Test platforms for ortho-para hydrogen conversion at cryogenic conditions

Xinyu Wei[1], Junjie Teng[1], Song Fang[1], Shaolong Zhu[1], Kai Wang[1*], Limin Qiu[1]

[1] Institute of Refrigeration and Cryogenics, Key Laboratory of Refrigeration and Cryogenic Technology of Zhejiang Province, Zhejiang University, Hangzhou 310027, China

[*]E-mail: kaiwang19@zju.edu.cn

Abstract. Large-scale, low-energy-consumption hydrogen liquefaction technologies are crucial for the widespread adoption of liquid hydrogen. However, fundamental data on continuous ortho-para hydrogen conversion at cryogenic temperatures remain limited. To address this, a series of test platforms has been established to investigate ortho-para hydrogen conversion under a wide range of cryogenic conditions, providing essential data that support the precise design of cryogenic hydrogen heat exchangers. These platforms include a small-scale catalyst sample test platform at 77 K, an intermediate-scale single-channel plate-fin heat exchanger test platform, and a large-scale prototype heat exchanger test platform. At the smallest scale, catalyst performance is measured at 77 K to obtain conversion rates and pressure drops so as to derive useful correlations. At the intermediate scale, a plate-fin heat exchanger configuration is used with a single hydrogen flow channel containing approximately 2 kg of catalyst, sandwiched between two helium coolant channels. This setup operates between 30 K and 80 K, with mass flowrates ranging from 0 g/s to 1 g/s, pressures up to 2.1 MPa, and inlet ortho-para hydrogen concentrations of 25%-50%. At the largest scale, a prototype heat exchanger operates between 80 K and 300 K, supporting mass flowrates up to 3 g/s (about 0.26 tons per day) and pressures up to 2.5 MPa. These systematic experiments provide a comprehensive dataset covering a wide range of conditions. The resulting data enable the development of accurate models and correlations for flow, heat transfer, and conversion, ultimately guiding the optimization and improved performance of cryogenic hydrogen liquefaction systems.

1. Introduction

Hydrogen is recognized as a critical energy carrier for achieving carbon neutrality, but its large-scale utilization requires efficient liquefaction technologies. A key challenge lies in managing the ortho-para hydrogen (o-p H_2) conversion, an exothermic spin isomerization process that releases substantial heat (e.g., ~527 kJ/kg at 20 K) [1]. At ambient temperatures, hydrogen exists as a 75%:25% equilibrium mixture of ortho- and para-hydrogen ("normal hydrogen"). When cooled to 80 K, the equilibrium para-hydrogen concentration increases to 50%, eventually exceeding 95% near liquid hydrogen temperatures (20-30 K) [2]. However, uncontrolled o-p H_2 conversion during liquefaction causes delayed heat release, leading to boil-off losses and

Content from this work may be used under the terms of the Creative Commons Attribution 4.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

reduced energy efficiency [3]. Therefore, catalytic acceleration of this conversion process must be thermally integrated with refrigeration cycles in industrial systems.

While catalytic o-p H_2 conversion under constant temperatures (e.g., fixed-bed reactors) has been extensively studied [4], practical liquefaction requires continuous conversion within cryogenic heat exchangers. In this design, catalysts are filled in heat exchangers where conversion heat is immediately removed by coolant flow [5]. This approach eliminates two major limitations: 1) excessive cooling demands from temperature rise in adiabatic systems, and 2) high energy costs of maintaining constant temperatures in isothermal systems. As a result, the continuous conversion process demonstrates 21.8% and 28.7% lower energy consumption than adiabatic and isothermal methods, respectively [6]. Nevertheless, the complex interactions between heat transfer, fluid flow, and catalytic reactions under thermal gradients are fundamentally different from isothermal conditions [7]. Existing correlations derived from isothermal experiments may overestimate conversion efficiency by neglecting these coupled effects, resulting in suboptimal heat exchanger designs.

To address these limitations, a three-stage experimental methodology is developed (Figure 1), systematically progressing from catalyst testing to industrial validation:

1. Cryogenic o-p catalyst testing platform:

While conversion performance under flow conditions is well-studied using small catalyst samples, the corresponding hydraulic impact (e.g., pressure drop) remains poorly characterized. This platform quantifies both flow-dependent conversion and these hydraulic effects within simulated packed-bed heat exchanger environments.

