HiSST: 4th International Conference on
High-Speed Vehicle Science Technology
22 -26 September 2025, Tours, France

# Numerical Study on Flame Evolution Process in a Kerosene-Fueled Tandem Cavity Scramjet Combustor

*Seung-Min Jeong[1], Inyoung Yang[1*], Kyungjae Lee[1], Yang Ji Lee[1], Sanghoon Lee[1]*

## Abstract

This study numerically investigates the flame evolution process in a tandem-cavity scramjet combustor for a Turbine-Based Combined Cycle (TBCC) engine. The combustor utilizes preheated kerosene, supplied via wall-mounted heat exchangers. The inflow conditions at the isolator inlet are a mass flow rate of 1.0 kg/s and a Mach number of 2.0. The simulation employed an Improved Delayed Detached Eddy Simulation (IDDES) model for turbulence and a quasi-laminar approach for chemistry. Spatial discretization was achieved using a fifth-order oMLP scheme for convective terms and a second-order central difference for viscous terms, while a second-order implicit LU-SGS scheme was used for time marching. The results demonstrate successful flameholding in the first cavity and secondary combustion in the second cavity. However, insufficient fuel-air mixing was observed, attributed to interactions between the fuel streams. This numerical framework, having demonstrated its capability to capture the key combustion phenomena, will be applied to the design of a scaled-up combustor operating at a substantially higher mass flow rate.

**Keywords**: Scramjet combustor, Kerosene-fueled, Numerical simulation, Flame structure

## 1. Introduction

This study numerically investigates the flame structure of a tandem cavity, kerosene-fueled scramjet combustor, building upon previous ground combustion tests. The combustor is equipped with heat exchangers on its upper and lower plates, which serve a dual purpose: preheating the kerosene fuel to enhance flame stabilization and combustion performance, while simultaneously cooling the combustor structure [1,2].

The computational domain has an axial length of 1025 mm from the isolator inlet to the combustor exit. The inflow conditions at the isolator inlet are defined with a static pressure of 1.004 bar, a Mach number of 2.0, and a static temperature of 756.4 K. In the corresponding experiment, high-enthalpy air was generated using an Electric Air Heater (EAH) and a Vitiated Air Heater (VAH) [3]. Consequently, the mole fractions of the incoming air were $N_2$:$O_2$:$CO_2$:$H_2O$ = 0.7274:0.2100:0.0174:0.0452.

The total mass flow rate of the incoming air is 1,000 g/s, and the duration of the fuel injection for the combustion test was approximately 30 seconds. Among the various equivalence ratio conditions tested, this study focuses on the case with an equivalence ratio (ER) of 0.24, corresponding to a fuel flow rate of 15 g/s. The fuel, supplied at ambient temperature, is gradually preheated as it passes through the heat exchangers installed on the combustor walls during the experiment. The target fuel total pressure and temperature at the injector plenum are 21.5 bar and 747.25 K, respectively.

This study employs an in-house solver that solves the density-based, finite-rate, compressible reactive flow equations [4,5]. Turbulence was modeled using the improved delayed Detached Eddy Simulation (IDDES) model. The turbulence and viscous terms were discretized with a second-order central

[1] *Future Aeropropulsion Research Team, Korea Aerospace Research Institute (KARI), Daejeon, Korea*
* *Corresponding Author: iyyang@kari.re.kr*

difference scheme, and the spatial discretization of convective terms was treated with a fifth-order oMLP scheme. The numerical flux was computed using the AUSMPW+ scheme, and a fully implicit, second-order accurate LU-SGS scheme with a maximum of four sub-iterations was applied for temporal integration. Since the simulation models the injection of preheated gaseous kerosene with multi-heat exchanger, a multiphase model was not considered.

The chemical kinetics were modeled using Franzelli's two-step kerosene-air global chemical reaction mechanism [6]. To the authors' knowledge, a turbulence-combustion interaction (TCI) model with appropriate corrections for high-Mach-number compressible reactive flows has not been developed. Therefore, a "quasi-laminar" approach was adopted, wherein the chemical source terms were computed directly from the mean flow variables without a dedicated TCI model.

