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Investigation of Combustion Characteristics in a Vortexing Fluidized-bed Combustor with a Contraction Chamber

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This investigation was undertaken to obtain information on the effects of a contraction chamber and secondary air ratio (λ) on combustion temperature distribution, gas emissions of rice husk combustion and flow behaviours in a vortexing fluidized-bed combustor with a contracted chamber (VFBCC).The combustor chamber was modified by reducing the diameter chamber size (contraction) near the top part of the chamber to create a large central recirculation zone. In the experiment, the effects of secondary air ratio (λ) of 0.0, 0.25 and 0.4, and the equivalent ratio, (ϕ) of 0.2, 0.25, 0.3 on combustion characteristics and temperature distribution were examined. The results indicated that the temperature profile inside the combustor between a typical vortexing fluidized-bed combustor (VFBC) and VFBCC was slightly different.The emission of VFBCC was lower than in the original VFBC. At the equivalent ratio of 0.3 and secondary air ratio of 0.4, the average concentrations of O_2, CO_2, CO and NO_x of the flue gases from the original VFBC were 10.5%, 6.7%, 717 ppm and 287 ppm, respectively while those from the modified VFBCC were 9.7%, 6.3%, 357 ppm, and 250 ppm, respectively. In addition, flow visualization results showed the presence of a contracted part led to the recirculation formation in the top chamber.

1. Introduction

The global energy challenges are securing energy supply to meet growing demand.Alternative renewable energy sources become more important because of the alarming rate of exhaustion of traditional fossil fuel power sources. Biomass fuels are one of the energy sources that potentially replace fossil fuels, and they are receiving steadily more attention due to their potential on a worldwide scale. Rice is the world's third-most produced agricultural crop behind sugarcane and corn. Therefore, rice husk is abundantly available. In Thailand, between 10 and 15 % of the rice husk is utilized as a source of thermal energy. The rice husk can be effectively transformed into usable energy to satisfy the local need for thermal and mechanical energy. Vortexing fluidized-bed combustors (VFBC) are ones of the most suitable for converting various solid fuels or agricultural residues into energy, due to their advantages such as excellent mixing, high combustion efficiency and low elutriation of fine particles.The VFBC low-pollution solid waste incineration combustor was originally concepted by Soward (1974). The combination of a foaming fluidized bed and a cyclone burner to reduce flushing was developed and demonstrated by Korenberge (1984a). It was reported that injecting secondary air into the freeboard in the tangent direction which caused a strong eddy flow. In accordance with the concept of VFBC, Nieh *et al.* (1992) reported the effects of secondary air fraction and swirl number on the particle mass flux, gas flow structure in a VFBC model. The VFBC process could significantly reduce particulate elution as compared to that a typical FBC. Lee and Chun (1997) developed a two-stage swirling fluidized bed burner. Duan *et al.* (2013) investigated the rice husk combustion in a VFBC with flue gas recirculation (FGR). The combustion efficiency reached 99% at optimal operation condition and NO_x emissions were effectively reduced by flue gas recirculation. Vondál and Hájek (2012) predicted the swirling flow in model combustor with axial guide vane swirler.They found that the velocity predictions have significant deviation no matter what turbulence model was utilized from common set

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of commercially available turbulence models. Using PIV methods, Dechnan and Shang (2012) investigated the flow characteristics in a vortex combustion cold-wall chamber. The tests found that the injection velocity is the primary factor that determines the vortex strength and propellant mixing efficiency. It was discovered that tangential velocity increases with injection velocity. Naduvilethil *et al.* (2018) investigated the combustion behaviors in a vortex combustion chamber utilizing gaseous oxygen and gaseous hydrogen as propellants by altering their mixture ratios and nozzle throat diameter.Their findings revealed that the chamber pressure increased with the inlet pressure. The chamber pressure increased due to the decrease in throat diameter. Duan *et al.* (2015) studied bed agglomeration and combustion of pelletized rice straw in a VFBC.They found that the defluidization time was extended at elevated superficial gas velocity and lower bed temperature. Maicke *et al.* (2016) investigated the effect of different injection settings on the velocity distribution in a vortex combustor. It was established that the injector velocity, number of nozzles, and nozzle diameter had a direct effect on the propellant mass flow rate and, therefore, the swirl velocity. Chokphoemphun *et al.* (2019) examined the rice husk combustion behaviors in a rectangular FBC with triple pairs of 30° chevron-shaped discrete ribbed walls that fitted at the wall of the bottom chamber.The experimental results revealed that the highest combustion efficiency was 99.2% and the lowest emissions of CO_2 and NO_x were 2.55 ppm and 110 ppm. Sirisomboon and Laowthong (2019) reported the heat transfer coefficient in a twin-cyclonic VFBC at various secondary air ratios using silica sand with different diameters. Their results showed that the heat transfer coefficient was promoted with the increase of the primary air flow rate. The maximum temperature was found at the combustor core. The effect of percent excess air (EA) on the characteristics of rice husk combustion in a FBC was reported by Manop *et al.* (2022). The maximum CO, NO CO_2 and O_2 contents in exhaust gases were 1452 ppm, 303 ppm, 9.5%, and 12.8%, respectively. Arromdee and Sirisomboon (2021) examined the firing of ground nut/peanut shells in a twin-cyclonic FBC at various flue gas recirculation (FGR).They reported that NO_x decreased with increasing FGR while the opposite trend was observed for CO. The use of FGR of 10-18% resulted in low emissions and high combustion efficiency up to 99%.

