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Cryogenic Techniques in Hydrogen Energy Application

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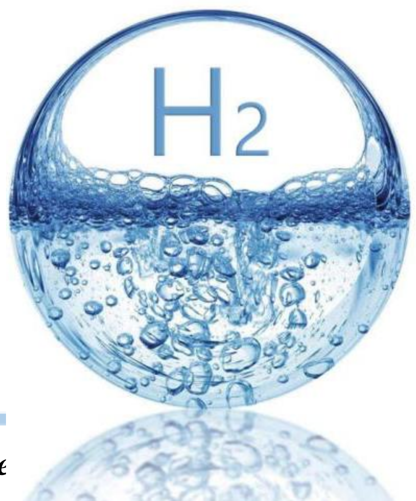
01 Hydrogen Characteristics and Situation

Characteristics

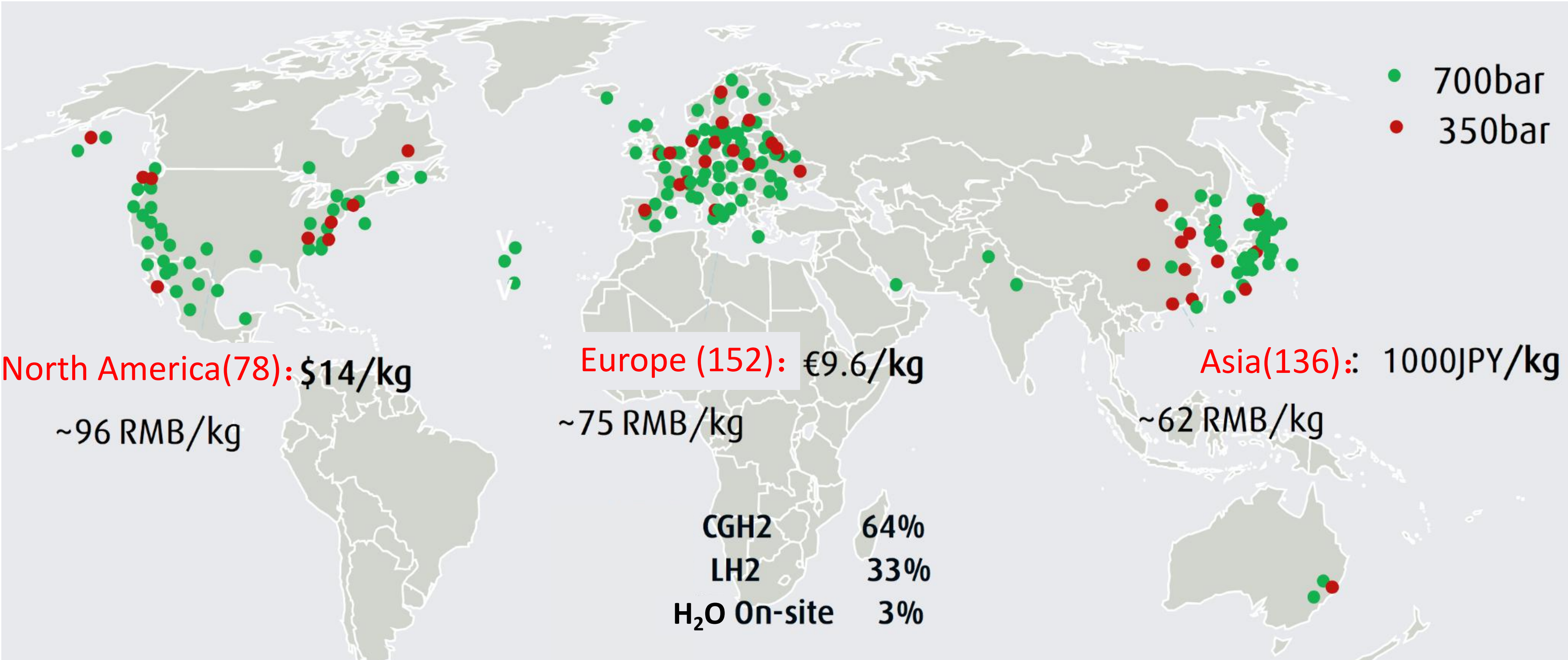
- The first element in periodic table of the elements
- The lightest and the most widespread element
- Mainly exists in the form of compound: H_2O, CH_4, NH_3

Fuel	Energy density (kJ/g)	Energy conversion (kWh/kg)
Coal	33	8
Oil	48	9
Natural gas	56	10
H_2	**142**	**39**

- Environmentally friendly
- Non-toxic, Pollution-free
- Higher energy density
- Higher producing cost



Current situation



2018: 369 hydrogen refueling stations around the world

Production capacity: uneven, limited

Price: higher than traditional energies

China 2050: H_2 energy will occupy 10% of all energy demands

Current situation

Trend: Great demand and expection

Restraint: H2 Production Cost, FC Techniques

High cost of H_2 energy
- Production
- Storage
- Transportation

Mutual restriction

Limited applications

Immature technology
- Fuel cell electric vehicles (FCEVs)
- Industries
- Power fuel

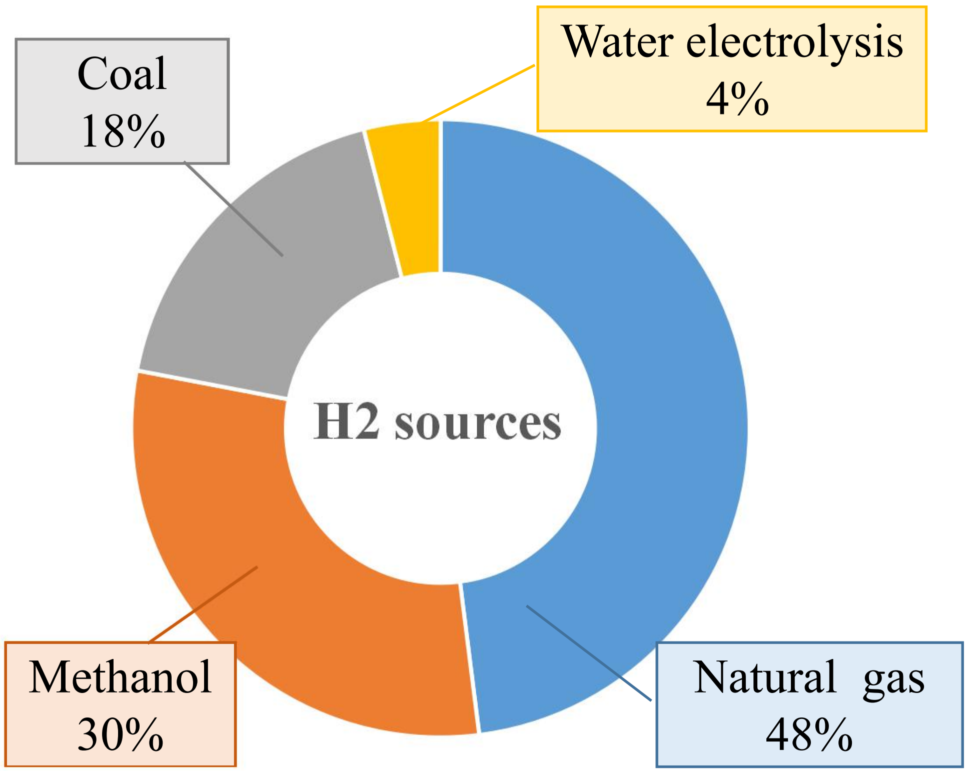
Increasing demands to reduce price

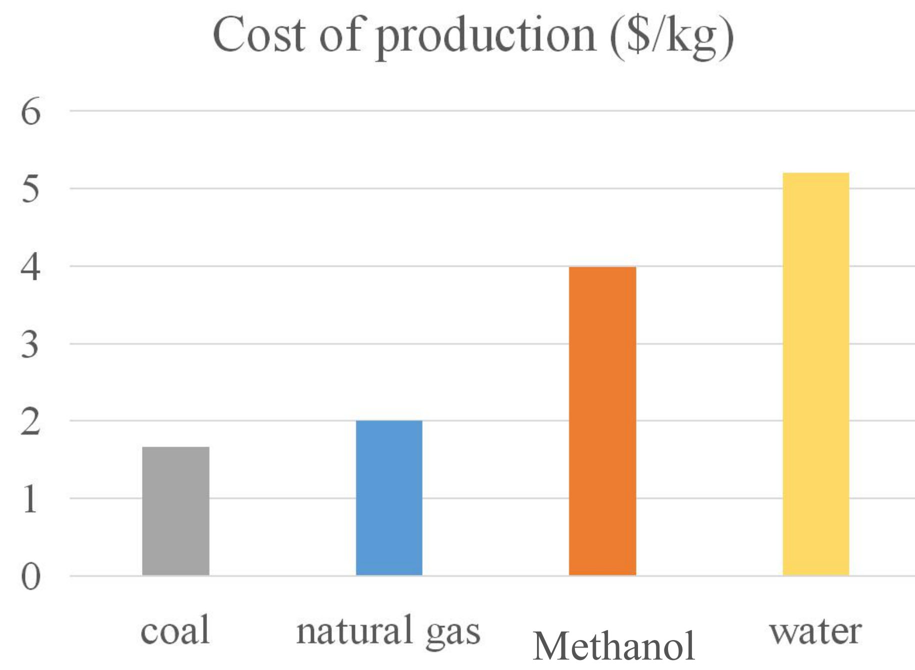
Lower price to promote popularization and application

