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Experimental reactor for analysing biomass combustion properties

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The objective of the present contribution is to summarise the main parameters of a new-generation experimental grate combustion reactor. The conclusions are based on a review of the main properties and construction details of existing grate combustion reactors. Grate combustion reactors are used for the collection of data necessary for detailed modelling of grate combustion of solid biomass fuels, solid municipal waste, wood or coal. Due to the complexity of the grate combustion process its mathematical models and simulation software tools must be developed and verified using experimental data. This work highlights required properties of laboratory reactors, discusses design and operational issues and concludes by drawing several key design recommendations.

1. Review of experimental grate combustion reactors for solid biomass fuels

Experimental grate reactors may be generally categorized as small, large and very large. As the main criterion for this classification we use the fuel capacity for which they are designed. Small reactors are typically charged with 150-200 g of fuel, whereas large reactors typically have capacity of 2-7 kg of fuel. As a sub-class of small reactors, single particle test facilities also bring important information for samples formed typically by spherical particles of fuel with diameter less than 1 cm.

The focus of this article is on large reactors as they offer probably the most effective way to simulate grate combustion on a laboratory scale. They enable continuous measurement of a number of parameters including e.g. fuel sample weight and temperature. Small reactors are covered in the review as well, as they typically provide less, but more accurate information than large reactors. Their specialization enables some interesting design solutions that could be inspiring also for the class of large reactors. Reactors of both these categories are mostly batch type.

On the other hand, very large reactors are continuous reactors resembling industrial rather than laboratory units, see e.g. Frey et al. (2003). They are used namely for coal combustion or municipal solid waste incineration and they are naturally extremely expensive.

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Most of the laboratory grate combustion reactors are cylindrical in shape. The sole exception of which the authors of this work are aware is a test facility at Lappeenranta University of Technology, which has a hexahedral pot furnace (150 × 150 × 900 mm), as described by Horttanainen et al. (2000) and Partanen (2003).

1.1 Small reactors

Small reactors have typically diameter of about 100 mm. One of the smallest is a single particle facility presented in Peters (2002), situated in Forschungszentrum Karlsruhe. The reaction chamber consists of an insulated cylinder (diameter 50 mm, height 100 mm), electrically heated to the desired temperature.

A more complex small laboratory scale combustor can be found in Graz University of Technology. According to Weissinger et al. (2004) it is composed of a cylindrical retort (internal diameter 120 mm, height 350 mm), heated electrically by two separately controlled heating circuits. The fuel is put into a cylindrical holder (internal diameter 95 mm, height 100 mm). Both parts are made of fibre-reinforced SiC ceramics to avoid CO, NO, and ash reacting with the wall. The sample holder is mounted on a plate, which is put on a balance to investigate the mass loss during fuel oxidation. Six thermocouples are placed in the sample holder of the fuel bed to follow the propagation of the reaction front by measuring the time-dependent temperature distribution in the bed of fuel. Five thermocouples are placed in the bed. One thermocouple is placed on the axis of the combustor, directly beneath the bed to measure the temperature of the combustion air.

Another interesting small reactor was built in the Waste Incineration Centre of the Sheffield University (SUWIC). According to Yang et al. (2006) a stainless-steel reactor (diameter 125 mm, height 500 mm) is placed inside a furnace with inner temperature control. The temperature within the reactor is monitored by three K-type thermocouples. Nitrogen is supplied from below the reactor to purge the volatile gases released from the sample during pyrolysis. Increasing nitrogen flow rate can reduce the residence time of pyrolysis species in the bed and hence subdue re-polymerisation processes, affecting final char, oil and gas yields. Volatile gases and nitrogen leaving the reactor pass through two water-cooled condensers to separate tar vapours from the gas stream. Tar is collected in a disposable plastic container at the bottom of each trap. The composition of gas products past the condensers is monitored by a gas analyser and by taking samples for further analysis using a gas chromatograph.

1.2 Large reactors

The SUWIC operates also a large fixed bed reactor as described by Yang et al. (2004). It consists of a vertical cylindrical combustion chamber (interior tube surrounded by a thick layer of insulating material and an external casing), pilot burner, grate, air supply system and weighing scale, as shown in figure 1. The grate consists of a perforated plate made of stainless steel with approximately 700 holes of 2 mm diameter, representing 7% open area. This reactor is the only one of those studied in this article, which has been reportedly used for solid waste combustion.