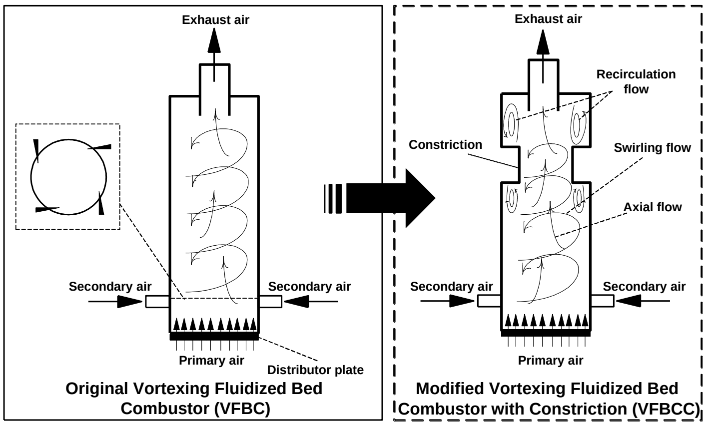

Figure 1: *Configuration of the conventional vortexing fluidized-bed combustor (VFBC) and vortexing fluidized-bed combustor with contraction (VFBCC)*.

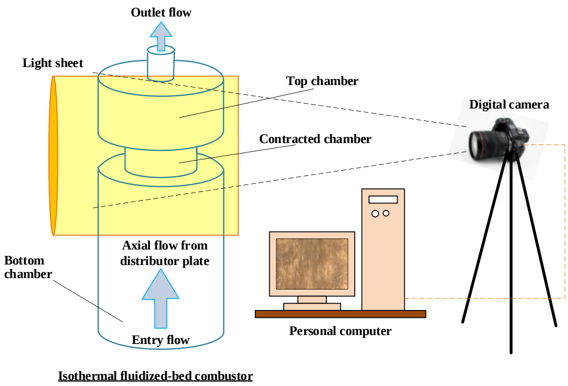

Figure 2: *Visualization setup of cold-flow model*.

Most relevant works focused on the effects of the size and shape of the combustor, fuel/biomass, equivalent ratio and secondary air ratio. In the present work, the contracted part was formed in the middle of the height of combustor.The part was expected to initiate a recirculation flow in the upper chamber.The recirculation potentially promotes combustion and reduces emissions. A sketch of the modified VFBC is demonstrated in Figure 1. The current work also aims to study the effects of equivalent ratios (0.2, 0.25, and 0.3) and secondary air ratios (0.0, 0.25, and 0.4) on the combustion and temperature characteristics.

2. Experimental apparatus

In the current experimental setup, the visualization part explores the flow characteristics of the cold model. In the second part, the combustion temperature, emissions of exhaust gas and combustion efficiency are evaluated.

2.1 Flow visualization set-up (Cold model)

Schematic diagram of the flow visualization facility performed in this investigation is shown in Figure 2. The main components are: the isothermal fluidized bed chamber with contraction, a 0.5 hp water pump, settling chamber with a water filter, camera, light sheet, and the instrumentation. At the entrance of the bed, water from the pump was conditioned in the setting chamber by a common household screen. The isothermal fluidized bed chamber had a diameter of 50 mm and a height of 350 mm. The contracted part near the top had a diameter of 25 mm and a height of 25 mm. In the experiment, water at room temperature was pumped into the test bed/chamber, and flowed through the chamber. During the test, water was recirculated between the test chamber and the reservoir tank.

