ENERGETIKA. 2021. T. 67. Nr. 1–2. P. 48–54

Swirler geometry effects (d_h/d_o ratio) on synthetic gas flames: Part 1: Combustion and emission characteristics

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Swirling flows increase combustion performance via favouring flame stability, pollutant emissions, and combustion intensity. The strength of a swirling flow is characterized by a parameter known as swirl number, which is highly related to the d_h/d_o ratio. In this study, effects of the swirler d_h/d_o ratio on combustion and emission characteristics of the synthetic gas flames of premixed 20%CNG/30%H_2/30%CO/20%CO_2 mixture were experimentally investigated in a laboratory-scale swirl stabilized combustor. For this purpose, twelve different swirl generators were designed and manufactured. d_h/d_o ratios of these swirlers were set as 0.30 and 0.50, and the geometric swirl number was varied between the values of 0.4 and 1.4 (at 0.2 intervals). All experiments were conducted at a fuel-lean equivalence ratio (ϕ = 0.6), room temperature, and local atmospheric conditions of the city of Kayseri, Turkey. A data logger was utilized to plot axial and radial temperatures and NO_x, CO, and CO_2 profiles, which were exploited to assess combustion and emission performance. Results showed that the d_h/d_o ratio had a non-monotonic effect on the behaviour of combustion and emission of the tested synthetic gas mixture. Depending on the swirl number, increments and decrements were observed in temperature and emission values.

Keywords: synthetic gas, d_h/d_o ratio, swirler, combustion, emission

INTRODUCTION

In a flow, swirl can be generated in two ways, actively (1) or passively (2). The active technique requires an external power source to mechanically introduce a tangential component to the flow; in the passive technique, the flow structure is altered by the implementation of a geometric design to the burner nozzle or surface. Compared to the former one, the latter technique favours by means of energy demand and structural complexity [1]. The swirl number (the ratio of axial flux of tangential momentum to axial flux of axial momentum) is the parameter that characterizes the strength of the swirl and can be presented as

$$\text{Swirl number } (S) = \frac{G_{tg}}{RG_{ax}} = \frac{\int_0^R wu\, r^2\, dr}{R\int_0^R u^2 r\, dr}, \quad (1)$$

where R – outer radius of the annulus; w – tangential velocity component; u – axial velocity component; r – radial position [2]. The strength of swirl also can be approximated by using the formula below:

$$S = \frac{2}{3} = \left[\frac{1-(\frac{d_h}{d_0})^2}{1-(\frac{d_h}{d_0})^2} \right] \tan(\theta) \quad (2)$$

where θ, d_h and d_o are swirler vane angle, hub, and outer diameters of the swirl generator, respectively [3]. Many researchers used this formulation and conducted both experimental and numerical studies on swirling flows.

Ilbas et al. conducted numerical studies on hydrogen containing fuel blends to investigate effects of the swirl number on combustion and emission behaviour of such mixtures. They varied the swirl number between the values of 0.2–0.8 (swirler vane angle was also varied accordingly) and kept d_h/d_o ratio constant. Results showed that an increasing swirl number in tested range causes emissions of NO_x and temperature values in radial direction to increase [4]. The recirculation zone formed in a swirling flow (after a critical condition-swirl number) enhances residence time, improves the fuel/air mixing condition, and hence reduces pollutant emissions and increases flame stability. Therefore, swirl generator design is of great importance by means of flame stability, combustion efficiency, pollutant emissions, and pressure losses. Considering this, Khandelwal et al. investigated effects of design parameters of a swirl generator (such as swirler vane angle and the number of vanes) and the mass flow rate through swirler on the non-reactive flow field. For this purpose, they designed five different swirl generators with different swirl numbers (0.625–1.34) and a constant d_h/d_o ratio (0.5). It was concluded that increasing vane angle led to reverse flow velocity and turbulence in axial direction, and pressure drop to increase. They commented this situation as a better mixing condition at high vane angles with the payoff of the pressure drop. Moreover, they reported that turbulence energy rose and flow velocity reduced with vane number increments [5]. Ishaka et al. studied effects of inlet velocity on the structure of the swirling flow in a combustor by keeping all design parameters of the swirl generator constant. They found that inlet velocity slightly altered the flow field and as inlet velocity increased, reverse flow velocity rose but the area of core flow did not significantly change [6]. Yilmaz et al. built an experimental test rig to analyse the effects of the swirl number on temperature and pollutant distributions throughout the combustor, and stability limits of (blowout and flashback equivalence ratios) synthetic gases in respective burner. They also examined swirl number effects on flame structure by utilizing instant flame images. It was shown that the swirl number had a non-monotonous effect on stability limits and these limits were differently affected by the swirl number; the place where the concentration of reactive intermediates was high moved towards combustor walls and axial temperature values decreased as swirl number increased; CO emissions were highly susceptible to the swirl number [3]. Readers may refer to the literature to find more studies related to both reactive and non-reactive swirling flows [7–13].

