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Experimental investigation of wood combustion in a fixed bed with hot air

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ABSTRACT

Waste combustion on a grate with energy recovery is an important pillar of municipal solid waste (MSW) management in the Netherlands. In MSW incinerators fresh waste stacked on a grate enters the combustion chamber, heats up by radiation from the flame above the layer and ignition occurs. Typically, the reaction zone starts at the top of the waste layer and propagates downwards, producing heat for drying and devolatilization of the fresh waste below it until the ignition front reaches the grate. The control of this process is mainly based on empiricism.

MSW is a highly inhomogeneous fuel with continuous fluctuating moisture content, heating value and chemical composition. The resulting process fluctuations may cause process control difficulties, fouling and corrosion issues, extra maintenance, and unplanned stops. In the new concept the fuel layer is ignited by means of preheated air ($T > 220$ °C) from below without any external ignition source. As a result a combustion front will be formed close to the grate and will propagate upwards. That is why this approach is denoted by upward combustion.

Experimental research has been carried out in a batch reactor with height of 4.55 m, an inner diameter of 200 mm and a fuel layer height up to 1 m. Due to a high quality two-layer insulation adiabatic conditions can be assumed. The primary air can be preheated up to 350 °C, and the secondary air is distributed via nozzles above the waste layer. During the experiments, temperatures along the height of the reactor, gas composition and total weight decrease are continuously monitored. The influence of the primary air speed, fuel moisture and inert content on the combustion characteristics (ignition rate, combustion rate, ignition front speed and temperature of the reaction zone) is evaluated.

The upward combustion concept decouples the drying, devolatilization and burnout phase. In this way the moisture and inert content of the waste have almost no influence on the combustion process. In this paper an experimental comparison between conventional and reversed combustion is presented.

1. Introduction

The amount of waste generated by modern societies and the consequent increased health and environmental problems connected to landfill raises the question of an efficient solution for waste disposal and treatment. Recycling is a preferred option and governments have set their goals. In the Netherlands, more than 80% of household waste is recycled. For the remainder other options are required. One option is the combustion of municipal solid waste (MSW). The first incinerator (known at that time as "the destructor") designed by Albert Fryer was built in Nottingham in 1874, and its only purpose was waste volume reduction (Lewis, 2007). Energy recovery was included in the process in the late 1960s. The percentage of heat that can be recovered, or the amount of electricity that can be generated from such a process, has risen over the years from modest net efficiencies (~15% in the early 1980s) to a very high level in modern state-of-the-art MSW incinerators (electrical efficiency ~30% in AEB Amsterdam[1]).

Typically, in moving grate furnaces a stack of waste is supplied on a grate with or without previous mechanical treatment. Primary air is supplied below the grate, while secondary air is introduced above the waste layer through nozzles in order to stabilize the flame and improve mixing of the gases in the furnace. A layer of fresh waste is introduced in the hot furnace and the top of the layer starts to heat up and ignites due to radiative heat transfer from the flame. The ignition front, formed at the top of the layer, propagates downwards, producing heat, which is used for devolatilizing and drying the feedstock until the ignition front reaches the grate. When the reaction front reaches the grate, the new reaction front goes up and converts the remaining char during the rest of the residence time in the furnace. Total conversion is achieved more or less

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[1] http://www.amsterdam.nl/aeb/english/about-us/facts-figures/.

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close to the exit of the grate, depending on the furnace construction (co-current, counter-current or cross-current concept) and process conditions. The remains of the process, called bottom ash, falls out through the opening on the rear side of the furnace. The aim of the process is to achieve total conversion, meaning that the combustible fraction in bottom ash should be minimized or be zero.

During this conversion process over the length of the grate, different amounts of primary air are required, which is achieved by primary air sectioning, usually 4–5 zones. The combustion behaviour of the solid fuel layer in these circumstances is explained by the classical theory suggested in the analysis of Rogers (1973). In some cases, primary air is preheated in the first section to relatively low temperatures (up to 140 °C).

The general opinion was that this would lead to additional drying of the waste, but simple calculations show that this is wrong (van Kessel et al., 2004). The effect of primary air preheating to this extent was that a small part of the moisture in the area close to the grate evaporated, consequently cooling down the primary air stream. Depending on the amount and temperature of the primary air, evaporated moisture can condense on the upper layers of the stack or, at best, primary air flow with increased water content will meet the already ignited top of the layer. In both cases, ignition of the fuel is not enhanced, as is commonly considered.

Due to the highly inhomogeneous composition and stochastic properties of the incoming waste, the conversion process is subject to a lot of disturbances. These disturbances are reflected in process instabilities that can lead to: incomplete combustion and increased residual carbon content in the bottom ash; increased slagging and fouling of the heat exchanger surfaces; uncontrollable emissions from the fuel layer and, in some cases, extinction of the fire and power plant shutdown. Therefore, the process of thermal conversion on the moving grate needs to be further analysed, so that the scientifically based findings can be applied in practice to achieve better understanding and control of the process.