The computational domain, which extends from the isolator inlet to the combustor exit, consists of a structured grid with approximately 43 million cells. The simulation was conducted in two stages. First, a non-reactive flow simulation was run for the initial 3.0 ms to establish a stable supersonic flow field. Subsequently, fuel injection was initiated, and the reactive simulation was continued until approximately 5.5 ms.

## 2. Discussion

Figs. 1 and 2 present the instantaneous distributions of various physical properties at a simulation time of 5.5 ms. Based on a comparison with experimental data (Fig. 3) and the stabilization trend of the pressure field (Fig. 4), it is concluded that the flame has stabilized by this time.

The kerosene, preheated to approximately 750 K, reacts primarily within the first cavity, which accounts for the majority of the heat release. The pressure rise resulting from combustion in the first cavity close-out region propagates upstream into the isolator, creating a pre-combustion shock train.

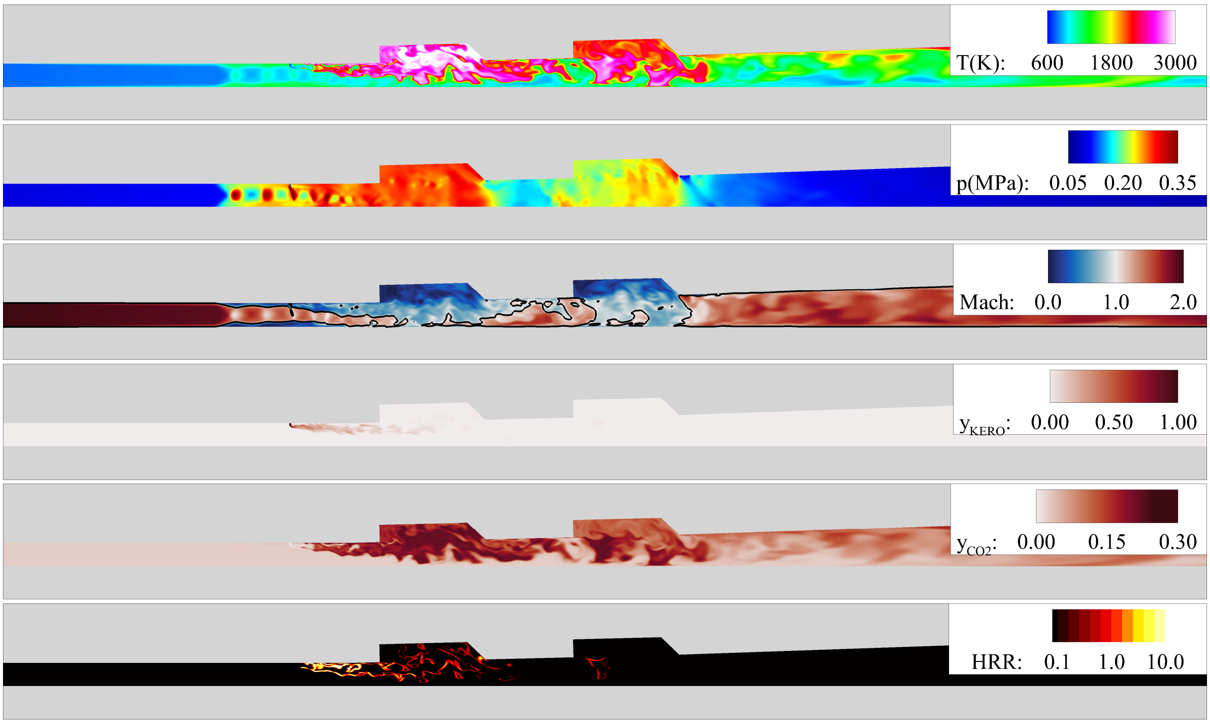


**Fig 1.** Instantaneous results of static temperature, pressure, Mach Number, fuel (KERO) mass fraction, CO2 mass fraction, and dimensionless heat release rate at the center plane: 5.5 ms, approximately 10 FTT(Flow Through Time)

Unconsumed fuel from the first cavity subsequently burns within the high-temperature environment of the second cavity. This process leads to a further slight increase in combustion pressure. The secondary combustion within the second cavity decelerates the reactive flow to subsonic speeds after it has re-accelerated to supersonic velocity upon exiting the first cavity.

