CONCEPTUAL DEVELOPMENT OF A PULVERIZED COAL COMBUSTOR RIG (PCCR) FOR TESTING CO-FIRING PULVERIZED COAL AND AMMONIA FUEL

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Abstract: In Malaysia, the National Energy Policy 2022 - 2040 is focusing on achieving global net-zero greenhouse gas (GHG) emissions by 2050. To accelerate the energy transition plan, the National Energy Transition Roadmap (NETR) has been developed, which also includes the development of hydrogen, H_2 and ammonia, NH_3 co-firing for power generation. The ammonia co-firing with coal has a significant effect on reducing carbon dioxide, CO_2 emissions but it also increases the nitrogen oxide, NOx content due to the high nitrogen content in its molecules. Additionally, the flame characteristic of the ammonia combustion has a narrow flammable range and slow flame propagation. Therefore, by introducing the ammonia injection swirl nozzle in the co-firing combustion, it enables a higher flammable range and increase flame propagation to achieve a higher temperature at the burner tip. The objective of this study is to conceptually develop a new test rig for co-firing pulverized coal and ammonia fuel with ammonia injection axial swirl nozzle. The significance of this development is to further improve GHG reduction for CO_2 and NO_X emissions. The conceptual test rig is designed for conducting experiments with the variation of axial swirl nozzle angle between 30^o to 60^o and also swirl number, S_n between 0.50 to 1.48. The test rig design concept is also expected to be able to test up to 100% ammonia firing.

Keywords: green fuel; pulverized coal; ammonia; co-firing; swirl nozzle

1. Introduction

In Malaysia, the National Energy Policy 2022 - 2040 has been implemented to achieve a global net-zero greenhouse gas (GHG) emissions by year 2050. To accelerate the energy transition, the Malaysian government has also developed the National Energy Transition Roadmap (NETR), which includes the development of hydrogen (H_2) and ammonia (NH_3) co-firing for power generation [1]-[2]. The interest in co-fired ammonia has been increasing to reduce GHG emission, particularly in carbon dioxide (CO_2) due to its carbon-free fuel [3]. The ammonia co-firing with coal has a significant effect on reducing CO_2 emissions [4]-[5]. Although H_2 and NH_3 have been known as alternative fuel for the carbon-free fuel, it also increases the nitrogen oxide, NOx content due to the high nitrogen content in their molecules. The combustion characteristic of H_2 and NH_3 will enable the NOx formation, fuel-NOx, thermal-NOx and prompt-NOx at specific conditions during combustion. Furthermore, the flame characteristic of ammonia combustion has a narrow flammable range and a slow flame propagation [3]-[4]. Nonetheless, the NOx formation from NH_3 and H_2 combustion can be possibly controlled with proper combustor and new technology. One of the proposed ways for this is by introducing the ammonia injection swirl nozzle in the co-firing combustion, which will enable a higher flammable range and also increase flame propagation to achieve higher temperature at the burner tip. Based on the previous conducted studies, when the co-firing ratio increases between 20% and 30%, the flame will be changed from swirl flame to elongated flame [6]-[7].

In a previous experiment, the swirl vane angle is adjusted to reduce the flame length and obtain a similar result to that of the single coal combustion [7]. The flame appearance from this previous study is shown in Figure 1. However, experimental method to investigate the effect of flame characteristics and NOx emission when selecting different vane angles for the swirl nozzle has not yet been performed.

