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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 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 to store a variable heat flux and to release it on demand as a steady heat flux. By means of this technology it is possible to avoid 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 ones. 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.

KEYWORDS: *Phase Change Material; Thermal Energy Storage; Waste-to-Energy plants; High temperature; Corrosion; Thermal power fluctuation;*

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1. INTRODUCTION

In the last decades, the design of Waste-to-Energy (WtE) plants was focused on lowering the discharge rate of pollutants, while maximizing the waste throughput and minimizing the maintenances costs. This goal has been achieved by using costly flue gas treatment units, which has led to the increase of the capital cost of whole WtE plant. 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 aim. Nevertheless, higher steam parameters increase the corrosion risk and the associated cost for 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 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 has been used to protect radiant superheaters located in the upper furnace area. In this case, the limits regard 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 closer to the hottest zone of the plant the radiant superheater is, more difficult the control of the superheated steam temperature. 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.

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 to store 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 could be applied to any type of combustion system where there is 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 assessed 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 Waste-to-Energy 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 Figure 1).

Figure 1. Typical configuration of heat recovery by steam generation in WtE plants

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

- 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;
- 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.

Figure 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 (Figure 2a) and Inconel alloy pipes (Figure 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 in 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 (5,000÷8,000 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.

Figure 2. Corrosion diagram of a) steel and b) Inconel alloy (Bogale and Viganò, 2014)

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, maintaining the process stability for combustion of household waste is a significant challenge. 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 steam production in WtE boilers exhibits a fluctuating pattern; in Figure 3a is reported the fluctuation of the steam production (blue line) in a real WtE plant. In addition to this, likewise in any other large industrial system or process, the thermal inertia of a 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 $\pm 5\%$ with respect to the baseline whereas, in plants using PID controllers, the fluctuation can be reduced to $\pm 3\%$. 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 Figure 3b) even when

optimized control systems are used. In particular, from Figure 3b, it is possible to observe that two types of temperature fluctuations exist: the fast and slow fluctuations which occur within few minutes and few hours respectively.

Figure 3. a) Fluctuation in steam production in a WtE plant with PID control (De Greef et al., 2013); b) Temperature fluctuation in the combustion chamber of a WtE plant (Costa et al., 2012)

The slow temperature fluctuations can be controlled and mitigated by means of the combustion control system, whereas the fast temperature fluctuations cannot be avoided since the control system cannot react fast enough; in order to achieve a rapid response and an optimum control system for the combustion process, high costs are required for both the measurement instrumentation and the plant modifications needed for its installation (Costa et al., 2012).

For these reasons, fast temperature fluctuations are the most dangerous type of temperature fluctuations in WtE plants and they represent the main risk of tube failure for superheaters installed in the combustion chamber. The PCM-based brick is then aimed to solve this issue by absorbing the fast temperature fluctuation in the form of latent heat at constant temperature, so that the superheater tubes will not be subjected to the risk of failure due to uncontrolled temperature increase.

2. PROPOSED SOLUTION: PCM-BASED REFRACTORY BRICK

The proposed solution consists in replacing the typical refractory brick installed into the combustion chamber with a PCM-based refractory brick capable to store a variable heat flux coming from a high temperature heat source (i.e. incineration chamber) and to release it on demand as a steady heat flux. By introducing the PCM-based refractory brick, an extra degree of freedom in the heat recovery/management which did not exist before in combustion

processes is introduced. In fact, the steady heat flux will be used to avoid steam production fluctuation and to increase temperature of superheated steam over current corrosion limits (450°C) without using coated superheaters.