As shown in Fig. 3, the wall pressure distribution obtained from the numerical simulation agrees well with the experimental data, accurately capturing the characteristics of the reactive flow field described previously. The intense combustion concentrated in the first cavity generates a substantial pressure rise, which propagates the pre-combustion shock train significantly upstream within the isolator. This phenomenon, observed even at a moderate ER of 0.24, suggests that to mitigate the risk of inlet unstart, it may be necessary to either relocate the fuel injection point further downstream or implement a wall expansion at the injection site.

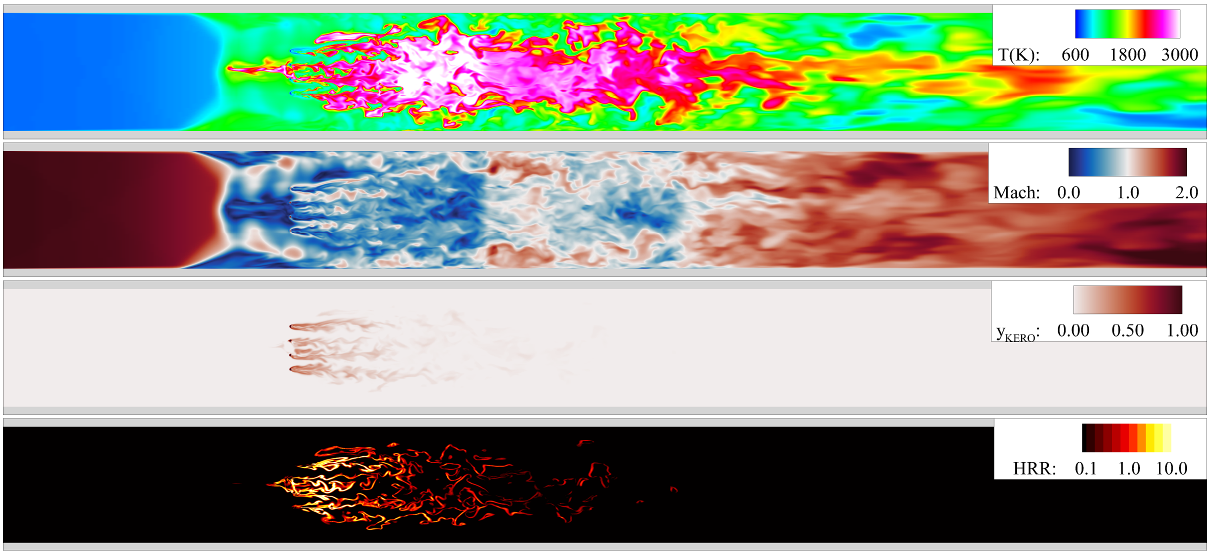


**Fig 2.** Instantaneous results of static temperature, Mach Number, fuel (KERO) mass fraction and dimensionless heat release rate at the near wall plane: 5.5 ms, approximately 12 FTT(Flow Through Time)

