中国科学院
CHINESE ACADEMY OF SCIENCES

Research Progress in Advanced Compressed Air Energy Storage System in China

Haisheng Chen

Institute of Engineering Thermophysics, Chinese Academy of Sciences, China



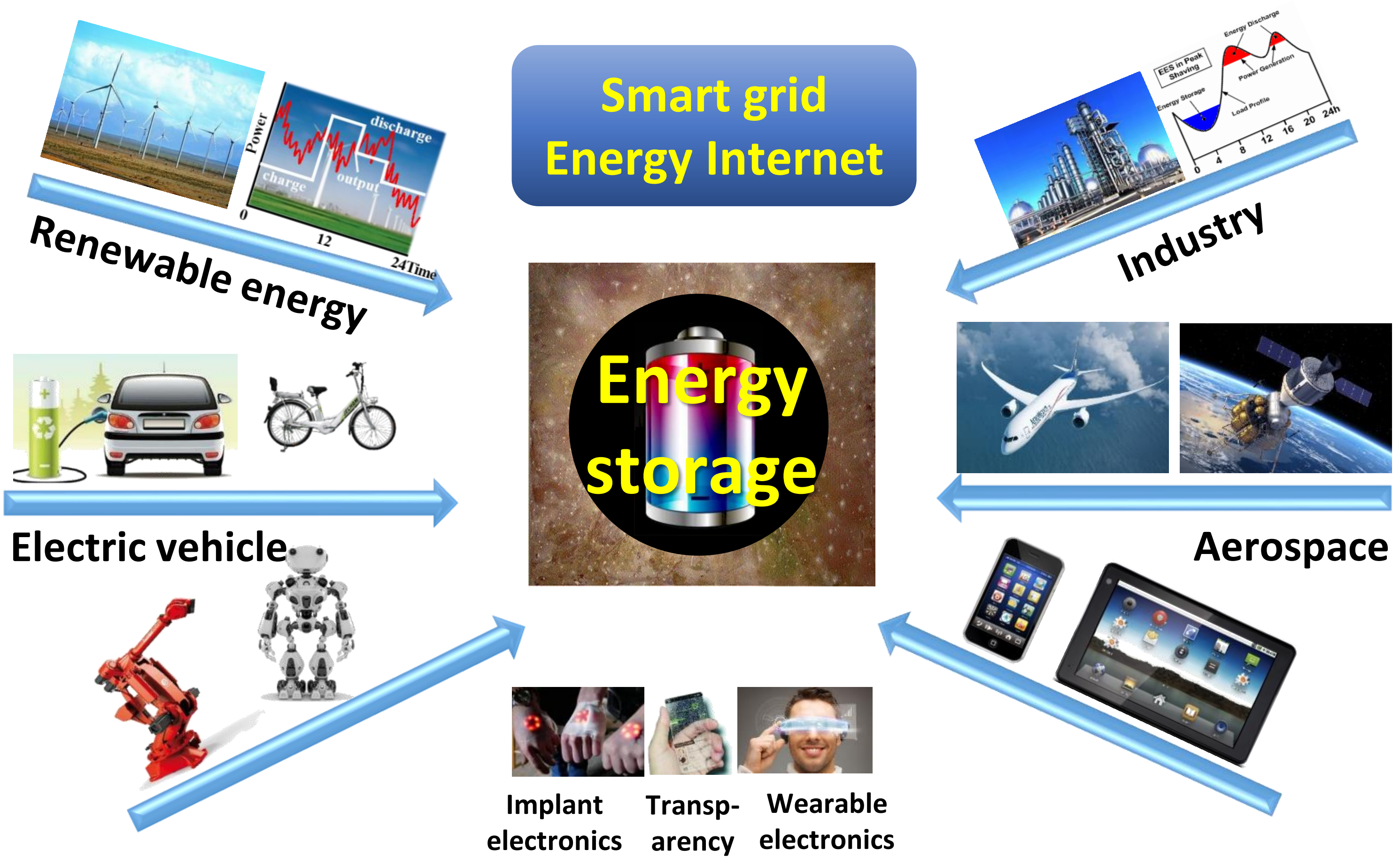



Contents

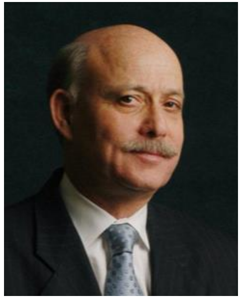
Contents

I、 Introduction

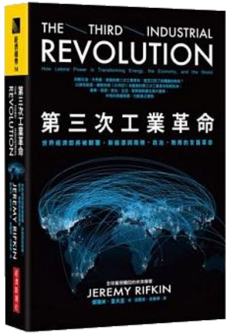
Strategic Significance of Energy Storage

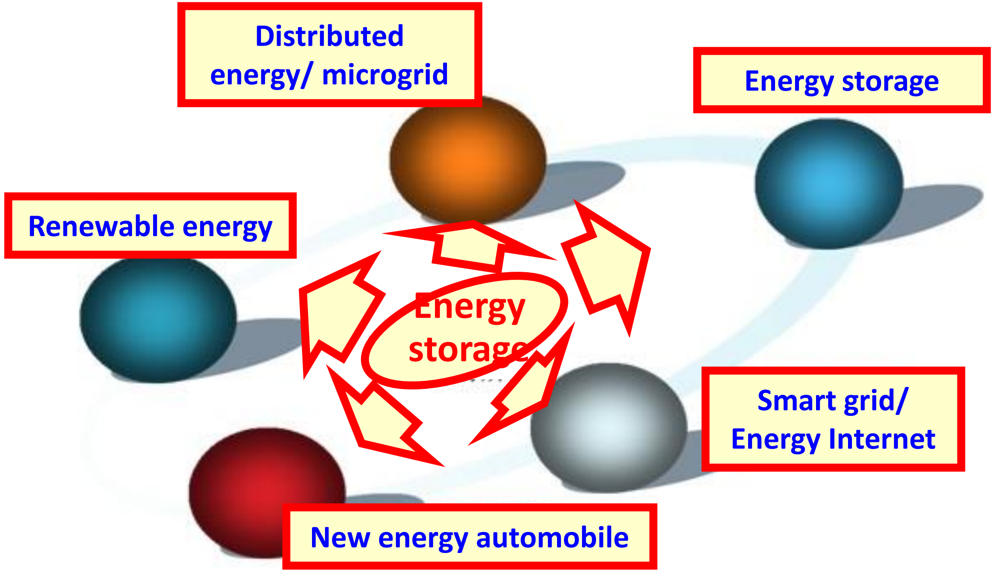


Energy storage is supporting technology of energy revolution



Jeremy Rifkin





Five pillars of the third industrial revolution:

Renewable energy, distributed energy/ microgrid, smart grid/energy Internet, new energy automobile, energy storage.

Energy storage is national strategic emerging industry of China

China's 13th five-year plan for national economic and social development:

Promote the innovation and industrialization of emerging frontiers including high-efficiency energy storage and distributed energy system, smart material...

The 37th of 100 Key tasks: energy storage and distributed energy.

Keqiang Li

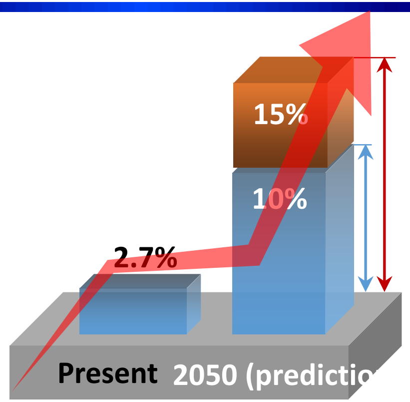
National energy council meeting:

"Concentrate on the development and utilization of renewable energy, especially achieving break-through on the technology of new energy grid connection, energy storage and smart grid. Comprehensively construct 'Internet+' smart energy. Seize the commanding point of energy technology competition." -Nov 17, 2016

Energy storage possesses huge market demand

- **Until 2018**, global installed energy storage capacity is about **181 GW**, covering **2.9%** of global installed power generation capacity.
- **In 2050**, the share is estimated to be **10%-15%.**
- **Until 2018**, the installed energy storage capacity of China is about **31.2 GW**, covering **1.6%** of national installed power generation capacity.
- **In 2050**, the installed energy storage capacity of China will increase to **200 GW**, covering **10%-15%** of national installed power generation capacity.

The installed capacity of China's energy storage will increase by 10 times in 30 years.



