Experimental Investigations on Cold Recovery Efficiency of Packed-bed in Cryogenic Energy Storage System

Rohan Dutta and Pavitra Sandilya
Cryogenic Engineering Centre, IIT Kharagpur, Kharagpur, Paschim Medinipore, West Bengal, India-721302
E-mail: rohankrdutta@gmail.com

Abstract. Cryogenic Energy Storage (CES) system has large power generation capability, and comparable cost with respect to the non-cryogenic technologies (pumped-hydro, compressed air energy storage systems). This is not location specific unlike the non-cryogenic energy storage systems and also is environment friendly. High-energy requirement for liquefaction process in the CES system, however, leads to low turnaround efficiency of the system. Efforts have been made to reduce the specific work-requirement in the liquefaction process by thermal energy storage at temperature around 150 K as available during power generation stage of the system. One of the methods of storing the thermal energy at such low temperature is using packed-bed of pebbles. A few studies have been reported in the available literature indicating a reduction in storage efficiency during continuous operation of such packed-beds leading to reduction in turnaround efficiency of the CES system. In this paper, experimental findings for better insight into the packed-bed behavior are reported. An experimental setup of packed-bed thermal energy storage using rock pebbles as bed material was used for this purpose. Temperatures along the axial direction inside the bed were measured and the results were analyzed and the storage efficiencies during full-load and part-load of operations were determined.

1. Introduction
Large-scale energy storage has gained significant attention due to penetration of renewable energy sources [1]. Existing large-scale energy storage systems are pumped-hydro, Compressed Air Energy Storage (CAES) etc. [1, 2]. These systems are commercially used. However, these systems are location specific that restricts their application in energy storage sector [2, 3]. Cryogenic Energy Storage (CES) can overcome this limitation. Because CES is a decoupled system with large power generation capability and low pickup time (the time required to attain maximum power generation); it is also scalable and has comparable cost and mature equipment technologies [2, 4].

A typical CES system has primarily three subsystems, namely, charging or the liquefaction process, storage of liquid and discharging or the power cycle as shown in figure 1. The liquefaction cycle may be based on the Claude cycle or its derivatives [2], while the power cycle may be based on open Rankine cycle with gas turbines [4]. This primary cycle has low turnaround efficiency (ratio of the energy output to energy input to the system) of around 30% or less [4, 5]. This efficiency is much less compared to those of the other techniques. It has been suggested that
an efficiency more than 50% is required to make this technique commercially viable [5]. One of the ways to improve the performance of such systems is by recovery of the refrigeration available with a high pressure supercritical fluid in the power cycle using thermal energy storage in packed-bed [5]. This stored refrigeration may later be used in the liquefaction cycle for precooling the high pressure fluid, thereby increasing the rate of liquefaction for a given specific power. This may improve the turnaround efficiency to 50% and higher. However, like any other thermal storage, losses due to heat in-leak/loss, partial charging, variable thermodynamic properties have significant effect on the performance of packed-bed energy storage that could cause a reduction in overall system efficiency, thus leading to overdesign of auxiliary system including the bed [5, 6].

Figure 1. Block diagram of a typical Cryogenic Energy Storage system [6].

Packed-bed energy storage system is commonly used for storing thermal energy from solar-powered systems etc. and packed-bed system with rocks and air as heat transfer fluid is the most common solution solar concentrators in various range of storage requirements [7].

In view of this, a packed bed with rock (pebbles) has been considered to store thermal energy at low temperature. The experimental setup with such a packed bed has been described in this paper.

1.1. Objectives
- To measure the temperature profiles inside the packed-bed thermal storage during both charging and discharging processes.
- To determine the storage efficiency during full-load and part-load with prolonged standby operation of the system.
2. Methodology
The packed-bed thermal storage system comprises a cyclic operation with three periodic processes: bed charging, standby, and bed discharging. In the charging process, refrigeration is stored in bed material inside an insulated vessel, to be utilized during the discharging process. The system then goes to standby mode during which necessary manipulations in the system is done to prepare the bed for discharge. During the charging and discharging of the bed, compressed air or nitrogen is circulated through the bed to either cool down or heat up the bed. The highest and lowest temperatures are dictated by the temperatures of the energy source and the available refrigeration. In our study, the highest temperature has been taken as the room temperature and the lowest as 150 K and 175 K.

