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EXPERIMENTAL CHARACTERISATION OF THERMAL STRATIFICATION IN ICE-BASED DIRECT CONTAT LATENT COLD STORAGE

Summary

Hyperloop systems operate in low-pressure tubes where conventional air cooling is limited, requiring effective thermal management systems. Direct-contact latent cold storage using ice as a phase change material and water as the heat transfer fluid is a promising compact solution. This study experimentally investigates a direct contact latent cold storage prototype and compares two ice configurations: crushed ice and a single ice block. Experiments were conducted at constant heating powers and evaluated using dimensionless temperature and time parameters to analyze thermal stratification. The results show that crushed ice provides homogeneous temperatures during melting and stable stratification afterward, while the ice block leads to uneven melting and unstable temperature behavior. Therefore, crushed ice is more suitable for latent cold storage in Hyperloop thermal management systems.

Keywords: thermal energy storage; direct contact; latent heat storage; ice; phase change material; Hyperloop; thermal management system

Field of application for the findings: Thermal Energy Storage

Addressed audience: Technical academic

1. Indroduction

Hyperloop transport operates in low-pressure tubes that reduce aerodynamic drag but limit cooling by ambient air. Therefore, an effective thermal management system (TMS) is required to remove waste heat from onboard components such as linear motors, power electronics, and batteries. Similar concepts of high-speed transport in partial-vacuum tunnels were previously proposed in projects such as Swissmetro by EPFL and ETH Zurich (SwissMetro-NG).

According to the Delft Hyperloop study (Wit and Terpstra, 2023), three active cooling approaches are possible: radiation, sublimation of ice, and latent heat storage (LHS). Radiative cooling is limited by small temperature gradients, while sublimation requires additional infrastructure such as condensers upstream of the vacuum pumps. Therefore, LHS is considered the most promising.

LHS systems store thermal energy using phase change materials (PCMs), which absorb large amounts of heat during melting at nearly constant temperature. In the context of Hyperloop, the melting temperature of ice (0 °C) lies within the desired cooling range for maintaining component temperatures and passenger comfort. Given its supreme this work, latent heat and specific heat capacity, resulting in high thermal energy density, ice is therefore the most promising PCM candidate and is used in this study. A common limitation of LHS systems is the low heat transfer rate within the solid PCM. Conventional solutions integrate heat exchanger structures, increasing heat transfer area but also system mass. An alternative is direct contact latent heat storage (DCLHS), where the HTF is injected directly into the PCM storage. This creates droplets and large contact surfaces between HTF and PCM, enhancing heat transfer. Due to density differences, the HTF forms flow channels that act as a direct contact heat exchanger (Kunkel et al., 2020).

This study experimentally investigates a DCLHS system using ice as PCM and water as HTF for Hyperloop pod cooling. A key parameter is the geometry of the ice within the storage unit, as it affects both heat transfer and PCM utilization. Smaller particles increase heat transfer surface and thermal response, while larger blocks improve volumetric storage efficiency.

Two ice configurations are examined: crushed ice and a single ice block. Crushed ice provides a large surface area, enabling faster melting and more uniform temperatures. In contrast, a single ice block maximizes storage capacity by minimizing void space but may reduce heat transfer due to its smaller surface area. The focus of this study is on the thermal stratification behaviour of these two configurations and how the different ice geometries influence temperature distribution and stratification within the storage tank.

2. Materials and Methods

For the comparison of the different ice-shape experiments, tests were conducted at constant heating powers. At the beginning of each experiment, the inlet of the storage tank was heated over a heat exchanger whit a heat source while the storage tank itself was initially cold and filled with ice (Figure 1). The flow through the storage tank was directed from top to bottom, as this direction provides the most favourable conditions (Estermann et al. 2025). The tank was then heated using a constant power input. The mean heating power was 2.5 kW. Additional experiments were performed at 3.8 kW (1.5 × 2.5 kW) and 1.25 kW (0.5 × 2.5 kW). For each power level, experiments were carried out with the different ice configurations. To analytically compare the experiments, the dimensionless temperature difference over the storage tank was used. This parameter compares the maximum possible temperature difference in the tank with the actual temperature difference measured during the experiment.

$$T^* = \frac{T_{top} - T_{bottom}}{T_{in} - T_0} \qquad \text{(eq. 1)}$$

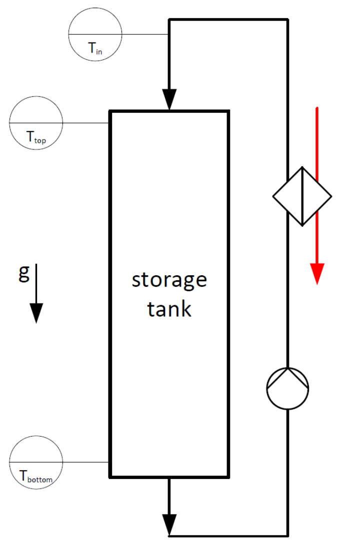

Fig. 1: Simplified schematic diagram of the setup

Where T_{top} is the temperature at the top of the storage tank, T_{bottom} is the temperature at the bottom of the storage tank, T_{in} is the inlet temperature of the storage tank, and T_0 is the initial temperature of the tank at the start of the experiment.

