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# Regimes of Turbulent Supersonic Combustion depending on Fuel Temperature

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## Abstract

A series of high-resolution numerical study is carried out to understand the effects of fuel temperature the characteristics of supersonic combustion. Constant mass flow rate condition was selected to investigate the effect of fuel temperature on the supersonic turbulent flame. The Mathematical and numerical formulations are hybrid RANS/LES formulation and multi-dimensional 5th-order oMLP scheme, those were validated for the experimental case from the previous study. The combustion characteristics were investigated through the comparison of the combustion parameters including OH mass fraction, scalar dissipation rate, flame index and so on. As a result of investigation, it is found that it is found that the combustion regime changes from partially-premixed-combustion to mixing dominant non-premixed combustion.

**Keywords**: *Fuel Temperature, Supersonic Combustion, Turbulent Non-premixed Flame, Numerical Combustion*

## 1. Introduction

Liquid rocket and scramjet engines are working at high load conditions where the flow becomes turbulent inevitably by the high Reynolds number caused by the high mass flow rate and high speed flows. In the meanwhile, the fuel is delivered at the high temperature condition in regenerative cooling engines or at the preburned condition in staged combustion rocket engines. Almost all the liquid rocket engines and the scramjet engines of X-51A employ the regenerative cooling, while many high pressure liquid rocket engines use staged combustion cycle and HyFly (Hypersonic Flight Demonstration) program uses the dual combustion ramjet (DCR) engine. Previously, the possibility of the high-performance rocket and scramjet engines was suspected, but the realization during last decade was greatly helped by the application of high temperature fuel.

However, the effect of fuel temperature on the supersonic combustion was not studied in detail. It is readily understood that the flame speed is increasing and the combustion stability is enhanced since the reaction rate is the exponential function of temperature. Nonetheless, a little number of studies are found for the quantitative investigation on the effect of fuel temperature on the turbulent flame structure and stability. In the present study, the effect of fuel temperature on the turbulent structure of the supersonic flame was investigated by large eddy simulation (LES) with detailed chemistry based on the previous study [1] on the experimental case by Evans and Schexnayder [2], where the supersonic turbulent combustion of hydrogen with co-flowing vitiated air.

## 2. Numerical Modelling Approach

The supersonic combustion has the traditional characteristics of turbulent lifted flame where the fuel is burned in the mixing layer with co-flowing supersonic air. The coupled form of species, momentum, energy conservation equations and turbulent transport equations are used as governing equations of the physical model. Menter's detached eddy simulation (DES) formulation is used to capture the eddy motion in the separated combustion field. Since the air temperature in scramjet is quite high, a high temperature hydrogen combustion model is used, which consists of six reacting species (O, O2, H, H2,

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OH, H2O) and nitrogen (N2) assumed as inert. The model is subset of the combustion model developed by Singh and Jachimowski [3]. The governing equations were solved in fully coupled manner using fully implicit formulation.

The computational code has been used for a supersonic combustor studies and further developed with the optimized multi-dimensional limiting process (oMLP) scheme and the modified AUSMPW+ scheme for convective fluxes. Viscous fluxes are formulated by 4th order central difference scheme. The second order implicit time integration is used with sub-iterations for time accurate computation. The code is parallelized by OpenMP for the optimum performance in multi-core shared memory processors (SMP) machines. Further details on the numerical procedure and validation are included in the previous study [1].

## 3. Computational Domain and Conditions

### 3.1. Computational Domain

Figure 1 shows the schematic of reference experimental condition studied in reference [2]. A comprehensive grid independency study has been studied with 4 levels of different grid for the experimental grid with different high resolution scheme. Fig. 2 is the smallest grid constructed for the computational domain for the understanding of grid schemes. The grid is clustered to the solid walls and shear layer region. No slip adiabatic condition was assumed for the solid boundaries, while outer boundary is assumed as slip wall for the computational efficiency.

