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Modelling of a Dual Purpose Plant for Waste Incineration

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In the present paper, the modelling of a dual-purpose plant for the production of electrical and thermal energy from the heat treatment of wastes is presented. Particularly, the model has been developed with the aim of performing a study about the simulation of a solid waste incineration process, which involves complex gas-solid reactions, in a fluidized bed combustor. The incineration plant is made of three sections, and namely a RDF combustion section, a flue gas treatment section and a thermal recovery section. This paper is mainly focused on the combustion section. Model results have been compared with the experimental data obtained derived from literature, showing a very good agreement. The proposed model may represent a useful and a reliable instrument to be used in both design and planning of new plants and in control and retrofit of existing plants.

1. Introduction

Cogeneration is the thermodynamically sequential production of two or more useful forms of energy from the same energy source; in particular, solid waste thermal treatment (incineration) allows wasting the refuse and producing energy by means of a heat recovery section. According to the recent European regulations (European Community, 2008) when the plant efficiency is high enough incineration of waste can be considered a recovery process (Poggio and Grieco, 2009). Municipal solid waste (MSW) can be converted into energy both by the direct burning of MSW to produce electricity and by indirect burning by converting MSW into refuse derived fuel (RDF). RDF, prepared by drying and reducing the size of the waste and separating metals, glass, and other quantities of inorganic materials, can be combusted in an appropriate incineration plant (Jannelli and Minutillo, 2007). An incineration plant with energy recovery is mainly made of three sections, and namely a refuse derived fuel (RDF) combustion section, a flue gas treatment section and a thermal recovery section, which produces steam by using flue gas heat content. As for combustion, grate firing is the leading technology because of the high availability, flexibility and efficiency (Grieco and Poggio, 2009) but there is a considerable interest when the combustion process is achieved in a fluidized bed reactor, whose use only recently has been extended to the incineration of biomass and pretreated waste, for either power generation or waste disposal. The success of fluidized bed combustion (FBC) is mainly due to high combustion efficiency, fuel flexibility as for the fuel quality and reduction in pollutants emitted with the flue gas, even though with alternative fuels as RDF, great attention is to be paid to the fuel pre-treatment principally to prevent obstructions in the equipment, but also to maintain fluidization conditions by removing agglomerates and ashes and to prevent erosion by removing alkali (Ravelli et al., 2008). While literature analysis reveals a good knowledge of coal fluidized bed combustion, the comprehension of phenomena occurring during the FBC of alternative fuel such as RDF is less complete, since there are chemical and physical features that are very different from those of fossil fuels (Ravelli et al., 2008). Moreover, experimentation in full-scale furnaces may be very expensive since there are a lot of variables (bed temperature, superficial gas velocity, air excess, particle size distribution, bed and freeboard height) that affect combustion; therefore the prediction of process efficiency according to different operating conditions could be very difficult. From this point of view, process simulation could be satisfactorily used for numerical modelling of RDF FBC, since it is a powerful methodology for the analysis of existing processes, synthesis of new processes, implementation of a control strategy and fast screening of process alternatives to select the best solution - economic aspects, environmental aspects, energy consumption aspects, flexibility of the proposed process (Cimini et al., 2005). In this paper, the simulation of a dual-purpose plant for the production of electrical and thermal energy from the heat treatment of wastes is presented, in which the combustion section is achieved in a FBC with internal heat recovery system; the flue gas treatment section is composed by a cyclone, a dry reactor for the acid gas content reduction, a baghouse filter and a scrubber with a $Ca(OH)_2$ dosing; the energy production section consists of the heat recovery steam generator and a steam turbine, with air condenser and de-aeration tower. A simplified process scheme is reported in Figure 1. Model results, as for what concerns the combustion section, have been compared with literature experimental data (Consonni, 1997), showing a very good agreement.

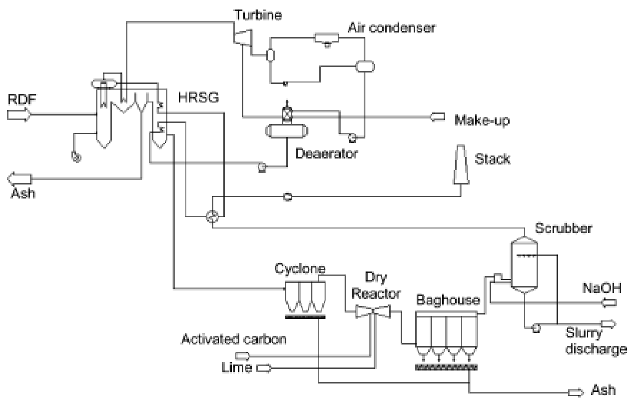

Figure 1: Simplified diagram of solid waste treatment plant.

