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Research Paper

Investigation of isothermal convective heat transfer in an optical combustor with a low-emissions swirl fuel nozzle

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HIGHLIGHTS

- Infrared thermography through fused silica with correction for three dimensional heat losses.
- Combustor isothermal convective heat transfer for Reynolds numbers up to 138,000.
- Approximately constant augmentation with respect to fully developed pipe flow observed.
- Realizable k-ε model calculations with an average discrepancy of 13% with experiments.
- Comparison with other studies is presented and relevant geometrical effects discussed.

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ABSTRACT

Modern combustor design optimization is contingent on the accurate characterization of the combustor flame side heat loads. The present work focuses on the experimental measurement of the isothermal (non-reacting) convective heat transfer along a fused silica optical can combustor liner for Reynolds numbers ranging between 11,500 and 138,000. The model combustor was equipped with the SoLoNOx swirl fuel nozzle from Solar Turbines Incorporated, subjecting the liner walls to realistic isothermal flow and turbulence fields. Infrared (IR) imaging through fused silica was demonstrated, and a novel estimation of the three-dimensional conduction heat losses for steady state constant heat flux experiments was developed. A maximum heat transfer augmentation of ~18 was observed with respect to fully developed turbulent pipe flow correlations. Contrary to other investigations, the augmentation magnitude and distribution are shown to be approximately constant with Reynolds number (particularly away from the impingement location). Particle Image Velocimetry (PIV) was included to support the heat transfer measurements, suggesting that peak heat transfer occurred 0.12 nozzle diameters upstream of the jet reattachment point along the liner. Reynolds-Averaged Navier Stokes (RANS) computations are shown to yield peak heat transfer predictions within 17.4% of the experimental results when using the realizable k-ε turbulence model and enhanced wall treatment. The measurements were further analyzed in the context of results from other heat transfer studies on gas turbine combustors.

1. Introduction

The continued development of gas turbine engines for improved efficiency and performance requires operating at higher turbine inlet temperatures, while simultaneously avoiding any increase in pollutant emissions or failure of the components exposed to the hot gas path. To improve efficiency, modern gas turbines operate at increasingly higher compression ratios, thus increasing the air temperature at the inlet to the combustion system and reducing its cooling potential. To limit the production of NO_x, combustors burn at lean equivalence ratios, which in turn demands excess air in the fuel-air mixture and further decreases the amount of air available for cooling. Modern combustor liners moreover limit the use of film cooling, to prevent quenching of the intermediate combustion products and the subsequent formation of unburned hydrocarbons and carbon monoxide near the walls. For these reasons, thermal management has become a critical aspect during the design phase of gas turbine combustors. In order to optimize coolant utilization, detailed heat transfer data

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Nomenclature

A	area [m^2]
a	absorptance
B_λ	spectral radiance from Planck's Law [$W\,m^{-3}\,sr^{-1}$]
c	speed of light [299,792,458 $m\,s^{-1}$]
D	diameter [m]
f	frequency [Hz]
h	heat transfer coefficient [$W\,m^{-2}\,K^{-1}$]
h_P	Planck's constant [$6.62607004 \times 10^{-34} m^2\,kg/s$]
K	absorption coefficient
k	conductivity
K_B	Boltzmann constant [$1.38064852 \times 10^{-23}\,J\,K^{-1}$]
L	thickness of the quartz liner [4 mm]/reference length or direction [m]
Nu	Nusselt number
P	power [W]
P_4	pressure at the combustor outlet
P_3	pressure at the combustor inlet
Pr	Prandtl number
Q	heat rate [W]
Q''	heat flux [$W\,m^{-2}$]
R	radiance [$W\,m^{-2}\,sr^{-1}$]
R_Ω	resistance [Ω]
Re	Reynolds number
T	temperature
t	transmittance
V	voltage [Volts]
α	thermal diffusivity [$m^2\,s^{-1}$]
ϵ	emissivity
λ	wavelength [m]
μ	dynamic viscosity [$kg\,m^{-1}\,s^{-1}$]

Subscripts

C	evaluated with respect to the combustor dimension
F	evaluated at the film temperature
IR	refers to the infrared camera
LOSS	refers to thermal conduction heat losses
N	evaluated with respect to the nozzle dimension
nat	refers to natural convection
Q	refers to the quartz liner
R	radial direction (with respect to the combustor axis)
W	evaluated at the wall or at the wall temperature
X	axial direction (with respect to the combustor)
Y	vertical direction (for a 2D image)
λ	spectral
∞	evaluated at the flow bulk temperature

for gas turbine combustion chambers is required. In particular, information on the convective heat loads is limited, due to the complex flows generated by industrial swirl fuel nozzles and the challenging conditions at which combustors operate.

