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Concept and Validation of Electric Energy Storage by a Fluidized Bed

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ABSTRACT

In this paper, the concept of electric energy storage by a fluidized bed (EESFB) is introduced and validated. In this novel EESFB system, sand is used as the medium for energy storage. In the heating mode, sand is heated up in a fluidized bed by a group of embedded electric heating elements to a high temperature and then stored in thermally insulated tank. In the heat release mode, the stored thermal energy can be released to generate hot air, steam and electricity as necessary. Compared with other thermal energy storage technologies, EESFB is prevailing in cost-effective, environmental-friendly, high efficiency, high energy density, high flexibility to meet load fluctuations and always-ready characteristics to supply high-temperature thermal energy. It also could have a potential for massive energy storage. An experimental system with 100 kW input power was setup to study the feasibility of the novel technology. Results showed that EESFB system can be operated smoothly and sand can be efficiently heated up to a high temperature with embedded heating elements in the fluidized bed.

Keywords: energy storage, electric energy storage, heat storage, fluidized bed, high temperature

1. INTRODUCTION

Renewable-energy-based energy system will play a dominate role in the era of carbon neutral in the future. However, attributed to the features of fluctuation, intermittence, and uncertainty, renewable energies, mainly of solar and wind power, are not allowed to connect into the power grid with a high proportion as the unsteady supply of renewable energy cannot match the demand of electricity consumption. As a result, part of wind/solar power has to be curtailed to maintain stability of the electricity grid. Therefore, to meet safety requirements of the power grid, the electric energy storage (EES) is demanded in the development of renewable energy-based energy system [1, 2].

Electric energy storage technologies can be divided into five categories as the mechanical, electrical, electrochemical, thermal, and chemical energy storage. Mechanical energy storage includes pumped hydro, compressed air, and flywheel etc. [1-5]. Electrical energy storage includes supercapacitor and superconductor energy storage. Electrochemical energy storage refers to the energy storage using all kinds of batteries. Thermal energy storage stores electricity in the forms of sensible, latent heats, or chemical heat in the medium in a thermal insulation container, and then converts the stored heat into power or uses it as a thermal source. Chemical energy storage refers to the use of electricity to produce hydrogen or synthetic gas, ammonia, and other secondary energy carriers.

Energy density and power density are two key index to describe the performance of an EES technology [1-5]. The former one refers to the amount of energy stored, while the latter one refers to the speed of energy storage and release. At the present time, every EES technology could has its own application scenario but none of them could meet the requirements in both energy and power densities in a massive application with acceptable cost. For example, batteries are desired for power density performance but they are still too expensive to meet the energy density requirement in a massive application. So far, the pumped hydro is mostly popular EES used in a large capacity [4,5]. The new and improvements of EES technologies are still greatly needed.

In many cases, thermal energy in either heat or steam is desired for the end users. Thus, thermal EES is of importance and has been actively studied as well. Several kinds of thermal energy storage technologies have been developed and used. However, they are limited by the low energy density, incapability to scale up or too complex system. In this paper, a novel energy storage technology, i.e., energy storage by a fluidized bed (referred to as "EESFB" below) is introduced. In this heat storage system, sand is heated by exceeded electricity and then moved to high temperature tank and stored there. Due to the possible high temperature, the hot sand can generate hot air, steam and electricity when necessary. The EESFB could have advantages of cost-effective, environmental-friendly, high efficiency, high energy density, high flexibility to meet load fluctuations and always-ready characteristics to supply high-temperature energy.

2. THE CONCEPT AND ADVANATGES OF EESFB

2.1 Heat storage vs other energy storage

Table 1 Main disadvantages of typical kinds of energy storage systems

Energy Storage System	Main Disadvanatges
Pumped Hydro [5-7]	Geographic and Capacity limits
Compress Air [2-5,8,9]	Geo limit, needs big gas tanks and assisted fossil fuel
Flywheel[2-5, 10]	High self discharge, invalid for daily peak adjustment
Supercapacitor[2-5,11]	Low energy density, invalid for daily peak adjustment
Battery [2- 5,12]	High cost, safety issue such as overheating, fire
H2/Fuel Cell[4, 13]	Low efficiency in life cycle, small capacity
Heat storage[1-5, 14]	Speicial requirments needed for the medium

Figure 1 compares the heat storage with other kinds of energy storage in terms of cost and energy density. It can be found that the heat storage system can have rather large energy density while at a low cost. Table 1 further lists the main disadvantages of the typical kinds of energy storage systems.