2. Model description

The model here proposed is a short-cut one, able to predict the amount of energy which can be recovered from the combustion of RDF in a fluidized bed in both a Rankine and a cogeneration cycle. It is based on the material and energy balances towards the combustor. Primary input parameters are RDF mass flow, composition and LHV. Particularly percentage composition of RDF allows the model to compute combustion products, in the hypothesis of complete combustion, through the following equations:

$$C + O_2 \rightarrow CO_2 \quad (1)$$
$$S + O_2 \rightarrow SO_2 \quad (2)$$
$$2H + ½\, O_2 \rightarrow H_2O \quad (3)$$
$$½\, H_2 + ½\, Cl_2 \rightarrow HCl \quad (4)$$
$$N + O_2 \rightarrow NO_2 \quad (5)$$

During material and energy balances CO species is neglected, as the whole amount of carbon of RDF is hypothesized to be transformed in CO_2 compound. This supposition is confirmed by the very high performance of fluidized bed combustor.

$$SO_2 + ½\, O_2 \rightarrow SO_3 \quad (6)$$

As for sulphur, it is oxidized by Equation (2) in sulphur dioxide; then it is transformed in SO_3 compound by equation (6). However, reaction (6) has a mean exothermic value, it is not very efficient at high temperature and finally it shows strong limits from a kinetically point of view. For these reasons neglecting both formation of SO_2 and SO_3 is not a big inaccuracy. Halogens like Cl, Br, I, F react with hydrogen to give corresponding acids, mainly HCl and HF: these reactions are favored in case of high temperature values. The amount of NO which forms inside the fluidized bed is the sum of two contributes: the first is due to nitrogen that states inside RDF (the largest part), the second is the result of the reaction with molecular nitrogen in the air. From stoichiometric considerations the exact amount of oxygen aimed to the complete combustion of RDF is possible to compute. Finally mass flow rate of gas phase produced is calculated. An enthalpy balance between input energy, output energy (heat transfer) and energy losses (irradiative heat exchange, not complete combustion and miscalculation) has been used to determine the temperature of the gas phase. Heat losses are estimated as a percentage of the total heat produced by the combustion. The equation with the enthalpy balance is the following:

$$M_{RDF}\, LHV\, (1 - \text{heat losses}) = Q_c + M_G\, cp_G\, (T_G)(T_G - T_{REF}) \quad (7)$$

M_{RDF} is the mass flow of RDF, LHV is the low heating value, heat losses take account of energy losses, Q_c is the thermal power, M_G is the gas mass flow, cp_G is the thermal capacity of gas phase, T_G, unknown, is the temperature of gas phase and T_{REF} is the reference temperature.

3. Model validation – results

In this section, experimental results obtained from simulation as for concern the combustion section are reported, with the aim of validating the model by using literature results (Consonni, 1997) as a reference. The following tables report the main parameter values used for simulation: in particular Table 1 reports RDF composition and heating value (left) and combustion flue gas characteristics (right), Table 2 resumes the main combustion parameters, and Table 3 highlights the energy power obtained from simulation.

Table 1 Characteristics of RDF and gas phase used during the model validation step

	% on dry basis	*Combustion air*	*56.273 kg/h*
Carbon	55.7	Gas phase mass flow	60.890 kg/h
Hydrogen	4.6	Ashes	1.010 kg/h
Oxygen	17.80	CO_2	11.32 % vol
Nitrogen	0.7	H_2O	7.08 % vol
Sulfur	0.5	NO_2	74.52 % vol
Chlorine	0.7	O_2	7.02 % vol
Ashes	20	SO_2	0.04 % vol
Moisture (as it is)	15.8	HCl	0.02 % vol
LHV (kcal/kg	4000		

Table 2 Combustion parameters

Excess air	*55%*
Combustion air moisture	0.01 $kg_{H2O}/kg_{dry\ air}$
Combustion air temperature	50°C
Reference temperature	25°C
Thermal power to heat exchangers	7300000 kcal/h

Table 3 Energy recovery section

	Rankine cycle	*Cogeneration cycle*
Thermal horsepower	38786 kg/h	38786 kg/h
Electric power	6100 kW	4494 kW
Heat		23318 kW
Steam/RDF	6.464 t_{steam}/t_{RDF}	6.464 t_{steam}/t_{RDF}

Model main results, compared with literature results published by Consonni (1997), are shown in the following figures.

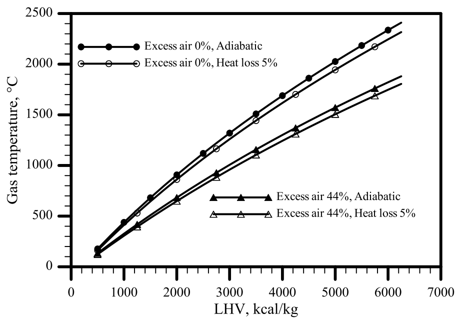

Figure 2: Gas temperature as a function of RDF LHV.

