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Compatibility study between aluminium alloys and alternative recycled ceramics for thermal energy storage applications

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HIGHLIGHTS

- Conducted high temperature corrosion tests at 1000 °C for 100 h.
- Performed ESEM and XRD characterization for reliable post-corrosion analysis.
- First time to report the compatibility between molten al-based alloys and three recycled ceramics.
- Concluded possible encapsulation materials from wastes for molten aluminium alloys.

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ABSTRACT

Recycled ceramics from industrial wastes, compared with traditional high-purity ceramics, present high market potential as refractory materials due to their low cost production process with very low environmental impacts. However, there still exists a research gap of how recycled ceramics behave while in contact with liquid metal. In order to study the feasibility of using recycled ceramics as the encapsulation material in the application of high temperature Latent Heat Thermal Energy Storage system, this paper investigates the compatibility of recycled ceramics with three kinds of aluminium-based alloys at high temperature, with a comparison to the corrosion resistant behaviour of alumina. The recycled ceramics explored include Cofalit from asbestos containing waste, blast furnace slags from steel production, and coal fly ashes sintered ceramics from incineration plants. The study consists of a steady state thermal treatment of ceramic samples in contact with the three different alloys at 1000 °C for 100 h, and a post instrumental characterization of ceramic samples by Environmental Scanning Electron Microscopy, Energy Dispersive Spectrometry and X-ray diffractometer, to understand the chemical and structural transformation of the ceramics. Results demonstrate that Cofalit shows chemical stability with Al99% but instability with AlSi5% and AlSi12%. Blast furnace slag presents quite good thermochemical stability towards molten AlSi5% and AlSi12%. Coal fly ashes sintered ceramics are highly interactive towards all three aluminium alloys. In conclusion, besides alumina, Cofalit is recommended as alternative encapsulation material for molten Al99%, while blast furnace slag being recommended for molten AlSi5% and AlSi12%.

1. Introduction

1.1. Thermal Energy Storage (TES) system in industrial waste heat recovery process

Latent Heat Thermal Energy Storage systems (LHTES) utilize the Phase Change Materials (PCMs) to accommodate excess or intermittent thermal energy sources for a steady and controlled output, by storing and releasing the thermal energy within phase transformation process. Their abilities to store thermal energy at a high density and provide a constant temperature output, make the PCMs an attractive technology in industries for effective and sustainable energy usage [1,2]. Although there have been many applications of LHTES (e.g. domestic hot water supply, space heating/cooling), high temperature LHTES application remains to be a challenge due to its complexity in material selection, configuration design and operation [3] despite its high potential to improve the efficiency of high temperature processes, such as Waste to Energy (WtE) plants [4] and solar industry [5].

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Nomenclature

Acronyms

CFA	Coal Fly Ashes
CTE	Coefficient of Thermal Expansion (1/K)
EDS	Energy Dispersive Spectrometry
ESEM	Environmental Scanning Electron Microscopy
LHTES	Latent Heat Thermal Energy Storage Systems
PCMs	Phase Change Materials
TES	Thermal Energy Storage
WtE	Waste to Energy
XRD	X-ray Diffractometer

Latin letters

C_p	heat capacity (kJ/kg·K)
k	thermal conductivity (W/m·K)
T_{mp}	melting point temperature (°C)
ρ	density (kg/m^3)

A recent study by Dal Magro et al. [6] proposed a new PCMs tile technology to buffer the fluctuation of steam generation in WtE plants. Fig. 1 illustrates the new design featuring PCM-based refractory brick. As shown, the design exploits the latent heat of PCMs filled into the holes inside of the refractory brick, thus buffering the fluctuation of heat flux from waste combustion. From the preliminary study and simulation results, this design can not only buffer heat flow, reduce thermal gradient, deliver higher flux to steam flow, it can also avoid steam production fluctuation, increase temperature of superheated steam without using coated super-heaters, and therefore increase overall plant efficiency by over 30%. As a continuation study of the proposed technology, it is critical to choose the best materials to meet the demanding challenge.

Table 1 summarizes the main high temperature PCMs (T_{mp} above 500 °C) available for LHTES design. There are numerous studies dedicated to high temperature LHTES using molten salt, including nitrates, chlorides and carbonates [7]. Molten salt presents advantages such as good storage density, low storage cost and a wide melting temperature range to fit into various applications. However, the low thermal conductivity, their corrosive behaviour towards constructional materials and their high volume expansion rate during phase transformation pose great challenge in the design and construction [8]. Another PCMs option for high temperature LHTES is metal alloys, including aluminium series, copper series and iron series. Metal alloys as PCMs, present high storage density, remarkably high thermal conductivity, and low volume expansion rate, which make them an attractive choice for the previously proposed PCM-tile technology [4,7]. Nonetheless, their chemical corrosive behaviour when in contact with metallic encapsulation material restricts their application in many scenarios.