2. Single-layer heat exchanger platform:

Building on catalyst data, this stage investigates the interplay between heat transfer, flow resistance, and catalytic conversion - three coupled factors determining system efficiency. Controlled non-isothermal conditions enable systematic separation of these effects for mechanism understanding.

3. Full-scale prototype platform:

In the final verification phase, the platform simulated the continuous conversion heat exchanger within the industrial precooling system. Its geometrically representative design and operational conditions directly address the scaling challenges encountered in extrapolating laboratory data to real-world hydrogen liquefaction plants.

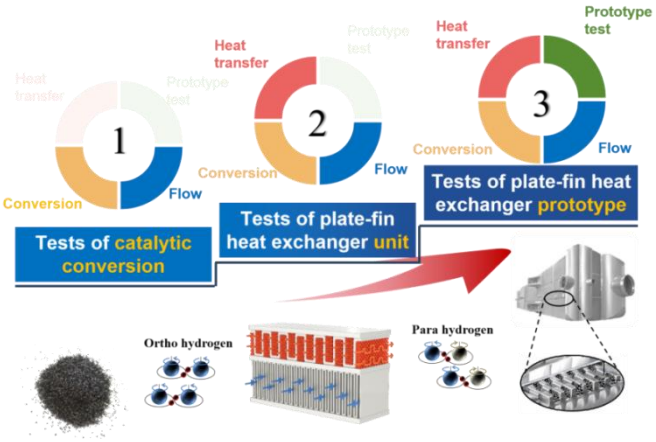

Figure 1. Three-stage experimental methodology for continuous ortho-para hydrogen conversion research

This tiered methodology—from fundamental flow-catalysis interactions in Stage I (where heat transfer is minimized in catalyst-only tests), to coupled thermo-fluidic mechanisms in Stage II (with controlled non-isothermal conditions to separate effects), and finally to industrial prototype validation in Stage III (full coupling)—allows systematic decoupling. Stage I isolates hydraulic and catalytic parameters, Stage II adds heat transfer for pairwise interaction studies, and Stage III integrates all aspects for scaling validation. The resulting database not only rectifies the over-simplifications inherent in isothermal models but also provides first-principle guidelines for optimizing cryogenic heat exchangers, a critical step toward achieving <10 kWh/kg energy efficiency targets in hydrogen liquefaction.

2. Three-stage experimental platform system

To systematically investigate the continuous-flow cryogenic ortho-para hydrogen conversion mechanism, three progressive experimental platforms were developed. These include: 1) a catalyst performance characterization system, 2) a thermal coupling verification unit for heat exchangers, and 3) an industrial-scale heat exchanger prototype testing facility. This progressive research strategy effectively bridges the gap between catalyst performance and macroscopic system behaviors. The approach enables decoupling of flow-heat transfer-catalysis interactions, thereby providing multi-scale data support for hydrogen liquefaction system optimization.

2.1 Stage I: Cryogenic o-p catalyst testing platform

Figure 2 illustrates the schematic of experimental setup for the cryogenic o-p catalyst testing platform, and the photo is shown in Figure 3. Before introducing hydrogen gas, the system is purged with nitrogen to prevent contact with air. Hydrogen gas is then introduced and its initial para hydrogen concentration is measured as follows:

A. Hydrogen gas pressure is reduced to 2 MPa via a pressure reducing valve.
B. Valve (3) is opened, further reducing pressure to atmospheric pressure before entering the chromatographic device to record the initial para hydrogen peak.
C. Valve (3) is closed to begin the experiment.

Hydrogen flow is controlled using a mass flow meter and controller to regulate the Reynolds number. Temperature and pressure readings are taken once flow stabilizes. Post-reaction, the gas is reheated and analyzed in the chromatograph, with excess gas discharged through a back-pressure valve.

