Measuring the External Solids Flux in a CFB boiler

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Abstract
In circulating fluidized bed (CFB) boilers, the flow rate of externally recirculated bed material is important, since it influences combustion, fluid dynamics, solids segregation and heat transfer. However, in CFB boilers (as well as in other industrial CFB units), the solids recirculation rate is difficult to determine, as no standard method is available to measure it directly. In this work, a methodology for measurement of the external solid flux is developed, based on heat and mass balances over parts of the return loop of a CFB boiler. Continuous measurements of temperatures and flow rates of gas and water entering and exiting different sections of the return loop are needed to determine both instantaneous and time-averaged solids recirculation rates. The method was evaluated in the Chalmers 12 MWth CFB boiler with good results.

Introduction

The flow rate of externally circulated bed material in a circulating fluidized bed (CFB) boiler is an important operation parameter, since it affects solids segregation, fluid dynamics, heat transfer and combustion efficiency. However, there is still no standard technique available for continuous measurement of this flux in CFB boilers [1]. Such a method should be on-line, sensitive, not interfere with the solids flow, possible to use in high-temperature and large-scale units, and suitable at a broad range of solids flow rates without calibration [2]. A number of methods are available to measure the recirculation flux in CFB units, but most of them are either not applicable to full-scale industrial boilers or not on-line.

Burkell et al. [2] reviewed previously proposed methods and investigated five different techniques for measuring the solids circulation rates in CFBs. Only one of the methods, an estimation of the solids flow from a heat balance over a jacketted heat transfer section in a vertical standpipe, was reported to work well both on-line and at high temperatures. However, the technique was found to be sensitive to the radial position in the standpipe where the temperatures are measured, making careful calibration necessary. Kim et al. [3] noted similar calibration requirements due to the variation in solids flux with radial position using an impact probe for solids circulation rate measurements. Several researchers [4, 5, 6, 7, 8] have developed techniques for on-line measurement of the circulation flux by inserting devices into dense solid flows or fluidized flows in the cyclone return leg. In general, the methods require in-situ calibration and have not been tested in high-temperature environments. Davies and Tallon [1] tried periodical discharges of high-pressure air at the wall of a standpipe with dense solids flow and measured the time lag between the arrival of the pressure wave to points upstream and downstream of the disturbance. However, the expected linear relationship between the time lag and the solids flux proved difficult to establish. Pressure drop measurements in different parts of the boiler have been suggested as non-interfering on-line methods for measuring the solids recirculation rate. These include, for example, measurement of pressure drop in the horizontal exit section connecting riser and cyclone [9], pressure drop over the loop seal [10], and pressure loop analysis [11, 12]. Besides thorough calibration, pressure measurements in CFB boilers require careful surveillance due to the clogging tendency of pressure taps in dust-laden environments. The pressure drop can be related to the solids flux by estimation of the local solids velocity and concentration; however, a reliable method for predicting the latter parameter is not available. Johnsson and Leckner [13] approximated the solids flux in the Chalmers 12 MWth CFB boiler based on the solids concentration at the furnace exit (as estimated from pressure drop measurements and wall layer thickness), the gas velocity and the terminal velocity of the particles. A factor that complicates the estimation of the external solids flux in this way is the effect of the furnace exit. Johnsson et al. [14] showed that, although there is little effect of exit geometry on the ratio of external to internal recirculating flow, a decrease in exit size (and, hence, an increase in gas velocity in the exit) results in an increased external recirculation. Pallarès and Johnsson [15] suggested that the ratio of external to internal recirculation depend both on height of the furnace exit and local fluid dynamic conditions. They proposed an empirical correlation, based on fits to experimental data of solids fluxes from three large-scale CFB units, relating the probability of entrainment of a particle to its slip velocity and to the solids flux in the core region at the furnace exit.

It appears that none of the methods described can be readily applied in a large-scale boiler, as they require one or more of the following: meticulous calibration or surveillance, a complete mapping of the pressure loop, or detailed knowledge of the fluid dynamic conditions and particle properties in the boiler. A simpler, more robust method is required for supervision of the recirculation process. This method could be used both as a tool for process optimization and as a diagnostic method to detect bed agglomeration or unexpected variations in the bed material size distribution at an early stage, in order to prevent defluidization and shutdown of the boiler. The aim of the present work is to investigate a method to determine the externally recirculated solids flux in a CFB boiler based on heat and mass balances over parts of the return system, in principle making it possible to measure both instantaneous and time-averaged solids recirculation flows. To test the method, the externally recirculated solids flux in the Chalmers 12 MW CFB boiler is evaluated, using data gathered under different operating conditions.