Hydrogen Production, Transportation and Application

02

Production



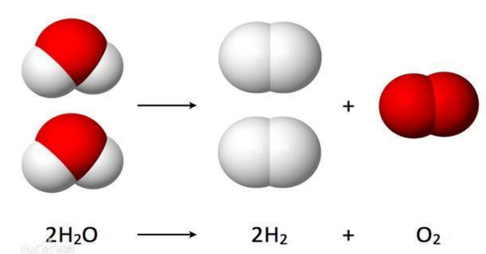


Current：thermochemical reforming of traditionnal fuels

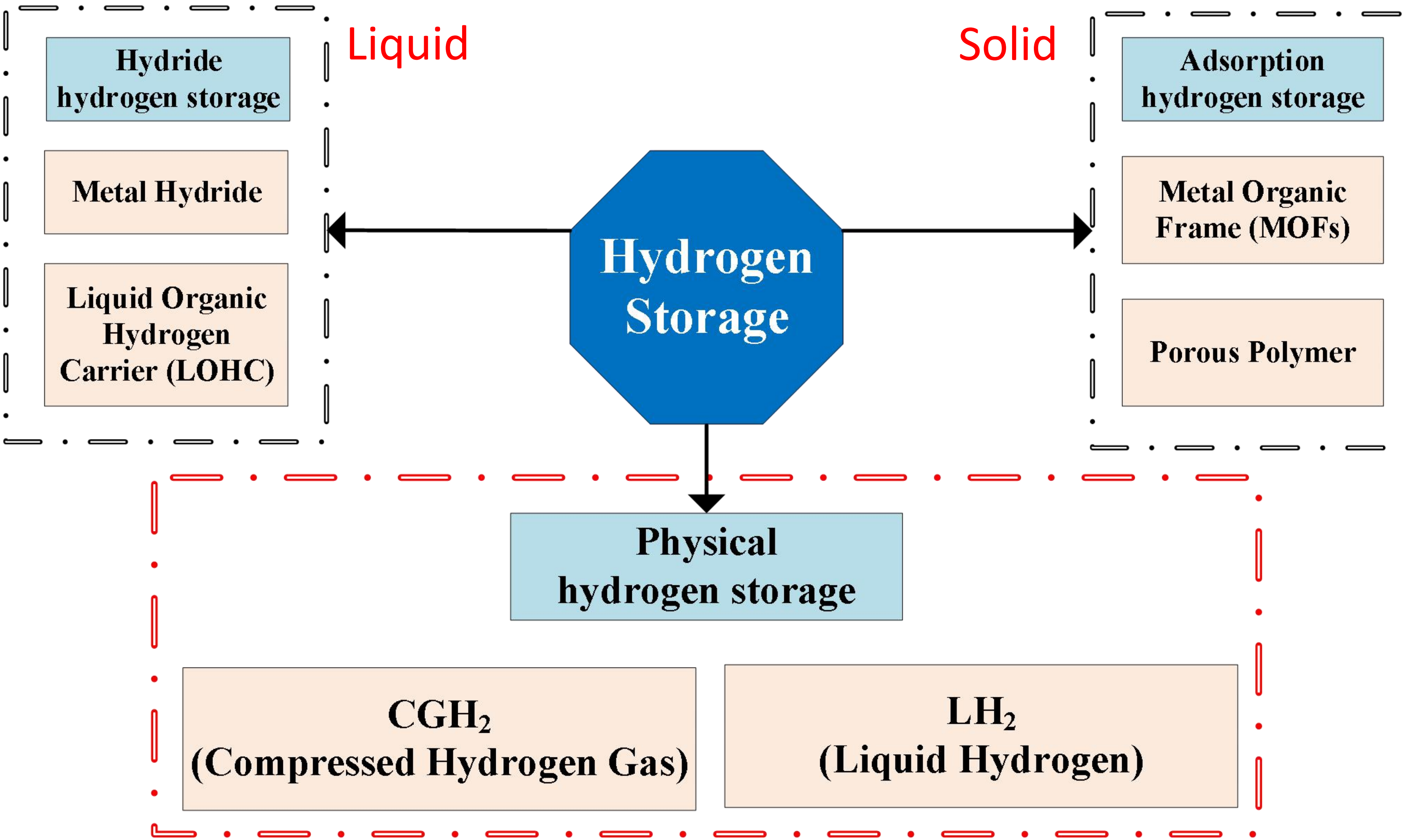
Future：produced by renewable resource

water electrolysis

biomass and biogas



Storage and transport



Storage and transport

pipeline	gas cylinder trailer	tank trailer	ship

CGH_2

Pressure container
Compression power

Problems

LH_2

Liquefaction cost
Insulation technique

Pressure	35 MPa	70 MPa	14.6 MPa	3.2 MPa	0.1 MPa	1 MPa
Temperature	20℃	20℃	80 K	40 K	20 K	20 K
Density kg/m3	23.7	39.7	39.7	39.7	71.3	72.4

Current： GH_2 is the main pathway considering the cost and techniques

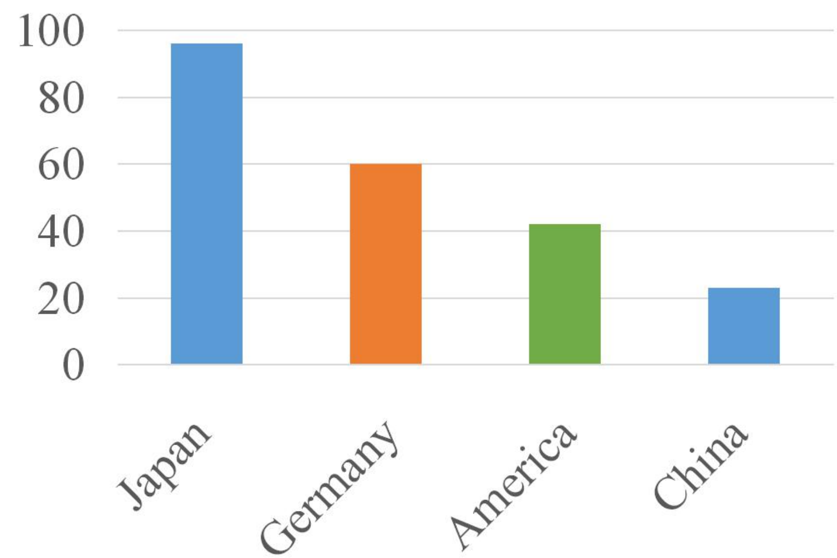
Future： LH_2 is the ideal way for large-scale transportation of hydrogen energy

Storage and transport

Japan：2014 stated a strategy named "Hydrogen Society" (2050)

- Output of GH_2 >0.6 billion m^3 in 2025
- Reduce GH_2 price to 1/5 in 2050 compared with 2017
- Promote H_2 energy to become one of the three pillars of secondary energy with electricity and heat, applied in transportation, building, power, et. al

LH_2 is the best solution for:
production of ultra purity hydrogen (6N)
storage
ocean transportation
medium & long distance land transport
commercial hydrogen stations



2018: Amount of hydrogen refueling stations

2018: Japan has the highest number of hydrogen refueling stations, ~50% are LH_2 stations

Storage and transport

Zero Carbon Hydrogen Chain

Norway

wind→ electricity→ H_2

LH_2: 150 t/d

Australia

Lignite+CCS→H_2

LH_2: 770 t/d

other countries

LH_2 ships

170 t-2500 m³

LH_2 ships (2030)

11000 t-160000 m³

Gas turbine Generator

Fuel cell Vehicle

Overseas: green production

LH_2 Transport & Storage

Japan Applications

Applications

- Liquid propellants: LH_2 +LOX

  widely used in the new generation rockets

  - Highest specific impulse (457 s)
  - Nontoxicity
  - …

Low temperature (Thermal control problems)

Low boiling point (Storage problems)

USA: Delta

SpaceX: Falcon heavy

ULA: Ariane

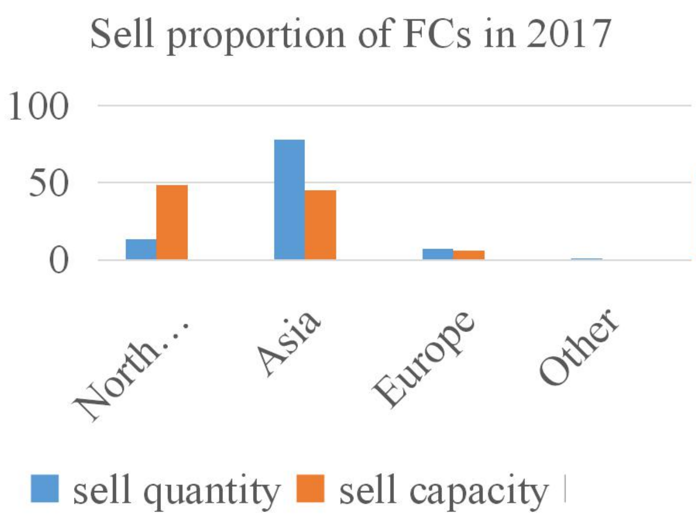
China: CZ

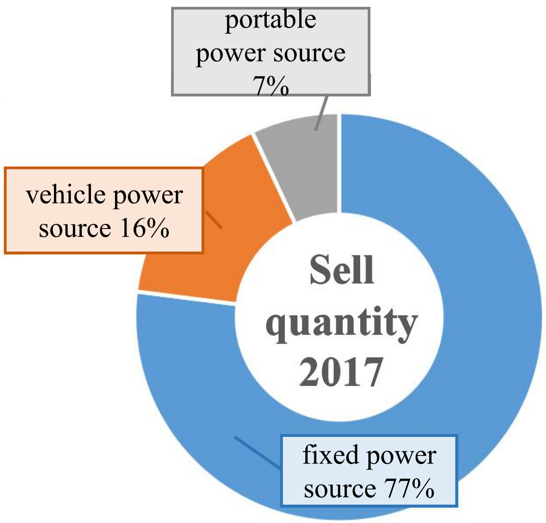
Russia: Angara

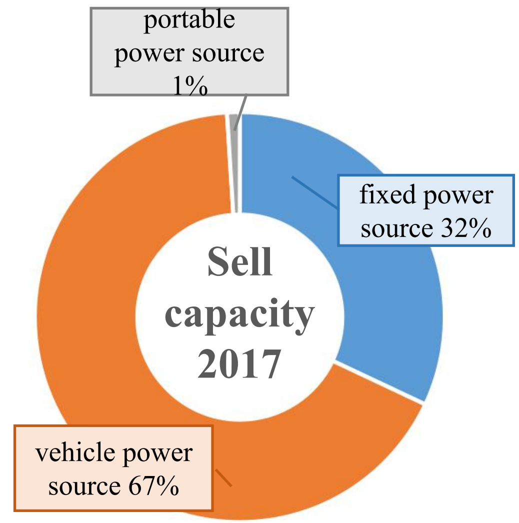
Applications

Hydrogen-Oxygen Fuel Cell

- Fuel cell electric vehicles (FCEVs), bus, ship, airplane
- Power sources
- …







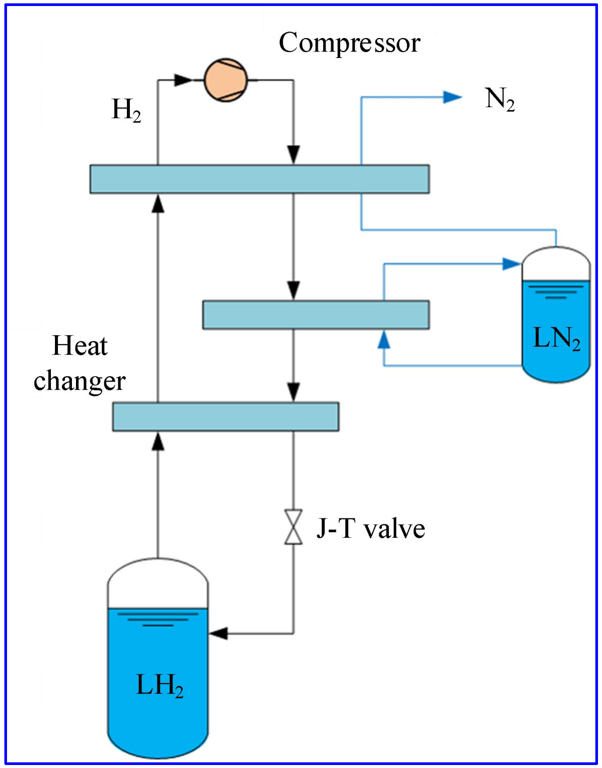
Asia is a main market for FCs

The energy capacity of FC was mainly used by FCEVs

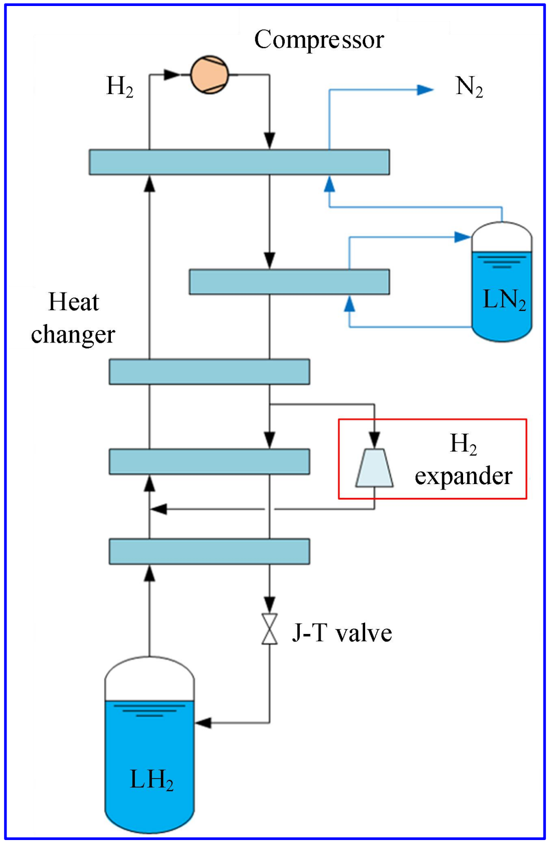
Cryogenic Techniques in Application

03

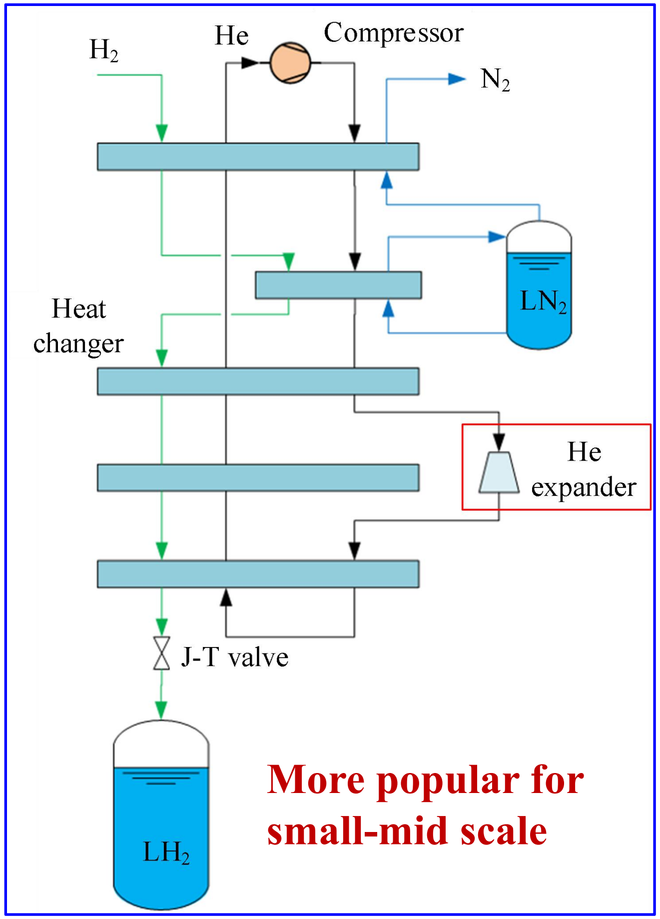
Hydrogen liquefaction



Precooled Linde-Hampson system for hydrogen



Precooled Claude system for hydrogen



He-refrigerated hydrogen-liquefaction system

Advantages of Liquid Hydrogen

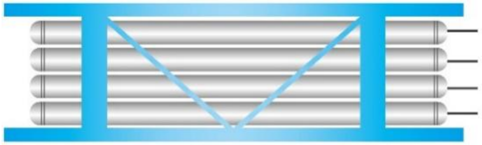
□ Comparison of two storage and transportation modes

