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Fuel 83 (2004) 1123–1131

www.fuelfirst.com

The effect of air preheating on the combustion of solid fuels on a grate

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Received 13 November 2003; revised 17 November 2003; accepted 18 November 2003; available online 13 December 2003

Abstract

Combustion of solid fuels on a grate is widely used. Mostly, the combustion behaviour is explained by the classical theory of Rogers. However, that theory cannot explain the combustion process when primary air preheating is applied. Solid fuel grate combustion is studied by experiments in a pot furnace. Experiments with and without primary air heating are described. These are compared with conclusions learnt from real plant experiments. It was found that the pot furnace experiments have a limited value in explaining the combustion behaviour of solid fuels on a grate. In order to be able to explain the results from practice an quantitative extension of Rogers' theory for the case with air preheating is presented.

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Keywords: Grate combustion; Municipal solid waste; Air preheating; Solid fuels

1. Introduction

The conversion of solid fuels on a grate is one of the main processes in municipal solid waste combustion (MSWC). However, grate firing is not only used for MSWC but also for combustion of other solid fuels, like wood and other biofuels, e.g. straw or chicken-manure, into heat and power. For process control and development of furnaces and grates, it is very important to understand the processes occurring on the grate well. In the early 1970s, Rogers [1] published a qualitative description of municipal solid fuel conversion on a grate, see Fig. 1. He described the conversion with an ignition front that propagates from the upper side of the bed towards the grate surface. The upper layer of the bed is heated by radiation from the flame in the gas phase. During this propagation oxidation produces heat, which is used to dry and devolatilise the raw material below the reaction zone. Due to the counter current flow of primary air, the reaction zone is small and very distinctive. If there is a shortage of oxygen in the reaction zone, a char layer can be formed. From the moment that the reaction front reaches the grate, the reaction front goes up and converts the remaining char with oxygen into CO and CO_2 during the rest of the residence time of the fuel on the grate in the furnace. However, this theory has some shortcomings. As will be shown later, it is not valid in the case of using primary air preheating. This is important as many MSWC suppliers are using primary air preheating. The general accepted explanation is that the preheated air dries the fuel and the ignition will take place earlier on the grate. In this article, it will be shown that it is impossible to dry the fuel with the preheated air during the residence time of the fuel in certain sections. So, other phenomena in the waste layer have to be considered.

Furthermore, Rogers did not present any quantitative description of the phenomena. Gort [2] studied this subject extensively. As real-scale installations are not very suitable for studying in detail the combustion behaviour, in the early nineties erected Gort [3,4] a batch-type reactor (pot furnace) for grate combustion experiments with solid fuels. Later in the nineties, a number of researchers used the same type of reactor to study the ignition phenomena of solid fuels [5–8]. Most of these authors used these experiments to validate a static model of solid fuel combustion on a grate. Most of these descriptions have the drawback that they are not translating the results from the laboratory to real plant with moving grates. Recently, Thunman [5] made a start

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doi:10.1016/j.fuel.2003.11.008

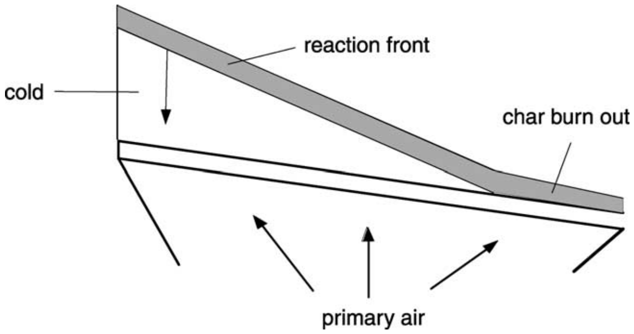

Fig. 1. Combustion of municipal solid waste according to Rogers.

by applying the results from laboratory experiments to real-scale furnaces. It was found that it is not straightforward to apply the results on real-scale combustion of wood chips. A new theory was developed, where it is proposed that the bed is not ignited from the top by radiation, but at the grate surfaces.

All studies consider the combustion process to be stationary. However, the continuously changing composition of the waste makes the process instationary. Furthermore, some grate suppliers are using discontinuously moving grate systems, which makes the system inherent dynamic. For these reasons, in this study, observed dynamic behaviour will be used to develop a theory for combustion of solid fuels on a grate.

This article is outlined in the following way. In Section 2 of this article experiments with solid fuels in a pot furnace will be discussed. The experiments are divided in two parts: without and with air preheating. Section 3 of this article will compare observations in real-scale plants with the pot furnace experiments. Here, also conclusions about the usefulness of pot furnace experiments for studying the combustion behaviour of a solid fuel on a grate will be given. In Section 4, an extension of Rogers's theory will be presented. In Section 5, the proposed theory will be applied to observations in real plants. Finally, conclusions will be given.

