Sub Topic: IC Engines, Gas Turbines, and Rockets

Spring Technical Meeting
Eastern States Section of the Combustion Institute
March 10-13, 2024
Athens, Georgia

Flashback Characterization of Additively Manufactured Swirl-Stabilized Fuel Injector with Varying Surface Roughness

Pratikshya Mohanty[1], Sagar Jalui[1], Guha Manogharan[1], Jacqueline O'Connor[1], and Yuan Xuan[1]

[1]*Department of Mechanical Engineering, The Pennsylvania State University, University Park, PA*
[*]*Corresponding author:* pqm5504@psu.edu

Abstract: This work investigates the effects of as-built surface roughness on the flashback propensity in additively manufactured (AM) swirl-stabilized lean premixed (LPM) fuel injectors. Adoption of AM for rapid prototyping and fabrication of complex fuel-flexible injector designs requires investigating surface roughness effects on the flow and flame stability characteristics of the combustor. Wall roughness increases the near-wall shear, which could alter the boundary layer structure and change the propensity for flame flashback. Accounting for the realistic as-built surface roughness is crucial in carrying out computational modeling and experimental analysis to establish a feedback loop for the precision designing of fuel-flexible injectors. The presented numerical analysis of as-built AM injector is an essential consideration to optimize injector design for aerodynamics and additive manufacturability.
***Keywords:* Flashback, Additive manufacturing, Swirl-stabilized flames, Surface roughness**

1. Introduction

Gas turbines face increasing demands for stringent emission performance and operational resilience necessitating innovative and often complex combustor designs that can accommodate drastically differing thermochemical and transport properties of high-hydrogen fuels such as NH_3 or H_2. Lean-premixed swirl injectors employed in modern gas turbines utilize vortex breakdown for lean flame stabilization, but unsteady flow features can impact stability limits [1]. Precision engineering of these injectors renders complex flow geometries, posing fabrication challenges using traditional methods and impeding product validation and testing.

Laser powder bed fusion (L-PBF) is an advanced additive manufacturing method gaining popularity for rapid prototyping and cost-effective manufacturing of complex, end-use parts at a small production volume High-temperature nickel-based superalloys, crucial to advanced gas turbine components, are compatible with this technique [2]. However, a drawback of L-PBF is inferior as-built surface quality compared to traditionally machined metal productionAM process parameters can be optimized to improve as-built surface quality, as post-processing for complex features can be logistically challenging [2]. Residual wall roughness in L-PBF parts can alter flow features in injectors, affecting heat transfer and flame structures, potentially leading to increased flashback propensity [3]. High as-built surface roughness alters the viscous sublayer within the turbulent boundary layer. AS the logarithmic profile of the turbulent boundary layer wall functions is shifted downwards, the viscous layer is fully destroyed, causing a consequential increase in wall shear stress and corresponding skin friction [3]. Prior studies have examined AM test coupons for representative chacterization of flow and heat effects in cooling channels [4]. Additionally, a body of literature has focused on effectively characterizing surface roughness, offering pertinent sand-grain roughness scalings [4, 5]. Furthermore, efficacy of turbulence modeling in accurately capturing roughness effects are explored, predominantly through generic flat plate analyses [6–8]. However, there remains a gap in the literature regarding the accurate modeling of surface roughness in fuel injectors, where surface roughness can affect flameholding. This work entails the establishment of a realistic and selective roughness specification, which varies within the injector due to built orientations.

2. CFD setup and modeling

A single-nozzle industrial swirl injector is assembled in an atmospheric combustor rig consisting of a centerbody with a central jet for a pilot flame and a swirling main flow, as shown in Figure 1(a). The configuration is modeled in Simcenter STARCCM+, ver. 17.02.008. A preheated (523 K), fully premixed flow of 0.0632 kg/s enters the rig inlet; 5% of the flow goes into the pilot flow and the rest flow through the main annulus of width, D = 0.027 m. The mixture density is 0.656 kg/m^3 and the kinematic viscosity, ν is calculated from Sutterland's equation for air temperature of 523 K. The bulk velocity at the main annulus is sustained at 40 m/s. The wall temperatures are defined as per Li et al. [9]. The fuel is a mixture of 40% by vol. H_2 in CH_4. The USC-II MECH detailed chemistry is used to generate a flamelet-generated manifold (FGM) model based on a 1D freely propagating constant-pressure reactor. The global equivalence ratio for both the main and pilot flame is equal at 0.58.

