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The combustion tuning methodology of an industrial gas turbine using a sensitivity analysis

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HIGHLIGHTS

► A tuning methodology of gas turbine combustor using sensitivity analysis is proposed.
► Ambient pressure combustion test was conducted and rig–engine correlation was verified.
► Combustor's vital control parameters and their priority were determined by sensitivity analysis.
► Pilot to total fuel ratio was selected as the vital control parameter.
► After tuning, NO*x* was reduced from 18 to 2.2 ppm at base load with stable combustion.

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ABSTRACT

This paper presents the results of combustion performance testing of a 5.25 MWe industrial gas turbine which features a conical counter-flow double-swirl stabilized, premixed combustor and the Combustion Tuning methodology using a Sensitivity Analysis (abbreviated to CTSA). The combustion performance test was conducted in an atmospheric pressure, optically accessible, real engine scale combustor. The atmospheric rig and real engine correlation was verified by comparing real engine data which were gathered from high pressure tests. NO*x* and CO emissions, combustor temperature at the fuel nozzle, dump plane and exhaust, dynamic pressure and flame structure, using planer laser induced fluorescence, were investigated with respect to power load and ambient temperature. To enhance the NO*x* and CO emission performances with stable combustion, the relative sensitivities of five control parameters were analyzed, and on the basis of sensitivity analysis data, combustion tuning testing was conducted. By using the CTSA, NO*x* emission in exhaust gas was reduced from 18 to 2.2 ppm at base load, with high combustion efficiency (>99.9%), and very little pressure fluctuation ($P_{rms} < 0.1$ kPa).

1. Introduction

1.1. Background

In line with the increasing severity of certain environmental problems—including global warming, urban atmospheric pollution, and the depletion of energy resources—many governments, research institutes and businesses are striving to develop high-efficiency, eco-friendly energy resources. Such efforts include developing new and renewable energy resources, utilizing distributed power sources, and improving the efficiency of power plants. Within recent decades, there has been a significant increase in the use of micro or small-scale gas turbines, as well as heavy duty gas turbines due to their relatively low capital cost and low emissions profiles relative to other power generation systems,. The present paper deals with the development of small gas turbines (5.25 MWe), with the intention of utilizing high-efficiency cogeneration systems as a distributed power source. In particular, this paper discusses and analyzes the results from a performance test of a double-swirl combustor for a small gas turbine. Our aim is to improve the efficiency and reliability of the power plant through optimizing combustion.

1.2. Prior research on the tuning methodology of gas turbine combustors

In recent decades, due to efficiency, reliability and simplicity, the lean premixed combustion method has become the industry standard to achieve low NO*x* emission. However since the Dry Low

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Abbreviations

AF	air mass flow rate
AT	air temperature
c	sonic velocity in the air at the temperature of T
CCS	carbon capture and storage
CTL	coal to liquid
CTSA	combustion tuning methodology using a sensitivity analysis
DLN	dry low NOx
DLE	dry low emission
D_{swril_in}	inner diameter of swirler
D_{swril_out}	outer diameter of swirler
LHV	lower heating value
LNG	liquefied natural gas
MFF	mass flow rate of main fuel
PC	pulverized coal
PFF	mass flow rate of pilot fuel
PFR	pilot to total fuel flow ratio
PLIF	planar laser induced fluorescence
ppm	parts per million
ϕ	equivalence ratio
$P'_{(1)}$	root mean square of the dynamic pressure at the dump plane
$P'_{(2)}$	root mean square of the dynamic pressure at the combustion chamber liner
P_2	plenum air pressure
P_3	compressor discharge pressure
S_n	swirl number
TIT	turbine inlet temperature
T_4	combustor discharge temperature
T_n	fuel nozzle temperature
T_d	dump plane temperature of the combustion chamber
T_e	mean temperature of gas upon exiting the combustion chamber
$T_{e,\ mr}$	maximum circumferential mean temperature of T_e
T_∞	ambient air temperature
$T_{in,\ air}$	heated air temperature at combustor inlet
T_f	flame temperature
θ	swirl vane angle
X_i	control parameter
WLN	wet low NOx
1.0 N	base load of gas turbine (=5.25 MWe)