Ryu et al. (2006) give some further specification of the SUWIC large reactor. The combustion chamber is made of Inconel 600 alloy and has inner diameter of 200 mm and a height 1500 mm with 80 mm of outside thermal insulation. The chamber is equipped with 11 measuring ports in the wall for access of K-type thermocouples and sampling probes. Seven of them are located within 430 mm above the grate level. A gas burner is directed at a 45° toward the waste from 750 mm above the grate. The gas burner is used to initiate the burning process of the waste sample and to maintain combustor temperature during the experiment. Primary air is fed from the bottom of the fixed-bed reactor through the grate without preheating. The data logger records the measured temperatures, gas concentrations and mass loss every 15 or 30 s.

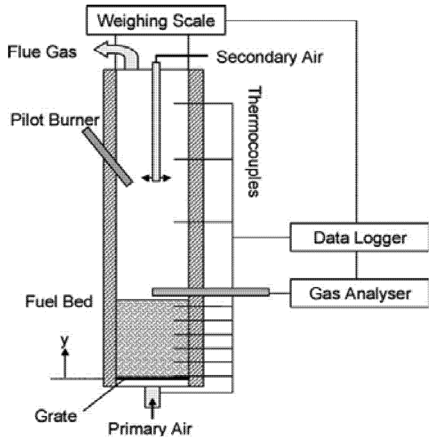

Figure 1. Schematic drawing of the large reactor of SUWIC, from Ryu et al. (2006)

A very specific reactor is described by Wiinikka and Gebart (2004). They use a 10 kW pellets reactor that has been custom designed for systematic investigations of particle emissions from wood pellets. In contrast to all other lab reactors discussed in this text it has a continuous fuel supply. The design is similar to commercial pellets stoves but has been made rotationally symmetric and relatively high to simplify measurements. The reactor is a vertical cylinder, 200 mm in diameter and 1700 mm in length. The grate is a perforated stainless steel plate with 121 holes and 2,3% open area. The secondary air is supplied by 24 holes in three horizontal sections, eight holes in each section. The height from the grate to the first inlet section in the secondary zone is 360 mm. The holes are located symmetrically around the centre line and their diameter is 3 mm. The injection angle of the jets in the secondary zone can be changed to allow an adjustable amount of swirl flow in the reactor. The initial 1200 mm from the bottom of the cylindrical walls is insulated to minimise heat loss. The remaining 500 mm of the walls are left in free contact with the ambient air.
The last large experimental reactor discussed in detail in this work is situated in the Technical University of Denmark in Lyngby and is used mainly for the combustion of straw. Based on Zhou et al. (2005) the rig consists of a fuel bed combustion chamber and a secondary combustion chamber. The height of the fuel bed chamber is 1275 mm with an internal diameter of 154 mm. The inner tube is an externally insulated cylindrical steel vessel, which is able to withstand temperatures up to 1500 K. At the bottom of the facility, an electric heater is installed to preheat the primary air up to 573 K. The air is introduced into the bed through a plate distributor. Ten thermocouples

were placed at the centreline of the reactor to monitor the temperature of primary air, temperature in the bed at several levels and the temperature of the flue gas above the bed. The lowest thermocouple inside the fuel bed is 30 mm above the distributor. According to Van der Lans et al. (2000) the reactor is open at the top and an electrical radiation heater is placed a few centimetres above the top of the bed in order to ignite the fuel.

A summary of the main dimensions of the various reactors discussed above and some others collected from the open literature can be found in Table 1.

Table 1 Experimental reactors

Reactor	Dimensions	Location	Source
Single particle test facility	d=5cm, h=10cm	Karlsruhe	Peters (2002)
Test facility at LTU	15*15*90cm	Lappeeranta	Horttanainen (2000)
SUWIC Small reactor	d=12,5cm, h=50cm	Sheffield	Yang et al. (2006)
SUWIC Large reactor	d=20cm, h=150cm	Sheffield	Ryu et al. (2006)
Test facility at VTT	d=24,4cm, h=30cm		Horttanainen (2000)
10 kW pellets reactor	d=20cm, h=170cm	Piteå	Wiinikka (2004)
Test facility at Lyngby	d=15,4cm, h=127,5cm	Lyngby	Zhou et al. (2004)
ENSMA reactor	d=20cm, h=120cm	Cedex	Rogaume (2009)
Test rig at Harbin	d=18cm, h=130cm	Harbin	Zhengqi Li (2008)
Laboratory combustor	d=12cm, h=35cm	Graz	Weissinger (2004)

