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Research Paper

Effect of freeboard deflectors on the exergy in a fixed bed combustor

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HIGHLIGHTS

- The influence of deflectors on the exergy analysis in a fixed bed biomass combustor is studied.
- Deflectors affect the axial mechanical exergy profiles inside the combustor.
- CO chemical exergy and thermomechanical exergy decrease when the λ increases irrespective of deflectors.
- Deflectors don't have a significant impact on the exhaust gasses availability.

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ABSTRACT

Deflectors have been employed in industrial combustors and boilers with an expectation they reduce both radiation heat losses from the fuel bed and impact particle emissions. Despite much research into lab-scale biomass combustion, there have been no systematic studies to investigate the effects of deflectors on the axially resolved and flue gas availability in laboratory scale fixed bed biomass combustors.

This study includes experiments conducted on a continuous feed pellet combustor, with a freeboard deflector located at different axial locations. The aim is to characterize the relative impact of freeboard deflectors on the mechanical exergy profiles and exhaust gas total exergy, over a range of stoichiometry (primary and secondary air flow rates). Results indicate that deflectors affect the mechanical exergy in the downstream, however their influence depends on their relative (axial) position (H). Furthermore, results reveal that for the tests with and without deflector, both CO chemical exergy and total exergy decrease in a similar manner when the air-fuel equivalence ratio (λ) increases. It has been found that deflectors do not appear to affect the total and CO chemical exergy at the exhaust section of a lab-scale combustor, bearing in mind a ±3% variation in temperature, CO emissions as well as exergies is estimated based on the uncertainty analyses undertaken.

1. Introduction

Biomass is a plentiful and well-utilised source of renewable energy which presents an opportunity to affect greenhouse gases emissions. Combustion of solid biomass fuels is a major technology in this regard which can help generate both heat and power [1,2]. In this context, grate-fired systems are widely used for biomass combustion in industrial plants [3], whereby moving grate systems are used in high thermal capacity industrial scale combustors [4]. Smaller scale combustors (<50 kW) incorporating fixed grates are also used [5]. However, in many combustion studies, laboratory scale combustors are used to investigate the effects of different process variables on combustion performance [6–8]. Because heat and mass transfer in the vertical direction is considered as the dominating factor in a grate boiler, the results of the fixed bed laboratory scale biomass combustion models find some bearing to those in industrial moving bed [9], albeit with simplifying assumptions.

Four parameters, none of which include exergy, are often used to quantify the performance of combustion in fixed beds [10]; the ignition front speed, burning rate, peak temperature and emissions.

- Ignition speed: Ignition speed which is also referred as flame front speed or reaction front velocity is based on the temperature change along the bed [11]. It shows the distance travelled by the reaction front per unit time [8].
- Burning rate: The burning rate (ignition rate) is defined as the mass of fuel converted normalized to the combustor cross sectional and time (kg/m^2 s) and expressed as:

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$$\dot{m}_b = \frac{1}{A}\frac{dM}{dt} \quad (1)$$

In this regard, A is the cross section area of the fuel bed and *dM/dt* is the change in fuel mass per change in time [8] and includes raw (moist) fuel conversion into both char or gas. To calculate the fuel mass conversion, combustor mass can be monitored by a scale or weight mechanism.

- Peak temperature: The localised temperature has many effects on combustion processes such as drying pyrolysis and gasification. The increase of the bed temperature results in an increase of fuel density, because chemical compounds with relatively low evaporation points, such as water and volatiles, are released to gas phase (vaporisation, devolatilization), leaving behind a solid phase which contains char and ash. Fig. 1 shows a typical relationship between the wood pellet density and temperature [8]. As such, the moisture content and solid fuel composition will vary continuously during combustion process as a function of bed temperature which also influences adiabatic combustion temperature.
- Emissions: Biomass is the most difficult to burn of the commonly used heating fuels. The amount of pollutants emitted to the atmosphere from different types of biomass combustion are highly dependent on the combustion technology implemented, the fuel properties and the combustion process conditions [12]. The amount of emissions released is one of the most important performance indicators in the biomass combustion. Many variables directly or indirectly influence emission levels such as bed temperature [8], fuel properties [13,14], air distribution rate and secondary air [15]. Table 1 shows some important characteristics of combustors used in the literature.