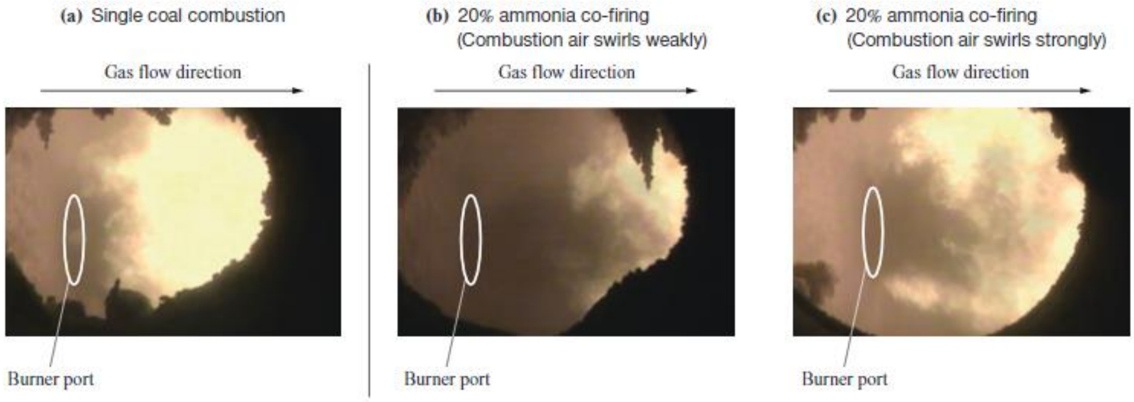


Figure 1: Flame appearance: (a) single coal combustion; (b) 20% ammonia co-firing (combustion air swirls weakly; (c) 20% ammonia co-firing (combustion air swirls strongly) [7]

In the meantime, based on another previous experiment, the CO_2 emission is found to be reduced by increasing the co-firing ratio of ammonia [4], which is observed in Figure 2. By applying an ammonia axial swirl nozzle at different vane angles, it is expected to achieve higher reduction of CO_2. Moreover, by combining the air-staging method at several points and applying an ammonia axial swirl nozzle at a higher swirl number, $Sn \geq 0.60$, it is expected to achieve lower velocity at the burner exit and fuel-rich conditions occur at the burner zone and reduce NOx formation [8]-[9].

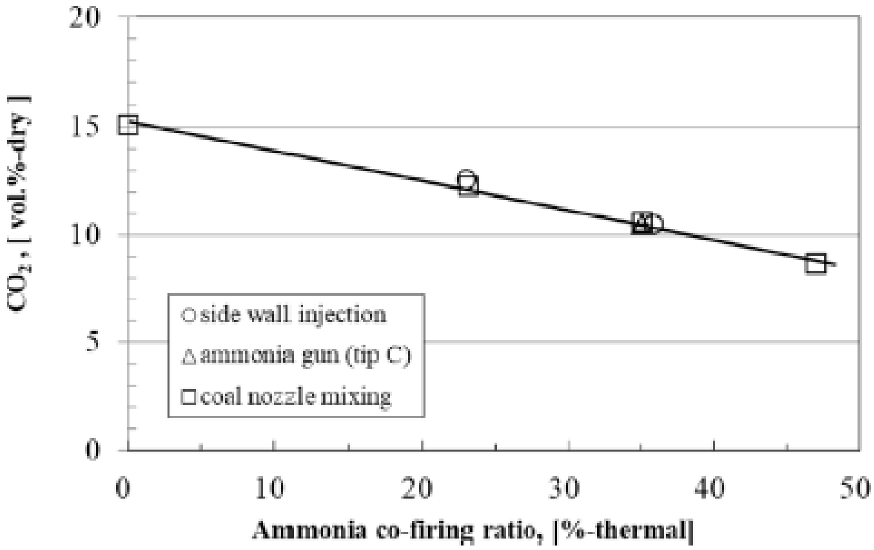


Figure 2: Change of CO_2 concentration due to ammonia co-firing ratio [4]

It should be noted that the flame characteristic has been separated into two main categories. The first is the flame length, type, size and color, which are measured by using high-speed camera and quartz combustion chamber. Second is to determine the flame temperature and combustion emission, which is in CO_2 and NO_X emission. The flame characteristic when co-firing with 20% ammonia is to be away from the burner port compared with single coal combustion [7]. This is because the flame propagation velocity of ammonia co-firing with pulverized coal is higher than firing with pure coal. Figure 3 shows the comparison of flame appearance that is more stable when ammonia co-fired with other combustion fuel such as methane.

