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

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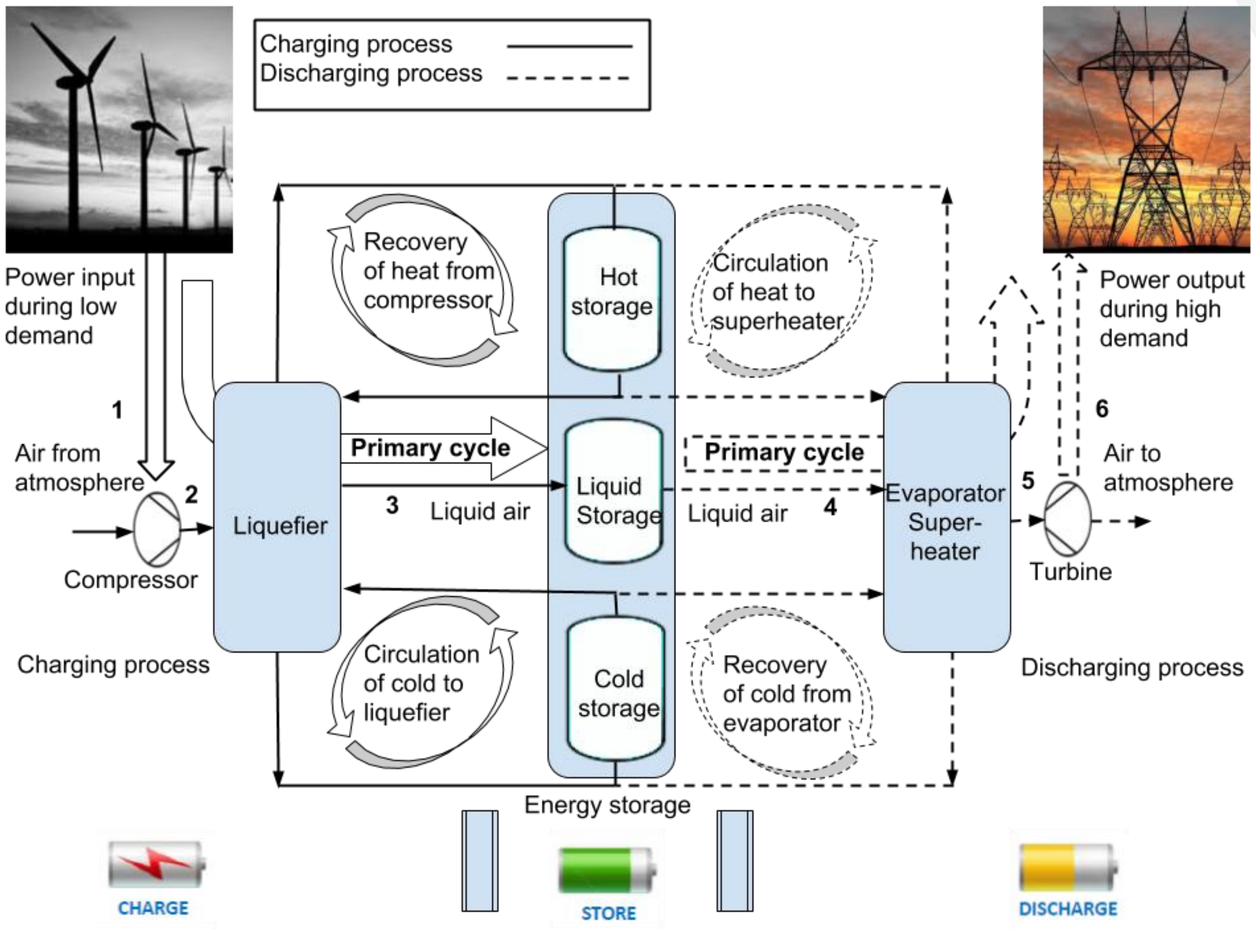
Introduction

- Significant attention on large-scale energy storage due to penetration of renewable energy sources [1]
- Existing large-scale energy storage systems: Pumped-hydro, Compressed Air Energy Storage (CAES) etc. [1,2,3]
- Limitations of such systems:
  - Coupled system
  - Location specific
  - High cost

Type of storage	Turnaround efficiency	Location specific	Capital cost ($/kW)	Discharge time at rated power	Power rating (MW)	Lifetime
Pumped hydro	87	Yes	2700-4600	12 hrs	250 to > 1000	30 years
CAES	54-88	Yes	500-1500	2-24 hrs	15 to 400	35 years
SMES	90	No	700-2000	100 s to 5-10 hrs	100-200	> 30,000 cycles
Li-ion batteries	90 (DC)	No	4000-5000	15 mins to several hrs	5	15 years
CES	> 70	No	400-1500	6-8 hrs	> 100	35 years