The percentage of energy storage in global power generation capacity


In China, the nation's best renewable energy resources are widely dispersed. Hydropower resources are primarily concentrated in China's Southwest, while wind power is distributed throughout the whole North of the country, as well as the east and southeast coastal areas. China's best solar energy resources are mostly found in the Tibetan Plateau, Gansu, northern

plants involved in regulating the power system, energy storage technologies are expected to play an important role in improving system flexibility and supporting the accommodation of renewable energy resources. Under SCERI's high renewable energy scenario studies, it is expected that China's demand for energy storage could reach over 200 GW by 2050.

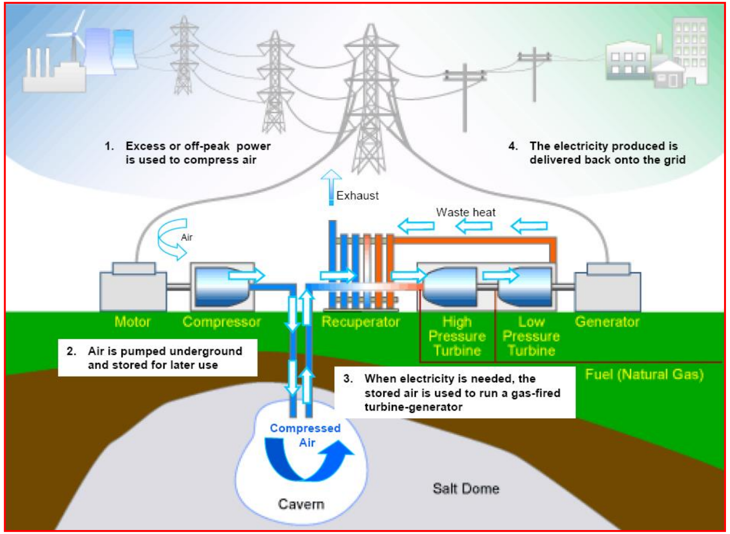
(.../...)

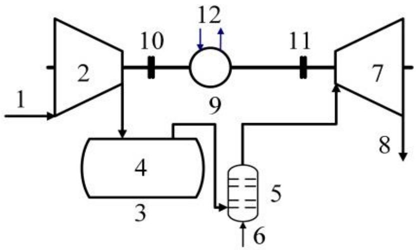
Figure 15: Future electricity grid configuration in China

Source: Modified from IEA and Energy Research Institute (2011), Technology Roadmap: China Wind Energy Development Roadmap 2050, OECD/IEA, Paris, France.

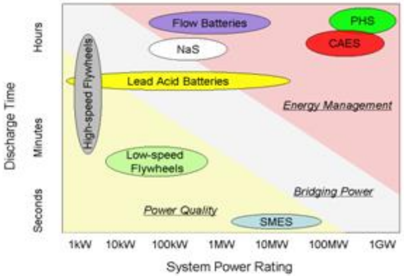
*Source: International Energy Agency

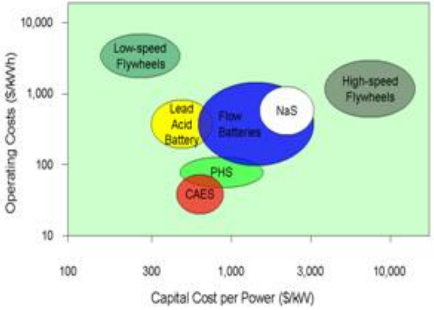
CAES is one of the main technologies of energy storage

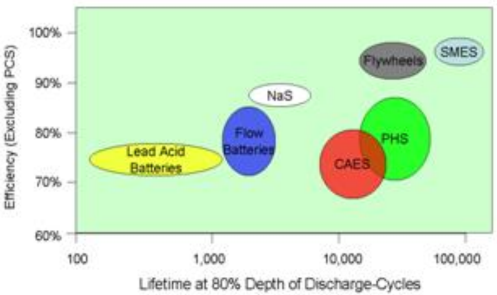




- High power rating (100MW)
- Low cost (800-1000$/kW)
- Long lifetime (30-50 years)
- Unlimited storage duration

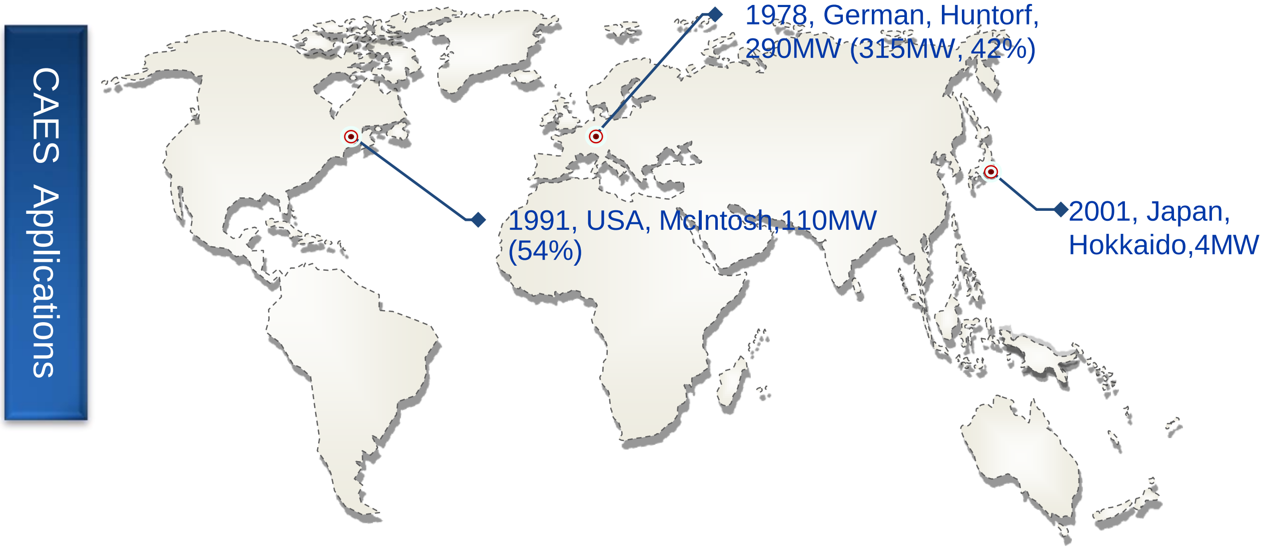






Chen et al. Compressed Air Energy Storage, Energy Storage, InTech Publisher, ISBN 979-953-307-768-9

CAES is one of the main technologies of energy storage



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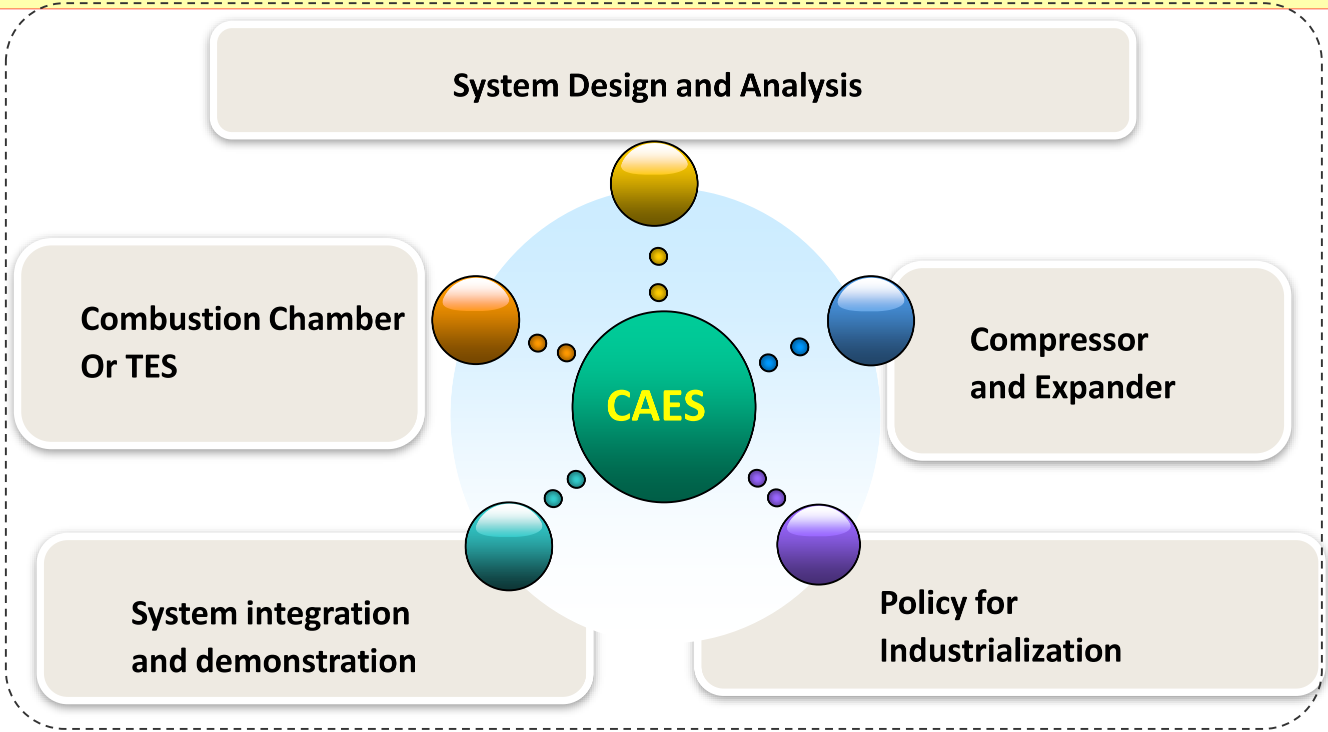
CAES in China: Overview

In China, there is no CAES in commercially operation yet. Most of the R&D activities on CAES are in lab or pilot-scale. However, the R&D of CAES in China have involved various aspects of CAES. And several demonstration projects have been launched.