In this study, effects of swirler hub diameter to outer diameter on combustion and emission behaviour of synthetic gas flames of premixed 20%CNG/30%H_2/30%CO/20%CO_2 mixture were experimentally investigated in a laboratory-scale combustor. To this end, 12 different swirl generators with different swirl numbers (0.4–1.4, at 0.2 intervals) and d_h/d_o ratios (0.3 and 0.5) were designed and manufactured so that effects of the d_h/d_o ratio could be evaluated at different swirl numbers. During experiments, the equivalence ratio (0.6) and thermal power of the combustor (3 kW) were maintained constant. For temperature and emission measurements, K- and B-type thermocouples and a portable flue gas analyser were used, respectively.

EXPERIMENTAL SETUP

The layout of the overall combustion system is presented in Fig. 1. Each synthetic gas constituent

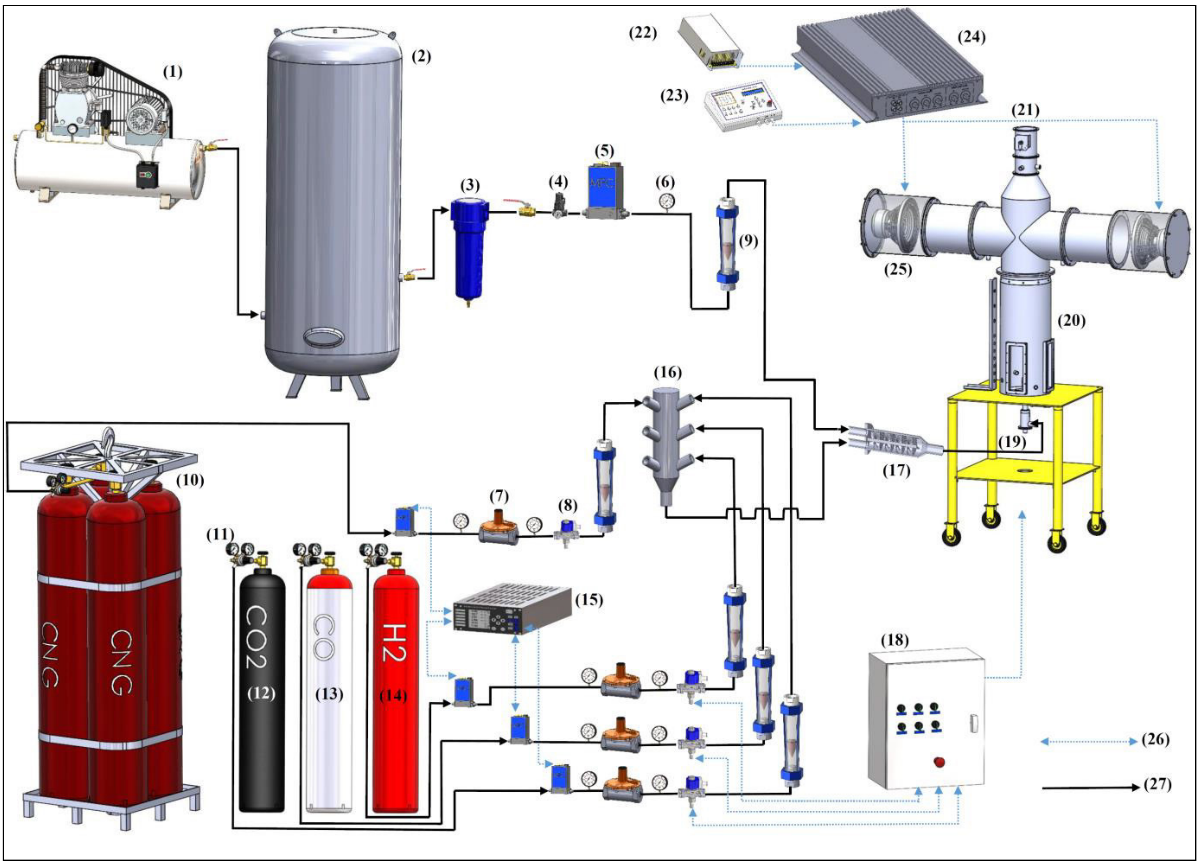

Fig. 1. Layout of the overall combustion system

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

is provided from a gas cylinder and their amounts are adjusted by a digital mass flow controller, which is governed by a vacuum system controller. Pressure regulators (on the gas cylinder and flow line) are used to drop pressure to the desired value (burner requirement, 20 mbar). For safety purposes, a solenoid valve is assembled for each flow line. This valve cuts off the gas flow in the case of flame absence, which may be caused by blowout, flashback, lift off, etc. Fuel gases are then mixed in a collector and directed to a static pre-mixer, where combustion air and fuel gases are completely mixed before entering the combustor.

The combustor is 1755 mm long, its walls are 5 mm thick; it is made of stainless steel. It has many slots for thermocouple and other measurement equipment installations. It also contains an external air fan for cooling the combustor material. The burner is also made of stainless steel and can operate thermal powers of up to 10 kW. It also incorporates a pressure sensor. In addition, there is a pilot ignition system to ignite fuel air mixture.

All experiments have been conducted at local atmospheric conditions. Mixing of fuel and air takes place at room temperature. As stated previously, equivalence ratio and thermal power of the combustor are 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

Temperature profiles throughout the combustor are one of the decisive parameters that characterize effectiveness of a combustion process. In Fig. 2, temperature profiles at different swirl numbers and d_h/d_o ratios are illustrated. Temperature values are differently affected by the variation of d_h/d_o ratio at different swirl numbers. In other words, effect of d_h/d_o ratio on temperature distribution is not monotonous. However, all temperature curves show a good consistency by means of trend.