Cryogenic Energy Storage

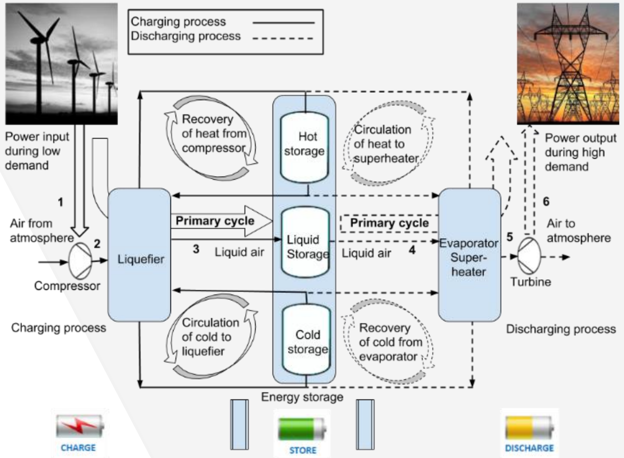
Cryogenic Energy Storage (CES): A potential alternative as it is:

- Decoupled system
- With large power generation capability
- With low picking time
- Scalable
- With comparable cost, and
- With mature equipment technologies [2,3]
- Three subsystems:
  - Charging or the liquefaction process,
  - Storage of liquid, and
  - Discharging or the power cycle.

Introduction

CES systems:

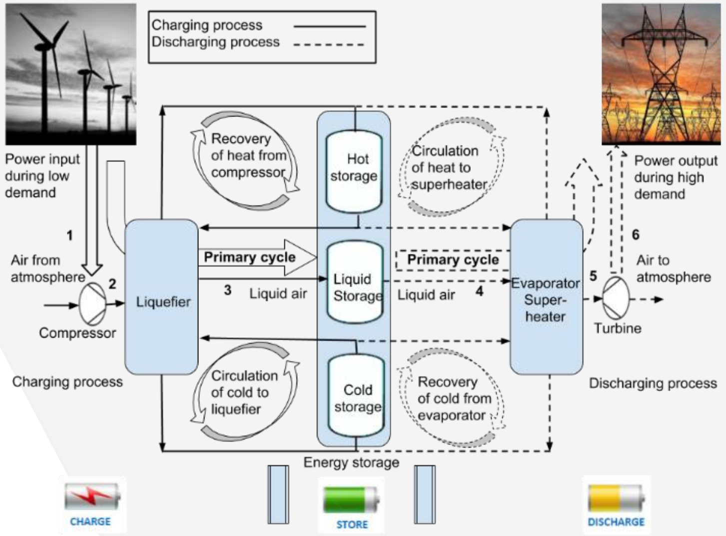
- Low turnaround efficiency of around 30% or less [4-5]
- Suggested method to improve the efficiency [5,6]:
    - **Storage of available heat/refrigeration using packed-bed thermal storage**
    - Use heat of compression by Organic Rankine Cycle to produce waste to power
    - Using industrial waste-heat for superheating in power cycle etc.



Introduction

Packed-bed thermal energy storage:

- A key auxiliary sub-system for recovery of cold from evaporator-superheater in power cycle
    - Used for storing solar thermal energy
    - Common bed materials: Rocks, metals
    - Air as heat transfer fluid [7]
    - Temperature range from room temperature to higher



- A few studies on such energy storage at low temperature

Objectives

The objectives are to develop the experimental setup and perform the following.

- Measure the temperature profiles inside the packed-bed thermal storage during both charging and discharging processes
- Determine the storage efficiency during full-load and part-load with prolonged standby operation of the system

Methodology

- Performed two sets of experiments:
  1. Full-load operation with bed cut-off temperature of 150 K
  2. Partial charging of the bed or part-load with prolonged standby time and cut-off temperature of 175 K
- Used three non-dimensional parameters:
  - Non-dimensional temperature (*θ*)

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

  - Non-dimensional length (*x/L*)
  - Non-dimensional time (*t/τ*).
- The equation for storage efficiency calculation [8]:

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

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Experimental

- **Equipment:**
  - Packed-bed,
  - Air compressor,
  - A liquid nitrogen dewar,
  - Copper coil heater,
  - Two gate valves (V03, V04)
  - Two needle valves (V02, V05)
- **Instrumentation:**
  - The inlet and outlet pressures (PI01,PI02) using dial gauges and temperatures (TI01, TI02, TI03) using platinum RTDs
  - The temperatures inside the packed-bed including the ullage volume above it using platinum RTDs placed axially interfaced with DT80, dataTaker data acquisition system
  - Uncertainty of the temperature sensors in 78 K to 373 K range: ±2 K