System Design and Analysis

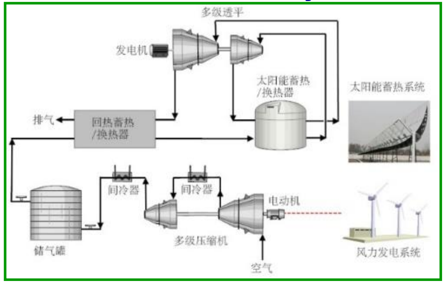
- IET, CAS
- North China Electric Power University
- Zhejiang University
- Shandong University
- Beijing University of Technology
- Tsinghua University
- Huazhong University of Science and Technology
- Xi'an Jiaotong University

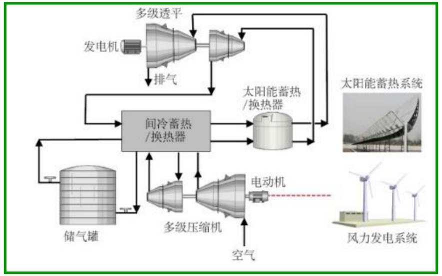
- IET, CAS
- North China Electric Power University
- Xi'an Jiaotong University
- Chongqing University
- Zhejiang University
- Huazhong University of Science and Technology
- Tsinghua University

● System design and thermodynamic analysis

- 10-100kW: Huazhong University
  Shandong University
  IET, CAS
  BJUT
- 100-1000kW: Tsinghua University
  IET, CAS
  IPC, CAS
- 10MW-100MW: IET, CAS
  Gezhouba Lt.d
  Tsinghua University

● Tech-Eco analysis and evaluation



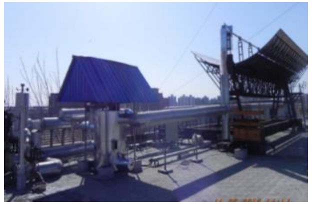


Components

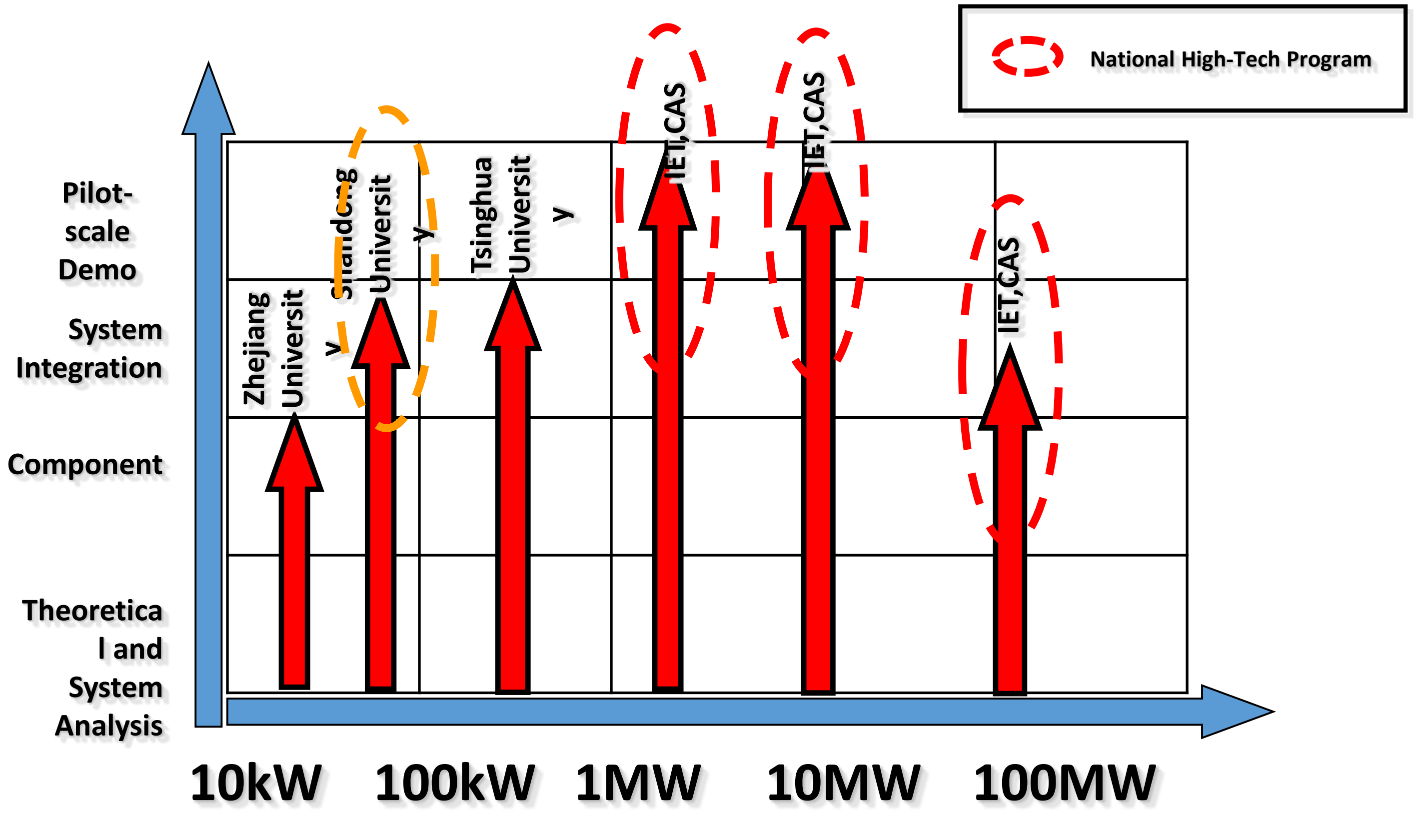
- IET, CAS
- North China Electric Power University
- Zhejiang University
- Beijing University of Technology
- Xi'an Jiaotong University
- Beijing University of Aeronautics and Astronautics
- Institute of Process Engineering, CAS

- Institute of Rock and Soil Mechanics, CAS
- Chongqing University
- Harbin Institute of Technology
- Hebei Institute of Technology
- Taiyuan University of Technology

- **Compressor**
  - Piston: Zhejiang Uni./IET
  - Scroll: Shandong Uni.
  - Radial: IET/Tsinghua Uni.
- **Expander**
  - Piston: Zhejiang Uni./IET
  - Scroll: Shandong Uni.
  - Screw: BJUT
  - Radial: IET/Tsinghua Uni.
  - Axial: IET
- **Combustion Chamber**
  - Xi'an Jiaotong University
- **TES:** IET/CAS BJUT and IPE
- **Cavern/Tank**