2.1. Working principle and component description

The proposed PCM-based refractory brick exploits the working principle of thermal energy storage based on latent heat. This type of heat storage system stores or releases latent heat when a phase change material, which can be a pure material (e.g. aluminium) or a eutectic compound (e.g. Al-12%Si), undergoes the phase transition from solid to liquid, or vice versa. The storage and release of heat occurs at the phase transition temperature of the PCM, which can be considered to be constant. This technique for heat storage allows designing thermal energy storage systems with a high energy density capable to store heat at high temperature (>300°C). The PCM-based technology presented in this paper employs aluminium and its eutectic alloys because they offer the best thermal properties amongst high temperature PCMs (Kenisarin, 2010):

- High thermal conductivity (solid state > 200 W/mK – liquid state > 90 W/mK);
- High latent heat of fusion (280-560 kJ/kg)
- High melting temperature (470-660°C)

Although aluminium and its alloys own the best thermal properties, their usage as PCM is limited by the high Coefficient of linear Thermal Expansion (CTE) and the high reactivity when in liquid phase. As reported in (Fukahori et al., 2016), the limit of the high reactivity (i.e. high corrosivity) of the molten aluminium (pure or alloyed) can be overcome by using high density ceramics (such as Al_2O_3 , AlN and Si_3N_4) to contain the PCM. Furthermore, the use of ceramics to contain the PCM allows the PCM-based technology to operate at very high temperature and in extremely corrosive environment, such as the combustion chamber of a WtE plant. Since aluminium and its alloys have one of the highest CTE ($23 \cdot 10^{-6}/\text{K}$) amongst the various engineering materials, it is very likely that the material used for containment will have a lower CTE. The mismatch between the CTE of the PCM (i.e. aluminium or its alloys) and that of the container material leads to non-negligible thermal stresses, which can affect the structural integrity of the PCM container. Thus, the PCM should be encapsulated within the ceramic material by adopting cylindrical holes with round bottom edges (see Figure 4a and 4b).

Figure 4. (a) Top view and (b) Section A-A of the PCM-based refractory brick; (c) Water-wall or radiant superheater protected by PCM-based refractory brick

In addition to this, an empty space is left at the top of the brick in such a way that the PCM is free to expand along the vertical direction (both in solid and liquid state). In this way, the thermal stresses within the ceramic container can be controlled by setting the diameter of the holes and the interaxis between them. In order to facilitate the installation of the PCM-based refractory brick, its shape and size should be similar to the ones of traditional bricks. Figure 4c shows an example of installation by using mortar of the PCM-based refractory brick. However, depending on the requirements of WtE plant operator, the PCM-based refractory brick can also be installed without mortar.

2.2. System layout

Figure 5 shows an example of the layout of a WtE plant where the PCM-based refractory brick is employed to avoid the fluctuation in steam production and to increase the temperature of the superheated steam. Comparing Figure 1 to Figure 5, it can be observed that the PCM-based refractory bricks simply replace the traditional refractory bricks in the protection of the water-walls, while an additional radiant superheater is installed in the lower bottom part of the furnace.

Depending on the employed PCM, two different components can be identified: the PCM-based Evaporator and the PCM-based Superheater. The PCM-based refractory brick stores a part of the fluctuating thermal power generated by the waste combustion process. The stored thermal energy is then steadily transferred to the PCM-Superheater for steam temperature increase and to the PCM-evaporator for steam production control. Steam generation into the

PCM-evaporator can easily be managed by varying the mass flow rate of the steam control pump which connects the steam drum to the PCM-evaporator; the generated steam is then used to completely avoid fluctuation in steam production.

Figure 5. Integration between the PCM-based technology and heat recovery boiler based on steam generation in a WtE plant

For what concerns the PCM-based superheater, aluminium is the most suitable PCM to be employed because of its high melting temperature (660°C). The use of aluminium as high temperature PCM allows heating the superheated steam up to 550-600°C, thus leading to a significant increase in efficiency of the WtE plant. Since PCM-based superheater operates at a high steam temperature, the type of steel to be used for the steam pipes should be evaluated carefully in order to allow the WtE plant to operate safely during long-term operation. In addition to this, different type of steel should be used to minimize the cost of the PCM-based superheater; in this case carbon steel pipes could be used up to 500°C, while ASME SA213-T22 steel could be used to heat up the steam from 500°C to 600°C. In the PCM-based Evaporator instead, the eutectic alloy Al-12%Si (in mass %) is more suitable because of its higher latent heat of fusion (560 KJ/kg) and lower melting point (576°C); it is worth noting that aluminium and Al-12%Si are both commercially available and do not require developing

new/special alloy for this specific application. Table 1 reports the comparison of the efficiencies which can be achieved in a WtE plant adopting the proposed PCM-based superheater and some of the existing techniques available in the market. The comparison is based on the methodology described in (Main and Maghon, 2010) and it considers as baseline the typical WtE plant configuration (400°C at 40 bar). From the table it can be seen that WtE plants adopting the PCM-based superheater can potentially achieve a steam temperature up to 600°C leading to a dramatic increase in gross electrical efficiency up to 34.6%.