Experimental: Equipment specifications

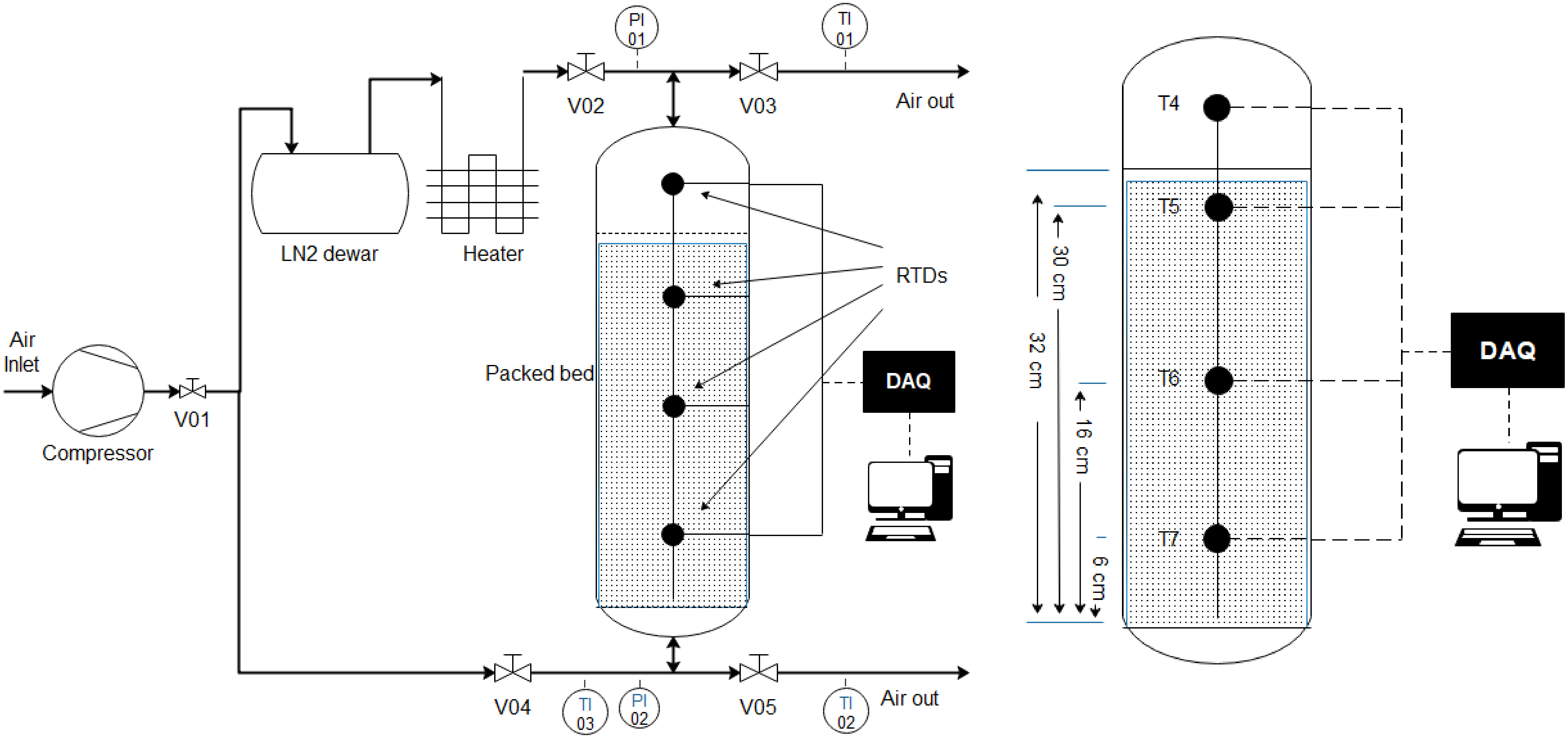
Specifications of the equipment of the process

Equipment	Parameter	Value	Equipment	Parameter	Value
Heater	No. of tubes	3/5	Temperature	Type	Pt100
	Tube length	85 cm	sensor	Uncertainty	±2 K
	Tube ID/OD	1.5 cm/1.9 cm		Number	7
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