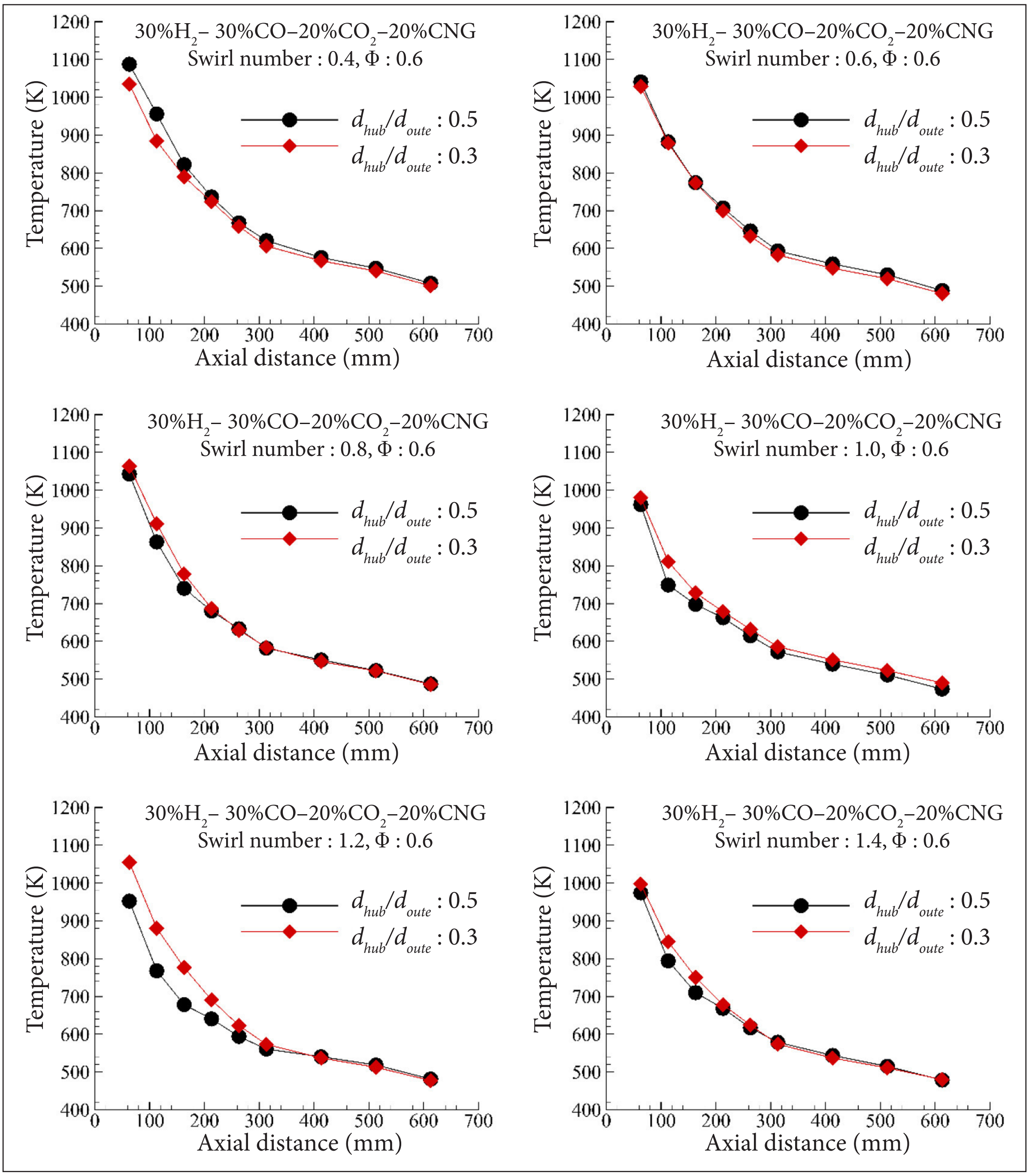

Fig. 2. Temperature profiles at different swirl numbers and d_h/d_o ratios

At 0.4 swirl number, temperature values at 0.5 d_h/d_o ratio are higher than those at 0.3 d_h/d_o ratio throughout the combustion chamber. Nevertheless, this difference diminishes towards the outlet sections of the combustion chamber and becomes nearly insensitive to the axial location after the axial distance of 300 mm. At 0.6 swirl number, temperature curves in the flame zone are almost coincident for both tested d_h/d_o ratios. Starting from the axial position of 200 mm, lower temperature values form at 0.3 d_h/d_o ratio. The opposite behaviour is the case for 0.8, 1.2, and 1.4 swirl numbers. While temperature values are lower in and near the flame zone at 0.5 d_h/d_o ratio (this difference is much more distinct at 1.2 swirl number), temperature profiles are nearly inline in the post flame zone (slightly lower at 1.4 swirl number). At 1.0 swirl number, higher temperature values form at 0.3 d_h/d_o ratio throughout the combustion chamber unlike other swirl numbers tested. In conclusion, it can be said that the effect of the d_h/d_o ratio is mainly controlled by the swirl number. Depending on the swirl number, this ratio slightly or dramatically varies temperature distribution in and near the flame region. However, post flame region temperature values are nearly irresponsive to the d_h/d_o ratio.

All emission measurements were performed at a fixed position at combustor outlet by waiting at least 5 min to reach the thermal equilibrium. In Fig. 3, measured CO values at different swirl numbers and d_h/d_o ratios are illustrated.

Likewise, d_h/d_o ratio effects on temperature profiles, d_h/d_o ratio non-monotonically affects emissions of CO. At 0.4 swirl number, the difference between CO emissions at different d_h/d_o ratios is very high (the highest at 1.4 swirl number). Consistent with temperature profiles, lower CO values form at 0.5 d_h/d_o ratio since CO oxidation kinetics favour at higher temperatures. At 0.6 swirl number, emissions of CO do not change with d_h/d_o ratio. At 0.8 swirl number, emissions of CO are higher at 0.3 d_h/d_o ratio, although temperature values are higher at 0.3 d_h/d_o ratio than at 0.5 d_h/d_o ratio. This situation indicates that CO emissions depend not only on temperature distribution but also on flow field variations. CO emission values at 1.0, 1.2, and 1.4 swirl numbers also confirm this phenomenon. Overall, it can be concluded that emissions of CO are negatively affected by the decrement in the d_h/d_o ratio (except for 1.0 swirl number).