2.2 Heat storage by different medium

There are several kinds of materials can be used for the heat storage medium. Some of them use the sensible heat only, while some of them use the latent heat as well. Tables 2 and 3 compare the physical properties, and energy storage performance of the material commonly used for heat storage. The last column in Table is the energy storage density.

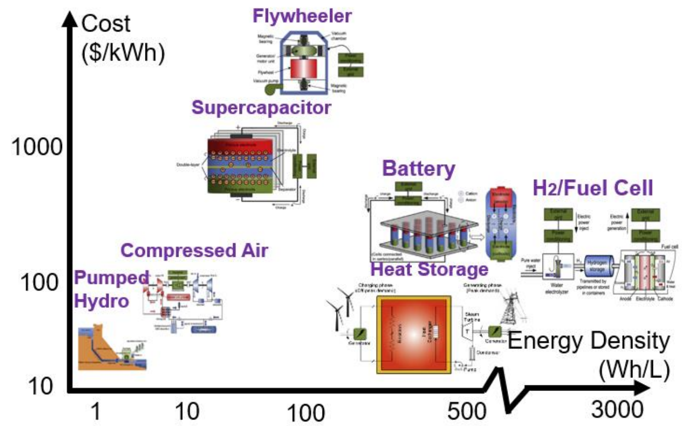

Figure 1. The cost and energy density for various energy storage system

Table 2 Main physical properties of the materials commonly used for heat storage

Material	Working Temp. /℃	Thermal coductivity W/(m K)	Specific heat capacity J/(kg K)	$c_p * \Delta T$ kJ/kg
High Temperature Concrete[15]	200-400	0.5~1.0	~910	~180
Ceramic [16]	~1000	1.35	~860	~840
Sand[17]	~1000	0.27	~920	~900
Metal and Alloy [18]	~800	~7	~850	~660
Water[19]	<100	~0.6	~4200	~420
Thermal Conductive Oil [20]	200-400	~0.14	~2800	~560
Melten Salt[21,22]	290-565	~0.5	~1500	~410

Tables 2 and 3 show that sand is low cost, and can work at high temperature thereby good for high quality thermal energy [18]. However, its thermal conductivity is low. Thus, it is inefficient in static heating. Therefore, some improvement is must for heating the sand. Studies in the concentrating solar power plants already found that in a fluidized bed, sand particles can be rapidly heated up due to the existent of strong interaction

Table 3 Comparison of the performance of different materials commonly used for heat storage

Material	Cost	Efficiency	Stability
High Temperature Concrete	Low	Low	High
Filled Ceramic	High	High	High
Sand	Low	Mid High	High
Water	Low	Medium	Low
Thermal Conductive Oil	High	High	Low
Liquid Sodium	High	High	Low
Molten Salt	Medium	High	Low
Water-Vaper (phase change)	Low	High	Medium
Metal and Alloy	High	High	High
Inorganic Salt	Low	High	Low

between the gas-solid phases, and between the two-phase and the solid walls [23,24]. Consequently, fluidized bed is introduced to compensate the low thermal conductivity of the sand particle in the electric energy storage.