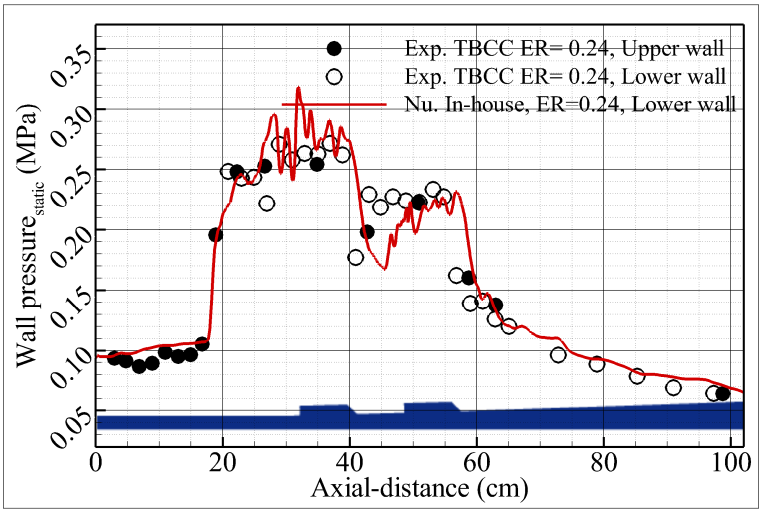


**Fig 3.** Comparison of pressure distribution on the combustor wall derived from experiment test and numerical simulation

Furthermore, the strong agreement shown in Fig. 3 suggests that a two-step global chemical reaction mechanism can yield reliable results for scramjet combustion simulations with preheated kerosene fuel, provided that high-resolution numerical schemes and sufficiently dense grids are employed. This indicates that a critical trade-off between employing detailed skeletal reaction schemes (often comprising dozens of chemical species) and utilizing high-order, high-resolution numerical methods must be carefully considered in such simulations.

