Regression rate response in spin-stabilized solid fuel ramjets

Amir Mahdi Tahsini *1

1School of Mechanical Engineering, Iran University of Science and Technology, Tehran, Iran

*Corresponding author: am_tahsini@iust.ac.ir

ABSTRACT

The regression rate of the solid fuel in the spinning solid fuel ramjet is investigated here using numerical simulations. The finite volume solver of the reacting turbulent flow is developed to study the flow field in the back-step combustion chamber where the burning rate of the solid fuel is computed using the conjugate heat transfer. The dependence of the burning rate on the circumferential velocity of the ramjet is studied, and it is shown that the spin augments the burning rate due to the enhancement of the convective heat flux along the fuel grain. So, the spin can be used to improve the performance of the solid fuel ramjets. In addition, the effect of rapid change in spin velocity on the regression rate of the fuel is investigated, which shows the transient-burning behavior. The results show that although the spin may increase the burning rate by ∼10% in steady-state operation of the ramjet, the spin acceleration may cause the overshoot in burning rate with the peak value > 30% in the unsteady operation.

KEYWORDS: regression rate, ramjet, solid fuel, spin

1. INTRODUCTION

Ramjet engines are variant types of the air-breathing jet engines that do not have any rotary parts as the compressor or turbine; rather, they use high-speed forward motion to compress the incoming air stream and provide the high-temperature and high-pressure oxidizer flow into the combustion chamber. In solid fuel ramjets (SFRJs), the inlet air flows through the solid fuel port that burns along its length. The tubular fuel grain releases the combustible fuel gas into the incoming air as an oxidizer, for mixing and combustion, where the combustion occurs in a boundary layer of the oxidizer stream along the solid fuel grain as a diffusion flame. This turbulent flame heats up the solid fuel surface and gasifies it to be injected into the oxidizer air stream. The difficulties in reliable flame holding to burn the solid hydrocarbons in SFRJs are resolved by using a rearward-facing step at the combustor’s head end, where the low-speed flow is dumped and a recirculating zone is formed in the sudden expansion region and acts like the flame holder.

Although the combustion chamber of a typical SFRJ has a very simple configuration, its turbulent reacting flow features are very complicated and numerous researchers in recent decades have attempted to characterize these features using experimental studies and numerical simulations. Netzer [1] developed a numerical procedure to qualitatively study the influence of the combustor geometry and inlet flow condition on the reacting flow characteristics within the SFRJ combustion chamber. Schadow et al. [2] experimentally studied the effect of air mass flow rate on the combustion efficiency and showed that the mixing and soot particles’ combustion are important processes there. Metochianakis and Netzer [3] numerically analyzed the effect of radiation on the fuel regression rate in SFRJs and also improved the dependence of the regression rate on the chamber pressure and inlet air mass flow rate. Raghunandan et al. [4] proposed the regression rate model for the SFRJs using some experimental investigations. Schulte [5] performed the experimental studies on SFRJs in order to determine the flame stability limits and also the fuel regression rate, and showed that the regression rate depends on the air mass flux, combustion chamber pressure and inlet air temperature. Schulte et al. [6] experimentally investigated the SFRJ combustor and found that the recirculating flow behind the backward-facing step is the fuel-rich region and is not well stirred and also has very large temperature gradient inside. Korting et al. [7] experimentally analyzed the influence of different parameters on the solid fuel regression rate and found that the effect of chamber pressure is strong at low chamber pressures. Zvuloni et al. [8] performed the comprehensive experiments on the burning rate of the solid fuel in the SFRJ combustor and showed that the fuel regression rate closely depends on the convective heat flux, and proposed some non-dimensional parameters to express the regression rate model well. Nusca [9] numerically simulated the SFRJ combustor using a fast chemistry model, and compared the burn time and thrust predictions favorably with some flight test data. Natan and Gany [10] investigated the effect of the addition of boron particles to the fuel and demonstrated that the general characteristics of the combustor flow field are inherently unfavorable for the combustion of boron particles. Ben-Arosh and Gany [11] theoretically analyzed the combustion characteristics in SFRJs and found some similarity conditions and scaling rules that demonstrated good agreement with their experimental results. Krishnan and George [12] comprehensively reviewed the studies on combustion aspects of the SFRJs in the twentieth century, and gathered
different proposed regression rate models and explained the combustion characteristics. Yang et al. [13] numerically studied the effect of gasified fuel injection rate on the main stream and the location of the reattachment point of the recirculating zone. Lee [14] analyzed the effect of inlet air temperature on the performance of SFRJs and showed that the higher inlet temperature leads to higher combustion efficiencies, but with lower performance efficiencies. Tyurenkova and Smirnova [15] introduced the exact solution for the solid fuel surface burning in an oxidizer cross-flow for the steady diffusion flame and showed that the zone corresponding to chemical kinetics is very small and the main role is played by the diffusion process.

