDF turbulence-combustion interaction model. Simulations evaluated flow distribution and injector pressure drops, revealing discrepancies between the target and predicted mixture ratios. To resolve this, design changes, especially to the oxidizer jet channels, are planned. Future work will involve updated simulations to ensure the modified design meets target flow rates and mixture ratios.

1. Introduction

The Korea Aerospace Research Institute (KARI) is currently developing a high-performance liquid rocket engine for the next-generation launch vehicle[1]. Unlike the Nuri rocket, which employed a gas generator cycle, the engine for the next-generation launch vehicle adopts a staged combustion cycle, which offers superior propulsion efficiency. The engine under development consists of booster-stage and upper-stage engines, each utilizing turbopumps to elevate the propellant pressure to high levels. The turbopumps are driven by high-temperature gas generated in the pre-burner. In this staged combustion cycle engine, the pre-burner operates under an oxidizer-rich condition to both power the turbine and serve as an oxidizer source for the main combustion chamber. In the gas generator cycle used in the Nuri rocket, the turbine driving gas was discarded through an exhaust system, resulting in energy losses. In contrast, the staged combustion cycle reintroduces all combustion products into the main chamber, significantly improving specific impulse and overall engine efficiency. Although this approach introduces greater system complexity, it is considered an essential advancement for achieving higher performance. The design of the oxidizer-rich pre-burner includes multiple engineering considerations such as injector configuration, coolant flow paths, and combustion stability. In particular, the pre-burner studied in this research employs a triple-injection scheme for the oxidizer, dividing the flow among the injector, injector cooling channel, and chamber cooling channel. However, it is difficult to experimentally verify whether the flow is correctly distributed according to the design intent and whether the designed pressure drops are achieved. Therefore, this study aims to numerically analyze the flow distribution and pressure characteristics of the pre-burner. Through computational simulations, we verify whether the flow division matches the design specifications and assess the validity of the pre-burner design before physical testing. The goal is to quantitatively evaluate the performance of the fuel and oxidizer supply systems and confirm the feasibility of the design using numerical methods.

2. Numerical method and modelling

In this study, ANSYS Fluent Ver. 18 was employed as the computational fluid dynamics (CFD) tool. A pressure-based coupled scheme was used for the numerical solution approach, and the two-equation k-ε turbulence model was applied to model turbulence. Since the study involves combustion analysis, a non-premixed chemical equilibrium combustion model was adopted to simulate the combustion processes. The flow rate and mixture ratio conditions for the 10-tonf and 100-tonf class pre-burners used in the analysis are summarized in the table below.

Table 1: Mass flow rate and Mixing ratio

	Oxidizer mass flow rate [kg//s]	Fuel mass flow rate [kg/s]	Mixing ratio
10-tonf class	19.7	0.342	57.6
100-tonf class	213.72	4	53.43

2.1 10-tonf pre-burner geometry and modelling

The figure below shows the three-dimensional geometry of the 10-tonf class pre-burner analyzed in this study, along with the projection views and cross-sectional view of the pre-burner modelled for numerical simulation purposes.

Figure 1: 10tonf pre-burner geometry and 3D model

2.2 100-tonf pre-burner geometry and modelling

The figure below shows the geometry of the 100-tonf class preburner, which was also modeled for numerical analysis. Projection views and cross-sectional views of the modeled preburner are illustrated as well.

