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Swirler geometry effects (d_h/d_o ratio) on synthetic gas flames. Part 2: dynamic flame behaviour at externally altered acoustic conditions

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In a combustion device, unsteady heat release causes acoustic energy to increase when acoustic damping (energy loss) is not that effective, and, as a result, thermo-acoustic flame instabilities occur. In this study, effects of the swirler d_h/d_o ratio (at different swirl numbers) on dynamic flame behaviour of the premixed 20%CNG/30%H_2/30%CO/20%CO_2 mixture under externally altered acoustic boundary conditions and stability limits (flashback and blowout equivalence ratios) of such mixture were investigated in a laboratory-scale variable geometric swirl number combustor. Therefore, swirl generators with different d_h/d_o ratios (0.3 and 0.5) and geometric swirl numbers (0.4, 0.6, 0.8, 1.0 1.2 and 1.4) were designed and manufactured. Acoustic boundary conditions in the combustion chamber were altered using loudspeakers, and flame response to these conditions was perceived using photodiodes and pressure sensors. Dynamic flame behaviour of respective mixture was evaluated using luminous intensity and pressure profiles. Results showed that the d_h/d_o ratio has a minor impact on dynamic flame behaviour.

Keywords: synthetic gas, d_h/d_o ratio, thermo-acoustic, dynamic flame behaviour

INTRODUCTION

In a combustion process, an oscillating variable (mass flow inlet velocity, heat release rate, etc.) interacts with natural acoustic modes of the combustor, a feedback circuit grows up between these two, and combustion instabilities arise [1]. Flame instabilities such as blowout, flashback, auto-ignition, etc. are referred to transient combustor concerns that limit the stable operation range of a combustor, hence power output [1–2]. On the other hand, thermo-acoustic instabilities occur when the difference between the amount of energy augmented by the combustion process to the acoustic field and the amount of energy dampened as a consequence of the energy loss (heat transfer) and viscous dissipation is positive. Combustion instabilities may cause severe structural damage in hot path combustor components. Considering this, many researchers have investigated combustion instabilities both experimentally and numerically.

In a combustion device, self-triggered large-amplitude pressure waves cause thermo-acoustic flame instabilities. To examine the role of mass flow rate of reactants on the onset of thermo-acoustic instabilities is of crucial importance. Zhao et al. experimentally studied the effects of inlet parameters (equivalence ratio, mass flow rate of reactants) on the initiation of such instabilities in a swirl stabilised combustor. They found that self-activated thermo-acoustic instabilities do not occur at low fuel flow rates. On the contrary, limit-cycle thermo-acoustic instabilities become present based on the equivalence ratio at higher fuel flow rates.

Han et al. conducted experimental studies on premixed CH_4/air flames to investigate the interrelationship between flame structure and acoustic flame instabilities. They also used the LES (Large Eddy Simulation) technique to analyse flame reaction to acoustic forcing at 300 Hz (the frequency value at which limit-cycle instabilities arise). During experiments, they observed three different flame modes depending on the equivalence ratio. They demonstrated that lifted and V-type flames are more prone to flame instabilities [4].

Laera et al. built up an experimental setup to determine the capability of the burner in detecting thermo-acoustic instabilities. The main purpose of their study was to develop a model that could predict the inception of acoustic instabilities (the frequency at which instabilities arise). Therefore, they used the respective method in the test rig to validate the applicability of the method. The numerical model was found to reproduce an even wave shape of the unsteady flame, with an inaccuracy at the location of the minimum pressure [5].

Shahi et al. numerically investigated the mechanisms of acoustic instabilities in lean-partially-premixed combustors at conditions relevant to gas turbine operating. They tested a variety of combustion models and simulation approaches to designate the initiation of acoustic instabilities and implemented these methods to the testing apparatus to evaluate the applicability of the methods. They also tried to characterise the conjugation between heat release rate oscillations and acoustic field at specified acoustic and thermal conditions. They concluded that the BVM (burning velocity) model provides the highest accuracy with experimental data, and implementing appropriate thermal boundary conditions are very important with respect to determination of limit-cycle oscillations [6]. In the literature, numerous studies conducted on thermo-acoustic flames instabilities can be found [7–13].

In this study, effects of the swirler d_h/d_o ratio on flame response of the premixed 20%CNG/30%H_2/30%CO/20%CO_2 mixture under externally altered acoustic boundary conditions were investigated in a laboratory-scale variable geometric swirl number combustor. Stability limits (flashback and blowout equivalence ratios) of such a mixture were also determined. For this purpose, swirl generators with different d_h/d_o ratios (0.3 and 0.5) and swirl numbers (0.4–1.4, at intervals of 0.2) were designed and manufactured. The alteration of the acoustic boundary condition was performed via side mounted loudspeakers (in the frequency range of 0–600 Hz). Dynamic flame behaviour was evaluated by examining pressure and luminous intensity profiles throughout the combustor, which were obtained from pressure sensors and photodiodes, respectively.