Table 1 Comparison between expected efficiency in a WtE plant using PCM-based superheater and some of the current techniques to improve WtE plant efficiency

		<i>Baseline</i>	<i>High steam parameters</i>	<i>Steam reheating</i>	<i>PCM superheater</i>
Max Steam Temperature	°C	400	500	420	600
Steam pressure	Bar	40	90	90	90
Flue Gas Temperature at Boiler Outlet	°C	190	190	190	190
Excess Air	%	60	60	60	60
Gross electrical efficiency	%	26.4	30.2	29.9	34.6

3. METHODOLOGY AND TOOLS

In order to demonstrate the technological feasibility of the proposed technology, a detailed thermo-mechanical analysis has been carried out together with a CFD simulation aimed at comparing the performance of the traditional refractory brick technology with that proposed in this paper. The thermo-mechanical analysis is carried out by means of a commercial software (ANSYS Mechanical APDL) employing the Finite Element Method (FEM), while for the CFD simulation ANSYS Fluent has been used.

3.1. Thermo-mechanical analysis

The typical duty cycle of the PCM-based refractory brick follows the usual operative phases of WtE plants: start-up phase, running phase and shut-down phase. According to (Tejima et al., 2007) the start-up phase follows the steps listed below:

- Temperature is raised using the auxiliary burner (gas temperature inside the combustion chamber: from ambient to 400°C in 2 h).
- The gas temperature is kept at 400°C (2 h).
- The gas temperature is further raised by the auxiliary burner from 400 to 600°C in 2 h, from 600 to 900°C in 2 h.

- d. When the gas temperature at the baghouse inlet exceeds 160°C, the gas flow begins.
- e. When the gas temperature at the de-NO_x catalytic reactor inlet exceeds 180°C, the gas begins to flow through the reactor.
- f. When the combustion gas exceeds 750°C, the refuse feeding is started.
- g. When the steam generation rate reaches target, the start-up phase is completed.

Operations (d) to (f) are carried out simultaneously with the raising of the temperature under step (c). The shutdown phase is simpler, since it follows the following steps:

- a. The refuse hopper is closed. The gas temperature falls from 850 to 400°C in 2 h.
- b. When the gas temperature inside the combustion chamber falls below 450°C, the forced draft fan is turned off.
- c. When the gas temperature at the baghouse inlet falls below 125°C, the baghouse is bypassed, the induced draft fan is turned off and the shutdown phase is completed.

During the start-up phase, the PCM-based refractory brick is heated from room temperature up to the melting point of the contained PCM. Once melting point is reached, the control system will maintain the PCM-refractory brick in that operating condition as long as the shutdown phase begins.

When the PCM is subjected to phase change, the coexistence of both liquid and solid states leads to a drastic reduction of the mechanical properties of the PCM (see Table 2). Therefore, the mechanical stresses in the PCM-based brick are very small, as they are only due to the metallostatic pressure. On the other hand, when the PCM is at solid state and CTE of the containment material is lower than that of the PCM, the maximum stresses in the PCM-based refractory brick will be generated. Thus, the following thermo-mechanical analysis considers only the thermal conditions during which the PCM is at solid state, which is the condition encountered during the start-up and shut-down phases of the WtE plant.

Thermo-mechanical analyses available in literature usually study expansion of PCM in liquid phase (Blaney et al., 2013; Maruoka and Akiyama, 2003; Parrado et al., 2015). To the author's knowledge, only (Dal Magro et al., 2016) have analysed thermo-mechanical stresses generated by the expansion of PCM (aluminium) in solid phase. In particular, that study developed a simplified methodology to identify the most relevant design parameters for subsequent experimental validation.