Although lots of studies have been performed to analyze the steady-state performance of the SFRJ combustors, there are less research works on the ignition process. Yang et al. [16] carried out some experiments on auto-ignition of a solid fuel in a rearward-facing step geometry and concluded that the ignition process is diffusion controlled, but Tahsini and Farshchi [17] demonstrated that the ignition is diffusion controlled only for high inlet temperatures, and it is kinetic controlled for lower inlet temperatures. Tahsini and Farshchi [18] numerically analyzed the location of the igniter exit flow in the SFRJ combustors and explained that the proper location is the top of the back-step to have a reliable ignition process. Tahsini [19] also investigated the pilot-ignition of the solid fuel in back-step combustors and showed that it is better sometimes to use weak igniters with longer ignition delay times to have a reliable ignition process, because strong igniters may lead to extinction after quick ignition.

The fuel regression rate in the combustor of the SFRJs is directly determined by the heat transfer from the reacting flow field to the solid surface, and is usually <1 mm/s. The regression rate mainly affects the thrust of the SFRJ, so its increment may directly improve the performance. One way to increase the fuel regression rate is imposing the swirl on the air flow at the combustor inlet. Duesterhaus and Hogl [20] and Campbell et al. [21] experimentally studied the inlet swirl effects on the fuel regression and combustion efficiency of the SFRJ combustor and found that although the use of swirl considerably increases the regression rate, it increases the combustor’s pressure loss too. Pein and Vinnemeier [22] also investigated the inlet swirl effects on the specific thrust of the SFRJ containing metalized fuel and demonstrated that the swirling flow provides better mixing and combustion for the metal particles, so increases the combustion efficiency. Recently, Musa et al. [23, 24] conducted some experimental studies and proposed an empirical correlation for the regression rate versus the inlet swirl number.

The major disadvantage of using the inlet swirl for burning rate augmentation in SFRJs is the imposed pressure loss due to placing the swirler upstream the combustion chamber. Therefore, the spin may be used instead of the inlet swirl for burning rate enhancement. Although the spin is sometimes used for dynamic stability of the propulsion systems, it may be utilized for performance improvement of spin-stabilized SFRJs by regression rate augmentation; the spin of the solid fuel grain may increase the convective heat flux of the reacting flow field within the combustion chamber and so increases the burning rate but without pressure losses. In this study, the regression rate response of the solid fuel in the spinning SFRJ is investigated for both steady-state and unsteady spinning conditions.

2. GOVERNING EQUATIONS AND NUMERICAL SCHEME

The flow field within a combustion chamber of the spinning SFRJ (Fig. 1) with cylindrical fuel grain is three-dimensional, but the flow is circumferentially symmetric and there is no change with change in circumferential direction. So, the three-dimensional flow equations are utilized here considering the condition of symmetry, and can be solved on the two-dimensional grids.