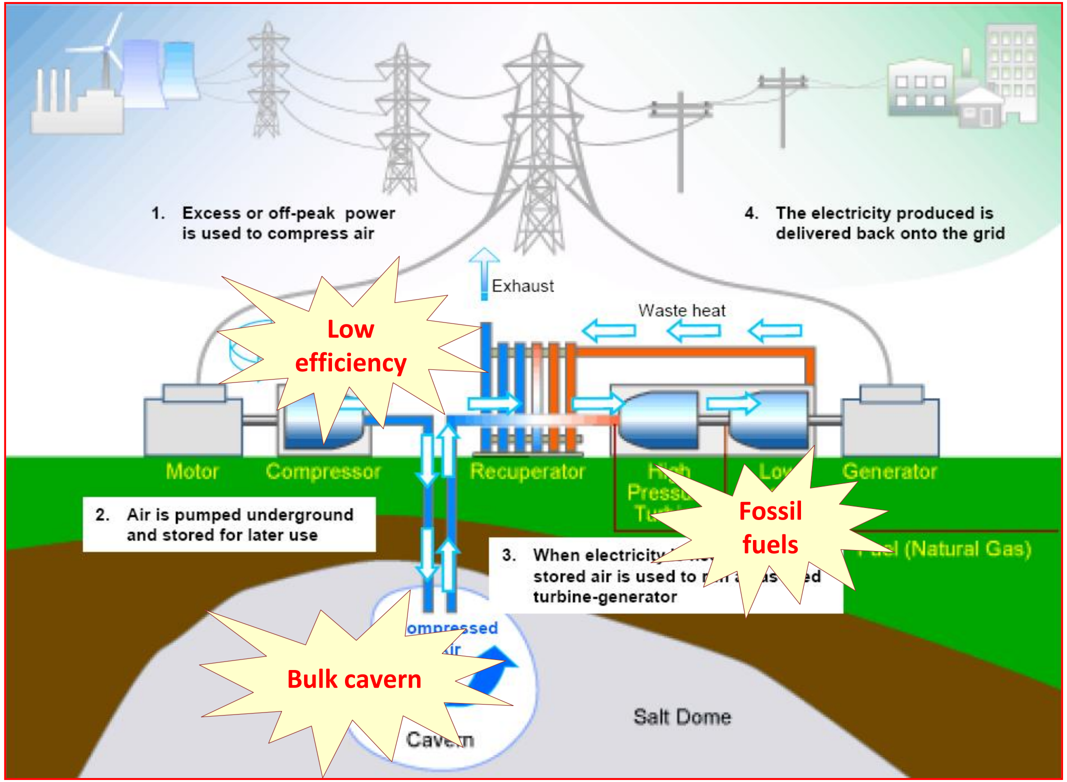
System integration and Demonstration



Contents

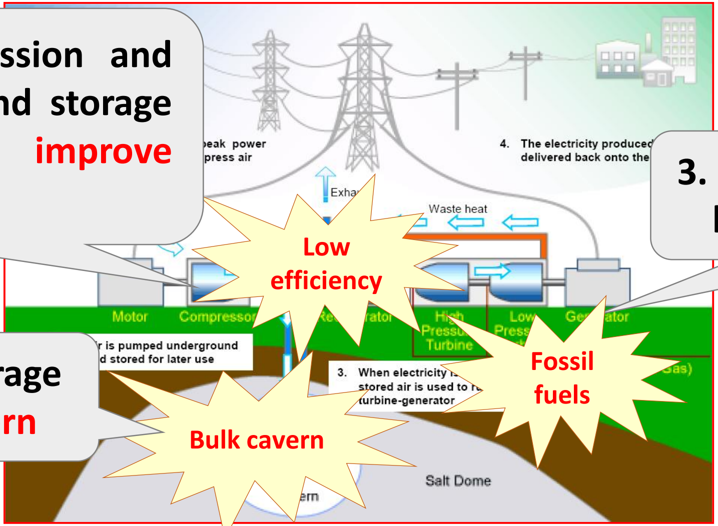
II、Overall Strategy

Bottlenecks of Conventional CAES



Overall Strategy for Advanced CAES

1. High efficiency compression and expansion, heat transfer and storage at supercritical state **to improve system efficiency**



3. Recycling of compression heat **to avoid fossil fuel**

2. Liquid/high-pressure storage **to avoid bulk storage cavern**

Bottleneck:

- Relying on bulk cavern
- Relying on fossil fuels
- Low efficiency

Solution:

- Recycle compression heat
- High-pressure/liquid storage
- Improve efficiency

Advanced compressed air energy storage: Academic ideas

Contents

III、Fundamental Study

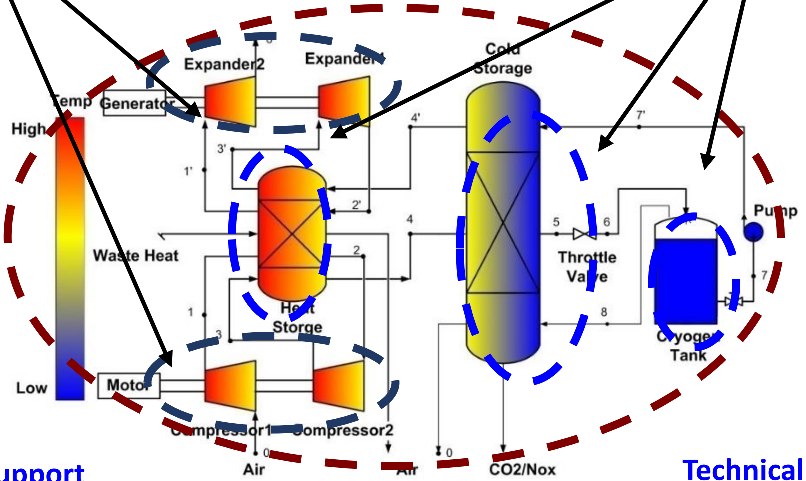
Fundamental Study

Scientific Issue 2:
Internal flow fields of compressor and expander

Scientific Issue 3:
Flow, heat transfer&storage in confined space

Coupling and integration

Theoretic guidance



Theoretic guidance

Technical Support

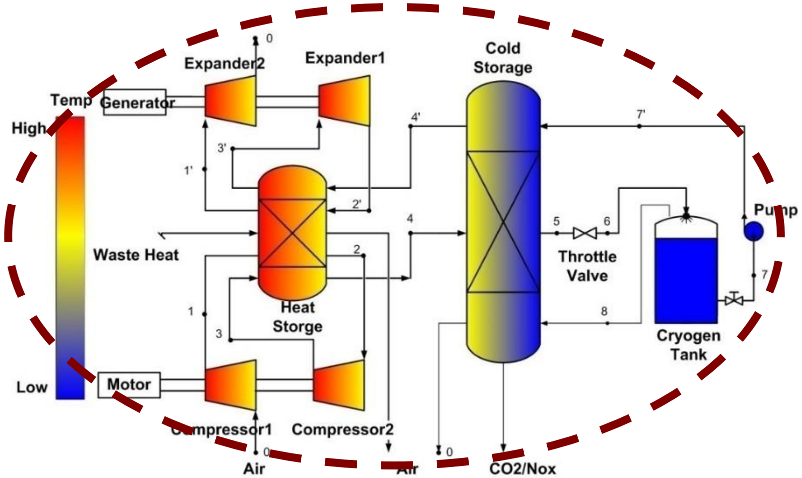
Technical Support

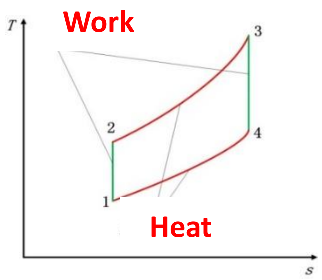
Scientific Issue 1:
Process coupling and energy loss mechanism of CAES System

Issue 1: Process coupling and energy loss mechanism of System

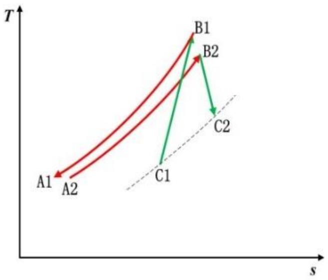
Challenges

1. Cycle is not closed/ different from heat engine cycle
2. Nonlinear coupling of multi-processes
3. Unstable operation with frequent change of input and output





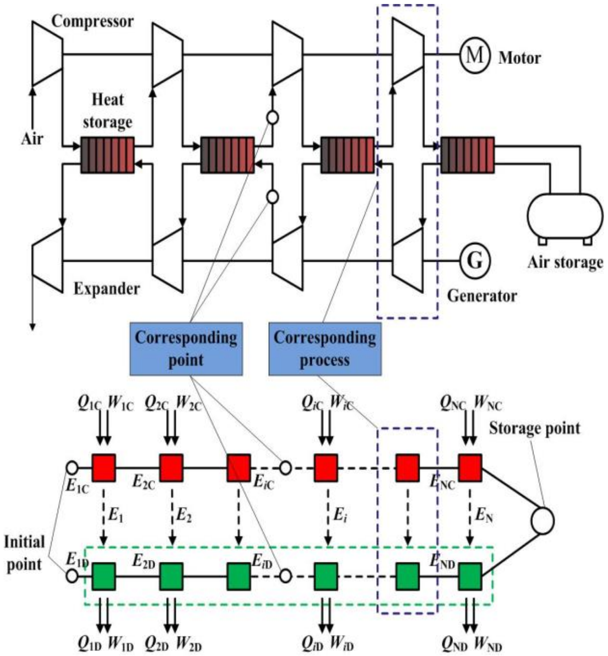
Conventional Heat Engine Cycle



Cycle of Advanced CAES

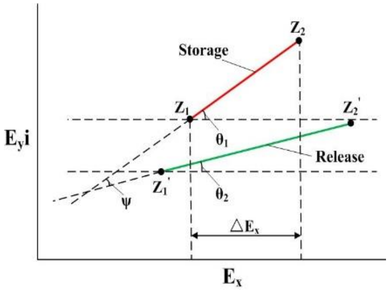
Progress 1： Corresponding-point methodology (CPM) for CAES

