Experimental study of cryogenic fluid flow in porous thermal insulation materials

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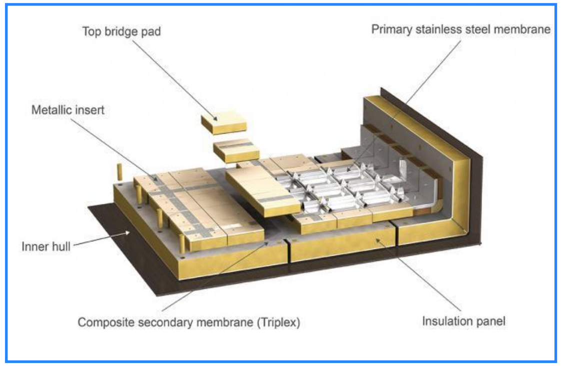
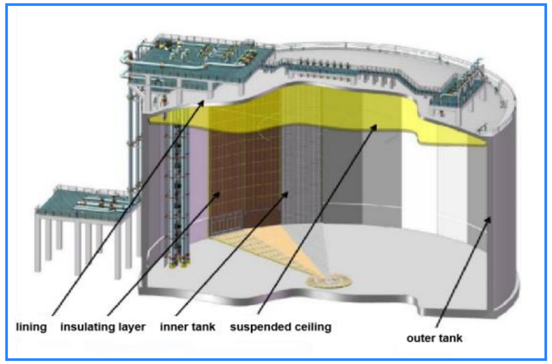
Background

Porous materials with low thermal conductivity are commonly employed as thermal insulation materials for cryogenic systems.



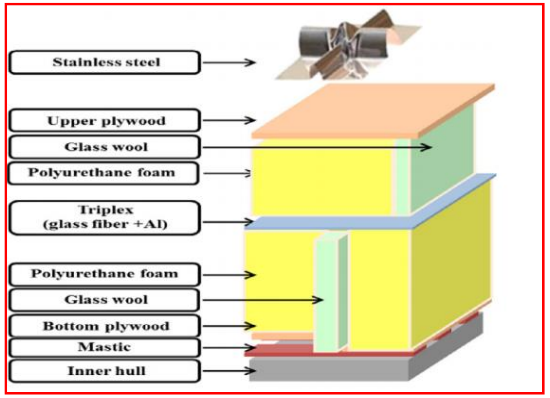
LNG carrier Mark III membrane system
Insulation materials: polyurethane, glass wool



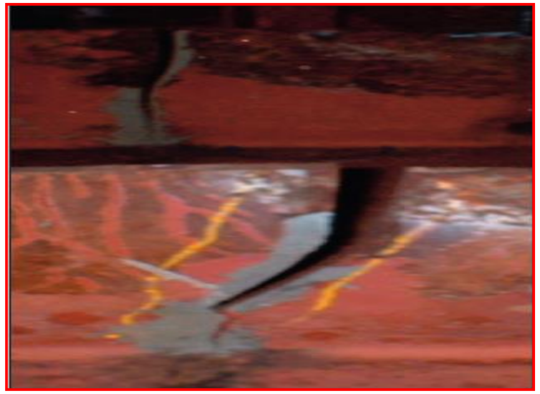
Membrane type LNG storage tank
Insulation material: polyurethane, glass wool

Cryogenic spherical storage tank
Insulation material: polyurethane, glass wool

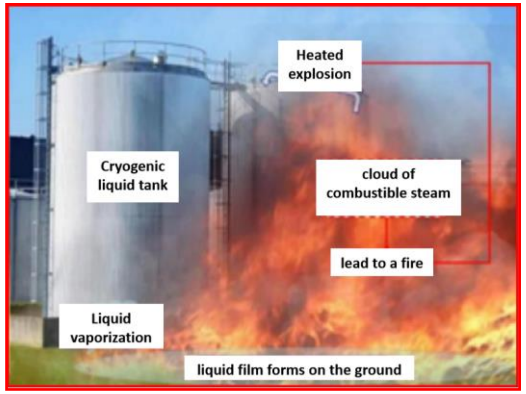
The occurrence of cracks in the system package can lead to severe accidents



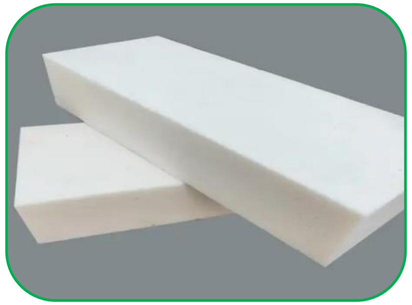
Mark III system
structure schematic



Low temperature brittle
fracture of hull plate



Storage tank leakage incident



Polyurethane foam

Glass wool

Aerogel blanket

Expanded perlite

Porous insulation material

With excellent thermal insulation performance, these porous insulation materials have found extensive applications in various fields

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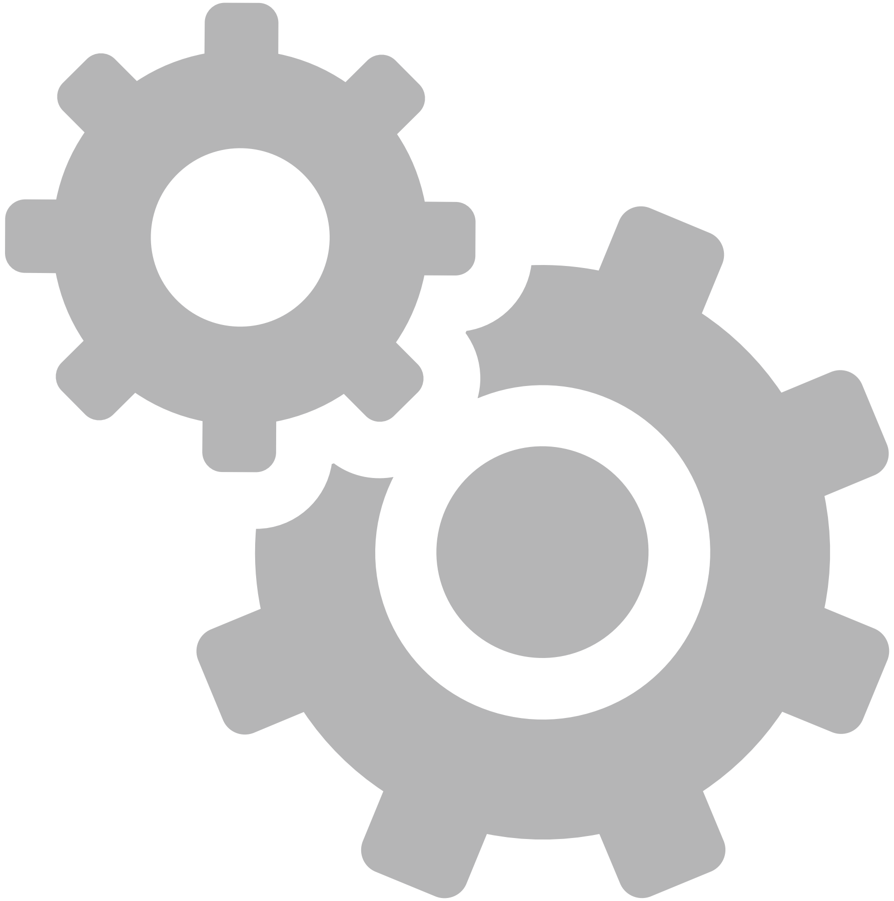

