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Numerical study of a low emission gas turbine like combustor for turbulent ammonia/air premixed swirl flames with a secondary air injection at high pressure

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ABSTRACT

The present study is dedicated to understand the emission characteristics of turbulent premixed ammonia/air swirl flames in a gas turbine like combustor at high pressure with and without secondary air injection. Ammonia has recently created an attention as a sustainable energy source not only because of its carbon free nature but also owing to its high hydrogen capacity of 17.8% in weight. Thus, in the present study, the effect of pressure on NO, unburnt NH_3, and H_2 emissions in ammonia/air premixed combustion was discussed by having space and time average emissions (STAE) at the exit of cylindrical combustor for various equivalence ratios and high pressures up to 0.5 MPa. The study found that NO emission decreases with an increase in pressure whereas unburnt NH_3 emission in rich flame conditions also decreases with increase in pressure, and the study realizes that, at the equivalence ratio of 1.2, NO and unburnt NH_3 emissions are minimal and in the same order of 200 ppm of mole fraction, even though still there is an unburnt H_2 emission of 6% volumetric exhaust flow at the operating pressure of 0.5 MPa. Subsequently, secondary air injection system was introduced to the combustor, and eventually, the study realizes a low emission combustor with the STAE of NO in the order of 100 ppm of mole fraction at 16% of O_2 concentration and zero NH_3 and H_2 emissions, at the primary zone equivalence ratio of 1.2.

Introduction

Sustainable energy resources are desired to be increasingly applied in order to prevent the detrimental effects of fossil fuels on the environment. As a carbon-free sustainable alternative fuel, recently, ammonia (NH_3) has created an attention on this matter, and moreover, it is anticipated as a hydrogen energy carrier because of high hydrogen capacity of 17.8% in weight. In addition, NH_3 has some attractive features than hydrogen such as less expensive cost per unit stored energy, higher volumetric density, existing infrastructure for production and handling and much safer transportation [1]. Nevertheless, much lower laminar burning velocity such that

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7 cm/s at the stoichiometric condition, NH_3/air mixture temperature of 300 K and pressure of 0.1 MPa [2–4], and high fuel NO generation in the combustion, because NH_3 contains the nitrogen itself than that of conventional hydrocarbon fuels, hinder the use of NH_3 as a commercial fuel.

On the other hand, the history of utilization of NH_3 as a fuel is not a new idea. There were two technical reports issued on utilization of ammonia as an alternative fuel in army aircraft engines by US army aviation material laboratories, Fort Eustis, Virginia [5] and on development of ammonia burning gas turbine engines by US army engineer research and development laboratories, Fort Belvoir, Virginia [6] in 1966. However, the study of [6] was concluded that the use of ammonia, as a gas turbine fuel, results in considerably lower aircraft productivity than the productivity obtained from use of hydrocarbon fuels, and henceforth, the research and developments of NH_3 fueled gas turbines were not restarted until few years ago.

Subsequently, recent three-dimensional (3D) numerical study of Somarathne et al. [7,8] and experimental study of Hayakawa et al. [9] have illustrated that by introducing a swirl flow, and thereby, making a recirculation near the downstream of the burner, NH_3/air premixed turbulent flames have successfully achieved a stable combustion in various turbulent intensities and atmospheric pressure at the initial mixture temperatures of 500 K and 300 K. Moreover, these studies [7–9] elucidated that fuel NO generation can be significantly reduced by using the rich flame conditions, and there is a specific equivalence ratio in rich flame condition in which NO and unburnt NH_3 emissions are minimal and in a same order of mole fraction. However, this specific equivalence ratio is like to be depended on the initial mixture temperature and heat transfer characteristics of the combustion chamber. In the cases of adiabatic chamber walls and initial mixture temperatures of 500 K and 300 K, the NO and unburnt NH_3 emissions were minimal at the equivalence ratios of 1.2 and 1.15, respectively [7,8]. On the other hand, with isothermal chamber walls and initial mixture temperature of 300 K, specific equivalence ratio is about 1.05 [9]. This specific equivalence ratio is the best operating point for the selective catalytic NO reduction (SCR) process in the downstream of a combustor. Moreover, these studies revealed that there is a significant unburnt H_2 emission in the rich flame conditions, which increases with increase in the equivalence ratio.