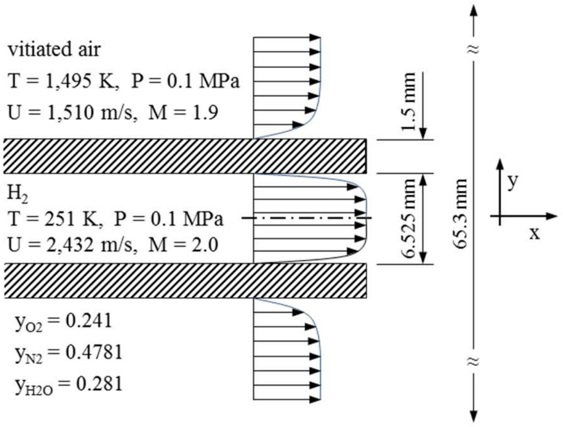


**Fig. 1** Geometry of the injector and flow conditions

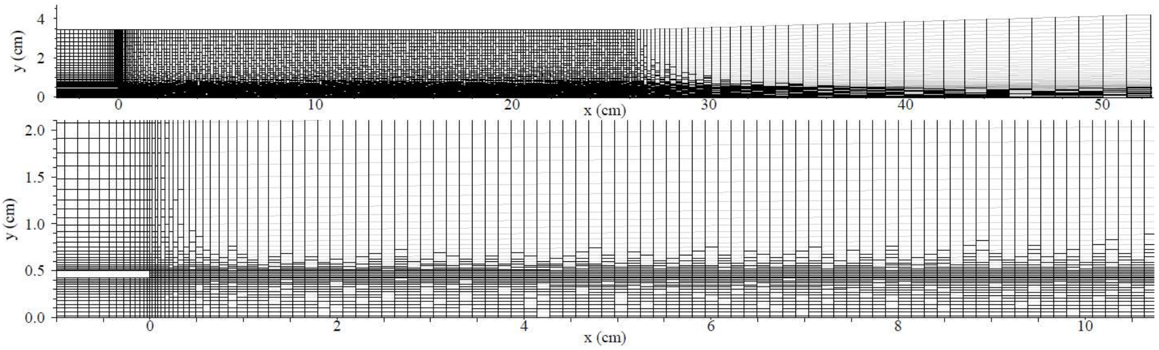


**Fig. 2** Smallest grid for the grid convergence study. Entire domain (upper) and plot around the injector (lower) [1]

### 3.2. Conditions of Numerical Analysis

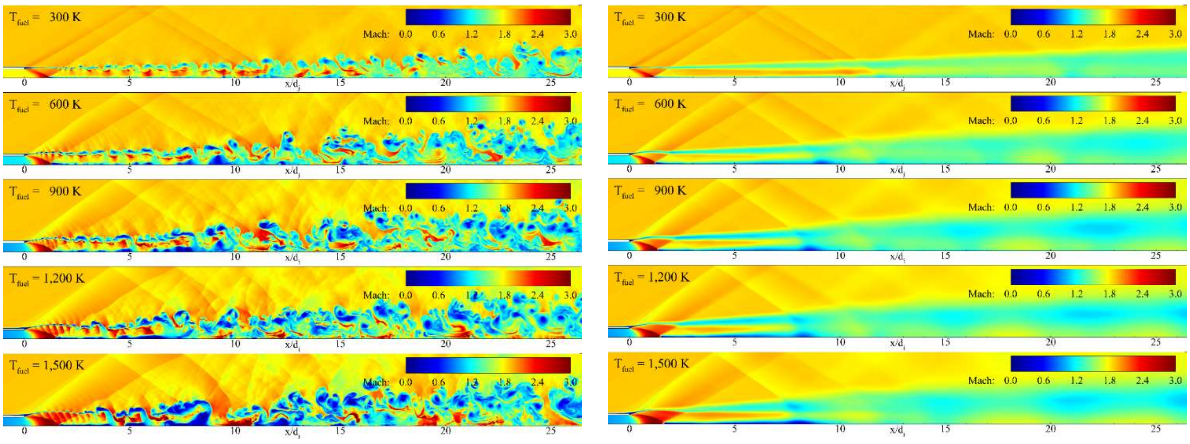
A primary purpose of the present study is the investigation of the effect of fuel temperature on the supersonic combustion characteristics. But, other flow variables are affected by the nature of compressible flow when the temperature is changed. Therefore, additional constraints should be enforced for the fair comparison. In the present study, fuel temperature is changed from 300 to 1,500 K while the mass flow rate and flow speed were fixed to the reference experimental condition. As the fuel temperature, fuel pressure increases and Mach number decays from the reference condition, as listed in Table 1 for selected cases.