2. Experiments in pot furnaces

2.1. Solid fuel combustion without preheated air

As already mentioned in Section 1, Gort and Brem [3] were one of the first who carried out quantitative research in the mechanisms of solid waste combustion on a grate. They studied the incineration process in a packed bed experimentally as well as theoretically. Assuming that no mixing of waste occurs over the length of the grate, an assumption which holds very good in practise and is also confirmed by others [9], a batch packed bed reactor, also called a pot furnace reactor, can simulate the incineration process of a volume of burning waste that travels along a grate with constant speed. In real plants, there is a feedback of radiation from the back-end of the fire to the beginning of the fire. This 'radiation interaction' is not completely covered by this process, but the experiments give a good view on the processes which occur in the waste layer. Furthermore, the influence of grate movements are not incorporated.

Gort [3] carried out almost all experiments without air preheating and used wood blocks, cokes, as well as shredded municipal solid waste. Furthermore, Ortmanns [10] carried out experiments where municipal solid waste with different compositions (moisture, combustible, and inert fractions) was used. In this way, it was possible to determine more precisely the calorific value of the waste and the influence of it on the experiments. The used experimental setup is shown in Fig. 2. From beneath primary air is supplied while above the waste layer secondary air is supplied to enable a further burnout of the gases. The system is placed on a mass balance to monitor the decrease of the weight. Thermocouples are placed along the height (six in total, 15 cm equidistant) and flue gas is sampled at the top of the bed in

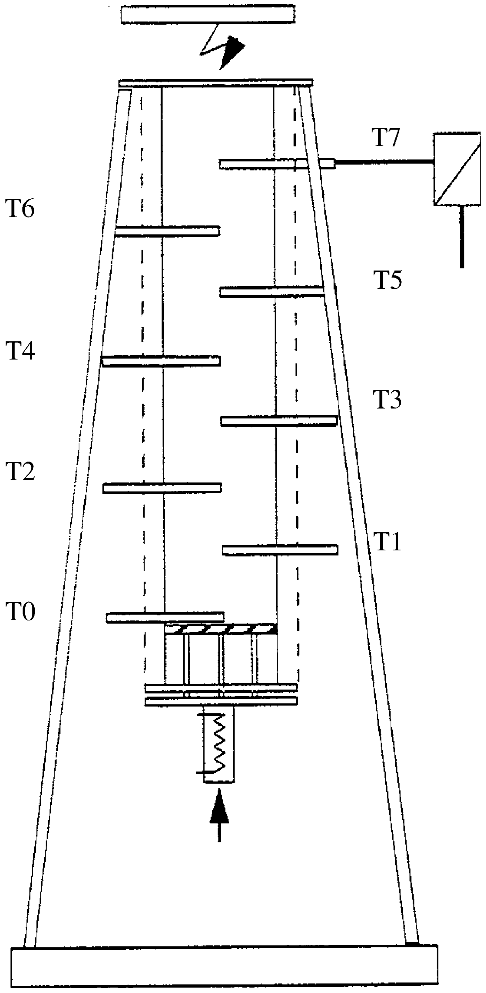

Fig. 2. Schematic of the experimental set-up for packed-bed combustion.

order to study the incineration behaviour. The process is started by using a heating element above the reactor. After ignition, the heating element is removed and the process runs autonomously. The reactor has a height of about 150 cm, while the internal diameter is 15 cm. The reactor can contain about 5–7 kg of fuel. The primary air temperature can be heated up to 500 °C. Every 20 s, temperatures and concentrations signals are sent to a computer.

Gort [2], Ortmanns [10] and Koch [11], discovered that the process behaves like a reaction front that slowly moves from the top of the bed to the bottom. There is a very clear distinction between a hot burning part (active) and a cold fresh (non-active) part. These results are in agreement with the results of Ref. [1] and later studies [5–7,12–15]. The purpose of the performed research was to find a practical description of the combustion behaviour, which can be used in models describing the complete MSWC process. From these experiments, an empirical relation was obtained, where the ignition rate was dependent on the moisture concentration and the superficial air velocity. It has to be noticed that in the empirical relation, the reaction rate is not dependent on the amount of mass, but linear dependent on the cross-sectional area of the reactor. However, in Section 3, it will be shown that for real plants this relation is not valid. In Section 4, attention will be given how to translate this result into a useful relation for a real-scale plant. Furthermore, the presented relationship is only valid for non-preheated air situations. Therefore, in Section 4, the influence of air preheating will be discussed.

