

Rubbing-Induced Metal Ignition in Oxygen-Rich Turbomachinery

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Abstract

Blade-tip clearance and turbine operating temperature are critical efficiency parameters in turbomachinery design. Smaller clearances reduce tip leakage, but increase blade-to-casing rub risk. Higher temperatures improve thermal efficiency and generate more turbine power, but reduce margin to material limits. In conventional turbomachinery, tip rubs are generally treated as wear, vibration, or frictional-heating problems. Oxygen-rich turbopumps add a more severe hazard: a high-speed tip rub may remove protective oxides, heat the underlying metal, and initiate oxidation-driven thermal runaway (i.e., a metal fire), causing catastrophic turbopump damage and engine failure.

The present work demonstrates a numerical model for predicting frictional heat-flux and rub-duration combinations that produce bounded heating, melt-limited damage, or oxidation-driven runaway. Ignition is controlled by the spatially resolved thermal state produced by the entire rub temporal history. The post-rub thermal trajectory is identified as the ignition discriminator rather than a prescribed temperature threshold. The results of these ignition tests allow component-level assessment of ignition events, which can subsequently be related to design criteria such as interference or contact pressure through separate contact models, and then mitigations can be tailored to the system to reduce the risk of ignition.

The model provides a physics-based means of comparing component designs and operating conditions, identifying local ignition hotspots, and targeting design changes before hardware testing. More broadly, it establishes a computational approach for relating transient blade-casing rub severity to ignition margin in high-performance oxygen-rich turbomachinery.

Keywords: Frictional ignition; oxygen-rich turbomachinery; turbopump; turbine blade damage; frictional heating; thermal damage; ignition-margin; transient heat transfer; moving heat sources; heat partitioning

Introduction

Oxygen-rich turbomachinery in full-flow staged-combustion engines must provide high power and efficiency while maintaining adequate margin to material damage and ignition. Reduced blade-tip clearance and increased turbine operating temperature are two levers that improve engine performance, but both reduce margin to rub-induced damage. Smaller clearances decrease leakage losses while increasing the likelihood of blade-casing contact, and higher temperatures increase work extracted from the turbine while bringing structural materials closer to thermal and mechanical limits.

In conventional turbomachinery, such rubs are typically treated as problems of wear, vibration, contact loading, or incidental frictional heating. In an oxygen-rich turbine, however, the same event can become an ignition hazard: friction may disrupt protective surface oxides, rapidly heat the exposed metal, and initiate oxidation whose heat release further accelerates the local temperature rise.

The resulting risk depends on material properties, the transient rub history and the local pressure, temperature, and convective environment.

While previous assessments relied on simplified models or hardware tests, this work develops a component-resolved COMSOL framework, combining CFD-derived aerothermal conditions with transient frictional heating, conjugate blade-casing heat transfer, and oxidation. Representative sustained-blade and periodic-casing rub histories are examined to identify the thermal mechanisms leading to bounded heating, melting, or oxidation-driven runaway. With these results, we assess the margin to ignition and identify factors that influence local ignition behavior.

Numerical Model and Simulation Methods

Model Geometry, Operating Conditions, and Material Properties

The turbine geometry is illustrated in Figure 1, and is derived from the oxygen-side turbopump of a full-flow staged combustion engine. The relevant operating conditions are summarized in Table 1.

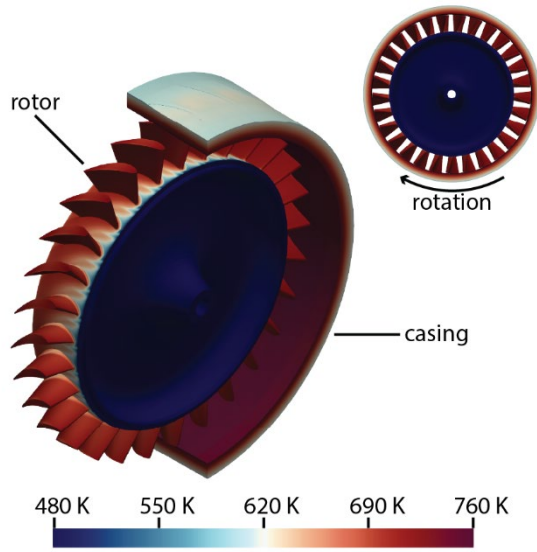


Figure 1. Cutaway of initial rotor and casing temperature field, $T_0(\mathbf{x})$, at rated power.