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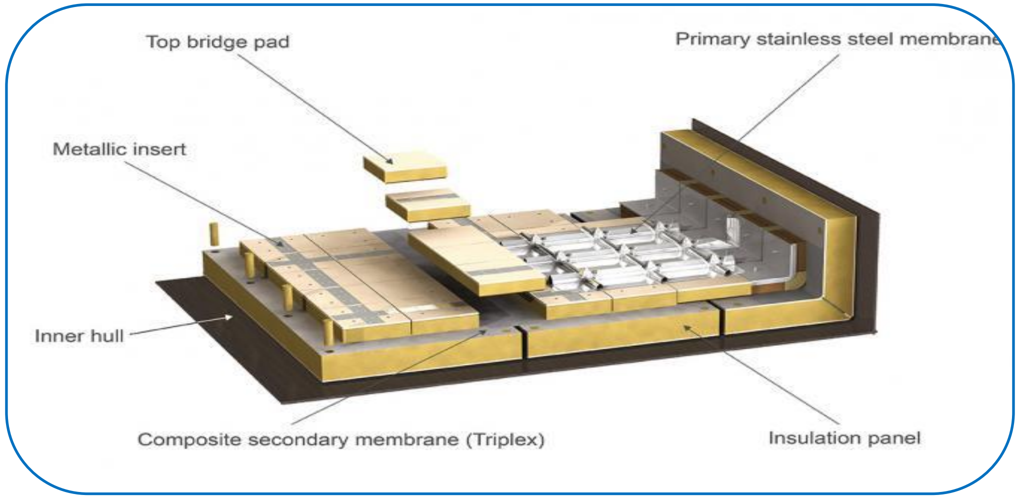
2 Experimental apparatus

3 Results and discussion

4 Conclusion

Experimental apparatus

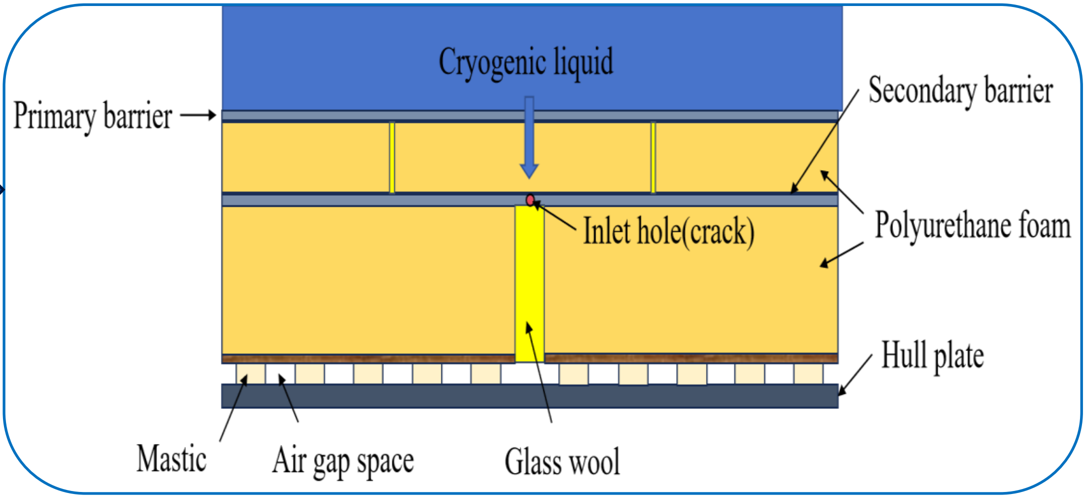
Physical model



Membrane system of LNG carrier

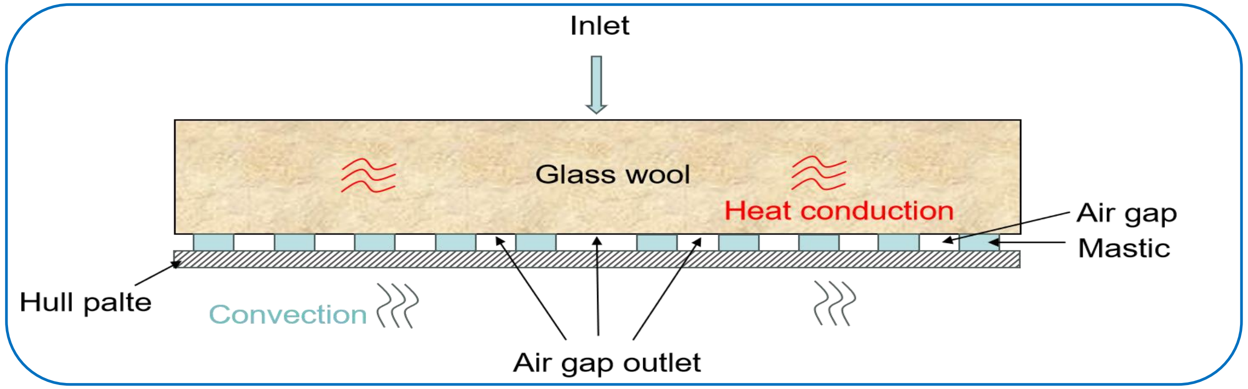
Most widely used system

Glass wool serves as a conduit for leakage



Schematic diagram of the insulating system

Physical process

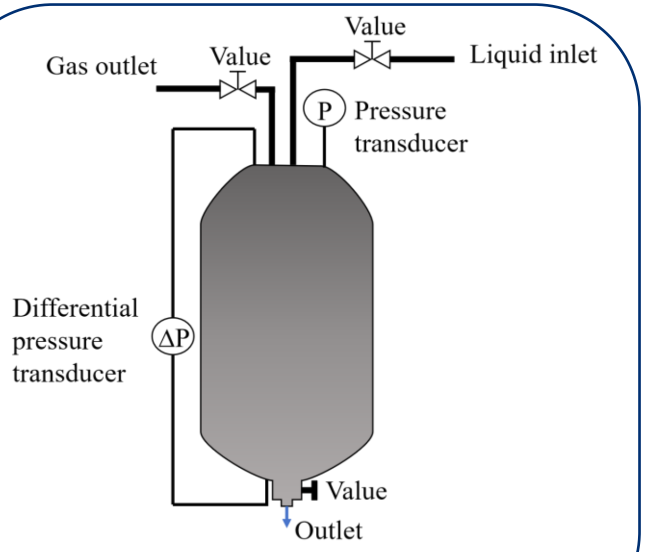


The cryogenic liquid nitrogen leaks from the top of the glass wool (secondary shield layer), flows through the glass wool (porous matreial), the air gap layer, and finall contacts the hull plate.