EXPERIMENTAL SETUP

The schematic of the experimental setup is presented in Fig. 1. To constitute synthetic gas, each component is supplied from a commercially available external gas tank. Fuel gas then flows through a pressure regulator (from 200–300 bar to 0–1.5 bar) to meet mass flow controller pressure requirement. The thermal-pressure-based mass flow controller ensures the correct amount of gas flow (based on the synthetic gas composition and thermal power), which is externally controlled by a vacuum system controller. Solenoid valve installed in each gas flow line automatically blocks the gas flow in the case of flame absence. All synthetic gas components aggregate in a collector before completely pre-mixing with combustion air, which is supplied from an air compressor.

Air/fuel mixture is then directed to a premixed swirl stabilised burner that can operate in the thermal power range of 2–10. The outlet nozzle of the burner allows swirl generator displacement without demounting burner.

The stainless steel combustor is 1755 mm in length; the inner diameter is 320 mm and the outer 330 mm. There are many slots on the combustor for thermocouple and flue gas analyser probe instalment. There are also two openings, which

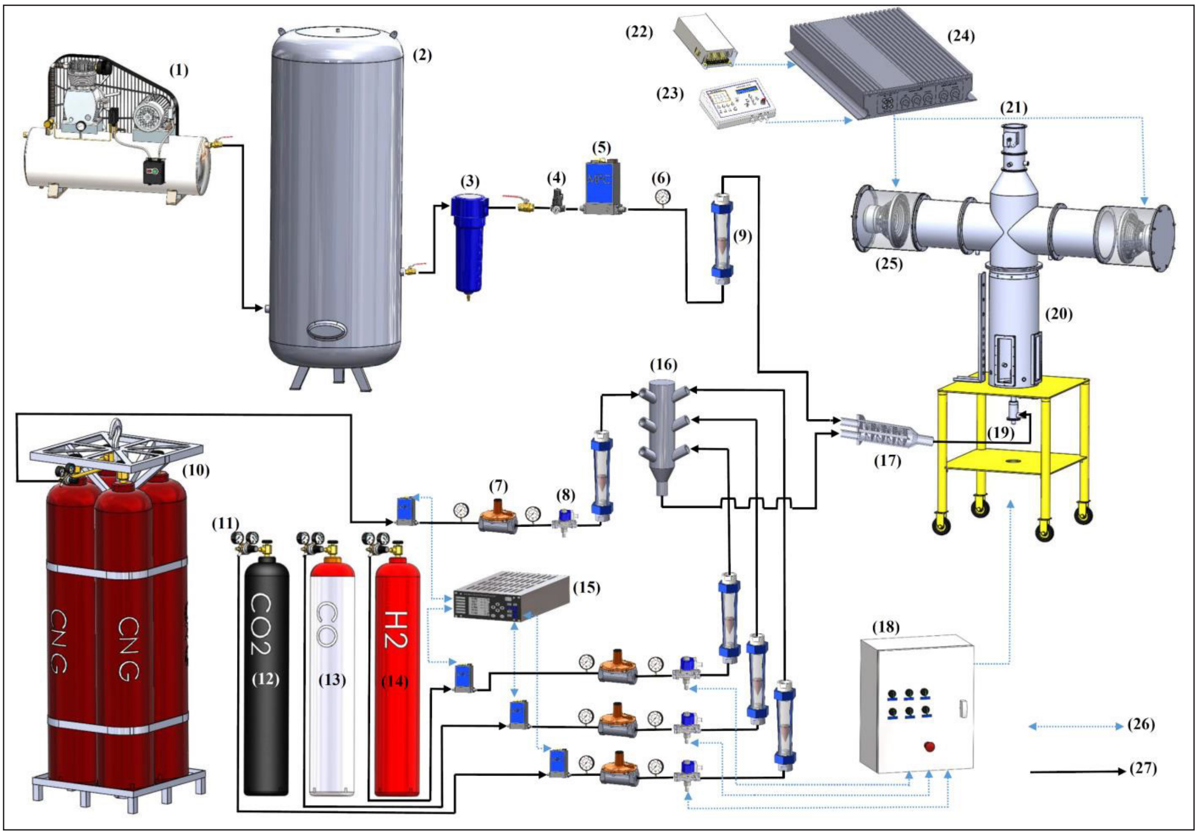

Fig. 1. Layout of the overall combustion system

1. Air compressor (5.5 hp, 500 lt)	10. CNG tank	19. Burner
2. External air tank (1 m^3)	11. Pressure regulator	20. Combustion chamber
3. Filter (for steam and oil removal)	12. CO_2 tank	21. Flue
4. Pressure regulator (1 MPa to 0.3 MPa)	13. CO tank	22. Power source
5. Mass Flow Controller	14. H_2 tank	23. Function generator
6. Manometer	15. Vacuum system controller	24. Audio amplifier
7. Pressure Regulator	16. Gas collector	25. Loudspeaker
8. Solenoid Valve	17. Fuel/air pre-mixer (static)	26. Electrical connections
9. Float type flowmeter	18. Control panel	27. Gas supply lines

are covered by tempered glass on bottom parts of the combustor for direct flame imaging and photodiode installation.

As mentioned before, acoustic boundary conditions in the combustor are altered via side mounted loudspeakers. Audio power of the loudspeaker is 1400 W. The effective operating range of the loudspeakers is 20–125 Hz (power output reduces out of this range). The signal generator and the audio amplifier are used to generate waveforms and to amplify audio signals to a degree at which the loudspeakers can be driven, respectively. Lastly, a data logger was used to store measured values.