The governing equations for the conservation of mass, momentum, energy and species are used in the conservation form:

\[
\begin{align*}
\frac{\partial U}{\partial t} + \frac{\partial (F + F_\varepsilon)}{\partial x} &+ \frac{\partial (G + G_\varepsilon)}{\partial r} + \frac{G_v}{r} = \text{ST},
\end{align*}
\]

where

\[
U = \begin{bmatrix} \rho \\ \rho u \\ \rho v \\ \rho w \\ \rho e \\ \rho m_j \end{bmatrix}, \quad F = \begin{bmatrix} \rho u \\ \rho uu + p \\ \rho uv + p \\ \rho uv + p \\ \rho vh \\ \rho vm_j \end{bmatrix}, \quad G = \begin{bmatrix} \rho v \\ \rho vv + p \\ \rho vw \\ \rho wv \\ \rho hh \\ \rho vm_j \end{bmatrix}.
\]

\[
G' = \begin{bmatrix} 0 \\ -\rho w w - p \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}, \quad F_v = \begin{bmatrix} 0 \\ -\tau_{xx} \\ -\tau_{yy} \\ -\tau_{zz} \\ q_x - \nu \tau_{xx} - \nu \tau_{yy} - \nu \tau_{zz} - \omega \tau_{y} \\ -\rho D_{eff} m_{i,xx} \end{bmatrix}
\]

\[
G_v' = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}, \quad \text{ST} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -\omega H_i \\ -\omega \end{bmatrix}
\]
The stress tensors are determined by

\[
\tau_{xx} = \mu_{\text{eff}} \left( \frac{\partial u}{\partial x} - \frac{2}{3} \nabla \cdot V \right),
\]

\[
\tau_{xy} = \mu_{\text{eff}} \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right),
\]

\[
\tau_{yx} = \mu_{\text{eff}} \left( \frac{\partial v}{\partial y} - \frac{2}{3} \nabla \cdot V \right),
\]

\[
\tau_{zz} = \mu_{\text{eff}} \left( \frac{\partial w}{\partial z} \right),
\]

\[
\tau_{zz} = \mu_{\text{eff}} \left( \frac{\partial w}{\partial z} - \frac{1}{r} \right),
\]

\[
\tau_{\theta\theta} = \mu_{\text{eff}} \left( \frac{\partial v}{\partial r} - \frac{2}{3} \frac{\partial \omega}{\partial z} \right),
\]

(3)

in which

\[
\mu_{\text{eff}} = \mu + \mu_t,
\]

\[
e = c_v T + (uu + vv + wv) / 2 + \sum m_j \Delta h_{f,j}^0, \]

\[
q = -k_{\text{eff}} \nabla T - \rho D_{\text{eff}} \sum h_i \nabla m_i,
\]

\[
h_i = \Delta h_{f,i}^0 + \int_{c_i} \partial T.
\]

(4)

The Schmidt number is assumed to be unity and a one-step second-order reaction in the gas phase is considered. Different species are considered in this reacting flow: oxygen (ox), fuel (fu), diluents (d) and products (p). So, the source terms of the equations are due to the chemical reactions in the gas phase and are defined as

\[
\dot{\omega}_{\text{fu}} = -A_g \rho^2 m_{i_{\text{fu}}} m_{i_{\text{ox}}} \exp \left( -\frac{E_{\text{ox}}}{R_u T} \right), \quad \dot{\omega}_d = 0,
\]

\[
\dot{\omega}_p = -(1 + i) \dot{\omega}_{\text{fu}}, \quad \dot{\omega}_{\text{ox}} = i \dot{\omega}_{\text{fu}}.
\]

(5)

In addition, the one-equation turbulence model of Spalart and Allmaras is used to compute the effective transport properties [25]. The governing equation for the eddy viscosity is given here:

\[
\frac{D(\nu)}{Dt} = c_{12} S \nu + \frac{1}{\sigma} \left[ \nabla \cdot \left( \nu \left( \nabla \nu \right) + c_{12} \left( \nabla \nu \right)^2 \right) \right]
\]

\[- \epsilon_{12} f_v \left( \frac{\nu}{d} \right)^2.
\]

(6)