Experimental apparatus

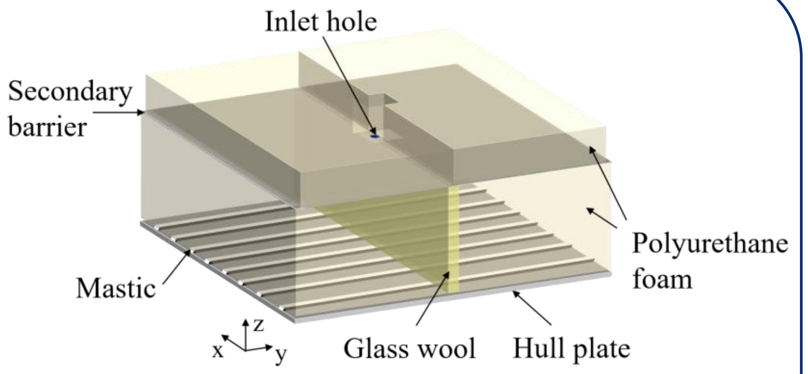
Cryogenic fluid flow

Photo of the experimental apparatus



Liquid nitrogen supply section

- A custom storage tank
- The outlet aperture and pressure are controllable
- Reduce heat transfer of liquid nitrogen before entering the test section

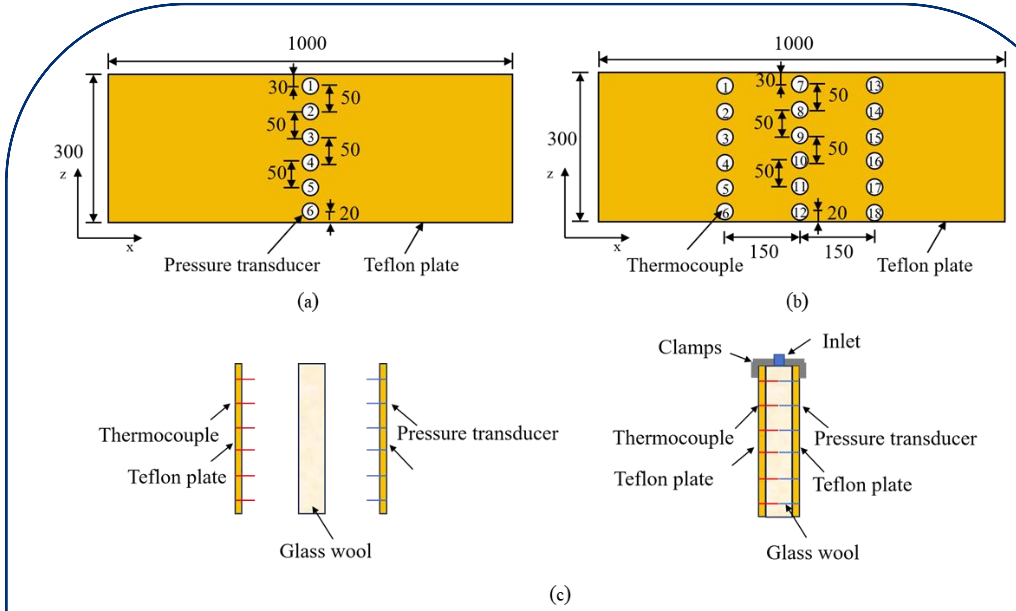


Test section

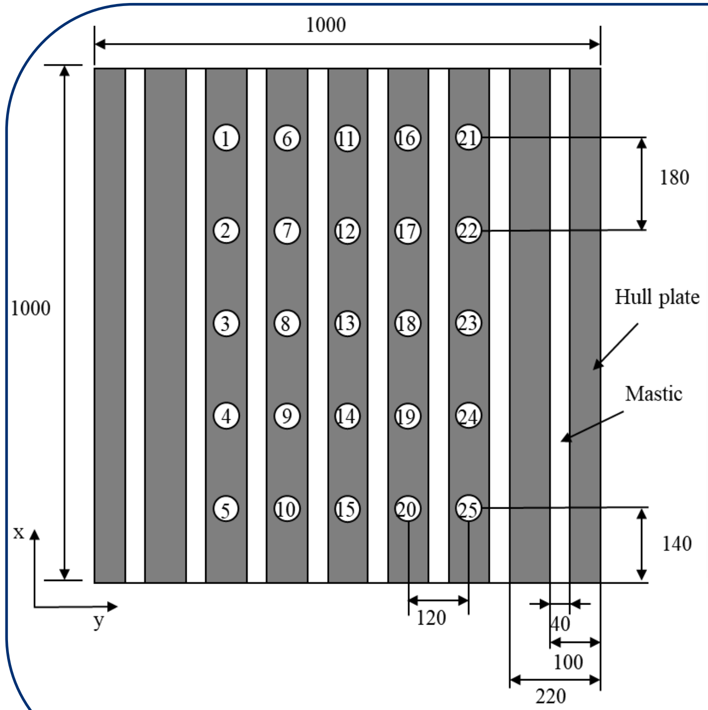
- Adheres to a typically dimension used in the insulating system
- The influence on the glass wool and the hull plate is considered at the same time