The design of packed-bed systems has been discussed elsewhere [6]. Performance of the packed-bed has been evaluated using some non-dimensional parameters. Two separate experiments were conducted. The first one was with full-load operation, where the entire bed was cooled down to the temperature of the input fluid. The lowest temperature of the bed after the end of the charging process was noted; this is the cut-off temperature of the bed. The second experiment was conducted at partial charging of the bed and is called operation under part-load. In addition, a prolonged standby time of about 2 hrs was also tested.

2.1. Storage efficiency
The storage efficiency of the packed-bed is determined using equation 1 [8].

$$
\eta_{PB} = \frac{\int_{x_{in}}^{x_{out}} \int_{T_{c,L,min}}^{T_{c,L,max}} C_s(T, x) dT dx - \int_{x_{in}}^{x_{out}} \int_{T_{c,0,min}}^{T_{c,0,max}} C_{s,0}(T, x) dT dx}{L \int_{T_{dch,in}}^{T_{dch,in}} C_s(T) dT}
$$

Here, $C_s$ is the heat capacity of the solid, $T$ is the bed temperatures, and $T_c$ and $T_{dch}$ are the charging and discharging temperatures, respectively.

3. Experimental
The process flowsheet with instrumentation is presented in figure 2. The process consists of a packed-bed, an air compressor, a liquid nitrogen dewar, copper coil heater, two gate valves (V03, V04), two needle valves (V02, V05), temperature and pressure sensors. Pressure gauges and RTDs were used for the pressure and temperature measurements. Necessary specifications of some of the equipment are listed in table 1.

Liquid nitrogen flow was initiated and maintained by introducing compressed air into the dewar. Compressed air was also used to heat up the cold bed during discharging period, figure 2. It is to be noted that the relative humidity of the air was found to vary between 74% to 92% during all the experimental runs. The heater during charging cycle evaporated and superheated the incoming liquid to 150 K for the first experiment, and to 175 K for the second experiment. This cold nitrogen gas was used to cool down the packed-bed to the desired temperatures.

During the warm-up phase, pressurized air was passed through the packed-bed and got cooled down before exiting through V04. The inlet and outlet pressures (P101,P102) using dial gauges and temperatures (T101, T102, T103) using platinum resistance temperature detectors (RTDs) to the packed-bed were measured continuously. The temperatures inside the packed-bed and the ullage volume were also measured. The platinum RTDs (Pt100) were placed axially. The positions of RTDs inside the bed and the ullage volume are shown in figure 3. The temperature sensors are calibrated in the range of 78 K to 373 K with the uncertainty of ±2 K. All the measurements were recorded using a data aquisition system DT80, dataTaker®.
Figure 2. The layout of the experimental setup showing all the equipment and data acquisition system.

Figure 3. Bed height and placement of RTDs inside the vessel.

3.1. Description of the packed-bed
A vacuum insulated vessel of inner volume 27.3 ltrs. with required bi-directional inlet and outlet ports was used as packed-bed. The bed height \((L)\) is 32 cm and the diameter \((D)\) is 15 cm. Above the bed, the ullage space is of 10 cm. Rock pebbles were taken as the packing material and the dimensions were between 12.5 mm \(\times\) 12.5 mm and 10 mm \(\times\) 10 mm. The average equivalent diameter \((d)\) of the pebbles was 11.25 mm. Average density and mean average heat capacity of this material are 2688 kg/m\(^3\) and 0.7 kJ/kg-K, respectively [6]. The porosity of the bed \((\epsilon)\) was calculated as 0.38 using equation 2 [6].

\[
\epsilon = 0.375 + 0.78 \left( \frac{d}{D} \right)
\]  

(2)

The operating flow rate \((\dot{m})\) through the packed-bed may be estimated based on the charging

| Equipment       | Parameter       | Value       | Equipment       | Parameter       | Value       |
|-----------------|-----------------|-------------|-----------------|-----------------|-------------|
| Heater          | No. of tubes    | 3 for 175 K| Temperature     | Type            | Pt100       |
|                 |                 | 5 for 150 K| sensor          | Uncertainty     | ±2 K        |
| Tube length     | 85 cm           |             | Number          | 7               |
| Tube ID/OD      | 1.5/1.9 cm      |             | Range           | 0-4 barg        |
| Packed-bed      | Height          | 40 cm       | Pressure        | Type            | Dial gauge  |
|                 | Diameter        | 15 cm       | sensor          | Range           | 0-4 barg    |
|                 | Ullage height   | 10 cm       | Uncertainty     | ±2%             |
|                 | Operating pressure | 1.5 bar   | Gas buffer      | Max. pressure   | 12 barg     |