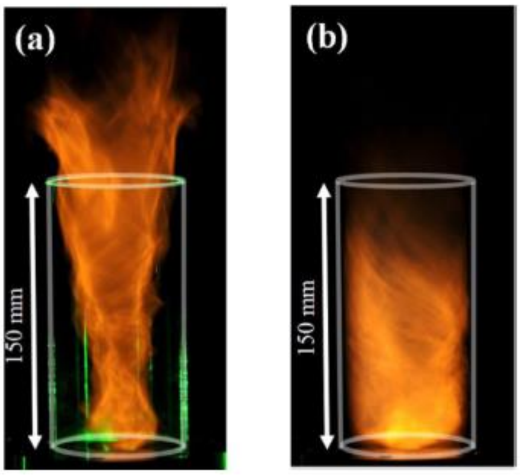


Figure 3: (a) Pure liquid ammonia spray flame; (b) Liquid ammonia spray flame co-fired with methane [10]

In conjunction to the abovementioned findings, the objective of this study is to develop a new test rig design for co-firing pulverized coal and ammonia fuel using an ammonia injection axial swirl nozzle. The test rig is designed and developed to be used to conduct experiments with variable axial swirl nozzle angle between 30^o to 60^o and the swirl number, S_n between 0.50 to 1.48. By having this test rig, the right setting could be tested to lower CO_2 emissions. It is expected that CO_2 emission significantly decreases concurrently with increase of the co-firing ratio while NOx emission can be further reduced at higher swirl number, $S_n \geq 0.60$.

2. Methodology

In this study, the test rig is conceptually designed and developed to analyze the flame characteristic and combustion emission of CO_2 and NO_X gases when co-firing ammonia and pulverized coal. Based on the findings in the literatures and established requirements for the intended experiments that will be conducted using the test rig, design concept for the test rig can be derived. Among others, the developed test rig will be comprised of burner, furnace, ammonia injection gun, pulverized coal bin, and primary and secondary air supply. The pulverized coal burner consists of an ammonia gun at the center of the coal nozzle for ammonia gas injection, secondary air with the swirl air vane and an annular coal nozzle to supply pulverized coal with primary air. A summary of the overall methodology for this study, starting from the selection of fuel and up to the analysis of the flame characteristics and pollutant (CO_2 and NO_X) emissions in co-firing pulverized coal and ammonia, is depicted in Figure 4. However, it should be noted that the presented study in this paper only covers the conceptual design development of the test rig. The expected experiments from the use of this test rig requires the capability to vary several of the parameters such as ammonia injection axial swirl nozzle vane angle, ammonia mass flow rate, co-firing ratio for ammonia and also secondary air vane angle.

The design for test rig, known as Pulverized Coal Combustor Rig (PCCR), consists of fuel system supply and furnace body for combustion and pollutant emission monitoring system. Each section in the PCCR is developed according to the intended experiments that will be conducted using it, which include to determine the flame characteristics, temperature of the flame and pollutant (CO_2 and NO_X) emissions concentration during testing with single fuel using pulverized coal and co-firing pulverized coal with ammonia injection.