Transportation

GH2 Trailer

LH2 trailer

Storage



GH2

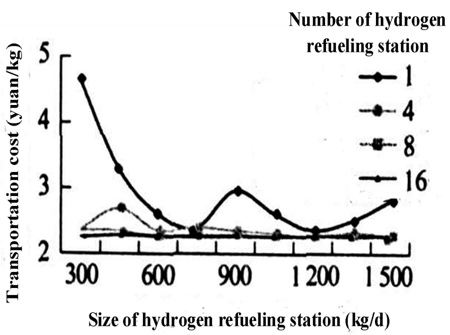
LH2 tank

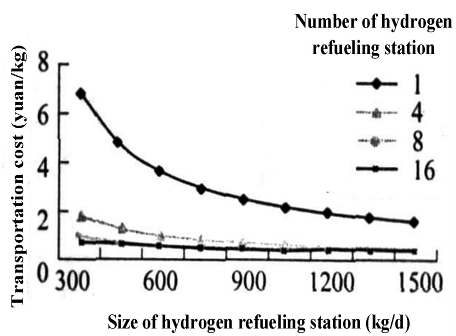
Loading capacity	350kg	3000kg
Loading time	4~8h	30~60min
Unloading time	4~8h	30~60min
Residual volume	5%~30%	<3%

Amount of storage	350~700kg	400~20000kg
Pressure	20~35MPa	0.03~0.13MPa
Occupying space	60~80m²	15~30m²

Advantages of Liquid Hydrogen

☐ Comparison of Hydrogen Liquefaction Cost and Transportation Cost



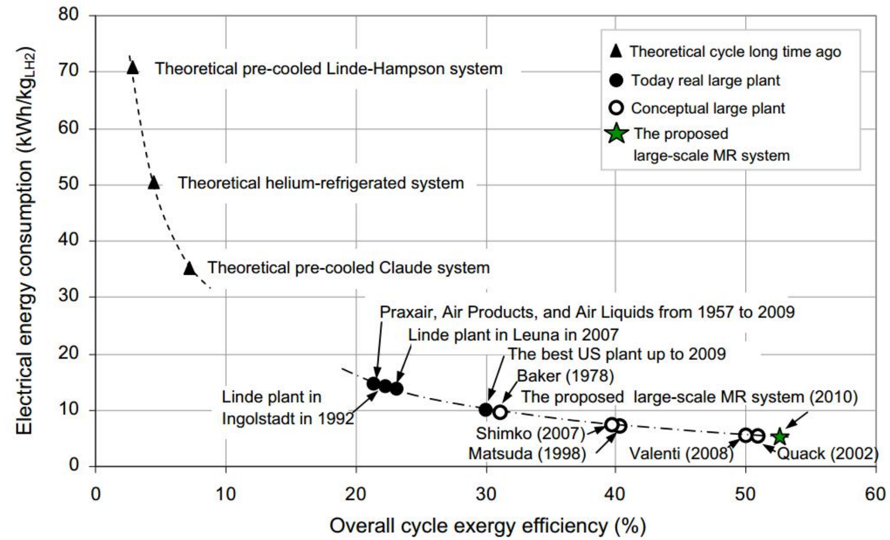


GH2 Trailer **LH2 trailer**

Transportation Cost

2.3 Yuan **0.8 Yuan**

RMB/kg



Liquefaction Cost

H2 liquefaction： **12.5~15 kWh/kg LH_2**

Future： **4~5.35 kWh/kg LH_2**

H2 production： **1 kWh/Nm^3 H_2**

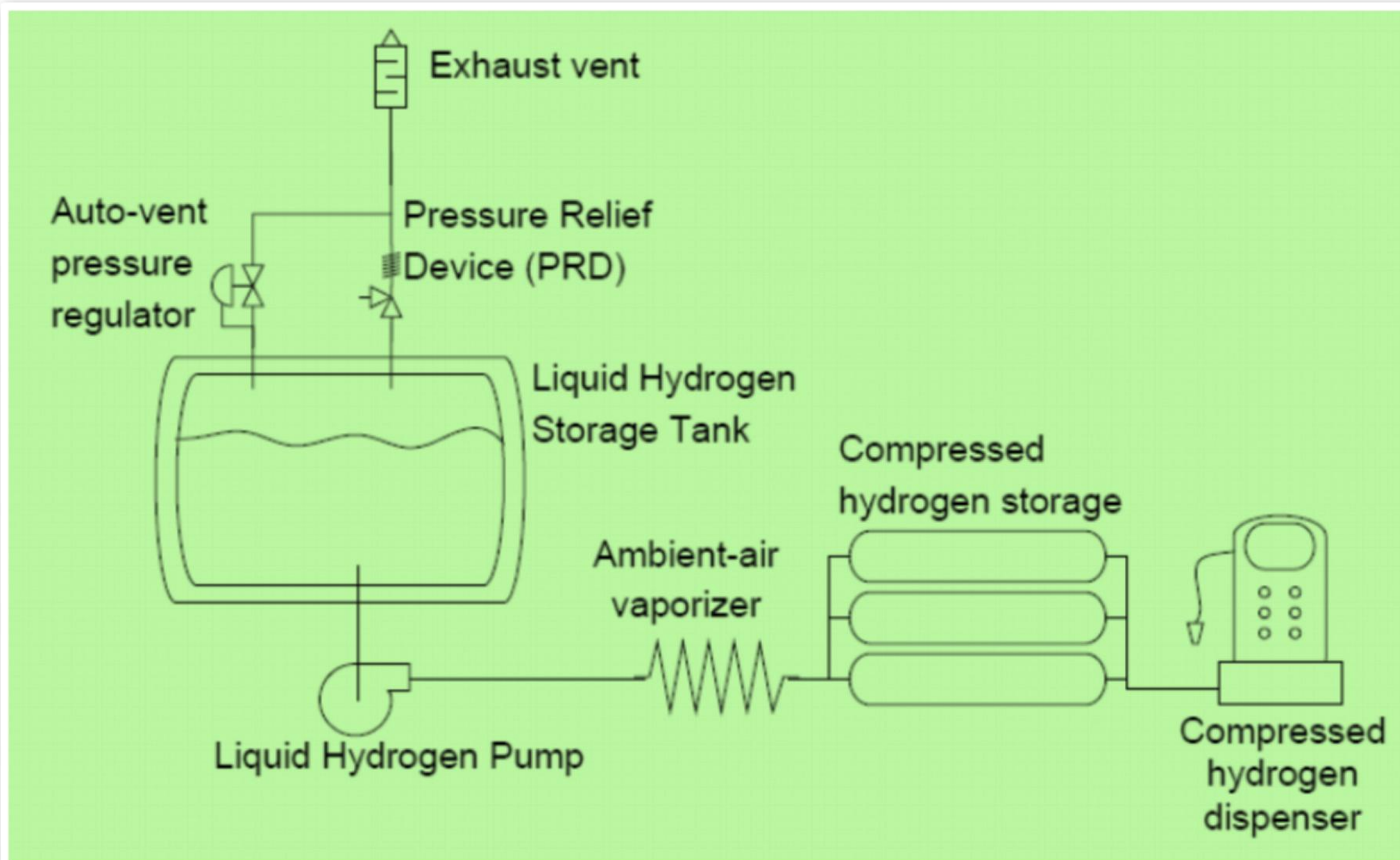
Future： **0.5 kWh/Nm^3 H_2**

Advantages of Liquid Hydrogen

- ✓ Density of the liquid hydrogen is the largest,
- ✓ Convenient for long-distance transportation,
- ✓ Liquid hydrogen pipeline, large liquid hydrogen ship and liquid hydrogen tanker.

Liquid hydrogen is a best choice in the face of greater hydrogenation demand in the future.