Table 1. Specifications of the equipment of the process.
or discharging times ($T_{c/dch}$) from equation 3 [6].

$$\dot{m} = \frac{V_{vessel}}{t_{c/dch}} \left( \epsilon (\rho c)_f + (1 - \epsilon) (\rho c)_s \right) \tag{3}$$

In deriving equation 3, lumped parameter heat-transfer between the bed and the fluid has been assumed. Thus the density ($\rho$) and heat capacity ($c_f$) of the fluid, and heat capacity of the bed ($c_s$) have been taken constant. The actual charging or discharging times may differ from the ones taken as basis to arrive at equation 3, due to differential heat transfer in the bed.

4. Results and discussions

Two different sets of operating conditions were studied in the experimental setup. For all the experiments, seven temperatures and two pressure sensors were employed. The sampling time in the data acquisition system was set as five minutes. Two temperatures (T3 and T6) and two pressure sensor outputs (P1 and P2) were recorded manually once in every five minutes. The flowrate to the packed-bed was maintained by maintaining constant pressure in the liquid dewar as well as the pressure drop in the entire setup. The results of the experiments are shown in figure 4 to 7. These figures have been drawn in terms of non-dimensional temperature ($\theta$), non-dimensional length ($x/L$) and non-dimensional time ($t/\tau$). $\theta$ is given by equation 4.

$$\theta = \frac{T - T_{min}}{T_{max} - T_{min}} \tag{4}$$

where, $T$ is the measured temperature, $T_{max}$ and $T_{min}$ are the maximum and minimum temperatures in the entire process respectively, $x$ is the axial distance from the bottom surface of the bed, $L$ is the height of the bed, $t$ denotes the time elapsed from the startup of the operation, and $\tau$ is the total time of the operation.

![Figure 4](image_url)

**Figure 4.** Temperature profile inside packed-bed operating under full-load condition with cut-off temperature of 150 K.

4.1. Operation of the packed-bed under full-load condition

Under full-load operation, the entire bed was cooled down to the bed cut-off temperature using gaseous nitrogen. The experiment was conducted with a charging time of 6 hrs and a discharging
time of 4.5 hrs. The standby time was five minutes. Two different flow rates were taken during the charging and discharging processes with higher flow rate during discharging process. The atmospheric temperature was 31.9°C and the compressor discharge pressure was maintained at 1.5 bar.

Temperatures at two locations at different time instant inside the packed-bed are presented in figure 4, 5 and 6. The cut-off temperature of the bed was found to be 154.15 K. Though this is the lowest temperature inside the bed, most of the bed at the bottom of it were found to be still at higher temperature as can be seen in figure 5. Following observations were made during the experiment.

- Typical thermocline profile inside the bed was found both during charging and discharging processes.
- Due to lower flow rate during charging process, the rate of reduction in temperature is lower in this period.
- Overall pressure drop (including the bed, transfer lines and heater) was found to be 30 kPa.
- The pressure drop in the bed varied in a range of ±5 kPa. This in-turn varied the flow rate in the bed periodically. However, this was not found to have any significant influence in the performance of the bed deep inside.
- Ullage volume temperature was found to increase after it reached below 190 K. The temperature at the adjacent of the ullage space and inside the bed (T5) was found increasing proportionally. However, after it reached above 190 K, it again started reducing as also in the case of T5.

![Figure 5. Temperature distribution inside the packed-bed during the charging cycle.](image1)

![Figure 6. Temperature distribution inside the packed-bed during the discharging cycle.](image2)

These experiments on storage of refrigeration and utilization of the stored refrigeration gave a storage efficiency of 94.71%, table 2. The efficiency loss may be due to: 1) higher charging time that gives higher heat in-leak, thereby leading to loss of stored refrigeration; 2) variation of flow rate during cooling down might reduce the heat transfer between fluid and the solid inside the bed periodically. Influence of other factors such as warming up of ullage space and corresponding changes in the bed temperature on the storage efficiency requires to be investigated. In addition, the effect of moisture content in the air during warm-up process requires to be investigated.
4.2. Operation of the packed-bed under part-load condition with prolonged standby period

The second set of experiments was performed with partial cooling of the bed at higher temperature than earlier. It was also aimed to investigate the effect on bed storage efficiency for prolonged standby period. The charging and discharging times were of 2 hrs and 2.5 hrs, respectively. The bed was kept at standby with no flow for 2 hrs. The inlet temperature during charging process was 175 K with a compressor discharge pressure of 1.5 bar. The atmospheric temperature was 306 K. The bed temperature profiles inside are shown in figure 7.