2. Design of a new grate combustion reactor

The design of experimental combustion reactors is related to the character of data it has to provide. Reactors yielding information about fuel drying, devolatilization and combustion on a grate that may serve for mathematical model development and validation belong among the most complex. Reactors, used for the investigation of a particular aspect of the combustion process (e.g. investigation of emissions from a single fuel) may on the other hand be much simpler. In both cases however, measuring and process control instrumentation plays a vital role. Also important is the range of fuels combusted in the reactor. Namely, reactors combusting municipal solid waste or contaminated biomass must be resistant to higher temperatures and corrosion than reactors for ordinary biomass fuels.

2.1 Standard features

Size of the reactor as well as grate design (number and size of holes) must correspond to the type (mainly size of particles) and packing conditions of fuel. The goal is to have homogeneous fuel distribution in horizontal cross sections with a plug flow of the gas.

All measuring instrumentation is typically connected to a data acquisition system and a PC, enabling online monitoring and data storage. This includes also readings from inlet air flow meters, ventilators, etc.

K-type thermocouples are typically used to monitor the temperature of primary airflow, temperature inside the bed at different heights and temperature of the flue gases. The main components that need to be monitored include O_2, CO and CO_2, H_2, hydrocarbons, NO_x and SO_x.

2.2 The challenge of weight monitoring

Weight loss monitoring constitutes one of the most difficult technical obstacles in the design of the grate combustion reactor. In general, two different approaches are possible: in the first the whole reactor is suspended from or placed on a weighing scale. This solution uses the large reactor in SUWIC. According to Ryu et al. (2006) the reactor is suspended from two weighing beams having four load cells. The weighing scale has a resolution of ±20 g, while the initial sample feed is 2-7 kg depending on the density and bed height. However, the reactor is partially restricted by the flexible air supply line at the bottom end and stretched by thermal expansion during the combustion test. This results in a negative reading of the weighing scale near the end of the test. Thus, the mass loss needs to be normalised, based on the weights of the initial sample and the bottom ash collected after each test. The accuracy of this solution is thus significantly limited. Second possibility is to separate the fuel holder from the rest of the reactor. The main advantage of this solution is lower overall weight which enables to use more precise weighing scale. An example is the small combustor in Graz University of Technology with a resolution of ±0.1 g according to Weissinger et al. (2004). The overall accuracy is however still compromised by connections of primary air supply and instrumentation (thermocouples, pressure sensors) to the fuel holder. The resulting technical and operational difficulties present a number of challenges.

Further complications may be caused by periodic movements of the grate that would secure realistic fuel settling, similar to the effect of grate movement in real applications.

2.3 Novel features

One of the most important parameters in mathematical modelling of grate combustion of solid fuels is the bed porosity (packing conditions in general) and its dynamic changes during the combustion process as shown by Zhou et al. (2005). The main consequence of the dynamic changes of porosity is the variation of fuel bed pressure drop. A new experimental reactor design should therefore place emphasis on the precise determination of the fluid resistance properties by multiple pressure sensors. This could lead to improved understanding of the combustion process and better modelling capabilities. Another novel feature of the new reactor serving the same purpose should be optical access along the bed height using a sapphire window, enabling the measurement of bed height and detailed observations of dynamic changes of the fuel packing conditions.

3. Conclusions

Laboratory reactors are required to provide key data necessary for detailed modelling of grate combustion of solid biomass fuels, like weight loss rate, flame front velocity or drying and devolatilization rates. Construction of the reactors differs according to the kind of fuel and the size and shape of fuel particles.

Accurate weight measurement of the fuel sample, temperature measurement in the fuel bed and gas sampling from the bed pose a number of difficult reactor design issues. Various design approaches collected from the literature are summarised and evaluated. To the knowledge of the authors, precise measurements of bed pressure drop and bed height have not been reported in the open literature so far and present the main challenges for the development of a new-generation reactor.

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