Method

Heat and mass balances over the return system are used to determine the mass flows of recirculated solids in a CFB boiler. In a general case, the circulation loop of such a boiler consists of a cyclone followed by a cyclone leg, a fluidized loop seal/seal pot (with or without heat exchanger) and a return pipe to the furnace. The parts following the cyclone are schematically illustrated in Fig. 1. The solution of simple heat and mass balances over the seal, equipped with a heat exchanger, gives the flow of circulating bed material, provided the following parameters are measured:

- Flows and temperatures of fluidizing air/gas
- Temperatures of the gas-solids mixture in the seal and of the entering and exiting flows
- Temperature of the surroundings

- Cooling water flow through the heat exchanger and water inlet and outlet temperatures

If the recirculated bed material contains a significant portion of unburned fuel (especially in the case of coal combustion), the accuracy of the result can be improved if char combustion in the region is taken into account. If the fraction of unburned fuel in the circulating solids entering the system is known, an estimate of the extent of combustion can be made based on measurement of concentrations of O_2, CO and CO_2 in the fluidizing air/gas and in the fluidized bed section(s).

The number of equations required for calculation of the external solids flux in a CFB boiler depends on the configuration of the return system. In this paper, the method is applied on the configuration of the return loop of the Chalmers 12 MWth boiler, consisting of a cyclone, a seal pot and an external heat exchanger arranged in series. Fig. 2 shows the parts of the return system located after the primary cyclone. 1 to 5 denote cyclone leg, seal pot, overflow pipe, external heat exchanger and return pipe. Dashed lines enclose the three control volumes used in this work (2, 4 and 5). In this arrangement, it is possible for the recirculated solids to pass through both seal pot and heat exchanger or to pass directly from the seal pot into the return pipe leading back into the furnace, without passing the external heat exchanger. This requires the calculation of four solids flows in order to obtain the external solids flux: the solids flow entering the seal pot from the cyclone leg (F_{s1}), the total solids flow leaving the seal pot (F_{s2}), the solids flow leaving the seal pot through the overflow pipe (F_{s3}) and the solids flow leaving the external heat exchanger (F_{s4}). Thus, four equations are required (compared to two equations for the configuration in Fig. 1). The seal pot and heat exchanger operate in the bubbling fluidized bed mode and are regarded as well-stirred tanks. The temperatures of the gas and solids are assumed to be equal at the measuring points. Combustion may take place in the both seal pot and in the external heat exchanger. Heat losses to the surroundings are taken into account from the external heat exchanger only. Since combustion and heat losses are neglected in the overflow pipe, the temperature here is assumed to be equal to the temperature in the seal pot (T_3 = T_2 in Fig. 2). Continuous measurement of the parameters listed in Table 1 is required in order to solve the system of equations. For estimating the heat loss to the surroundings, the area, the thermal conductivity and the thickness of the heat exchanger wall must be known in addition to the temperature of the surroundings. The solids mass balance over the seal pot (2) is

$$F_{s1} - F_{s2} = \Delta m_{c2} \tag{1}$$

where Δm_{c2} is the rate of char combustion in the seal pot. A solids mass balance over the external heat exchanger (4) is

$$F_{s2} - F_{s3} - F_{s4} = \Delta m_{c4} \tag{2}$$

where Δm_{c4} is the rate of char combustion in the external heat exchanger. The gas exiting the seal pot is assumed to take the path through the overflow pipe (3), not passing the external heat exchanger (4). Gas exiting the seal pot through the cyclone leg (1) is neglected. A heat balance over the return pipe (5) can be written as

$$F_{s3}\int_{T_2}^{T_5} c_{ps}\,dT + F_{s4}\int_{T_4}^{T_5} c_{ps}\,dT + \left(F_{g2}+\Delta m_{c2}\right)\int_{T_2}^{T_5} c_{pg}\,dT + \left(F_{g4}+\Delta m_{c4}\right)\int_{T_4}^{T_5} c_{pg}\,dT = 0 \quad (3)$$