Since it is virtually impossible to maintain a stationary working condition in a full-scale facility for a longer period, which is required for serious analysis, and because measuring on a real scale is very difficult due to numerous constructional restrictions, a method for experimental investigation had to be developed. Many authors showed the possibility of investigating a moving grate furnace in batch-type fixed bed reactors (Fatehi and Kaviany, 1994; Gort, 1995; Shin and Choi, 2000; van Blijderveen, 2012; van Kessel et al., 2004; Yang et al., 2005; van Kuijk et al., 2008). In general, the imaginary vertical slice of the layer is followed during the movement along the grate. In this way, the spatial coordinate along the grate corresponds to the time coordinate in a batch-type fixed bed reactor.

It is important to mention that this simulation does not take into account heat and mass fluxes in horizontal direction and the mixing effects of the grate element movement. Some investigators claim that the results obtained from such tests are useful in practice (van Kessel et al., 2003, 2004). This statement can be validated by the fact that the dominant heat and mass transfer is in vertical direction, but from the other side the grate element movement has an influence on combustion behaviour, so results from batch reactors should be translated to real scale with caution. Many authors (Shin and Choi, 2000; Fatehi and Kaviany, 1994; Ryu et al., 2006; Yang et al., 2003, 2004, 2005; Pérez et al., 2012) conducted parameter studies on the combustion behaviour of a solid fuel bed.

The parameters can be separated into two groups:

(1) Operating conditions (primary air flow or velocity, primary air temperature and oxygen content of the air).
(2) Fuel properties (moisture content, volatile content, ash content, chemical composition, heating value, particle size).

While the combustion behaviour is usually evaluated by:

(1) Ignition front velocity V_{front} (m/s) (defined as vertical speed of ignition front).
(2) Ignition rate $R_{ign} = V_{front} \cdot \rho_{bed}$ (kg/m^2 s) (defined as product of ignition front velocity and actual bed density ρ_{bed} (kg/m^3).
(3) Combustion (conversion) rate $R_{comb} = (dm/dt)/A$ (kg/m^2 s) (defined as amount of converted solid mass in time over a specific area).
(4) Temperature of reaction zone T_{ign} (°C).
(5) Composition of flue gases.

In some cases, the increase of the thickness of the reaction zone in time $d\delta_{char}/dt$ is defined when the difference of ignition and combustion rate is divided by packed bed density of reacting char. In general, with regard to the primary air velocity we can identify two main regimes: the gasification (partial or oxygen limited) regime and the combustion (complete or fuel limited) regime (Gort, 1995) separated by the stoichiometric fuel-to-air ratio. An increase in the primary air feed in the gasification regime leads to an increase of the reaction zone temperature T_{ign}, which is accompanied by an increase in the fuel consumption and ignition front velocity V_{front}. An increase in primary air feed in the combustion regime, however, led to a decrease of both the reaction zone temperature T_{ign} and the ignition front velocity V_{front} leading to a slower fuel consumption than in the stoichiometric case (Shin and Choi, 2000; Fatehi and Kaviany, 1994; Yang et al., 2004; Rogers, 1973). This can be explained by a simple energy balance of the solid fuel bed consisting of two elements: heat produced by reactions Q_{react} and heat transferred between the airflow and the fuel bed by convection Q_{conv} (Semenov, 1959). In the gasification regime, the gain in Q_{react} influenced by an increase of the primary air flow is still higher than the gain in convective cooling of the reaction zone Q_{conv}, leading to an increase of the T_{ign}, V_{front} and conversion rate. In the combustion regime, the situation is the opposite. If the primary air flow is significantly increased, the flame will be extinct (Fatehi and Kaviany, 1994).

The influence of an increased primary air temperature up to 100 °C was investigated by Gort (1995), up to 170 °C by van Kessel et al. (2003, 2004), and higher than 170 °C by Nichols (2007), van Blijderveen et al. (2010); van Blijderveen (2012); Bovy (2008); Liu and Liu (2005). For the temperatures above 170 °C, autoignition is observed, and that case will be elaborated on in detail later in this paper.

Gort (1995) clearly established the relationship between the ignition rate and the airflow rate at different moisture levels of the fuel (wood in his case). It was confirmed by Yang et al. (2004) that an increase in the fuel moisture content will have a decreasing effect on the reaction zone temperatures, consequently decreasing the ignition rate. The conversion rate is inversely proportional to the moisture content in the fuel and the critical primary air flow rate, where conversion rate reaches a peak value, is higher for drier fuel.

Despite the information obtained from these studies, in-depth knowledge of the main processes occurring in MSW incinerator grate furnaces is still needed. Fluctuations in fuel composition, particle size, moisture level, heating value, non-uniform fuel bed density and the existence of channels in the fuel layer where the primary air passes through the layer without any reaction with the fuel, all create major difficulties in waste-to-energy power plants. Operators are guided by empirical relations to deal with process instabilities. More fundamental knowledge would be very helpful for a better understanding of the processes on the grate.

In the late 1990s, van Kessel et al. (2003, 2004) investigated the effect of air preheating on the combustion of solid fuels on a grate,