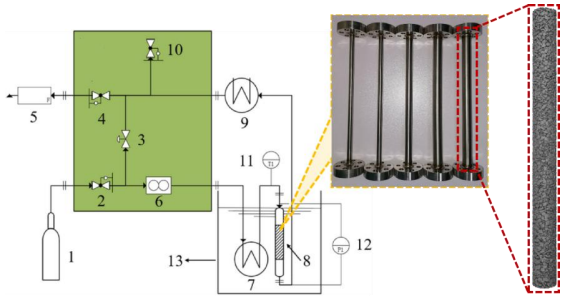

Figure 2. Schematic of experimental setup: 1-hydrogen gas cylinder, 2-pressure reducing valve, 3-by-pass valve, 4-pressure reducing valve, 5-chromatograph, 6-mass flow meter and controller, 7-precooling coil, 8-test section of ortho-para hydrogen catalytic convertor, 9-reheating coil, 10-back-pressure valve, 11-PT100 temperature sensor, 12-differential pressure transmitter, 13-liquid nitrogen container.

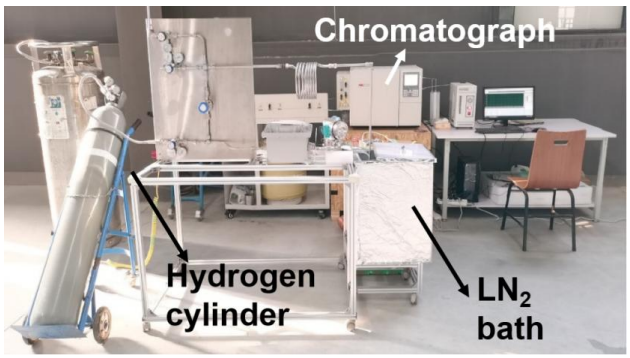

Figure 3. Photo of experimental setup.

The experimental conditions of the cryogenic ortho-para hydrogen conversion catalyst testing platform are shown in Table 1.

Table 1. Testing conditions and instrumentation specifications

Parameter	Range	Measurement Accuracy
Temperature	77 K	± (0.15 + 0.002 |t|)
Mass flowrate	0-0.09 g/s	±1% FS
Pressure	0.1-2.5 MPa	±1.6%
Pressure drop	0-80 kPa	±0.065%

* Additional technical details of the experimental setup are provided in the published literature [8].

Developing the relationship between the outlet para hydrogen concentration and mass velocity of the converters of significant importance for converter design. Based on the experimental data, a plot illustrating the relationship between the outlet para hydrogen concentration and the mass velocity of the converter is depicted in Figure 4.

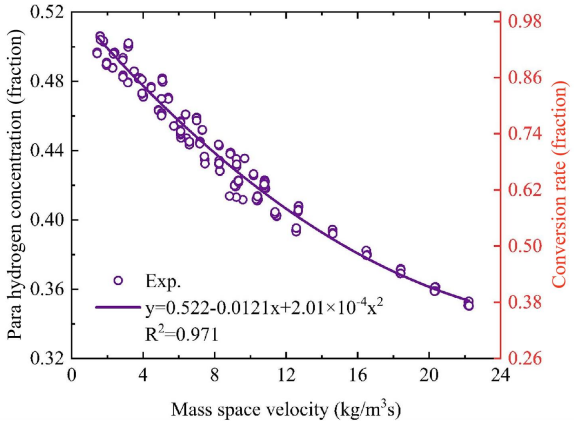

Figure 4. Para hydrogen concentration at the outlet of the test section as a function of space velocity [8]

Using experimental data for 40-60 mesh Fe_2O_3 catalyst particles, this study modifies the viscosity and inertia coefficients in the Ergun equation. The friction coefficient f is defined as:

$$f = \frac{\Delta p d_e}{Lu^2 \rho} = \frac{92}{\mathrm{Re_p}} \frac{(1-\varepsilon)^2}{\varepsilon^3} + 3.3 \frac{1-\varepsilon}{\varepsilon^3}$$

For other catalyst particle sizes, refer to established correlations in published literature [8].

2.2 Stage II: Single-layer plate-fin heat exchanger (PFHX) testing platform

The cryogenic testing platform for evaluating single-layer plate-fin heat exchangers comprises three subsystems: a helium circulation loop, a hydrogen supply system, and a test Dewar, as shown in Figure 5. The helium loop integrates liquid nitrogen precooling and three single-stage GM cryocoolers to achieve precise temperature control. The hydrogen subsystem adjusts the inlet hydrogen temperature (40-80 K) and para-hydrogen concentration (25%-50%) via bypass flow ratio control and a precooling/pre-conversion unit.