A new method, CPM, for analyzing and optimizing system is created on the basis of the correspondence of the system flow; a diagram of thermal exergy and mechanical exergy (E_{th}-E_{mech} diagram), which reflects energy loss characteristics, is proposed in a complex plane



$$E_x = T_0 R_g \ln \frac{P}{P_0}$$

$$E_y = c_p[(T - T_0) - T_0 \ln \frac{T}{T_0}]$$

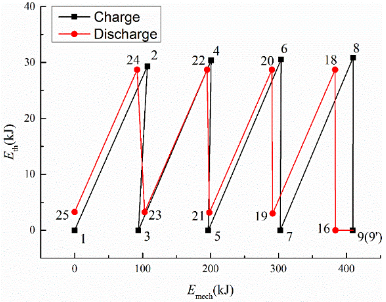


$$e(T,p) = \int_{T_0,p}^{T,p} c_p \left(1 - \frac{T_0}{T}\right) dT + \int_{p_0,T_0}^{p,T_0} v dp$$

Thermal exergy

mechanical exergy

Parameters of the method shown in corresponding process



Eth-Emech diagram of CAES

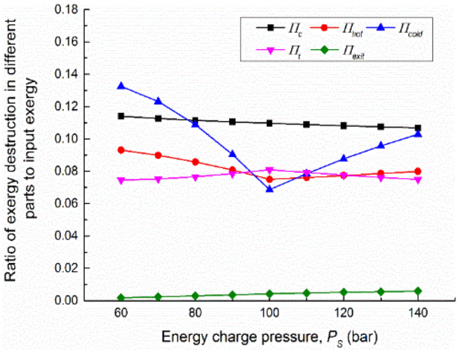
Guo and Chen et al. Applied Energy, 2016

Progress 2： Mechanism of Energy Conversion, Transmission and Loss

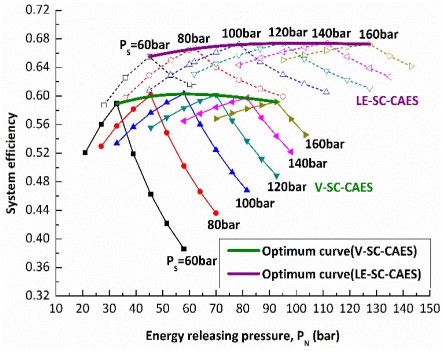
The relation of energy conversion and transmission is established; energy loss characteristics and the matching characteristics of the key parameters are revealed

- Effect of pressure on heat recovery
- Heat exchange temperature difference
- Pressure loss
- Compressor efficiency and expander efficiency
- Cold storage efficiency

$$\eta_{sys}=[A_{C,s}k_c\ln\varepsilon_{i,c}+(1-\frac{\Delta T_{rehe}+\Delta T_{inter}}{T_0})](1-\frac{\bar{\varsigma}_{rehe}}{\ln\varepsilon_{i,t}}-\frac{\bar{\varsigma}_{inter}}{\ln\varepsilon_{i,c}})\frac{A_{T,s}}{A_{C,s}}\eta_{i,s,c}\eta_{i,s,t}\eta_{coldstorage}$$



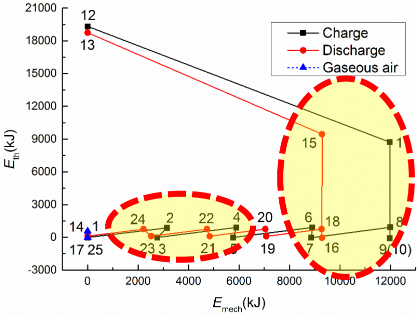
Exergy loss varies with energy storage pressure



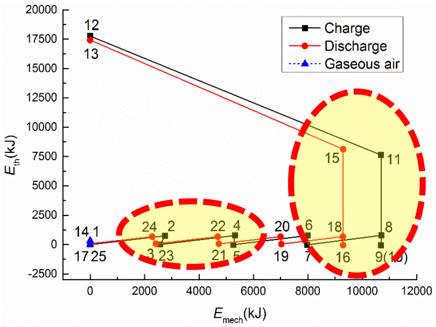
Matching relation between charge pressure and discharge pressure

Guo and Chen et al. Applied Energy, 2017

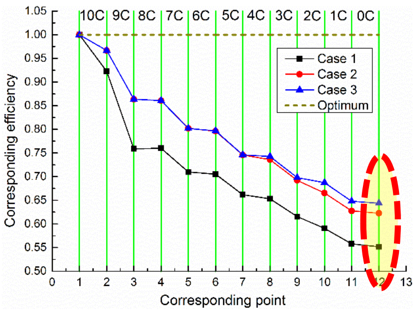
Progress 3： To reveal dynamic characteristics of CAES at full working condition



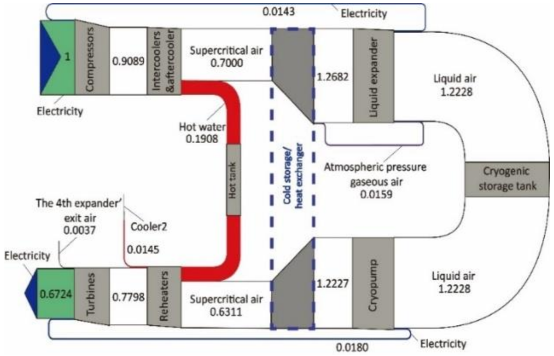
E_{th}-E_{mech} diagram of case 1



E_{th}-E_{mech} diagram of case 3



Corresponding efficiency

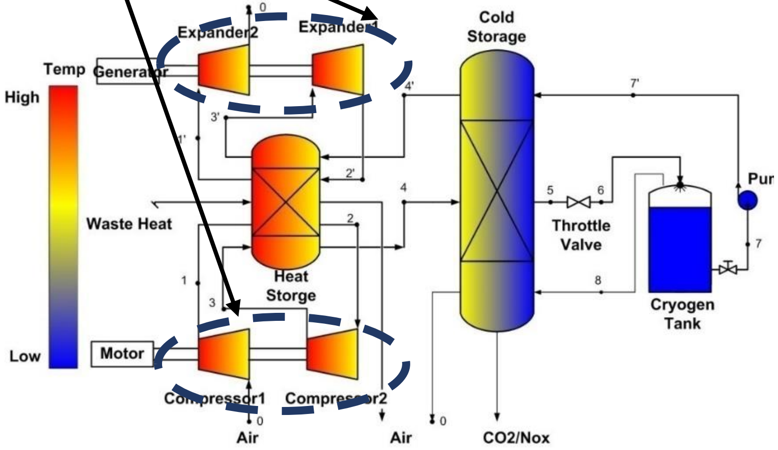


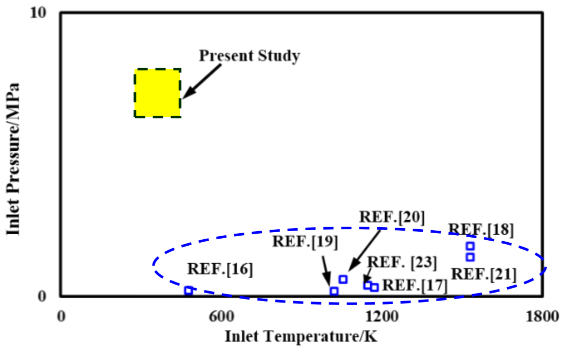
Exergy flow diagram

Guo and Chen et al. Energy, 2017

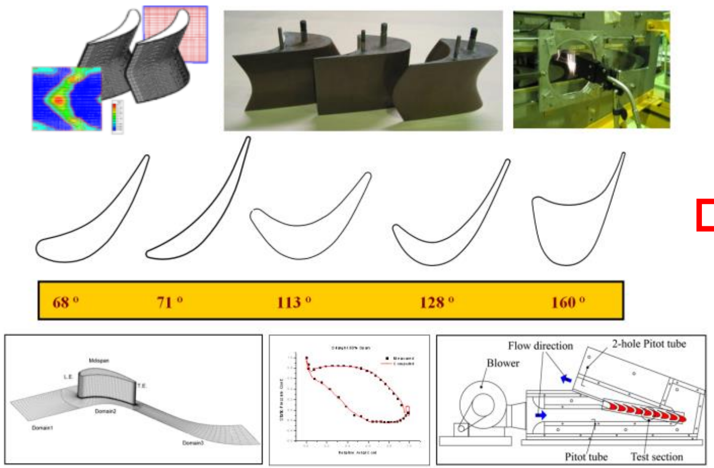
Issue 2: Internal flow fields and loss of compressor and expander