The first attempts to semi-empirically characterize the heat transfer along the combustor liner walls were carried out by Lefebvre and coworkers [1,2]. The radiative component of the thermal load is relatively well understood [3,4]. For internal convection, Lefebvre and Ballal [1] pointed out that the "uncertainties regarding the airflow pattern, the state of the boundary layer development, and the effective gas temperature make the choice of a realistic model almost arbitrary" [1]. The authors estimated the convective heat transfer according to early correlations for fully developed turbulent pipe flow, arguing that a similar formulation should apply within combustor flows when no film cooling is used. Lefebvre and Ballal [1] suggested Eq. (1) to estimate the convective heat fluxes within combustors.

$$Q''_C = 0.02\, Re_{C,\infty}^{0.8} \frac{k_\infty}{D_C}(T_\infty - T_W) \tag{1}$$

The authors further proposed a reduction of the 0.02 coefficient to 0.017 in the primary zone to account for reduced near wall gas temperatures. Eq. (1) is approximately equivalent to evaluating the Dittus-Boelter heat transfer correlation, given by Eq. (2), with $Pr \approx 0.706$ (air). The gas properties for the Dittus-Boelter equation are typically evaluated at the local film temperature and the exponent n_T is equal to 0.4 for $T_W > T_\infty$ and 0.3 for $T_W < T_\infty$.

$$Nu_{Dittus-Boelter} = 0.023 Re_{C,f}^{0.8} Pr_f^{n_T} \tag{2}$$

The Dittus-Boelter equation is accurate within $10,000 < Re < 120,000$, applicable only for wall to gas temperature differences of no more than 56 K, and cannot properly account for the temperature dependence of the gas properties near the wall [5,6]. Since the time of the work by Lefebvre, there have been significant improvements to turbulent flow heat transfer correlations [7–10] and a more comprehensive understanding of the flow within combustors [11–13]. Work on heat transfer enhancement in swirling flows and sudden expansions has also provided insight that can be applied to understanding convective loads within modern gas turbine burners. Dellenback et al. [14] for instance, worked on the experimental characterization of the heat transfer downstream of a sudden pipe expansion with swirling flow. While their swirl generator was not representative of combustor fuel injectors, it provided important details on the effects of swirl and Reynolds number ($Re_C < 51,000$). The authors showed that increasing the swirl number resulted in larger heat transfer to the wall, and that the location of peak heat transfer consistently occurred upstream of the location of flow reattachment. Similar heat transfer investigations on turbulent decaying swirl flow have also been conducted without the sudden expansion to study the effects of swirl number and type of swirl generator [15]. Work on heat transfer in an abrupt expansion without swirling flow, such as that conducted by Baughn et al. [16], is also partly relevant to combustor flows as it exhibits flow reattachment and the formation of a corner recirculation region.

While combustor cooling technologies have been studied extensively in the open literature [17,18], information on combustor heat loads is lacking. Combustor convective heat transfer has been studied by Ekkad and coworkers for both can [19–21] and annular [22,23] combustor geometries, using approximated swirlers representative of industrial fuel nozzles. The work of these authors included isothermal convective heat transfer measurements supplemented by numerical simulations and flow characterization using particle image velocimetry (PIV). The work by Patil et al. [22] reported Nusselt numbers several times higher than those obtained from the Dittus-Boelter equation, suggesting that the correlation underestimates the convective heat loads within burners. Recent work by Andreini et al. [24] and Lorenzo [25] have also experimentally and computationally studied the isothermal convective heat transfer and flow within combustors using a three swirl nozzle combustor model. Their results include the effects of neighboring nozzles and of the cooling film at the start of the liner. Detailed PIV by the authors provided insight into the interaction between nozzles and the relationship between flow and convective heat transfer.