The test Dewar integrates key components including a precooler, regenerators, and the tested single-channel PFHX unit as shown in Figure 6, enabling coupled thermal-hydraulic and ortho-para conversion performance evaluation under cryogenic conditions. A modular design employing VCR quick-disconnect fittings enables rapid replacement of PFHX units, while integrated safety systems ensure hydrogen leak detection and explosion prevention.

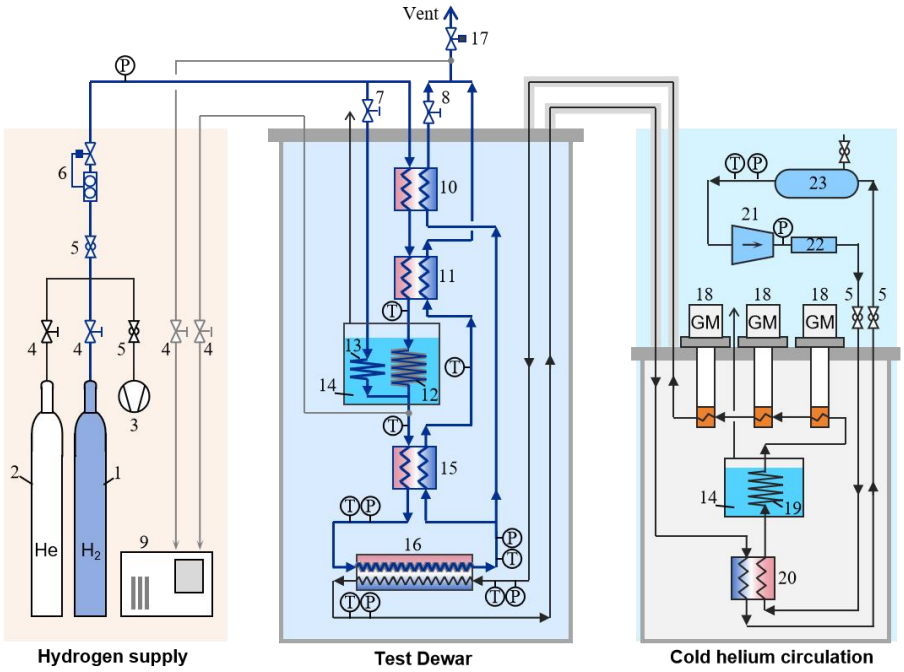

Figure 5. Process diagram of the experimental platform for performance evaluation of cryogenic hydrogen PFHX: 1-Hydrogen vessels, 2-Helium vessels, 3-Vacuum pump, 4-Pressure reducing valve, 5-Global valve, 6-Flowrate controller, 7-Composition adjusting valve, 8-Temperature adjusting valve, 9-Gas chromatograph, 10-Re-warmer, 11-First regenerator, 12-H precooler pre-convertor, 13-Bypass H2 precooler 14-LN2 bath 15-Second regenerator 16-Tested CPFHX unit, 17-Back-pressure valve, 18-G-M cryocooler, 19-He precooler, 20-Helium regenerator, 21-Compressor, 22-Buffer tank, 23-Helium storage tank. [9]

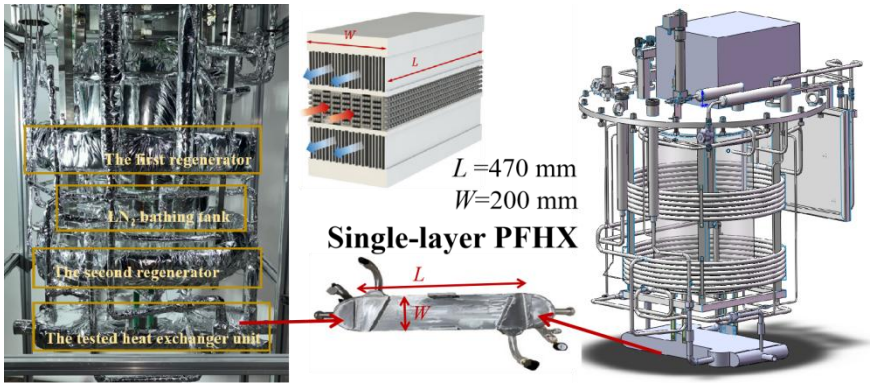

Figure 6. Internal structure of the test Dewar, tested PFHX unit, and catalyst-filled channels.