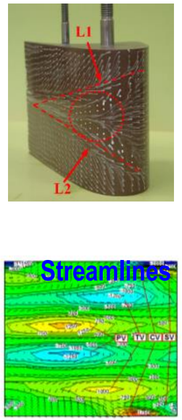
Challenges	
	1. **High pressure:** Multi-stage, high-load & leakage
	2. **Unstable operation:** Unsteady & control
	3. **Coupling:** flow and heat transfer



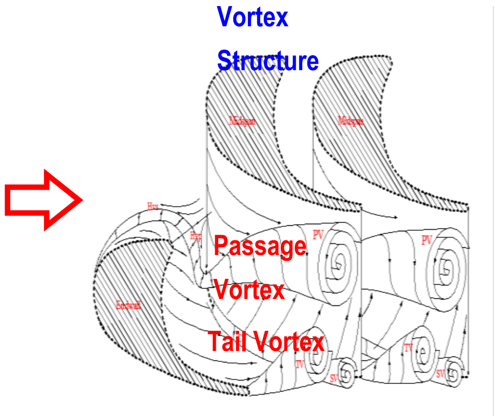


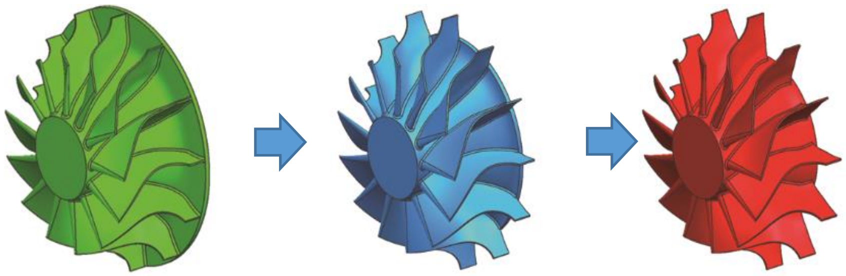
Progress1: Internal flow fields

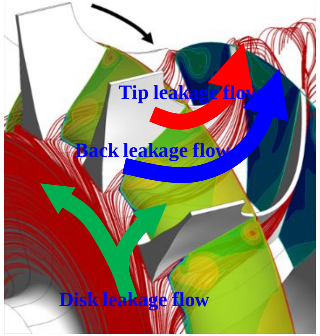




Vorticity

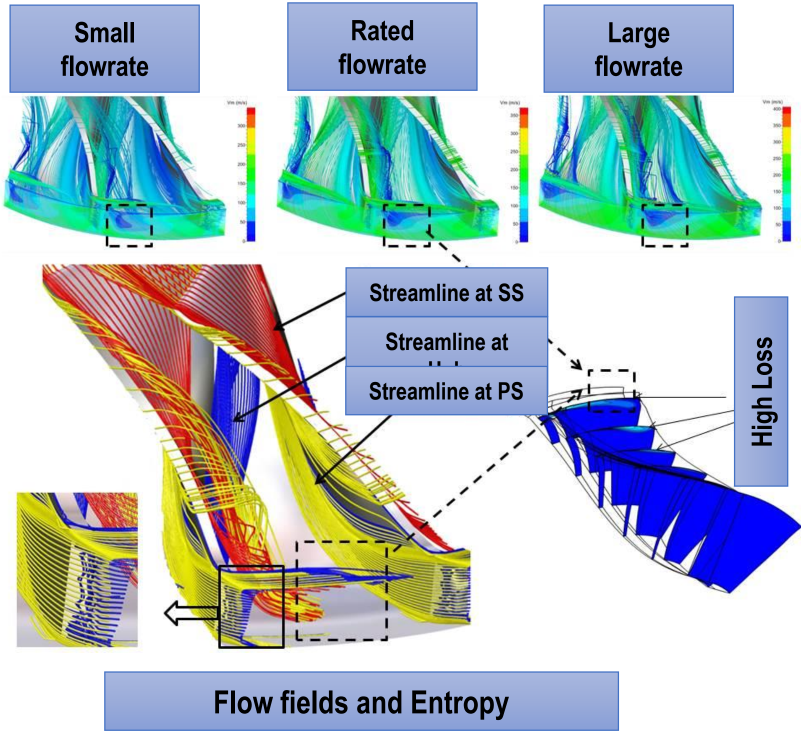


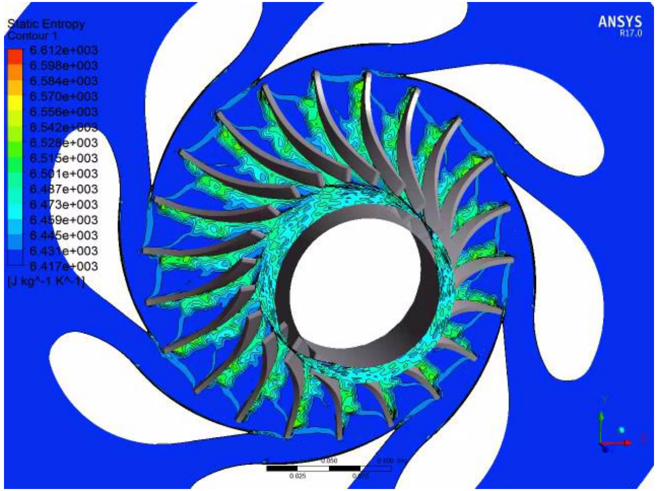


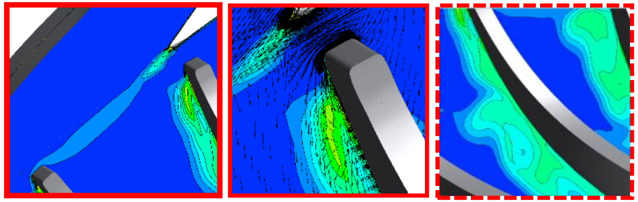


Tan and Chen et al. AIAA J.(2003, 2004) Proc IMechE A: J Power Energy(2009,2012, 2015, 2016, 2018, 2019)