Table 1: Rotor and Aerothermal Conditions

Quantity	Value/Range
Blade Count	29
Rotor Speed	25,000 rpm
Blade Tip Radius	97.12 mm
Blade Tip Speed	254.3 m s ⁻¹
Blade Pass Period	82.76 μ s
Solid Temperature	~760 K
Heat Transfer Coefficient	50 - 300 (blade) 5 - 400 (casing) kW m ⁻² K ⁻¹
Oxygen Partial Pressure	17 - 50 MPa
Gas Temperature	660 - 810 K

The blade and casing are represented using a user-defined material for Inconel 718. Because heating from rubs may span the entire range from steady operating temperature to near-melting conditions, the temperature-dependent density ($\rho(T)$), heat capacity at constant pressure ($c_p(T)$), and thermal conductivity ($k(T)$) are derived from references [9] and [10]. These properties are extrapolated between the last reported data point and the melting temperature, and representative values at 298 K and 1400 K are shown in Table 2. The spatially-varying initial solid temperatures ($T_0(\mathbf{x})$) and gas-side oxygen pressure ($p_{O_2}(\mathbf{x})$), temperature ($T_g(\mathbf{x})$), and heat-transfer coefficient fields ($h(\mathbf{x})$) are imported from a separately computed high-fidelity CFD operating point using COMSOL interpolation functions fixed to the blade frame. The fields therefore stay fixed during continuous rub scenario and rotate during the periodic rub scenario. Blade-tip and blade-shank data are mapped as separate interpolation functions on individual boundaries to preserve rapidly changing properties near the tip, as the field morphology influences ignition behavior.

Rubs occur on time scales several orders of magnitude shorter than the engine operating transients (10^{-3} s vs. 1 s), and the heated contact region represents a small perturbation to the total turbine enthalpy flow. The CFD fields are therefore held fixed during each rub. This one-way coupling neglects modification of the local boundary layer by extreme surface heating.

CFD Solution and Aerothermal Environment

The spatially-varying $T_0(\mathbf{x})$, $p_{O_2}(\mathbf{x})$, $T_g(\mathbf{x})$, and $h(\mathbf{x})$ fields for both the blade and the casing are imported from the CFD solution at its steady-state, full-power operating point. $h(\mathbf{x})$ was calculated from the CFD thermodynamic data using the process given in [11]. Figure 2 illustrates the extreme variation in $h(\mathbf{x})$ across the surface of the blade and casing, and its range is described in Table 1. Only the distribution of $h(\mathbf{x})$ will be shown in this section; the variation in gas temperature and pressure across these surfaces are less severe.

$h(\mathbf{x})$ sharply increases under the trailing edge and then falls off rapidly until the next blade approaches. This initially high $h(\mathbf{x})$ can quickly quench a hotspot as the blade leaves a point, but if the thermal state remains sufficiently hot, oxidation can quickly start to dominate and accelerate towards thermal runaway.

Simpler approximations for these fields fail to capture their rapid spatial variation. This resolution is critical for ignition prediction: the highest $h(\mathbf{x})$ occurs very nearly where the highest temperature from a rub would occur.

Heat Transfer and Rub Sequencing

The transient heat equation, given below, governs the flow of heat between bodies in sliding contact and accounts for their relative motion [1].

$$\rho(T)c_p(T) \left(\frac{\partial T}{\partial t} + \mathbf{u} \cdot \nabla T \right) = \nabla \cdot [k(T) \nabla T] + Q \quad (1)$$

The time-dependent Heat Transfer in Solids interface solves this equation.

We apply a different treatment to relative motion in each limiting case. For the continuous-rub case, the reference frame is fixed to the blade, so casing motion is represented using Solid with Translational Motion. For the periodic-rub case, the casing is fixed and each blade is advanced using a Moving Mesh–Rotating Domain feature.

Periodic rubs are represented using three virtual blades, the minimum number required to span the 27° rub region. When a blade exits this region, an Events interface simultaneously resets temperature field with an explicit event while switching the active Moving Mesh–Rotating Domain feature for that blade in the model, recycling it into the next open blade-pitch position.