This is solved for the variable \( \nu \) and the eddy viscosity is computed as \( \nu = \nu_{f,i} \), where the function \( f_{i1} \) is a damping function that is used to treat the buffer layer and the viscous sublayer:

\[
S = S + \left( \nu / \kappa^2 d^2 \right) f_{i2},
\]

\[
f_{i2} = 1 - X / (1 + X f_{i1}),
\]

\[
f_{i1} = X^3 / (X^3 + \lambda_{i1}^3),
\]

\[
X = \nu / \nu,
\]

(7)

Equation (6) is solved coupled with flow governing equations. The heat conduction equation within the solid fuel is used besides the flow equations as a conjugate heat transfer problem to compute the fuel regression rate (\( \dot{r} \)) due to the applied convective heat transfer from the gas phase, as presented:

\[
\frac{\partial T}{\partial t} = \alpha \nabla^2 T + \frac{\partial T}{\partial r}, \quad q_g = q_i + \rho_c H_i.
\]

(10)

The developed numerical program utilizes the finite-volume method to discretize the flow field governing equations on a structured grid (as Fig. 2), where the viscous terms are treated by a centered scheme and the inviscid fluxes are computed using the AUSM+ method [26]. Every grid cell is defined as a control volume in this method, and flow properties are stored at the center of the grid. The fluxes are computed at each face of the control volume. Then, fluxes are integrated over cell to define flow properties at the center of the control volume. The Green’s theorem is used to compute first derivative of velocity’s components, temperature and mass fraction of species at the faces of every grid cell. After the derivatives are computed, viscous fluxes can be calculated at each face.

The explicit method is employed for discretization in time after the fluxes are integrated over the control volume. The ghost cells are used to impose proper boundary condition for numerical simulation. To study the flow field within a combustor, as boundary conditions, the inlet Mach number is set to the inlet, and the considered working pressure is set at the outlet. On the fuel surface, the fuel mass fraction is applied unity and the energy equation is solved to find the regression rate of the solid fuel as mentioned earlier, and the axial velocity is set to be zero. The axis boundary condition is applied as symmetry. More details on the governing equations, numerical procedure and validation are presented in [17–19].

### 3. RESULTS AND DISCUSSION

A problem under consideration is the reacting flow of the cylindrical solid fuel grain in the back-step combustion chamber of the spinning SFRJ. The inlet diameter of the combustor is 4 cm, the internal diameter of the cylindrical fuel grain is 7 cm and the

![Figure 2 Schematic of the mesh and geometry of the combustor.](https://academic.oup.com/jom/article/doi/10.1093/jom/ufaa012/6015291)
The fuel length is 20 cm. The combustor pressure is 0.6 MPa and the inlet Mach number is \( \sim 0.36 \). The inlet static temperature is 600 K and the inlet axial velocity profile is uniform. The working pressure of the SFRJs is usually <1 MPa and an assumed pressure is in the common range that is assumed for the studies. The fuel is poly(methyl methacrylate), which has the specific heat of 2100 J/(kg K), density of 1190 kg/m³ and thermal diffusivity of \( 8 \times 10^{-8} \) m²/s. Four species are considered in the gas phase: oxygen, nitrogen, fuel and products. The one-step forward reaction is considered where the activation energy is 88 kJ/mol and the heat of reaction is 26 MJ/kg. When the SFRJ is spinning, the gasified fuel is injected to the flow field with an initial circumferential velocity that is equal to the solid fuel circumferential velocity. The studies are categorized here into two parts: first, the effect of circumferential velocity on the regression rate of the fuel is investigated using steady-state simulations, and then the unsteady simulations are performed to analyze the transient-burning behavior of the fuel when the spin is rapidly changed.

At first, the reacting flow within a combustion chamber is simulated by applying different circumferential velocities of the SFRJ, in steady-state condition. The studies of grid independence are performed to find the efficient grid point for the simulations. The results illustrate that the 180 \( \times \) 120 grid resolution is proper for this flow field with regard to the regression rate and flow properties’ profiles, as an outlet temperature profile that is presented in Fig. 3.

