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Development of a Combustor to burn raw producer gas

Srinivasan Dattarajan *, Ramsatish Kaluri, G. Sridhar

Siemens Technology and Services Pvt. Ltd., Research and Technology Center India, 84 Keonics Electronics City, Hosur Road, Bangalore 560100

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ABSTRACT

The development of a combustor, designed to burn raw producer gas that is not subjected to conventional gas cleaning processes, is presented. The combustor had tangential fuel and air inlets that caused a swirling flow inside it in order to facilitate fuel-air mixing and flame stabilization. The mixing and combustion performances of the combustor are characterized herein experimentally and via numerical simulations. Both measurements and simulations indicated good fuel-air mixing, the presence of a stable flame over a range of operating conditions and complete combustion of fuel. Measurement of particulate matter concentration at the combustor exit indicated that the combustor conforms to Indian regulatory norms.

1. Introduction

Clean energy technologies have been gaining prominence the world over in order to combat Green House Gas (GHG) emissions. Among them, advanced technologies such as gasification are being pursued for fuels such as coal and biomass. Biomass gasification is one such technology that makes economic sense in addition to curbing GHG emissions, especially for emerging economies such as India, China and Brazil. These technologies are suitable for both power generation and heating applications wherein fossil fuels can be easily substituted for.

Biomass gasification essentially comprises the conversion of biomass such as wood, coconut shells etc. into producer gas in an air-starved environment. This gas can in turn be used either for heating applications or be burnt in a gas engine-generator in which electrical power is generated. Producer gas emanates from a biomass gasifier at a temperature of about 500–600 °C, and contains a significant amount of particulate matter (carbon and inorganic particles) and tar (composed of higher hydrocarbons). The typical composition of producer gas from one such reactor design, called an open-top downdraft gasifier and using coconut shells as feedstock, is shown in Table 1. The concentration of particulate matter in the producer gas generated by this gasifier was about 700 mg/Nm^3 and that of tar, less than 200 mg/Nm^3 [1]. However, this gas cannot be used directly in prime movers such as diesel or gas engines, but requires to be put through an elaborate cooling and cleaning procedure [2,3], which in turn requires several hardware components such as gas cooler, scrubbers, chiller, fabric filter, water treatment plant etc. [1,4]. The steps involved in gas cleaning of a typical downdraft gasifier system are shown schematically in Fig. 1. The extensive gas cooling and cleaning system requires a large amount of captive power, which reduces the net overall efficiency of the plant. Therefore, from the point of view of reducing captive power consumption, equipment footprint and capital cost, it is desirable to minimize or eliminate the steps involved in gas cleaning/cooling. The approach of directly burning producer gas laden with tar and particulate matter, and using it in conjunction with a Stirling engine, has been developed here. This is expected to improve the overall efficiency.

The Stirling Engine, unlike a gas engine, is an external combustion engine, and can be used to convert heat to mechanical work or electrical power. Being an external combustion engine, it is immaterial how the heat provided to it is produced; this makes it versatile in that it can accept heat from a variety of sources such as solar radiation, combustion of fossil fuels or biomass, and even waste heat from industrial processes. Another advantage of the Stirling engine is that its theoretical efficiency equals the maximum permitted thermodynamically.

The experimental test facility of the present work had a 38 kWe Stirling engine installed. This engine had its own burner designed to operate on clean gaseous fuels such as Liquefied Petroleum Gas (Propane – 40%, Butane – 60%). However, this burner was not suitable for burning unclean producer gas as its passages, which were too narrow, would get clogged. This is true of other commercially available gas burners as well. Therefore, there was a need for a burner that could burn producer gas laden with tar and particulate matter. The hot products of combustion of such a burner could be used for electricity generation in conjunction with a Stirling engine; they could also be used for heating and cooling applications. Space heating, steam production and operation of furnaces in agro-based industries are examples of potential applications.

The motivation for undertaking the present development work is the non-availability of burners/combustors commercially for raw producer gas. To the best of the knowledge of the authors, there has been

* Corresponding author. Tel.: +91 80 3313 3634; fax: +91 80 3313 4503.
E-mail address: srinivasan.dattarajan@siemens.com (S. Dattarajan).

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Table 1
Composition of raw producer gas.

Major constituent	% by volume
H_2	15–16
CO	20–21
CH_4	1.5–1.8
CO_2	10–12
H_2O	3.5–4
N_2	Balance

no systematic work carried out or reported using raw producer gas as fuel. The development work reported herein aims to address this gap. Design, prototype building and testing with raw producer gas have been reported here for the first time. Critical aspects of combustor performance such as sustenance of a flame without blow-off over a range of operating conditions and compliance with emission norms have been addressed.