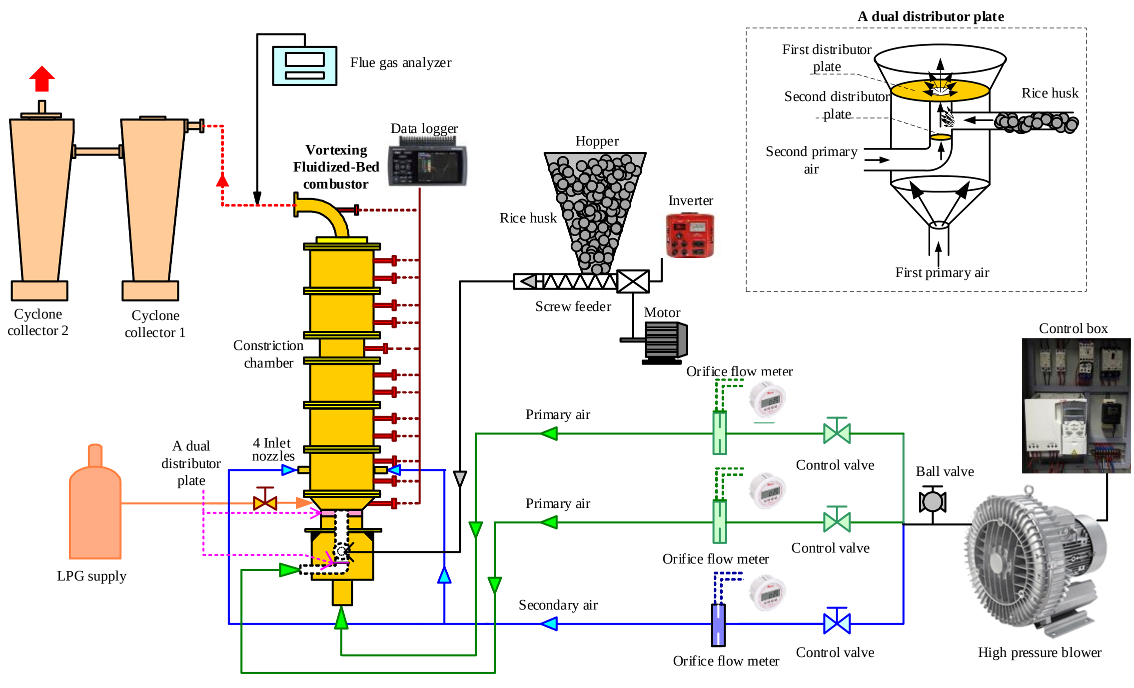

Figure 3: The experimental facility of the combustion test.

2.2 Combustion set-up (Hot model)

The experimental apparatus (Fig. 3) consisted of: (1) the vortexing fluidized-bed combustor (VFBC), (2) a 10 hp blower supplying the combustion air (Model: 7.5 kW, 1450 rpm, 15 A 380 V, backward inclined capacity 100 m^3/min, pressure 200 mm Aq.), (3) an orifice flow meter, (4) a dual distributor plate, (5) LPG supply for pre-heating the combustion air temperature in the chamber, (6) a hopper (7) a screw feeder driven with 1.0 hp motor controlled the rpm by inverter, (8) a set of thermocouple sensor for measuring the temperature profiles in the chamber (9) a data logger, (10) flue gas analyzer for measuring emission gases, and (11) two cyclones. The VFBC had a diameter of 300 mm (*D*) and a total height of 2720 mm. In this experiment, the contracted part was created in the combustor. It was expected that the small part can create recirculation flows in the top chamber. Recirculation is expected to boost combustion and minimize emissions. As seen in Figure 3, the combustion chamber diameter was reduced from 300 mm to 150 mm (0.5D) for chamber heights between 1050 and 1200 mm. A set of 4 injection nozzles was mounted at a height of 25 mm from the bottom chamber.