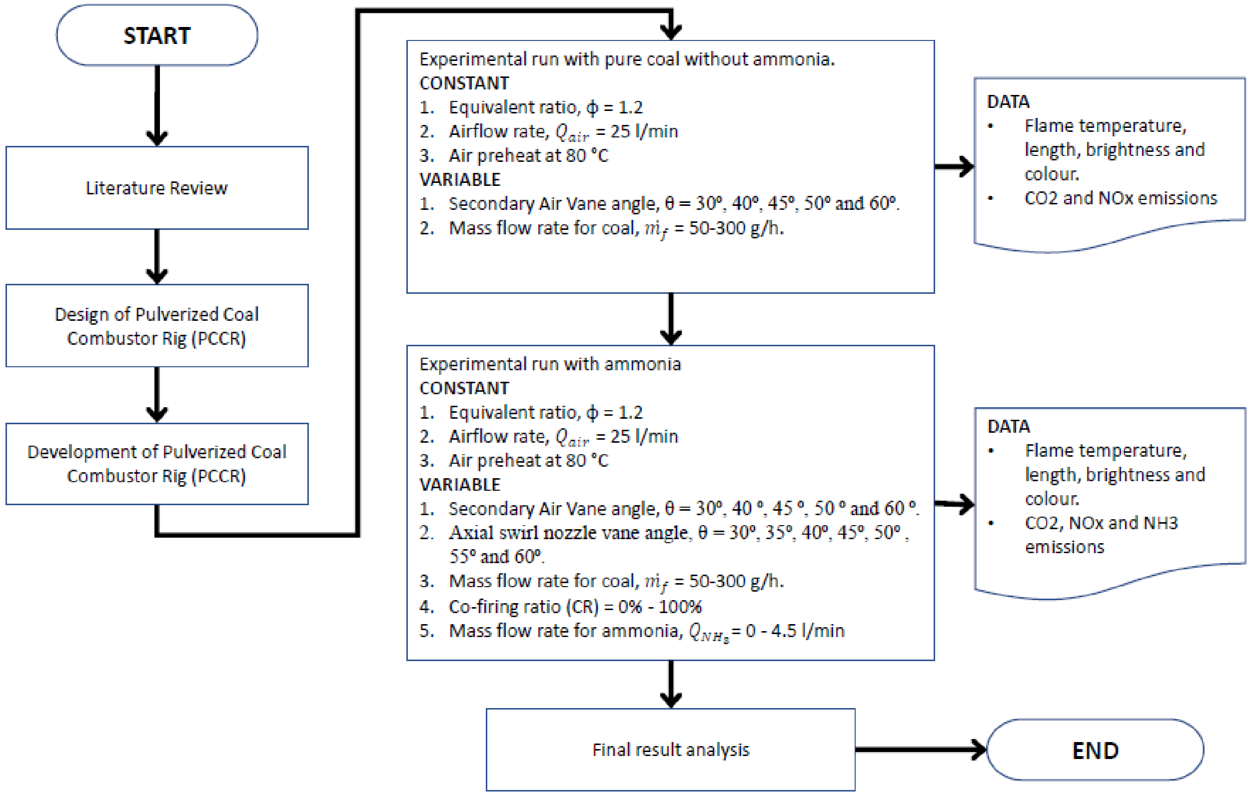


Figure 4: Flowchart of the combustion analysis of co-firing pulverized coal and ammonia from the use of the proposed test rig design

Based on the flowchart in Figure 4, an initial test will be conducted once the test rig has been fully developed. The initial testing is without ammonia to acquire the stable flame from the single fuel using pulverized coal. In this initial testing, the value for equivalent ratio, Φ is kept constant at 1.2 by adjusting the mass flow rate for pulverized coal and airflow rate from the air compressor. The air supply is heated to 80 °C through an electric heater before premixed with the pulverized coal. Both secondary air vane angle and also mass flow rate for coal are adjusted to optimize the swirl effect and obtain a stable flame. The flame characteristic is recorded for its brightness, length, color and temperature. The gas analyzer measures the CO_2 and NO_X gas concentration at the furnace exhaust in part per million (ppm) unit.

Once satisfied with the results of the initial test, the following experiment to be conducted using the test rig will use ammonia as secondary fuel for co-firing with the pulverized coal. Mass flow rate for ammonia fuel, mass flow rate for coal and airflow rate are adjusted to maintain the constant value of the equivalent ratio, Φ at 1.2. The air supply from air compressor is heated to 80 °C to supply hot air for premixed pulverized coal before entering the burner nozzle. The ammonia fuel is injected into the burner from the center of the tip nozzle. The co-firing ratio is assessed by increasing the mass flow rate of ammonia and reducing the mass flow rate for pulverized coal, which is tested up to 100% firing with ammonia. The ammonia nozzle has an axial swirl angle to produce high turbulence recirculation zone, which will stabilize the flame. The experiment with co-firing ammonia is using different nozzles with specific angle (i.e. θ = 30°, 35°, 40°, 45°, 50°, 55° and 60°). In the similar fashion to the initial test, the flame characteristics will be recorded and CO_2, NO_X and NH_3 gas concentration at the furnace exhaust will be measured by the gas analyzer.