Liquid Hydrogen Fueling Station

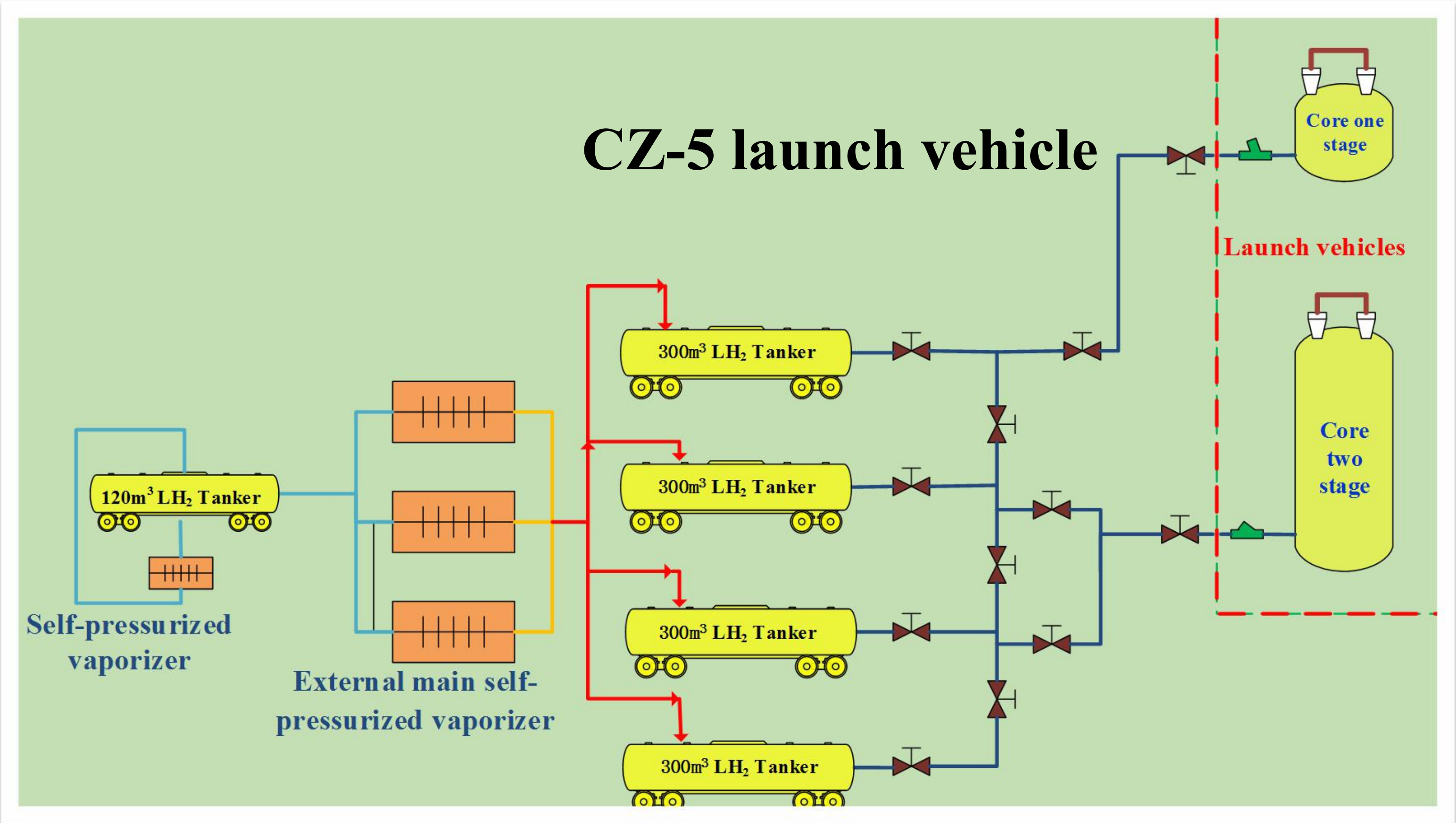


A configuration of a hydrogen station with liquid hydrogen delivery

LH2 → CGH2

Liquid Hydrogen Filling System

- Launching Site technology： Self-pressurized transportation of LH_2



Liquid hydrogen filling system of launching site

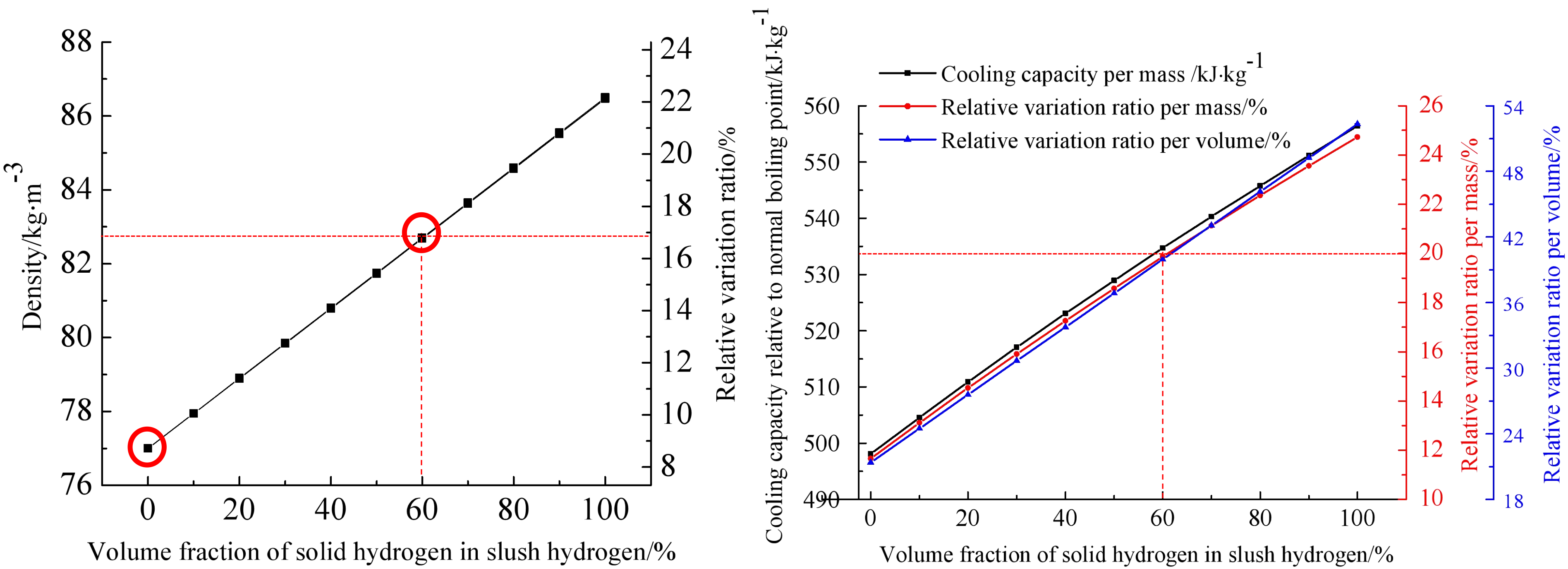
LH2 →GH2 → LH2

Subcooled and Slush Liquid Hydrogen

- **Subcooled LH2 and slush LH2 are the better choice for transportation**

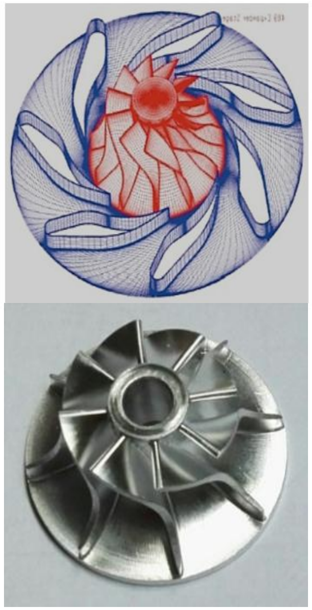
  boiling point (20.39 K), triple point (13.8 K) and slush with 60% solid fractions

- **Density increased by 8.8% and 16.8%, respectively.**



Physical properties of slush hydrogen

Key Technologies of Hydrogen Liquefaction

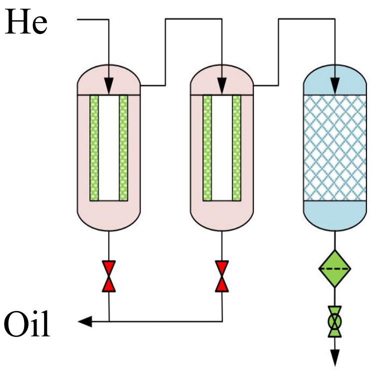


Turbine expander

Gas bearing，0.2 million r/min
Efficiency >70%
Continuous operation 8000 h

Cryogenic control valve

Outer leakage rate<5×10^{-8}Pa·m³/s
Inner leakage rate<1×10^{-9}Pa·m³/s
Leakage heat<2W@4.5K

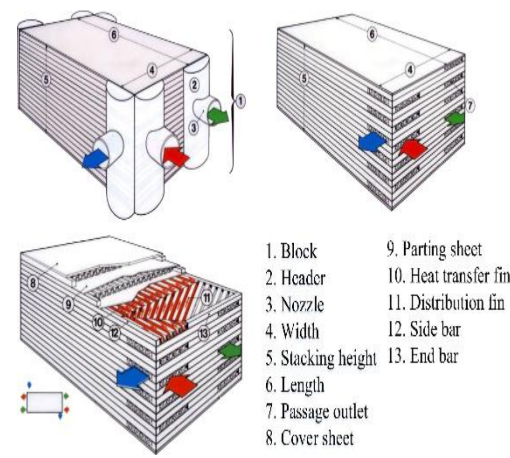


Compress and oil filtration system

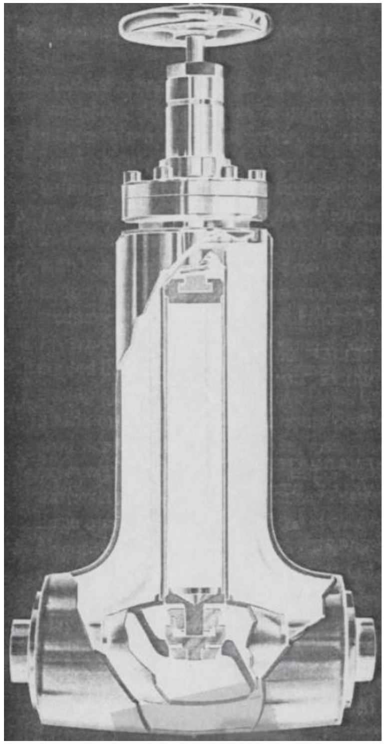
Oil content at outlet<10ppb

Cryogenic heat exchanger

Outer leakage rate <5×10^{-8}Pa·m³/s
Inner leakage rate <1×10^{-9}Pa·m³/s



Liquid Hydrogen Key Equipment



Typical vacuum-jacketed valve

Hydrogen compressor
22 000 rpm

In-line hydrogen pump
60,000 rpm

Unique performance of Liquid Hydrogen

04

Unique performance of Liquid Hydrogen

Typical properties

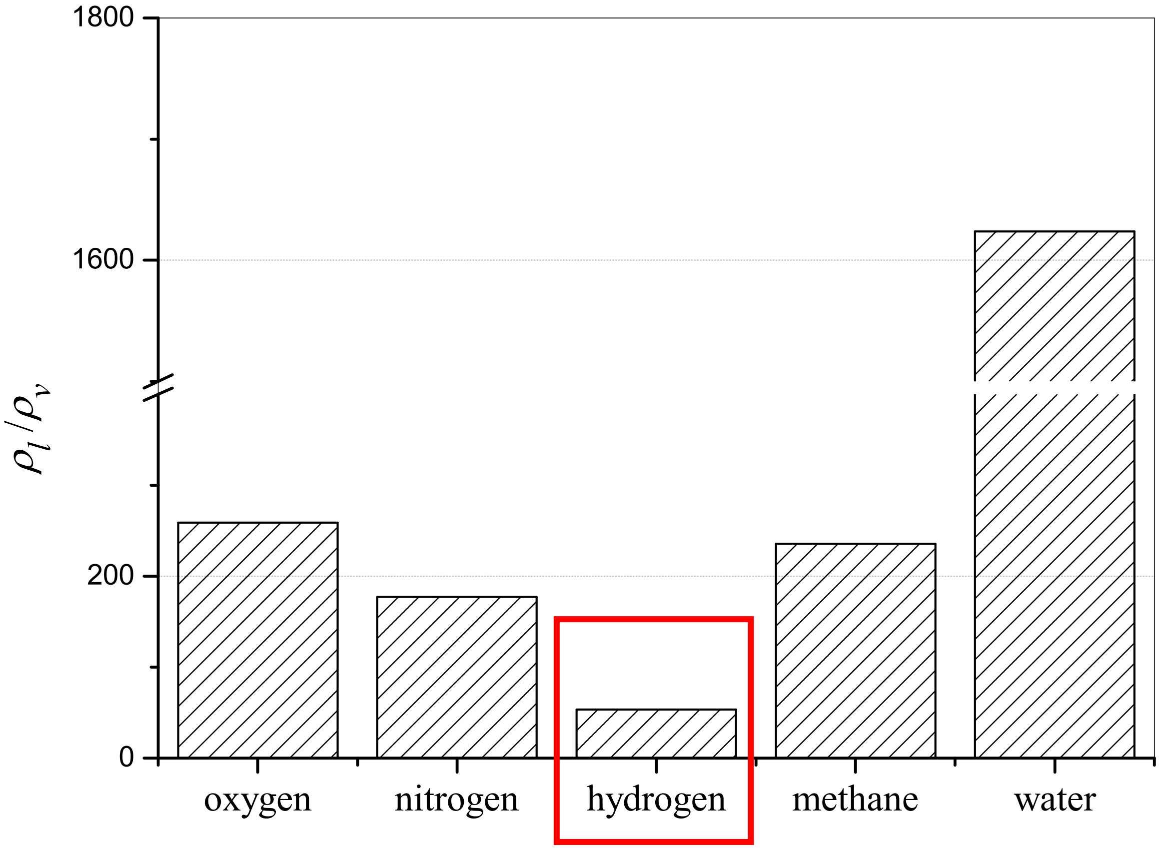
- The lightest substance in nature, 1/14 as dense as air;
- Low Temperature: Boiling point of 20.23K, Triple point 13.8K;
- Diffuse easily with the smallest mass and highest moving speed, about four times as much as air;
- Permeable: almost all substances contain hydrogen

- High: specific heat and volume expansion coefficient;
- Small: dynamic viscosity and thermal conductivity;
- Low: surface tension, small contact angle with solid.