2.2. Influence of preheated air on solid fuel conversion

Up till now, the general opinion is that air preheating is responsible for the drying of the waste in the first zone of a grate. However, the primary air temperature is mostly maximised by about 170 °C. Given the amount of primary flow that is used in practise in the first zone of a grate, with some simple calculations it can be shown that only a few percent of the moisture in the waste can evaporate in the first zone. So, it can be concluded that this opinion is not supported by physical laws. Therefore, it would be useful to know the exact influence of air preheating on the process behaviour. With this knowledge, it is for example possible to use the primary air temperature as an active control variable. The main goal is to reveal the influence of air preheating on the combustion process. Pot furnace experiments have been used to study the effects. Although, in normal practice inhomogeneous waste is burned in our experiments is chosen for a more well-defined fuel. The aim is not to achieve a complete detailed description of the effect of primary air heating, but to present some general conclusions regarding air preheating, that can be translated in formulae to be used in combustion models.

2.2.1. Experimental observations

To study the process behaviour with primary air preheating, experiments have been carried out with the experimental set-up described in Section 2.1. General observations during the experiments with air preheating showed that in the beginning there is an ignition front, like in the experiments with no air preheating. Furthermore, as a result from the energy in the primary air, moisture is evaporated in the lower part of the reactor. Due to this evaporation, the temperature of the primary air will decrease. Depending on the amount of primary air and temperature, the evaporated water can condense on the fuel more upstream in the reactor. Anyway, the gas that flows through the burning layer contains a higher content of water vapor compared to the case without preheating. During the experiments, the evaporation will continue and as a result, an evaporation front will propagate along the height of the reactor. At the same time, the combustion front propagates down the packed bed. At a specific time, these two fronts will meet each other. At that moment, the ignition rate increases significantly and reaches very quickly the bottom of the bed. As a result, the total remaining mass burns, so the combustion regime has changed completely. The duration of the conversion process after the breakthrough is small (5–15 min) compared to the time before the breakthrough (120–180 min). It was tried to distinguish between the mass converted before the breakthrough time and the remaining mass, but this was not possible because of the amount of char remaining after combustion.

2.2.2. Reference experiment

In all experiments, the same well-defined fuels were used: cubic wood blocks of 18 mm and a moisture fraction of 30%. First, a reference experiment with no preheated air ($T_{pa} = 20$ °C) was carried out. Although, the primary air preheating is only 20 °C in this experiment, also evaporation will take place. After 181 min, the ignition rate accelerates with a factor 2. The value for the ignition rate R ($0.029\ \mathrm{kg\ m^{-2}\ s^{-1}}$) is in good agreement with earlier experiments [2,11,10]. Exact comparison is not possible because the last two used municipal solid waste. Gort also used wood blocks, but his wood blocks had other dimensions (10–30 mm), while the moisture fractions were 10 and 30% for the 10 mm wood cubes and 10% for the 30 mm ones.

2.2.3. Experiments with only wood cubes

In these experiments, the superficial gas velocity of the primary air has been changed at two different primary air temperatures, 140 and 170 °C. The main interest of this study was to investigate the effect of primary air preheating on the ignition behaviour. During all this experiments, the same phenomena were observed as in the experiments without primary air preheating. Therefore, here only, the two main results will be discussed shortly. For more detailed results, the interested reader is referred to Ref. [16]. The first conclusion is that the total reaction time is shortened when primary air preheating is used. An evaporation front is moving upwards, while the ignition front travels downwards. When they meet, the ignition accelerates due to the fact that the remaining fuel is already dried. The second main conclusion is that after the breakthrough time, no proportional relation between the reaction rate and the remaining mass can be found. This was not possible due to the already formed char during the combustion. So, it was not possible to distinguish between the mass formed by char that is formed before the breakthrough, and the remaining unconverted mass. Based upon these experiments, no conclusions can be given about the relation between the reaction rate and the amount of unconverted mass.

2.2.4. Experiments with wood cubes mixed with plastics

Experiments carried out at the TNO-laboratories in the past showed that when waste is heated up with preheated air of about 180 °C, waste can ignite spontaneously. This phenomenon is also observed when waste is put into an electric oven and the temperature is increased up to 180 °C. Furthermore, from literature [17–21], it is known that condensed-enhanced ignition can occur in piles of fuels. This theory says that when humid air flows along relative dry fuel, the moisture will condense and release its heat. As the time-scale for heat transfer is smaller than the time-scale for mass transfer, in some circumstances this condensing can locally give a concentrated heat release, by which the temperature increases, locally intense. Sometimes, it can cause an ignition of the fuel. Another mechanism is that the saturated air cannot contain more moisture. So the released heat cannot be used for evaporation. In that case, it will be transferred to the non-moisture parts, which could ignite then. So, a critical heat loss rate should exist to avoid self-ignition. This is described by the classical theory of Frank-Kaminetskii [17].

