天津大学 Tianjin University

天津大学内燃机燃烧学国家重点实验室 (SKLE)

内燃机余热回收循环技术

Waste heat recovery cycle technology for internal combustion engines

汇报人：田 华
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天津大学内燃机燃烧学国家重点实验室副主任

研究领域与方向：内燃机余热回收节能技术，sCO_2发电、先进动力，CO_2冬奥会制冰

主要经历

2002-2010：天津大学，本/硕/博学习

2011-至 今：天津大学内燃机燃烧学国家重点实验室，讲师/副教授/教授/英才教授

科研项目

近五年先后主持**国家重点研发-科技冬奥重点专项项目**、**国家优秀青年基金项目**、**JW科技委某重点专项**、国家重点研发课题、GF973课题等项目，总经费>8000万元。

主要成果及荣誉

获**国家自然科学二等奖**、教育部科学研究优秀成果青年科学奖、天津市自然科学一等奖、以第一/通讯作者发表SCI论文103篇，高被引论文11篇，授权发明专利23项。

汇报提纲 Report outline

天津大學
Tianjin University

01 研究背景及意义
Research background

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Current status of research

03 主要研究进展
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04 结论与展望
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01

研究背景及意义
Research background

1 内燃机是主要的石油消耗源和CO_2排放源
Engines are major source of oil consumption and CO_2 emissions

内燃机—广泛应用于分布式发电和车辆/船舶等移动装置的动力机械。

Internal combustion engine - widely used in distributed power generation and as power machinery for mobile units

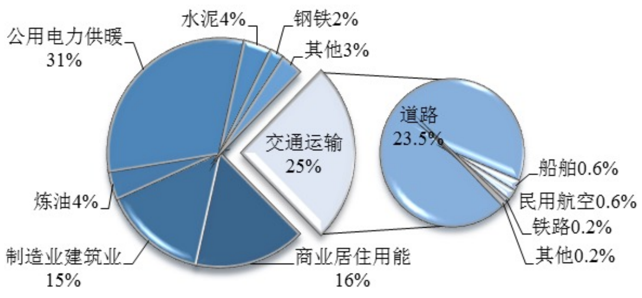
固定式内燃机（分布式发电等）

低速二冲程船用内燃机

移动式内燃机（重载卡车等）

- **我国石油消耗源：>石油总消耗的60%；**
  60% of total oil consumption, in China
- **全球CO_2排放源：移动式内燃机占25%。**
  25% of CO_2 emissions all over the world