Great attention to its thermodynamic and transport properties

Unique performance of Liquid Hydrogen

Density ratio

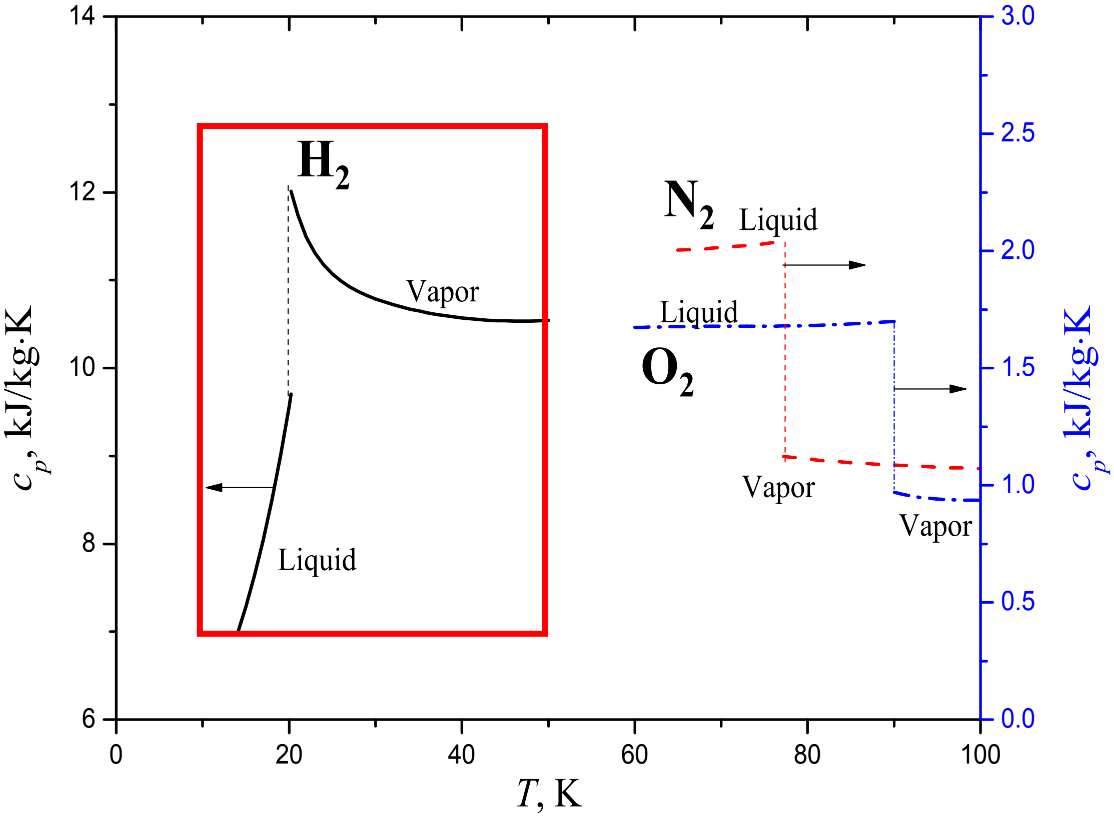


Gas-liquid density ratio in saturation state at 0.1MPa

- Gas-liquid separation is difficult owing to the low gas-liquid density ratio
- Unstable gas-liquid interphase
- Hard to form stable annular flow or inverted-annular flow

Particularity of hydrogen two-phase flow pattern

Unique performance of Liquid Hydrogen



Effect of specific heat on temperature at 0.1MPa

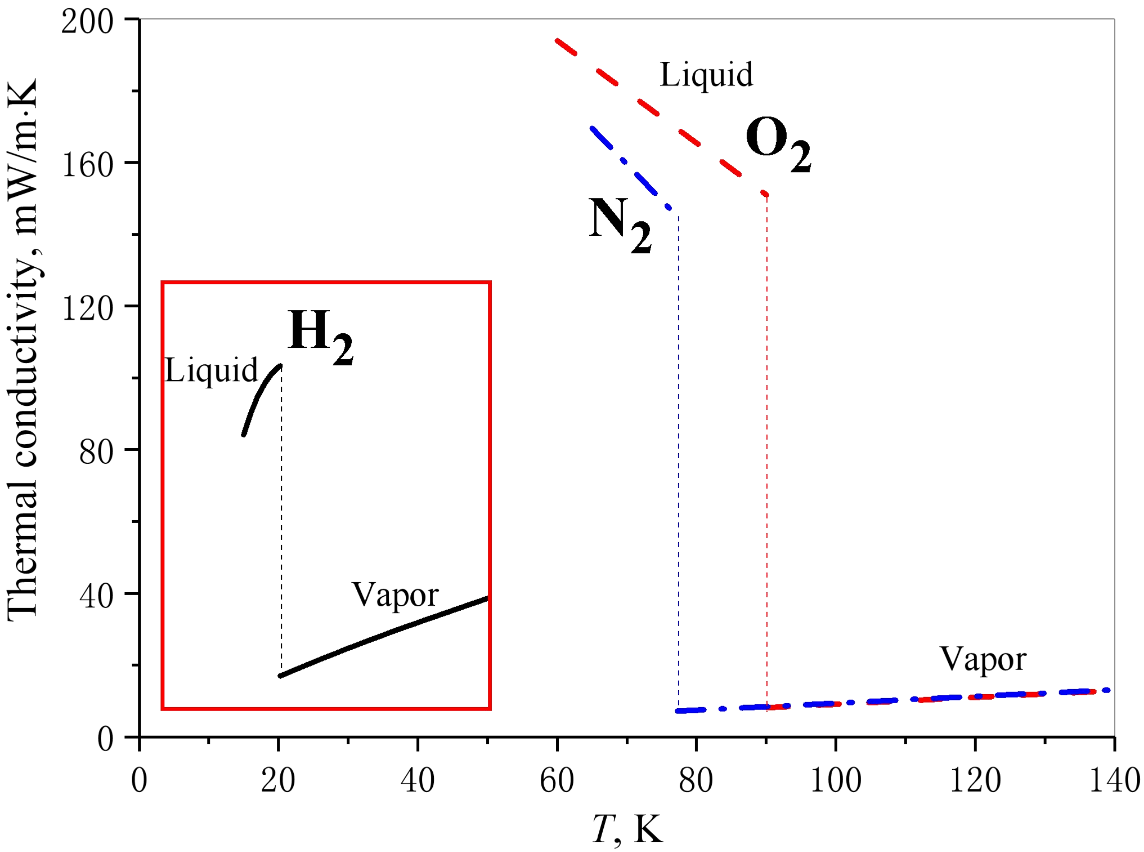
Specific heat

- In saturation state, c_p for GH_2 > c_p for LH_2
- Large c_p for GH_2 and the inversion of gas-liquid specific heat ratio
- Other fluids (nitrogen, oxygen, etc.) have a higher c_p for LH_2 than c_p for GH_2

Difference of hydrogen phase-change heat transfer

Unique performance of Liquid Hydrogen

Thermal conductivity



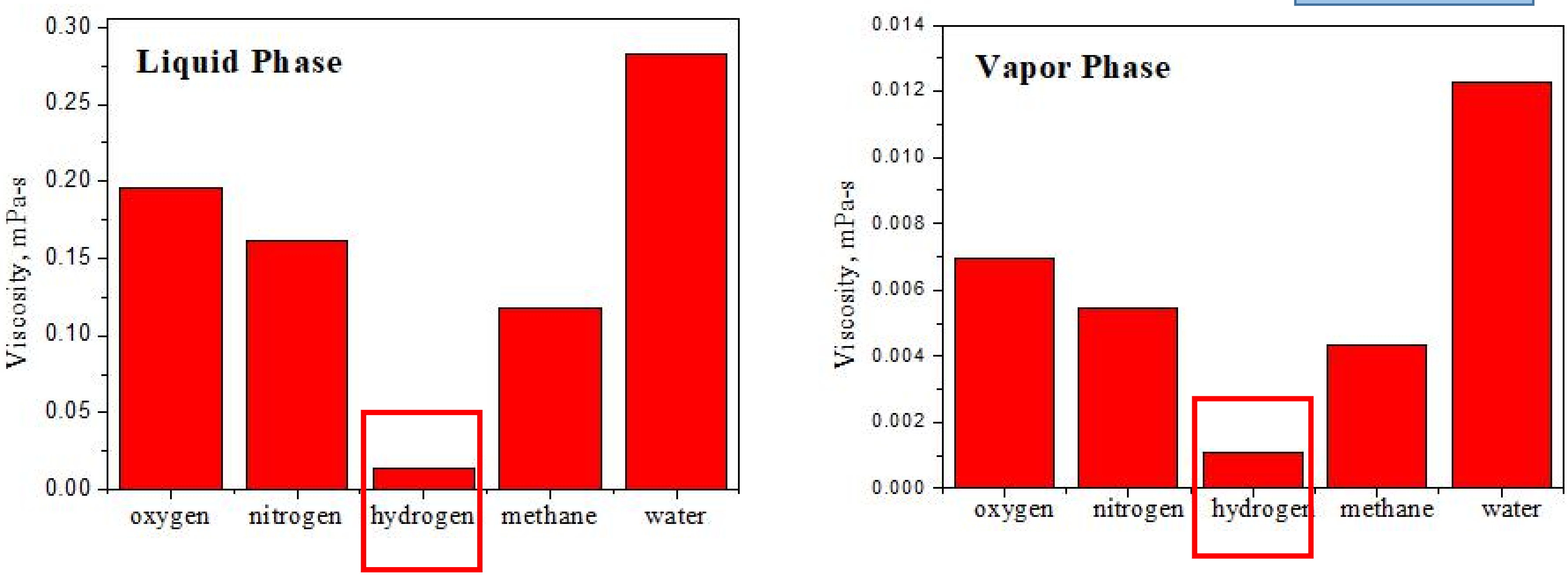
Effect of thermal conductivity on temperature at 0.1MPa

- $\lambda_{l,H2}$ increases as temperature rises, while $\lambda_{l,N2}$, $\lambda_{l,O2}$ decreases
- $\lambda_{v,H2}$ increases remarkably as temperature rises, compared with $\lambda_{v,N2}$, $\lambda_{v,O2}$

Difference of hydrogen thermal conductivity

Unique performance of Liquid Hydrogen

Viscosity



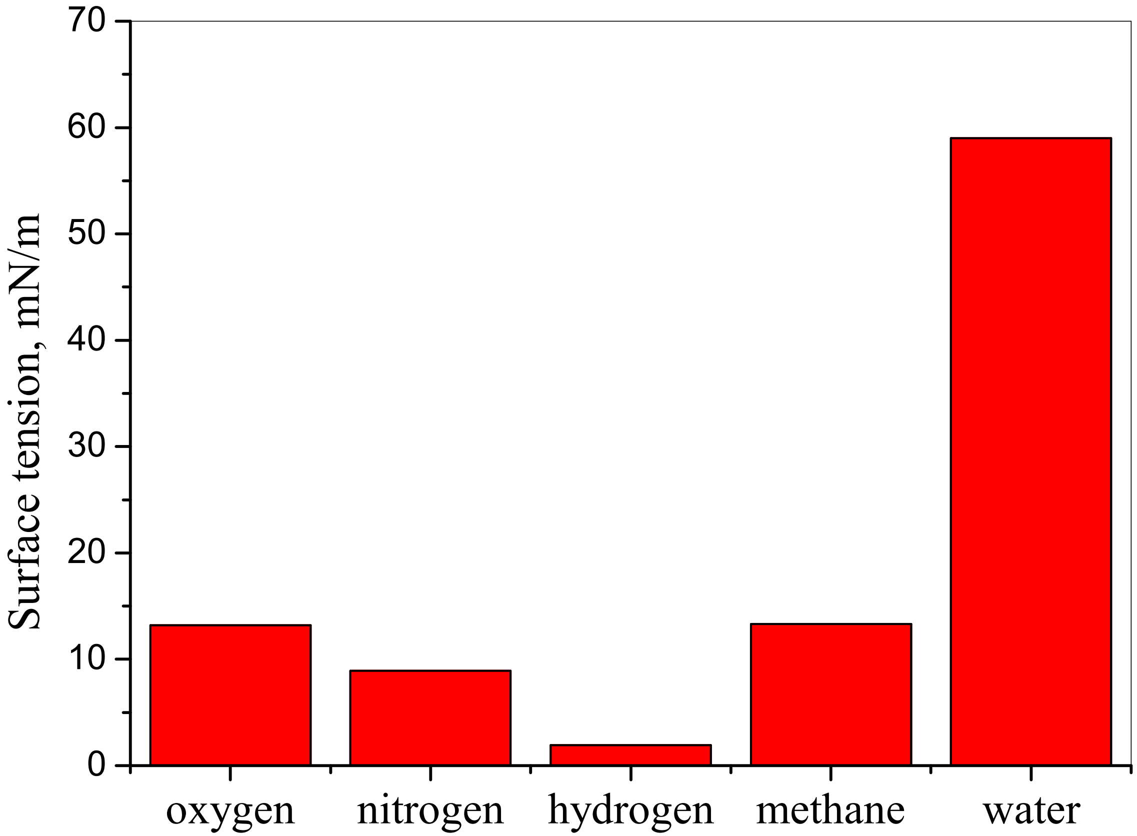
Comparison of dynamic viscosity for several fluids at 0.1MPa