where F_{g2} and F_{g4} are the rates of fluidization air/gas fed to the seal pot and external heat exchanger, respectively, c_{pg}, c_{ps} and c_{pw} are the specific heat capacities of gas, solids and water, and T_2, T_4 and T_5 are the temperatures measured by thermocouples placed according to Fig. 2. Correspondingly, the heat balance over the external heat exchanger (4) can be written as

$$\begin{aligned} &\left(F_{s2}-F_{s3}\right)\int_{T_{ref}}^{T_2} c_{ps}\,dT - F_{s4}\int_{T_{ref}}^{T_4} c_{ps}\,dT = \\ &= -\Delta m_{c4}\left(\Delta H_r - \int_{T_{ref}}^{T_4} c_{pg}\,dT\right) + F_{g4}\int_{T_{g,in}}^{T_4} c_{ps}\,dT + F_w\int_{T_{w,in}}^{T_{w,out}} c_{pw}\,dT + A_4\frac{k_{c,wall}}{x_{wall}}\left(T_4-T_{sur}\right) \end{aligned} \quad (4)$$

The left-hand side is the difference between the heat entering and leaving the external heat exchanger with the solids. The right-hand side is the heat generated by char combustion, heat leaving with the combustion gas, heating of the fluidization air/gas, heating of the cooling water and heat loss through the walls of the heat exchanger. ΔH_r is the heat evolved per unit mass of burned char, T_{ref} is the reference temperature, A_4 is the wall area of the external heat exchanger, $k_{c,wall}$ is the thermal conductivity of the wall, x_{wall} is the wall thickness and T_{sur} is the temperature of the surroundings. When char combustion is neglected (e.g. during combustion of biomass), Δm_{c2} and $\Delta m_{c4} \approx 0$, and the system of equations can be solved for F_{s1} to F_{s4}.

When char combustion in the return system is significant and has to be considered, the char in the recycled solids is assumed to react with the oxygen in the fluidizing air/gas by the reaction

$$C(s) + (1-0.5\,\phi)O_2 \rightarrow \phi\, CO + (1-\phi)\, CO_2 \quad \text{(R1)}$$

where ϕ is the CO/C product ratio for combustion, which may be determined by gas analysis. To determine Δm_{c2} and Δm_{c4} (in Eqs. 1 and 4), the fraction of char in the entering solids must be known, and the limiting reactant for combustion in both the seal pot and the external heat exchanger must be identified. If the oxygen in the fluidizing air/gas is assumed to be the limiting reactant in Reaction R1, the amount of char burned in section i (according to Fig. 2) can be calculated as

$$\Delta m_{ci} = \Omega \cdot Y_{O_2} \cdot F_{gi} \cdot \gamma \quad (5)$$

where the mass of carbon burned per mass of oxygen consumed by the reaction is given by $\Omega = M_C/(M_{O2}(1-0.5\phi))$, where M_C and M_{O2} are the molar masses of carbon and oxygen, respectively. Y_{O2} is the mass concentration of oxygen in the fluidization air/gas, F_{gi} is the mass flow rate of fluidization air/gas in section i, and γ is the fraction of the available oxygen which is consumed by combustion, given by gas analysis. The heat of reaction of the char combustion per mass of carbon burned is calculated as

$$\Delta H_r = \frac{\left(\left(h_C - h_{CO_2}\right) - \phi\left(h_{CO} - h_{CO_2}\right)\right)}{M_C} \tag{6}$$

where h_j is the molar reference enthalpy for species j. Having characterized the combustion, the system of equations can be solved for F_{s1} to F_{s4}.

Finally, the total flux of externally recycled solids (in kg/m^2,s) is given by

$$G_{s,ext} = \frac{F_{s1}}{A_{cs}} \tag{7}$$

where A_{cs} is the cross-sectional area of the furnace at the height of the cyclone inlet.