Progress 2: Off-design performance and Unsteady flow



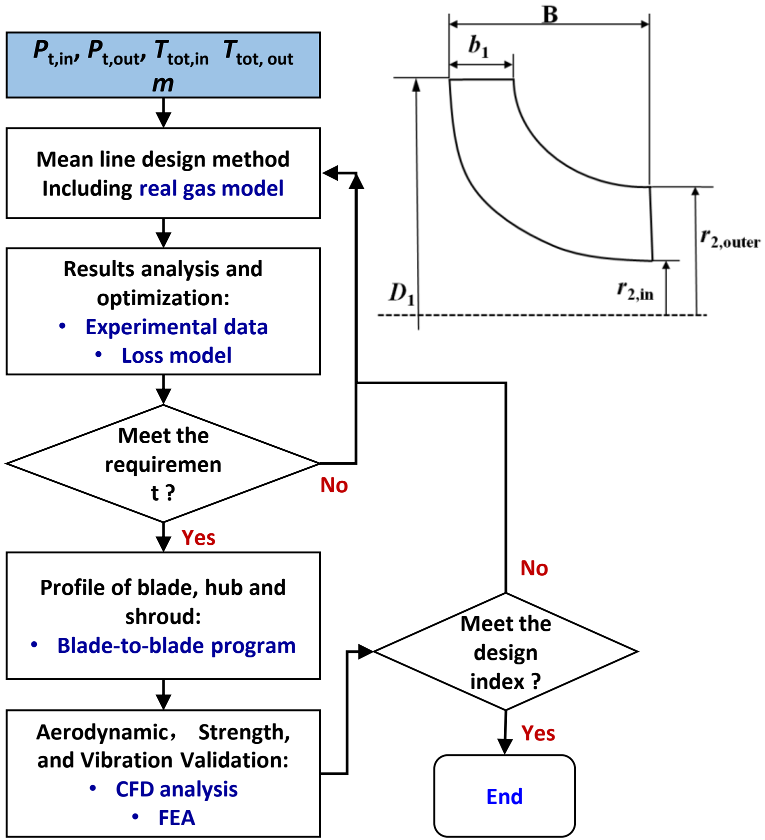




Off-design performance and Unsteady flow

P. He and H.Chen* (2013), ASME Journal of Turbomachinery, 135(4), 021002-1

Progress 3: Coupling mechanism of flow and heat transfer

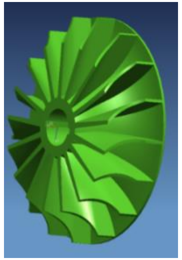


Geometry parameters for expanders

Stage 1

Stage 2

Stage 3



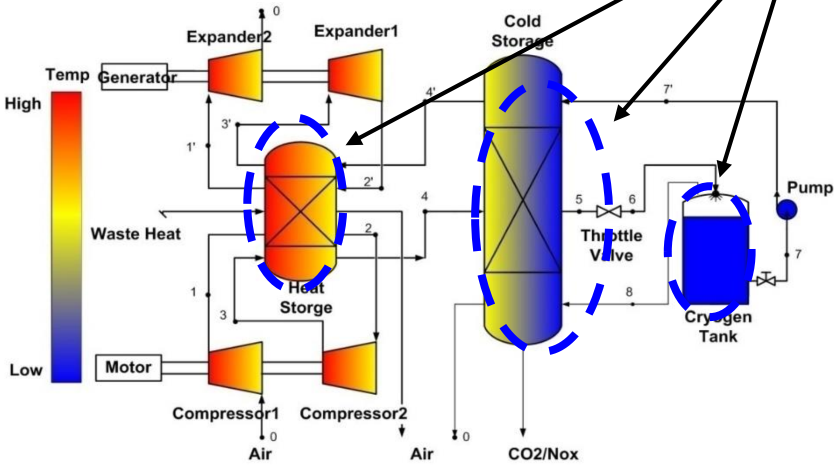
Stage 4

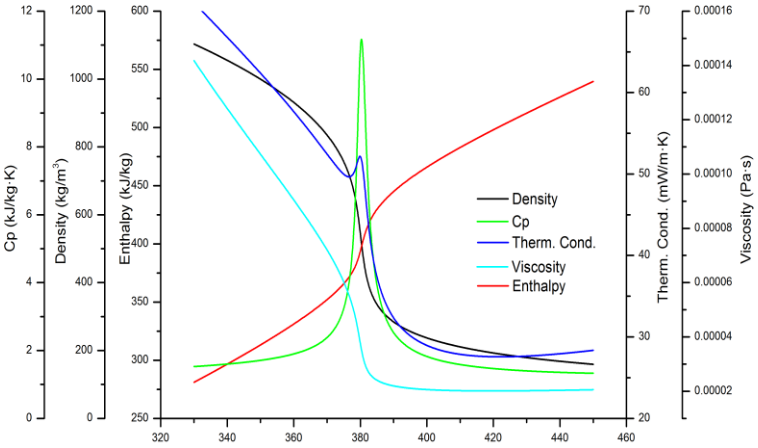
- ➢ The Design method for high efficiency multi-stage expander in CAES is provided;
- ➢ The geometry parameters of the optimized expanders are obtained

Issue 3: Flow, heat transfer and storage in confined space

Challenges

1. High pressure and supercritical condition
2. Coupling with flow of expander and compressor
3. Unstable operation condition





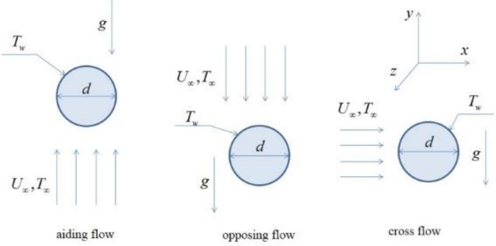
Property around supercritical point

Progress 1: Flow and/or heat transfer characteristics of HT fluids and heat storage materials

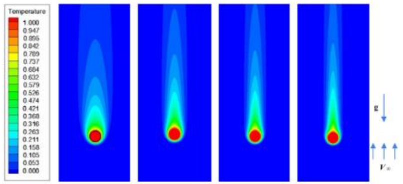
$$\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} = -\frac{\nabla p}{\rho} + \frac{\mu}{\rho} \nabla^2 \mathbf{v} + \mathbf{g}$$

High Pressure → **High density**

Forced convection → **Mixed convection**

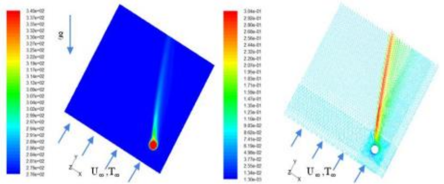


Richardson number $\mathrm{Ri} = \mathrm{Gr} / \mathrm{Re}^2$



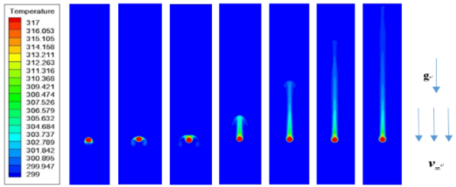
Ri=0 Ri=2 Ri=4 Ri=8

Aiding flow

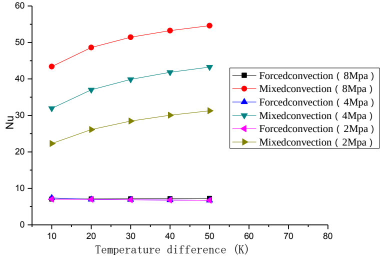


Re=100, Ri=6, ϕ=30º

Cross flow



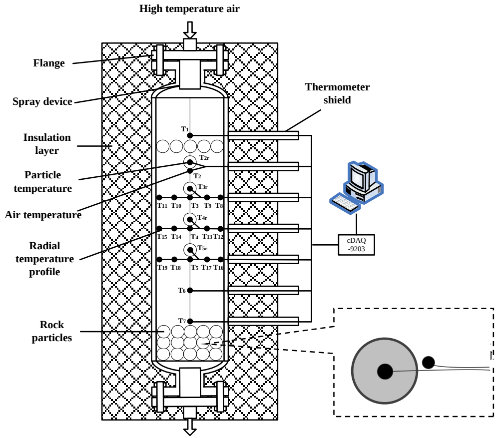
Re=100, Ri=2 Opposing flow



HT Nu vs temperature difference under different pressures

- **The gas-solid HT Nu of mixed convection increase with the pressure, Re and particle sizes.**
- **Pressure is the most significant factor.**

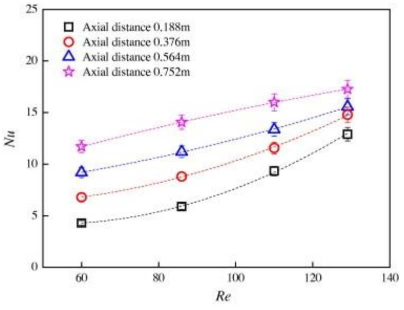
Progress 2: Interaction between heat transfer fluids and heat storage materials



Fluid $$\frac{\partial T_F}{\partial t} = -U\frac{\partial T_F}{\partial x} - \frac{h_p a}{\varepsilon c_F \rho_F}(T_F - T_S)$$

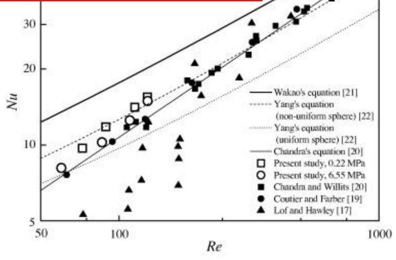
Solid $$(1-\varepsilon)\frac{\partial T_S}{\partial t} = \frac{h_p a}{c_S \rho_S}(T_F - T_S)$$

$$h_p = \frac{c_S \rho_S (1-\varepsilon)}{a(T_F - T_S)}\frac{\partial T_S}{\partial t} \qquad Nu_p = \frac{h_p d_p}{\lambda_f}$$



Nusselt number vs. Reynolds number at 6.55 MPa.