NOx (DLN) or Dry Low Emission (DLE) combustion method based on lean premixed combustion has relatively weak combustion stability, many fatal accidents caused by high combustion vibration were reported in many gas turbines [1]. Thus numerous researchers have studied about the combustion instabilities in gas turbines. Lieuwen et al. reported that the feedback loop among the equivalence ratio fluctuations, heat release oscillations and acoustic oscillations in combustor inlets and fuel lines are responsible for the combustion instabilities of gas turbines [2]. Seo also stated that the incompleteness of premixing is identified as significant perturbation source for inducing unstable combustion [3]. Kulsheimer et al. noted the relationship between vortex formation and Strouhal number, and gave a comprehensive understanding of the formation and reaction of large-scale coherent vortex structures in turbulent flames as drivers of combustion instabilities [4].

To attenuate these combustion instabilities, active, passive or their hybrid control methods have been derived. The active control methods are used to adjust some input parameters such as fuel distributions [5], or to modulate the acoustic boundary conditions of the combustion chamber [6]. On the other hand, passive control methods mainly consist of geometrical modifications of the combustion chamber [7] or sound-absorbing devices such as perforated plates [8] and Helmholtz resonators [9,10]. Some of these methods or ideas were applied to real engines and improved their efficiency. Oh et al. suggested a tuning methodology of a GE7FA +e DLN-2.6 gas turbine and reported that the tuning methodology effectively reduced both NOx emission and combustion vibration, which were significantly higher before tuning during the start-up mode [11]. In addition, Johnson et al. presented successful demonstrations of active control of combustion instabilities on a full-scale Siemens-Westinghouse gas turbine combustor [12]. This active control method attenuated the dominant acoustic modes by up to 15 dB and reduced NOx emission by approximately 10%. Hibshman et al. also designed and implemented active control systems on both subscale and full-scale combustors [13,14]. This control system through modulation of the fuel supply led to a 6.5-dB decrease in magnitude of the dominant instability frequency, while retaining comparable emission characteristics. Afgan et al. raised the concept of an expert control system for fault diagnosis and monitoring of gas turbine combustion chambers and explained the set-up procedure of such an expert system in detail [15]. Kelsall et al. suggested three potential solutions to instabilities, which are: 1) passive damping, 2) active control system based on high frequency actuator and low frequency fuel staging and 3) neural network based control system [16]. While Sen Li et al. also used a passive control method which requires retrofitting a power plant to improve its performance [17], we propose a new combustion tuning methodology of industrial gas turbines by using sensitivity analysis (CTSA) as an active control method which adjusts control parameters without modifying any part of a plant. Though the sensitivity analysis method is applicable for various purposes, it has never been applied to combustion tuning. In the combustion field, sensitivity analysis is usually used to evaluate the chemistry model of combustion calculations [18,19]. However, in this study the relative sensitivities of control parameters to combustion performance were analyzed in order to prioritize or rank them as control factors.

2. Description of the test method

2.1. The gas turbine combustion test facility

For the purposes of this study, an atmospheric pressure combustion test facility for 5.25 MW industrial gas turbines was constructed as shown in Fig. 1. This facility consists of an air compressor, an air heater, a cooling and combustion air feed line, an atmospheric pressure combustor, a water sprayer for cooling exhaust gas, a control system, and an external stack. In the system, both the fuel and the air were processed to meet the choking condition immediately upstream of the combustor to prevent the perturbation of air and fuel in the combustor chamber by blocking the influence of pressure variation on the upstream flow. As shown in Table 1, the tests are conducted from Idle to base load for cold, standard and hot-day conditions. In the real gas turbine engine, the load is controlled by turbine inlet temperature, and the flow rates of air and fuel at each load are determined by considering the combustion stability also. In the case of hot day conditions, the load is limited until 0.61 N due to the limitation of turbine inlet temperature. In this study, the flow rates of air and fuel are scaled