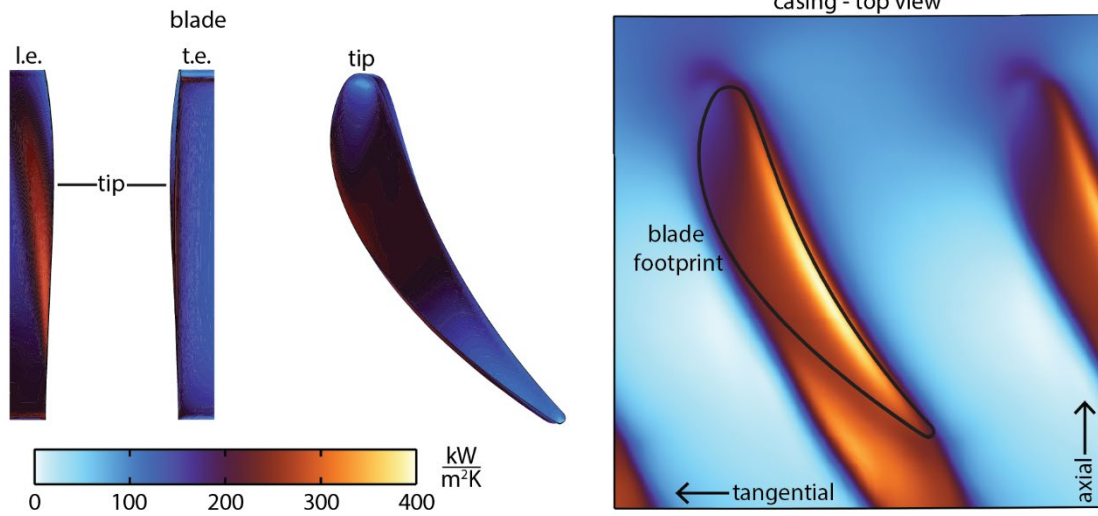


Figure 2. Spatial distribution of heat-transfer coefficient in the vicinity of the blade leading edge, trailing edge, and tip (left) and across the casing (right) with superimposed blade footprint.

Separate cooldown calculations showed that for both limiting cases, even a near-melting component returns close to its initial thermal state after one rotational period elapses.

Interfacial Frictional Heating

The frictional heat flux, q''_{fric} , is derived from the classical tribological treatment.

$$q''_{fric} = \mu P v_{tip} \quad (2)$$

Sliding contact generates a frictional heat flux which cannot be divided between the two bodies with constant scalar partition: it varies across both time and the interface [1]. Under ideal thermal contact, the interface must satisfy the local constraints of Equations 3 and 4 [2], [3].

$$T_1(\mathbf{x}, t) = T_2(\mathbf{x}, t) \text{ for } \mathbf{x} \in \Gamma_{int} \quad (3)$$

$$q''_1(\mathbf{x}, t) + q''_2(\mathbf{x}, t) = q''_{fric}(\mathbf{x}, t) \quad (4)$$

Full-speed SSME rub studies observed discrete blade-casing contact over finite circumferential arcs and represented the tangential rub force using a half-sine distribution over the contact interval. This kinematic description motivates the treatment of the position-dependent friction flux for periodic rubs evaluated in the present work [4].

The friction flux is treated differently in each limiting case. In the continuous rub scenario, q''_{fric} is maintained at its maximum value. For the periodic rub scenario, we choose the half-sine forcing function of reference [4], shown below, to represent q''_{fric} . We take $\theta_{rub}=27^\circ$, corresponding to the upper end of the reported rub arcs. Blade vibration is not solved; consequently, the imposed peak heat flux remains constant from rub to rub.

$$q''_{fric} = \begin{cases} q''_{fric,max} \cos\left(\frac{\pi\Delta\theta}{\theta_{rub}}\right), & |\Delta\theta| \leq \frac{\theta_{rub}}{2} \\ 0, & |\Delta\theta| > \frac{\theta_{rub}}{2} \end{cases} \quad (5)$$

Each blade tip and casing surface form a Contact Pair, with a Continuity feature applied using classical weak constraints to enforce Equations 3 and 4. A paired Boundary Heat Source then supplies q''_{fric} to the contact pair. This follows the framework developed in [2] and [3], and produces a spatially and temporally varying temperature and partition field.

