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Tests and simulations on 200N paraffin-oxygen hybrid rocket engines with different fuel grain lengths

Stefano Mungiguerra[1,a *], Daniele Cardillo[2,b], Giuseppe Gallo[3,c], Raffaele Savino[1,d], Francesco Battista[2,e]

[1]Department of Industrial Engineering, University of Naples Federico II, 80 Piazzale Tecchio, Naples, 80125, Italy

[2]CIRA “Italian Aerospace Research Centre”, 81043 Capua, Italy

[3]Department of Mechanical and Space Engineering, Hokkaido University, Hokkaido 060-0808, Japan

[a]stefano.mungiguerra@unina.it, [b]d.cardillo@cira.it, [c]gallo@eng.hokudai.ac.jp, [d]rasavino@unina.it, [e]f.battista@cira.it

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Abstract. An experimental campaign, in the framework of the HYPROB-NEW hybrid rocket studies, was carried out on a 200N-thrust class hybrid rocket engine, using gaseous oxygen as the oxidizer and paraffin wax-based fuel, to investigate the effect of fuel grain length on motor performance and internal ballistics. Numerical analysis have been also performed to support the experimental findings. It was observed that, for given oxidizer flow rate, fuel grain length directly affects the characteristic velocity, because of its influence on residence time and mixing efficiency, so that the shortest grain configuration displayed the lowest performance. Moreover, CFD simulations provided an estimation of the regression rate profile along the grain length, providing a possible interpretation for the measured space-time-averaged fuel regression rate. Finally, a method for the rebuilding of the convective heat-transfer coefficient in the nozzle was used, based on a combination of numerical simulations and experimental acquisitions.

Introduction

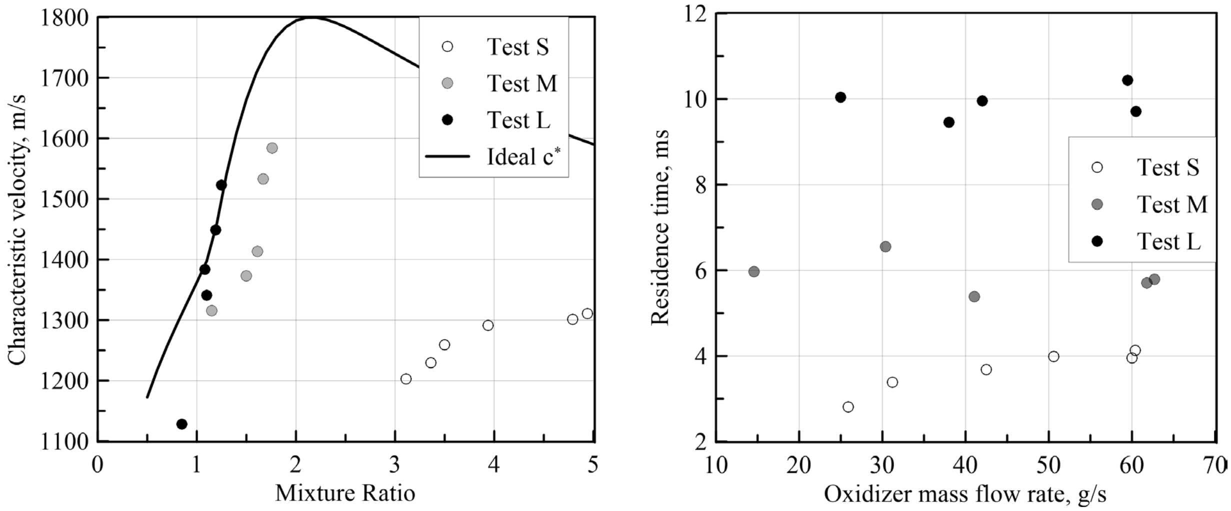
The application field of hybrid rockets is currently still limited much probably for the low fuel regression rate compared to solid rockets, especially when the use of conventional polymeric fuels is foreseen, because of the diffusion-limited phenomena affecting grain regression [1]. One of the most investigated solutions to overcome limitation in fuel regression rate and thus rocket thrust is the use of liquefying fuels, characterized by a relevant liquid droplet entrainment component, which can substantially enhance fuel mass flow rate [2].