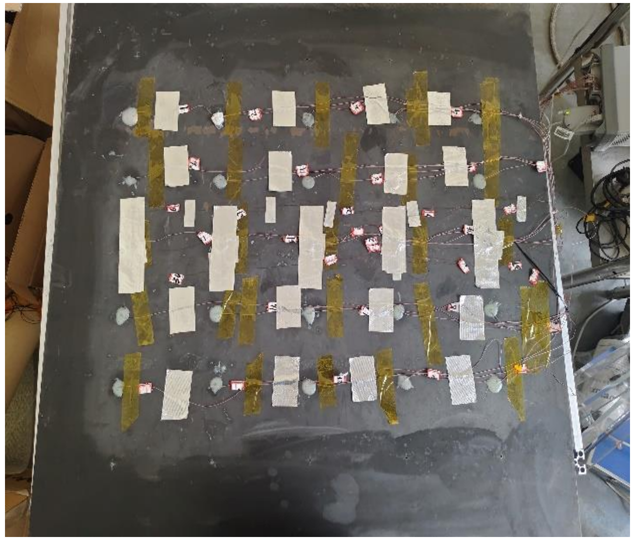
Experimental apparatus

Sensor installation



Distribution of sensors in glass wool



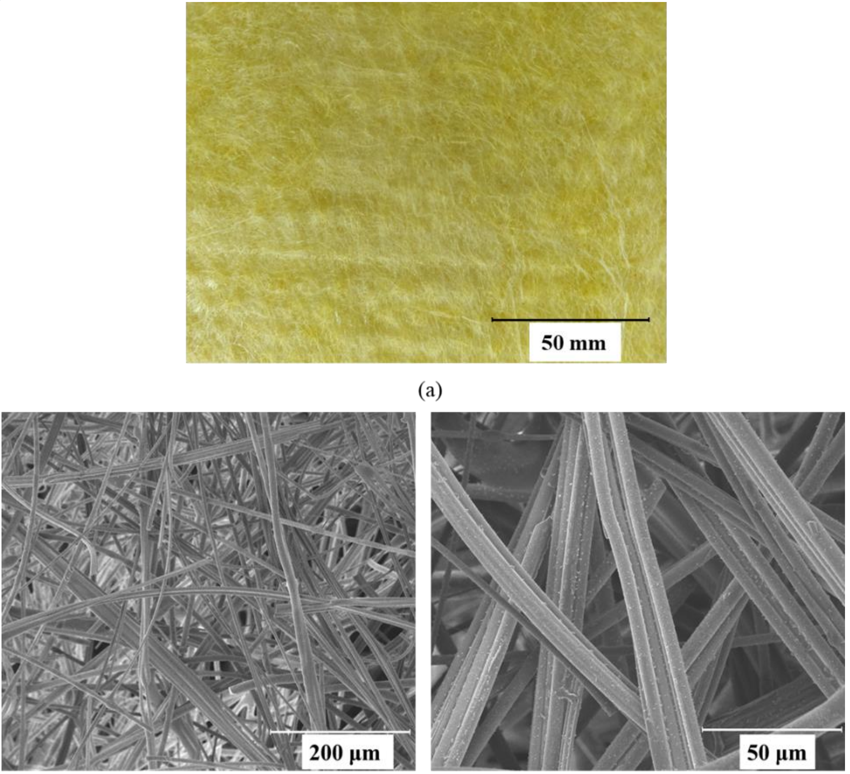


Thermocouples’ distribution on hull plate

- **To measure the fluid pressure and temperature, thermocouples (T type) and pressure transducers were installed within the glass wool.**
- **To assess the impact of flow on the hull plate, thermocouples are installed on the hull plate.**

Experimental apparatus

Experimental material



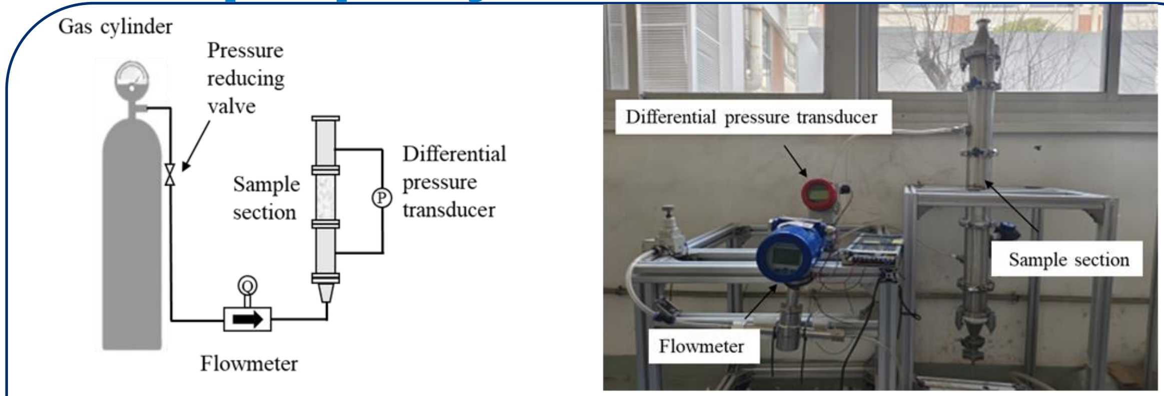
(a)

(b) (c)

Features of glass wool (48 kg/m³).

The porous media we discussed is glass wool (bulk density: 32 kg/m³, 48 kg/m³, 80 kg/m³).

Material property



(a) (b)

Experimental apparatus for Resistance coefficient measurement

Resistance coefficient of the glass wools.

bulk density（kg/m³）	direction	viscosity resistance coefficient（1/m²）	inertial resistance coefficient（1/m）
32	*z*	1.31×10^8	509.5
	x	1.92×10^8	677.3
48	*z*	1.49×10^8	613.7
	x	2.08×10^8	705.2
80	*z*	1.96×10^8	688.85
	x	2.38×10^8	739.2

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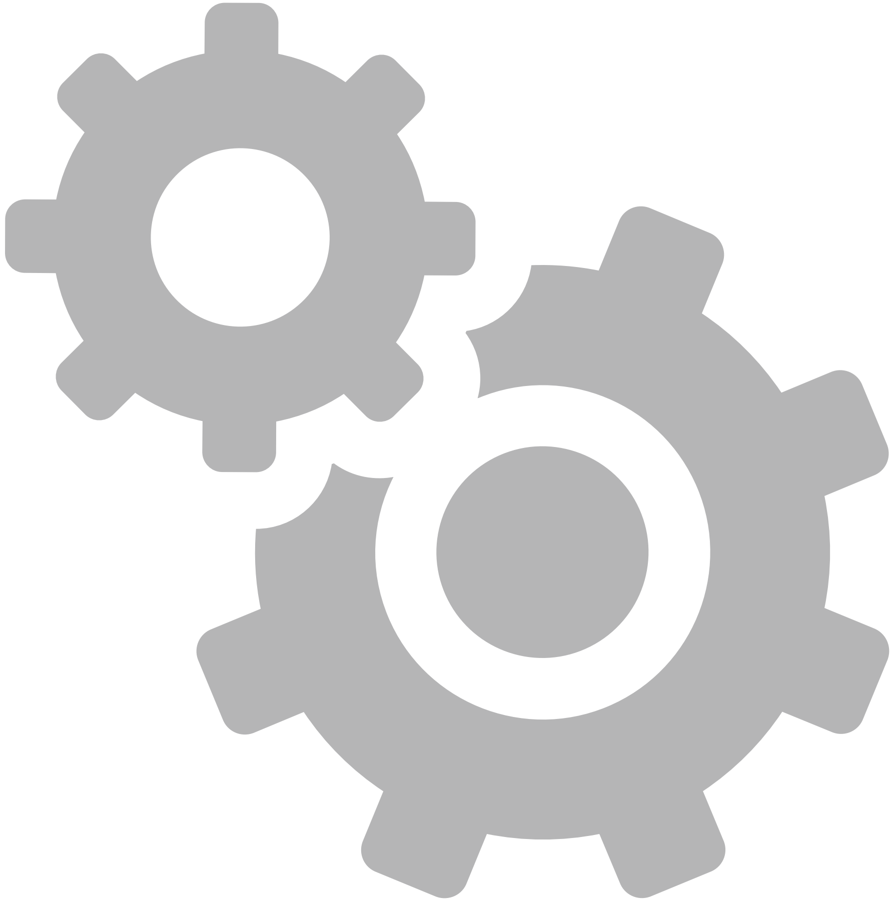
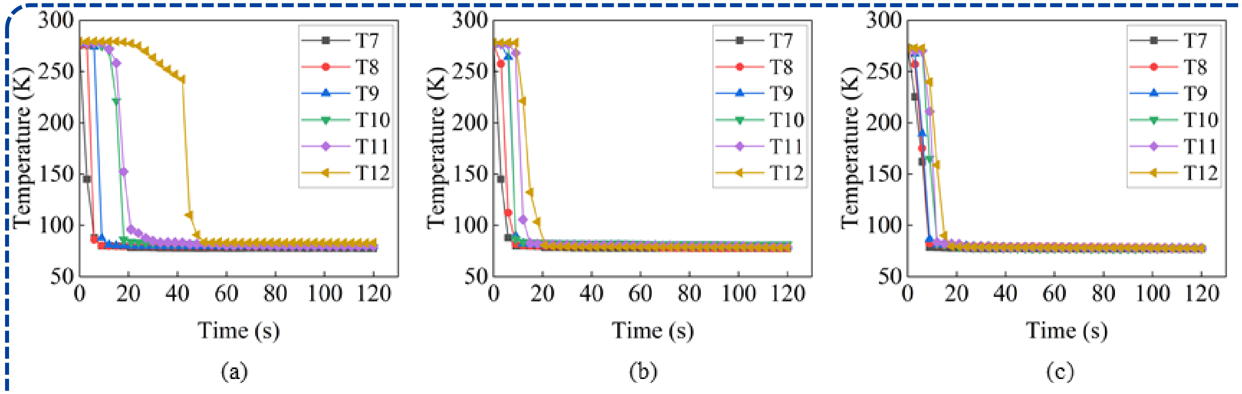