All experiments were conducted at local atmospheric conditions. Mixing of fuel and air took place at room temperature. As stated previously, the equivalence ratio and thermal power of the combustor were 0.6 and 3 kW, respectively. Mass flow rate of air and each synthetic gas constituent were specified based on these values.

RESULTS AND DISCUSSIONS

Synthetic gas is an alternative and renewable (depending on the raw material used to produce synthetic gas – wood, organic waste, etc.) energy source that can meet today's energy demand in terms of both energy density and emission requirements. It is mainly composed of CO and H_2 and may contain inert constituents (CO_2, N_2) and other hydrocarbons. However, varying gas composition, lower heating value and the Wobbe Index of synthetic gases require a thorough characterisation of the basic combustion properties of such gases before using them in conventional burners [14]. In this study, preliminarily, stable operating range (which is marked off by flashback and blowout equivalence ratios) of the 20%CNG/30%H_2/30%CO/20%CO_2 mixture at different swirl numbers and d_h/d_o ratios were determined. Blowout refers to flame extinction and takes place when chemical time scale is longer than residence time. On the other hand, flashback refers to flame propagation towards burner nozzle and is controlled by the interrelationship between burning velocity, local flow field conditions, and combustion instabilities [15–16].

In Fig. 2, stable operating range of 20%CNG/30%H_2/30%CO/20%CO_2 mixture at different swirl numbers and d_h/d_o ratios are presented. As is clearly seen, blowout equivalence ratios do not significantly vary with the swirl number at both tested d_h/d_o ratios. However, the d_h/d_o ratio merely alters blowout limits. At 0.4 and 0.6 swirl numbers, blowout limits are very close at 0.3 and 0.5 d_h/d_o ratios. In the swirl number range of 0.8–1.4, flame blows out at slightly higher equivalence ratios when the d_h/d_o ratio is 0.5.

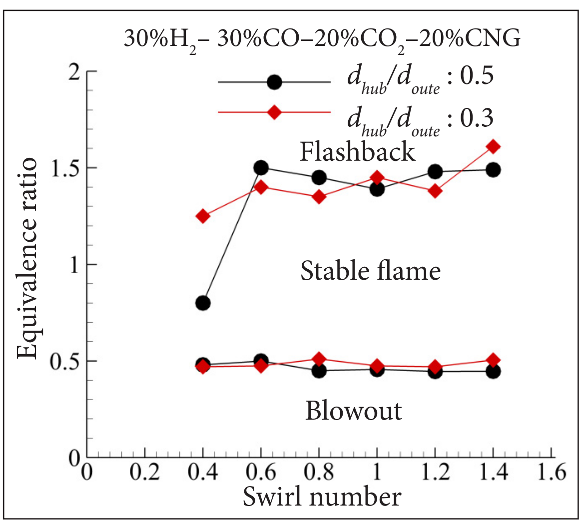

Fig. 2. Stable operating range of 20%CNG/30%H_2/30%CO/20%CO_2 mixture at different swirl numbers and d_h/d_o ratios

Likewise, the d_h/d_o ratio barely affects flashback limits except for 0.4 swirl number, but, its effects on flashback limits are more profound compared to blowout limits. Depending on the swirl number and the d_h/d_o ratio, increments and decrements are present at flashback limits. Adversely, the swirl number modifies flashback limits considerably. In conclusion, it can be asserted that stable operating range broadens with swirl number increments and d_h/d_o ratio decrements (opposite behaviour is observed at some swirl numbers).