Experimental conditions

The Chalmers 12 MWth research boiler is smaller than most commercial CFB boilers, but it has most of the features of such units. Fig. 3 shows an outline of the boiler; a detailed description was given by Åmand and Leckner [16]. Data were gathered during combustion of coal, co-combustion of coal and wood chips and co-combustion of coal, wood chips and sewage sludge under different operating conditions. Eight cases were investigated, where the bottom bed temperature was approximately 850 ^{o}C, the air-to-fuel ratio was 1.2 and silica sand (mass-weighted mean diameter 0.3 mm) was used as additional bed material. The flow of primary air, the air staging, and the pressure drop over the furnace were varied between the cases. In one case (with primary air only), the total pressure drop over the furnace was gradually increased during the measurement period (7.4-9 kPa). The temperatures and flows shown in Table 1 were continuously measured during boiler operation using permanently mounted flow meters and thermocouples. The fluidization velocities in the seal pot were constant in all cases (0.45 m/s), whereas the fluidization velocities in the external heat exchanger varied between the different combustion cases (0.17-0.42 m/s). For most of the cases, the characteristics of the char combustion were evaluated from concentrations of O_2, CO and CO_2 in the seal pot and the external heat exchanger using a gas extraction probe and analysis equipment described by Åmand et al. [17]. The fraction of unburned fuel in the circulating solids was determined from proximate analysis of solid samples extracted in the top of the furnace or in the cyclone return leg (before entering the seal pot). In the cases where no solid samples were extracted, the fraction of unburned fuel was estimated, based on results from similar operating conditions. The temperature of the surroundings was measured in the boiler room at 0.5 m from the external heat exchanger wall. In the calculations, the specific heat capacities of bed material and flue gas were approximated by those of silica sand and air, respectively.

Results and discussion

Figure 4 illustrates the influence of primary air velocity on the time-average solids circulation flux calculated from Eq. 7. The diagram uses available data from tests in the research plant of Fig 3. The circles denote data from tests with various fuels resulting in wide particle size distributions, evaluated with the present method, where the open markers represent cases with secondary air and the filled markers cases with primary air only. The solid line is a tentative fit to these data (with $G_{s,ext} \propto u_0^2$), starting from the minimum particle size in a wide size distribution (caused by the dilution of the original sand with fuel ash). The squares refer to data from tests with low ash content in the bed, resulting in narrow particle size distributions, evaluated by slip velocity and density in the upper part of the riser (Johnsson and Leckner [13]). Dashed curves connect the fluxes derived from these tests, starting from the lowest measured flux where sufficiently accurate density assessment was possible. As shown in the diagram, the relationship between the external circulation flux and the primary gas velocity is the result of a wide size distribution with its related segregation between bottom bed and circulated material (tests with wide size distribution result in a flatter curve compared to tests with narrow size distribution).

Figs. 5 and 6 show the effect of the superficial gas velocity in the top of the furnace and the pressure drop over the furnace on the external solids flux. Fig. 7 shows that within the relatively narrow pressure drop range of 7.4 to 9 kPa (corresponding to a proportional increase in furnace bed inventory), there is no measurable variation in the externally recirculated solids flux. The primary air velocity was kept constant during this test and is included in the diagram for comparison. These results indicate that within the range of operating conditions studied, the external solids flux is mainly influenced by the primary gas velocity. Secondary air supply as well as bed inventory have small effects.

Fig. 8 shows curves of circulation flux vs. primary gas velocity in a case with coal combustion, assuming no char combustion in the heat balance over the loop seal and the external heat exchanger (dotted line), compared with the case when combustion based on measured gas concentrations (O_2, CO, CO_2) is included (solid line, same as solid line in Fig 4), or under the assumption that combustion uses all the oxygen in the fluidizing gas (dashed line). For the investigated cases, it is evident that almost all of the oxygen introduced to the seal pot and external heat exchanger was consumed. Temperatures measured in different points in the same section did not differ substantially. However, for other return loop configurations, this may not be the case. Werdermann and Werther [18] investigated the solids flow pattern and heat transfer in an industrial-scale fluidized bed heat exchanger consisting of four placed in series, of which all but the first chamber contained heat exchanger tube bundles. They noted that a large fraction of the ash flowing through the heat exchanger never came in contact with the tube bundles, and concluded that the chambers of the heat exchanger could not be considered perfectly stirred tanks without temperature variations. However, the phenomena observed indicated that the heat exchangers did not perform as desired, and they are probably improved in later designs.