Table 2. Thermo-physical properties of the aluminium (UNI, 2000)

Thermal conductivity (Solid State), λ_a (W/mK)	211
Melting temperature, T_m (°C)	660	
Latent heat of fusion, H_{mass} (kJ/kg)	396	
Volumetric latent heat of fusion, H_{vol} (MJ/m ³)	1089	
Density, ρ_a (kg/m ³)	2750	
Coefficient of thermal expansion, CTE (10 ⁻⁶ /K)	23	
Poisson modulus, ν	0.34	

In this paper, the FEM is used to analyse the thermo-mechanical behaviour of the PCM-based refractory brick. In particular, a simple bidimensional FEM model (see Figure 6a) has been preferred over a complex three dimensional FEM model because the use of complex model tends to hinder the understanding of the basic mechanisms that govern the thermo-mechanical response, as well as the identification of the relevant design parameters.

According to (Dal Magro et al., 2016), the plane stress hypothesis (i.e. axial stress $\sigma_z = 0$) is a reasonable assumption for the bidimensional FEM model of the PCM-based refractory brick. The symmetry of the component allows the computational domain to be reduced to a small part, as shown in Figure 6b. The FEM model shown in Figure 6b, adopts 4-nodes isoparametric linear elements to discretise both the PCM and the ceramic parts; a mapped mesh is used for the whole domain. The thermal analysis is firstly carried out to compute the temperature in each node; then the calculated nodal temperatures are used as thermal loads input in the mechanical analysis.

Figure 6. a) Computational domain, b) FEM model and c) Complex thermal model

The start-up and shut-down phases previously described suggest that the thermal response

of the PCM-based brick should be studied by a transient analysis with phase change. In addition to this, the flue gas side should be modelled with a radiation-convection model, while the steam side should be modelled with a convection model (see Figure 6c); the bulk temperature on both sides (i.e. flue gas and steam sides) should represent the start-up and shut-down phases. The long duration of both start-up and shut-down phases and the high thermal conductivity of the PCMs suggest that it is reasonable to assume the whole system domain to have uniform temperature at any time instant (quasi-steady assumption). To justify this assumption, two different thermal models have been developed and compared:

- a. Complex model: it considers radiation and convection heat transfer models on the flue gas side and a temperature ramp (representing the start-up of the steam loop) on the steam side. Bulk temperatures on both flue gas and steam sides are time dependent and they are derived from the temperature profiles reported in (Tejima et al., 2007); both start-up and shut-down phases are modelled.
- b. Simplified model: it considers the whole domain to be at uniform temperature at any instant in time.

The ceramic with the lowest thermal conductivity (i.e. mullite) has been used as reference material for the model comparison, while the maximum principal stress has been used as comparison criteria.

A numerical uncertainty analysis has initially been performed to assess the approximation errors of the finite element solution. In particular, a sensitivity analysis on the mesh size has been carried out to identify at which element size the solution of the finite model becomes grid independent.

The results of the simulations have shown that the maximum difference in the maximum principal stress between the complex and the simplified models is less than 2%; this validates the assumption of uniform temperature; the analysis also showed that the complex model is roughly 6 times slower to converge than the simplified one.

The assumption of uniform temperature allows simulating the thermo-mechanic behaviour of the component by a sequence of steady state analyses. Thus, the applied thermal load is simply a uniform temperature on the whole finite element model.

Six commercial high density ceramics (i.e. no porosity) have been considered as containment material for the PCM-based refractory brick: aluminium nitride (AlN), aluminium oxide at 96% purity level (Al_2O_3), mullite, sialon, silicon carbide (SiC) and silicon nitride (Si_3N_4). The thermo-mechanical properties reported in Table 3 have been obtained by comparing the

data reported in the online database Matweb, which are provided by ceramic suppliers. Since the maximum considered temperature for the thermo-mechanical analysis is 660°C (i.e. PCM melting temperature), the ceramic properties can reasonably assumed to be constant.

Since ceramics are brittle materials and their strength properties vary with the applied load (i.e. tensile strength is much lower than compressive strength), the equivalent stress along the first principal direction σ_{S1} has to be used to evaluate the material failure. More in particular, the maximum first principal stress $\sigma_{S1,max}$ must be lower than the modulus of rupture of the evaluated ceramic.