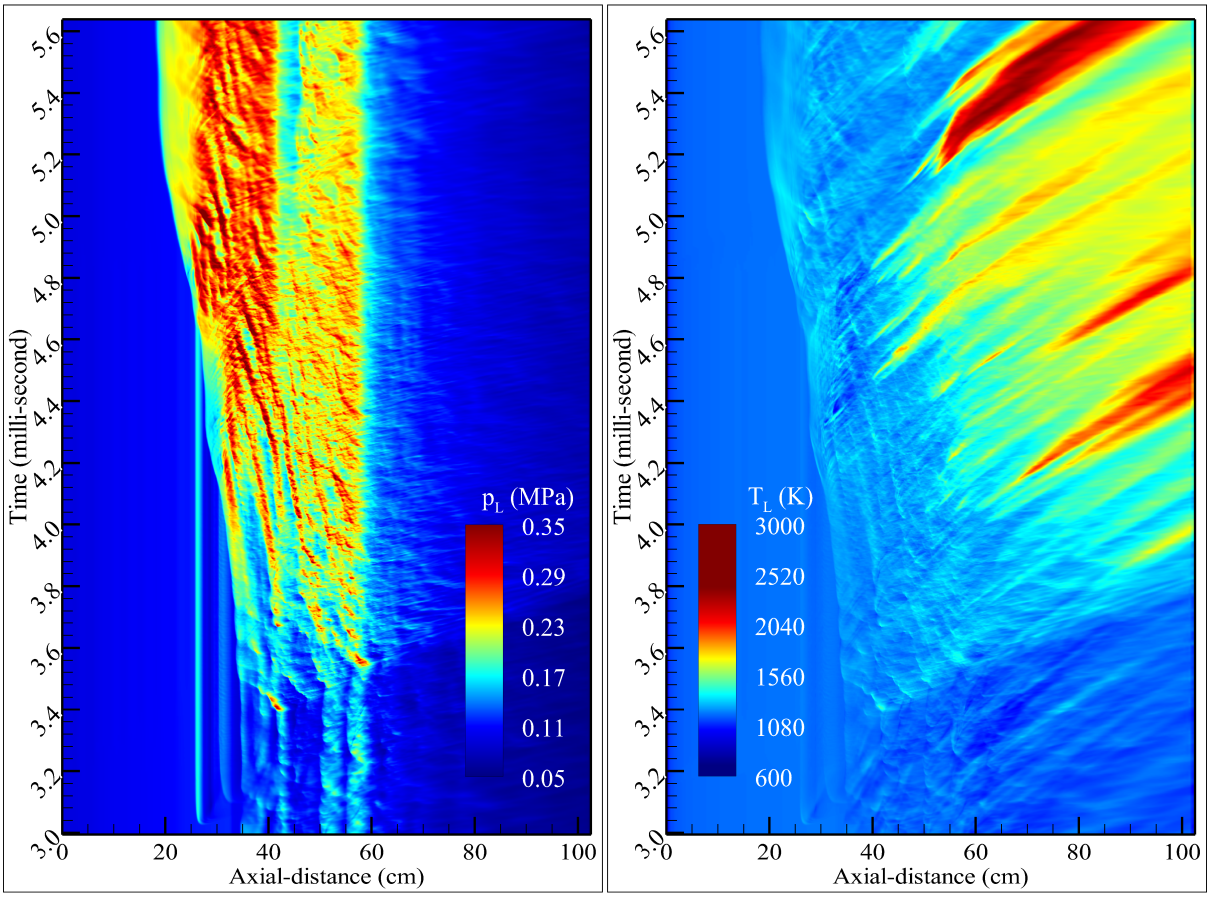


**Fig 4.** X-t graph for lower wall static pressure and temperature

An interesting observation in the present results is the formation of a localized, high-temperature region on the center plane between the four injectors, as depicted in Fig. 2. Although this feature is not expected to affect the overall reliability of the results, further investigation is required to determine whether it is caused by the interaction of the Counter-Rotating Vortex Pairs (CRVPs) generated by the unique injector configuration.

## 3. Conclusion

This study conducted a numerical investigation of a tandem-cavity scramjet combustor fueled with preheated kerosene, building upon a configuration for which ground combustion tests were previously conducted. By employing high-order, high-resolution numerical schemes, reliable results were obtained despite utilizing a simplified kerosene-air two-step global chemical reaction mechanism. The simulation results provided detailed insights into the complex flow dynamics, including the characteristic deceleration-reacceleration-deceleration pattern, as well as the flame and shock structures within the combustor. The findings from this study will inform future work, which will involve designing and testing a scaled-up scramjet combustor capable of operating with a significantly increased air mass flow rate.

## Acknowledgements

This work was supported by Korea Research Institute for defense Technology planning and advancement (KRIT) grant funded by the Korea government (DAPA (Defense Acquisition Program Administration)) (No. KRIT-CT-23-047).

## References


1. Yang, I., Lee, Y.J., Lee, K.J., Choi, S., Park, C.: Combustion Experiments for a Liquid Hydrocarbon Fueled Mach 5 Scramjet Engine Model. J. Propuls. Power 30, 1433–1438 (2014).
2. Yang, I.: Regenerative Cooling Channel Design of a Supersonic Combustor Considering High-Temperature Property of Fuel. J. Korean Soc. Propuls. Eng. 22, 37–46 (2018).
3. Yang, I., Lee, K.J., Lee, Y.J., Lee, S.H., Kim, H.M., Park, P.M.: Combustion Test for a Supersonic Combustor Using a Direct-Connected Facility. J. Korean Soc. Propuls. Eng. 22, 1–7 (2018).
4. Jeong, S.-M., Lee, J.-H., Choi, J.-Y.: Numerical investigation of low-frequency instability and frequency shifting in a scramjet combustor. Proc. Combust. Inst. 39, 3107–3116 (2023).
5. Jeong, S.-M., Kim, J.-E., Kim, M.-S., Sung, B.-K., Choi, J.-Y.: Numerical study on the combustion characteristics and performances of single and multi-injectors in a scramjet combustor. Aerosp. Sci. Technol. 155, 109697 (2024).
6. Franzelli, B., Riber, E., Sanjosé, M., Poinsot, T.: A two-step chemical scheme for kerosene–air premixed flames. Combust. Flame 157, 1364–1373 (2010).