- Hydrogen has significantly lower viscosity than other fluids, and LH_2 is easy to leak
- Lower pipe flow resistance and higher flow velocity —— high Re flow ($Re \sim 10^5$)
- Hydrogen has the particularity for two-phase pipe flow pattern

Hydrogen has strong permeability

Unique performance of Liquid Hydrogen

Surface tension



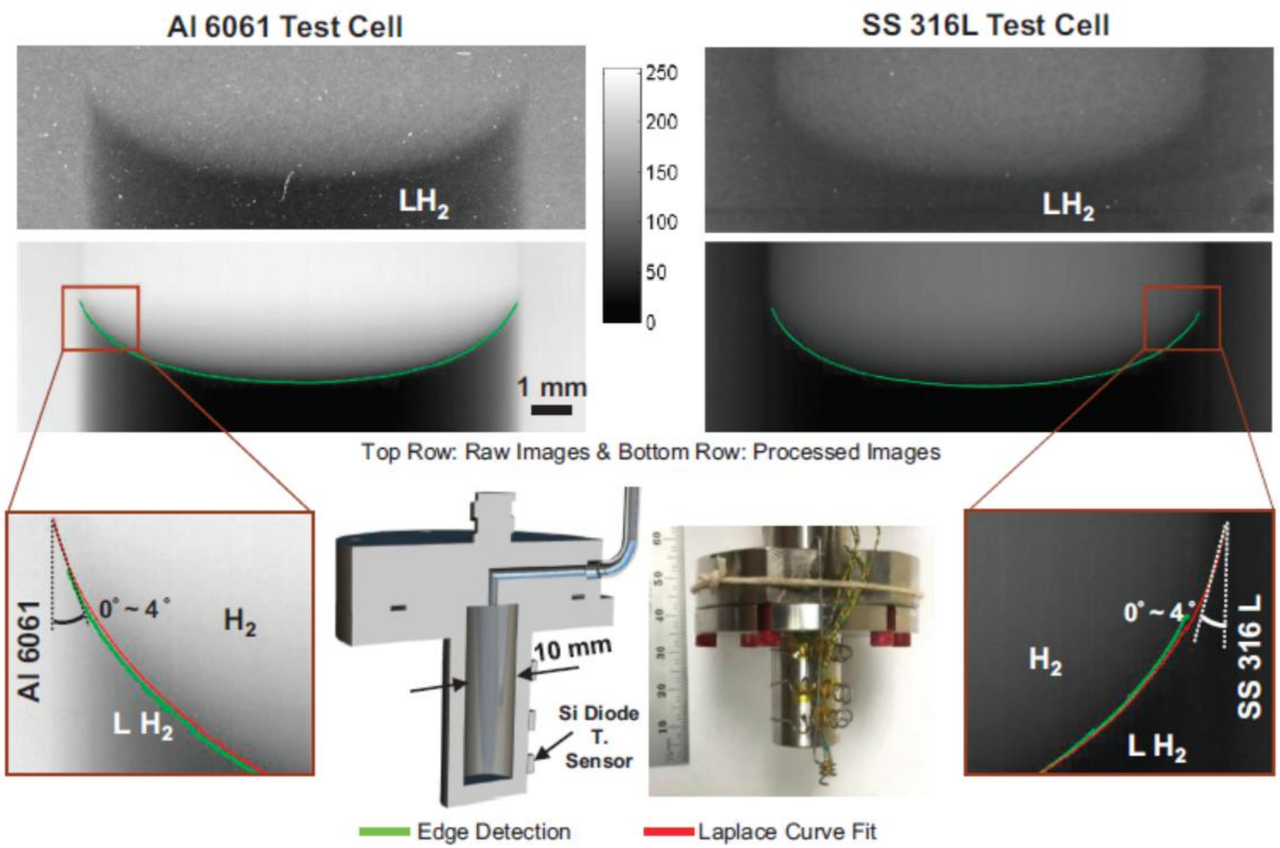
Comparison of surface tension for several fluids at 0.1MPa

- Hydrogen has extremely low surface tension
- The gas-liquid interphase is easily disturbed in the hydrogen tank
- Two-phase pipe flow pattern of hydrogen is unstable
- Difficult for gas-liquid separation by surface tension in microgravity
- Effect of gas-liquid interphase force is weak

Specificity of gas-liquid interphase change

Unique performance of Liquid Hydrogen

Contact angle

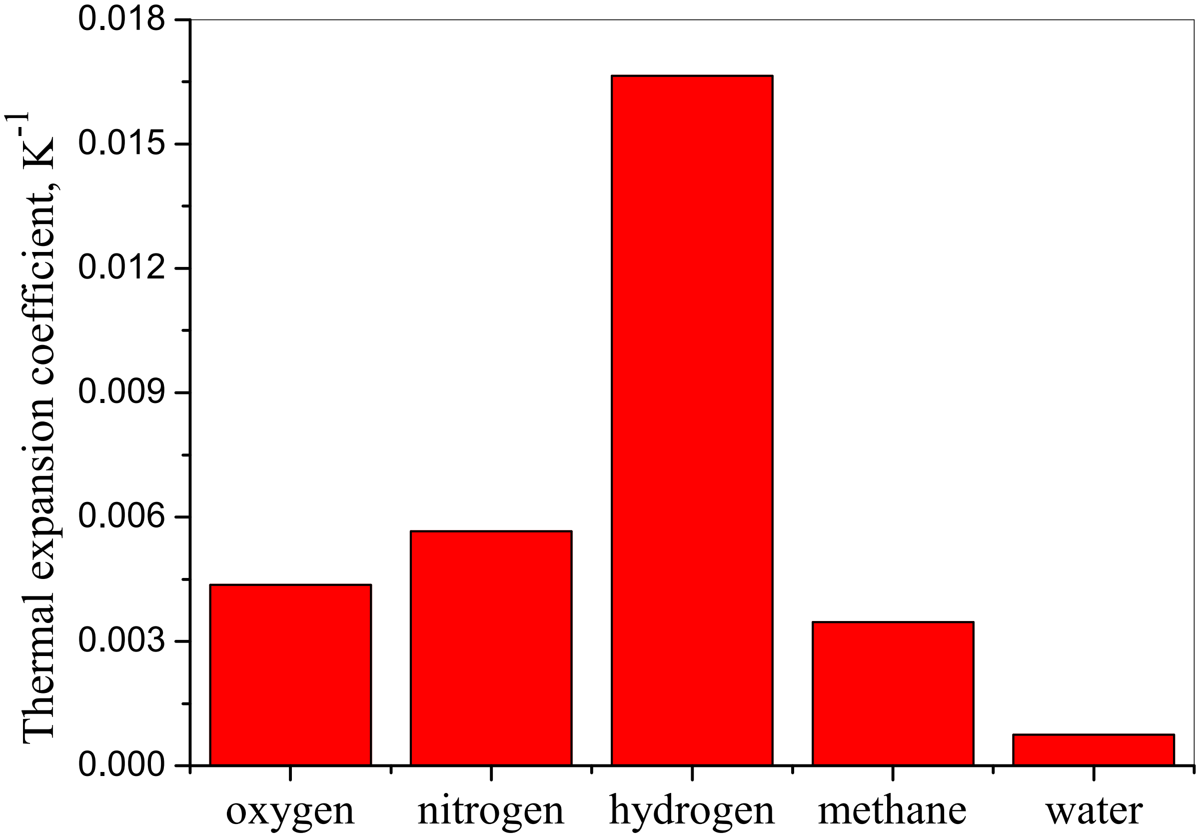


Hydrogen contact angle with aluminum alloy and stainless steel

- contact angle <10°
- Influence the gas-liquid phase distribution and heat flow trend in microgravity
- Bubbles hardly attach to walls

Different behavior between fluid and solid

Unique performance of Liquid Hydrogen



Comparison of thermal expansion for several liquids at 0.1MPa

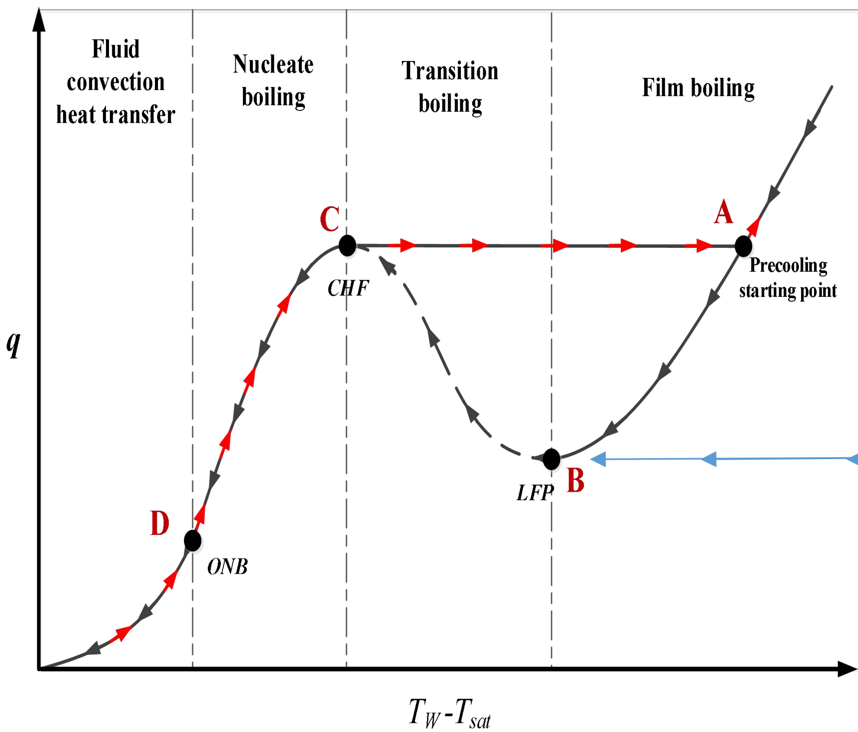
Thermal expansion

- Highest thermal expansion rate for LH_2
- Strong diffusion and penetration ability
- Easy to form the significant thermal stratification in the hydrogen tank