The initial temperature T_0 was −10°C for the ice block experiments and 0°C for the crushed ice experiments. Since the experiments had slightly different durations, a dimensionless time parameter was used to compare the results:

$$\tau^* = \frac{t}{t_{tot}} \qquad \text{(eq. 2)}$$

Where t is the current time and t_{tot} is the total duration of the experiment.

The dimensionless temperature T^* is typically used to evaluate thermal stratification in sensible heat storage systems. In such systems, a perfectly stratified tank would yield $T^* = 1$ (Senthil Kumar et al., 2016). However, for latent heat storage, the desired behaviour is different. During the latent phase change, the storage tank should ideally maintain a homogeneous temperature, which would correspond to $T^* = 0$. Once the phase change is completed and the system enters the sensible heating region, a clear stratification should develop, leading to $T^* = 1$. Therefore, the ideal temperature curve for a latent storage tank would resemble a step response, transitioning from 0 to 1.

3. Results

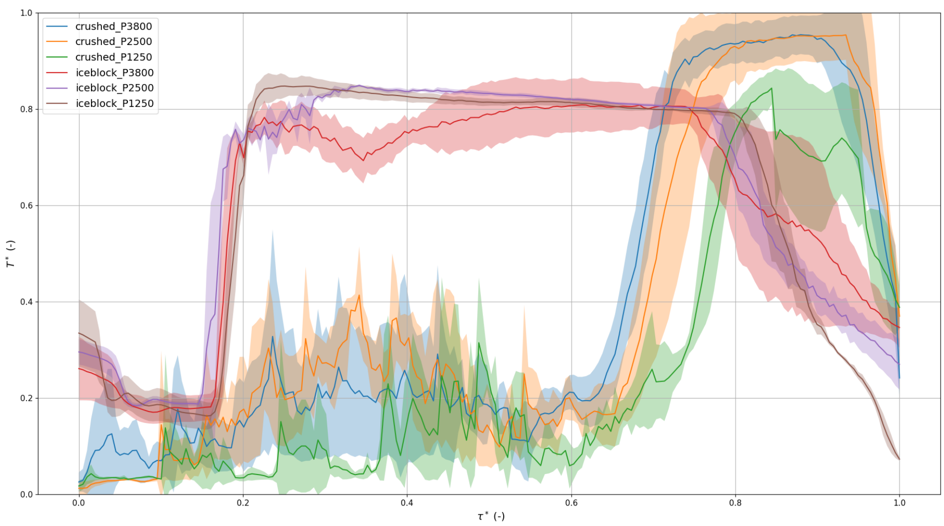

Fig. 2: dimensionless temperature over dimensionless time

Figure 1 presents the dimensionless temperature distribution for both ice geometries under varying power levels, denoted as P3800 (3.8 kW), P2500 (2.5 kW), and P1250 (1.25 kW). The results indicate that the crushed ice experiments closely follow the expected behaviour. At the beginning of the experiment, the dimensionless temperature remains close to 0, indicating a homogeneous temperature distribution in the tank during the melting process. Later, when the system transitions to sensible heating, the value increases toward 1, indicating a clear stratification. This behaviour is supported by the density anomaly of water, where water at approximately 4°C sinks to the bottom, enhancing the stratification in the tank.

In contrast, the ice block experiments do not exhibit this behaviour. At the beginning of the experiment, the dimensionless temperature already increases, reaching approximately 0.8 instead of remaining near 0. This occurs because the top surface of the ice block melts first. As a result, the temperature sensor at the top of the storage tank detects warmer water, while the sensor at the bottom remains surrounded by frozen ice. Consequently, the tank does not exhibit a homogeneous temperature distribution during the latent phase. Additionally, toward the end of the experiment, the dimensionless temperature drops rapidly instead of maintaining a stable stratification. This indicates that a clear and stable stratification does not develop in the storage tank when using ice blocks.

4. Conclusion

The results show that crushed ice provides significantly better thermal behaviour for latent cold storage compared to ice blocks. The crushed ice experiments demonstrate the expected temperature evolution, with a homogeneous temperature distribution during the melting phase followed by the development of thermal stratification during the sensible heating phase. In contrast, the ice block configuration leads to non-uniform melting and distorted temperature measurements, which prevent the formation of a homogeneous temperature field during the latent phase and a stable stratification afterward. This behaviour is mainly caused by the localized melting of the ice block and the resulting uneven heat transfer within the storage tank.

Overall, the experiments indicate that crushed ice is more suitable for achieving the desired thermal performance and stratification behaviour in latent cold storage systems for Hyperloop TMS.

References

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Abbreviations

T^*	dimensionless temperature
T_{top}	top temperature
T_{bottom}	bottom temperature
T_{in}	inlet temperature
T_0	initial temperature
τ^*	dimensionless time
t	time
t_{tot}	total experiment time