2.3 The concept of ESFB

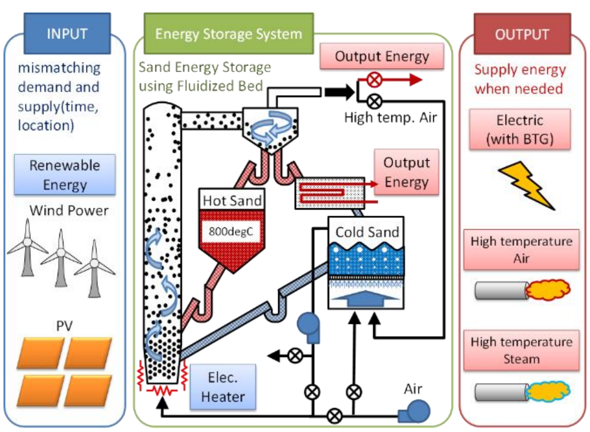

Figure 2. The concept of EESFB [26]

Figure 2 depict the concept and schematic of EESFB system [25,26]. The system can operate in a heating mode and a heat release mode. In the heating mode, cold sand is heated at the bottom of the riser and attains to more than 800°C. With the inlet air, the hot sand is transported to the top of riser and enters the cyclone. After separation by the cyclone, the hot sand drops into and stores in the high temperature hopper, and the hot flue gas recycles into the riser. In the heat release mode, the hot sand enters into the heat exchanger and exchange heat with water. The cooled sand enters into the low temperature hopper and then returns to the riser. The heated water can be used in the working equipment.

2.4 Advantages of EESFB

There are many kinds of heat storage technologies, using different storage medium. Table 1 compares the cost, working temperature and stability of the mediums. It can be found that sand has advantages in low cost, relatively high efficiency and excellent stability in heat storage. Moreover, sand can work at a wide range of temperature, which is benefit to keep the quality of the energy such that part of the stored energy can be converted in electricity as necessary. Also, sand has excellent fluidity and transport properties. Therefore, the sand-based heat storage technology has special advantages and competitive power.

3. EXPERIMENTAL VAILIDATION OF EESFB

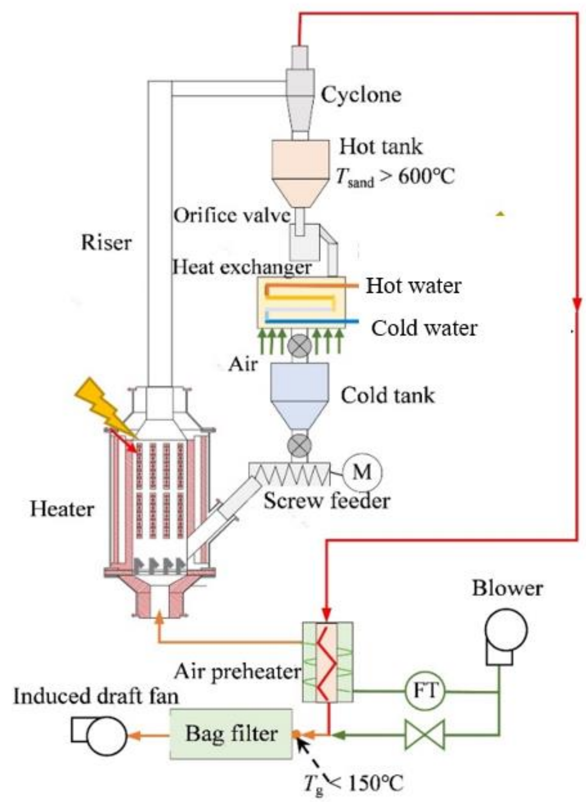

Figure 3. The schematic of a 100 kW e-input experimental system of EESFB

To validate the feasibility of EESFB, a series of experiments have been conducted.

Figure 3 shows an experimental EESFB system with 100 kW electricity input. The heat is recovered by using a gas-gas heat exchanger instead of the bubbling fluidized bed, to make the recovery more reliable and simpler to operate. The cold sand is fed into the heating chamber from a screw feeder and initial temperature of the sand is nearly ambient temperature (~25 °C). The inlet air is given from the bottom of the riser and the velocity of the air is ~3 m/s in the chamber. The sand is fluidized by inlet air and the heat transfer process is enhanced so that the sand can be heated by a group of plate heaters to a preset high temperature. The hot sand is transported to the top of riser and separated by the cyclone. Then the hot sand falls into the high-temperature hopper and the energy can be stored in this way. When needed in heat release mode, the valve is opened and the hot sand falls into the bubbling bed heat exchanger and exchanges heat with cooling water. The cooled sand falls into the low-temperature hopper and then flows into a screw feeder. The main parameters of the experimental system are given in Table 4.