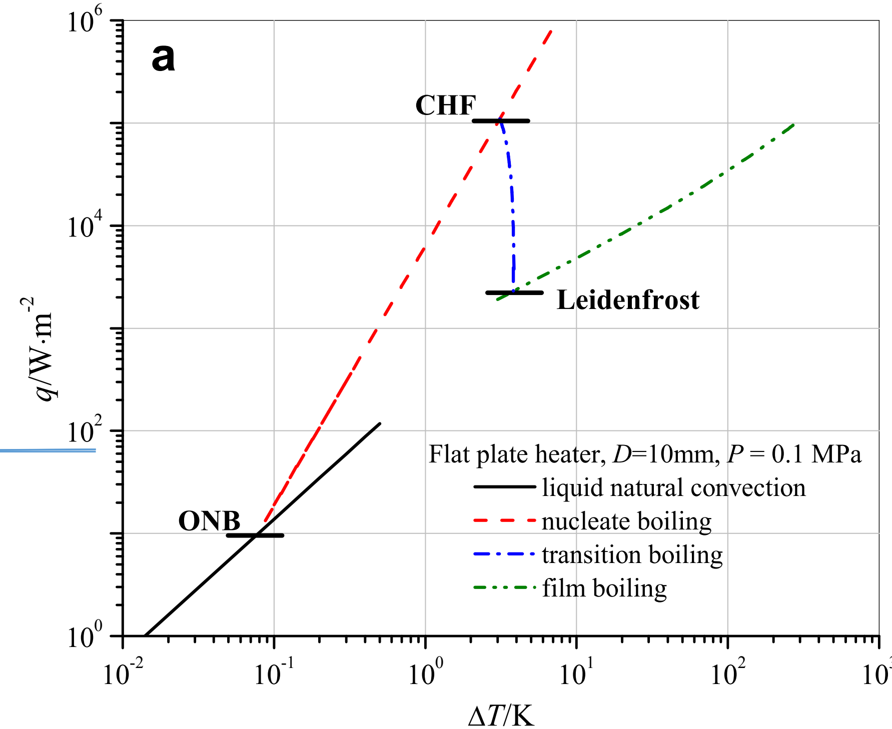
Serious thermal stratification for LH_2

Unique performance of Liquid Hydrogen

Typical boiling curve

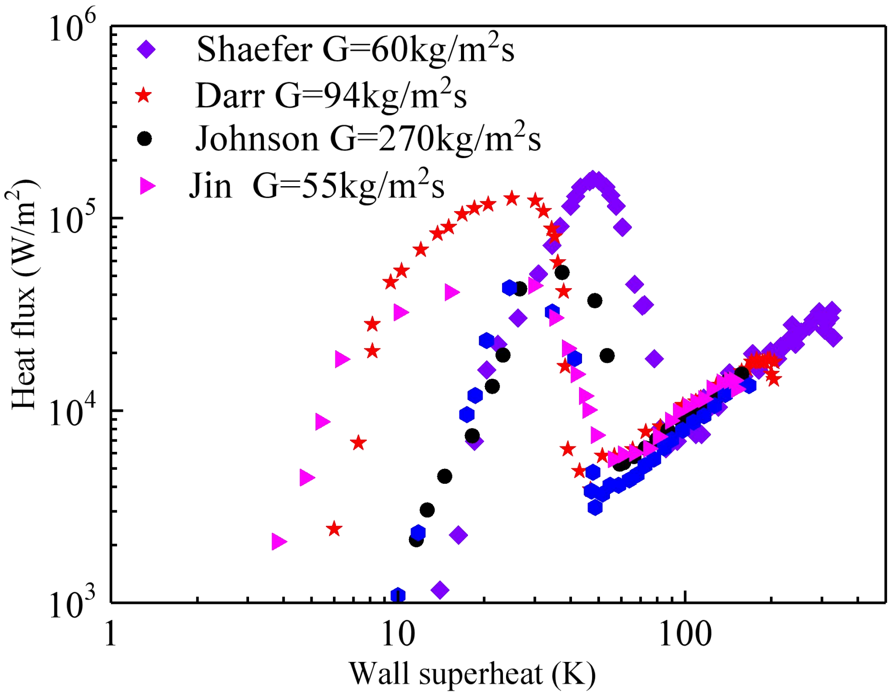


Hydrogen boiling



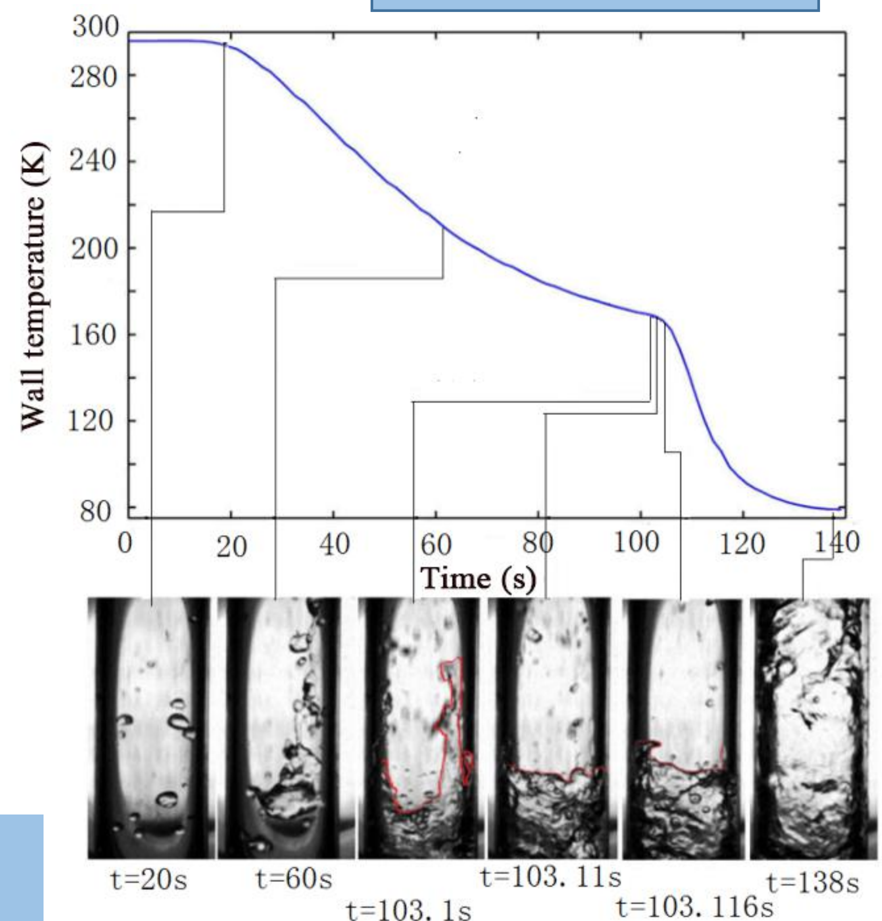
Pool boiling basically follows the classical law, with a short transition region
Easy to enter the film region

Unique performance of Liquid Hydrogen



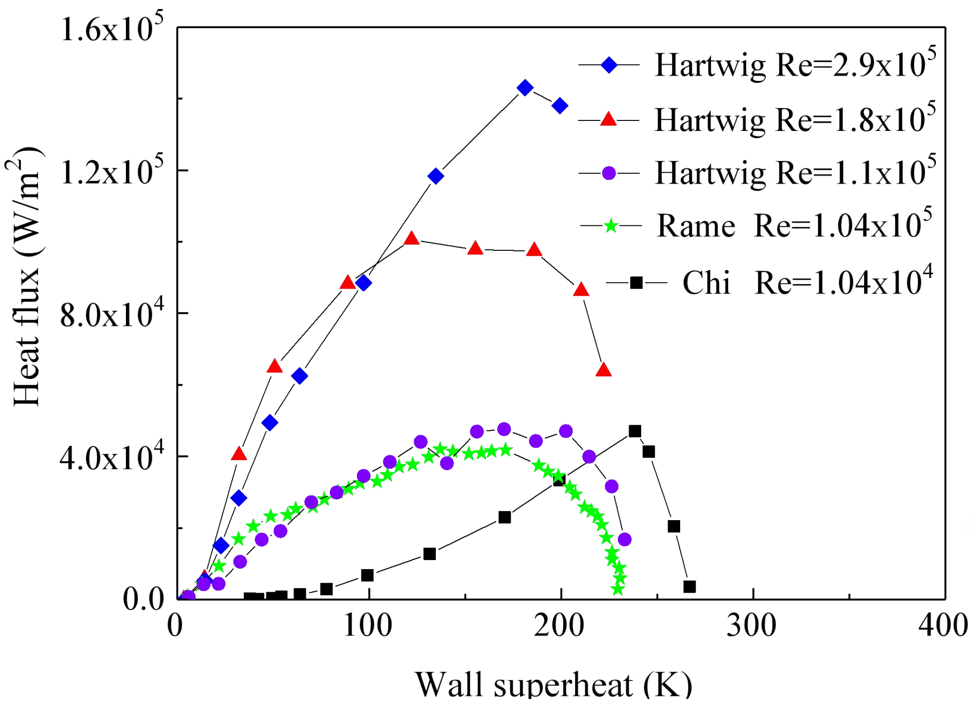
Flow boiling of LN_2 in pipe, including nucleate boiling, transition boiling, and film boiling

LN$_2$ Flow boiling

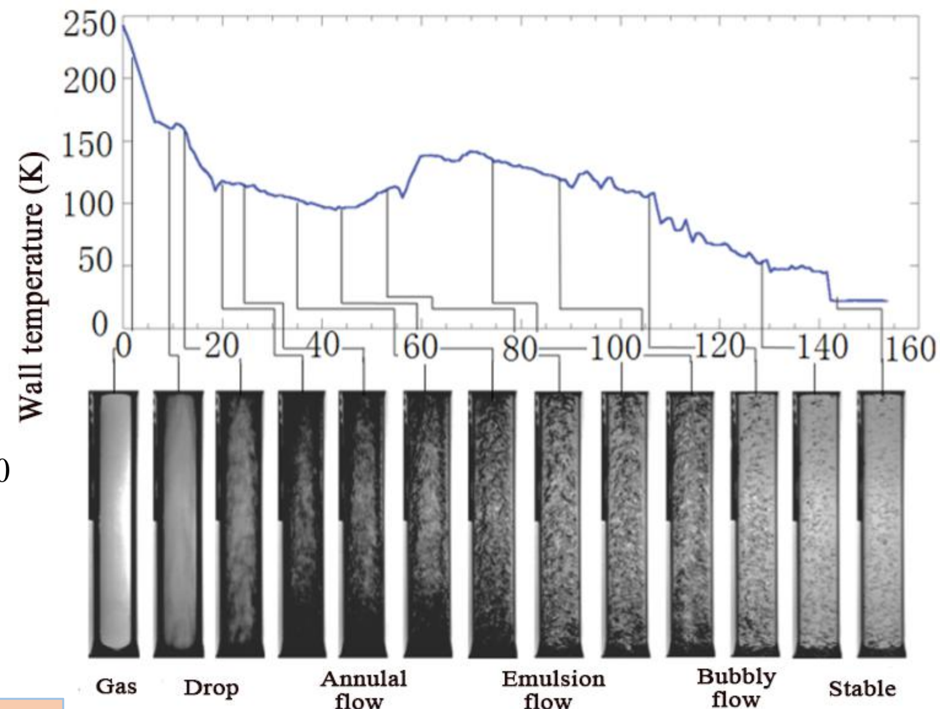


Precooling and flow pattern for LN_2 pipe flow

Unique performance of Liquid Hydrogen



LH_2 Flow boiling

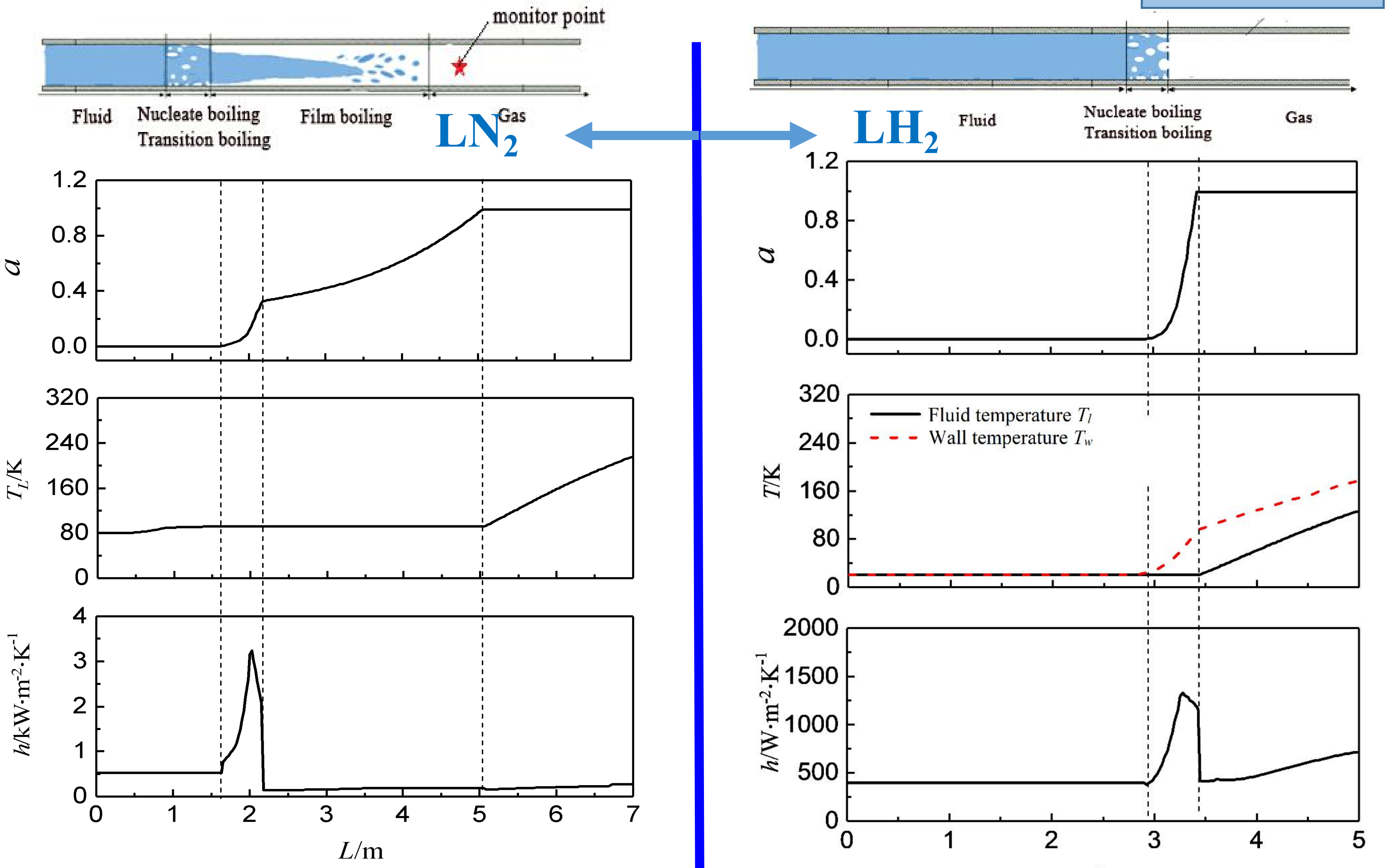


Flow boiling of LH_2 in pipe, including nucleate boiling, transition boiling, excluding film boiling