The platform covers typical operational parameters of hydrogen liquefaction processes, with detailed test ranges and measurement accuracies summarized in Table 2.

Table 2. Testing conditions and instrumentation specifications

Parameter	Range	Measurement Accuracy
Inlet temperature	40-80 K	± (0.1 + 0.002 |t|)
Mass flowrate	0-1 g/s	±0.5% FS
Inlet pressure	0.1-2.1 MPa	±0.04% FS
Pressure drop	0-80 kPa	±0.065%
Inlet concentration of para-hydrogen	25%-50%	±3%

* Additional technical details of the experimental setup are provided in the published literature [9].

2.3 Stage III: Industrial-scale PFHX validation platform

The industrial-scale validation platform is specifically designed to study continuous ortho-para hydrogen conversion during the liquid nitrogen precooling stage of hydrogen liquefaction plants. As illustrated in Figure 7, the system integrates a hydrogen precooling module using liquid nitrogen baths, a catalytic PFHX test module housed in a vacuum-insulated Dewar, and a helium refrigeration loop for thermal management. Figure 8 details the PFHX prototype with alternating hydrogen and helium channels.

Temperature regulation is achieved through bypass valves that adjust mixing ratios between precooled main streams (77 K via liquid nitrogen heat exchangers) and warm bypass streams. Pressure control is maintained by upstream reducing valves and downstream back-pressure regulators. Mass flow rates are precisely managed using calibrated mass flow controllers at critical junctions.

This configuration replicates the thermal conditions of industrial liquefaction processes, where precooled hydrogen (80-160 K) undergoes continuous catalytic conversion while rejecting heat to helium coolant streams.

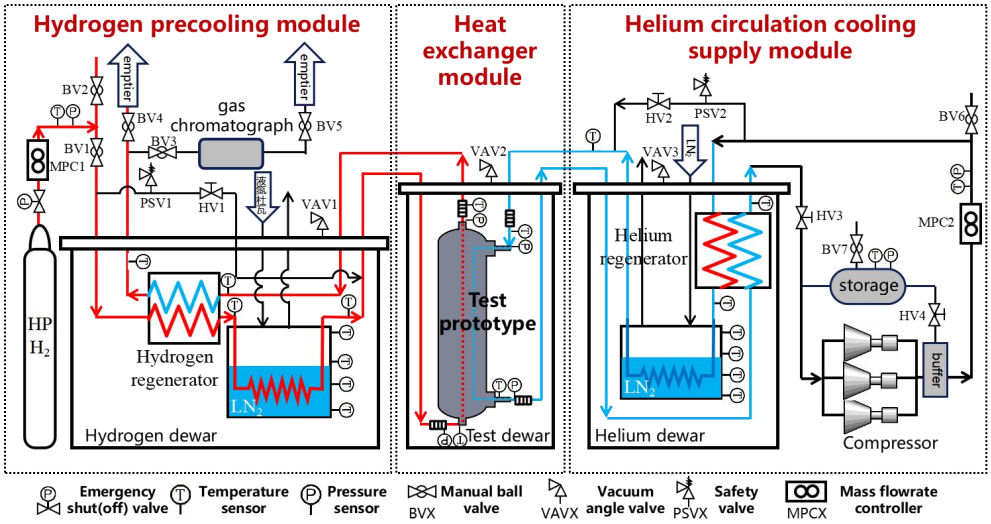

Figure 7. Process flow diagram of the industrial-scale validation platform.

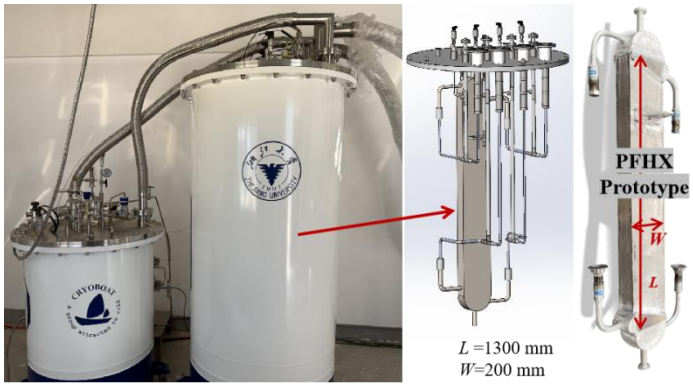

Figure 8. Internal structure of the test Dewar and PFHX prototype

The platform covers operational parameters typical of liquid nitrogen precooling stage of hydrogen liquefaction processes, with detailed test ranges and measurement accuracies summarized in Table 3.