![Figure 7. Temperature profile inside packed-bed operating under part-load and high stand-by time with cut-off temperature of 175 K.](image)

As the bed was partially cooled down, the temperature of the bed was not uniform. The lower part of the bed (below 6 cm) was found to be 10% warmer than the upper part of the bed (above 16 cm). It was observed that during standby period, the bed temperature increased due to heat in-leak from the atmosphere. In addition, partial cooling led to higher temperature gradient inside the bed. Therefore, settling of refrigeration from the upper part to the lower part of the bed was observed due to conduction heat transfer between the packing. This settling of refrigeration increased the bed cut-off temperature by 30%.

Settling of refrigeration together with the heat in-leak during standby period drastically reduced the storage efficiency of the packed-bed to 64.57%, table 2. The variation of temperatures inside the bed during standby period as shown in figure 7 can be used for determining the potential losses in storage efficiencies with different standby periods during part-load operation. The ullage space was found being affected the highest due to this long standby period and correspondingly the adjacent locations in the bed were also found to have highest temperature gradient though they were far from the warmer bottom part of the bed. Overall pressure drop in the process was found to be 0.3 bar and during this experiment no pressure drop fluctuation was observed as found in the earlier case. Therefore, constant flow rate through the bed during the entire operation could be maintained. Table 2 summerizes the results from the two sets of experiments.

5. Conclusion

Cryogenic Energy Storage (CES) is a potential alternative to the existing large-scale energy storage systems. A key to improvement in turnaround efficiency of CES system to be commercially viable is packed-bed thermal storage for both cold and heat storage. In order to understand and investigate the performance of such packed-bed, an experimental setup has
Table 2. Storage efficiencies of the packed-bed for different operation scenerio.

| Mode of operation                  | T$_{\text{max}}$ (K) | T$_{\text{min}}$ (K) | Storage efficiency (%) |
|------------------------------------|----------------------|----------------------|------------------------|
| Full-load with 5 mins standby      | 305                  | 154                  | 94.71                  |
| Part-load with 2 hrs standby       | 306                  | 175                  | 67.57                  |

been developed and the tested. The results of two sets of experiments are presented in this paper. It was identified that this packed-bed with rock pebbles may give a storage efficiency as high as 95%. Uniform temperature profile inside the entire bed was observed after the end of the charging period. Operating the bed under part-load and with prolonged standby period was shown to reduce this efficiency to 65%. Besides, during the operation under full-load condition, flow instability inside the bed, high ullage space temperature fluctuation below 190 K were observed. During part-load, the settling of refrigeration from the bottom of the bed to upper locations was observed that might have reduced the storage efficiency further. In future, efforts will be made to identify the effects of such factors by varying the ullage space, using different standby times etc.

6. References

[1] Inage S I 2009 International Energy Agency 90
[2] Ding Y, Tong L, Zhang P, Li Y, Radcliffe J and Wang L 2016 Chapter 9 - Liquid Air Energy Storage ISBN 9780128034408
[3] Dutta R and Ghosh P 2018 The Society Of Air-Conditioning And Refrigerating Engineers Of Korea, Magazine of the SAREK-47(4) 44–49
[4] Dutta R, Ghosh P and Chowdhury K 2017 Cryogenics 88 ISSN 00112275
[5] Peng H, Shan X, Yang Y and Ling X 2018 Applied Energy 211 126–135 ISSN 03062619 URL https://doi.org/10.1016/j.apenergy.2017.11.045
[6] Dutta R, Gour A and Sandilya P 2019 NSCS-2019, IIT Bombay, Mumbai, India
[7] Cascetta M, Cau G, Puddu P and Serra F 2015 Journal of Physics: Conference Series 655 ISSN 17426596
[8] Hüttermann L and Span R 2017 Energy Procedia ISSN 18766102

Acknowledgments

Authors gratefully acknowledge the contributions and support of Parthasarathi Ghosh, V.V. Rao, T.K. Nandi, A.S. Gour, Biswajit Dey of the Cryogenic Engineering Centre, IIT Kharagpur. Authors would also like to acknowledge the financial support of IIT Kharagpur for the first authors fellowship.