Although the prescribed frictional heat fluxes are large, they correspond to plausible local contact pressures because of the high blade-tip speed. At the nominal blade tip speed, Equation 2 gives interfacial pressures of approximately 7.9 MPa and 29.5 MPa for fluxes of 0.4 and 1.5 GWm^{-2} , respectively, using $\mu=0.2$. Garcia Jimenez measured IN718 ignition at a contact pressure of 7.7 MPa during slower sliding experiments, with the friction coefficient decreasing from approximately 0.1 to 0.045 as a lubricating tribolayer developed [5]. Reference [4] provides a complementary high-speed comparison. The SSME rub tests used a nominal 2.54 micron tip incursion for each test, and inferred a 0.5 kN normal force for $\mu=0.2$. This force reproduced the 53.9 MPa peak stress in the blade shank calculated from the maximum strain measured during testing. At the SSME's nominal tip speed of 498 m/s, this corresponds to a peak frictional power of 50.5 kW. The full blade-tip area is estimated from published SSME turbopump geometry as approximately 47 mm^2 . Distributing this power over the entire blade tip results in a frictional heat flux of 1.1 GWm^{-2} ; nonuniform contact, like that identified in post-test inspections, would produce larger local values. The results of these experiments support the use of the local heat flux levels we prescribe.

Gas-Side Boundary Conditions

Exposed surface boundary conditions are modeled as

$$q''_{surf} = q''_{conv} + q''_{ox} \quad (6)$$

Convective and oxidative heat fluxes are applied only to gas-exposed surfaces and are described by Equations 7 and 8, respectively. Radiative cooling is neglected because it remains small relative to convective heat transfer over the temperature range considered.

$$q''_{conv} = h(x)[T_{gas}(x) - T_{solid}] \quad (7)$$

$$q''_{ox} = \frac{H_{ox}\beta\alpha P_g}{\sqrt{2\pi M_{O_2} RT_{gas}}} e^{-\frac{Q_{ad}}{RT}} \quad (8)$$

Rubbing is conservatively assumed to expose hot, reactive metal to an oxidizing environment and oxidation initially generates heat according to the above Hertz–Knudsen formulation [5]. Classical thermal-explosion theory describes ignition as loss of a stable balance between heat generation and removal [6], [7]; accordingly, the present transient model classifies the post-rub thermal state by whether it decays or progresses toward oxidation-driven runaway [8].

For this demonstration, the activation energy, Q_{ad} , is taken as 75 kJ/mol as illustrative lower bound selected from the range referred to in reference [5], and we use Garcia Jimenez’s reported H_{ox} , β , and α values for Inconel 718, shown in Table 2. Sensitivity to oxidation kinetics is reserved for future work.

Table 2: Inconel 718 Material Properties

Quantity	Value/Range (298-1400K)
Density	8193 - 7712 kg m ⁻³
Heat Capacity	425 - 634 J kg ⁻¹ K ⁻¹
Thermal Conductivity	9.9 - 25.3 W m ⁻¹ K ⁻¹
Melting Temperature	1609 K
Oxidation Enthalpy (H_{ox})	355 kJ mol ⁻¹
Metal-O ₂ Molar Ratio (β)	1.56
Sticking Coefficient (α)	1

Additionally, thermally remote hub and casing boundaries are truncated and treated as adiabatic; domain-size sensitivity confirmed that the resulting boundaries do not materially alter hotspot temperatures.

Ignition and Damage Criteria

A two-stage assessment classifies the thermal state produced by each rub event.

Rub Stage: a rub is applied and the temperature fields are systematically stored at intervals until one of four outcomes occurs: (1) oxidation-driven runaway in the blade shank above the contact region; (2) runaway in casing material after it exits the contact region; (3) melting of either component; or (4) a quasi-steady state without runaway or melting.

Non-contact Ignition Test Stage: Each selected stored thermal state during the rub stage is used as

the initial condition to test ignition. Blade-casing contact ceases and the frictional heat flux is removed, exposing the interfacial surfaces to convection and oxidation. The resulting trajectory from this initial state has two outcomes: (1) ignition or (2) stability.