Experimental

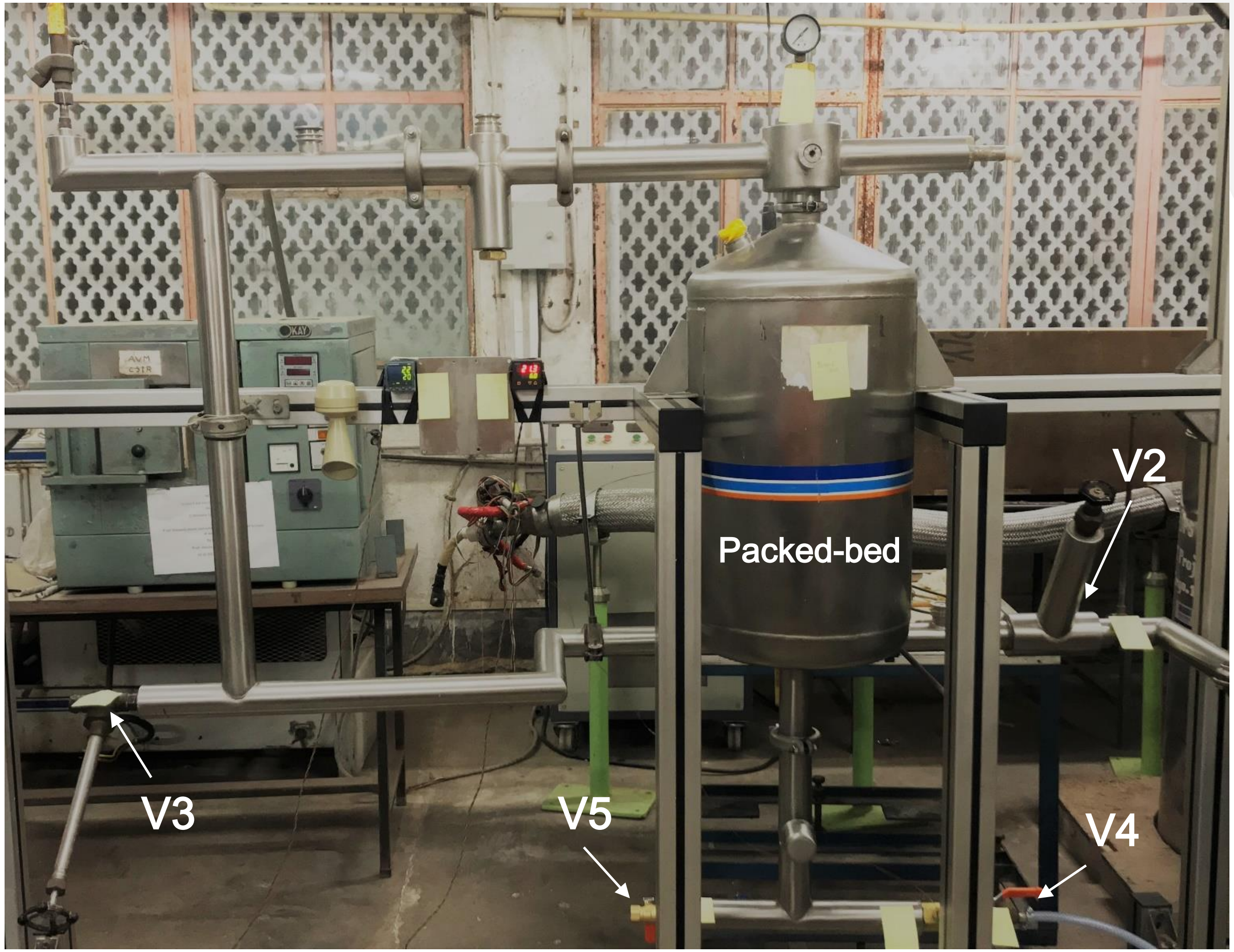
- **Charging process:** Superheated liquid to 150 K/175 K for cooling down the bed
- **Discharging process:** Pressurized air to warm up the packed-bed to room temperature

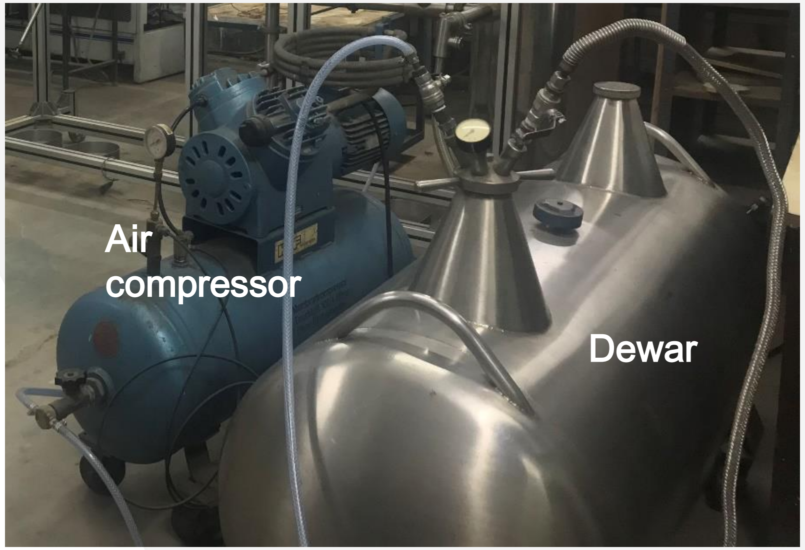
Experimental: Process flow diagram with instrumentation



Left: Layout of the experimental setup; **Right**: Bed height and placement of RTDs inside the vessel