Experimental investigation

1.The influence of inlet hole aperture

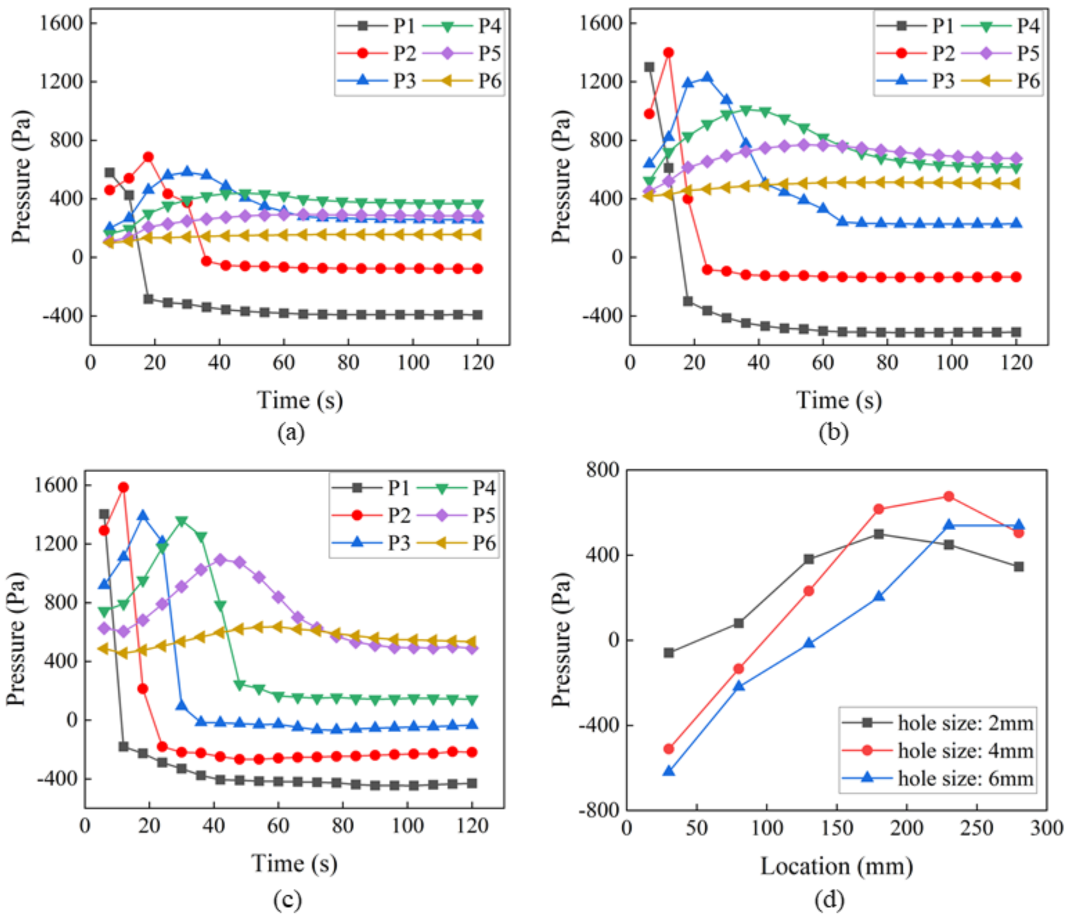


Temperature of glass wool under different inlet hole apertures:

(a) 2 mm，(b) 4 mm，(c) 6 mm

- **The temperature of the glass wool at thermocouples T7-T12, located directly below the inlet hole, reached liquid nitrogen temperature within 60 seconds for all the three holes' apertures.**

- **In all three inlet hole apertures, the flow of liquid nitrogen generated a region of negative pressure within the glass wool, and all pressure measuring points exhibited near stability within 120 s.**

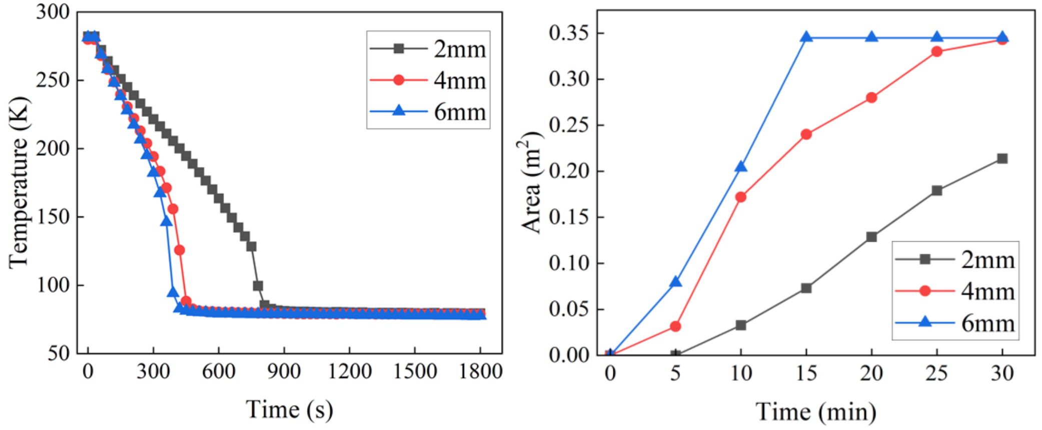


Pressure of glass wool under different inlet hole aperture：

(a) 2 mm，(b) 4 mm，(c) 6 mm , and (d) Pressure distribution in glass wool (30 min)