The contours of the circumferential velocities in the flow fields are shown in Fig. 4 for the applied spin velocity of 50 m/s on the solid fuel. Its profile is also shown in Fig. 5 for the combustor’s head end and aft end. In spin-stabilized solid rocket motors, it has been illustrated [27] that the circumferential velocity of the flow increases with decreasing radial location due to the angular momentum of the injected gasified fuel. Here, the inlet flow has no circumferential velocity and dominated the flow features and such behavior is just observed in a small region of the back-step recirculating flow (at the chamber’s head end as shown in Fig. 5).

Anyway, resulting flow circumferential velocity due to the combustor’s spin increases the convective heat flux along the solid fuel surface and increases the burning rate. The fuel regression rate along the grain is illustrated in Fig. 6 for different spin velocities, which shows the regression rate augmentation due to the spinning of the SFRJ. Such behavior is observed for the propellants in spin-stabilized solid rocket motors, too [27]. The location of the maximum regression rate also
The maximum regression rate is presented in Fig. 7 versus a non-dimensional spin velocity, which shows that the second-order polynomial fits well this dependence. So, the spin may be used for performance improvement of the SFRJs by burning rate enhancement, and also the regression rate response to the spin must be considered in spin-stabilized SFRJs. However, the important point here is that although the dependence of the regression rate on the ratio of the fuel circumferential velocity to the inlet velocity is shown, this non-dimensional velocity is not an independent parameter. This is illustrated in Fig. 8 for two other inlet velocities. The results demonstrate that the spin effect on the regression rate is stronger for lower inlet velocities of the combustion chamber (lower air mass flow rates).

Although the burning rate of the solid fuel under steady-state spinning condition of the SFRJ is investigated here, its response to the rapid variation of the spin must be analyzed. The angular velocity of the SFRJ may change during the combustor’s operation, and there is a potential for transient-burning phenomenon. When there are different timescales in unsteady problems especially those including the solid and the gas phases, the transient behavior may be observed particularly for high time rate of imposed changes [28]. For solid fuels, the regression rate is determined by the balance between the incoming heat flux from the reacting gas phase and the conducted heat flux into the solid phase. So, the temperature profile inside the fuel is determined for each steady-state condition. The solid phase’s response time is larger than the gas phase’s response time, and if there is rapid change imposed on this problem, the solid phase is sluggish and the temperature gradient inside the fuel cannot adjust itself quickly with the gas phase, and the instantaneous burning rate may differ with the expected behavior, which is called the transient burning. The transient burning also occurs in solid propellants such that the burning rate amplification appears for rapid pressure growth, or the extinguishment sometimes appears for rapid pressure reduction in the combustion chamber of the solid rocket motors [29].

In spinning SFRJs, increasing the angular velocity enhances the gas phase heat flux and augments the regression rate of the fuel, and changes the temperature profile inside the fuel as shown in Fig. 9. If the angular velocity is increased fast, the regression rate of the fuel may show the transient behavior as an overshoot that must be considered in the performance prediction of the spinning SFRJs. This is illustrated later with two different methods: the decoupled solid phase simulation and coupled gas–solid phase simulation.

This unsteady problem should be analyzed again by the coupled phase simulations (the conjugate heat transfer) as has been used for the mentioned steady-state studies, but this method needs very large computational costs. So, the quasi-steady
decoupling method [17] may be used instead, where the convective heat transfer coefficient of the gas phase is computed using the steady-state simulations in some time intervals of the unsteady process, and then the unsteady solid phase is calculated to predict its transient response under time-variable gas-phase heat flux. The computational time of this procedure is considerably lower than that for the coupled method [28]. The problem under consideration is the SFRJ that works with no spin, and then its circumferential velocity increases linearly to 30 m/s during specified acceleration time.

Performing the quasi-steady procedure, the results properly demonstrate the transient burning as shown in Fig. 10. When the time duration of the spin enhancement is decreased, and the time rate of changes in the problem is intensified, the transient behavior emerges and the instantaneous burning rate of the solid fuel shows the overshoot that is significant for fast maneuvers. The results illustrate that although the spin augments the maximum burning rate by ∼7% in the considered steady-state operation, there is >30% augmentation for rapid acceleration of the spin that should be considered in the performance prediction of the spinning SFRJs.