Simulation Results and Discussion

Continuous Blade Rub

We first examine the behavior of a blade that undergoes a sustained rub with a net friction flux of 1.5 GW/m². A snapshot of the setup, taken from early in the rub, is illustrated in Figure 3.

For a sustained rub, we see in Figure 4 that the temperature at the evaluated point quickly rises to its peak. This evaluated point lies just upstream of the trailing edge, near the liftoff hotspot shown in Figure 6. Its interfacial temperature rises rapidly during sustained contact. We also observe that the transient rapidly changes throughout the whole rub. As time progresses, the routing of heat to each point on the surface varies due to the constraints of Equations 3 and 4, reducing the heat flow to the blade, as seen in the lower panel of Figure 4. Each point along the interface has its own time-dependent partition, rapidly redistributing heat and creating localized effects that build a thermal history in the blade

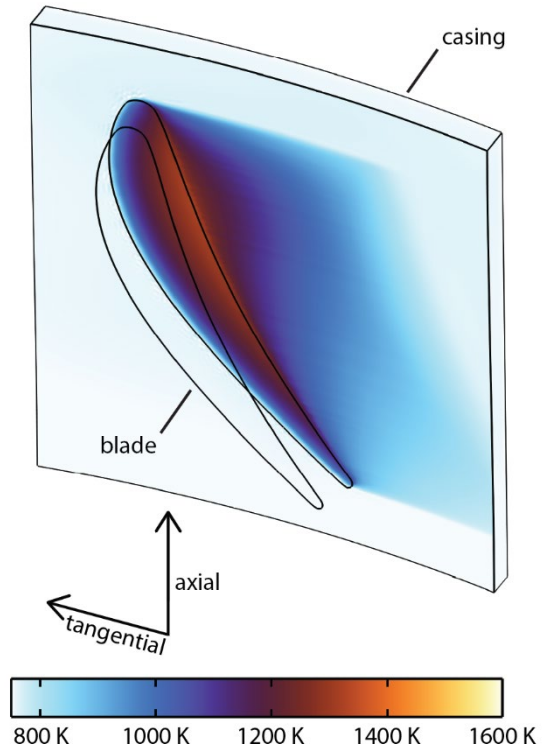


Figure 3. Blade (outline) undergoing a rub sustained for 70μs against casing (shown) with $q_{fric}=1.5$ GW/m².

This thermal trajectory is important: the combined effects of conduction (a time dependent thermal process) and convection (a surface state driven process) compete with oxidation at the surface to determine if ignition occurs.

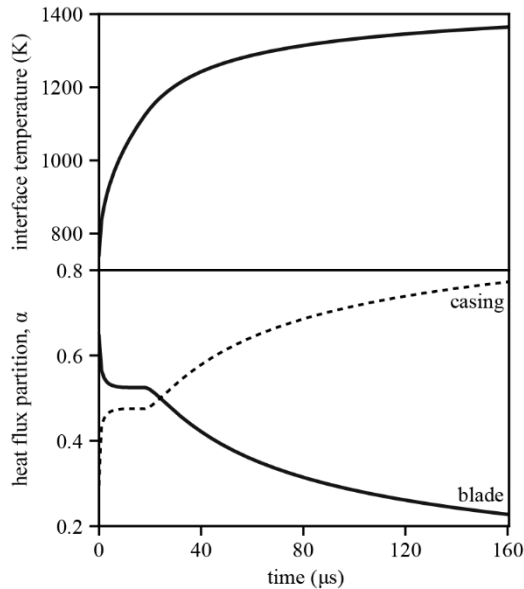


Figure 4. Interfacial temperature trajectory (upper) and transient local heat flux partition (lower) resulting from a sustained rub with $q_{fric}=1.5 \text{ GW/m}^2$. The examined point is upstream of the trailing edge, located where a tip lift results in ignition.

