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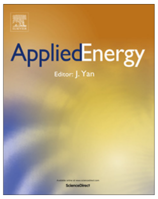

A new method for controlling the ignition state of a regenerative combustor using a heat storage device

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HIGHLIGHTS

- Dynamic modelling using heterogeneous one-dimensional models.
- Design and simulation of regenerative thermal oxidizer and heat storage system.
- Feedback control determines the heat extracted/introduced in the oxidizer.
- Demonstration for a real coal mine ventilation air emission.

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ABSTRACT

Regenerative oxidizers are very useful for combustion of methane–air lean mixtures (<1 vol.% and as low as 0.15%), as those generated in coal mines (ventilation air methane, VAM). However, the performance of the oxidizer is unstable, leading to overheating or extinction, when methane concentration varies. We propose a new procedure for overcoming this problem, using the heat storage concept. Thus, this issue is addressed by proposing the use of an external sensible heat storage system, added to the regenerative oxidizer, capable of storing the excess of heat released in the oxidizer during rich concentration periods, and using it to heat the feed as needed during lean concentration periods. The performance of the heat storage system has been studied by simulating the behaviour of a regenerative thermal oxidizer designed to operate at 0.25 vol.% nominal feed methane concentration. It was found that the regenerative oxidizer, provided with the heat storage system together with a feedback controller that regulates the heat extracted/introduced in the oxidizers can operate satisfactory, dealing with the variations in methane concentration found in ventilations of coal mines.

1. Introduction

The environmental concern about methane emissions has risen in the last years, because this gas is the second contributor to global warming, after carbon dioxide. The most important sources of methane emissions are coal mines, natural gas extraction and processing facilities, landfills, etc. Among the different technologies for controlling methane in air emissions, oxidation to carbon dioxide is the most effective: methane global warming potential is 20 times higher than that of carbon dioxide, so there is a clear environmental advantage in oxidizing methane to carbon dioxide before releasing it to the atmosphere [1–3].

The most appropriate combustion technology depends on the concentration of methane in the emission. Gas turbines allow direct production of electricity from the combustion reaction, but require a high concentration of methane [4]. For lower concentrations, autothermal oxidation of methane (e.g., without the need of additional fuel) is feasible, but it requires heat exchange between the inlet and outlet streams. This heat exchange can be done using recuperative or regenerative devices [5,6]. Recuperative heat exchange is based on indirect heat exchangers, whereas in regenerative heat exchange, the heat of the outlet stream is first stored in a solid bed, which is later used to pre-heat the inlet stream. Due to the direct gas-to-solid heat transfer, the thermal efficiency of regenerative heat transfer is higher. For this reason, regenerative oxidizers are usually the most appropriate devices to carry out methane combustion at low concentration [7–9].

Regenerative oxidizers operate under forced unsteady-state conditions, created by periodically reversing the feed flow direction. Therefore, the heat released by the exothermic reaction is trapped inside the reactor bed between two consecutive flow reversals, being used to preheat the cold feed up to the reaction temperature. Further explanations about this technology and its applications have been exhaustively reported in recent reviews and articles cited therein [9–11].

There are two types of regenerative oxidizers, depending on the type of methane oxidation reaction: regenerative thermal oxidizers

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Nomenclature

a	specific surface area (m^2/m^3_{bed})
c	mole concentration (mol/m^3)
C_P	heat capacity (J/kg k)
D_{ax}	effective axial dispersion coefficient (m^2/s)
e	error
f_{extr}	fraction of gas extracted (–)
G	transfer function (°C/%)
h	gas to solid heat transfer coefficient (W/m^2 K)
k	thermal conductivity (W/m K)
K_C	proportional constant (–)
K_P	process gain (°C)
r_{ho}	homogeneous reaction rate of methane (mol/m^3_{gas} s)
t	time (s)
T	temperature (K)
t_{sw}	switching time (s)
u	gas superficial velocity (m/s)
y	mole fraction of methane (–)
z	spatial coordinate (m)

Greek symbols

ΔH	reaction enthalpy (J/mol)
ε_b	bed porosity (–)
θ	dead time (s)
ρ	density (kg/m^3)
τ	process time constant (s)
τ_I	integral time (s)