Table 3. Thermo-mechanical properties of the considered ceramics

Ceramic	Young's modulus E (GPa)	Coefficient of thermal expansion CTE ($10^{-6}/K$)	Thermal conductivity k (W/m·K)	Flexural strength MOR (MPa)
AlN	330	4.5	160	320
Al ₂ O ₃ (96% purity)	300	8.2	25	345
Mullite	151	5.4	6	180
Sialon	288	3	17.5	760
SiC	410	4.0	120	550
Si ₃ N ₄ (Sintered)	310	3.3	29	689

The main performance parameter of the PCM-based refractory brick is the energy density E_p , which represents the amount of energy that can be stored in the form of latent heat per unit of volume. Energy density is strictly related with the geometric parameters of the PCM-based refractory brick; in particular, referring to the bidimensional model, the ratio between the PCM area and the total area, which represents the PCM filling ratio, relates the energy density to the geometry of the PCM-based refractory brick.

3.2. Thermo-fluid dynamic analysis

A CFD analysis is carried out to compare the performance of a traditional refractory brick technology with that of the PCM-based refractory brick, when they are used to protect superheaters installed in the combustion chamber. In particular, the total heat flux entering the steam has been used as comparison criteria.

Two different bidimensional CFD models have been developed: the baseline model (see Figure 7a) and the PCM-brick model (see Figure 7b). In the baseline model, thermal properties of traditional alumina refractory brick have been used; in particular, a value of 3.5 W/mK has been used for the thermal conductivity. In the PCM-brick model, the considered PCM is the aluminium (see thermal properties in Table 2), while the adopted ceramic is the high density Al₂O₃ (96% purity), which properties are reported in Table 3. Both models share same material

for steam pipe (i.e. carbon steel) and the mortar, which is a SiC-based mortar.

The same boundary conditions are applied in both models: radiation-convection heat transfer on the flue gas side (red line in Figure 7) and convection heat transfer on the steam side (green line in Figure 7). On the flue gas side, a sinusoidal temperature profile (average temperature 950°C, amplitude 75°C and period 600 s) is applied by means of a user-defined function (UDF); the emissivity of the flue gas is assumed to be 0.5, while the emissivity of the alumina refractory brick can be assumed to be 0.8 (Woskov and Sundaram, 2002). On the steam side, a constant temperature of 450°C and a convection heat transfer coefficient of 250 W/m²K have been applied.

Figure 7. Geometry and materials of the CFD models of the a) baseline and b) PCM-based brick

The geometric parameters of both models are reported in Table 4; it has to be pointed out that width W has been selected in such a way that the temperature fluctuation applied on the flue gas side is absorbed by the traditional refractory brick (i.e. negligible temperature fluctuations are present in the steel pipe).

Table 4. Geometric parameters of the CFD models

Width, W (mm)	72
Length, L (mm)	36
PCM hole diameter, D (mm)	4
PCM hole x interaxis, S_x (mm)	9
PCM hole y interaxis, S_y (mm)	9
Steam pipe inner radius, R_i (mm)	20
Steam pipe thickness, t_p (mm)	4
Mortar thickness, t_m (mm)	5

4. RESULTS AND DISCUSSION

In order to demonstrate the technological feasibility and the performance of the PCM-based technology, a thermo-mechanical and a thermo-fluid dynamic analyses have been carried out.

Figure 8a shows an example of the distribution of the first principal stress around the PCM (grey area); it can be observed the maximum stresses are concentrated at the interface between the PCM and the ceramic. Figure 8b reports the typical distribution of the maximum first principal stress as a function of temperature for the considered ceramics; the reported stress distributions refer to the same geometric parameters (i.e. same hole diameter and interaxis). It can be observed that ceramics with low CTE and high young's modulus (i.e. AlN, SiC, Si₃N₄ and Sialon) generate the highest thermal stresses, while ceramics with low CTE and low Young's modulus (i.e. mullite) or with high CTE and high Young's modulus (i.e. Al₂O₃) generates the lowest thermal stresses.