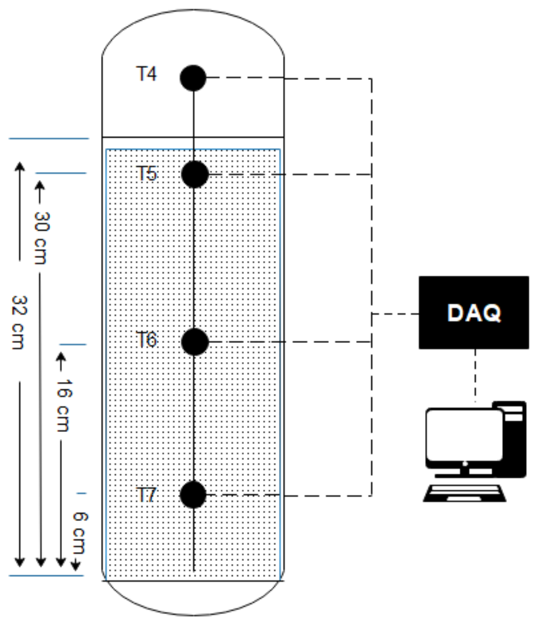
Experimental





Experimental: Description of the packed-bed

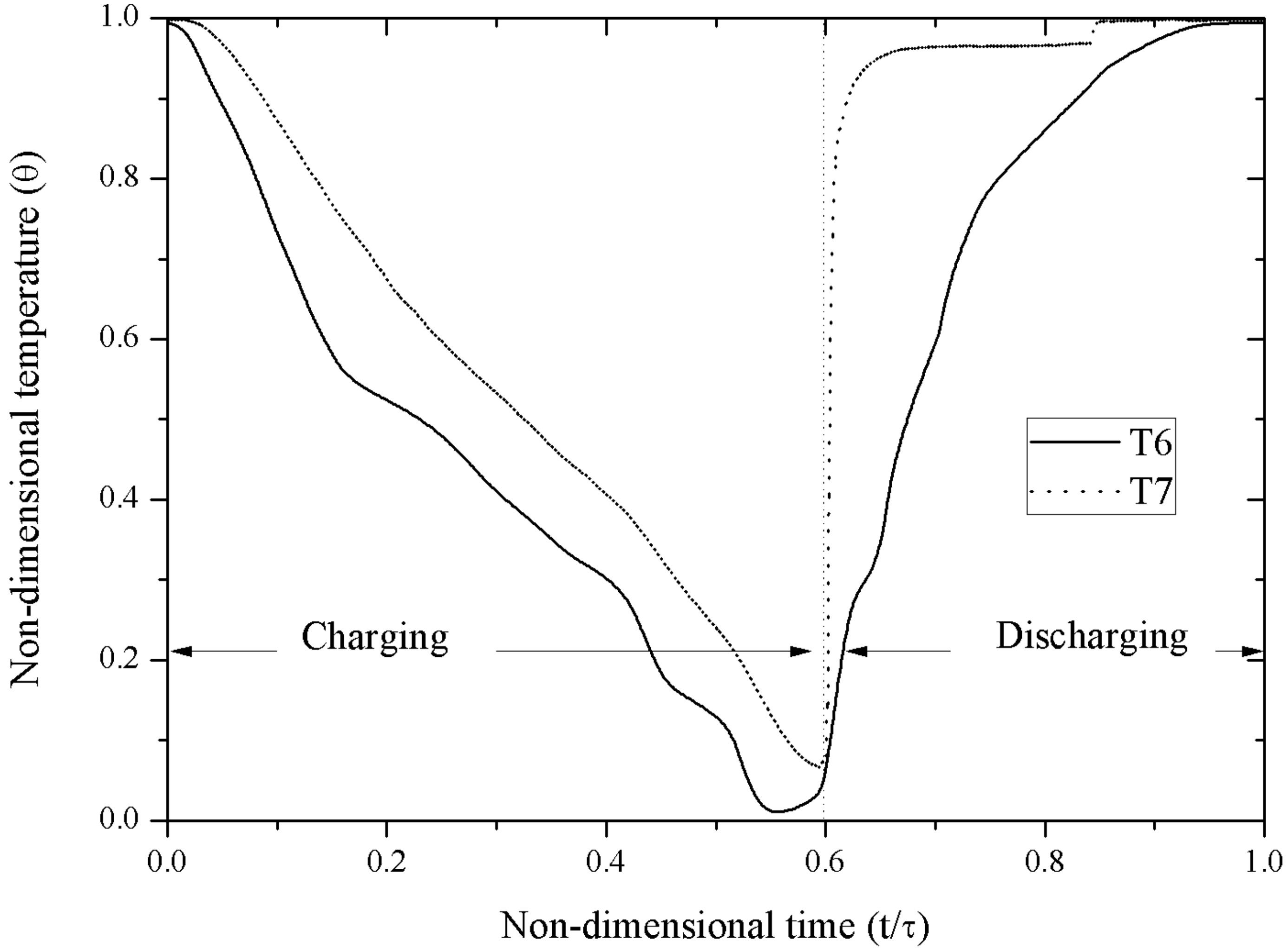
- Used a vacuum insulated vessel of inner volume 27.3 ltrs. with required bi-directional inlet and outlet ports as packed-bed
  - Bed height (*L*): 32 cm
  - Bed diameter (*D*): 15 cm
  - Ullage space: 10 cm
- Granite pebbles as packing material with dimensions between 12.5 mm×12.5 mm and 10 mm×10 mm
  - Average equivalent diameter (*d*): 11.25 mm.
  - Average density: 2688 kg/m^3
  - Mean average heat capacity: 0.7 kJ/kg-K
  - The porosity of the bed (ε): 0.38



