Applied Thermal Engineering 82 (2015) 30–38

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research paper

Experimental and numerical studies of pressure effects on syngas combustor liner temperature

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HIGHLIGHTS

- The liner temperature of a combustor is studied within pressure range of 0.1–2.0 MPa.
- The liner temperature increases with pressure in rear but deceases in head zones.
- Peak temperature increases and flame is longer and narrower under higher pressure.
- Nu augmentation ratio reduces and tends steady with pressure increase.
- Radiation intensity of the liner tends to be steady under high pressure.

ARTICLE INFO

Article history:
Received 28 September 2014
Accepted 23 February 2015
Available online 28 February 2015

Keywords:
Syngas combustor
Liner temperature
Pressure effects
Diffusion flame structure
Heat transfer

ABSTRACT

Pressure effects on the liner temperature of a syngas model combustor are studied by experimental and numerical methods, with an attempt to analyze the influence mechanism. The model combustor, fueled with 10 MJ/Nm^3 coal-derived syngas, is installed in a pressurized test-rig. Several diffusion flames with thermal powers up to 180 kw at pressures within 0.1–0.35 MPa are studied using a variety of measurement techniques. The liner temperature varies monotonically along the flow direction, and the maximum temperature appears around the dilution holes. Moreover, the liner temperature increases in the dilution zone but decreases in the primary zone with the increase of operating pressure, when the combustor exit temperature is maintained at 1073 K. Then, the combustion behaviors of the model combustor within pressure range of 0.1–2.0 MPa are simulated using CFD method, and the computed liner temperatures of testing cases agree well with the experimental data. The liner temperature varies approximately from −20 K to 150 K depending on locations when the pressure rises from 0.1 MPa to 2.0 MPa. It shows notable variation with operating pressure under low pressure conditions. However, as the operating pressure continues to increase, its impact on the liner temperature and the maximum temperature turns out to be very small. In order to explain the influence mechanism of operating pressure on the linear temperature, its effects on the flame structure, the liner heat flux, the convection and radiation are analyzed under different pressures. This study could be valuable for predicting and analyzing temperature distribution of the liner of gas turbine combustor.

1. Introduction

As a crucial part of Integrated Gasification Combined Cycle (IGCC) system, the syngas turbine is of great significance to the development of clean coal technology. Currently, the pressure ratios of widely used heavy duty gas turbines such as SGT5-4000F (Siemens), MS9001FB (General Electric) and M701F4 (Mitsubishi) are close to 20 [1,2]. The life of gas turbine combustor will be

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http://dx.doi.org/10.1016/j.applthermaleng.2015.02.057
1359-4311/

Nomenclature

Roman symbols

C	convective heat flux, W
F	mixture fraction
G	incident radiation intensity, W
H	net convective/radiative heat flux, W
L	total length of the combustor, m
Nu	Nusselt number
Pr	Prandtl number
p	pressure, Pa
Q	heat flux, W
R	radiative heat flux, W
Re	Reynolds number
R_c	combustor radius, m
T	temperature, K
TC	thermocouple
v	velocity, m/s
x	axial position, m
y	radial position, m

Greek symbols

θ	incident radiative temperature, K
κ	turbulent kinetic energy, m^2/s^2
σ	Stephan–Boltzmann constant

Subscripts

0	baseline
ave	average
cold	cold side
hot	hot side
max	maximum
non	without radiation

strongly affected by the level and uniformity of the combustor liner temperature [3]. The liner temperature is mainly determined by the temperature distribution in the combustor and the liner heat transfer process [3–5]. Therefore, it is necessary to investigate how the operating pressure affects liner temperature of gas turbine combustor, and to understand its mechanism, which will be meaningful for the design of gas turbine combustor.

