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Experimental and numerical investigations of an adsorption water-zeolite heat storage for refrigeration applications

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Abstract

A zeolite 13XBF - water adsorption heat storage for refrigeration purposes is presented in this paper. The system comprises a reactor, in which the adsorption process takes place, and a condenser/evaporator unit. The aim is to be able to recover waste heat, excess solar heat or off-peak electricity (electricity-to-heat), to store it with minor losses and to use the available energy when it is needed, either for cooling and/or for heating.
A prototype of the system has been developed and tested. The studied configuration is designed to recover heat from air flows (at up to 300 °C) and to produce cooling of the indoor ambient air (range 12-20°C). The reactor includes only one bed and the entire system is designed to store energy (3 kWh) to provide the desired cooling effect for several hours.
Moreover, the heat and mass transfer has been numerically simulated with a CFD software. A 2D model of the sorption storage and a 0D model for the condenser/evaporator unit have been coupled.
The experimental results showed that the concept is suitable for the application, but some challenges still exists: heat transfer inside the adsorber (i) and vacuum tightness of the system (ii). The results of the simulation are consistent with the ones from the experiments, demonstrating the suitability of the theoretical model.

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Keywords: thermo-chemical heat storage; adsorption; waste heat recovery; solar heating; electricity to heat

1. Introduction

The need to address the climate change and the reduction of fossil fuel consumption increases the importance of energy storage technologies to improve utilization of renewable sources and to reduce the energy waste.

Very different principle and technologies can be used to store energy, either in thermal, electrical, chemical or mechanical form. Among the thermo-chemical technology, adsorption processes are interesting for their capability to store thermal energy with minor losses and with high storage density.

Adsorption processes work with a pair of material: a sorbent and a sorbate. There are several working pair which may be used. One of those is zeolite and water.

The process follows the equilibrium hydration reaction:

$$A_{(s)} + H_2O_{(g)} \leftrightarrow A \cdot H_2O_{(s)} + \Delta h_R \quad (1)$$

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Where Δh_R is the reaction enthalpy.

An adsorption system can either be "open" or "closed". In an open system, the reactor containing zeolite is at atmospheric pressure and the water vapour is transported through air flow moist air) through the reactor. Air itself is also the heat transfer fluid. In a closed system, the reactor is under vacuum condition and it is connected to one or more condensers and evaporators. The entire loop is sealed under vacuum and only water vapour flow into it. Heat transfer is provided by means of a secondary fluid (water, thermal oil, air, etc.) depending on the needs of the application.

Open systems have been investigated especially for seasonal storage applied to buildings [1], [2], [3], [4]. In fact, zeolites are able to store excess heat for long period without losses. Closed systems have been also investigated for seasonal storage [5]; however, the main commercial energy applications of closed systems have been as thermal heat pump for adsorption chillers [6], [7] and in gas powered heat pump [8] with possible applications in industrial and building sectors. In those commercial applications, the system does not accomplish the purpose of storage, but it is designed for continuous operation with fast switchable beds.

In this scenario, it is interesting to study a solution falling between the previous researches: a small compact system, able to store energy and to provide heating and cooling. The aim is to identify and optimize a solution which could be applied potentially to several applications: (i) heating and cooling of building with solar heat source, with multiple cycles a year (ii) waste heat recovery from CHP and internal combustion engine, both in industrial application or in automotive (iii) electricity to heat transformation when excess electricity is overproduce to provide heating and cooling when needed. Regarding the latter option, such system could be used as an alternative to ice storage for air conditioning peak shaving, a technology which is already available on the market and always more often used in large commercial building in the United States.

Notwithstanding the several possible applications, the current work has been developed focusing on a niche possible application of thermal storage: the overnight cooling needs of a truck driver cabin. Long-haul truck drivers usually sleep overnight in the cabin. When the truck engine is off, the standard cooling devices cannot be used, because of the lack of mechanical power to run the compressor. Several solutions can be implemented in this case: (i) electrical storage, (ii) ice storage, (iii) engine idling.

The first solution includes the utilization of electrical batteries to provide the power to run an electrical compressor. Batteries are simple to implement, but they have problems of high cost and durability, especially in high ambient temperature environment. Moreover, the energy needed to charge the batteries must be delivered by the engine during the day, which means an additional fuel consumption and an oversizing of the electrical components.

Ice storage is a commercially available solution. During the day, the power of the engine is used to produce ice and, during the night, ice is melted to provide the cooling power needed. Also with this solution, the energy is provided by the engine with an additional fuel consumption.

The third solution is the less environmental friendly solution, but it is still very often used. Engine is kept running overnight only to run air conditioning. Problems of fuel consumption, pollution and noise are obvious. Only in United States, Argonne National Laboratory estimated that about 3 million tons of diesel have been burned only to provide "hotel loads" – cooling, heating and electricity – during rest periods in long haul tucks [9]. The North American Council for Freight Efficiency reports a value 3 times higher for the total idling consumption (including loading time, queueing, border crossing, etc.) [10].

As widely known, internal combustion engine releases a high fraction of the thermal power to the ambient through the gas exhaust of the combustion. The energy is released at high temperature and virtually at zero cost, because it is wasted into the ambient. Therefore, it would be interesting to use this source of energy available during the day and use it at nighttime. The system under study has the aim to store the thermal energy and use it to generate a cooling effect overnight.

2. System description: Experimental setup

The system is composed by two main components: the adsorber (reactor) and the condenser/evaporator. Figure 1 shows a basic scheme of the experimental setup. Figure 2 shows a picture of the prototype.

Considering the possibility to be directly coupled with the gas exhaust of a combustion engine, air has been chosen as heat transfer fluid for the adsorber. In the picture, the adsorber and its air loop stand on the front. The electric heater is on the left side. A pipe connects the top of the reactor to the condenser/evaporator-unit, which includes a