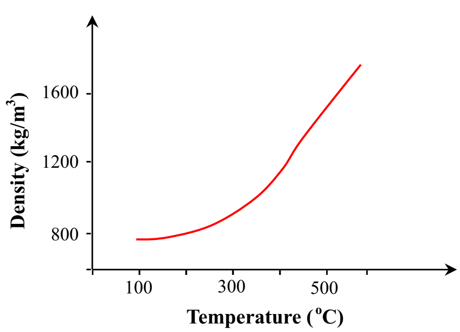

Fig. 1. Variation of density with temperature [8].

However, in addition to the above four performance parameters, exergy conversion and efficiency are important to combustion in industrial applications of biomass, such as within power plants [16]. In this regard, the work producing potential of combustion products is a significant performance indicator for the combustion process [17] and is worthy of further study, as undertaken by this paper.

The exergy analysis of combustion processes can play an important role in optimizing the design and operation of combustors. Exergy is a thermodynamic concept that describes the maximum work producing potential of a thermodynamic system when it is conducted into equilibrium reversibly with a reference environment [18,19]. Exergy analysis remains the subject of ongoing investigation in energy conversion units such as pulverized coal fired power plants [17], biomass gasifiers [20,21], internal combustion engines [22], industrial boilers [23,24], fluidized bed combustors [25], heat pump systems [26,27] and nuclear power plants [28]. An ideal process is reversible and for such process the exergy destruction is zero. Exergy loss occurs in practical processes due to thermodynamic irreversibilities even when there is no energy loss to the external environment [16]. Exergy consumption during a process is proportional to the entropy created due to irreversibilities [29]. Combustion processes are inherently irreversible which restrains the conversion of fuel energy into useful work. Chemical reactions and physical transport processes are the source of irreversibilities in combustion [30].

In typical atmospheric combustors about one-third of the fuel exergy is lost because of the inherent irreversibilities, which mostly come from heat transfer between products and reactants [16]. Fuel properties and the particular design and operational aspects of the combustion application are important factors that affect this. Woudstra et. al. [39] investigated the exergy efficiency for the combustion of different fuels, and found that exergy loss for the wood is higher compared to natural gas and coal. This may be because the process of biomass combustion is very complex and consists of many physical and chemical aspects including drying, devolatilisation, char burning and oxidization [6].

The main products of biomass combustion are particulate matter, gaseous emissions (CO, HC, NO_x, SO_x) as well as volatile organic compounds [40,41]. In commercial systems particle removal

Table 1
Wall material and insulations of reactors used in the literature.

Principal Author	Cross-Section	Diameter (mm)	Height (mm)	Liner Material	Insulation
Nicholls [31]	Circular	510	1120	Refractory lining	No insulation
Gort [32]	Circular	300	800	Stainless steel	2 mm ceramic fibre (inside), 100 mm glass wool (outside)
Gort [32]	Circular	200	800	Stainless steel	2 mm ceramic fibre (inside), 100 mm glass wool (outside)
Katunzi [8]	Circular	56	500	Stainless steel	40 mm glass wool
Rogaume [33]	Circular	200	2000	–[a]	40 mm refractory layer, 40 mm rock fibre (outside)
Wiinikka [34]	Circular	200	1700	Stainless steel	The initial 600 mm of the cylindrical walls from the bottom of the reactor have been insulated
Van der Lans [35]	Circular	150	1370	Stainless steel	–
Saastamoinen [36]	Circular	224	300	–	–
Saastamoinen [36]	Square	150 × 150	900	–	–
Samuelsson [37]	Square	300 × 300	700	–	Well insulated
Weissinger [38]	Circular	120	300	SiC[b]	Loose external, casing of firebrick
Yang [14]	Circular	200	1500	Inconel[c]	Thick layer insulating material in tight casing
Ryu [13]	Circular	100	1500	Inconel	80 mm insulation

[a] No data available.
[b] Silicon carbide (SiC), also known as carborundum.
[c] A nickel-base alloy with chromium and iron.