Table 3. Testing conditions and instrumentation specifications for the industrial-scale platform

Parameter	Range	Measurement Accuracy
Inlet temperature	80-160 K	± (0.1 + 0.002 |t|)
Mass flowrate	0-3 g/s (~0.26 tons per day)	±0.5% FS
Inlet pressure	0.1-2.5 MPa	±0.04% FS
Pressure drop	0-100 kPa	±0.065%

3. Conclusion and future work

A systematic three-stage experimental methodology is developed to address the critical lack of fundamental data for continuous ortho-para hydrogen conversion under cryogenic conditions relevant to hydrogen liquefaction. These systematic experiments provide a comprehensive dataset covering a wide range of conditions. This systematic approach enables the development of validated correlations that can effectively guide the optimization of cryogenic hydrogen liquefaction systems, ultimately enhancing their thermodynamic efficiency and operational performance.

Based on the established platforms and initial findings, future research efforts will focus on the following areas:

A. **Expanded Test Range:** Experiments will be extended to lower temperature ranges (particularly below 30 K) representative of the final liquefaction stages, where equilibrium para-hydrogen concentrations exceed 95% and heat release is most significant.
B. **Advanced Catalyst:** The performance and long-term stability of novel or optimized catalyst materials and configurations (e.g., different geometries, loading densities) within the PFHX channels will be evaluated across all three platforms.
C. **Multi-Channel & Full PFHX Core Testing:** The methodology will be scaled from single-channel studies (Stage II) to testing multi-channel configurations and eventually full prototype PFHX cores within the Stage III platform, investigating flow distribution and thermal integration complexities.
D. **Model Validation and Refinement:** The extensive experimental data generated will be used to rigorously validate and refine multi-physics models coupling reaction kinetics, fluid dynamics, and heat transfer. Emphasis will be placed on accurately capturing non-isothermal effects neglected in simpler models.
E. **Dynamic Performance & Control:** The response of the continuous conversion process within the heat exchanger to transient conditions, such as flow or temperature fluctuations typical in liquefaction plants, will be investigated to inform control strategies.
F. **System Integration Studies:** The validated models and design rules derived from these platforms will be applied to optimize the thermal integration of the catalytic conversion process within complete hydrogen liquefaction cycles, assessing the overall impact on energy efficiency.

Acknowledgments

This work was financially supported by the National Key Research and Development Program of China (No. 2021YFB4000700).

References

[1] Zhang T, Uratani J, Huang Y, Xu L, Griffiths S and Ding Y 2023 *Renew. Sustain. Energy Rev.* **176** 113204
[2] Wei X, Fang S, Teng J, Zheng J, Zhu S, Wang K, Zhi X, Bao S and Qiu L 2025 *Int. J. Hydrog. Energy* **109** 67–80
[3] Al Ghafri S ZS, *et al* 2022 *Energy Environ. Sci.* **15** 2690–731
[4] Jiao F, Ghafri S A, O'Neill K T, Stanwix P S, Sellner G M, Fridjonsson E O, Robinson N, May E F and Johns M L 2024 *React. Chem. Eng.* **9** 2846–62
[5] Teng J, Zhu S, Wei X, Qi Y, Zhi X, Bao S, Qiu L and Wang K 2024 *Int. J. Heat Mass Transf.* **218** 124761
[6] Teng J, Wang K, Zhu S, Bao S, Zhi X, Zhang X and Qiu L 2023 *Energy* **271** 127016
[7] Wei X, Teng J, Fang S, Zhu S, Wang K, Zhi X, Bao S and Qiu L 2024 *Int. J. Hydrog. Energy* **91** 1058–69
[8] Wang K, Xu S, Zheng J, Zhu S, Fang S, Xiao H, Li N and Qiu L 2025 Cryogenics **147** 104041
[9] Wang K, Teng J, Wei X, Zhu S, Fang S and Qiu L 2024 Int. J. Hydrog. Energy **110** 814–25