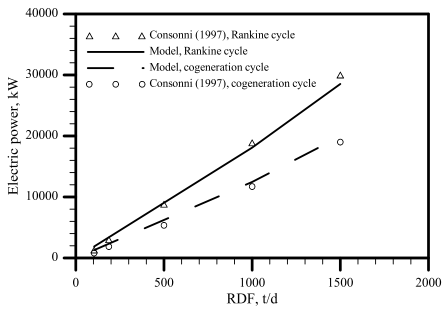

Figure 3: Electric power as a function of RDF mass flow.

Figure 2 shows the maximum flue gas temperature as a function of the RDF low heating value, in two different conditions: at stoichiometric conditions and with an excess air of 44%; each curve has been obtained by considering adiabatic conditions, and 5% of heat loss. Stoichiometric curves represent the theoretical upper limit. As can be noted, the model describes very well experimental results obtained by Consonni (1997) in each condition, showing a combustion gas temperature that obviously increases with increasing RDF LHV. Figure 3 shows that the model proposed provides computed data closed enough to the experimental ones (Consonni, 1997) in both case of Rankine and cogeneration cycle. However some discrepancies can be noted with high RDF mass flow, where experimental data show higher values.

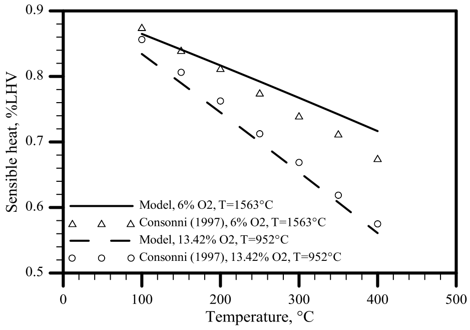

Figure 4: Sensible heat as a function of temperature in case of 6% and 13.42% O_2 dry basis in gas phase.

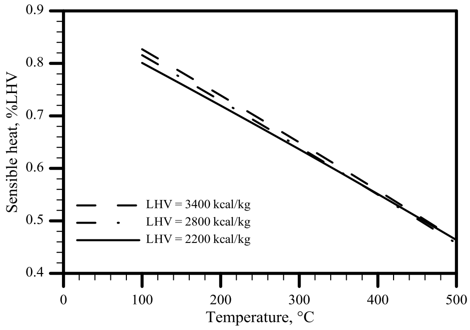

Figure 5:Sensible heat as a function of temperature, in case of different RDF LHV

This is probably due to the fact that the model assumes constant values of conversion efficiency, while actually this parameter decreases in case of RDF mass flow lower than 100 t/d. Figure 4 shows that the lower the temperature of the gas phase, the lower is the sensible heat that is lost. Computed data show a good agreement with experimental ones (Consonni, 1997) in both cases of gas phase temperature of 1570 °C and 952 °C. Figure 5 reports sensible heat as a function of temperature, in case of different RDF LHV. No appreciable gain of sensible heat is obtained increasing RDF LHV particularly at high temperature: this behaviour agrees with literature conclusions Consonni (1997).

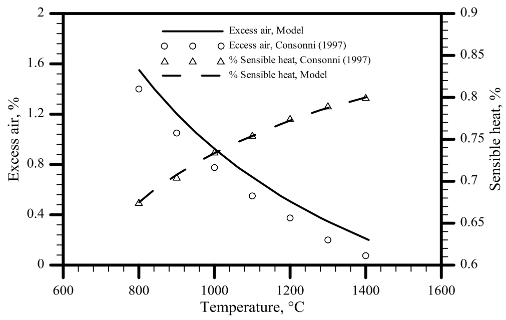

Figure 6: Excess air and sensible heat as a function of T. RDF LHV = 2200 kcal/kg

Figure 6 shows excess air and sensible heat as a function of the combustion temperature, for an RDF with 2200 kcal/kg LHV. A good agreement can be noticed between computed and experimental data (Consonni, 1997). Sensible heat has been calculated in case of 250 °C exhaust gas temperature, with an energy loss supposed be equal to the 5 % of LHV. The graph shows that in order to increase sensible heat recovered from gas phase, it is necessary to operate with high temperature values and low excess air. This is the right way to reduce gas flow and heat loss, too.

4. Conclusions

In the present paper, a model of the combustion section of a dual-purpose plant for the production of electrical energy only and both electrical and thermal energy from the heat treatment of RDF in a fluidized bed is presented. The proposed model may represent a useful and a reliable instrument to be used in both design and planning of new plants and in control and retrofit of existing plants. Model results have been validated with experimental ones available in literature. Particularly computed data that show the behavior of gas temperature as a function of RDF LHV, electric power as function of RDF mass flow, sensible heat and excess air as a function of temperature have been compared with experimental results obtained by Consonni (1997), showing a very good agreement in all the examined cases. Future work will present the update of the model proposed with the fluidized bed design and the description of the flue gas treatment section. Moreover, computed data will be compared with a real plant experimental data.

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