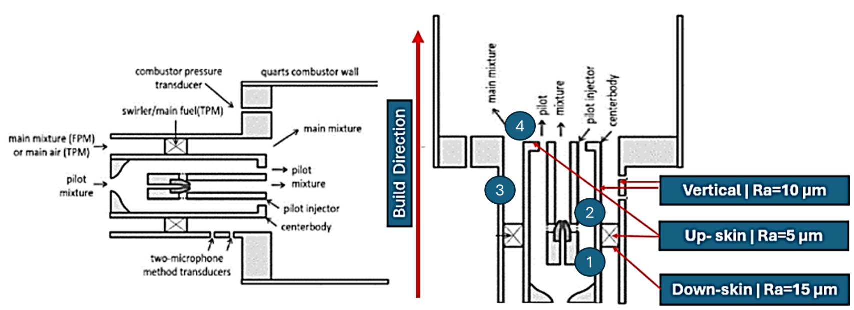

Figure 1: (a) Schematic of swirl injector in the Atmospheric rig, and (b) Regions of the injector with varying roughness [9].

An unstructured polyhedral mesh is auto-generated for the base cell size of 3 mm. The boundary layer in the swirler geometry is resolved to a Y^+_{wall} ~1 using prism cells [7], with a growth rate of 1.5 for a total thickness of 2 mm to capture the wall effects accurately. The rest of the mesh has a Y^+_{wall} ~17.5 for the same growth rate and total thickness. A historical mesh convergence study ascertains flame shape accuracy.

The arithmetic mean of surface roughness (R_a) of the as-built (L-PBF) swirl injector is quantified and scaled to equivalent sand-grain roughness for Inconel 718 alloy using $K_s = 10R_a$ [4].

The as-built surface roughness values (R_a) are defined for each section of the injector as shown in Figure 1(b). The downward-facing surface of the swirler vanes are the roughest (as defined in Table 1) due to a staircasing effect, high powder-melt pool interaction, and unsupported overhangs required to achieve the desired airfoil camber, while the upward facing regions show contour re-melting and self-supporting orientations [2]. The vertical surface roughness is usually a function of layer thickness and laser intensity. The surface is hydraulically smooth if the roughness Reynolds number, $K_s^+ = K_s u_\tau / \nu$, where u_τ is friction velocity, is less than 2.25 and hydraulically rough if it is greater than 90. These definitions modify the friction factor, f, that scales the offset in the log-layer of the blended wall function.

The unsteady shear stress transport (SST) k-ω Reynolds-averaged Navier-Stokes turbulence model is employed as it is better equipped to handle roughness effects than k-ε models [6]. All Y^+ wall treatment is applied since the boundary layer is refined only for the swirler regions. A second-order temporally discretized implicit solver is used with a timestep of 5e-4 sec. and 10 inner iterations. The Turbulent Flame speed Closure (TFC) model is used for transport equation closure. The rest of the modeling settings were maintained as default.

3. Results and Discussion

The simulations were independently run for two cases – case #1: smooth wall definition and case #2: rough region definition – until mass, momentum, and turbulent residuals converged below 1e-6. Mass conservation was checked in an initial non-reacting simulation; the difference in mass flowrates at the exit of the main annulus was less than 0.1% and corresponding change in exit bulk flow rates were less than 0.2% between the smooth and rough cases. These are attributed to numerical or precision errors.