我国油气进口输运渠道



欧盟环保署（EEA）2013年报告

内燃机节能对节约能源和CO_2减排有重大意义！

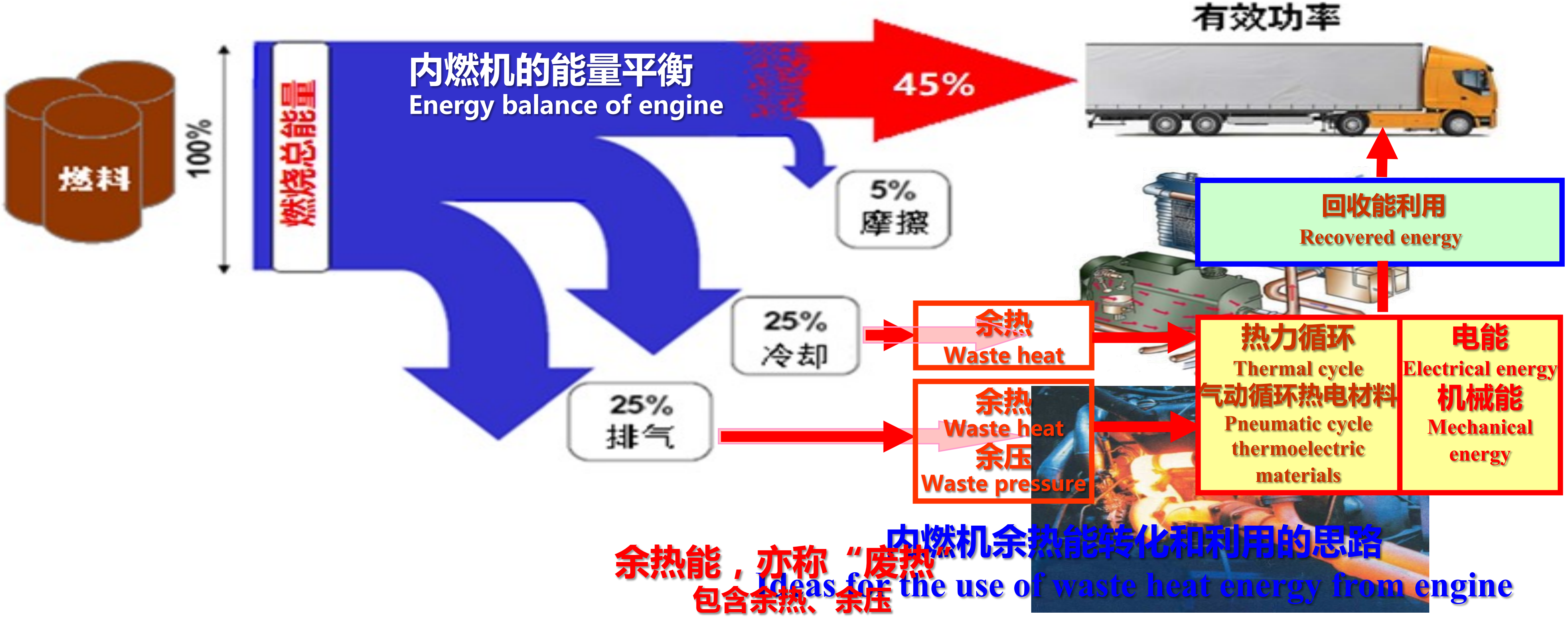
Energy efficiency in engines is of great importance for national energy saving and CO_2 reduction!

1 内燃机仍具有较大的节油潜力

Internal combustion engines still have a large potential for fuel savings

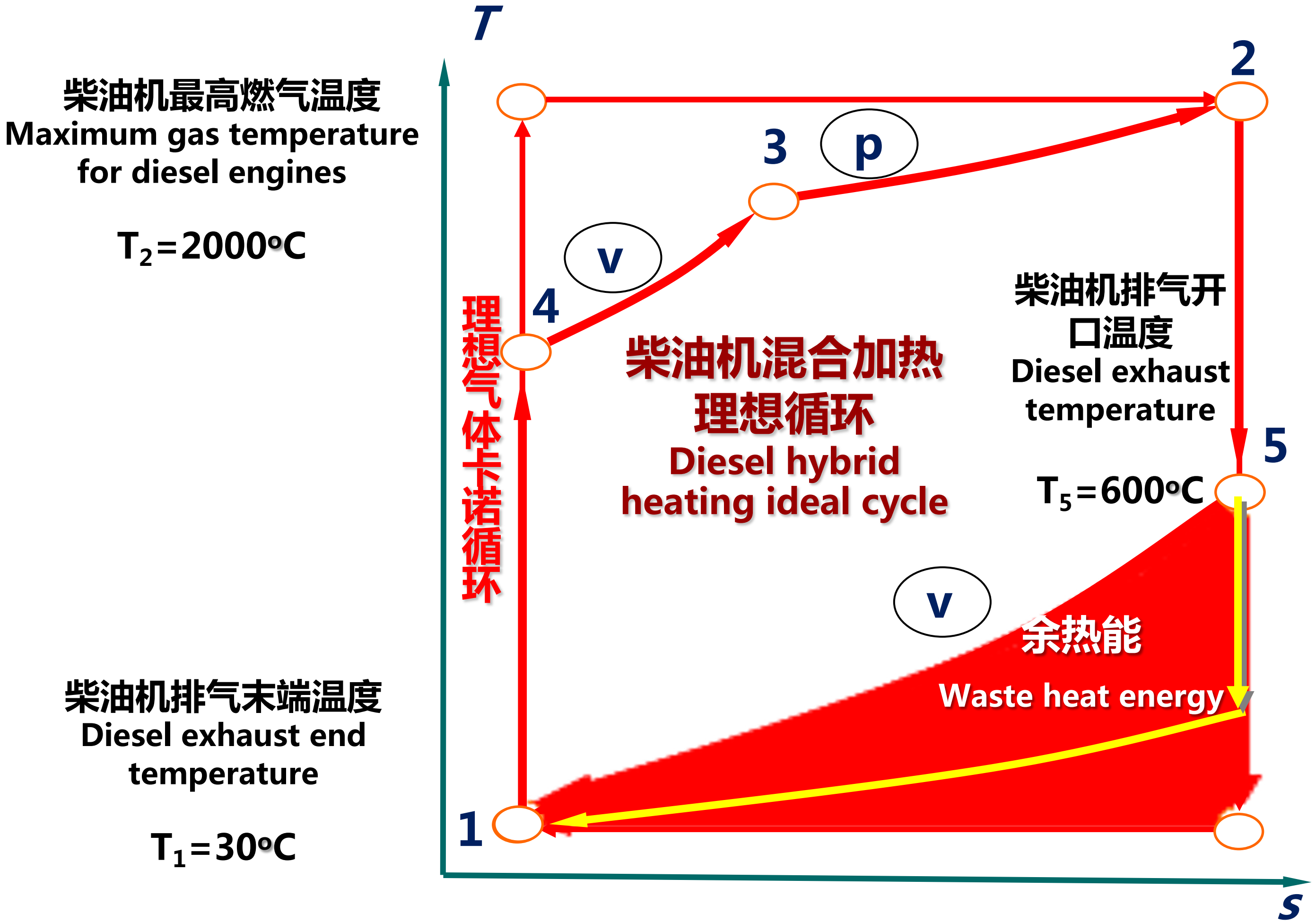
尽管国内外在提高内燃机经济性方面已做了大量的工作，但是预计内燃机仍有25%以上的节油潜力。