Additionally, as rub is sustained, heat diffuses along blade and towards the rotor hub. Eventually, the blade may heat sufficiently to reach an ignitable state at a spot away from the interface and above the trailing edge, due to the sharply falling heat transfer coefficient. This would likely only occur if the protective oxide tribolayer at that point were actually disrupted, but we observe this effect in the simulations because we treat all gas-exposed surfaces as fully reactive as a conservative assumption: in Figure 4, the blade shank attains thermal runaway at $160 \mu\text{s}$ sufficiently far away from the interface to not visibly heat the trailing edge. We begin to assess the local behavior of the blade tip as it ignites and achieves thermal runaway by again examining a blade that undergoes a $70 \mu\text{s}$ rub. After the blade is exposed to the gas-side conditions, the balance of oxidation, convection, and conduction at each point results in either stability or thermal runaway. In Figure 6, we see the initial temperature field at liftoff. The highest temperature is adjacent to the trailing edge at the broadest location on the blade. As time progresses, we see a broad hotspot develop, oxidize and continue to heat up while the majority of the blade quickly cools. We note that the hottest point at lift-off is no longer the hotspot at runaway:

the combined effects of conduction and convection suppressed heating at the original hotspot, which begins to quench. Importantly, ignition does not occur due to attainment of a surface temperature, but due to development of a thermal history that supports continued oxidative heating with the local boundary conditions. Neither the liftoff temperature nor the initial cooling rate alone determines the outcome; the post-liftoff trajectory must be followed long enough to distinguish quenching from runaway.

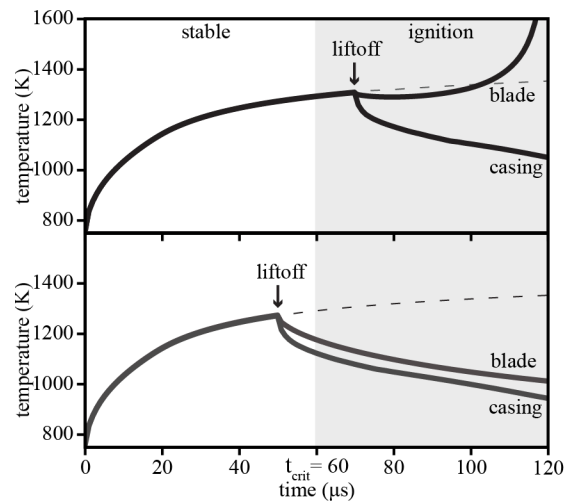


Figure 5. Component temperature trajectories bounding the post-liftoff ignition threshold of a 1.5 GW/m^2 sustained rub, with reference sustained rub given by dotted line.

Periodic Casing Rub

In this section, we demonstrate the ability to predict ignition for the limiting case in which every blade sequentially rubs the same sector of casing. A snapshot from early in the rub sequence is presented in Figure 7.

Each blade initially contributes strongly to the rising surface temperature of the casing, with diminishing returns as time progresses, slowly ratcheting the surface temperature upwards, as shown in Figure 8. At higher temperatures, oxidation has significant effects on the temperature response of the casing, yet the surface has not run away due to strong convective cooling from the rapidly changing $h(\mathbf{x})$. This increased convective flux overpowers oxidation and quenches the casing surface before the next rub. Also, when the casing temperature exceeds the blade temperature, conduction across the interface strongly cools the casing while in contact, an effect predicted in references [2] and [3]. Although the theoretical framework described earlier is well established, the complex interplay of these factors in a real system results in unique insights on how competing factors affect the overall ignition response of the system.