First, the surface averaged wall shear stresses were compared for the three different regions of the injector for smooth and rough region cases, as shown in Table 1. In fully turbulent flows, wall velocity gradient, $g = \tau_{wall}/\rho\nu$, is typically a measure of flame flashback propensity [3]. A 39% increase in the rough case with respect to smooth case was noted in the downskin region and the lowest of 14% in the centerbody tip. Figure 2 shows the velocity profile with non-dimensional wall distance, comparing the profile in the rough case compared to smooth walls. The velocity magnitude in the annular boundary layer volume, as shown in Figure 1, for smooth case was 62.02 m/s, which decreased by 7% to 57.70 m/s for the rough wall condition.

Table 1: Wall Shear Stress: Magnitude in (Pa) τ_{wall}

Regions	Roughness (K_s)	Smooth	Rough	% Increment in g w.r.t Smooth
R1 (Downskin of Vane)	150 μm	13.28	18.46	39%
R2 (Upskin of Vane)	50 μm	16.83	20.07	19%
R3 (Vertical Annulus)	100 μm	8.84	11.70	32%
R4 (Centerbody tip)	50 μm	0.77	0.89	14%

The flame location can be measured from the iso-contours of temperature or mole fractions of intermediate radicals such as CH, OH, and CH_2O. In Figure 3, the surface roughness effects can be compared with the change in iso-contour of 1000 K flame temperature, where maximum flame temperature for the fuel composition is ~1835 K. The onset of the preheat zone is marked

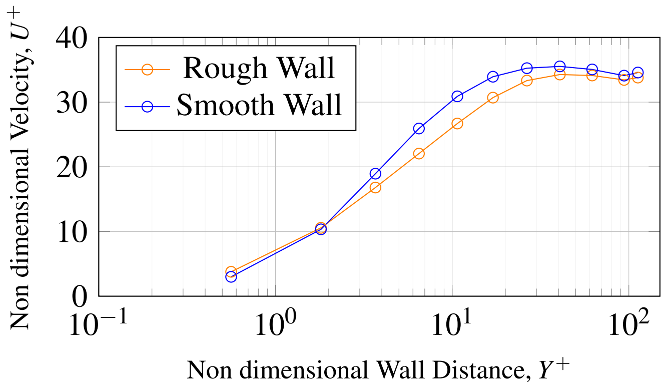

Figure 2: Law of the wall comparison for rough vs. smooth wall in the vertical region of the injector.

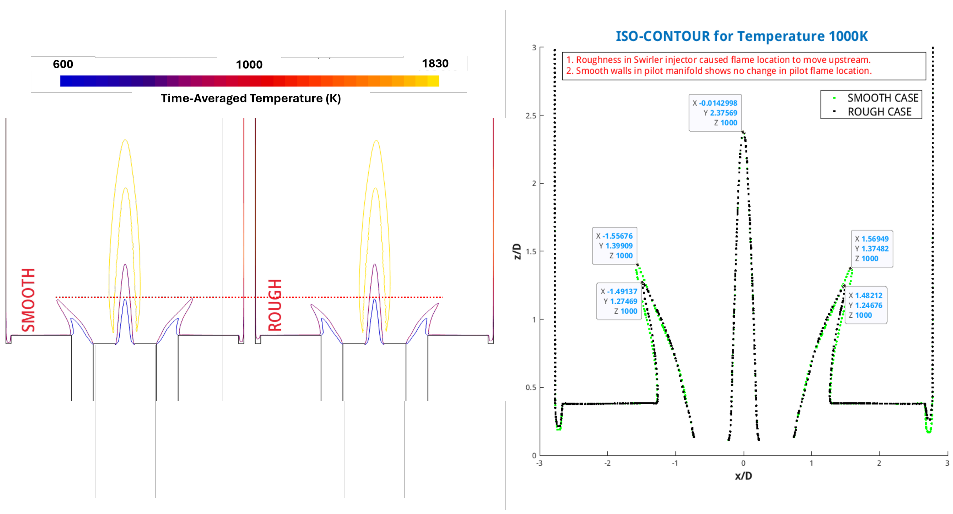

Figure 3: (a) Temperature iso-contours of flame shape, and (b) 1000 K iso-contour represents change in flame location due to roughness.

by 600 K. The flame location moves upstream by $\sim$ (0.087, 0.128) non-dimensional units in (x, z) direction respectively due to wall roughness.

