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Application of high temperature phase change materials for improved efficiency in waste-to-energy plants

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ABSTRACT

This study reports the thermal analysis of a novel thermal energy storage based on high temperature phase change material (PCM) used to improve efficiency in waste-to-energy plants. Current waste-to-energy plants efficiency is limited by the steam generation cycle which is carried out with boilers composed by water-walls (i.e. radiant evaporators), evaporators, economizers and superheaters. Although being well established, this technology is subjected to limitations related with high temperature corrosion and fluctuation in steam production due to the non-homogenous composition of solid waste; this leads to increased maintenance costs and limited plants availability and electrical efficiency.

The proposed solution in this paper consists of replacing the typical refractory brick installed in the combustion chamber with a PCM-based refractory brick capable of storing a variable heat flux and to release it on demand as a steady heat flux. By means of this technology it is possible to mitigate steam production fluctuation, to increase temperature of superheated steam over current corrosion limits (450 °C) without using coated superheaters and to increase the electrical efficiency beyond 34%. In the current paper a detailed thermo-mechanical analysis has been carried out in order to compare the performance of the PCM-based refractory brick against the traditional alumina refractory bricks. The PCM considered in this paper is aluminium (and its alloys) whereas its container consists of high density ceramics (such as Al_2O_3, AlN and Si_3N_4); the different coefficient of linear thermal expansion for the different materials requires a detailed thermo-mechanical analysis to be carried out to ascertain the feasibility of the proposed technology.

1. Introduction

In the last decades, the design of Waste-to-Energy (WtE) plants has been focussing on lowering the discharge rate of pollutants, while maximizing the waste throughput and minimizing the maintenance costs. This goal has been achieved by using costly flue gas treatment units, which has led to the increase of the capital cost of WtE plants. Nowadays, to counterbalance this cost increase, the research is focused on improving the overall efficiency of the WtE plants. Steam boiler operating with higher steam parameters (temperature and pressure) is one of the main technical solutions that can be adopted to achieve this goal. Nevertheless, higher steam parameters present higher corrosion risk and higher costs associated with plant downtime and repair.

Some WtE plants (Stuttgart-Germany and Naples-Italy) have achieved higher steam temperature (up to 500 °C) by using monolithic SiC concrete to protect the superheaters operating at temperature higher than 400 °C. The disadvantage of this solution is the lower plant availability due to higher inspection and maintenance requirements. An alternative solution has been tested in the WtE plant in Rosenheim (Germany), where rear-ventilated tiles have been used to protect radiant superheaters located in the upper furnace area. In this case, the main limitations regard the maximum steam temperature achieved (i.e. 480 °C) and the increased plant complexity, which requires additional skills and competences for plant design, process control and operation. In addition to this, it has to be considered that the closer the radiant superheater is to the hottest zone of the WtE plant, the more difficult the control of the superheated steam temperature is. In fact, the inhomogeneous nature of Municipal Solid Waste (and hence the variation in the calorific value associated with it) causes disturbances during the combustion process which lead to significant fluctuations in the thermal power of the flue gas. As a consequence of this variability, the risk of failure of the superheater tubes due to excessive overheating is increased.

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In this paper, an innovative refractory brick technology based on phase change material (PCM) for corrosion protection of the radiant superheaters is proposed. PCM-based technologies exploit the phase change phenomenon of pure material or eutectic compounds, in which the latent heat of phase transition is absorbed or released at constant temperature. Exploiting this working principle, the PCM-based refractory brick is capable of storing the fluctuating thermal power generated by the waste combustion and to release the stored thermal energy on demand as a steady heat flux. Thus, the proposed technology could enable the installation of radiant superheater in the hottest zone of the WtE plants, which then allows the steam to be heated up to 600 °C.

The proposed technology considers aluminium and its eutectic alloys as PCMs since they offer good thermal properties (i.e. high thermal conductivity, high latent heat of fusion and high melting temperature) amongst high temperature PCMs. Several commercial ceramics are instead considered as containment material since they offer high resistance to high temperature corrosion.

It is worth noting that the proposed PCM-based technology can be applied to any type of combustion system where there are unpredictable thermal power fluctuations. However, this paper is focused just on grate-fired WtE plants burning Municipal Solid Waste.

The design challenge is given by the remarkable difference in the coefficient of thermal expansion between the selected PCMs and ceramics. Thus, a detailed thermomechanical analysis is performed in the paper in order to demonstrate the technological feasibility of the proposed technology. Finally, a computational fluid dynamic (CFD) simulation is carried out in order to compare the performance of the traditional refractory brick technology with that proposed in this paper.