Within this framework, the HYPROB-NEW project, funded by Italian Ministry of Research and managed by the Italian Aerospace Research Centre (CIRA), envisaged a collaboration between CIRA and University of Naples Federico II, and was focused on the study of paraffin as a potential high-performance fuel for hybrid rockets. Among the various activities, firing test campaigns were carried out on a 200 N thrust-class hybrid rocket engine, using axially injected gaseous oxygen as oxidizer and a paraffin wax-based fuel. Different cylindrical fuel grain lengths were adopted to extend fuel characterization under different operating conditions, and to evaluate rocket performances and internal ballistics in the different configurations. In addition to data collected with 220 mm propellant grain length [[3]] (labeled as L), two further test campaigns were carried out considering 130 mm (labeled as M) and 70 mm (labeled as S) grain lengths. Full details on the experimental setup and results are reported in [4]. In this work, based on measurements of pressures, temperatures, thrust and mass flow rate, and with the support of Computational Fluid

Dynamic (CFD) simulations, some considerations on performance, regression rate and graphite nozzle heat transfer.

Characteristic velocity analysis

In this subsection, the motor performances of the three configurations are discussed. Fig. 1a represents the characteristic velocity obtained in the firing tests and compared with the ideal one computed by CEA software [5]. It can be seen that the motor length affects the mixing of the oxygen with the fuel. The motor shows a combustion efficiency close to 1 in the L configuration. This value decreases from 1 to about 0.9 and 0.75 in the M and S configurations, respectively.



(a) (b)

Fig. 1 (a) Ideal and experimental characteristic velocity of Test S, M and L versus O/F, (b) estimated gas residence time versus oxidizer mass flow rate in the different configurations.

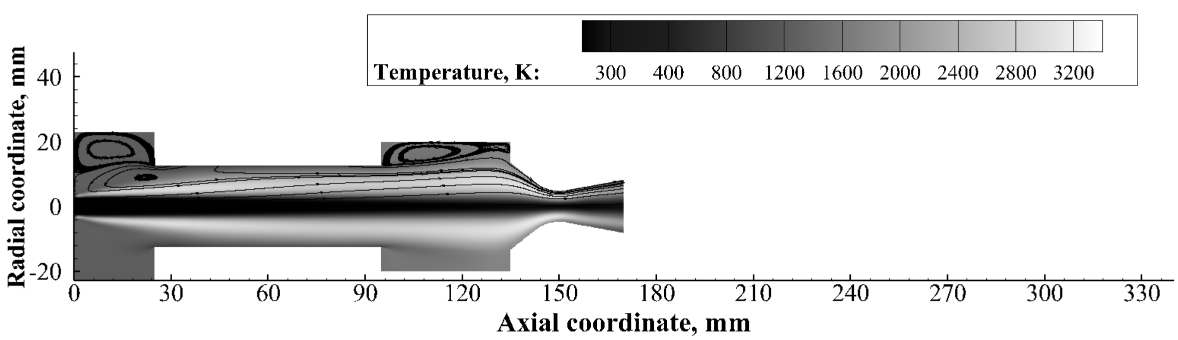


Fig. 2 Temperature contour plot with overlapped streamlines (top half) and mixture fraction iso-lines (bottom half) of test S at $\dot{m}_{ox} \approx 40\ g/s$ *and at the average grain port diameter.*

Therefore, it can be inferred that the grain length increases the motor combustion efficiency, because it increases the residence time of the gas mixture, which can be computed (Fig. 1b) as the ratio between the total motor length and the mean flow velocity in the chamber (weighted average among the flow velocities in pre-combustion chamber, grain port and post-combustion chamber, calculated by mass conservation using CEA software). The highest residence time (which is quite insensitive to mass flow rate) is shown by configuration L, which shows the highest combustion efficiency.