2. Approach

The development of a well-instrumented combustor test rig for raw producer gas was quite a challenge. Using existing information in literature, a cyclone combustor was designed. The swirl number [5] targeted was about 4 over the operating range of the combustor. The fact that the paths along which fuel and air entered were off-axis with respect to the combustor yielded the following advantages:

1. Both fuel and air were given a swirling motion in the presence of which they underwent rapid turbulent mixing with each other.
2. This enabled one to operate the combustor at near-stoichiometric conditions, i.e. without introducing a significant amount of excess air.
3. In heating applications, when the combustor is operated under fuel-lean conditions to ensure complete burning, fouling on the walls is accelerated due to the presence of excess air. This problem was avoided due to the effective fuel-air mixing facilitated by swirl.
4. Swirl is known to enhance the flame stability and therefore most suitable for low calorific value gas like the producer gas.
5. Further, swirl enhances the residence time of hot gases in the burner thereby increasing the possibility of complete burning of particulate matter and tar.

A number of configurations were initially identified and Computational Fluid Dynamics (CFD) simulations were carried out for mixing behaviour studies. Among the different configurations, one design was finalized based on criteria such as better mixing, low pressure drop and ease of manufacture. This cyclone combustor and its geometry will be discussed in the next section. Since fuel and air were introduced into the combustor via separate inlets before they burned, combustion was non-premixed. So it was essential for fuel and air to be able to mix effectively and rapidly once introduced into the combustor. The mixing performance of the combustor in the absence of combustion or heat release is studied in this paper with the aid of experimental measurements and numerical simulations, the results of which will be presented in Section 5.

Subsequent to ensuring good mixing behavior, the combustor was commissioned and successfully tested over a range of flow conditions; i.e., raw producer gas from a biomass gasifier was burnt in air inside the cyclone combustor. Measurements of particulate matter concentration indicated conformity with Indian Central Pollution Control Board (CPCB) norms. Numerical simulations to understand the burning characteristics of the combustor were carried out, and their results presented.

3. Experimental setup

Detailed descriptions of the test facility and the cyclone combustor are provided in Subsections 3.1 and 3.2 below. Two broad categories of experiments were performed in the present work – mixing and combustion. The modification done to the test setup in order to perform mixing measurements will be discussed in Subsection 3.4.

The air-fuel ratio λ is defined as the reciprocal of the equivalence ratio [6]. Thus fuel-air mixtures with $\lambda > 1$ are fuel-lean, whereas those with $\lambda < 1$ are fuel-rich. The combustion tests were performed over a λ range of 0.77 to 2.79.

3.1. Test facility

A schematic diagram of the combustor test facility is shown in Fig. 2. Solid biomass such as coconut shells was gasified in the biomass gasifier resulting in the production of producer gas, the particulate matter in which was partially removed in a cyclone separator. The concentrations of particulate matter and tar in the gas at the exit of the cyclone separator were about 400–450 mg/Nm^3 [7] and 200–250 mg/Nm^3, respectively. The producer gas exiting the cyclone separator could be directed into either of two flow paths. Using the first flow path, the producer gas could be introduced into the cyclone combustor via its fuel inlet. The second flow path led to a gas cleaning system and then either a gas engine or flare shown in Fig. 1. Since the cyclone combustor was located at a distance from the gasifier system, the hot producer gas from the exit of cyclone separator was conveyed using a long insulated pipe, resulting in drop in temperature of producer gas at the inlet of the cyclone combustor. The gas flow paths were operated one at a time using pneumatic valves V_1 and V_2.

The exhaust products of the cyclone combustor passed through a recuperator, a shell and tube heat-exchanger, in which they preheated air drawn from the surroundings. This pre-heated air was subsequently directed to the air-inlet of the cyclone combustor. The flowrate of air was regulated using an A/F (air-fuel ratio) controller, which for a given flowrate of gas into the fuel inlet, regulated the air flowrate until a desired fuel-air flowrate ratio was achieved. A blower at the downstream end of the test facility created the requisite suction to draw gases into the cyclone combustor, and product gases out of it. The cyclone combustor is described in the next subsection.

In order to reduce the temperature of the flue gases before they reached the recuperator, they were diluted with ambient air. The temperature limits on the recuperator inlet and the blower inlet arising from material constraints necessitated the use of dilution air under certain operating conditions.

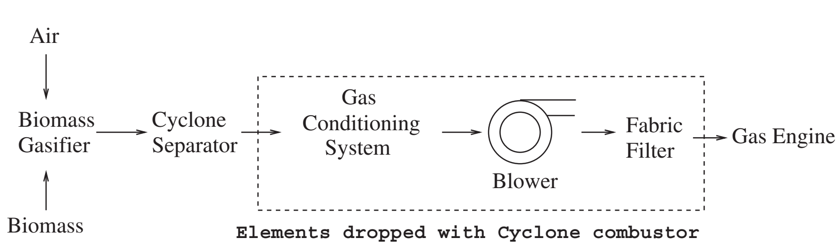

Fig. 1. Conventional approach to extraction of electrical power from biomass at sub-megawatt power level.