1.1. Problem statement

In current WtE plants, heat recovery of thermal power generated during combustion process is completely carried out by traditional steam generation boilers, which is usually composed by water-walls (i.e. radiant evaporators), evaporators, economizers and superheaters (see Fig. 1).

Although being well-established, this configuration of WtE plants is subjected to some technical limitations such as:

(a) The limits on the maximum steam temperature, due to high temperature corrosion caused by the contaminants in the gasses and occurring on the superheater tube surface.
(b) The fluctuation in steam production, due to non-homogeneous composition of waste.

These technical limitations affect the maximum electrical efficiency achievable and the proposed PCM-based technology intends to offer a novel solution to solve them.

1.1.1. Corrosion at high metal surface temperature

High temperature corrosion is generally caused by the high concentration of HCl in the gasses and the deposits of metal chlorides on the heat exchanger tubes (e.g. superheater and waterwall tubes) (Lee et al., 2007). High temperature of metal surface of the heat exchangers results in the melting of deposits and acceleration of the corrosion rate.

Fig. 2 shows typical charts of the corrosion risk on boiler tubes as function of flue gas temperature (Bogale and Viganò, 2014) when using steel pipes (Fig. 2a) and Inconel alloy pipes (Fig. 2b). The green area represents the conditions in which the corrosion risk is very low and the WtE plant can operate without particular limitations. Most of the newer generation WtE plants (net electrical efficiencies around 23%) operate in the green area, with typical steam temperature values of 400 °C at 40 bar (Lee et al., 2007).

When the operating conditions of heat exchangers move to the yellow area (transition area), the corrosion risk is no longer negligible and the lifetime of heat exchangers begins to reduce thus increasing the cost for preventive maintenance; in this area anti-corrosion coating is recommended. The red area represents the conditions in which heat exchangers are subjected to high corrosion rate. Uncoated heat exchangers have a short lifetime (5000–8000 working hours for steam temperature of 500 °C). Long lifetime of superheaters can be achieved by using monolithic SiC concrete, but under the precondition of ensuring regular inspections and direct repair of cracks before the tube itself shows corrosion attacks (Main and Maghon, 2010). The monolithic SiC concrete is currently employed in those WtE plants which adopt high steam parameters to increase gross electric efficiency up to 30%, such as the WtE plants in Stuttgart (Germany) and in Naples (Italy). An alternative solution has been tested in the WtE plant in Rosenheim (Germany), where rear-ventilated tiles have been used to protect radiant superheaters located in the upper furnace area (Martin et al., 2015). In this case, the limitations are on the maximum steam temperature achieved (i.e. 480 °C) and the increased plant complexity, which requires additional skills and competence for plant design, process control and operation.

In addition to this, it has to be considered that the closer to the hottest zone of the plant the radiant superheater is, the more difficult the control of the superheated steam temperature will be. In fact, the inhomogeneous nature of Municipal Solid Waste (and hence the variation in the calorific value associated with it) causes disturbances during the combustion process which lead to significant fluctuations in the thermal power of the flue gas. As a consequence of this variability, the risk of failure of the superheater tubes due to excessive overheating is increased.

1.1.2. Process stability: Fluctuating temperature and steam production

Good stability of the steam produced by the boiler (and hence of the combustion process) is required to maximise the annual waste throughput and the energy production. However, as mentioned earlier, maintaining the process stability for combustion of household waste is a significant challenge.

As a consequence of the inhomogeneous nature of Municipal Solid Waste, the steam production in WtE boilers exhibits a fluctuating pattern; in Fig. 3a is reported the fluctuation of the steam production (blue[1] line) in a real WtE plant. In addition to this, likewise any other large industrial system or process, the thermal inertia of the boiler gives rise to intrinsic over/undershoots of the steam curve. This delaying behaviour of the boiler is commonly tackled by means of conventional PID controllers whereas the waste-induced effects are usually stabilised by controlling the combustion process. However, these two techniques (PID controllers & combustion process control) only succeed in a partial mitigation of the fluctuation in steam production thus forcing the WtE plants' operators to limit the output from the steam turbine by reducing the waste throughput (hence reducing the energy output). On this issue, in WtE plants with no PID controllers, the fluctuation in steam production typically ranges between ±5% with respect to the baseline whereas, in plants using PID controllers, the fluctuation can be reduced to ±3%. Nevertheless, fluctuation in steam production cannot be completely avoided even if the best control systems are applied (De Greef et al., 2013). In addition to this, it has to be pointed out that temperature fluctuations are always present in the combustion chamber (see Fig. 3b) even when optimized

[1] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.