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Numerical study of the effects of refractory lining geometries on the swelling induced by oxidation

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ABSTRACT

Finite element (FE) computations have been performed to analyze the thermo-chemo-mechanical behavior of SiC-based refractory parts in linings used in waste-to-energy plants. These parts are in contact on one side with smoke and ashes at high temperature, and on the other side with the pressurized vapor pipe. Three multi-layered lining designs have been studied: two with tiles and one with a concrete panel. A coupled model taking into account the transport of dioxygen in the gas through the porosity, the reaction of dioxygen in contact with silicon carbide particles and the formation of solid components gradually clogging the pores, has been implemented in the finite element code ABAQUS ®. These phenomena affect the mass diffusion rate of dioxygen through the refractory layer and induce a macroscopic swelling of the material. The analysis of the numerical results allows for a better understanding of the influence of the lining design and the nature of the ceramics on the lifespan of such refractory parts.

1. Introduction

Optimizing the design of multi-layered linings used in furnaces, stoves, kilns, ovens, in plants dealing with the manufacturing of metal, cement, ceramic, glass products, chemical and petroleum products or plants generating energy from waste or biomass is a great challenge. These linings must withstand to high process temperature, abrasive wear by hot liquid and solid particles, and aggressive chemical environment (hot gases, acid or basic gases, liquids and solids in movement). Their optimization is required for sustainable development of the manufacturing process and also for enhancing the safety, extending the lifespan of the industrial tools and reducing the costs.

Today, numerical computations are already performed on such structures. But even the thermomechanical models accounting for damage and creep, do not permit to predict well the stress and strain states in-service – except the first heating of the structure – as they are not able to simulate the complex microstructure change of the refractory ceramics (usually called refractories) and their consequences. Thus, one main difficulty to overcome is to develop mechanical behavior that are strongly dependant on the environment conditions (i.e. oxydation, corrosion, etc.).

The first goal of the paper is to demonstrate that the development of numerical tools capable to describe the diffusion of mass, the heat transfer, the oxidation mechanisms and the mechanical behavior will permit a better understanding of the degradation process of the material in the linings.

Silicon carbide (SiC)-based refractories are well known for their high resistance to corrosion, thermal shock and abrasion at high temperature [1,2]. Because of their good thermal conductivity they are often used in municipal waste incinerators to ensure a good heat recovery by the metallic waterwall tubes they have to protect against aggressive gas. In such plants, the flame temperature reaches up to 1200 °C in the combustion chamber at the bottom level, while the waterwall temperature is approximately equal to 250 °C. Around 17 m higher at the top of the chamber, due to cooling the temperature of smoke and ashes is close to 500 °C.

As the incineration of domestic and industrial waste is a continuous process, extending the lifetime of the protective refractory layer in the combustion chamber of the waste-to-energy (WTE) plant facilities is one option to limit the maintenance operations. Currently the lifetime of the lining is several years with one or two maintenance operations per year.

Observations made on worn parts of the refractory layer of the lining revealed different types of degradation of the material and parts of the refractory layer (e.g. tiles). These degradations reduce the efficiency of the protection again hot smoke and ashes with

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Fig. 1. New (top) and old (bottom) SiC-based refractory tiles in a WTE facility; picture taken about 7 m from the burning grill after a long period of plant operation (tile height: 245 mm).

the consequence that the waterwall tubes can be corroded. As shown by Prigent [3], at the microstructural scale of the refractory several corrosion mechanisms take place over time. For example, post-mortem analysis on worn SiC-based tiles [4] has shown that molten salts react with SiC aggregates and matrix phases and form para-wollastonite around SiC grains and porosity near the zone close to the hot face of refractory tiles. Other phases such as cristobalite and microline are also formed down to the core of refractories. At the macroscopic scale cracks and rupture are common degradation that can be observed in the refractory layer of the lining. They result from excessive stresses induced by the progressive swelling of the material during the use. These degradations depend both on the material and the design of the lining. Fig. 1 illustrates the deformation of SiC-based tiles in the refractory lining parts that has occurred in-service.