Figure 5 illustrates the features of the experimental setup for the PCCR, including one-dimensional test furnace body, coal feeder, burner, staged air-providing system, flue gas sampling and monitoring system, and flue gas processing system. The test furnace body is a cylindrical quartz chamber with an internal diameter of 80 mm and a total length of 1000 mm, where the pulverized coal residence time can reach between 3.5 s to 4.2 s. The experimental rig is installed with a burner nozzle equipped with an ammonia injection gun tip at the center and an ammonia flow meter to control the flow rate and the co-firing ratio between ammonia and coal percentage.

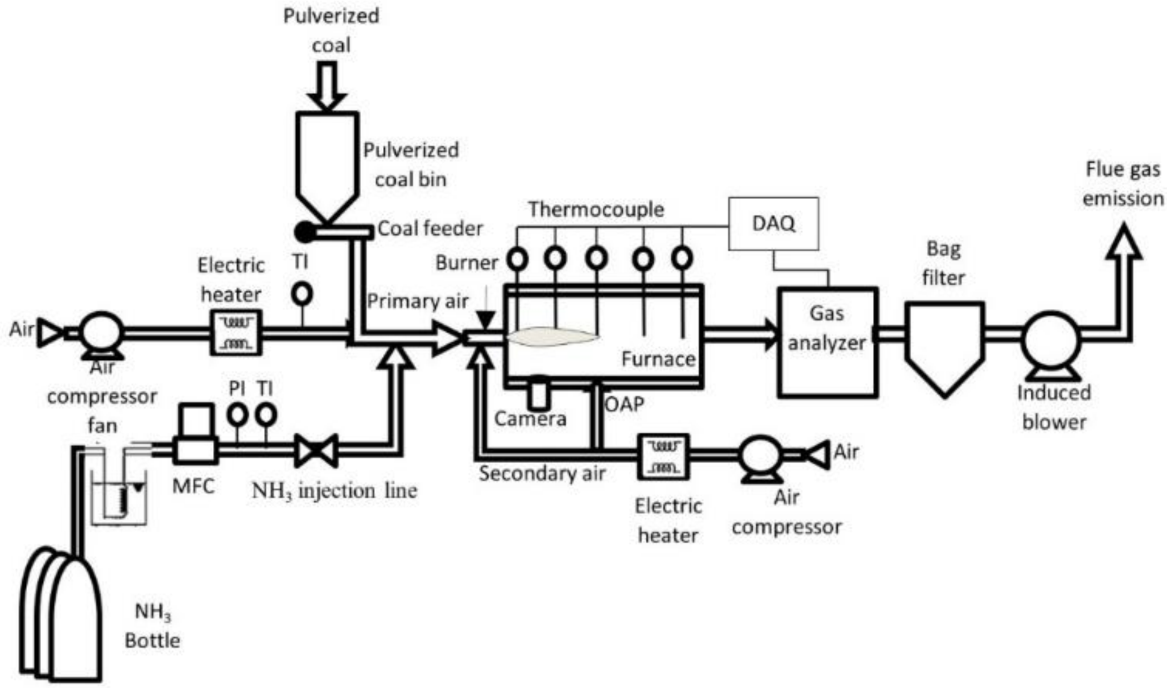
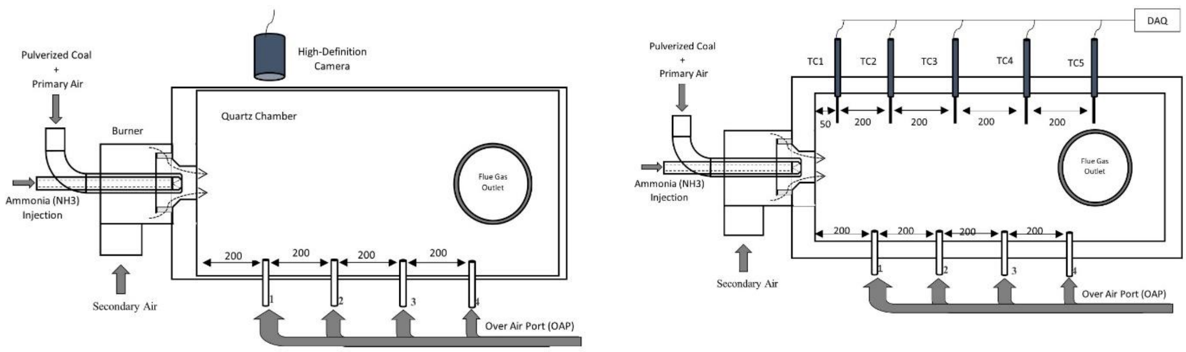