Keeping both phenomena in mind, experiments with plastics were designed. The idea was that plastics ignite more easily, compared to wet wood cubes. As in general, the initial plastic load is free of moisture, condensation of moisture on the plastics surface could cause a spontaneous ignition of the packed bed. Based upon this assumption, poly-ethylene spheres ($d = 3$ mm) were mixed with wood cubes, but with keeping the calorific value constant. This was achieved by increasing the moisture fraction of the wood up to 35%. Mixing 2.3% poly-ethylene with 97.7% wood results in constant calorific value of 12.6 MJ kg^{-1}. Only three experiments with poly-ethylene wood mixture have been carried out. In all three experiments, ignition of the packed bed due to preheated air was not observed. Therefore, it is concluded that ignition induced by recondensing of the moisture on plastic spheres will not be occurring. Also self-ignition, which from a theoretical point of view could have taken place in the dried lower parts of the packed bed, did not occur in the experiments. As the main objective was the investigation of ignition of the bed, no more experiments with plastic-wood mixtures were carried out.

2.3. Summary pot furnace experiments

The influence of primary air preheating in pot furnace laboratory experiments can be summarised as follows:

- The combustion front on the top of the bed remains, but the ignition rate will in general be lower than in the case without primary air heating. This is because of the condensing moisture in higher parts of the packed bed. Also, the heating of the evaporated water vapor up to about 900 °C in the reaction zone has a negative consequence on the ignition rate.
- At the same time, an evaporation front propagates from the bottom to the top of the bed. At higher primary air temperatures, this propagation speed will be higher. After a certain time, these two fronts meet each other. At that moment, the remaining mass starts to burn almost instantaneously. At high primary air temperatures, the combustion rate is accelerated about a factor 10. So, instead of one combustion regime there are two different combustion regimes in case of primary air preheating.
- The total reaction time is reduced with about 40–60 min for the situation with $U_g = 0.15$ ms^{-1}. For the other gas velocities, no experiments without primary air preheating have been performed. The difference in total reaction time between $T_{pa} = 140$ and 170 °C is limited.
- No autonomous ignition or ignition induced by moisture condensation is observed when mixtures of wood and plastic are used.

3. Comparison of pot furnace experiments with observations in real-scale plants

In this section, the results from the laboratory experiments will be verified against observations in real-scale plants.

3.1. General observations in MSWC plants

To translate the laboratory results to real MSWC plants, first observations from real MSWC plants will be summarised. As already mentioned in Section 1, some grate suppliers are using primary air preheating, while others do not, while the average calorific value is often the same for both. The difference can be seen in the dimensions of the grate and the grate damage. In general without air preheating, the combustion behaves like a pipe–bowl combustion as in the laboratory experiments. Based upon the laboratory experiments, it is known that when air preheating is used, two regimes will occur: pipe–bowl and total combustion. The advantage of the latter lies in the fact that a smaller grate can be used as the average combustion rate is higher. However, using no preheated air has the disadvantage of a larger, so more expensive grate, but there is the advantage of less grate damage due to corrosion. In plants with air preheating, in most cases in the vicinity of the end of the first section of the grate and the beginning of the second section the corrosion damages are the highest. Thermocouples placed at these places in the grate indicate that the temperature at the end of the first grate section is about 500 °C, which becomes lower further downstream the grate. At biomass grate incinerators Thunman [5] found the same temperature level and distribution along the grate. Furthermore, Thunman had the possibility to look through a small window to the fire front (normally, it is only possible to look to the fire end, near the grate end) and saw a lot of smoke coming from the bed in the first sections. He also found that volatiles are released from the first section up to the fourth section.