Results and discussions

- Conducted experiments on two different operating scenario
  - **Full-load**: Cooling down the entire bed to the bed cut-off temperature of 150 K; Charging time: 6 hrs., Standby: 5 min; Discharging time: 4.5 hrs
  - **Part-load with prolonged standby period:** Cooling down a part of the bed to the bed cut-off temperature of 175 K; Charging time: 2 hrs, Standby: 2 hrs, Discharging time: 2 hrs.
- Constant flow rate to the packed-bed
- Ambient temperature: 31.9^{0}C during full-load, 33^{0}C during part-load
- Compressor discharge pressure: 1.5 bar

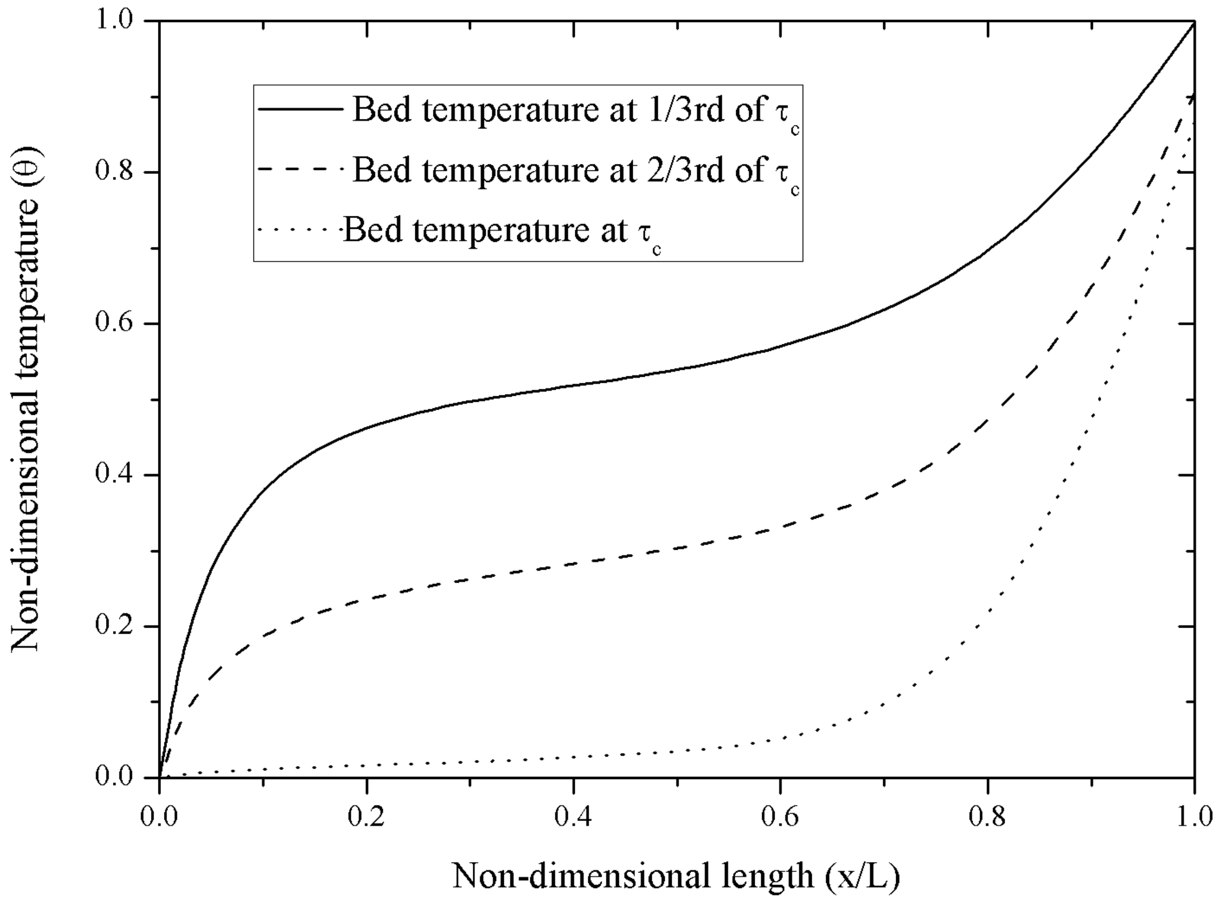
Results and discussions: Operation under full-load