Fuel components that contribute to the emissions of CO_2 are CO, carbon containing CNG constituents, and CO_2 itself. CO_2 emissions at 0.5 d_h/d_o ratio do not significantly change with the swirl number (Fig. 4). When the d_h/d_o ratio is 0.3, emissions of CO_2 vary identically at lower swirl numbers (0.4–0.8) but the variation becomes more unambiguous after the swirl number of 0.8. Consistently with the measured CO values, CO_2 concentrations in total exhaust gases are lower at 0.3 d_h/d_o ratio.

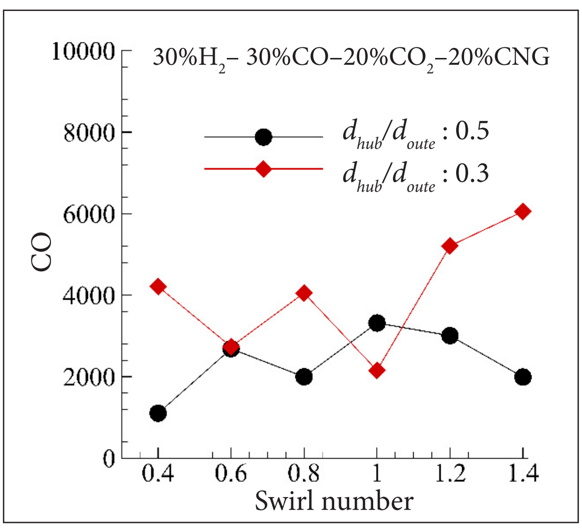

Fig. 3. Variation of emissions of CO (ppm) with the swirl number and the d_h/d_o ratio

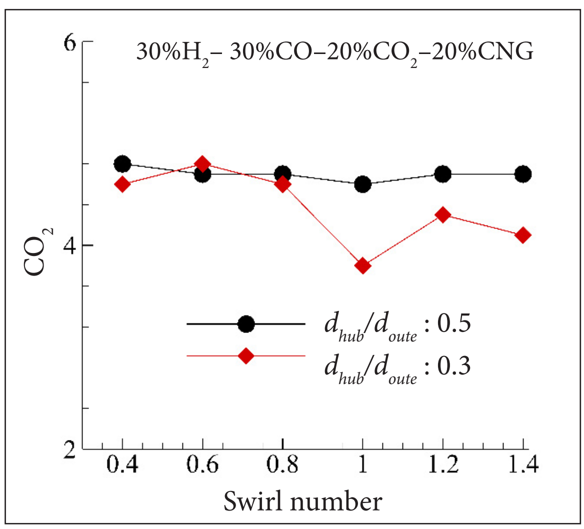

Fig. 4. CO_2 concentrations (% – as a percentage of total exhaust gases) at different swirl numbers and d_h/d_o ratios

Because all experiments were conducted under fuel lean equivalence ratio and there is no fuel originated nitrogen, measured NO_x values are low (Fig. 5). Similar to CO_2 emission values, NO_x values barely change with the swirl number at 0.5 d_h/d_o ratio. At 0.3 d_h/d_o ratio, emissions of NO_x largely increase mainly because of the flow field alterations (temperature increments also increase NO_x).