The presence of air preheating results in an ignition of the total waste layer at the end of the first zone of the grate. The first question that arises is to check whether it is possible to dry the waste completely in the first section of a grate. This can be calculated easily by an energy balance over the first section if the amount of primary air, the waste flow, the moisture content in the waste and the temperatures of the entering waste and primary air are known. Then, it follows that for normal operating conditions only a small part (5–15%) of the total moisture in the waste can evaporate in the first section. Thunman [5] came to the same conclusion by measurements in wood-fired grate systems. Hence, the influence of the primary air temperature must be different to what is generally thought. From real-scale plants, combustion rates can be easily deduced, as the grate surface area and the waste throughput are known. As the last part of the grate is mainly to achieve a good burn-out, only about 80% of the grate area is important for the combustion. Urban [22] has given values for the mass load for different suppliers. If this is corrected with a factor 0.8, the values for the ignition rate range from 0.09 to 0.17 kg m^{-2} s^{-1}. These values are in agreement with values found in a lot of MSWC plants and wood-fired boilers. For installations that are not using primary air preheating the values are generally lower (0.07–0.09 kg m^{-2} s^{-1}).

Another remarkable point is that the superficial velocities of the primary air are much higher (0.4–0.5 m s^{-1}) in the main part of the fire, compared to the velocities that can be achieved in laboratory experiments. This can be explained that due to the well-defined fuels used in the laboratory experiments the air distribution is almost optimal, while in practice the structure of the material is very complex resulting in a less good air distribution. Furthermore, the waste in real plants is moving due to the grate movement, which can result in air redistributions. Furthermore, although the superficial velocities in some pot furnace experiments are as in real plants, in practice the momentum of the air flow is much greater due to the small air nozzles in the grate bars at the bottom of the waste bed. Due to the locally high velocities not all air is well divided across the waste layer. To translate the results from the pot furnace experiments to real-scale MSWC plants, these effects have to be taken into account. It is very difficult to quantify these effects based upon theoretical considerations. Therefore, an empirical factor X_{air} is defined to incorporate the effect of the bad distribution of the primary air. This factor is defined as the fraction of air that goes through the waste layer into the gas phase without having interaction with the solid material in the bed. This value X_{air} has to be empirically derived from real-plant data. Recently, Yang [23] published results from a study where the effect of channelling in MSWC has been studied quantitatively.

It was already mentioned that from the pot furnace experiments without air preheating, an empirical correlation for the ignition rate was derived. This equation was originally used in a complete dynamic model that is described elsewhere [24,25]. However, it turned out that it was impossible to achieve any physical reliable results without multiplying the experimental equation with a multiplication factor. In other words, the experimental observed ignition rates are much lower than would be expected based upon modelling work and practical data from the pot furnace experiments.

3.2. Results from system identification experiments on real-scale plants

System identification is a method to reveal the dynamic behaviour of processes. The results from these experiments are models that describe the input–output behaviour of the plant without any physical meaning. With these relations, step responses can be made which can be used to study the plant behaviour in more detail. Here, only the main results of the system identification will be discussed. For more detailed information about system identification, the validation of the models and application to MSWC the reader is referred to Refs. [16,26,27].

Experiments at real plants have been performed at different primary air temperatures. At different primary air preheat temperatures, different step responses were found. The response of the steam production on a step change in the waste supply results in the case of $T_{pa} = 70$ °C in a response without inverse response, while in the case of $T_{pa} = 120$ °C there is a clear inverse response. In the plant, the situation with $T_{pa} = 70$ °C was only possible during a certain time when fresh, relative dry waste was burnt. This indicates that the calorific value was higher in the $T_{pa} = 70$ °C than in the $T_{pa} = 120$ °C case. Unfortunately, only the average calorific value (9.5 MJ kg^{-1}) during the experiments with $T_{pa} = 120$ °C was known. Furthermore, it was clear from the identification results that the reaction rate is proportional to the amount of burning mass on the grate [16]. This is in contrary to the observations in the pot furnace experiments, which indicate that the reaction rate is proportional to the surface area [16]. So, it can be concluded that the combustion mechanisms in the pilot plant experiments differ from real plants. The reason for this discrepancy can mainly be found in the dynamic movement of the waste on the actual grate ('poking'). In the packed bed, the waste-pile is a stationary pile, while in the plant continuously waste is fed in to the furnace strongly influencing the structure of the waste pile in the first zone.

3.3. Conclusions from observations

The major conclusion which can be made from the aforementioned phenomena is that in general, the results from pot furnace experiments cannot explain quantitative as well as qualitative observed phenomena in real plants. Hence, the conclusion that pot furnace experiments are not representing solid fuel combustion behaviour on grates is very well justified. The main reason for this deviation is the solid fuel movement that is induced by the grate movement. However, pot furnace experiments can be a useful tool to study some more general effects, like, e.g. the effect of self-ignition, air preheating and the general combustion behaviour. With the latter especially the structure of the relation between ignition rate and superficial air velocity is meant.