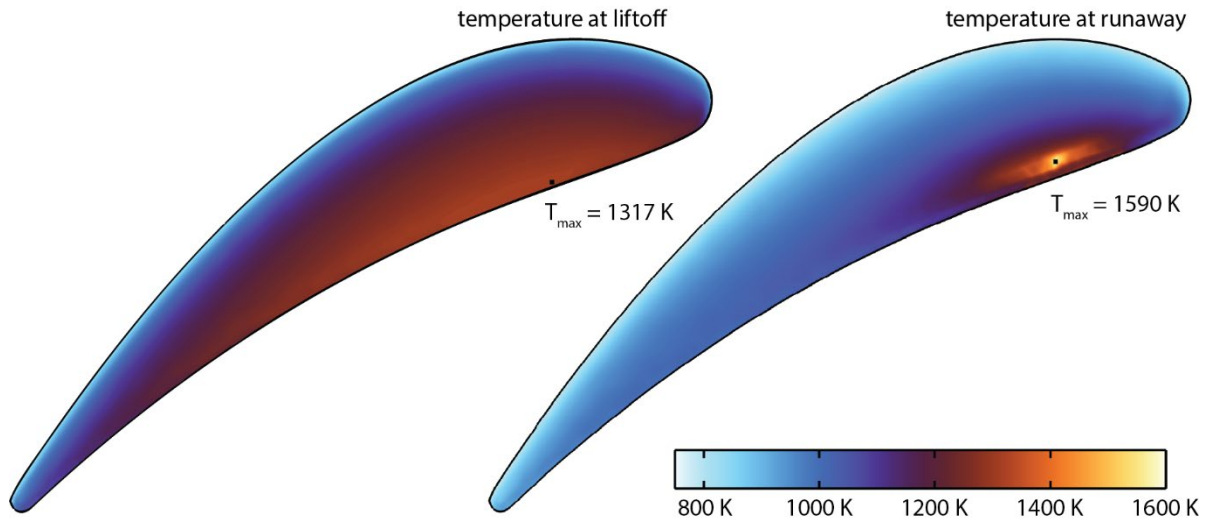


Figure 6. Comparison of blade-tip temperature distribution from lift-off following a $70\mu\text{s}$ rub (left) to a hotspot igniting $47\mu\text{s}$ later (right).

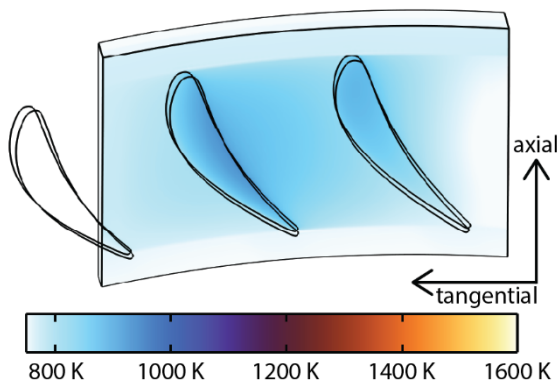


Figure 7. Casing (shown) being struck by sequential blades (outlined) with $q_{\text{fric}}=0.4 \text{ GW/m}^2$.

We see in Figure 8 that ignition in the casing is achieved at a much lower temperature and heat flux in this scenario than in the continuous blade rub scenario, although it requires a much longer time period for thermal runaway conditions to develop.

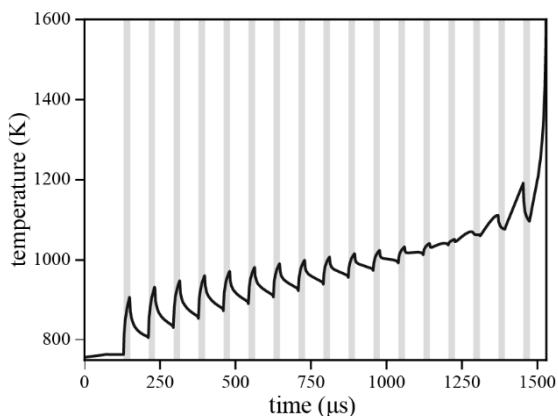


Figure 8. Temperature trajectory of point on casing surface undergoing oxidation-driven thermal runaway after seventeen rubs with $q_{\text{fric}}=0.4 \text{ GW/m}^2$.

This difference in behavior between the two limiting cases is due to the hottest spot that develops on the casing being exposed to a much lower $h(\mathbf{x})$ than the hottest point on the blade tip, for a transient once per blade pass. We see this local effect in Figure 9, where there is a broad hotspot that covers the majority of the blade's footprint. Interestingly, this hotspot does not occur where $h(\mathbf{x})$ achieves its minimum value, and it is also not located where the maximum heat flux along the rub arc is. It occurs where the thermal history and local boundary conditions combine to reach a state that supports ignition.