Previous studies have implied that combustor liner temperature varies obviously with the operating pressure. Claus et al. [6] experimentally and numerically studied the liner temperature, and the convection and radiation of a combustor within inlet pressure range of 0.1–2.0 MPa. Their results showed that the liner temperature increased with the increase of pressure in the primary, secondary and tertiary zones within low-pressure range. However, when the inlet pressure exceeded 0.35 MPa, the liner temperature started to decrease. Wang et al. [7] simulated a gas turbine combustor through CFD method within pressure range from 0.6 MPa to 1.4 MPa, and found that the combustor liner temperature declined as pressure increased. Furthermore, the liner temperature was sensitive to pressure in the main burning zone but insensitive in dilution zone. However, when the combustor configuration changes, the liner temperature distribution and the heat transfer features would be different, thus the liner temperature may vary differently with pressure. Hence it is essential to make a further investigation on the immanent mechanism affecting the liner temperature under high pressure.

Temperature distribution in the combustor, which is mainly determined by flame shapes such as flow pattern, turbulence intensity and reacting zones, has a direct influence on the liner temperature [4,5]. Previous studies indicated that the operating pressure had direct or indirect effects on the flame shape [8,9]. The work of Ribert et al. [10] on H_2/O_2 counter flow diffusion flame showed that the flame thickness σ was related to pressure p and strain rate ε, and quantitatively proportional to $1/(p\varepsilon)^{0.5}$. The numerical results on H_2-air turbulent non-premixed flames by Tabet et al. [11] suggested that the velocity dissipation rate declined with the pressure increase, which caused the variation of flame shape. Similar simulation results on the propane premixed flames were obtained by Liakos et al. [12,13], and they also found that the increase of pressure reduced the diffusing rate and turbulence intensity, which changed the temperature distribution. Hu et al. [14] found that the reaction zones of flames would be shortened under higher pressures through measurements and calculations. Besides numerical method, experimental studies on the flame flow field and structures were conducted using advanced measuring devices [15]. Stopper et al. [16] examined the flame structure in a gas turbine combustor under periodic pressure fluctuation by PIV measurement. They found that the velocity was higher while the vortex structure was smaller under high pressure. However, the impact of the flame shape changes on the liner temperature of real gas turbine combustors at elevated pressure needs to be further investigated.

Generally, when the combustor is working steadily, the heat flux through the liner will reach an equilibrium state, which determines the liner temperature. The heat load that affects the liner temperature includes convection and radiation [3]. The study of Claus et al. [6] showed that liner convection and radiation flux increased with the pressure increase, while the rising rate slowed down when the pressure was higher than 0.7 MPa. Similar conclusion was drawn from the numerical work of Coelho et al. [17] on the liner heat load within pressure range of 0.5–2.5 MPa. Reddy et al. [18] measured the liner radiation of a fluidized bed combustor, and found that it was similar to that of a gas turbine. Besides the same trend of radiation heat transfer changing with pressure as above, the authors illustrated that the concentration of three-atom gas such as CO_2 in the combustor had obvious effects on radiation. In addition, Patil et al. [19,20] studied the convective heat transfer in a combustor through experiment and Large Eddy Simulation. They found that the convection augmentation ratio to baseline decreased as Reynolds number grew higher. The major reason was that the increase of Reynolds number led to the decline of turbulent kinetic energy. Thus, to study the mechanism of pressure effects on the liner heat load would be significant to understand the liner temperature variation of gas turbine combustor under elevated pressure. It would be of theoretical and practical value for the cooling design of combustor liner.

In this work, a syngas model combustor is studied through the experimental measurements and the CFD simulations coupled with a detailed chemical mechanism. The liner temperature distribution is investigated within pressure range from 0.1 MPa to 2.0 MPa. The behavior of liner temperature under different pressure is explained from the aspects of the flame structure, the convection and radiation in the combustor.

2. Experimental setup

A syngas model combustor, mainly consisting of a single fuel swirling jet, an air swirler, a hermetic air case and a flame chamber, is shown in Fig. 1. It adopts non-premixed burning mode and air film cooling for the liner. There is no cooling hole at the rear of the