4. Extended theory for combustion of solid fuels on a grate

In this section, the present theory for the combustion of solid fuels on a grate will be extended in order to explain the observations with and without air preheating. The proposed extension is qualitative as well as quantitative; i.e. it can be used in overall dynamic process models.

First, a short description of the quantitive theory will be given. In Ref. [16], general mass and energy balances for the fuel layer and the gas phase are given. An analysis shows that for describing the main dynamics of the combustion process in the furnace, the derived partial differential equations can be transformed into some simple, ordinary differential equations. The resulting model comprises three instationary balances (mass and energy balance for the waste layer and one for the steam system) and one stationary gas phase balance. The gas phase can be considered to be stationary as the time constant of the gas phase is negligible compared to the other time constants in the process. In the model, the reaction rate is described by a classical first order surface reaction with externally limited mass transfer:

$$\text{Reaction rate} = RaM = \frac{1}{\dfrac{1}{k_\mathrm{d}} + \dfrac{1}{k_0\,\mathrm{e}^{\frac{-E_\mathrm{a}}{R_\mathrm{g}T_\mathrm{s}}}}}\,\frac{[\mathrm{O_2}]M_{\mathrm{O_2}}}{\nu_{\mathrm{O2}}}\,aM \qquad (1)$$

with k_d, the mass transfer coefficient (m $\mathrm{s^{-1}}$), E_a, the activation energy (J $\mathrm{mol^{-1}\,K^{-1}}$), $\mathrm{M_{O_2}}$, the molecular mass of oxygen (kg $\mathrm{mol^{-1}}$), k_0 a pre-exponential constant (m $\mathrm{s^{-1}}$), R_g the universal gas constant (J $\mathrm{mol^{-1}K^{-1}}$), $[\mathrm{O_2}]$ the oxygen concentration (mol $\mathrm{m^{-3}}$), ν_{O2}, the stoichiometric factor ($\mathrm{kg_{O_2}}$ $\mathrm{kgwaste^{-1}}$), a the interfacial area ($\mathrm{m^2\,kg^{-1}}$) and M the amount of burning fuel (kg).

Based upon the observations in real plants and the pot furnace experiments, it was found that there are two major combustion regimes: the pipe–bowl regime and the total combustion regime. It will depend on the specific circumstances which regime will occur. In Ref. [16], it is shown that for both regimes the above mentioned reaction rate can be used. In the subsequent sections, the two regimes will be described in more detail.

4.1. Pipe–bowl combustion regime

In the first section on the grate, the combustion process starts by heating the upper layer of the bed by radiation from the flames resulting in a high release of volatiles. After this initial phase, a propagation front is created which propagates slowly to the bottom of the bed. At the place where the front reaches the upper surface of the grate also the fire end is located. During the propagation, the processes occurring in the waste layer are drying and devolatising. Combustion of the gases will partly take place in the gas phase in the waste pile and partly in the gas phase above the waste pile. The oxygen is used for the conversion of the volatiles and if oxygen remains this will be used for gasification and combustion of the char layer.

From the laboratory experiments, no relation between the reaction rate and the amount of mass could be found, in contrast to the identification experiments, which were carried out in plants also where the pipe–bowl regime was present (i.e. situations without primary air preheating) [16]. Since it was also found that the pot furnace experiments have only limited usefulness for real plants, the proposed theory is for a great extent based upon the results from the real plants. Application of formula (1), shows that the ignition rate is dependent on the amount of mass and has the following relation:

$$R = k_\mathrm{d}\frac{[\mathrm{O_2}]M_{\mathrm{O_2}}}{\nu_{\mathrm{O2}}}aM = U_\mathrm{f}aM,$$

with U_f the ignition rate in kg $\mathrm{m^{-2}\,s^{-1}}$. Here M is the burning mass in kg, which means only the mass in the upper part of the layer. The interfacial area a has to be determined experimentally from the experiments in the real plants. From the experiments, it followed that the reaction rate is only dependent on the mass transfer coefficient k_d, i.e. the reaction is mass transfer limited. For U_f empirical relations from pot furnace experiments can be used, where the superficial air velocity has to be corrected by $U_\mathrm{g} = X_\mathrm{air}U_{\mathrm{g-plant}}$ and where the relation has to be multiplied by a correction factor (as discussed in Section 3.1) in order to achieve a good magnitude for the combustion rate. It is also possible to fit the k_d and ν_{O2} value to experiments from