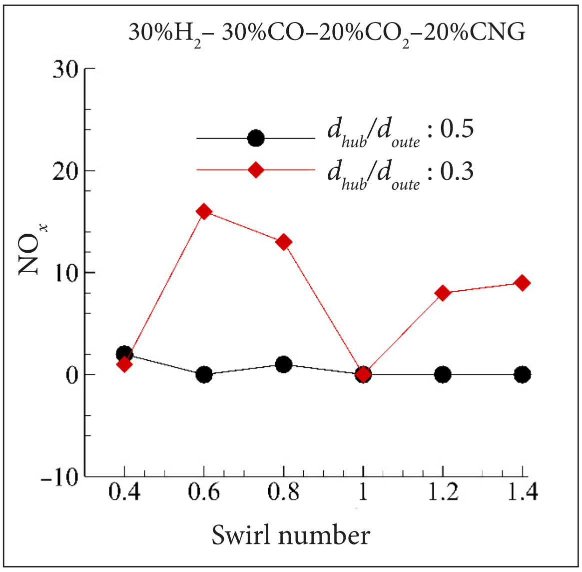

Fig. 5. Measured NO_x values at different swirl numbers and d_h/d_o ratios

CONCLUSIONS

In this study, effects of the d_h/d_o ratio on combustion and emission behaviour of premixed 20%CNG 30%H_2 30%CO 20%CO_2 mixture were experimentally investigated in a laboratory-scale combustor. Combustion behaviour was analysed by examining axial temperature profiles, whereas emission behaviour was evaluated by inspecting measured CO, NO_x, and CO_2 values at the combustor outlet. Within the scope of this study, swirl generators with different swirl numbers (0.4–1.4, at 0.2 intervals) and d_h/d_o ratios were produced and tested under the same physical and boundary conditions. Main findings of this study are summarized below:

– d_h/d_o ratio does not substantially change trend of temperature profiles and temperature values in post flame region but it differently affects temperature values in and near flame region depending on the swirl number. Besides, some similar behaviours were also observed at 0.8, 1.2, and 1.4 swirl numbers.

– emissions of CO are non-monotonically affected by d_h/d_o ratio.

– at 0.5 d_h/d_o ratio, emissions of CO_2 and NO_x are barely affected by swirl number variations. At 0.3 d_h/d_o ratio, both pollutants become more prone to the swirl number. In particular, emissions of NO_x change dramatically with the swirl number.

ACKNOWLEDGEMENTS

We would like to thank the Scientific and Technological Research Council of Turkey (TÜBİTAK-MAG-215M821) for its financial support.

Received 4 June 2021
Accepted 10 August 2021

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SUKTUVO GEOMETRIJOS (d_h/d_o) POVEIKIS SINTETINIŲ DUJŲ LIEPSNOMS. 1 DALIS: DEGIMO IR EMISIJŲ CHARAKTERISTIKOS

Santrauka

Sūkuriniai srautai padidina degimo efektyvumą, palankiai veikdami liepsnos stabilumą, teršalų emisijas ir degimo intensyvumą. Sukimosi srauto stiprumui būdingas parametras, susukimo skaičius, yra tiesiogiai priklausomas nuo d_h/d_o santykio. Šiame tyrime suktuvo d_h/d_o santykio poveikis iš anksto sumaišyto 20%SGD 30%H_2/30%CO/20%CO_2 mišinio degimo ir teršalų emisijų charakteristikoms buvo eksperimentiškai ištirtas laboratorijoje suktuvu stabilizuotu degikliu. Buvo suprojektuota ir pagaminta dvylika skirtingų suktuvų, jų d_h/d_o santykis nustatytas kaip 0,30 ir 0,50, o geometrinis susukimo skaičius svyravo nuo 0,4 iki 1,4 (0,2 intervalu). Visi eksperimentai buvo atlikti naudojant liesą kuro ir oro santykį (ϕ = 0,6) kambario temperatūros ir atmosferos sąlygomis, esančiomis Kayseri mieste, Turkijoje. Duomenų kaupiklis buvo naudojamas ašinės, radialinės temperatūros ir NO_x, CO, CO_2 profiliams pavaizduoti bei įvertinti degimo ir išmetamųjų teršalų emisijų savybes. Rezultatai parodė, kad d_h/d_o santykis turi nemonotoninį poveikį išbandytų sintetinių dujų mišinio degimui ir emisijoms. Priklausomai nuo sūkurių skaičiaus, buvo pastebėti temperatūros ir emisijos verčių padidėjimai ir sumažėjimai.

Raktažodžiai: sintetinės dujos, d_h/d_o santykis, sūkurys, degimas, emisija