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# Design and performance of a pressurized cyclone combustor (PCC) for high and low heating value gas combustion

K.A. Al-attab, Z.A. Zainal *

Universiti Sains Malaysia, School of Mechanical Engineering, Engineering Campus, 14300 Nibong Tebal, Seberang Perai Selatan, Penang, Malaysia

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ABSTRACT

The combustion difficulties for low heating value (LHV) gases derived from biomass fuels via a gasification process have led to more investigations into LHV gas combustors. Cyclone combustors provide good air/fuel mixing with long residence times. In this study, a small-scale pressurized cyclone combustor (PCC) was designed and optimized using computational fluid dynamics (CFD) simulation. The PCC, along with a turbocharger-based, two-stage microturbine engine, was first characterized experimentally with liquefied petroleum gas (LPG) fuel and then with both LPG and LHV gas derived from biomass in dual-fuel mode. The combustor achieved ultra-low CO and $NO_x$ emissions of about 5 and 7 ppm, respectively, for LPG fuel and of about 55 and 12 ppm, respectively, in dual-fuel mode at the maximum second-stage turbine speed of 26,000 rpm with stable turbine operation.



## 1. Introduction

The utilization of biomass fuels or biomass co-fired with other fossil fuels for medium and large scale gas turbine power plants has shown promise in terms of economical value compared with conventional power plants. The main concern with using low heating value (LHV) gaseous fuels derived from biomass is the large difference in gas mass-to-volume ratio between the high and low heating value gas fuels. Thus, LHV gases require a specially designed gas combustor that can provide a high air/gas mixing quality with the long residence time needed for the fuel to complete the combustion process. One of two designs is typically used to provide good air/fuel mixing: the cyclonic flow design that includes a radial or tangential introduction for the flow and the vane swirl generator that creates vortex flows.

Vane swirl generators are very compact in size, and they are the most-used type in the axial flow combustors of conventional turbine power systems because they produce low CO emissions. However, they provide low swirl numbers (less than 2) compared to 6–30 for the cyclone combustors that provide better mixing quality and longer combustion residence times.

There are numerous combustor designs for LHV gases. A paper was recently published on combustor design by Craig [1] for LHV gas fuel powered turbine. The combustor has multiple radial flow inlets (cyclonic flow) for air and fuel in a multi-chamber with rich and then lean combustion occurring in the primary and secondary chambers, respectively. A similar design with multiple air/fuel radial flow inlets but also equipped with a prechamber fitted with swirler vanes for better mixing has been studied by McMillan et al. [2]. The air/fuel mixture is then typically combusted in an axial flow chamber for turbine firing applications.

The other approach to LHV fuel combustion is to modify existing turbine combustors that use high calorific value fuels to be suitable for LHV fuel combustion. Charles and Neilson [3] have studied the modifications on a commercial gas turbine (LM2500PH) to be suitable for a 30 MW biomass co-generation power facility. The fuel delivery nozzle design has been expanded to handle the larger volumes of the flow with an additional gas or liquid auxiliary startup fuel nozzle. A larger fuel swirler has been provided for the singular annular combustor, along with a larger fuel delivery manifold.

Cyclone combustors have been studied in a wide range of designs for coal combustion as studied by Giles and Walter [4] and also co-firing coal with biomass as studied by Ohlsson [5] because these combustors can handle the high amounts of unburned fuel and ash particles. Hoppesteyn et al. [6] have investigated the use of cyclone combustors for LHV gas fuels derived from coal by a gasification process.

A biomass cyclone gasifier combined with cyclone combustors has been investigated by Syred et al. [7]. The investigation included both experimental and CFD modeling of the combustor under atmospheric pressure without the turbine and a maximum output thermal power of 560 kW. The cyclone combustor is a non-premixed, atmospheric type with four tangential inlets: two for air, one for gas and one for startup auxiliary fuel. The outlet of the

* Corresponding author. Tel.: +60 4 5937788; fax: +60 4 5941025.
*E-mail address:* mezainal@yahoo.com (Z.A. Zainal).

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**Nomenclature**

| | | | |
|---|---|---|---|
| $C$ | progress variable | MGT | microgas turbine |
| CFD | computational fluid dynamics | PCC | pressurized cyclone combustor |
| CHP | combined heat and power | PDF | probability density function |
| $Cp$ | specific heat at constant pressure (J/kg K) | PG | producer gas |
| $CV$ | calorific value (J/kg) | ppm | part per million |
| $\eta$ | efficiency | RSM | Reynolds Stress Model |
| LHV | low heating value | VCP | vortex collector pocket |
| LPG | liquefied petroleum gas mass | $T$ | temperature (K) |
| $\dot{m}$ | flow rate (kg/s) | $\Delta T$ | temperature difference |

combustor is tangential as well. The combustor has been used as a particle separator with a vortex collector pocket (VCP) on the side of the combustor, and no additional gas filtering.