Considering stable operating range, all dynamic flame behaviour experiments were performed at 0.6 equivalence ratio. All flames were forced by side mounted loudspeakers by producing sound waves in the frequency range of 0–600 Hz. In Fig. 3, static pressure and luminous intensity profiles at different swirl numbers and d_h/d_o ratios are illustrated. Irrespective of the swirl number and the d_h/d_o ratio, all flames start to oscillate at 95 Hz, which is one of the natural acoustic modes of the combustor. Because of the high reactants' inlet velocity (high amount of CO_2 and low equivalence ratio), no flame instabilities such as flashback, blowout, and flame lift-off are observed. The 20%CNG/30%H_2/30%CO/20%CO_2 mixture flame firmly attaches the burner nozzle and keeps burning from the beginning of the acoustic forcing. As clearly seen in Fig. 3, the amplitude of pressure fluctuations is nearly insensitive to the swirl number and the d_h/d_o ratio. However, the oscillating period and the pressure value (higher pressure values are present when the d_h/d_o ratio is 0.3) in the combustor vary depending on these parameters. Similarly, luminous intensity profiles do not substantially vary with the d_h/d_o ratio except for 0.4 and 1.2 swirl numbers. At 0.6, 0.8, 1.0, and 1.4 swirl numbers, luminous intensity profiles show a good agreement by means of trend and value. The swirl number only specifies the amount of decrement in luminous intensity rooted from acoustic perturbation. A lower number of decrements indicates high flame stability, which is encountered at high swirl numbers. Effects of the d_h/d_o ratio on luminous intensity profiles are not monotonous. Flame brightness alters differently at different swirl numbers and acoustic forcing frequencies. Lastly, the second decrement zone in luminous intensity profiles points out

