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Cryogenic energy storage characteristics of a packed bed at different pressures

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HIGHLIGHTS

- Cryogenic energy storage characteristics in a packed bed are investigated experimentally.
- A thermocline behavior of transient temperature was found along the packed bed.
- Temperature distribution in the packed bed differs significantly at low and high pressures.

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ABSTRACT

A packed bed cryogenic energy regenerator is investigated for use in a cryogenic energy storage (CES) system. With liquid nitrogen used as the working fluid, the cryogenic energy storage characteristics of the packed bed are investigated at pressures of 0.1 MPa and 6.5 MPa. The packed column is 1500 mm in height with a 345 mm inner diameter, and is made of 16 mm thick stainless steel. Granite pebbles about 9 mm in size are used as the medium for energy storage. The transient axial and radial temperature distributions of the packed bed were measured, and the results show that the transient temperature axial distribution exhibits a typical thermocline behavior at both low and high pressures. The temperature distribution does however vary significantly at the different pressures.

1. Introduction

As a process of converting between the electrical energy and a form that can be stored for conversion back to electrical energy, Electrical Energy Storage (EES) can strengthen the power grids and maintain the load levels by the electricity production at times of either low demand, low generation cost or from intermittent energy sources [1–3]. Since cryogens such as liquid nitrogen and liquid air have a high energy density (around 100–200 Wh/kg) and can be stored at atmospheric pressure, they are suitable for large-scale energy storage [4]. In addition, CES also has advantages such as low capital costs per unit energy, environmental benignity, and a relatively long storage period. A cryogen is a liquid (liquefied gas) that boils at a temperature below −150 °C [5]. Cryogens can be produced using off-peak power, renewable energy, or through direct mechanical work from hydro or wind turbines (electricity is stored). When on-peak power is needed, the liquid transforms to a high pressure gas by absorbing heat, which is used to generate electricity via a cryogenic heat engine (electricity is released) [6,7]. Cryogens contain high grade thermal energy in the form of latent heat and sensible heat. This energy can only be recovered effectively by the use of a thermodynamic method. Li et al. [8] proposed four methods of cryogenic energy recovery: direct expansion; indirect heating of the medium (working fluid) via Rankine cycle; Brayton cycle; and a combination of the above three methods. Li found that a combination of direct expansion and Rankine cycle was more attractive due to the low power consumption in the compression process when only ambient and/or a low grade heat source was used.

The University of Leeds, Highview (UK), Mitsubishi Heavy Industries, and Hitachi (Japan) are involved in this field. The University of Leeds and Highview [7,9,10] built the world's first independent CES system (500 kW/2 MWh). In this system, the air liquefaction unit and the energy release unit were fully integrated in a self-developed cryogenic storage unit. Highview claimed that the system was capable of being scaled up to hundreds of megawatts using existing supply chains and major equipment suppliers.

Mitsubishi Heavy Industries [11,12] developed liquid air energy storage based on liquid rocket engine technology. The air

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liquefaction process and energy release process operated independently in different units, resulting in an adiabatic efficiency of the energy release process being 77% (The adiabatic efficiency refers to the ratio of electricity generated by the generator turbine to the energy obtained by the pressurized, high-temperature gas). However, the air liquefaction unit was based on a conventional process, and the overall energy storage efficiency was not competitive.

Hitachi [13–15] proposed to integrate the air liquefaction unit with the energy release process by introducing a cold storage unit called a regenerator stored the cryogenic energy released by liquid air in the energy extraction process and reused it for air liquefaction in the energy storage process. They carried out simulations and experiments using solid materials and fluids as the cold carriers and found that the energy storage efficiency of the CES system could exceed 70% if the regenerator had a good performance. Smith [16] also suggested that there existed the potential for greatly improving the storage efficiency by recovering cryogenic heat from liquid air for utilization in the liquefaction process when the liquid air was fed into the gas turbine.

The above shows that the efficiency of a CES can be significantly increased when low-temperature liquid air is used to produce new liquid air, and that the performance of the regenerator is vitally important for the energy storage system. Due to the high heat transfer area to volume ratio, the combined effects of boundary layer shinning and fluid mixing intensification (thermal dispersion) of the porous medium [17,18], embedding the heat transfer surface into a packed bed is an effective technique for enhancing convective heat transfer. Furthermore, since the liquid or gaseous cryogen is in direct contact with the medium in the packed bed, the temperature difference between the surface of the medium and the fluid is small, and the exergy loss also becomes small according to the second law of thermodynamics [8]. For these reasons, a packed bed regenerator system was employed in this paper's experiments.