Figure 5: Schematic drawing of the Pulverized Coal Combustion Rig (PCCR)

The flame characteristic is monitored and recorded visually for its length, shape and color using a high-definition camera as shown in Figure 6(a). Secondary air vane angle for the swirler, θ that provides the secondary air into the furnace is adjusted from 30° to 60°. For this experiment, seven different vane angles for ammonia injection axial swirl nozzle are analyzed, which are 30°, 35°, 40°, 45°, 50°, 55° and 60°. Furthermore, gas properties for NO_X, CO_2 and NH_3 are analyzed in real-time monitoring by using gas analyzer, DURAG Emission Monitoring system. The flame temperature is measured at the installed thermocouple (TC) inside the furnace body at different distance from the burner tip (TC1, TC2, TC3, TC4 and TC5). The interval between the thermocouple is 50 mm from the burner throat and 200 mm between each thermocouple. The flame temperature is then recorded in the Data Acquisition (DAQ) system every 5 s during the experiment as shown in Figure 6(b).



(a) Burner and quartz chamber with high-definition camera

(b) Burner and quartz chamber with thermocouple

Figure 6: Furnace (a) to capture flame shape; (b) to measure flame temperature.

During the conduct of the experiment, the co-firing of ammonia and coal is performed to measure the effect of co-firing on both flame characteristics and combustion emission. It should be noted that the method used in this study is similar to other experiments using a bench-scale 1.2 MW-thermal coal-fired furnace to determine the effect of combustion emission on CO_2 and NOx using ammonia as co-firing fuel [4]. The pulverized coal is fed by the screw feeder with special ejector and the feeding rate of 50 g/h to 300 g/h. Moreover, the experiment involves adjustment of co-firing ratio with variable mass flow rate for coal between 50 g/h and 300 g/h, and mass flow rate for ammonia between zero and 4.5 l/min. The axial swirl nozzle angle is adjusted at seven different angles from 30^o to 60^o and the swirl number, S_n is tested between 0.50 and 1.48. Swirling induces a high turbulence recirculation zone, which stabilizes the flame, resulting in better mixing and combustion. In general, swirl is important to provide flame stability since it creates central reverse-flow zone [9, 11]. It also provides stable combustion and rapid heat release.

On the other hand, the pulverized coal burner consists of swirl air vanes, an annular type of coal nozzle and an ammonia injection gun that is located in the center of the burner. A single burner, which consists of a coal nozzle and ammonia injection gun, is mounted on one end. An indirect firing system is used and the pulverized coal is fed into the pulverized coal bin and transported using compressed air from the air compressor. The airflow rate, Q_{air} is 25 l/min and the excess air ratio (equivalent ratio) is fixed at 1.2. The compressed air is preheated using the electric heater to supply the high temperature of the air at 80 °C into the burner [12]-[13]. About 15% to 30% of the theoretical air, which is called the primary air, is supplied by the compressed air [14]. In this experiment, the coal mass flow rate is constant between 0 g/min to 3 g/min.