Subscripts

0	inlet
cha	combustion chamber
G	gas
S	solid

Acronyms

PID	proportional-integral-derivative
RCO	regenerative catalytic oxidation
RTO	regenerative thermal oxidation
VAM	ventilation air methane
VOC	volatile organic compound

(RTO) and regenerative catalytic oxidizers (RCO). In RTO methane oxidation takes place in the gas phase at high temperature, whereas in RCO methane is oxidized on the surface of a solid catalyst. The use of a catalyst produces a marked reduction of the methane ignition temperature, and hence of the reactor operating temperature. As a consequence, the size of the reactor and the need of insulation are lower. Another important advantage of RCO is the lower temperature dependence of the combustion reaction, which results in a better reactor operation, e.g., the reactor extinction and overheating are easier to control [12–14]. RCO has also disadvantages, the most important ones being the high cost and deactivation of the catalyst [15]. The latter takes place, depending on the catalyst, at high temperature and in the presence of other compounds, such as water or sulfur compounds [16].

Regenerative oxidizers have succeeded at a commercial scale in the treatment of volatile organic compounds (VOC) emissions to match environmental regulations [17–19].

In industrial applications, regenerative oxidizers have to deal with changes in feed concentration upon time, as in many emissions methane concentration changes during short periods of time, even though the day-averaged concentration is relatively constant. In these situations, the reactor must be designed not only considering the nominal or time-averaged concentration, but also the rich and low concentration periods. Thus, during the rich concentration periods the reactor should be able to drain the excess of heat released by the reaction; otherwise, there is a risk of overheating, damaging the catalyst (for RCO), insulation or reactor structure (RTO) or promoting the formation of nitrogen oxides (RTO). On the contrary, during the low concentration periods, the reactor must avoid extinction conditions.

Different control strategies have been proposed in the literature to deal with these problems, as summarized as follows. Some control strategies are based on adjusting the switching time according to the feed concentration [14,20,21]. It was experimentally demonstrated that this control can deal with moderate changes in concentration; however, for the case of sharp and sustained decreases in concentration, the reactor extinction cannot be prevented [14]. Other controllers regulate the excess of heat in the reactor by withdrawing part of the hot gas from the inside of the reactor [17,22–26]. Another possibility is the air dilution of the feed, and the use of electrical resistances or addition of supplementary fuels for feed fuel concentrations too high or low, respectively, but in this way the system losses its autothermicity [27,28]. So, the lack of a control system able of operating autothermically at both rich and lean concentrations is widely accepted.

In the present work, we propose an alternative approach for increasing the thermal stability of regenerative oxidizers. This approach consists of using an additional heat storage system (packed bed) connected to the reactor. The mission of the heat storage system is to store the excess of heat produced in the reactor during the feed rich concentration periods, and return this heat as needed during the low concentration periods. While other control systems are designed only to deal with a type of concentration disturbance (e.g., a decrease or increase in methane concentration), the proposed control system is able to deal with both of them. Moreover, this control system maintains the reactor stable operation during lean concentration periods by using the heat stored in the proposed heat storage system, instead of using a supplementary fuel, so it is more energy efficient.

The development of novel and more efficient heat storage systems is an active research field, particularly attractive for solar power plants [29,30]. Heat storage systems are classified into three main groups according to the way the heat is stored: sensible, latent and chemical. Latent and chemical heat storage systems are the most volume-efficient, as high amounts of heat can be stored in small volumes. However, these systems are based on the coupling with a phase change (latent) or a reaction (chemical), which limits their application to a certain, and sometimes narrow, range of operating temperature. On the contrary, sensible heat storage systems are very versatile with respect to the temperature range, the moment and the direction of the heat exchange [31]. This is particularly important for regenerative oxidizers, where the source temperature may change upon time, and the charging and discharging cycles of the heat storage system may be of different duration. In addition, they are very simple and have low cost. For this reason, a sensible heat storage system, formed by beds of refractory ceramics, is the option selected in this work.

The performance of the heat storage system has been studied for the combustion of methane in a regenerative thermal oxidizer, as RTO are more sensible to variations in the feed concentration.