This problem is computed again for the spin acceleration time of 0.1 s using the coupled method to investigate the regression rate behavior more accurately and to compare with the decoupled method. The results are compared in Fig. 11, which illustrates that the maximum overshoot of the regression rate is accurately predicted by the decoupled quick method, but the coupled method reveals the exact variation of the instantaneous burning rate, which, of course, needs much more computing time. The results show that the transient burning of the spinning SFRJ can be studied using the decoupled simulation to be utilized in performance predictions in unsteady operation.

4. CONCLUSIONS
The effect of the ramjet’s spin on the regression rate of the solid fuel is investigated numerically, using conjugate heat transfer besides a reacting turbulent flow field. For the steady-state spinning operation of the SFRJs, the results illustrate that the second-order correlation exists for the maximum regression rate versus the non-dimensional fuel spin velocity, which is defined as the ratio of the fuel circumferential velocity and the inlet velocity. However, it is demonstrated that this non-dimensional velocity is not an independent parameter, and the regression rate augmentation is higher for lower inlet velocities. In addition, the influence of the spin variation on the regression rate is analyzed for unsteady operation, using two methods: the decoupled gas and solid phases as a quasi-steady quick method and an unsteady coupled phase method. The results illustrate the transient-burning phenomenon when the spin acceleration is imposed on small times that emerge as an overshoot in the regression rate. Therefore, although the spinning of the SFRJ augments the maximum burning rate in steady-state operation, there is more considerable augmentation due to the transient burning for rapid spin accelerations, which should be considered in the performance prediction of the spinning SFRJs.

NOMENCLATURE

\( C_p \) = constant pressure specific heat  
\( C_v \) = constant volume specific heat  
\( D_{\text{eff}} \) = effective mass diffusion coefficient  
\( e \) = total internal energy  
\( h \) = total enthalpy  
\( H_r \) = heat of reaction  
\( H_s \) = solid fuel latent heat  
\( m_j \) = mass fraction of species \( j \)  
\( p \) = local pressure  
\( q \) = heat flux  
\( r \) = radial coordinate  
\( \dot{r} \) = fuel regression rate  
\( r_{\text{in}} \) = inlet radius  
\( T \) = local temperature  
\( u \) = axial velocity  
\( U_{\text{in}} \) = inlet axial velocity  
\( v \) = radial velocity
\[ w = \text{circumferential velocity} \]
\[ W_f = \text{fuel circumferential velocity} \]
\[ x = \text{axial coordinate} \]
\[ \alpha = \text{fuel thermal diffusivity} \]
\[ \mu = \text{molecular viscosity} \]
\[ \mu_{\text{eff}} = \text{effective viscosity} \]
\[ \rho = \text{flow density} \]
\[ \rho_s = \text{fuel density} \]
\[ \dot{\omega}_j = \text{mass rate of production of species } j \]

REFERENCES

1. Netzer DW. Modeling solid fuel ramjet combustion. *Journal of Spacecraft and Rocket* 1977;14(12):762–766.

2. Schadow KC, Cordes HF, Chieze DJ. Experimental studies of combustion processes in a tubular combustor with fuel addition along the wall. *Combustion Science and Technology* 1978;19:51–57.

3. Metochianakis ME, Netzer DW. Modeling solid fuel ramjet combustion, including radiation to the fuel surface. *Journal of Spacecraft and Rocket* 1983;20(4):405–406.

4. Raghunandan BN, Ravichandran ER, Marathe AG. Combustion related to solid fuel ramjets. *Journal of Propulsion and Power* 1985;1(6):502–504.

5. Schulte G. Fuel regression and flame stabilization studies of solid fuel ramjets. *Journal of Propulsion and Power* 1986;2(4):301–304.

6. Schulte G, Pein R, Hogl A. Temperature and concentration measurements in a solid fuel ramjet combustion chamber. *Journal of Propulsion and Power* 1987;3(2):114–120.