Figure 8. a) First Principal stress distribution around the PCM and b) comparison of distribution of the maximum first principal stress as a function of temperature for the considered ceramics

As explained in the section 5.3.1, the main performance parameter of the PCM-based refractory brick is represented by the energy density E_p , calculated according to equation (1), is directly proportional to the PCM filling ratio χ and the latent heat H of the PCM.

$$E_p = \chi \cdot H \quad (1)$$

The PCM filling ratio χ is defined as:

$$\chi = \frac{A_{PCM}}{A_{tot}} \quad (2)$$

where A_{PCM} is the area occupied by the PCM and A_{tot} is the total area of the FEM domain.

Table 5 reports the PCM filling ratio of the PCM-based refractory brick when the considered ceramics are used; the reported PCM filling ratios and energy densities have been calculated when the maximum first principal stress $\sigma_{S1,max}$ is equal to the 90% of the modulus of rupture.

To control the maximum first principal stress, the diameter of the PCM holes has been maintained constant while the interaxis S_x and S_y , which are assumed to be equal, have been varied. It can be observed that mullite has the lowest performance; this is due to the combination of a low CTE and a low modulus of rupture. The best material results to be the sialon, followed by silicon nitride Si_3N_4 and silicon carbide SiC . Nevertheless, all these ceramics are usually quite expensive. Alumina-based ceramics are usually cheaper, so the alumina Al_2O_3 at 96% of purity probably represents the best trade-off between performance and cost.

Table 5 Performances of the PCM-based refractory brick for the considered ceramics

	PCM Filling Ratio, χ	Energy density, E_p [MJ/m³]
Mullite	1%	8.55
AlN	6%	69.82
Al ₂ O ₃ (96% purity)	16%	168.95
SiC	21%	224.93
Si ₃ N ₄ (Sintered)	33%	356.00
Sialon	39%	421.20

Figure 9a shows the temperature of the PCM in different rows along the y axis, from the steam side ($y=0$) to the flue gas side ($y=72$ mm); the melting point temperature of aluminium is also illustrated with the dashed line. As it can be seen, all of the rows of PCM pipes successfully experience phase change during the temperature fluctuation. The closer the PCM row to the steam pipe is, the less fluctuation of temperature they experience. Figure 9b reports the temperature distributions across the refractory bricks along the y direction from the steam pipe to the radiation wall.

Figure 9. a) Temperature of the PCM in different rows and b) comparison of the temperature gradient of the traditional technology and the PCM-based refractory brick

Contrary to the baseline case, which experiences over 500°C of high temperature difference across the refractory material, the PCM case reveals much less temperature difference of less than 200°C. The result indicates that the proposed PCM-based technology helps to reduce more than half of the thermal gradient, thus mitigating the thermal stress exposed to the highly brittle refractory materials.

The time-averaged value of the total surface flux for PCM case is 22139 W/m², which is almost twice the value of the baseline case. This significant increasing of surface total heat flux demonstrates better heat transfer performance by using the PCM-based refractory brick.

The CFD and FEM simulation demonstrate high feasibility of this technology in terms of buffering heat flow, reducing thermal gradient within ceramics, and delivering much higher heat flux to the steam flow.

5. CONCLUSIONS

In this study, an innovative refractory brick technology based on phase change materials for corrosion protection of the radiant superheaters has been proposed. 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 and the efficiency to be increased up to 34%. Aluminium has been considered as high temperature PCM, while several commercial ceramics (e.g. Al₂O₃, AlN and Si₃N₄) have been evaluated as containment material due to their high resistance to corrosion. A detailed thermomechanical analysis has demonstrated the

technological feasibility of the proposed technology and it has identified Al_2O_3 has the most suitable ceramic for containing aluminium.

A computational fluid dynamic (CFD) simulation have been carried out to compare the performance of the traditional refractory brick technology with that proposed in this paper. The results showed that the PCM-based refractory brick can almost double the heat flux to the steam flow, while reducing thermal power fluctuations entering the steam.

The results of the present paper contribute to the establishment of high temperature phase change material thermal energy storage to improve energy efficiency of waste-to-energy plants.

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