Precooling and flow pattern for LH_2 pipe flow (dispersed flow)

Unique performance of Liquid Hydrogen

Flow boiling



Unique performance of Liquid Hydrogen

Summary

Pool boiling

- Due to the lower latent heat and higher conductivity, Nucleate boiling is very short, film boiling covers the most parts of boiling region.
- Due to greater thermal expansion, thermal stratification is serious.

Flow boiling

- Due to the low viscosity, it's easy to enter the turbulent region. Therefore, flow boiling belongs to the range of high Reynold number ($Re>10^4$).
- Due to low surface tension, small gas-liquid density difference, and unstable interphase, a stable gas film is hard to form, so annular flow and film boiling are unstable.

Energy network concept based on cryogenics

05

Energy network concept based on cryogenics

□ Producing

- □ Renewable Energy:

  Solar, wind, ocean, tidal, geothermal

- □ Other Clean Energy： Fusion

→ Electric Power

□ Storage

- □ Electric Power
- □ Other energy

→ Hydrogen

□ Transmitting

- □ Electricity, Hydrogen
- □ Electricity + Hydrogen --- Cryogenic Energy pipeline

Energy network concept based on cryogenics

□ Energy transmitting network

Long-term goal: Power + Hydrogen

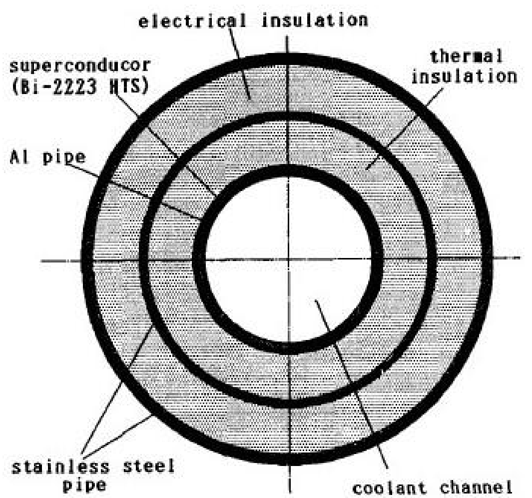


Fig.1. Fundamental configuraion of HETS

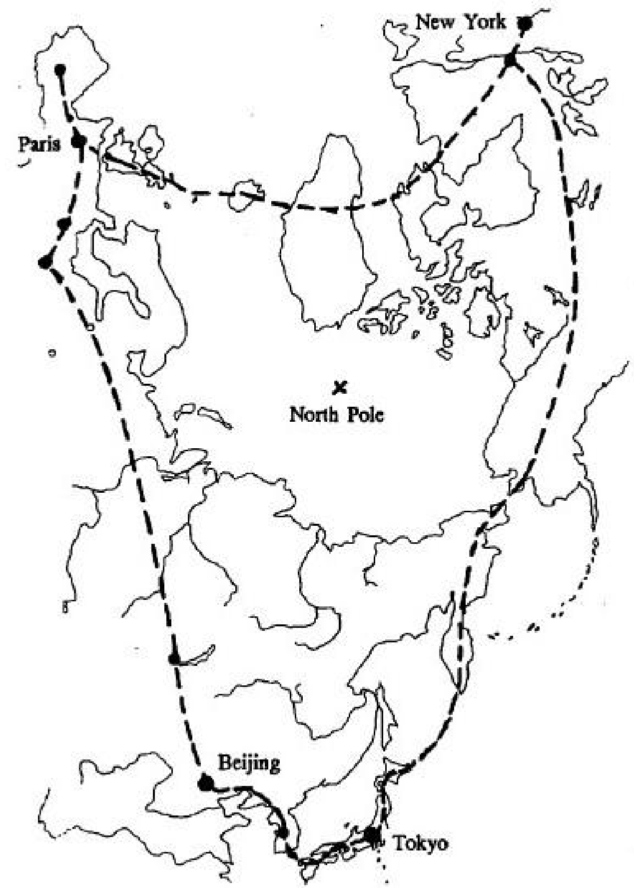


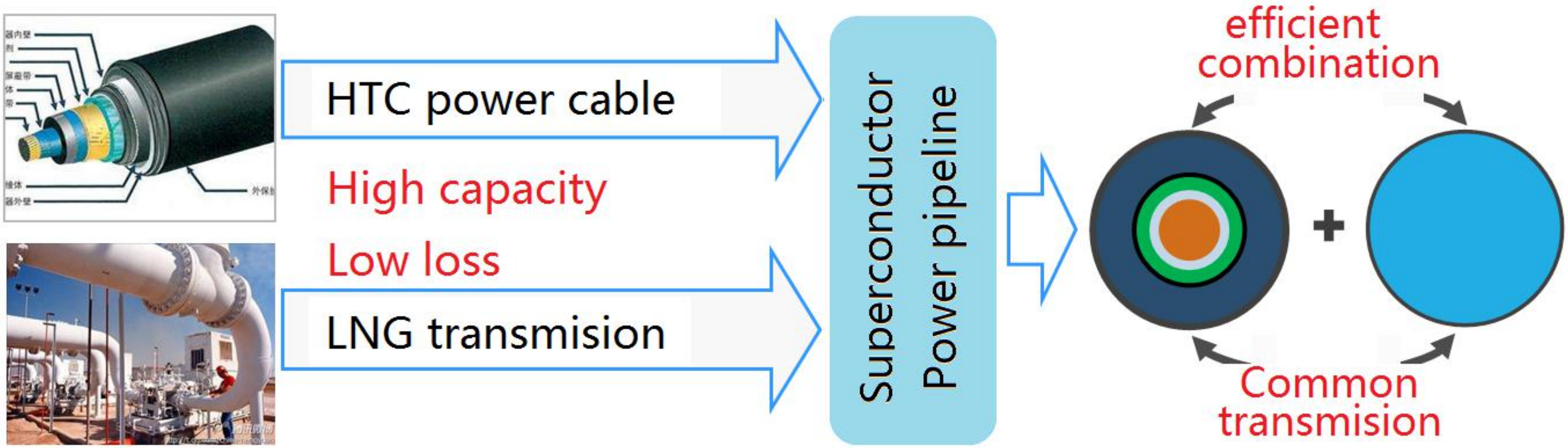
Fig.6 Future world-wide scale SCDCPC network

Type A: 50GW, 10000km, ±250kVA
LH2, 15-20K, 1.2m/s, 175km cool station

Ishigohka T. A feasibility study on a world-wide-scale superconducting power transmission system. *IEEE Transactions on Applied Superconductivity,* 1995

Energy network concept based on cryogenics

Short-term goal: Power + LNG



- Premote the common efficiency of transmision

LNG-HTS transmitting combination— "Energy Pipeline"

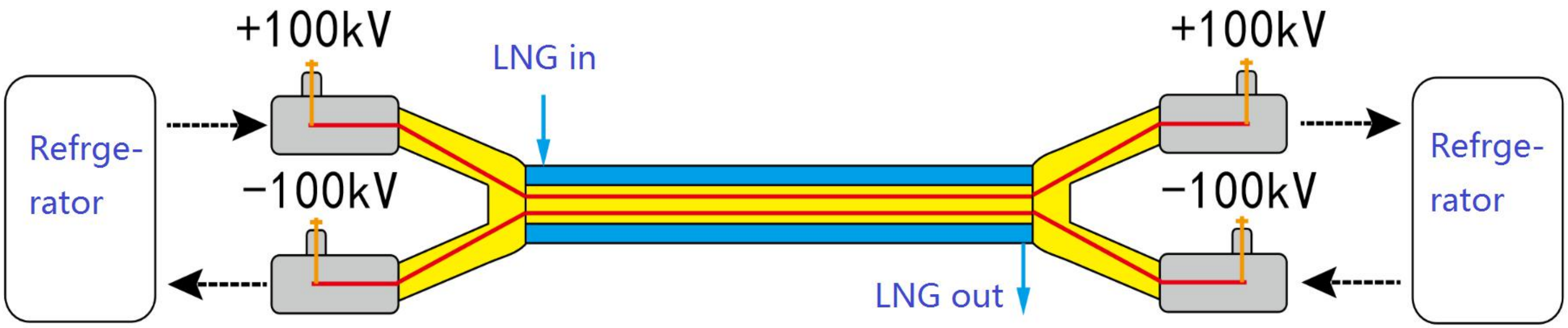
Li Yanzhong. A long distance transmission system base on HTC and LNG combination, *China Invention Patent*： ZL201210118316.1, 2012

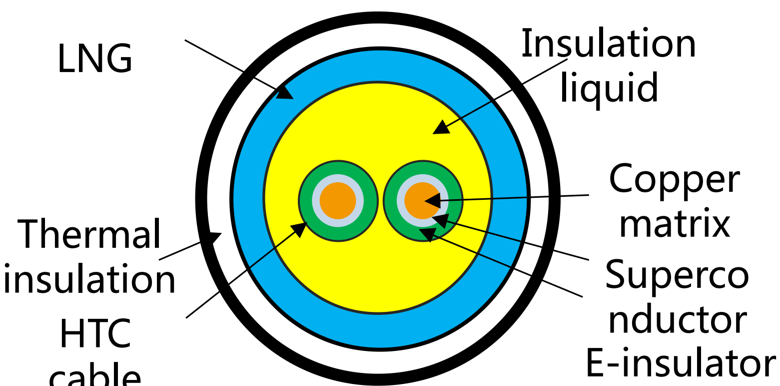
Energy network concept based on cryogenics

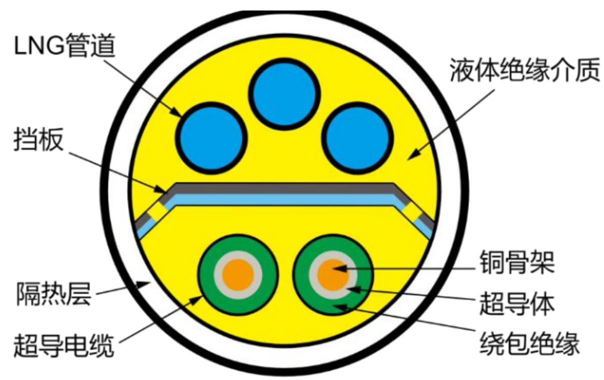
Short-term goal: Power + LNG

The National Key Research and Development Program **(2018)**
(2018YFB0904400)

30m pilot test is under study and developed







Energy network concept based on cryogenics

Hydrogen energy brings clean and efficiency,

Cryogenics provides strong support.

We need clean air and blue sky.

Thank you for your attention!

yzli-epe@mail.xjtu.edu.cn