Another experimental study has been conducted by Smith et al. [8] to investigate a two-stage, rice husk atmospheric non-premixed vortex combustor. It is a cyclone combustor with a tangential primary air inlet and four tangential secondary air inlets for each stage and a central exhaust pipe through the bottom of the combustor.

Cyclone gasifiers show better results than the fluidized bed gasifiers for direct turbine firing from the particle-cleaning point of view because they can eliminate the conventional gas cleaning units as been reported by Gabra et al. [9,10]. However, circulating fluidized bed gasifiers with a tar cracker [11–13] for gas turbine applications, such as the TPS Termiska Processer AB system in Sweden, have so far proven to be more stable and reliable in many countries.

Other technologies have been investigated to increase the efficiency of the biomass fueled gas turbine systems. The use of water–air mixture as the turbine working fluid to enhance the turbine efficiency and reduce $NO_x$ emissions has been widely investigated [14–17] with the conventional direct turbine firing and the externally turbine firing. Jonsson and Yan [18] reviewed a wide range of proposed and implemented humidified gas turbine cycles.

The current study proposes a tangential introduction of the flow in a cyclonic design with a tangential outlet. The air/fuel premixing method can improve the flame stability, especially for LHV gases fuels, by eliminating the introduction of cold air to the chamber, which can quench the flame. This technique also eliminates any requirement for a flame holder. For turbine applications, pressurized combustion is required. The common method is to use a pressurized fluidized bed combustor, as mentioned earlier. However, a pressurized cyclone combustor is presented here as an alternative for turbine power systems fueled by biomass. Novelty key elements in this study can be summarized as follow:

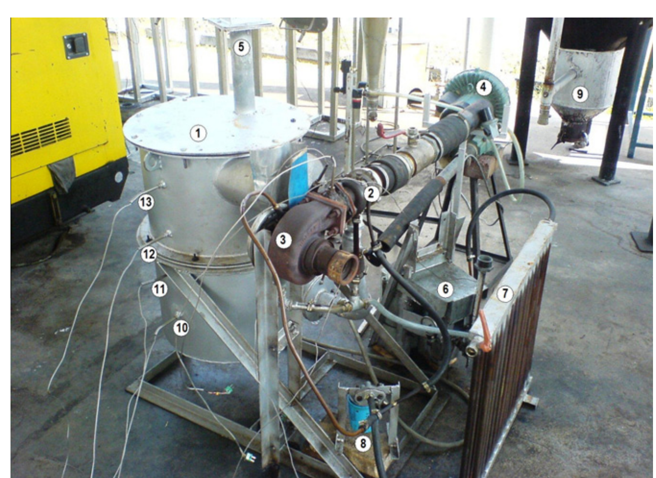
- The total premixed combustion of biomass derived LHV gases.
- The pressurized cyclonic combustion for gas turbine application.
- The experimental test of a microgas turbine (MGT) fired with a pressurized cyclone combustor.
- The implementation of a low-cost two-stage turbocharger as the MGT for biomass power applications.

## 2. System description

A small-scale pressurized cyclone combustor (PCC), along with a two-stage, turbocharger-based microgas turbine system, was designed and fabricated at the School of Mechanical Engineering, Universiti Sains Malaysia (USM), as shown in Fig. 1. The system is a standalone combined heat and power (CHP) unit where the large thermal power output can be used for drying processes in small industries, or with a recuperator for off-grid power generation. The PCC is designed for LHV gas combustion using a producer gas fuel derived from biomass via a gasification process. Fig. 2 shows a schematic drawing of the microgas turbine (MGT) system.

### 2.1. Gasification unit

A 100 kW downdraft gasifier was used to provide the LHV producer gas fuel for the combustor. It is an air-blown downdraft gasifier with a 750 W air blower that provided air for the gasification process. The biomass fuel used for the experiments was off-cut furniture wood blocks with a maximum length of about 15 cm. The producer gas passed through a narrow throat (150 mm in diameter) below the combustion zone before it exited the gasifier. The high temperature at the throat provided good tar cracking, which significantly reduced the amount of tar in the producer gas. The gasifier in this study had different hot and cold gas cleaning units with simple valve switching between the two units for the experiments. The cold gas cleaning unit included a cyclone separator, a spiral condenser for gas cooling and drying, an expansion box for further gas cooling down to 40 °C and an oil bath filter for further particle and tar removal. However, the hot gas cleaning unit




1-PCC 2-First stage turbine 3-Second stage turbine 4-Startup air blower 5-Sight glass 6-Oil gear pump 7-Oil cooling radiator 8-Oil filter 9-Downdraft gasifier 10- to 13-Thermocouples (T1 to T4) respectively.

**Fig. 1.** The two-stage MGT system.