Two distribution plates made of stainless steel, were placed at the bottom of the combustion chamber to distribute the main air (a: main supply plate) and (b: pad) feed the chaff (Fig. 3). The center of the main distributor plate was perforated with 75 mm in diameter. The perforation was surrounded by 207 small circular holes, each having a diameter of 2.0 mm. The secondary distributor plate was perforated to form 100 holes with 2.0 mm in diameter. In the test, secondary air was fed into the lower bottom chamber through a nozzle to generate a strong vortexing flow. The main air from the dual-distributor plates flowed through the bottom chamber. Exhaust emissions at the outlet were analyzed using a gas analyzer (Testo 300XL). All data were collected at steady states.

3. Experimental results

3.1 Flow pattern

The flow field in the combustion chamber with the contraction is depicted in Figure 4. The result was taken at the flow rate 1.0 l/min. Evidently, the inlet flow is in an axial direction. Then, the flow is distorted during flowing through the contraction as restricted by the part. After passing the contraction, recirculation occurred. There were two recirculation zones, the large one occurred adjacent to the contraction and the small zone formed near the exit (the top of the chamber). The velocity profiles at the top chamber indicated the negative velocities (re-circulation/reverse flow),implying that a flow separation took place behind the contraction.

The re-circulation/reverse flow led to high turbulence intensity and excellent mixing of the fuel and the gases in the hot combustion model.

3.2 Combustion results

3.2.1 Effect of chamber contraction on temperature distribution

The radial temperature profiles inside the typical VFBC and the VFBC with a contracted chamber (VFBCC) at constant rice husk feeding rate of 18 kg /h and various secondary air ratios (λ), are illustrated in Figure 5. In general, high temperature zones of both VFBC and VFBCC formed in the core region of the chambers. The combustion temperature patterns in the bottom, middle and top zones of VFBC were all similar. Note that for VFBCC, the temperatures in the middle and top zones were considerably higher than those in the bottom zone. Consequently, the combustion temperatures of the VFBCC in the middle and top zones especially, at x =1.275, 1.425, 1.575 and 1.725 m were higher than those of the VFBC. The combustion temperatures of the VFBCC with a contraction chamber were around 400-1100°C which were higher than those of VFBC without a contraction by around 20-180°C.The higher combustion temperatures are attributed to the presence of contracted chamber which accelerates the gas flow, causes a strong recirculation flow and thus, the better contact between the fine fuel and air. The final outcome was that more energy was released.

3.2.2 Effect of secondary air ratio

Figure 5 also presents the influence of secondary air ratio (λ = 0.0, 0.25, and 0.4) on temperature distribution. Evidently, the elevated λ resulted in higher combustion temperature around the core of the combustor. The effect was more obvious in VFBCC than in VFBC, especially, in the middle and top zones (x =1.275, 1.425, 1.575 and 1.725 m) which influenced by the contraction. It can be attributed to the promoted swirling intensity and turbulence of the air in VFBCC. It is noteworthy that the use secondary air ratio of 0.4 showed a negative effect on the combustion in bottom zone (x = 0.075, 0.225 and 0.375 m) indicated by low combustion temperatures. This can be explained by the fact that the quantity of primary air (60% of total air) is not sufficient for the combustion in the bottom zone.

3.2.3 Emissions of exhaust gas

The flue gas emissions from VFBC and VFBCC are presented in Figure 6. In general, VFBCC gave lower CO, CO_2, NO_x emission than VFBC. The results revealed that the maximum CO, CO_2 and NO_x concentrations from VFBCC and VFBC were 500 ppm and 1420 ppm, 8.5% and 7.5% and 300 ppm and 330 ppm, respectively. The results signify that the combustion in VFBCC is more complete than that in VFBC due to the existence of the contracted chamber. The contraction can help to reduce gas emissions efficiently as the results the promoted gas recirculation. In addition, the emissions of NO_x and CO_2 slightly decreased with decreasing equivalence ratio (or very lean mixture) while the emission of CO show opposite trend. The remaining O_2 in the flue gases became higher at lower equivalent ratio (more excess O_2). The constricted middle section of the VFBCC induces the recirculation flow in the top chamber, resulting in a high pressure and velocity [Naduvilethil *et al.*, 2018]. Recirculation can increase combustion and minimize CO and NO_x emissions.