4. Conclusions and Future work

This study showed that surface roughness can change flame stabilization and thereby increase flame flashback propensity compared to smooth walls. Realistic and selective definition of surface quality must be considered during injector design and validation. The role of appropriate sand-grain roughess scaling of absolute roughness is important for true surface quality evaluation. However, further investigation is required at equivalence ratio and fuel composition sweeps to characterize the overall operability performance affected from realistic surface roughness in the injector modeling. The same must be studied using high-pedigree turbulence models for capturing change in turbulence intensity due to rough walls. Roughness attributes of various post-processing technique such as abrasive flow machining [10] could be further explored to quantify critical wall velocity gradient, g_c in establishing AM tolerances in injector static stability limits.

5. Acknowledgments

This research was funded by the U.S. Department of Energy Grant DE-FE0031806 and Solar Turbines Incorporated. Computations were performed on the ICDS-HPC system at Penn State.

References

[1] Y. Huang and V. Yang, Effect of swirl on combustion dynamics in a lean-premixed swirl-stabilized combustor, Proceedings of the Combustion Institute 30 (2005) 1775–1782. DOI: 10.1016/J.PROCI.2004.08.237.

[2] J. C. Snyder and K. A. Thole, Understanding laser powder bed fusion surface roughness, Journal of Manufacturing Science and Engineering, Transactions of the ASME 142 (2020), DOI: 10.1115/1.4046504/1074958.

[3] X. Kalantarid and X. X. Mcdonelld, Boundary layer flashback of non-swirling premixed flames: Mechanisms, fundamental research, and recent advances, (2017), DOI: 10.1016/j.pecs.2017.03.001.

[4] C. K. Stimpson, J. C. Snyder, K. A. Thole, and D. Mongillo, Scaling roughness effects on pressure loss and heat transfer of additively manufactured channels, Journal of Turbomachinery 139 (2017), DOI: 10.1115/1.4034555/378795.

[5] T. Adams, C. Grant, and H. Watson, A Simple Algorithm to Relate Measured Surface Roughness to Equivalent Sand-grain Roughness, International Journal of Mechanical Engineering and Mechatronics 1 (2012), DOI: 10.11159/ijmem.2012.008.

[6] J. Weinmeister, Surface Roughness Modeling for Transformational Challenge Reactor Fuel Form, Oak Ridge National Laboratory, United States, (2021), URL: https://www.osti.gov/biblio/1838983.

[7] S. Altland, H. H. Xu, X. I. Yang, and R. Kunz, Modeling of Cube Array Roughness: RANS, Large Eddy Simulation, and Direct Numerical Simulation, Journal of Fluids Engineering, Transactions of the ASME 144 (2022), DOI: 10.1115/1.4053611/1131505.

[8] S. Ding, K. Huang, Y. Han, and D. Valiev, Numerical study of the influence of wall roughness on laminar boundary layer flashback, PHYSICAL REVIEW FLUIDS 6 (2021) 23201. DOI: 10.1103/PhysRevFluids.6.023201.

[9] J. Li, H. Kwon, D. Seksinsky, D. Doleiden, J. O'Connor, Y. Xuan, M. Akiki, and J. Blust, Describing the Mechanism of Instability Suppression Using a Central Pilot Flame With Coupled Experiments and Simulations, Journal of Engineering for Gas Turbines and Power 144 (2022), DOI: 10.1115/1.4052384.

[10] S. Jalui, T. Spurgeon, E. Jacobs, A. Chatterjee, T. Stecko, and G. Manogharan, Abrasive Flow Machining of Additively Manufactured Titanium: Thin Walls and Internal Channels, (2021), DOI: 10.26153/TSW/17674.