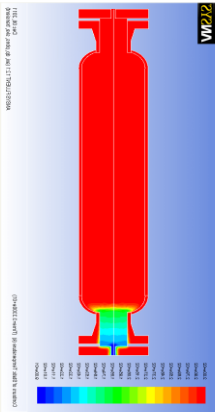
$$Nu = a_1 + a_1 Pr^{1/3} Re^n \left(\frac{d_p}{d_h}\varepsilon\right)^n$$

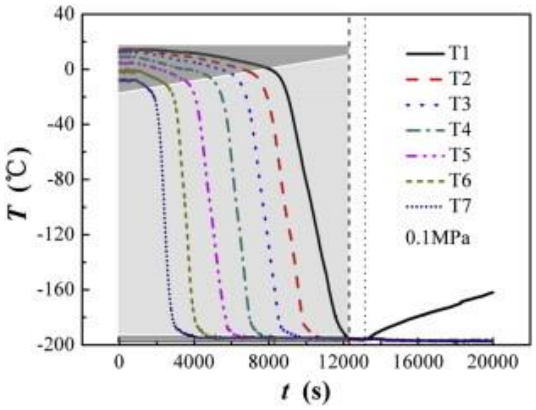


Average Nusselt number vs. Reynolds number at 0.22 MPa and 6.55 MPa

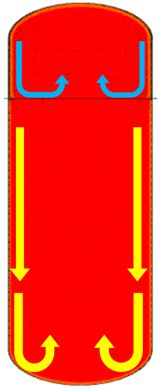
- The higher pressure would decrease the entrance effects on the heat transfer coefficients.
- The modified Yang's' correlation predicts the heat transfer coefficients well under supercritical pressures.

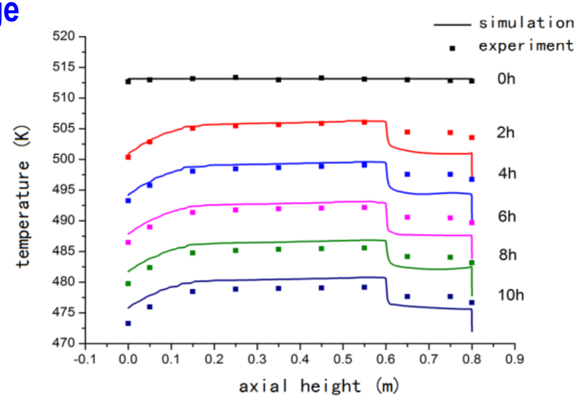
Progress 3: Unsteady behavior and mechanism of flow, heat transfer and storage





Cold Storage





Heat Storage

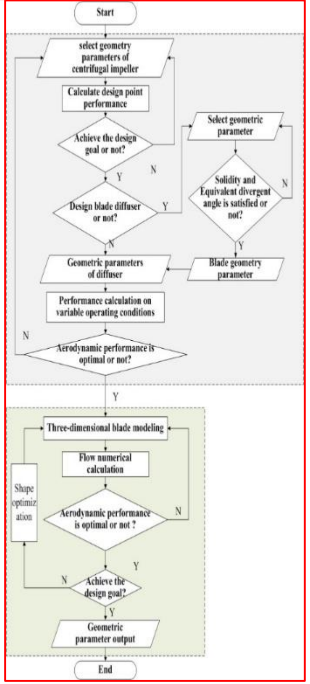
Yang and Chen et al. International Journal of Heat & Mass Transfer, 2017

Contents

IV、Technical Development

Technical Development

Design Software

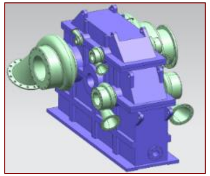
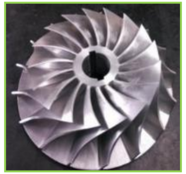


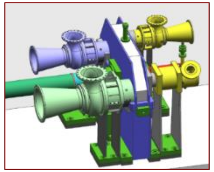
Experimental





Prototype

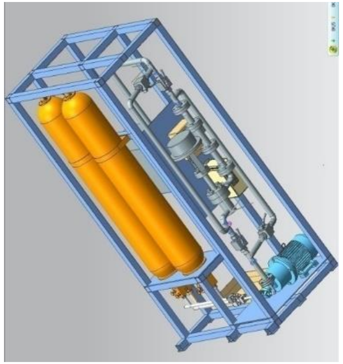



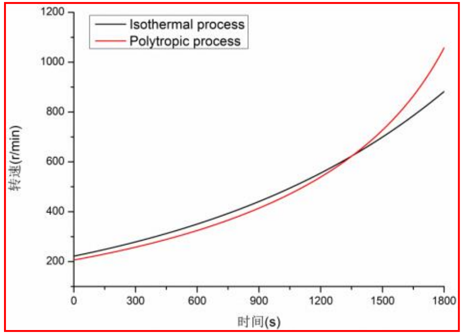



Integration and Demonstration

1． 1kW CAES System

- System Design and Analysis
- Test Rig
- Concept test





Integration and Demonstration

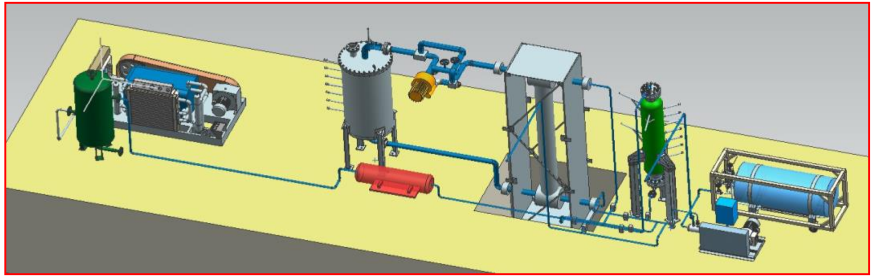
15kW CAES Experimental System

- Fundamental Studies
- Validation for modifications









Integration and Demonstration

The China's First 1.5MW CAES:

- In operation since April 2013
- Over 10000 hours operation in total
- Efficiency is 52.1%
- Over 400 hours continuous operation test

Integration and Demonstration

The World's First 10MW Advanced CAES

- Located in Guizhou Province, China
- In operation since December, 2016
- Efficiency is 60.2%
- Over 4000 hours test operation

Contents

VI、Discussion

Discussion

Performance and Cost Achieved (1.5MW):

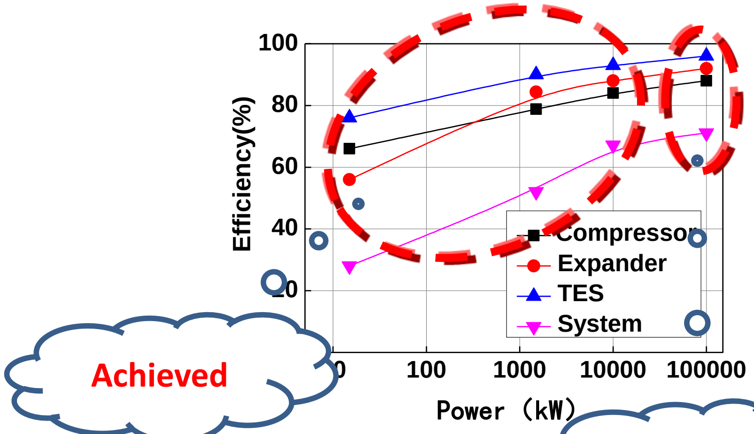
- Power: 1.5MW
- Efficiency: 50-55%
- Cost: 10k/kW (RMB)-2500RMB/kWh
- Area: 500 m^2
- Life: 30 Years

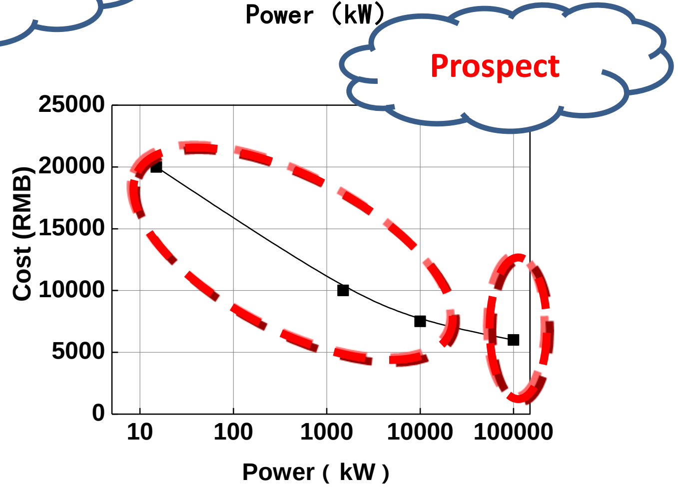
Performance and Cost Achieved(10MW):

- Power: 10MW
- Efficiency: 60-65%
- Cost: 6-8k/kW (RMB)-2000 RMB/kWh
- Area: 2000 m^2
- Life: 40 Years

Performance and Cost Achievable(100MW):

- Power: 100MW
- Efficiency: 65-70%
- Cost: 4-6k/kW (RMB)-1500 RMB/kWh
- Area: 5000 m^2
- Life: 50 Years





Thanks for your attention!

NSFC Newton Fund

To go fast, you may go alone.
To go further, let us go together!

chen_hs@iet.cn 0086-10-82543148

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