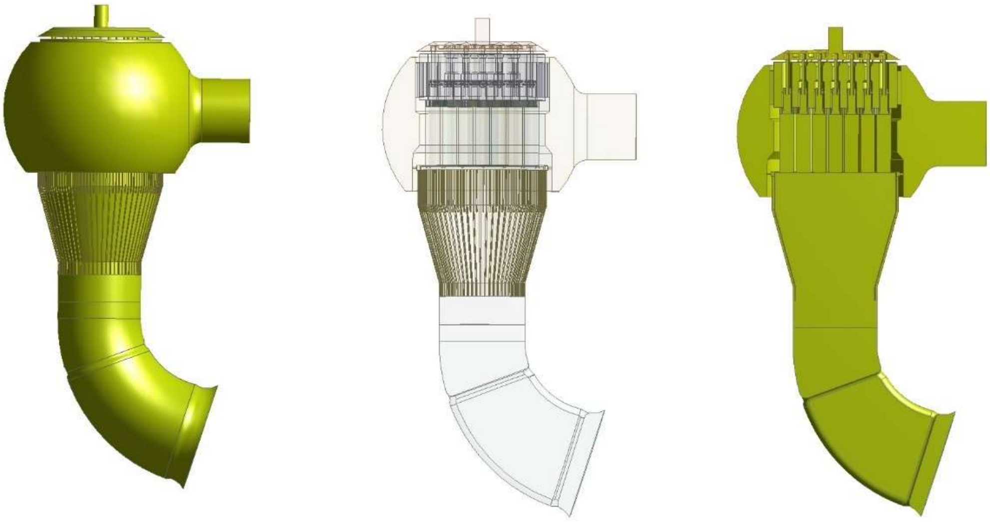

Figure 2: 100tonf pre-burner geometry and 3D model

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3. Results and Analysis

3.1 10-tonf Preburner

- Baseline Case Results

The figures below present the contours of density, temperature, and velocity for the baseline case, followed by the streamlines of the velocity field. As shown in the figures, the cryogenic oxidizer fills the manifold and is then divided to flow into the oxidizer injectors, the injector cooling channels, and the chamber cooling channels. Under a mixture ratio of 57.6, combustion occurs inside the chamber, and the flow is predicted to exit at approximately 800 K. According to the results shown in the table, the predicted values are as follows:

- Fuel injector pressure drop: 19.5 bar
- Oxidizer injector pressure drop: 15.9 bar
- Fuel flow rate: 4.35 kg/s
- Oxidizer jet channel flow rate: 15.33 kg/s
- Chamber cooling channel flow rate: 0.85 kg/s

The design targets are:

- Injector pressure drop: 19.47 bar, fuel flow rate: 4.86 kg/s
- Oxidizer jet channel flow rate: 14.34 kg/s
- Chamber cooling flow rate: 0.8 kg/s

Based on the simulation results, the fuel flow into the injector is lower than the design target, resulting in a slightly underpredicted pressure drop. In contrast, the oxidizer jet channel receives a higher-than-expected flow rate.

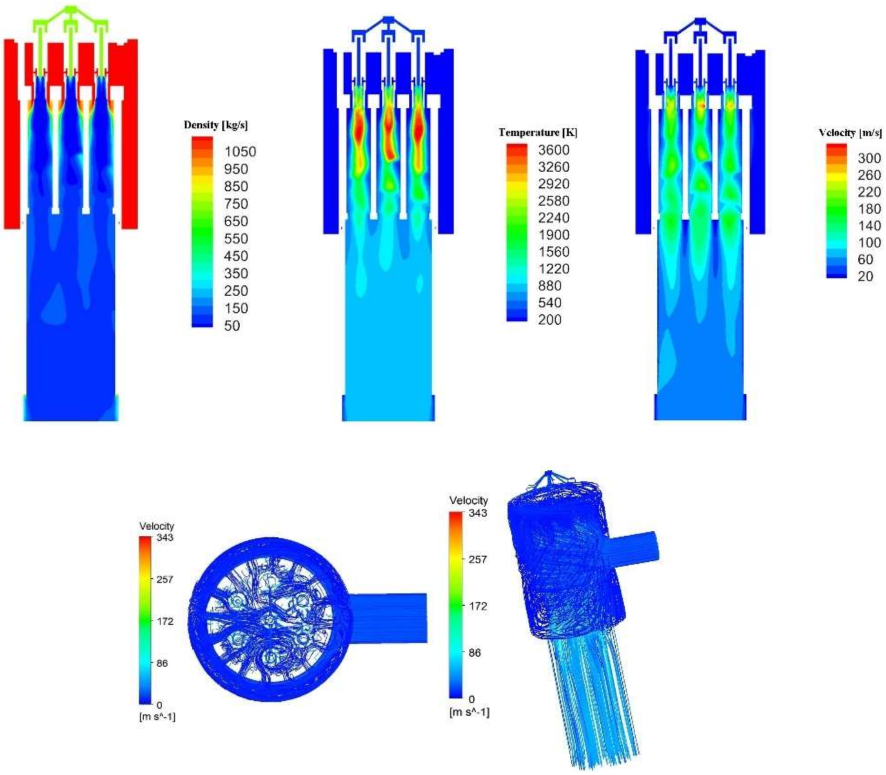

Figure 3: Density, temperature and velocity contour and velocity streamline

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- Variation of Oxidizer Jet Channel Area

To achieve the design target pressure drop across the oxidizer injector, the injector geometry was kept constant, and a design modification was made by reducing the cross-sectional area of the oxidizer jet channel compared to the baseline configuration. A new series of simulations was conducted based on this updated geometry.