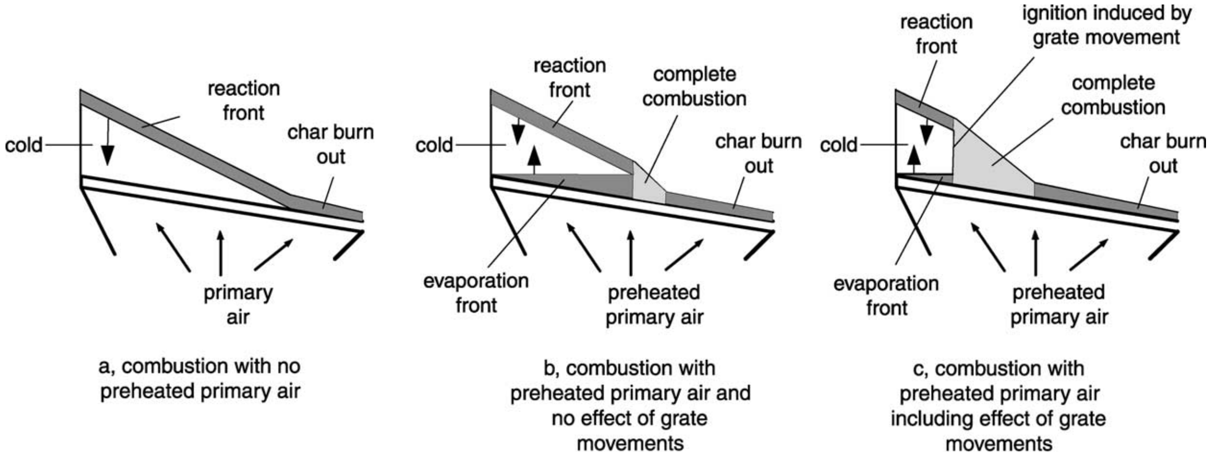

Fig. 3. Different combustion regimes in dependence of primary air temperature and grate movements.

the real plant. The achieved k_d value can be explained with classical Sherwood relations [16].

At the moment, the reaction front reaches the surface of the grate the fire is extinguished. In the remaining section, the remaining char will burnout. In fact, this part of the theory is equal to the theory of Rogers [1], with the advantage that quantitative relations are given.

4.2. Total combustion regime

The total combustion regime always starts with the pipe–bowl combustion regime. Due to the air preheating, the lower part of the waste pile will be dried. Two possible explanations for the sudden ignition can be given. First, due to the grate movement, burning particles will fall through the waste pile to lower, already dried, parts where they will induce the ignition of the complete pile. It will depend on local circumstances (grate movement, temperature primary air, calorific value waste) if and when the ignition will occur. Secondly, although in our experiments with wood cubes and plastic spheres no autonomous ignition was found in practise, with waste as fuel it is not impossible that self-ignition can occur. This is because in waste the interfacial area is higher than in the performed experiments and probably in waste there are some materials present with a lower ignition temperature than the used wood–poly ethylene mixture. From the moment of ignition, the conversion rate is higher and the process conversion is accelerated compared to the situation before.

Based upon the observations in real plants, the total mass converted is dependent on the total amount of mass burning. Therefore, the same type of relation (1) can be used. The difference compared to the pipe–bowl regime lies in the fact that M is the total burning mass on the grate, which is higher than in the case without air preheating. The consumption of oxygen is the same as in the case without air preheating. During both stages, the oxygen is consumed in the gas phase by the volatiles and only if oxygen remains, char is converted. Further, char combustion and gasification takes place after the fire has been extinguished.

Fig. 3 summarises the above outlined different combustion regimes as function of primary air temperatures and grate movement.

5. Application of the extended theory to observations from system identification experiments

In this section, the theory will be used to explain the phenomena observed in the real plants, as this is not so straightforward.

