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# On flames established with air jet in cross flow of fuel-rich combustion products

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## HIGHLIGHTS

- Modeled inverse diffusion flames in fuel-rich combustion products.
- Reacting flow associated with jet-in-cross-flow environment is simulated using a detailed chemical kinetics.
- Predicted the unusual flame movement when the blowing ratio or equivalence ratio was increased.
- Hydrogen in the cracked fuel products causes non-intuitive flame behavior due to preferential diffusion.

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## ABSTRACT

Advances in combustor technologies are driving aircraft gas turbine engines to operate at higher pressures, temperatures and equivalence ratios. A viable approach for protecting the combustor from the high-temperature environment is to inject air through the holes drilled on the surfaces. However, it is possible that the air intended for cooling purposes may react with fuel-rich combustion products and may increase heat flux. Air Force Research Laboratory (AFRL) has developed an experimental rig for studying the flames formed between the injected cold air and the cross flow of combustion products. Laser-based OH measurements revealed an upstream shift for the flames when the air injection velocity was increased and downstream shift when the fuel content in the cross flow was increased. As conventional understanding of the flame stability does not explain such shifts in flame anchoring location, a time-dependent, detailed-chemistry computational-fluid-dynamics model is used for identifying the mechanisms that are responsible. Combustion of propane fuel with air is modeled using a chemical-kinetics mechanism involving 52 species and 544 reactions. Calculations reveled that the flames in the film-cooling experiment are formed through autoignition process. Simulations have reproduced the various flame characteristics observed in the experiments. Numerical results are used for explaining the non-intuitive shifts in flame anchoring location to the changes in blowing ratio and equivalence ratio. The higher diffusive mass transfer rate of hydrogen in comparison to the local heat transport enhances $H_2$–$O_2$ mixing compared to thermal dissipation rate, which, in turn, affects the autoignition process. While increasing the blowing ratio abates the differences resulting from non-equal mass and heat transport rates, higher concentrations of hydrogen in the fuel-rich cross flows accelerate those differences.

## 1. Introduction

Efforts continue to be made to make gas turbine engines smaller, more efficient and operate with reduced environmental impact. Studies [1] have indicated that reheating of the combustion products between the high- and low-pressure turbine stages in a gas turbine engine could improve the specific thrust by as much as 50%. However, as a conventional combustor is too large to be incorporated for generating the extra heat between the two turbine stages, new technologies such as Ultra Compact Combustor (UCC) are being developed. The UCC reduces the length of the system by integrating turbine turning vanes within the combustor [2,3] and incorporating trapped-vortex concepts [4,5]. One challenge to developing UCC technology is providing adequate cooling

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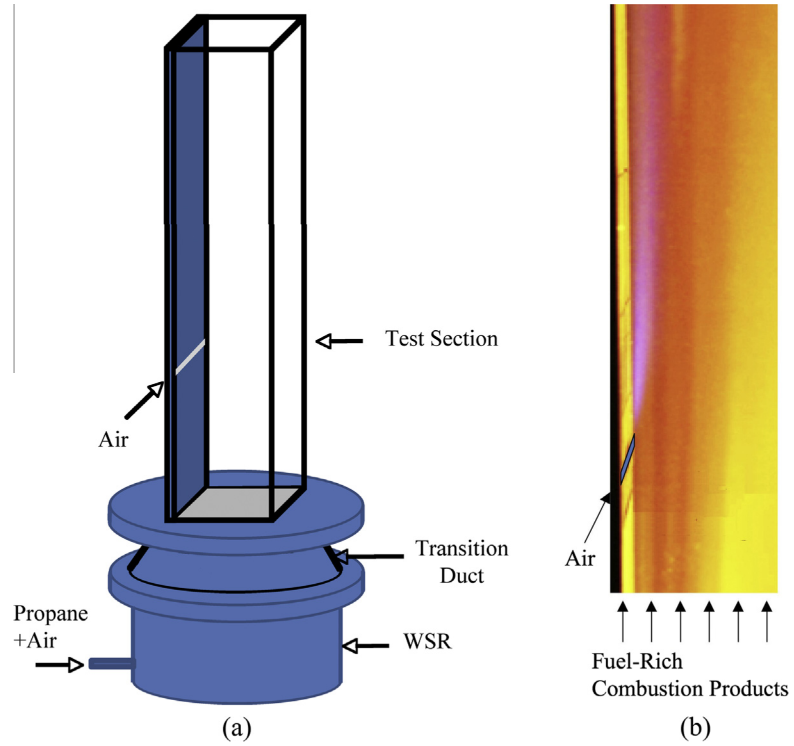