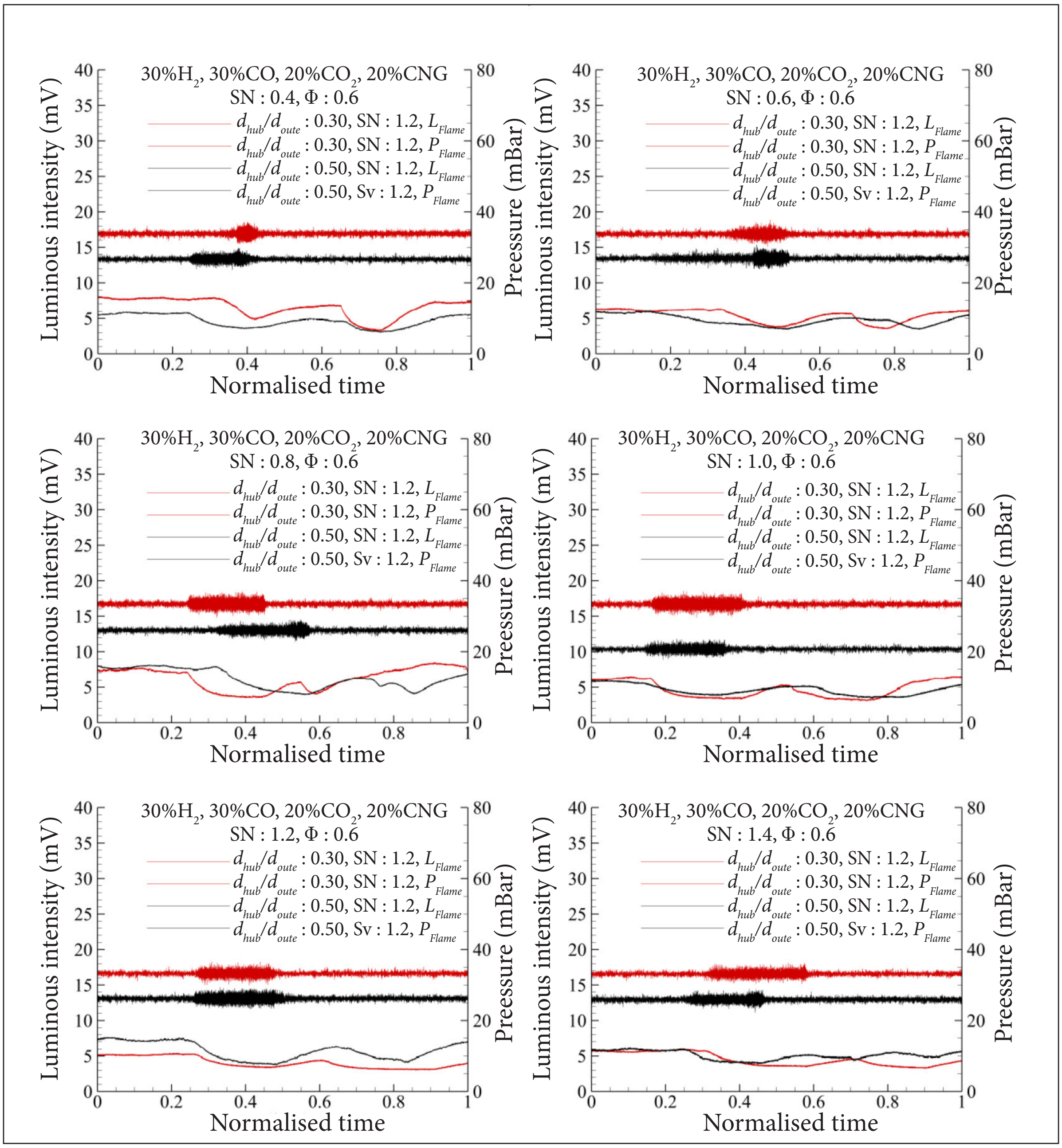

Fig. 3. Pressure and luminous intensity profiles at different swirl numbers (0.4–1.4) and d_h/d_o ratios (0.3 and 0.5)

the second natural acoustic mode of the combustor, which is achieved at 150 Hz.

Since no significant change was observed (large amplitude of pressure and luminous intensity variations) based on the swirl number and the d_h/d_o ratio (e.g., increments indicate flashback occurrence), the measured pressure and luminous intensity values at burner were not included in this study.

CONCLUSIONS

The study started with the investigation of the effects of the d_h/d_o ratio on stable operating range of 20%CNG/30%H_2/30%CO/20%CO_2 mixture flames at different swirl numbers (0.4–1.4, at 0.2 intervals) in a laboratory-scale swirl stabilised premixed combustor. Later on, acoustic boundary conditions in the respective combustor were altered by introducing sound waves in the frequency range of 0–600 Hz into the combustor and, under these circumstances, dynamic flame behaviour was evaluated by examining pressure and luminous intensity profiles. The results of this study showed that the swirl number and the d_h/d_o ratio slightly altered the blowout limits, while (1) the effects of these parameters on flashback limits were more profound, (2) natural acoustic modes of the tested combustor were at 95 Hz and 150 Hz, and (3) dynamic flame behaviour did not significantly change with the swirl number and the d_h/d_o ratio under acoustically modified conditions.

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SUKTUVO GEOMETRIJOS (d_h/d_o) POVEIKIS SINTETINIŲ DUJŲ LIEPSNOMS. 2 DALIS: DINAMINĖ LIEPSNOS ELGSENA VEIKIANT IŠORĖJE PAKEISTOMIS AKUSTINĖMIS SĄLYGOMIS

Santrauka

Degimo įrenginyje nestabilus šilumos išsiskyrimas padidina akustinę energiją, kai akustinis slopinimas (energijos nuostoliai) nėra itin efektyvus. Todėl atsiranda termoakustinis liepsnos nestabilumas. Šiame tyrime suktuko d_h/d_o santykio (esant skirtingiems susukimo skaičiams) poveikis iš anksto sumaišyto 20%SGD/30%H_2/30%CO/20%CO_2 mišinio dinamiškai liepsnos elgsenai esant išoriškai pakeistoms akustinėms ribinėms sąlygoms ir stabilumo riboms (liepsnos įtraukimo ir nupūtimo ekvivalentiškumo koeficientai) buvo tiriami laboratorijoje kintamo geometrinio susukimo skaičiaus degikliu. Sukurti ir pagaminti skirtingo d_h/d_o santykio (0,3 ir 0,5) ir geometrinių susukimo skaičiaus (0,4, 0,6, 0,8, 1,0 1,2 ir 1,4) suktukų generatoriai. Akustinės ribinės sąlygos degimo kameroje buvo pakeistos naudojant garsiakalbius, o liepsnos reakcija į šias sąlygas buvo fiksuota naudojant fotodiodus ir slėgio jutiklius. Dinaminė atitinkamo mišinio liepsnos elgsena buvo įvertinta naudojant šviesos intensyvumo ir slėgio profilius. Rezultatai parodė, kad d_h/d_o santykis turi nedidelį poveikį dinaminei liepsnos elgsenai.

Raktažodžiai: sintetinės dujos, d_h/d_o santykis, termoakustinis nestabilumas, dinamiška liepsnos elgsena