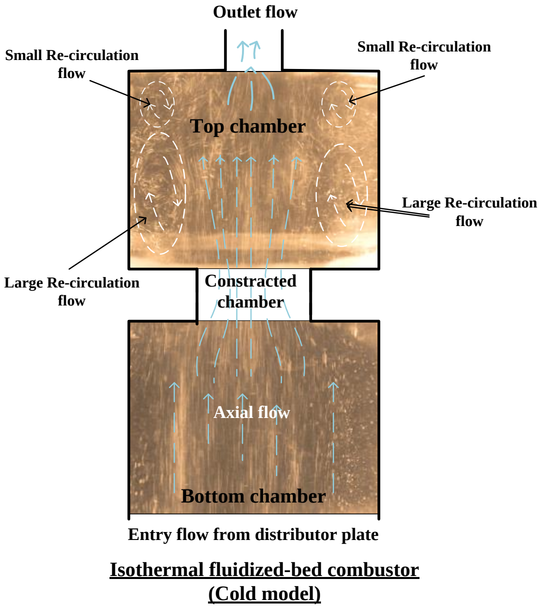

Figure 4: Flow field in the isothermal VFBCC.

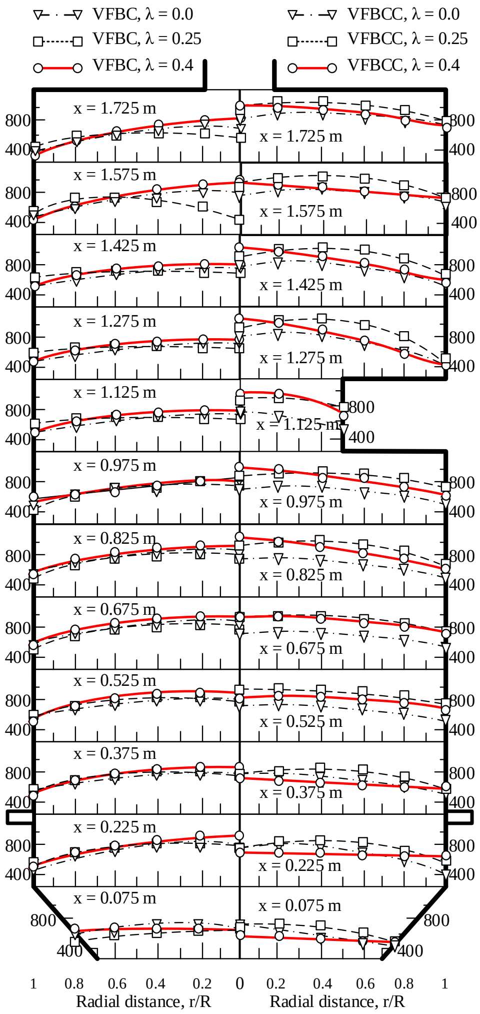

Figure 5: Radial temperature distributions in the combustor.

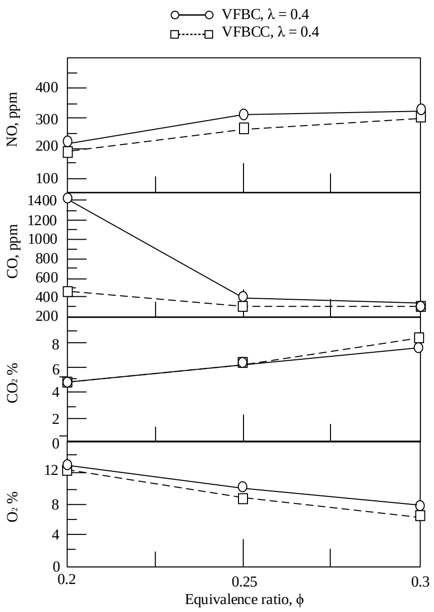

Figure 6: Emissions of exhaust gases of VFBCC.

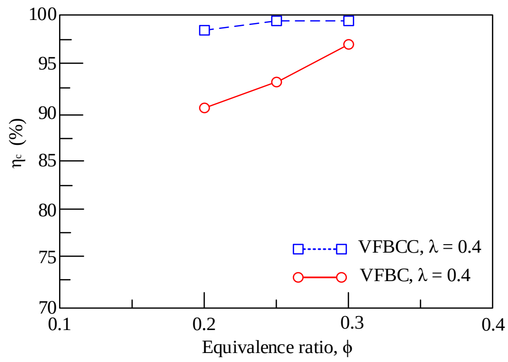

Figure 7: Combustion efficiency of VFBCC.