The variation in fluidization velocity in the external heat exchanger is not assumed to affect the results significantly. Johansson et al. [19] Conducted in-situ measurements in the loop seal of a 30 MW CFB boiler as well as in a 1/3 scaled model of the seal. They observed that, although the external flux increased with higher fluidization velocity in the loop seal, the external solids flux was primarily dependent on the riser's gas velocity, and the flow of fluidization air in the loop seal could be varied considerably without affecting the recirculation flux. Johansson et al. [20] studied the gas composition and the flow pattern in the loop seal described above. They concluded that, with external solids flow, only a small fraction of the flue gas entering the cyclone followed the solids down to the loop seal. In the measurements presented here, the gas entering the seal pot through the cyclone return leg has been neglected. This may have resulted in a slight overestimation of the extent of combustion in the return system.

In principle, the method proposed could be used in any CFB boiler equipped with a well-fluidized seal pot/loop seal with a heat exchanger or an external heat exchanger through which the circulating bed material passes, provided that continuous measurement of the required parameters is made.

Conclusions

A method is proposed to measure the instantaneous or time-averaged external solids circulation flux in a CFB boiler. The method is based upon heat and mass balances over parts of the return loop of the boiler. The conditions for its use are that the circulating solids pass through a fluidized seal pot with a heat exchanger or an external heat exchanger, well fluidized, i.e. devices that can be regarded as well-stirred tanks. Measurements should then include: the temperature, oxygen content and flow(s) of fluidizing air/gas, heat extracted by the cooling water (water flow and inlet and exit temperatures) and temperatures at well-mixed locations in the fluidised bed section(s) of the return loop, and in the gas-solids flow returning to the furnace. Heat losses from the system should be approximated. When char combustion in the return system is significant, the amount of heat provided by combustion of unburned solids can be estimated to increase the accuracy of the result.

The method was used to evaluate the external solids circulation flux in the Chalmers 12 MWth CFB boiler using data gathered during different operating conditions. The effect of char combustion in the return system was accounted for by measurements of O_2, CO and CO_2 concentrations in the gas phase, and the fraction of unburned fuel in the circulating flow was evaluated from proximate analysis of solid samples extracted during operation. The proposed method was proven suitable for external solids flux measurement. A clear relationship between solids flux and primary gas velocity was noted. Furthermore, it was shown that the solids flux was not influenced by the secondary air supply or by the bed inventory within the parameter ranges investigated. The solids size distribution in the present tests was considerably wider compared to those in previous tests. This complicated the comparison of the data sets available from two methods to determine the external solids flux.

Acknowledgements

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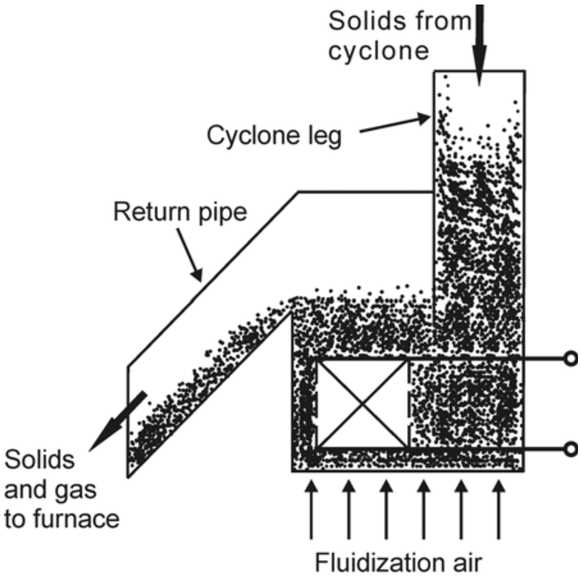

Figure 1 Parts of the return system in a CFB boiler following the primary cyclone. The loop seal is equipped with a heat exchanger.