Experimental investigation

1.The influence of inlet hole aperture

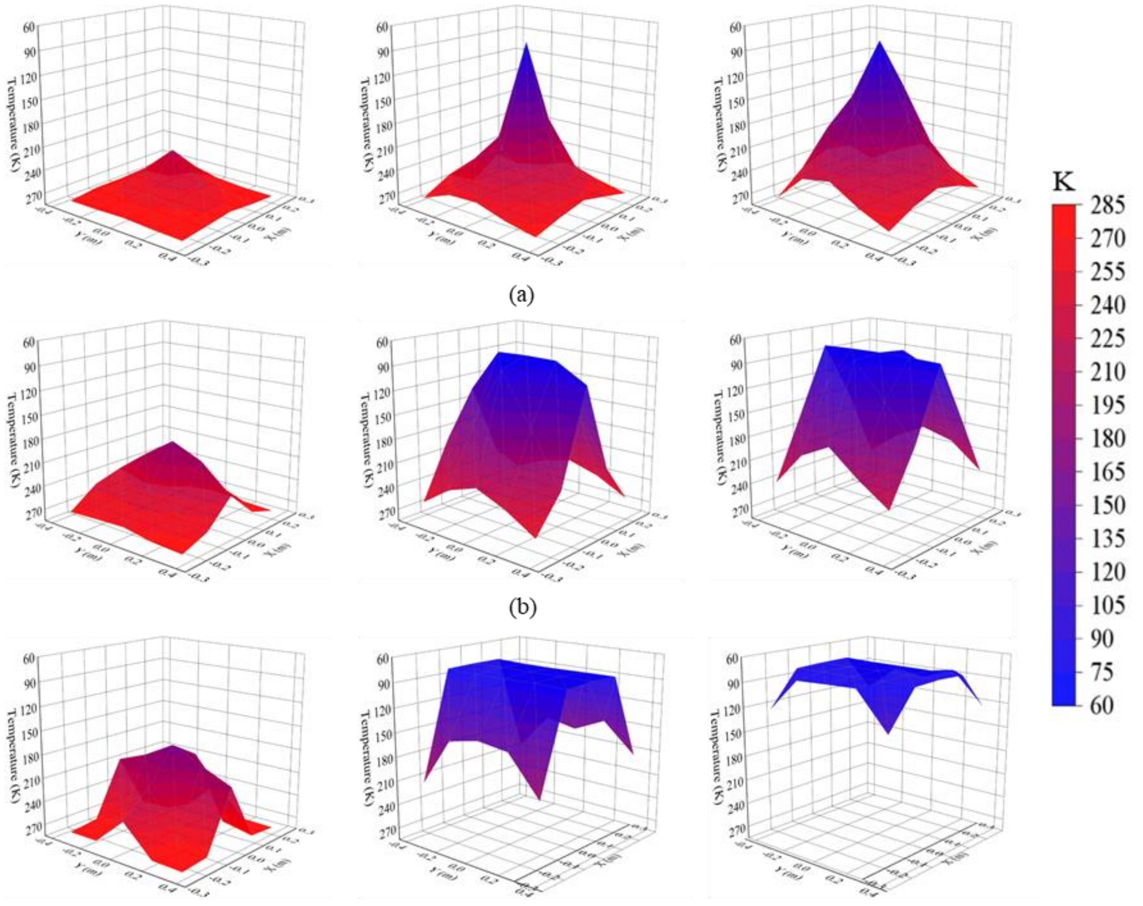


(a) (b)

The minimum temperature and low temperature area of hull plate change with time
(a) minimum temperature, (b) low temperature area

- **Specifically, for d = 2 mm, 4 mm, and 6 mm, the minimum temperature of the hull plate reaches 213 K within 330 s, 216 s and 198 s respectively**

- **After a flow duration of 30 minutes at a hole aperture of 2 mm, a low-temperature area measuring approximately 0.21m^2 is formed. Similarly, at hole apertures of 4 mm and 6 mm, complete transformation into a low-temperature area(0.34m^2) occurs after durations of only 15 minutes and 30 minutes respectively.**



(a)

(b)

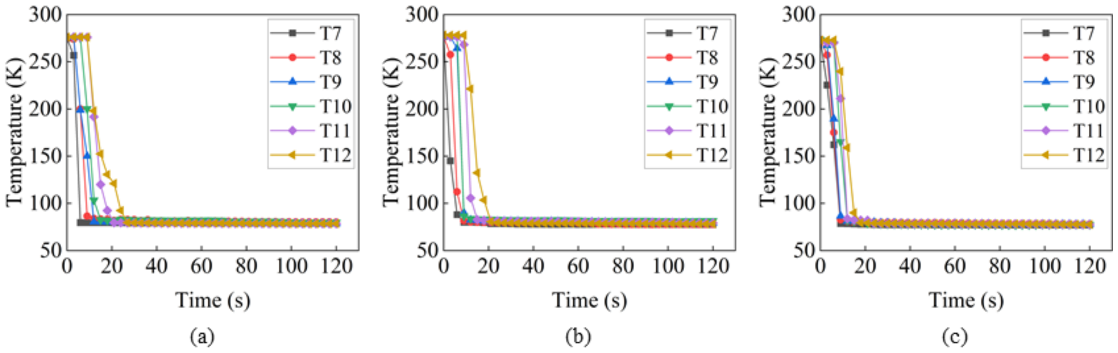
(c)