3.2.4 Combustion efficiency

Figure 7 shows the influence of the chamber contraction on combustion efficiency. Obviously, the VFBCC possessed higher combustion efficiencies than that the VFBC at all equivalence ratios (ϕ). The VFBCC boosts vortex strength [Dechnan and Shang, 2012], while the constriction chamber boosts recirculation flow in the upper chamber, thereby helping to improve combustion efficiency compared to those the VFBC. The combustion efficiencies of VFBCC ranged from 98.2% to 99.1% while those of VFBC ranged from 91.4% to 97.3%. The reason behind the higher combustion efficiency of VFBCC as compared to that of VFBC is the gas recirculation and thus more chaotic mixing between the fuel and air.

4. Conclusions

This study was conducted to determine the influences of a contraction chamber and secondary air ratio on combustion temperature distribution, gas emissions of rice husk combustion, and flow characteristics in a VFBCC. In order to generate a large central recirculation zone, the diameter of the combustor chamber was reduced (contraction) near the chamber's top. The major findings from this investigation can be drawn as below:

- The presence of contraction in a VFBCC increased air recirculation flow, leading in greater combustion temperatures and efficiencies than VFBC. The results indicated that the temperature profile within a typical vortexing fluidized bed combustor (VFBC) and a VFBCC differed slightly.
- VFBCC's emission was less than that of the original VFBC. At an equivalent air ratio of 0.3 and a secondary air ratio of 0.4, the average concentrations of O_2, CO_2, CO, and NO_x in the flue gases of the original VFBC were 10.5%, 6.7%, 717 ppm, and 287 ppm, whereas those of the modified VFBCC were 9.7%, 6.3%, 357 ppm, and 250 ppm, respectively.
- In addition, flow visualization data demonstrated that the existence of a contracted part was responsible for the creation of recirculation in the upper chamber.

Acknowledgments

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References

Arromdee P., Sirisomboon K., 2021, Effects of in-bed stoichiometric and flue gas recirculation on combustion and environmental performances of a swirling fluidized-bed combustor, Engineering Journal, 25, 207-214.
Chokphoemphun S., Eiamsa-ard S., Promvonge P., Chuwattanakul V., 2019, Rice husk combustion characteristics in a rectangular fluidized-bed combustor with triple pairs of chevron-shaped discrete ribbed walls, Case Studies in Thermal Engineering, 14, 100511.
Dechnan S., Shang L., 2012, Experimental research on bi directional vortices in cold wall thruster, Aerospace science and Technology, 18, 52-62.
Duan F., Chyang C., Lin C.W., Tso J., 2013, Experimental study on rice husk combustion in a vortexing fluidized-bed with flue gas recirculation (FGR), Bioresource Technology, 134, 204-211.
Duan F., Chyang C., Zhang L.H., Yin S.F., 2015, Bed agglomeration characteristics of rice straw combustion in a vortexing fluidized-bed combustor, Bioresource Technology, 183, 195-202.
Kornberg J., 1984a, Fast fluidized bed reactor and method of operating the reactor, U.S. Patent No. 4,457,289.
Lee J.K., H.S. Chun, 1997, Anthracite coal combustion in a bench scale two-stage swirl-flow fluidized bed combustor, Journal of Chemical Engineering of Japan, 30, 1125-1129.
Maicke B.A., Talamantes G.J., 2016, Effect of Injector Variation on the Bi-directional Vortex, 52nd Joint Propulsion Conference, AIAA 4581.
Manop C., Wongcharee K., Chuwattanakul V., Promvonge P., Saysroy A., Eiamsa-ard S., 2022, Temperature Distribution and Combustion Characteristics of Rice Husks in a Fluidized Bed Combustor, Chemical Engineering Transactions, 92, 715-720.
Naduvilethil R.T., Jegathjothi S.J.T., Thankappan J., 2018, Hot test studies in a spark ignited vortex combustion chamber, Chemical Engineering Transactions, 71, 1345-4350.
Nieh S., Yang G., Zhu A.Q., Zhao C.S., 1992, Measurements of gas-particle flows and elutriation of an 18 inch i.d cold vortexing fluidized-bed combustion model, Powder technology, 69, 139-146.
Sirisomboon K., Laowthong P., 2019, Experimental investigation and prediction of heat transfer in a swirling fluidized-bed combustor, Applied Thermal Engineering, 147, 718-727.
Soward N.K., 1974, Low pollution incineration of solid waste, U.S. Patent No. 3,834,326.
Vondál J., Hájek J., 2012, Swirling flow prediction in model combustor with axial guide vane swirler, Chemical Engineering Transactions, 29, 1069-1074.