1.2. Compatibility between Al based alloys and ceramics as potential encapsulation materials

In order to facilitate application of metal alloys as high temperature PCMs, it is crucial to find encapsulation material that meets the requirements of adequate thermal properties and mechanical strengths, availability with low price, and compatibility with metal alloys at operational temperature.

Literatures have indicated that ceramics could serve as good candidates for encapsulating molten aluminium alloys. A study by Fukahori et al. [8] investigated the corrosion behaviour between Al-Si alloys and commercial ceramics. The alloys and ceramics were placed in tube furnace and underwent thermal treatment at 1000 °C for 100 h. Then microstructural analysis of the sample surfaces was performed by means of Scanning Electron Microscopy and Energy-Dispersive Spectrometry. The results concluded that Al_2O_3, AlN and Si_3N_4 showed high corrosion resistance to the AlSi25% and Al99.7%. Another study by Yan and Fan [10] reviewed the durability of ceramic materials in molten aluminium alloys. They concluded that besides the aforementioned ceramics, graphite, sialons and aluminosilicate refractories were also characterized as inert in molten aluminium. However, the manufacturing process of commercial high purity ceramics are highly energy intensive and produces a large quantity of wastes since it involves multiple stages in which the product is subject to high temperature treatment [11]. The alumina refineries, according to the International Aluminium Institute, have an average total energy consumption of 11.2 GJ/ton [12].

Unlike the high purity ceramics from commercial sources, the ceramics recycled from industrial waste contribute to a more sustainable environmental pathway if used as refractory materials. These recycled ceramics are made from industrial wastes such as asbestos containing wastes, steel slags or coal-fired power plant fly ash. Due to the nature of the recycled ceramics, they are usually available in most of industrialized areas with a much lower costs. Besides being inexpensive, available in large quantity with potential environmental benefit such as low greenhouse gas emission and low embodied energy, the recycled ceramics also present quite good thermo-physical properties and mechanical strengths [13,14]. Gutierrez et al. [15] reviewed several industrial wastes from different sources and reported the origin, the properties and the current research works related. It is noteworthy that the thermal properties of some recycled ceramics are even comparable with the commercial high purity ones. For instance, the recycled ceramics made from asbestos containing wastes, Cofalit, has a density of around 3120 kg/m^3, a heat capacity of 0.8–1.03 kJ/kg·K. The Fly ashes coming from municipal wastes has a density of around 2900 kg/m^3, the heat capacity ranging from 0.9 to 1.1 kJ/kg·K. The mechanical strength of Cofalit is reported as very stable even after severe thermal cycling operating conditions.

In summary, recycled ceramics demonstrate great advantages of low environmental cost, low capital cost, and reasonably good thermo-mechanical properties as encapsulation materials for high temperature LHTES systems. A number of corrosion studies have been carried out [13,16,17] to examine the compatibility between molten salts and inorganic industrial waste ceramics, for their application in solar thermal

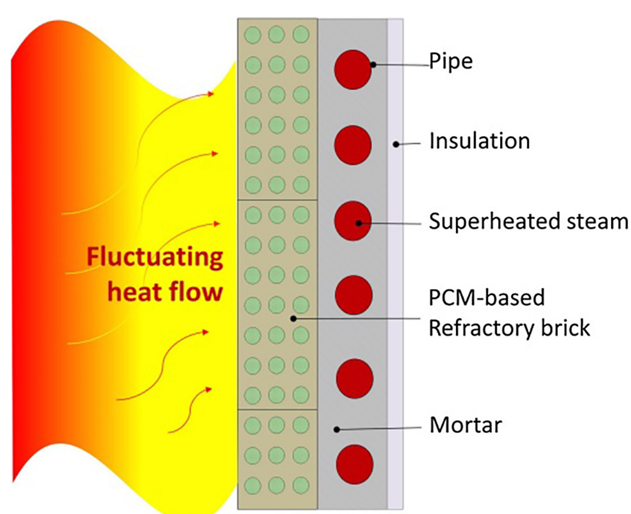

Fig. 1. Water-wall or radiant superheater protected by PCM-based refractory brick [6].