Last but not least, the safety of ammonia handling also needs to be taken care of according to the Chemical Safety Data Sheet (CSDS). Ammonia is classified as flammable, toxic and hazardous to human and aquatic life. Appropriate Protective Personal Equipment (PPE) including splash-proof goggles, neoprene rubber glove, face shield, respirator with ammonia filter cartridge, high boots, long sleeve shirt and long pants and boots for chemical handling. The most important area to be protected is the area exposed to the eye and skin because ammonia can cause severe skin burns and eye damage.

3. Results and Discussion

Based on the established design requirements, the PCCR test rig is developed to specifically capture the flame characteristics and monitor the combustion emissions when co-firing pulverized coal with ammonia. The design concept for the test rig is divided into three main sections. The first section is the fuel supply where the pulverized coal will be fed through the coal feeder and the ammonia liquid will be vaporized by hot water heater. The pulverized coal will be heated using supplied hot air where the heat source is an electric heater. In the meantime, the second section is the furnace body that is built in with high temperature resistance quartz chamber. This is where the burner nozzle that is equipped with an ammonia injection gun tip at the center is installed. The ammonia injection uses the axial swirl nozzle as the main variable to measure the stability of the flame during co-firing pulverized coal and ammonia. High-definition camera will be used to capture the flame characteristics whereas the flame temperature will be measured by the thermocouple. It can be noted that approximately five thermocouples will be installed at different distances from the burner tip. Finally, the third section is gas emission monitoring system using a gas analyzer to monitor the flue gas properties of CO_2 and NO_X during the experiment. The filter bag is installed to capture the fly ash exit from the furnace body to avoid from its release into the atmosphere. The gas analyzer will also monitor ammonia gas properties to ensure that the ammonia gas is within allowable limit. If the ammonia gas concentration exceeds the allowable limit, emergency shut down is taken immediately.

Swirling induces a high turbulence recirculation zone, which stabilizes the flame, resulting in better mixing and combustion. Swirl is important to provide flame stability because it creates central reverse-flow zone [9, 11]. It also provides stable combustion and rapid heat release. In terms of flame stability, the analysis using swirl burner nozzle tips for ammonia injection is crucial. It is expected to achieve a stable flame when using a swirl nozzle at swirl number, $S_n \geq 0.6$ [9]-[10]. Hence, the flame characteristic, flame temperature, and CO_2 and NO_X emission are analyzed using different burner swirl number, S_n as per Equation 1 and Table 1.

$$S_n = \frac{2}{3}\left[\frac{1-\left({D_i}/{D_o}\right)^3}{1-\left({D_i}/{D_o}\right)^2}\right]\tan\theta \tag{1}$$

Table 1: Ammonia injection axial swirl nozzle angle and swirl number [11]

Swirler No.	Vane angle for swirler, θ	Swirl number, S_n
1	30°	0.50
2	35°	0.60
3	40°	0.72
4	45°	0.86
5	50°	1.02
6	55°	1.22
7	60°	1.48
No. of vane: 10 **Vane thickness, T_v: 0.5 mm** **Hub diameter, D_i : 4.5 mm** **Tip diameter, D_o : 6.5 mm** **Swirl direction: counter clockwise**		

4. Conclusion

In this paper, the concept design of the test rig for conducting experiments of pulverized coal and ammonia co-firing has been developed. This new PCCR can be used to determine flame characteristic and also the effects of ammonia on combustion emissions of CO_2 and NO_X gases. The main sections for the test rig concept design can be divided into three major sections: (1) fuel supply, (2) furnace body for combustion, (3) gas emission monitoring. Once the test rig is developed and operational, it will be initially tested by conducting an experiment without ammonia fuel injection to obtain flame stability and expected CO_2 and NO_X emissions when firing with single fuel of pulverized coal. After achieving the required flame characteristics, and CO_2 and NO_X emission, the test rig will then be used to conduct experiment with co-firing of ammonia using injection axial swirl nozzle burner at different swirl angles. The co-firing ratio is determined by adjusting the mass flow rate for ammonia. In this experiment, the new PCCR test rig is expected to be capable to be tested up to 100% ammonia fuel and the gas analyzer can measure the excess of the ammonia gas. All in all, the new PCCR design concept is developed and has been discussed to be sufficient to measure flame characteristics and gas emission for CO_2 and NO_X. Following this conceptual development, the immediate future work involves the complete development of this test rig and it will be tested as outlined in the flowchart of the overall methodology.