In addition, the recent experiment and one-dimensional (1D) numerical study of Valera-Medina et al. [10] on the flame stability and emissions at various equivalence ratios and atmospheric and medium pressure (0.2 MPa) conditions using NH_3-methane (CH_4) blend (61% of NH_3 and 39% of CH_4 by mole fraction) in a generic tangential swirl burner showed that NO emission is significantly reduced at about equivalence ratio of 1.2 even though unburnt NH_3 emissions were not predicted correctly. Furthermore, the increase in pressure even up to 0.2 MPa also showed a substantial NO emission reduction. Moreover, NH_3/air combustion power generation has been successfully realized using a 50 kW micro gas turbine at the National Institute of Advanced Science and Technology (AIST), Japan by Kurata et al. [11]. In that study, stable turbulent non-premixed NH_3/air swirl flame has been achieved using a high swirling flow of air and a jet flow of NH_3, even though NO emission is still higher than that of the government environment regulations such that 70 ppm of mole fraction in 16% O_2 concentration [12]. Additionally, some research groups have made an attention on NH_3 in order to develop as a dual-fuel such that ammonia-gasoline, ammonia-hydrogen, or ammonia-diesel in the internal combustion engine systems [13–15].

However, according to the best of knowledge of authors, there is no any comprehensive study on turbulent NH_3/air premixed flames at high pressures, which is essential for the design of the gas turbine combustors, and there are only few numerical studies on 1D laminar NH_3/air premixed flames at the high pressure. Duynslaegher et al. [16] have showed that increase in pressure leads to decrease in NO emission, and Hayakawa et al. [17] illustrated that, by sensitivity analysis of NO at various pressures, the third body reaction of $OH + H + M \Leftrightarrow H_2O + M$ has high sensitivity at the high pressure, and thus, the reaction leads to the reduction of NO emission at the high pressures. However, another study of Hayakawa et al. [4] showed that the increase in pressure decreases the laminar burning velocity of NH_3/air mixture. In addition, Colson et al. [18] found that extinction-stretch rate of NH_3/air flame is lower compare to the CH_4/air flame, as could be expected from its low laminar burning velocity, however, the increase of extinction-stretch rate with pressure was greater in the cases of NH_3/air flames than that of CH_4/air flames by using the counter flow premixed flames.

Thus, the present study is dedicated to understand the emission characteristics of the turbulent premixed swirl flames of NH_3/air mixture at the high pressures in an ordinary cylindrical chamber, and subsequently investigate the combustion and emission characteristics with a secondary air injection system which is an essential element to complete the combustion of rich condition flames in the primary zone of the combustor and maintain the maximum permissible exhaust gas temperature to the gas turbine blades at about 1300 K [19]. Accordingly, relatively simple test cases were chosen as affordable tests to evaluate the feasibilities of more complex gas turbine combustors. However, gas turbine combustor modeling comprises a wide range of computational and modeling challenges because of the involvement of the interactions of many complex physical processes such as the turbulence-chemistry interaction. Consequently, in the present study, large eddy simulation (LES) with a finite rate chemistry is performed in a 3D computational domain in order to discuss the detailed resolutions of the reacting flow at the high pressures.

Numerical models and conditions

In the present study, LES with a finite rate chemistry was conducted using an open-source code, OpenFOAM [20] at the Advanced Fluid Information Research Center, Institute of Fluid Science, Tohoku University, Japan using the 32 CPU cores of scalar super computers, which consist of Intel Xeon Processor E5-4650v2 2.40 GHz. The LES in OpenFOAM with a two-step chemistry has been successfully used to predict the low swirl stratified premixed CH_4/air flames by Nogenmyr