Temperature distribution on hull plate of different inlet hole aperture

at 300 s, 900 s and 1500 s: (a) 2 mm, (b) 4 mm, (c) 6 mm

Experimental investigation

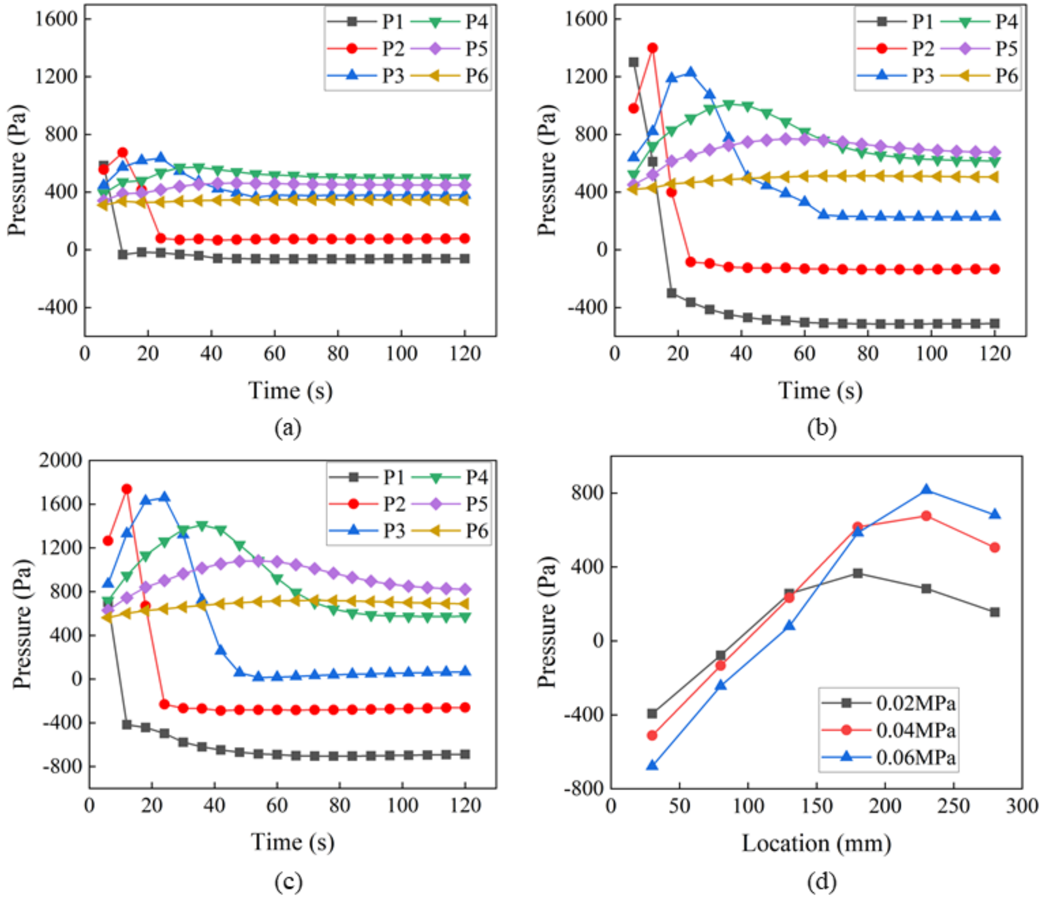
2.The influence of inlet pressure



Temperature of glass wool under different inlet pressure:

(a) 0.02 MPa, (b) 0.04 MPa, (c)0.06 MPa.

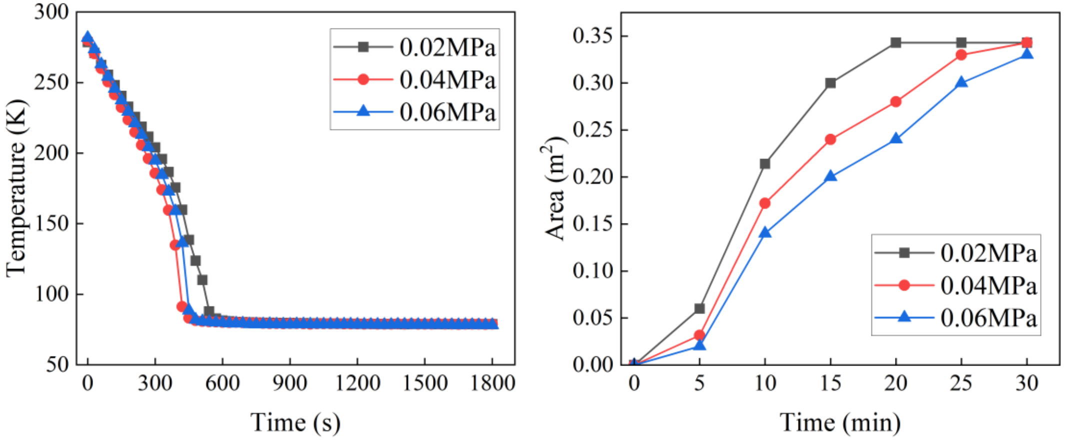
- The temperature at all six thermocouples within the glass wool reached liquid nitrogen temperature, at 18 s, 21 s, and 24 s respectively.
- Negative local pressure was observed at pressure transducer P1 and P2 near the inlet. With an increase in inlet pressure, there was an accompanying rise in liquid nitrogen flow rate leading to increased negative pressure. The peak of pressure occurred near sensor P4 under an inlet pressure of 0.02 MPa and near sensor P5 under pressures of 0.04 MPa and 0.06 MPa.



Pressure of glass wool under differen inlet pressure: (a) 0.02 MPa, (b) 0.04 MPa, (c)0.06 MPa, and (d) Pressure distribution in glass wool (30 min)

Experimental investigation

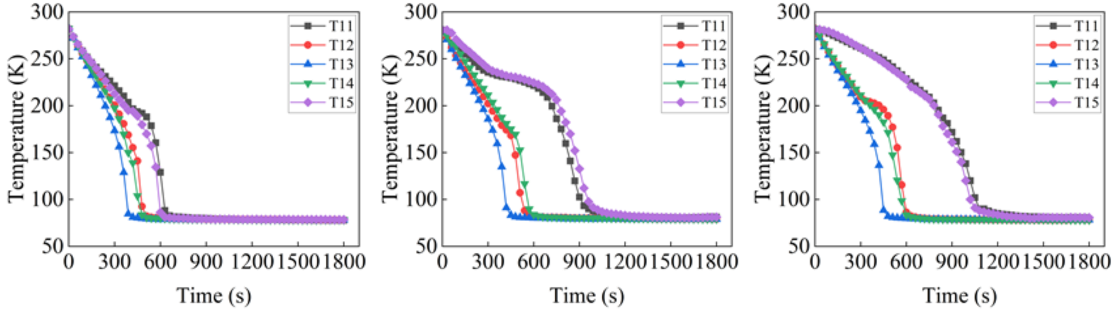
3.The influence of bulk density of glass wool



(a) (b)

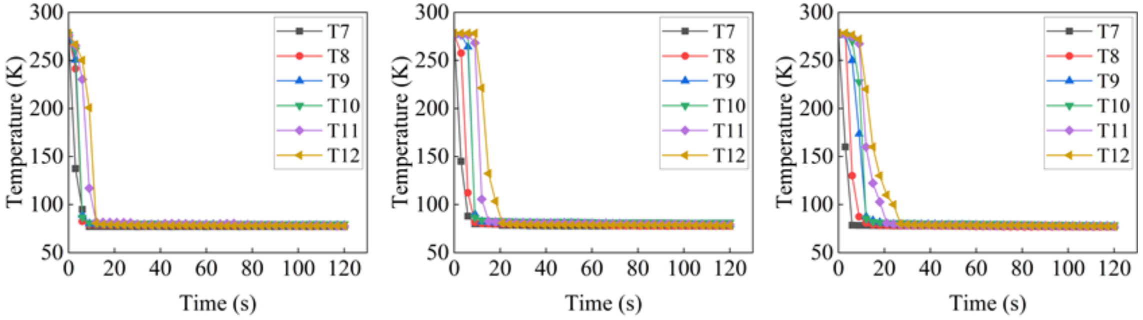
The minimum temperature and low temperature area of hull plate change with time
(a) minimum temperature, (b) low temperature area

- **With an increase in density, reduced permeability results in a narrower effective flow passage, leading to a lower flow velocity and slower rate of temperature drop.**
- **There is an extension of 680 s for thermocouple T11 and T15 on the hull plate to reach liquid nitrogen temperature when increasing glass wool density from 32 kg/m3 to 80 kg/m3. This indicates a noticeable way to weaken the liquid nitrogen flow on the hull plate. Increasing porous media density can effectively enhance system safety.**



(a) (b) (c)

The temperature of hull plate changes with time: (a) 32 kg/m3, (b) 48 kg/m3, (c) 80 kg/m3.



(a) (b) (c)

Temperature of glass wool under different bulk density:
(a) 32 kg/m3, (b) 48 kg/m3, (c) 80 kg/m3.