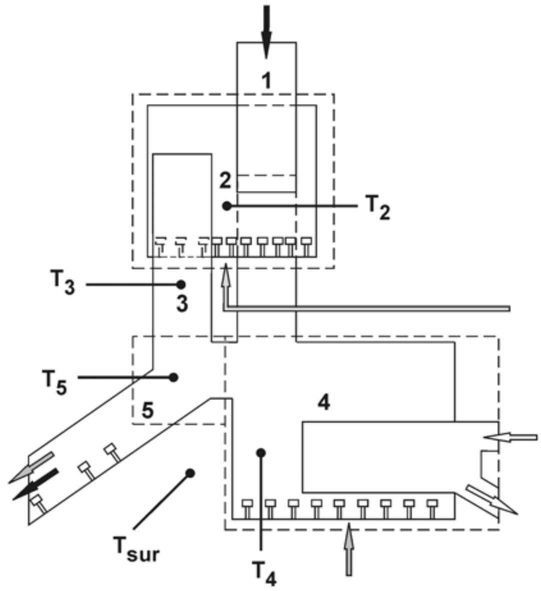

Figure 2 Return system of the Chalmers CFB boiler after the primary cyclone with parts (1) cyclone leg, (2) seal pot, (3) overflow pipe from seal pot, (4) external heat exchanger and (5) return pipe. Black, grey and white arrows correspond to flows of solids, gas and water, respectively.

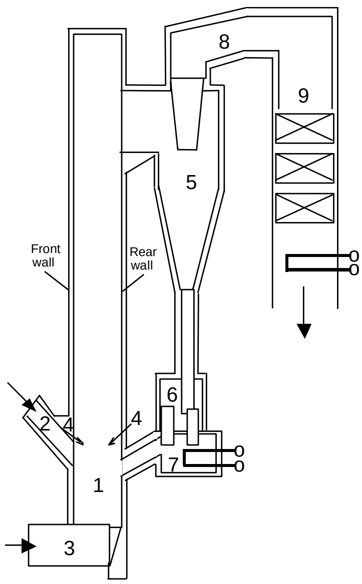

Figure 3 Outline of the 12-MW_{th} CFB boiler at Chalmers University of Technology with (1) furnace, (2) fuel feed chute, (3) air plenum, (4) secondary air nozzles, (5) cyclone, (6) loop seal, (7) external heat exchanger, (8) exit duct and (9) convection pass.

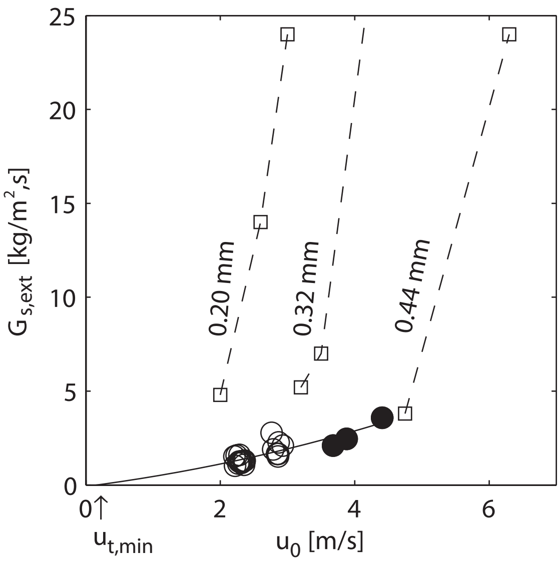

Figure 4 Externally recirculated solids flux vs. primary air velocity. Open circles correspond to cases with secondary air, and filled circles to cases with primary air only. Solid line present work. Squares and dashed lines Johnsson and Leckner [13].

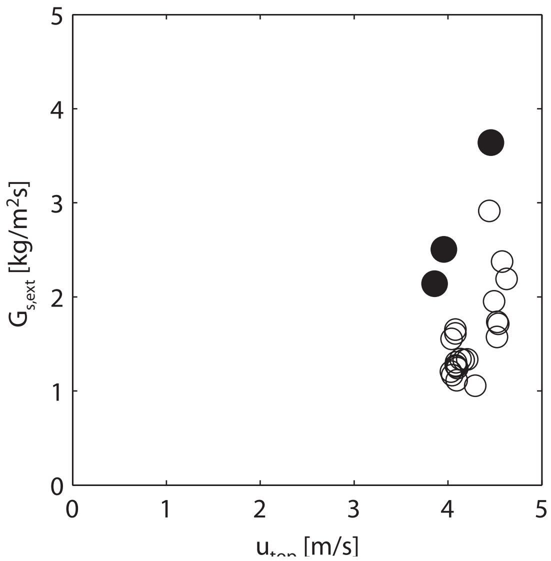

Figure 5 Externally recirculated solids flux (same data as in Fig. 4) vs. superficial velocity in top of furnace.