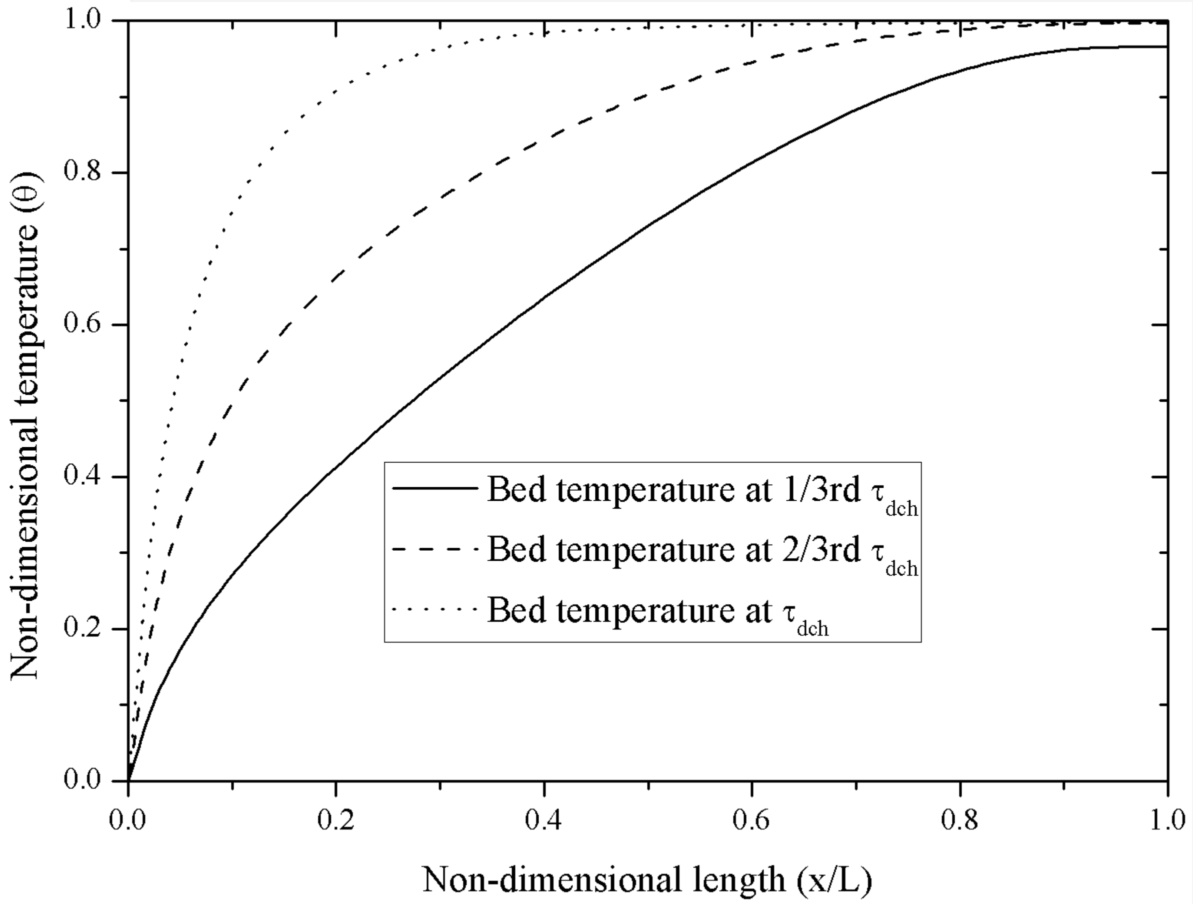
Temperature profile inside packed-bed operating under full-load condition with cut-off temperature of 150 K

- Demonstrated the process of storage and utilization with a storage efficiency of 94.71%
- Reasons behind the losses :
  - High heat in-leak due to higher charging time leading to loss of stored refrigeration
  - Variation of flow rate during cooling down reduced heat transfer between fluid and solid periodically