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References

[1] Malaysian Ministry of Economy. (2023). National Energy Transition Roadmap. Retrieved from www.ekonomi.gov.my/sites/default/files/2023-09/National%20Energy%20Transition%20Roadmap _0.pdf

[2] International Energy Agency. (2022). World Energy Outlook 2022. Retrieved from www.iea.org /reports/world-energy-outlook-2022

[3] H. Kobayashi, A. Hayakawa, K. D. K. Somarathne and E. C. Okafor, 'Science and Technology of Ammonia Combustion', Proceedings of the Combustion Institute, vol. 37, no. 1, pp. 109-133, 2019.

[4] M. Tamura, T. Gotou, H. Ishii and D. Riechelmann, 'Experimental Investigation of Ammonia Combustion in a Bench Scale 1.2 MW-thermal Pulverised Coal Firing Furnace', Applied Energy, vol. 277, 115580, 2020.

[5] M. K. H. Md Lias and M. Abdul Wahid, 'Advance Thermal Configuration using Computational Fluid Dynamic in Co-Firing Coal and Biomass', AIP Conference Proceeding, vol. 2749, 060003, 2023.

[6] M. Liu, S. Chen, H. Zhu, Z. Zhou and J. Xu, 'Numerical Investigation of Ammonia/Coal Co-Combustion in a Low NOx Swirl Burner', Energy, vol. 282, 2023.

[7] H. Ishii, E. Ohno, T. Kozaki, T. Ito and T. Fujimoro, 'Developing of Co-Firing Technology of Pulverized Coal and Ammonia for Supressing NOx Generation', IHI Engineering Review, vol. 55, no. 2, 2022.

[8] T. Ito, H. Ishii, J. Zhang, S. Ishihara and T. Suda, 'New Technology of the Ammonia Co-Firing with Pulverized Coal to Reduce the NOx Emission', Presented at AIChE Annual Meeting, Orlando, USA, 2019.

[9] M. N. Rahman, N. Shahril, S. Yusup and I. Shariff, 'Hydrogen Co-Firing Characteristics in a Single Swirl Burner: A Numerical Analysis', IOP Conference Series: Materials Science and Engineering, vol. 1257, no. 1, 012020, 2022.

[10] E. C. Okafor, H. Yamashita, A. Hayakawa, K. K. A. Somarathne, T. Kudo, T. Tsujimura, M. Uchida, S. Ito and H. Kobayashi, 'Flame Stability and Emissions Characteristics of Liquid Ammonia Spray Co-Fired with Methane in a Single Stage Swirl Combustor', Fuel, vol. 287, 119433, 2021.

[11] S. Sheykhbaglou and S. M. Robati, 'Effects of Coaxial Airflow Swirl Number on Combustion and Flame Characteristics of Methane/Air and n-Butane/Air Flames in a Miniature-Scale Swirl Burner', Engineering Research Express, vol. 4, no. 2, 025045, 2022.

[12] M. Tamura, S. Watanabe, K. Komaba and K. Okazaki, 'Combustion Behaviour of Pulverised Coal in High Temperature Air Condition for Utility Boilers', Applied Thermal Engineering, vol. 75, pp. 445-450, 2015.

[13] X. Wang, W. Fan, J. Chen, G. Feng and X. Zhang, 'Experimental Study and Kinetic Analysis of the Impact of Ammonia Co-Firing Ratio on Products Formation Characteristics in Ammonia/Coal Co-Firing Process', Fuel, vol. 329, 125496, 2022.

[14] Z. Ouyang, W. Liu, C. Man, J. Zhu and J. Liu, 'Experimental Study on Combustion, Flame and NO_X Emission of Pulverized Coal Preheated by a Preheating Burner', Fuel Processing Technology, vol. 179, pp. 197-202, 2018.