**Fig. 1.** (a) Schematic diagram of AFRL test rig, (b) direct photograph of the flame formed in the test section.

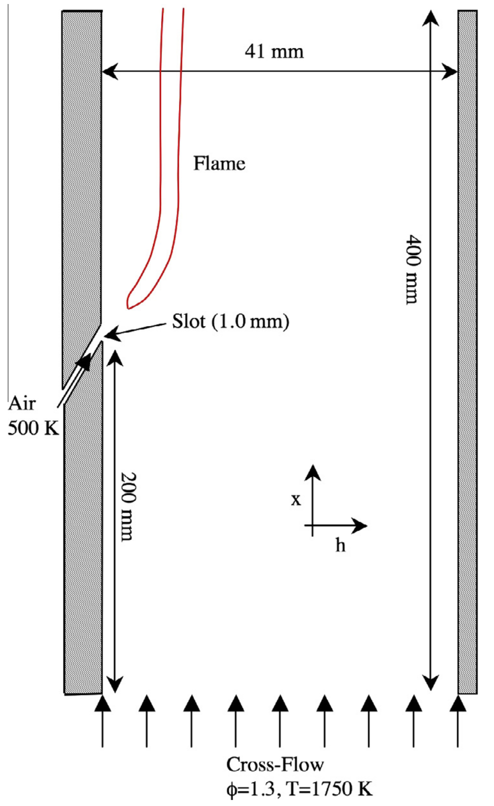

**Fig. 2.** Two-dimensional view of the test section of AFRL test rig. Left sidewall upstream of the slot is water cooled in the experiment.

for the vanes. A strategy for cooling the surface of vanes is to inject air through the perforations (holes). However, because portions of the vanes are exposed to fuel-rich combustion products there is a potential that the air supplied for cooling may actually react. Hence improperly designed air-cooling may actually increase heat flux to the surfaces. Irrespective of UCC technology, the motivation for increasing cycle efficiency is also pushing the combustors to operate at overall equivalence ratio closer to unity. This increases the opportunity for unburned fuel from the combustor to pass into the turbine section where air intended for cooling may cause flames to form. Reactions near the surfaces can increase temperatures-effectively deteriorating the cooling efficiencies obtained through injecting air [6,7].

Research studying reactions between film-cooling air and incomplete combustion products has typically been limited to quantifying increase in temperature or change in the heat flux near the surfaces [6–9]. For example, studies of Polanka et al. [6] and Kirk et al. [9] compared the heat fluxes resulted from the reacting and nonreacting environments for a range of freestream equivalence ratios and cooling-hole geometries. On the other hand, characterization of the reacting flow (for example, identification of flame and extinction zones) is also needed to help understand the causes for changes in measured heat flux and to help in applying the laboratory findings to practical systems. Two exceptions are the work of Polanka et al. [6] and Lin et al. [10] who performed CFD calculations using two-step reaction scheme. The reaction zone distribution for varying equivalence ratios and freestream conditions was reported. Such studies must be enhanced with measurements and calculations made with detailed chemical

**Table 1**
Cross-flow description.

| $\phi$ | $T$ (K) | $X_{H2}$ | $X_{CO}$ | $X_{CO2}$ | $X_{H2O}$ | $X_{N2}$ |
|---|---|---|---|---|---|---|
| 1.3 | 1750 | 0.0333 | 0.0731 | 0.0664 | 0.1521 | 0.675 |
| 1.4 | 1720 | 0.0488 | 0.0899 | 0.0567 | 0.1463 | 0.658 |
| 1.5 | 1670 | 0.0654 | 0.1040 | 0.0492 | 0.1388 | 0.642 |
| 1.6 | 1630 | 0.0999 | 0.1269 | 0.0390 | 0.1211 | 0.613 |