Results and discussions: Operation under full-load



Temperature distribution inside the packed-bed during the charging cycle



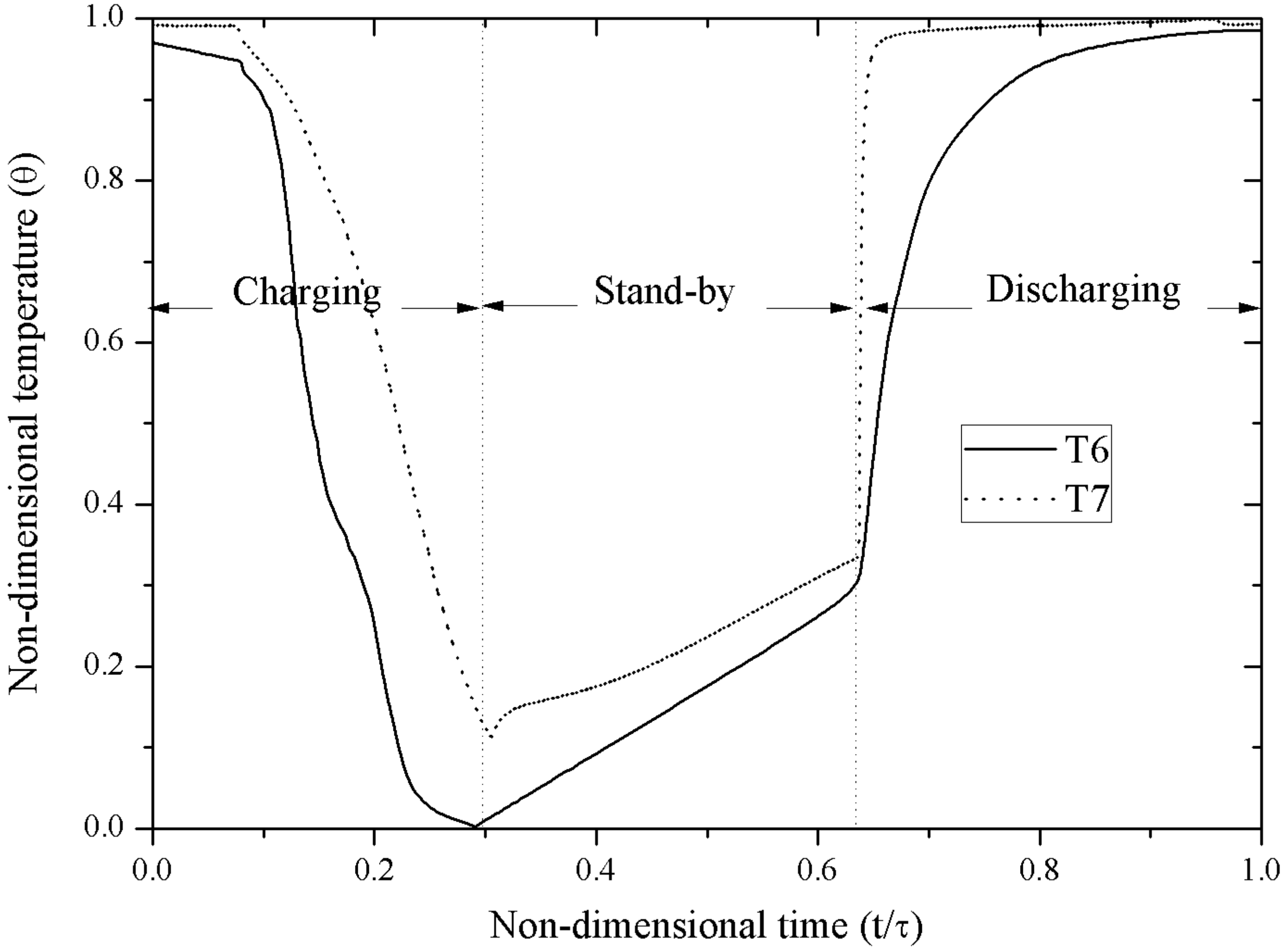
Temperature distribution inside the packed-bed during the discharging cycle

Results and discussions: Operation under full-load

Observations

- Typical thermocline profile inside the bed both during charging and discharging processes
- Due to lower flow rate during charging process, lower rate of reduction in temperature in this period
- Overall pressure drop of 30 kPa in the process (including the bed, transfer lines and heater)
- The pressure drop in the bed varied in a range of ±5 kPa
  - Flow rate varied periodically with little effect on the performance of the bed deep inside
- Variation in ullage volume temperature (T4) after reaching below 190 K
  - Temperature at adjacent to ullage space (T5) also increased proportionally.
  - After T4 reached above 190 K, both T4, T5 again started reducing

Results and discussions: Operation under part-load



Temperature profile inside packed-bed operating under part-load and prolonged standby condition with cut-off temperature of 175 K

- Non-uniform temperature profile of the bed due to partial cooling,
  - The lower part of the bed 10% warmer than the upper part
- Increase in bed temperature during standby period:
  - Due to the heat in-leak in the bed
  - Due to conduction inside the bed
- **Settling of refrigeration**
  - Due to presence of a finite temperature gradient inside the bed from the upper part to the lower part of the bed
  - Increased the bed cut-off temperature by 30%.

Results and discussion: Operation under part-load

- Low storage efficiency of 64.57% due to:
  - Settling of refrigeration together
  - Heat in-leak during standby period
- Highest rate of increase in temperature at:
  - Ullage space
  - Inside the bed: Locations adjacent to ullage space
- Pressure drop in the process remained constant at 0.3 bar
- Summary of the two sets of experiments:

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

Conclusions

- Developed an experimental setup to investigate the performance of such packed-bed with granite pebbles
  - Conducted two sets of experiments
- Full-load operation:
  - A storage efficiency as high as 95%
  - Uniform temperature profile inside the entire bed at the end of charging cycle
  - Flow instability, high ullage space temperature fluctuation below 190 K
- Part-load and prolonged standby operation:
  - Storage efficiency reduced to 65%
  - Observed settling of refrigeration from the bottom of the bed to upper locations
- Efforts will be made to identify the effects of such factors by varying the ullage space, using different standby times etc.

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THANK YOU!

Any questions?

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