**Table 1.** Fuel supply conditions

| T (K) | P (MPa) | M |
|---|---|---|
| 300 | 0.119522 | 1.82939 |
| 600 | 0.239044 | 1.29357 |
| 900 | 0.358566 | 1.05620 |
| 1200 | 0.478088 | 0.91469 |
| 1500 | 0.597610 | 0.81813 |

## 4. Results and Discussions

Instantaneous and time-averaged distributions of Mach number and temperature are plotted in Fig. 3 and 4. As the fuel temperature increase, it is found that the regime changes to under-expansion condition since incoming pressure increases while incoming Mach number decreases. Combustion is held upon the unsteady supersonic turbulent mixing layer and the enhancement of combustion efficiency is easily noticed with short flame length at high temperature condition.



(a) Instantaneous

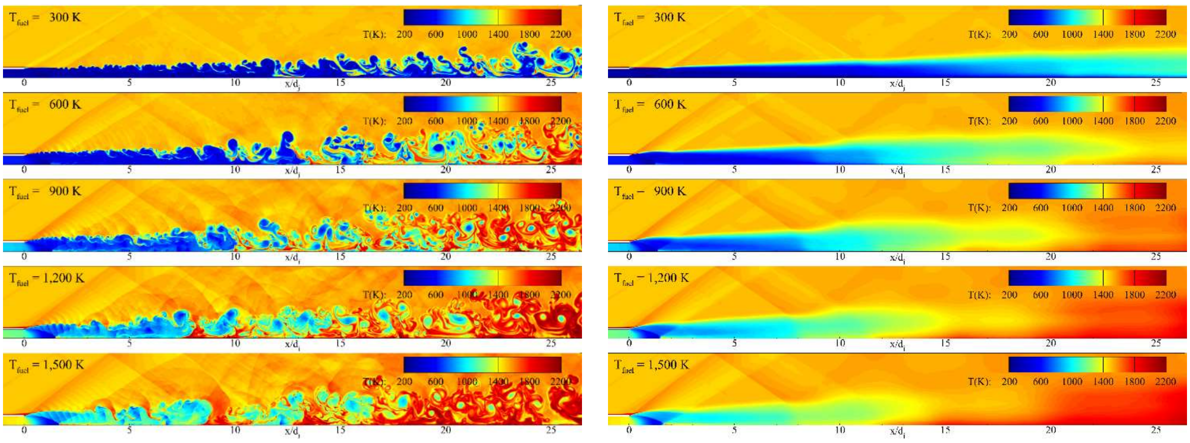
(b) Time-averaged

**Fig. 3** Mach number contours

As the fuel temperature increases while the flow speed keeps constant, the local Reynolds number is getting reduced and resulting larger eddy motion, suggested in Table 3 (a). Also, the shock strength is getting higher by the pressure difference between the fuel and air sides. As a result, shock/flame interaction is getting stronger and closer to the injector tip, and the flame is stabilized further downstream after the interaction region.

The density gradient plots in Fig. 5 show that there are very active acoustic interactions generated at the jet exit. So, it is considered that the acoustic noise at the jet exit has a big role generation of eddy motion and fuel/air mixing. The effect is getting stronger as the fuel temperature increases, since the convective Mach decreases and the shear rate grows faster.