As the pressure of the packed bed significantly affects cryogen production and the turbine's generation output, the experiment has been designed to test the energy storage characteristics of a packed bed under different pressures. This paper aims to obtain more detailed experimental data on the temperature field of the packed bed, analyze the effects of working pressure on the energy storage characteristics, and explore the mechanisms of the different CES behaviors.

2. Experimental description

2.1. Experimental setup

Fig. 1 shows the experimental system. It consists of two branches, a nitrogen branch and an air branch. In the nitrogen branch, liquid nitrogen is drawn out of a Dewar reservoir by an automatic pressure boosting system, and flows through a needle valve and a cryogenic flow meter for flow adjustment and the taking of flow rate measurements. It is then pumped to a preset pressure by a cryogenic liquid pump, and enters the bottom of the packed bed. As the nitrogen flows through the packed bed, the cryogenic energy is absorbed by packed pebbles and the liquid nitrogen becomes nitrogen gas. The nitrogen gas from the packed bed is measured for temperature, pressure, and flow rate just before being discharged directly into the atmosphere.

In the air branch, the dried air is compressed from atmospheric pressure to the preset pressure via a four-stage reciprocating compressor, and then enters a buffer tank, smoothing the pulse air flow from the piston compressor. The compressed air flows through an electric heater and is heated to a given temperature, and then enters the packed bed column from the top. The compressed air from the packed bed is then discharged directly into the atmosphere.

The four-stage reciprocating compressor functions throughout the cryogenic energy discharge process, as well as helps in providing the necessary pressure condition of the packed bed prior to the cryogenic energy storage process. During the storage process, the surge tank helps maintain stable operating pressure in the air branch. In order to decrease heat loss to the environment, high quality heat insulation material was wrapped around the outer surface of the cryogenic storage cylinder, the cryogenic liquid pump, the electric heater, and the corresponding connection tubes. Prior to the start of the experiment, all duct joints, pipe fittings, and flange connections were examined for leakage.

The flow rate of the liquid nitrogen was measured by a Shakic cryogenic electromagnetic flow meter with an effective range of 0–300 L/h and accuracy of ±1%. The flow rates of the air and nitrogen were measured by a Collihigh vortex flow meter with an effective range of 36–320 m^3/h and accuracy of ±1%. Four Pt100 temperature sensors with an effective range of −200 to 450 °C and accuracy of ±0.1 °C were installed at the end of the electric heater, the top and bottom of the packed bed, and the end of the

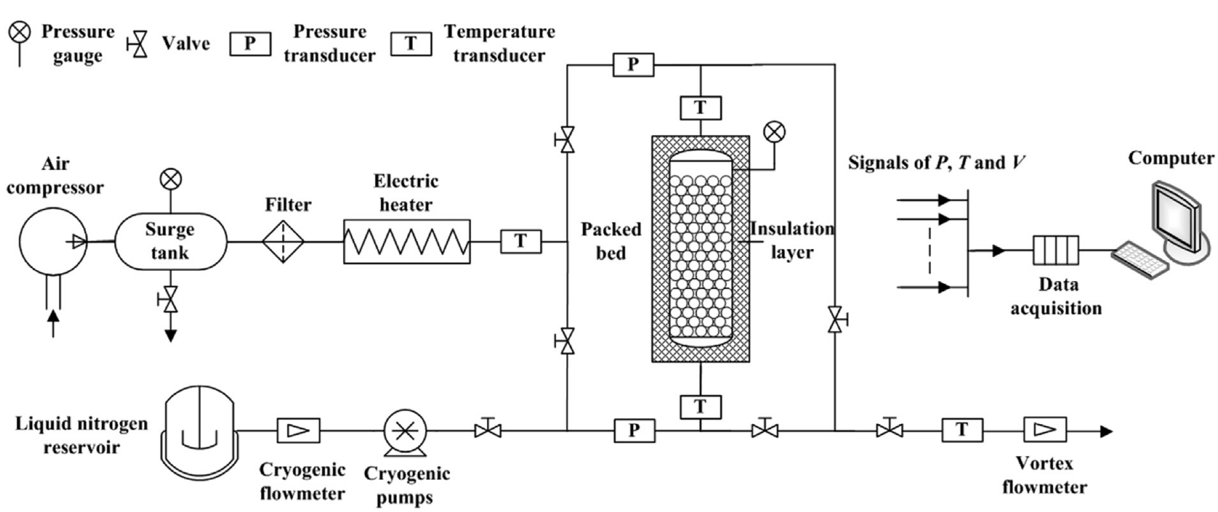

Fig. 1. Experiment setup and apparatus.