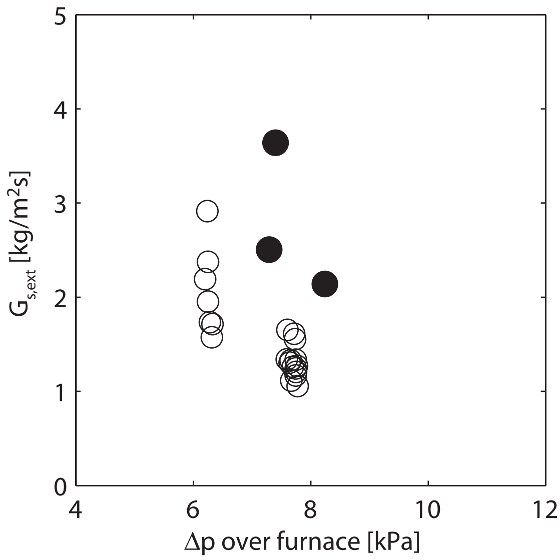

Figure 6 Externally recirculated solids flux (same data as in Fig. 4) vs. pressure drop over the furnace.

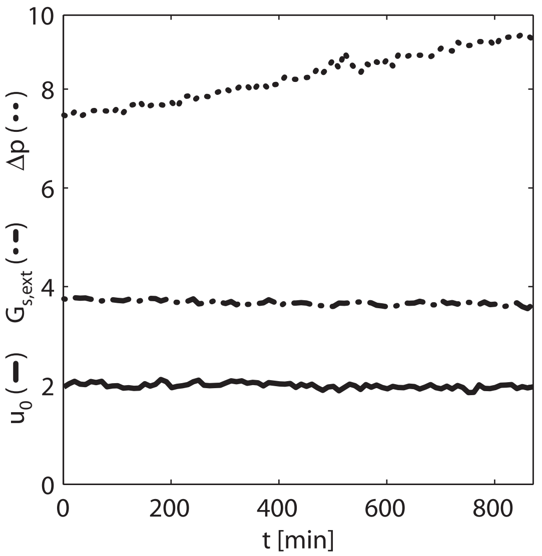

Figure 7 Measured pressure drop over furnace, primary air velocity and calculated flow of externally recycled solids vs. time for coal combustion with primary air only.

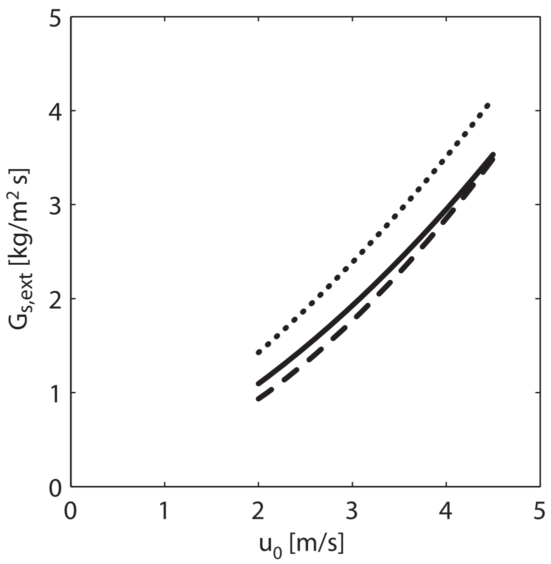

Figure 8 Influence of char combustion on calculated flow of externally recycled solids. Dotted line corresponds to no combustion, solid line to measured combustion, and dashed line to combustion using all available oxygen.

Table 1 Parameters that require measuring for solution of the equation system

Measured	Description	Measured	Description
T_2	Temp. seal pot	$T_{w,in}$	Temp. cooling water into h.e.
T_4	Temp. external h.e.	$T_{w,out}$	Temp. cooling water out of h.e.
T_5	Temp. return pipe	F_w	Flow rate water through h.e.
T_{g2}	Temp. fluidizing air/gas into seal pot	F_{g2}	Flow rate fluidizing air/gas into seal pot
T_{g4}	Temp. fluidizing air/gas into external h.e.	F_{g4}	Flow rate fluidizing air/gas into external h.e.