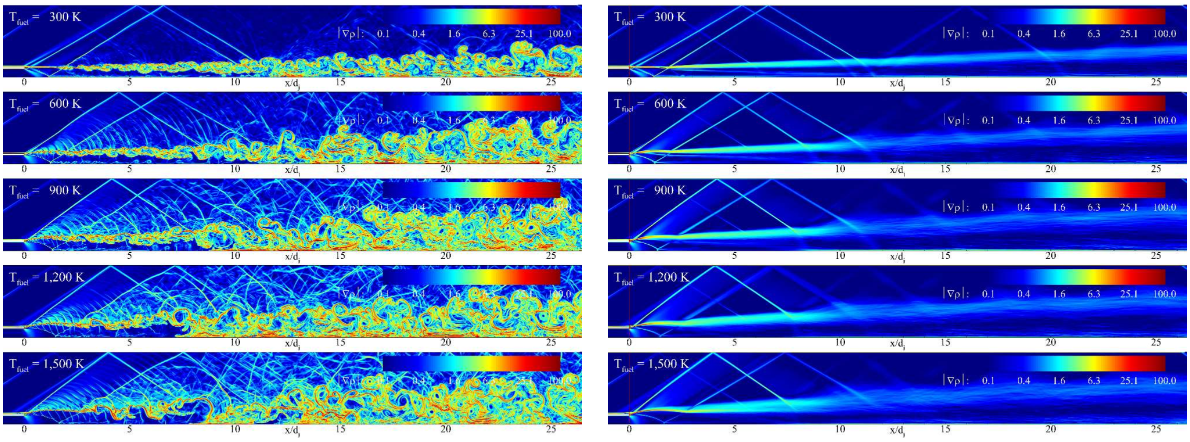
Time-averaged distributions of scalar dissipation rate (SDR) and OH mass fraction are plotted in Fig. 6 and 7. Flame has the characteristics of lifted flame around the 10 cm downstream of nozzle exit where the mixing layer is interacting with shock wave. It is found that the SDR is quite high at the early part of the shear layer where the combustion is hard to be held. By comparing Fig. 6 and Fig. 7, it is easily understood that the combustion product is produced at downstream of the shear layer where the SDR is reduced to low value. It is interesting that the SDR distribution is also similar for high fuel temperature cases above 600K. As the fuel temperature increases, the scalar dissipation rate is maintained at low level and wide distribution. Those have the role to prevent quenching and to enhance the combustion efficiency.



(a) Instantaneous

(b) Time-averaged

**Fig. 4** Temperature contours



(a) Instantaneous

(b) Time-averaged

**Fig. 5** Density gradient contours

Figure 8 and 9 are time-averaged distributions of mixture fraction and H2O mass fraction. From, the time-averaged distributions of mixture fraction and H2O mass fraction, it is clearly found that there is a transition region between fuel injection and flame stabilization which is getting shorter and closer to the injector tip, but the region is kept almost constant length around 4 cm and location 10 cm downstream from the injector tip above 1,000 K.

Instantaneous and time-averaged flame index distributions are drawn in Fig. 10 and Fig. 11. Dependency of flame length and width on fuel temperature at fixed mass flow rate condition is summarized in Fig. 12. As the fuel temperature increases, the combustion regime changes from the partially premixed flame to completely mixing dominated flame (diffusion flame). The premixed region remains only around the mixing layer, and other regions including core part of the combustor have a characteristics of non- premixed flame.

This result implies that the flame characteristics are changed to mixing dominated flame while the supersonic flame shown to have a combined nature of premixed and non-premixed flame at low fuel temperature conditions in the previous study [1]. It is readily understood from the fact that the reaction rate and flame speed is getting higher as fuel temperature increases.