Table 4. Main parameters of the experimental system

Item	Value	Unit
Power Input	100	kW
Sand inlet temp.	25-150	°C
Sand outlet temp.	700-800	°C
Sand flow rate	350	kg/h
Inlet air temperature	25	°C
Outlet air temp.	700-800	°C
Air flow rate	150-500	Nm^3/h
Air velocity in furnace	3	m/s
Solid flow rate	2.5	$kg/m^2 \cdot s$

Shown in Figure 4, when the heat exchanger of the exhaust air was used, and when the inlet exhaust air was 550 °C, the air stream to the heating chamber was heated up from ambient temperature to 250 °C while the exhaust air was reduced to 180 °C. The heat recovery rate was estimated at 45%.

The preheating of the air stream to the heating chamber showed several advantages. (1) it can reduce the mass flow rate of fluidizing air at a given solid input, and thereby the exhaust air heat; (2) it can improve the overall heat storage efficiency; and (3) it can also improve the fluidization condition in the chamber.

Figure 5 element was set to 800°C. It can be seen that the performance of sand heating was greatly improved due to the measurements of air preheating and increase of static bed material. The sand temperature at the riser exit is as high as 630 °C, only 170 °C less than that of the heating elements. The sand at the inlet of hot tank is also close to 600 °C. More experiments at a higher preset heating element temperature are undertaking.

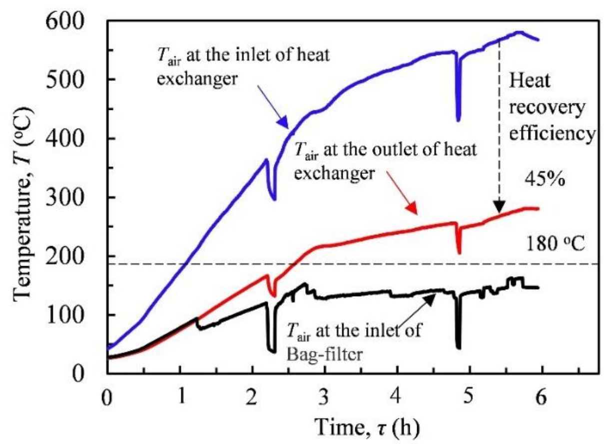

Figure 4 The heat recovery by air preheater in EESFB

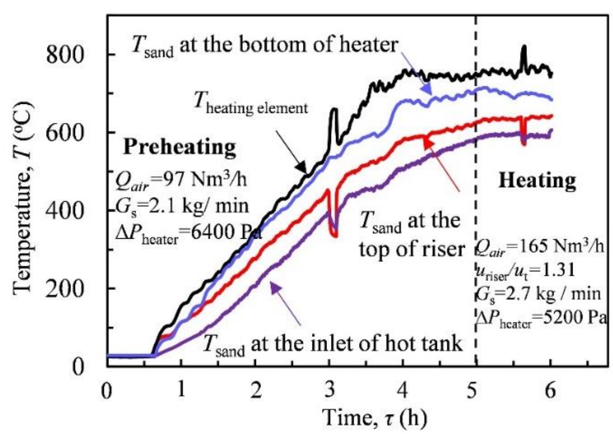

Figure 5 The performance of sand heating when heating element was set to 800 °C

4. CONCLUSIONS

This paper introduces a novel energy storage technology named electric energy storage by a fluidized bed (EESFB) and experimentally validates its feasibility. In the EESFB system, sand is used as the energy storage medium, and can be heated up in a fluidized bed by exceeded electricity to a high temperature. In the heat release mode, the hot sand stored in thermally insulated tank can be used to generate hot air, steam and electricity as necessary. The EESFB is benefit in the aspects of cost-effective, environmental-friendly, high efficiency, high energy density, high flexibility to meet load fluctuations and always-ready characteristics to supply high-temperature thermal energy. The feasibility of the novel technology was experimentally validated with 100 kW electricity input. More details studies on the fluid dynamics and heat transfer in the EESFB system, as well as the techno-economic analysis of the technology are undertaking.

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