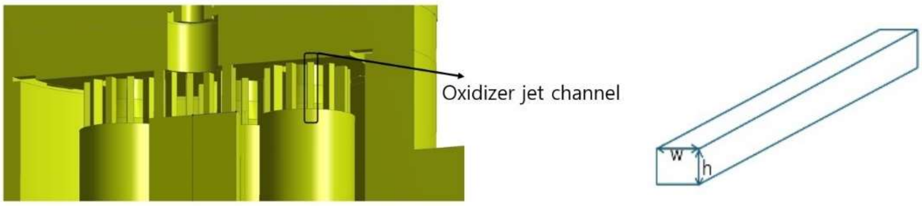

Figure 4: Oxidizer jet channel

Table 2: Area of Baseline and variants

	Baseline	Variant 1	Variant 2	Variant 3	Variant 4
W [mm]	2.21	2.21	2.21	2.21	2.21
H [mm]	1.5	1.45	1.4	1.35	1.3
Area [m2]	3.315e-6	3.2045e-6	3.094e-6	2.9835e-6	2.873e-6

The simulation results for each variant are summarized in the table. As shown in the table, reducing the jet channel area led to an increase in oxidizer flow into the injector, resulting in a higher pressure drop. Among the cases, Variant 4 exhibited pressure drop and flow rate values that were closest to the design targets. Furthermore, as more oxidizer was directed to the injector, the flow into the oxidizer jet channel decreased, and the resulting oxidizer jet channel flow rate also approached the target value.

Table 3: Pressure drop, mass flow rate of target design, baseline and the variants

	Pressure drop of fuel injector [bar]	Oxidizer injector		Oxidizer jet channel mass flow rate [kg/s]	Chamber cooling channel mass flow rate [kg/s]
		Pressure drop [bar]	Mass flow rate[kg/s]		
Target design	23.21	19.47	4.86	14.34	0.8
Baseline	19. 5	15.9	4.35	15.33	0.85
Variant1	19.45	17.1	4.49	15.11	0.87
Variant2	19.62	17.7	4.6	15.03	0.89
Variant3	19.53	18.5	4.75	14.84	0.91
Variant4	19.61	19.8	4.94	14.66	0.94

3.2 100-tonf Preburner

- Baseline Case Results

The 100-tonf class pre-burner was analyzed in a manner similar to the 10-tonf case. The figures below show the contours of density, temperature, and velocity for the baseline case, followed by the streamlines of the velocity field. Under a mixture ratio of 53.43, combustion occurs inside the chamber, and the combustion products are predicted to exit at a temperature of approximately 800 K. As shown in the table, the simulation results predicted the following:

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- Fuel injector pressure drop: 48 bar
- Oxidizer injector pressure drop: 31.13 bar
- Fuel flow rate: 46.95 kg/s
- Oxidizer jet channel flow rate: 162.36 kg/s
- Chamber cooling channel flow rate: 5.24 kg/s

The design target values are:

- Injector pressure drop: 32.3 bar, fuel flow rate: 56.21 kg/s
- Oxidizer jet channel flow rate: 154.01 kg/s
- Chamber cooling flow rate: 4.29 kg/s

As with the 10-tonf pre-burner, the results indicate that less fuel than intended flows into the injector, leading to an underpredicted pressure drop. Conversely, more oxidizer flows into the oxidizer jet channel than the design target.