7. Korting PAOG, Schoyer HFR, Timnat YM. Advanced hybrid rocket motor experiments. *Acta Astronautica* 1987;15(2):97–104.

8. Zvuloni R, Gany A, Levy Y. Geometric effects on the combustion in solid fuel ramjets. *Journal of Propulsion and Power* 1989;5(1):32–37.

9. Nusca MJ. Steady flow combustion model for solid fuel ramjet projectiles. *Journal of Propulsion and Power* 1990;6(3):348–352.

10. Natan B, Gany A. Ignition and combustion of boron particles in the flowfield of a solid fuel ramjet. *Journal of Propulsion and Power* 1991;7(1):37–43.

11. Ben-Arosh R, Gany A. Similarity and scale effects in solid fuel ramjet combustors. *Journal of Propulsion and Power* 1992;8(3):615–623.

12. Krishnan S, George P. Solid fuel ramjet combustor design. *Progress in Aerospace Science* 1998;34:219–256.

13. Yang JT, Lee SC, Chao YC. Analysis of entrainment in a sudden expansion channel with wall mass transfer. *Journal of Propulsion and Power* 2003;19(3):514–516.

14. Lee T. Inlet air temperature effects on the performance of the solid fuel ramjet. *Journal of Thermophysics and Heat Transfer* 2006;20(4):937–939.

15. Tyurenkova V, Smirnova M. Material combustion in oxidant flows: self-similar solutions. *Acta Astronautica* 2016;120:129–137.

16. Yang JT, Wu CYY, Din SJ. Ignition transient of a polymethylmethacrylate slab in a sudden expansion combustor. *Combustion and Flame* 1994;98:300–308.

17. Tahsini AM, Farshchi M. Numerical study of solid fuel evaporation and auto-ignition in a dump combustor. *ACTA Astronautica* 2010;67(7):774–783.

18. Tahsini AM, Farshchi M. Igniter jet dynamics in solid fuel ramjets. *ACTA Astronautica* 2009;64(2):166–175.

19. Tahsini AM. Piloted ignition of solid fuels in turbulent back-step flows. *Aerospace Science and Technology* 2012;18(1):8–14.

20. Duesterhaus DA, Hogl A. Measurements in a solid fuel ramjet combustion with swirl. In: *Proceedings of the AIAA 24th Joint Propulsion Conference*, Boston, MA, 1988, 3045–3055.

21. Campbell WH, Ko BN, Lowe SR, Netzer DW. Solid-fuel ramjet fuel regression rate/thrust modulation. *Journal of Propulsion and Power* 1992;8(3):624–629.

22. Pein R, Vinnemeier F. Swirl and fuel composition effects on boron combustion in solid-fuel ramjets. *Journal of Propulsion and Power* 1992;8(3):609–614.

23. Musa O, Xiong C, Changsheng Z. Effect of inlet conditions on swirling turbulent reacting flows in a solid fuel ramjet engine. *Applied Thermal Engineering* 2017;113:186–207.

24. Spalart PR, Allmaras SR. A one equation turbulence model for aerodynamic flows. In: *Proceedings of the 30th Aerospace Sciences Meeting and Exhibit*, Reno, NV, 1992, AIAA-92-439.

25. Liou MS. A sequel to AUSM: AUSM+. *Journal of Computational Physics* 1996;129:364–382.

26. Tahsini AM, Mazaheri K. Swirl effects on spinning solid propellant rocket performance. In: *Proceedings of the 42nd AIAA/ASME/S/AEE Joint Propulsion Conference and Exhibit*, Sacramento, CA, 2006, AIAA-2006–4781.

27. Tahsini AM. Qualitative phenomenological investigation of the transient temperature gradient during gas turbine’s hot section component cooling. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering* 2020;234(3):709–715.

28. Tahsini AM, Farshchi M. Thrust termination dynamics of solid propellant rocket motors. *Propulsion and Power* 2007;23(5):1141–1142.