When the residence time is extremely low as in the case of Test S, the experimental characteristic velocity is also little affected by the change in the overall mixture ratio. This is likely due to the fact that, when the residence time is too low, the fuel released from the grain does not have enough time to reach the axis and therefore mixing efficiency is lower, as highlighted by Fig.

2, showing the results of CFD simulations carried out, by means of the model presented in [6], for test S at $\dot{m}_{ox} \approx 40\ g/s$ with the corresponding average grain port diameter.

Fuel regression rate analysis

Another major experimental finding was that the space-time-averaged fuel regression rate appeared to be affected by fuel grain length. First, regression rate in tests L was roughly 10-15% higher than for tests S. Moreover, axial recession was observed for tests M. To provide a possible explanation for these experimental observations, a CFD simulation was performed by the same model used above for the configuration L at $\dot{m}_{ox} \approx 40\ g/s$, computing the wall heat flux along the fuel grain wall, whose normalized trend is shown in Fig. 3. The wall heat flux behavior can be outlined as the product of the heat transfer coefficient, h_c, and ΔT. Indeed, $\dot{q}$ increases with the temperature, reaching a maximum at the axial coordinate between 125 mm and 150 mm, where the stoichiometric conditions are achieved; then, it decreases because a fuel-rich mixture is obtained. Three stations are highlighted in the picture, which correspond to the lengths of the configuration S, M and L. It can be seen that the space-averaging process leads to an apparent underestimation of the fuel regression rate for the shortest configuration. Moreover, as shown, the peak of wall heat flux is approximately achieved at the end of configuration M, which explains the reason why this configuration was affected by the axial recession.

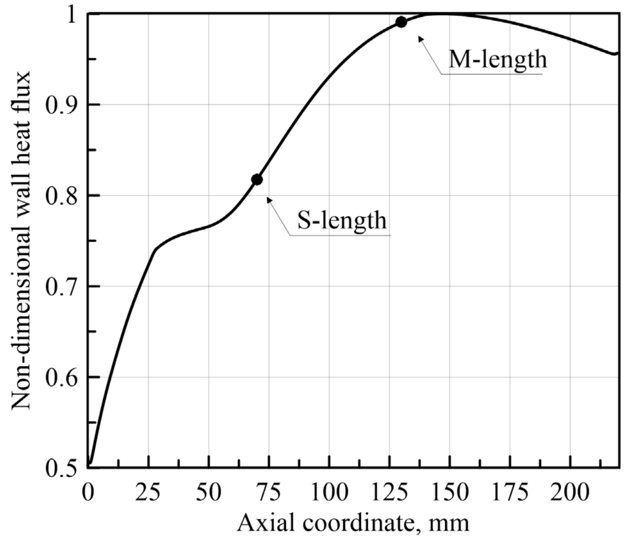
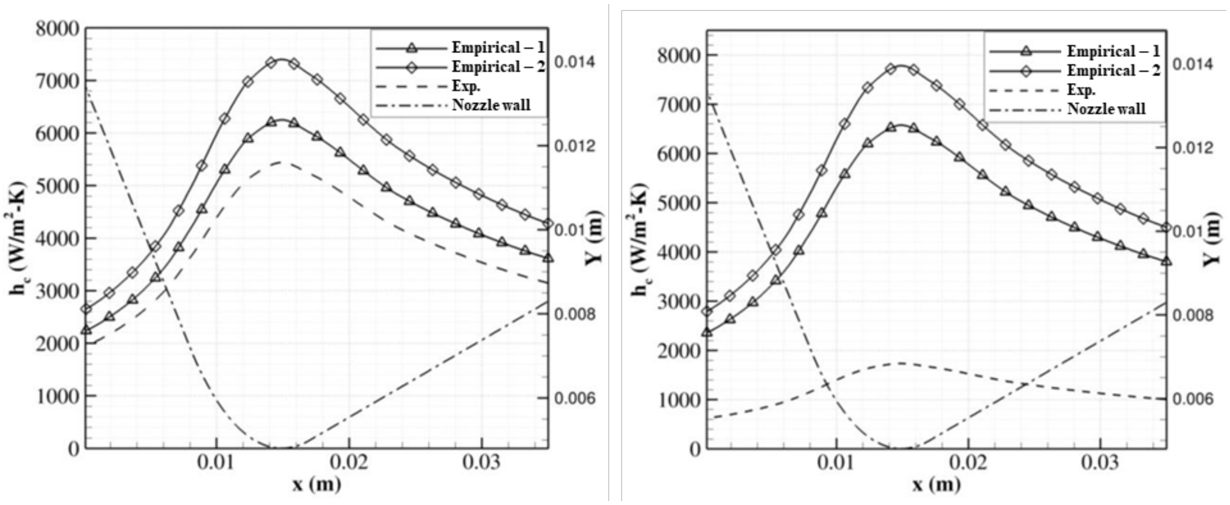