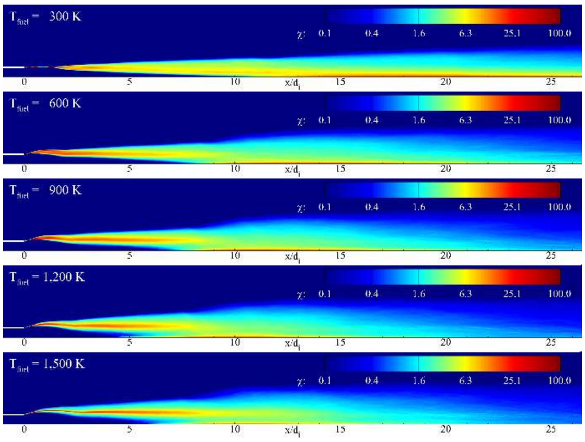


**Fig. 6** Time-averaged scalar dissipation rate contours

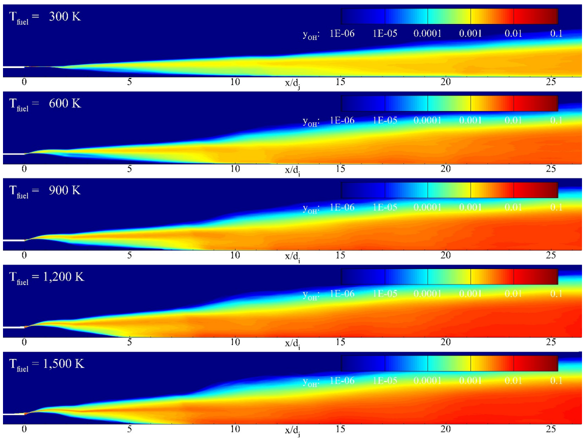


**Fig. 7** Time-averaged OH mass fraction contours

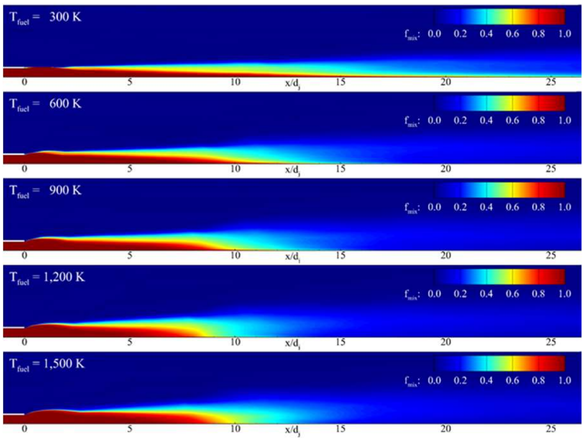


**Fig. 8** Time-averaged mixture fraction contours

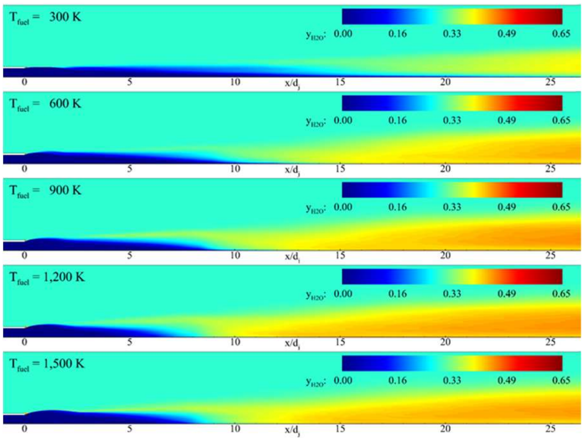


**Fig. 9** Time-averaged H2O mass fraction contours

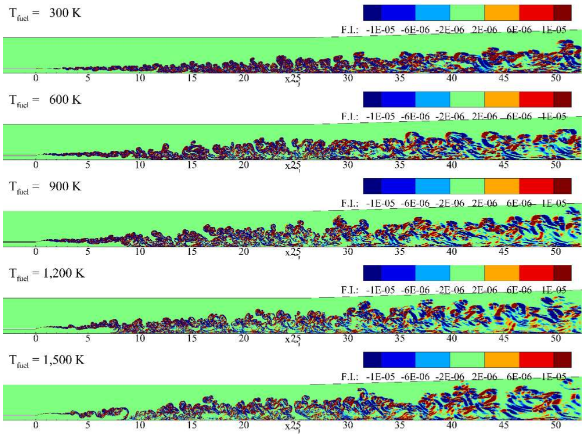


**Fig. 10** Instantaneous fame index contours

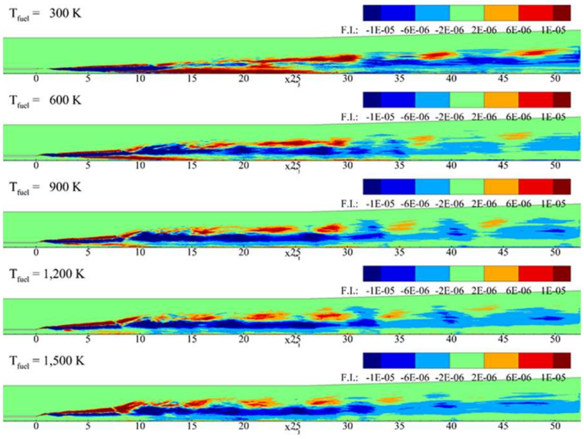


**Fig. 11** Time-averaged fame index contours

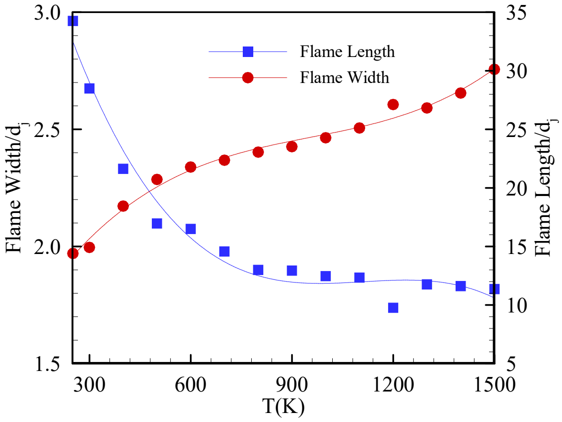


**Fig. 12** Dependency of flame length and width on fuel temperature at fixed mass flow rate condition

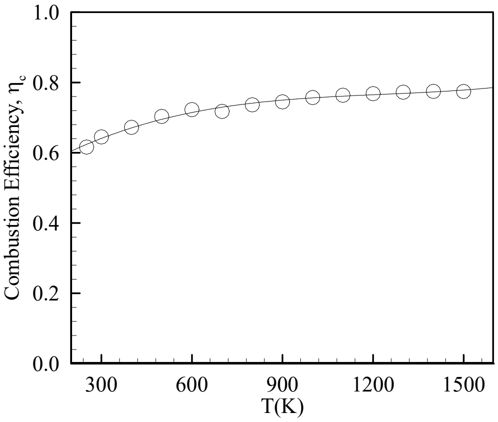


**Fig. 13** Dependency of combustion efficiency on fuel temperature at fixed mass flow rate condition

The combustion efficiency is plotted along the fuel temperature in Fig. 13. The plot shows that the combustion efficiency is getting higher as the fuel temperature is getting higher. But it almost converges on the high fuel temperature above 1,000 K.

## 5. Conclusions

A numerical study has been carried out to investigate the effect of fuel temperature on the characteristics of supersonic turbulent flame. Additionally, constant mass flow rate of fuel is assumed for fair comparison for the compressible flows, since the temperature effect cannot be isolated, but the other flow properties could be influenced by the change of temperature. As a result, the increase in fuel pressure and the decrease in fuel Mach number is introduced to the flow, those further enhances the shock/flame interactions and has a positive effect on the flame stabilization.

Overall effect of the fuel temperature could be summarized as regime changes from partially premixed flame to mixing dominated flame by the enhancement of reaction rate and flame speed. That is, fuel and air is burned as they mix at high temperature conditions, while the partially premixed nature is preserved in case the fuel temperature is low.

## References

1. Choi, J.-Y., Han, S.-H., Kim, K. H., and Yang, V., "High Resolution Numerical Study on the Coaxial Supersonic Turbulent Flame Structures," AIAA 2014 -3745, Proceedings of the 50th AIAA/ASME/SAE/ ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.
2. Evans, J. S., and Schexnayder, C. J., "Influence of Chemical Kinetics and Unmixedness on Burning in Supersonic Hydrogen Flames," AIAA Journal, Vol. 18, 1980, pp. 188-193.
3. Singh, D. J., and Jachinowski, C. J., "Quasiglobal Reaction Model for Ethylene Combustion," AIAA Journal, Vol. 32, No. 1, 1994, pp. 213-216.