The environmental conditions in the combustion chamber are not well known. Indeed, the nature of the chemical components of smoke and ashes depends on the waste burnt and the incinerator process. Moreover, the temperature field is strongly influenced by the incinerator management, the refractory lining design and the depth of the layer of ashes deposited on the hot face. Consequently different mechanisms of corrosion may be involved in the chemical degradation of the SiC-based refractory: chemical reactions between phases present in the initial composition of the material, chemical reactions between phases of the material and phases coming from the smoke and ashes. These reactions occur when phases in contact are not in chemical equilibrium. They strongly depend on the level of temperature and the transport conditions of the initial and produced species. The local mass change resulting from the disappearance of initial compounds and the deposition of new compounds explains the change in porosity and the macroscopic deformation. Porosity change and macroscopic deformation depends on the swelling and mechanical constraints at the local scale (i.e. the microstructure) and at the macroscopic scale (anchors design, thermal expansion, joint thickness, etc.).

These remarks show that thermomechanical phenomena and corrosion cannot be analyzed independently to fulfill the degradation observed. One way to study such degradation mechanisms consists in doing a multi-physical coupling analysis as already proposed in previous studies [5,6]. Such an analysis helps in selecting all phenomena involved, evaluating their importance and their interactions to finally select the main phenomena to model from a conceptual point of view.

In this paper, a multi-physics numerical model is developed in order to study the effect of lining design on the macroscopic deformation of the refractory layer induced by its corrosion (limited herein to oxidation). Currently, the level of knowledge and the data available do not allow the development of a highly complex model which takes into account all the mechanisms mentioned by Prigent [3]. Hereafter, attention is exclusively focused on the oxidation of SiC-based refractory. This choice is justified by the fact that this phenomenon is the first step in the degradation process of such linings and often participates substantially in the degradation of SiC-based refractory concrete structures [7].

The proposed thermo-chemo-mechanical model is built in the classical framework of irreversible thermodynamics of open continuous reactive media [8]. It takes into account a reactive diffusion of dioxygen present in the gas flowing through the porosity of the refractory layer. The formation of solid silica (SiO_2) deposits gradually clogs the porosity. It leads to a reduction of the gas diffusion and to the development of a chemical strain that adds to the classical mechanical and thermal strains. The constitutive equations describing the complex material behavior have already been validated by comparison with experimental results on a reference case [9].

The model is shortly summarized in the first section and identified for two refractory materials. The implementation of this model in the finite element (FE) software ABAQUS ® [10] and the numerical method applied for solving the coupled partial differential equations are briefly detailed in the next section. The following section is dedicated to the analyses of the results of the simulations of the long-term behavior of the protective refractory layer (a one-year in-service without maintenance) in order to check the ability of such models to provide an assistance for the refractory lining design.

To reach this second goal of the paper, three lining designs representative of those already used in WTE have been studied. In two linings (denoted *A* and *B*, respectively) the refractory layer consists of an assembly of tiles (denoted A_t and B_t, respectively). These tiles are manufactured in refractory plants; first cast by pressing the mix in a mold and sintered at high temperature. Tile A_t is attached on the waterwall tubes with its handle, while tile B_t is tied on the top handle with a mortar. In the third lining design (denoted *C*) the refractory layer is made of an assembly of concrete panels (denoted C_p). The panels are cast on-site and the first heating of the incinerator is managed to obtain the final properties of the material at high temperature. They are fixed to the metallic waterwall tubes by means of anchors.

For this three lining designs, computations have been carried out considering two SiC-based refractories supplied by Calderys a subsidiary of Imerys World Minerals under the brand names *SF*60 and *CV*85. The aim is to compare the response of these six different configurations in order to better understand and distinguish the effects of geometry and material behavior on the long-term behavior of the lining.

2. Thermo-chemo-mechanical model

2.1. Refractory lining ceramics

The parameters for the multi-physical model described below have been identified for two types of SiC-based refractory which contain approximately 60 wt% of SiC for the *SF*60 and 85 wt% of SiC for the *CV*85. Both materials have good resistance to corrosion and high temperatures.

The refractories are heterogeneous multi-phase concretes (also named castables) containing SiC grains with size ranging from several tenth micrometers to several millimeters. The grains are bonded with calcium-aluminate cement and form strong bonds in service at high temperature before the oxidation. The matrix phase is arbitrarily defined as the phase containing both fired cement and SiC aggregates with size below 200 μm. The mass content of the matrix is 51.7% in refractory *SF*60 and 53.6% in refractory *CV*85. The macroscopic porosity in both refractories is approximatively 16–17%. Mainly located in the matrix, it is open making easier the diffusion of oxygen through the bulk of the refractory layer.