Fig. 3 Non-dimensional wall heat flux along the motor axis

Nozzle heat transfer rebuilding

Finally, measurement of temperature inside the graphite nozzle allowed for a rebuilding of wall heat flux in the S configuration (the most oxidizing) [4]. An iterative procedure was used to determine a profile of the convective heat transfer coefficient h_c matching the experimental temperature measurement, by solving the unsteady energy equation inside the nozzle with CFD simulations. The obtained coefficient was compared to that provided by empirical correlations. Fig. 4 shows this comparison for a test at $\dot{m}_{ox} \approx 40\ g/s$ and O/F ≈ 3.5, and a test at $\dot{m}_{ox} \approx 60\ g/s$ and O/F ≈ 4.79. It can be observed that, in the less oxidizing condition, the experimental trend of h_c deviates more from the empirical correlations, likely because in that condition the wall temperature remains almost always below the gasification temperature of the fuel, therefore creating a liquid paraffin layer at wall acting as insulator and heat sink.



(a) (b)

Fig. 4 Comparison of h_c predictions with different methods: tests at $\dot{m}_{ox} \approx 60\ g/s$ (a) and $\dot{m}_{ox} \approx 40\ g/s$ (b)

Conclusions

The following main conclusions can be drawn:

- The characteristic velocity is affected by the grain length, with increasing efficiency for increasing length, because of the corresponding increase of gas mixture residence time, enhancing propellant mixing.
- The space-averaging process in the regression rate calculation is affected by the axially increasing grain consumption. Longer grains exhibit a higher space-time-averaged regression rate for a given Gox, but the regression rate trend in time is similar for all the configurations in the upstream region
- At low O/F, a significant part of the convective heat transfer to nozzle wall is absorbed by fuel gasification, leading to an overestimation of wall heat transfer by empirical correlation laws, while above a certain O/F threshold, the nozzle wall temperature is higher than fuel gasification temperature and the empirical correlations work properly.

References

[1] D. Altman, et al., Hybrid Rocket Propulsion Systems, in: R.W. Humble, et al. (Eds.), Space Propulsion Analysis and Design, 1st ed., McGraw–Hill, New York, 1995, 365–370.

[2] A. Mazzetti, et al., Paraffin-based hybrid rocket engines applications: a review and a market perspective, Acta Astronaut. 126 (2016) 286–297

[3] G. D. Di Martino, et al., Two-Hundred-Newton Laboratory-Scale Hybrid Rocket Testing for Paraffin Fuel-Performance Characterization, J. Propuls. Power 35 (2019) 224-235, https://doi.org/10.2514/1.B37017

[4] D. Cardillo, et al., Experimental Firing Test Campaign and Nozzle Heat Transfer Reconstruction in a 200 N Hybrid Rocket Engine with Different Paraffin-Based Fuel Grain Lengths. Aerosp. **2023**, 10, 546. https:// doi.org/10.3390/aerospace10060546

[5] S. Gordon, et al., Computer program of complex chemical equilibrium compositions and applications, NASA Ref. Publ. 1311 (1994).

[6] G. Gallo, et al., New Entrainment Model for Modelling the Regression Rate in Hybrid Rocket Engines, J. Propuls. Power 37 (2021) 893-909, https://doi.org/10.2514/1.B38333