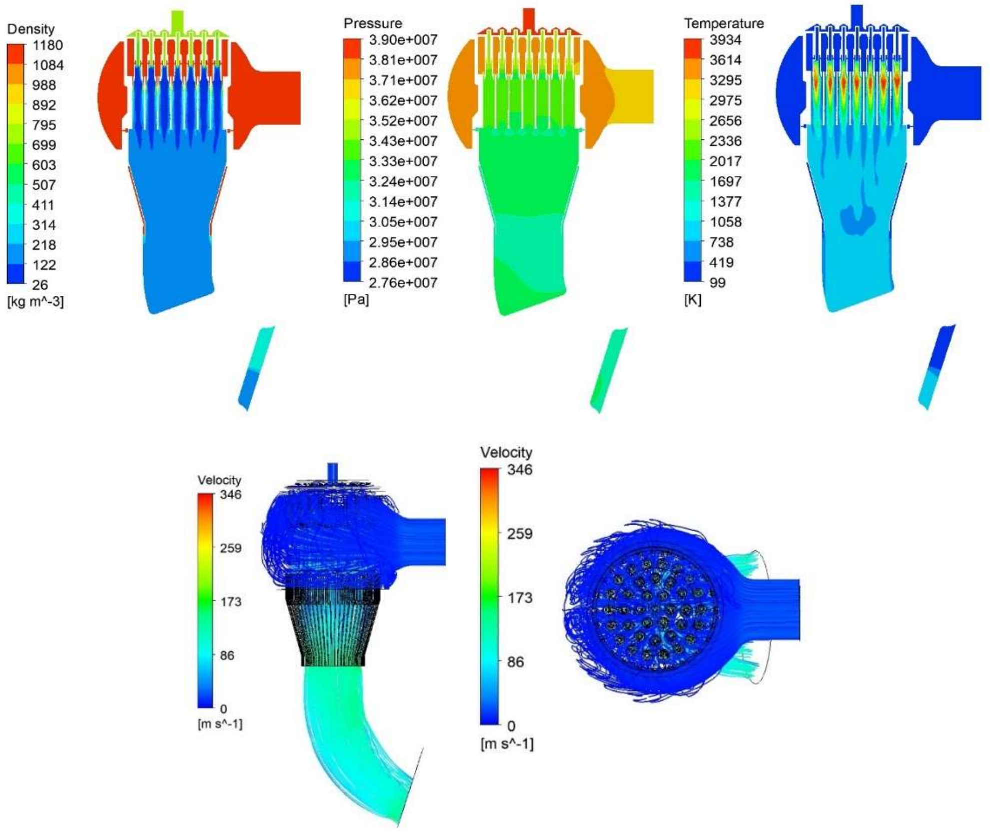

Figure 5: Density, temperature and velocity contour and velocity streamline

- Variation of Oxidizer Jet Channel Area

To achieve the design target pressure drop across the oxidizer injector, a strategy similar to the 10-tonf case was applied. The injector geometry was kept constant, and the cross-sectional area of the oxidizer jet channel was reduced compared to the baseline configuration. As shown in the figure, two design variants were created by adjusting the height of the jet channel. The table presents the cross-sectional areas of the baseline and the variant.

Table 4: Area of Baseline and variant

	Baseline	Variant
W [mm]	2.665	2.665
H [mm]	2.17	2.07
Area [m2]	5.78e-6	5.49e-6

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The simulation results for each variant are summarized in the table. As shown in the table, in Variant, which has the smallest jet channel area, the oxidizer flow into the injector increased, resulting in a higher pressure drop. This variant showed pressure drop and flow rate values close to the design targets. Furthermore, as more oxidizer was directed into the injector, the flow into the oxidizer jet channel decreased, leading to a jet channel flow rate that also closely matched the target value.

Table 5: Pressure drop, mass flow rate of target design, baseline and the variant

	Pressure drop of fuel injector [bar]	Oxidizer injector		Oxidizer jet channel mass flow rate [kg/s]	Chamber cooling channel mass flow rate [kg/s]
		Pressure drop [bar]	Mass flow rate[kg/s]		
Target design	51.7	32.3	56.21	154.01	4.29
Baseline	48	31.13	46.95	162.36	5.24
Variant	53.79	32.8	50.75	158.56	5.24

4. Conclusion and Future work

A fluid flow and combustion analysis was performed for the oxidizer-rich preburner, a key component of the staged combustion cycle liquid rocket engine currently under development by the Korea Aerospace Research Institute (KARI). Baseline designs for both 10-tonf and 100-tonf class preburners were established based on engineering design equations. To evaluate whether the pressure drops and flow distributions met the design targets, computational fluid dynamics (CFD) simulations including combustion modeling were carried out. The analysis results showed that, in both preburner configurations, the oxidizer injector pressure drop was lower than the design target. To address this issue, a design modification was implemented by reducing the cross-sectional area of the oxidizer jet channel while keeping the injector geometry fixed. The revised designs were then re-analyzed using CFD. The results confirmed that reducing the jet channel area effectively increased the oxidizer flow into the injector, thereby achieving a pressure drop close to the design goal. In future work, the simulation results will be compared with hot-fire test data from the manufactured preburners to validate the accuracy and reliability of the computational predictions.

References

[1] Kim, C. H., Han, Y. M., Cho, N. K., Kim S. H., Yu, B. I., Lee, K. J., So, Y. S., Woo, S. P., Im, J. H., Hwang C. H., Lee, J. H. and Kim, J. H., “Development Trend of Korean Staged Combustion Cycle Rocket Engine,” Journal of the Korean Society of Propulsion Engineers, Vol. 22, No. 3, 2018, pp. 109~118.