First, the case with low primary air heat temperatures will be discussed. In this situation with relative higher calorific values of the waste, the situation is that a reaction front will propagate down through the waste pile. In this situation, the front speed of evaporation is lower than in the situation with higher primary air temperatures. Therefore, a total ignition situation will probably not be reached. From the model and the observations, it was learnt that the reaction rate is linear to the amount of mass. This means that due to a step on the waste flow, the amount of mass converted in the top of the waste pile is increased. This increased conversion rate moves slowly down the grate, resulting in a gradual increase of the total mass burning. In the initial phase, the extra amount of waste has to be heated up. This is supported by the already shortly discussed physical–chemical derived model, which is described in Ref. [16]. Secondly, there is the case with higher primary air temperatures. In this situation, there are two combustion regimes: the pipe–bowl regime and the total combustion regime. Before total ignition takes place, an evaporation front propagates upwards in the bed. At the same time, the combustion front propagates downwards. Like the situation with lower primary air temperatures, the reaction rate is linear proportional to the amount of mass. So, when a step is applied on the waste a gradual increase of the amount of burning mass will also occur. But in this case an inverse response was found, which could only be explained by an increase of the moisture evaporation compared to the situation before the applied step, see Ref. [16]. The inverse response cannot be explained by heating up of the fresh new material. However, as discussed before, the evaporation in the lower part of the bed is limited by heat transfer. The only explanation is that compared to the situation with no primary air preheating the calorific value will be lower. This implies that the fuel, compared to the case without preheating, is relatively more wet and it takes more energy to heat up this more wet fuel. Due to the more needed energy, the gas temperature in the gas phase is lowered and due to the radiation interaction the adjacent waste is influenced by these step, resulting in a shift down the grate of the breakthrough point. Relative to the combustion this results temporarily in higher moisture evaporation. After a while when the waste is completely dried and the two fronts meet each other, the total combustion regime will start.

The last point to be discussed is the application of the theory to the observations of Thunman [5], as the proposed theory is somewhat in contradiction to Thunman's theory. They concluded that the observed phenomena can be explained by ignition of the fuel on the grate. This ignition is initiated by either heat transfer through the grate bars or by burning particles that are not transported along the grate by the grate movement. The first explanation cannot be the initiating mechanism as the same phenomena are also observed in incinerators with water-cooled grates. To our opinion, the second explanation is doubtful. If particles are not transported on the grate, they will be lying on the grate bars. This implies that they will be cooled and ignition will become very problematic. With the theory presented in Section 4, it is possible to explain phenomena observed by Thunman as will be outlined now.

Thunman used in his experiments wet wood (moisture content 50%) and the used primary air was saturated at 45 °C and further preheated up to 145 °C. Due to the very wet fuel, the combustion rate front at the top is very low, resulting in bad combustion and a lot of smoke. At the same time, the preheated air already contains a lot of moisture, which has the result that from the wet fuel not much moisture can be evaporated. To study the evaporation of moisture in pot furnace experiments, a plug flow model was developed which describes the evaporation front in a packed-bed [16]. From that it follows that with wood containing 50 (wt) % moisture and air preheating of 145 °C, the evaporation speed is about 30% lower than the experiments presented in this article. But, the moisture in the air will condense at higher parts in the bed resulting in a decrease of the ignition rate with the generation of smoke as possible consequence. From the moment the total fuel layer will burn, so after ignition, it will be limited by mass transfer of oxygen which explains the relatively high amount of volatiles along the grate up to the fourth section.

5.1. Consequences for solid fuel combustion on a grate

From this research, some suggestions can be given for practical use in MSWC or biomass combustion on a grate:

- From the results, it follows that the total combustion time can be reduced by using primary air preheating. This implies that smaller grates can be used. A disadvantage can be the higher thermal load on the grate, which can cause an increase in damage. Therefore, a well balanced integration with water-cooled grates can result in more compact furnace designs.
- When primary air preheating is used, the application should be limited to the first sections until the breakthrough of the reaction. Energy can be saved and maybe damages to the grate in later sections, due to locally too high thermal loads, can be avoided. In practice, it is difficult to determine the place where the breakthrough takes place. Often, it can be seen by looking to places where the grate is damaged. In general, primary air preheating in the first two zones would be sufficient. Maybe primary air preheating in the first zone may help to reduce the temperature at the top of the first zone, because of the amount of water that is heated up and evaporated. Furthermore, it can be considered to use preheating in the last zone in order to achieve a good burn-out of the bottom-ash.

6. Conclusions

In this article, the present theory for the combustion of solid fuels has been extended in order to explain the observed phenomena with air preheating. The combustion process without air preheating can be described with the classical theory proposed by Rogers. The extension of the theory with air preheating is able to explain all observed phenomena gathered in real plants and described in literature. The main point of the theory is that preheating of the primary air acts as a catalyst for the ignition on a grate rather than only drying of the waste. This means that air preheating can be used as an important control variable. A combination of water cooled grate with efficient primary air preheating can result in smaller and more compact furnaces.

Furthermore, the reaction rate for the conversion of waste on a grate is dependent on the amount of mass. Different primary air temperatures do not influence this dependency.

It has been concluded that pot furnace experiments have only a limited value in studying grate furnace combustion. The translation from plug flow movement into a batch-type reactor is limited by the fact that in the real plant, the grate movements have a large impact on the combustion behaviour. This effect is not simulated in the pot furnace experiments. For that reason, should the translation of results of pot furnace experiments to practical solutions be made with care.

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