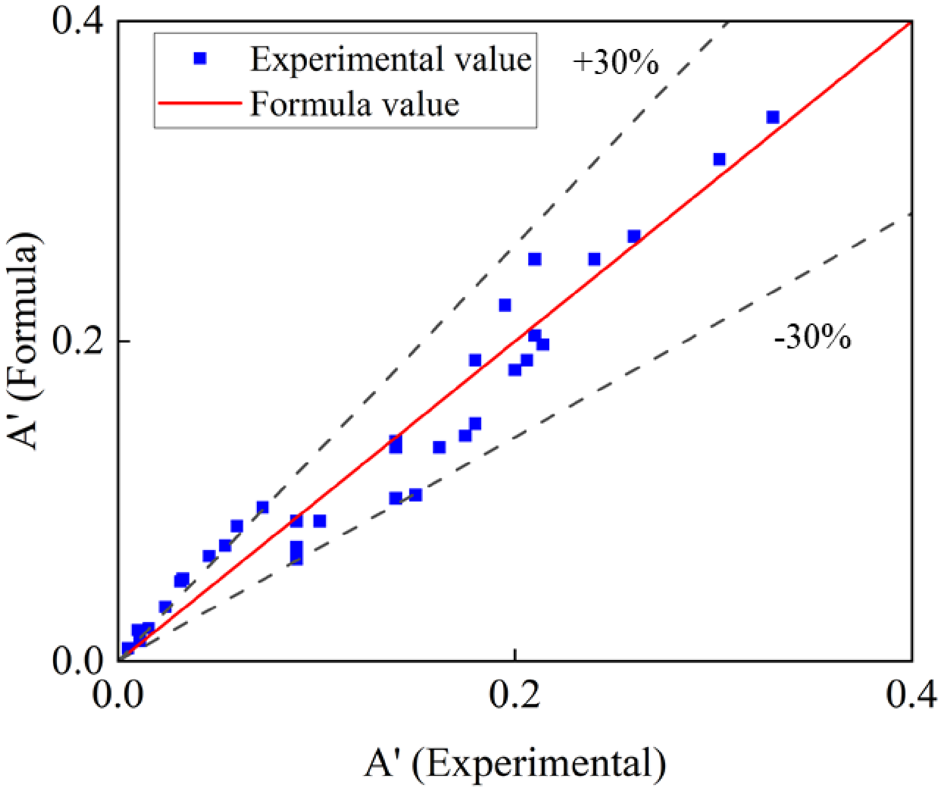
Experimental investigation

4.Empirical formula for low temperature area

Nondimensionalize

$$A' = \frac{A}{A^*},\ d' = \frac{d}{w},\ p' = \frac{p}{p_{atm}},\ \rho' = \frac{\rho}{\rho_{min}},\ t' = \frac{t}{t^*}$$

Where, A is the area of low temperature area on the hull plate. A^* is the area of the hull plate, 1 m². d is the inlet hole aperture,W is width of glass wool, 30 mm.p is the inlet pressure. ρ is the bulk density of glass wool. t^* is characteristic time.



Comparison of experimental and formula value of low temperature area on shell plate

The partial derivation of the three fitting formulas in the relevant parameters is obtained respectively. The relevant parameters in the above formula can be solved. After fitting and optimization, the final empirical formula is:

$$A' = 1.59 \times 10^{-4} \times d'^{0.87} p'^{-0.03} \rho'^{-0.526} t'^{2} + 0.766 \times d'^{1.95} p'^{1.7} \rho'^{0.769} t'$$

The R^2=0.944, indicating the formula fits the experimental data well. The formula is applicable to 0 s < t < 900 s, 2 mm < b < 6 mm, 0.02 MPa < p < 0.06 MPa and 32 kg/m3 < ρ < 80 kg/m3. These findings hold promising potential for both low prediction and assessment.

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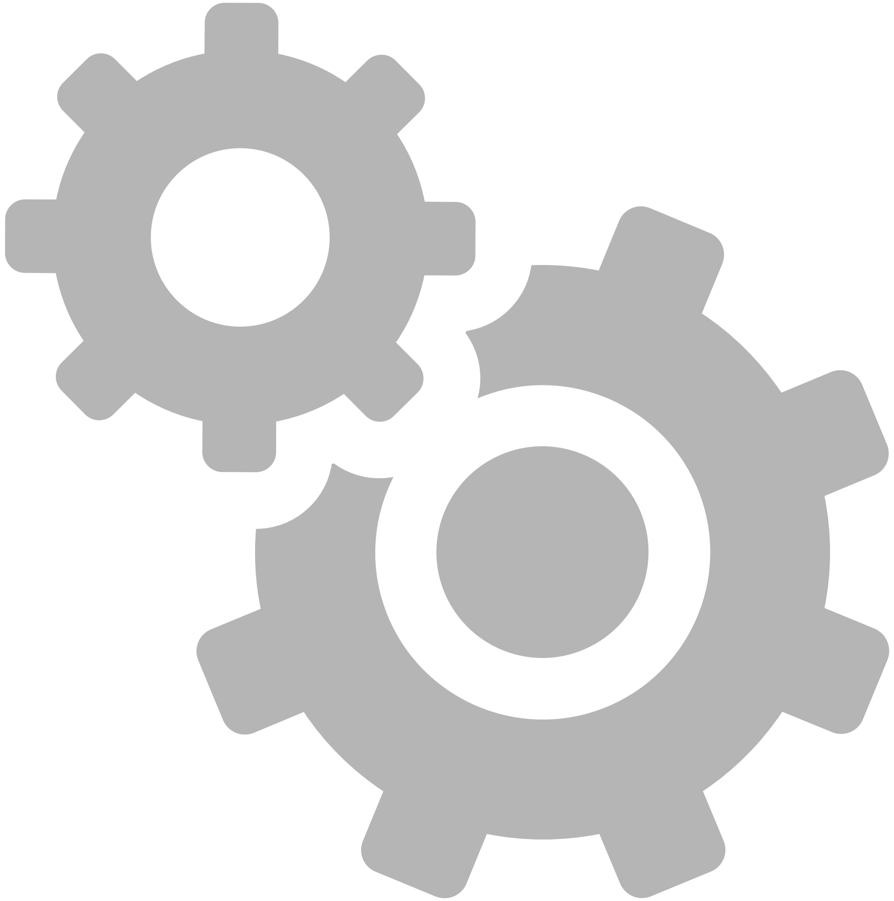

Conclusion

Conclusion

- The acceleration of flow and diffusion, as well as the rate of temperature drop, increases as the inlet diameter and pressure increase and the bulk density decreases.
- The deepening of negative pressure value is ascribed to the enlargement of inlet hole aperture, elevation in inlet pressure, and reduction in porous media density, indicating that the negative pressure is influenced by the inlet flow rate of liquid nitrogen.
- Liquid nitrogen flowed through the glass wool and came into contact with the hull plate, resulting in the temperature of the hull plate decreased below the transition temperature for toughness and brittleness. This led to the formation of low-temperature areas.
- The empirical formula summarizing the influence of inlet hole aperture, inlet pressure, bulk density of porous media, and flow time on the low-temperature area of the hull plate under experimental conditions demonstrates a strong fit with the experimental data.

Thank you!

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