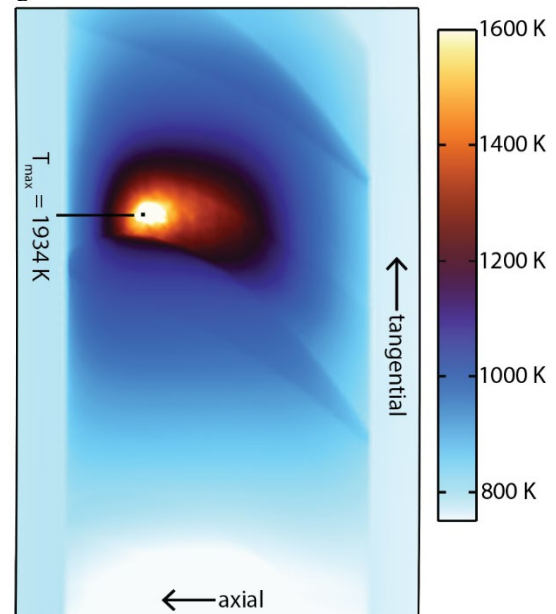


Figure 9. Temperature distribution on casing surface undergoing oxidation-driven thermal runaway after seventeen rubs with a peak frictional flux of 0.4 GW/m^2 .

Conclusions

A coupled COMSOL framework was developed to predict rub-induced ignition in oxygen-rich turbomachinery using spatially resolved aerothermal boundary conditions, transient conjugate blade-casing heat transfer, and oxidation.

For a representative sustained rub at a frictional flux of 1.5 GW/m^2 , post-liftoff calculations distinguish a stable $50 \text{ }\mu\text{s}$ rub from an igniting $70 \text{ }\mu\text{s}$ rub. For periodic casing rubbing under a peak frictional flux of 0.4 GW/m^2 , seventeen rubs slowly built up a thermal history that resulted in eventual thermal runaway. We demonstrated how to identify thermal runaway and rub-induced damage during a prescribed rub history. We plan to continue using this technique in future work to explore the design space and search for specific ways to provide protective effects and mitigate the risk of frictional ignition in oxygen-rich turbomachinery.

These results provide a component-level method that correlates frictional-rub severity to ignition margin and identifies local aerothermal conditions that control failure.

References

- [1] T. C. Kennedy, C. Plengsaard and R. F. Harder, "Transient heat partition factor for a sliding railcar wheel," *Wear*, vol. 261, no. 7-8, pp. 932-936, 2006.
- [2] R. Bosman and M. B. de Rooij, "Transient Thermal Effects and Heat Partition in Sliding Contacts," *Journal of Tribology*, vol. 132, no. 2, p. 021401, 2010.
- [3] J. Bos and H. Moes, "Frictional Heating of Tribological Contacts," *Journal of Tribology*, vol. 117, pp. 171-177, 1995.
- [4] G. A. Davis and R. C. Clough, "Blade Tip Rubbing Stress Prediction Final Report," Rockwell International, Rocketdyne Division, 1991.
- [5] A. Garcia Jimenez, "Tribochemistry of Frictional Ignition in High Pressure Oxygen," Massachusetts Institute of Technology, Cambridge, 2025.
- [6] N. N. Semenov, "Zur Theorie des Verbrennungsprozesses," *Zeitschrift für Physik*, vol. 48, pp. 571-582, 1928.
- [7] T. Boddington, C.-G. Feng and P. Gray, "Thermal Explosions, Criticality and the Disappearance of Criticality in Systems with Distributed Temperatures. I. Arbitrary Biot Number and General Reaction-Rate Laws," *Proc R Soc Lond A Math Phys Sci*, vol. 390, no. 1799, pp. 247-264, 1983.
- [8] I. Idris and V. N. Biktashev, "Analytical Approach to Initiation of Propagating Fronts," *Physical Review Letters*, vol. 101, p. 244101, 2008.
- [9] G. Pottlacher, H. Hosaeus, E. Kaschnitz and A. Seifert, "Thermophysical properties of solid and liquid Inconel 718 Alloy," *Scandinavian Journal of Metallurgy*, vol. 31, no. 3, pp. 161-168, 2002.
- [10] A. Sh. Agazhanov, D. A. Samoshkin and Yu. M., "Thermophysical properties of Inconel 718 alloy," in *XXXV Siberian Thermophysical Seminar*, Novosibirsk Akademgorodok, 2019.
- [11] C. M. Mazzoni, S. Luque and B. Rosic, "Capabilities of Thermal Wall Functions to Predict Heat Transfer on the NGVs of a Gas Turbine With Multiple Can Combustors," in *ASME Turbo Expo 2015: Turbine Technical Conference and Exposition*, Montreal, 2015.

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