It is expected that internal combustion engines still have a fuel saving potential of over 25%.



余热能，亦称"废热"
包含余热、余压
Waste heat energy, also known as "waste heat"
Includes waste heat, waste pressure

1 余热能回收是提升效率的有效途径
Waste heat energy recovery is an effective way to improve efficiency



<u>内燃机余热回收的热力学原理</u>

<u>Thermodynamic principles of WHR from engine</u>

卡诺循环效率：

Carnot cycle efficiency:

$$\eta_c = 1 - \frac{T_1}{T_2} = 86.4\%$$

柴油机混合加热理想循环效率：

Diesel mixed heating ideal cycle efficiency:

$$\eta_d = 1 - \frac{1}{\varepsilon_c^{k-1}} \frac{\lambda_p \rho_0^k - 1}{\lambda_p - 1 + k\lambda_p(\rho_0 - 1)} = 64.4\%$$

传热、强度等限制，实际效率：

35-40%(汽油机); 42%-45%(柴油机)

Limitations, actual efficiency:

35-40% (gasoline engines); 42%-45% (diesel engines)

余热能回收是提升效率的重要途径！

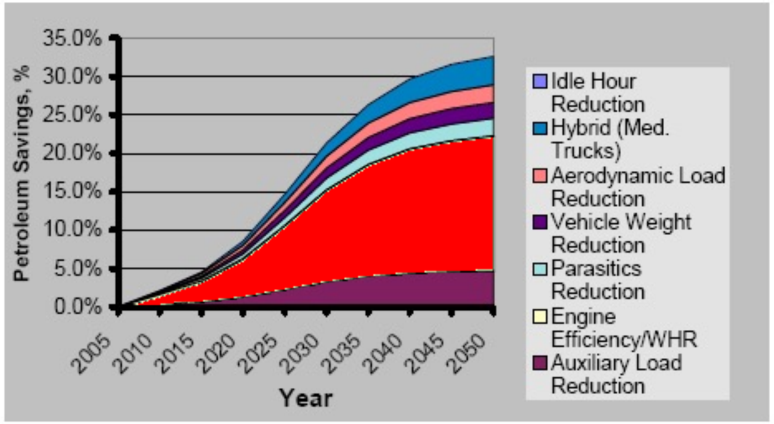
Waste heat energy recovery is an important way to improve efficiency!

1 余热能回收被认为是内燃机关键技术

Waste heat energy recovery is considered a key technology for engines

Exhibit ES-6:
Petroleum Reduction due to FCVT Technologies as a Percentage of Base Consumption

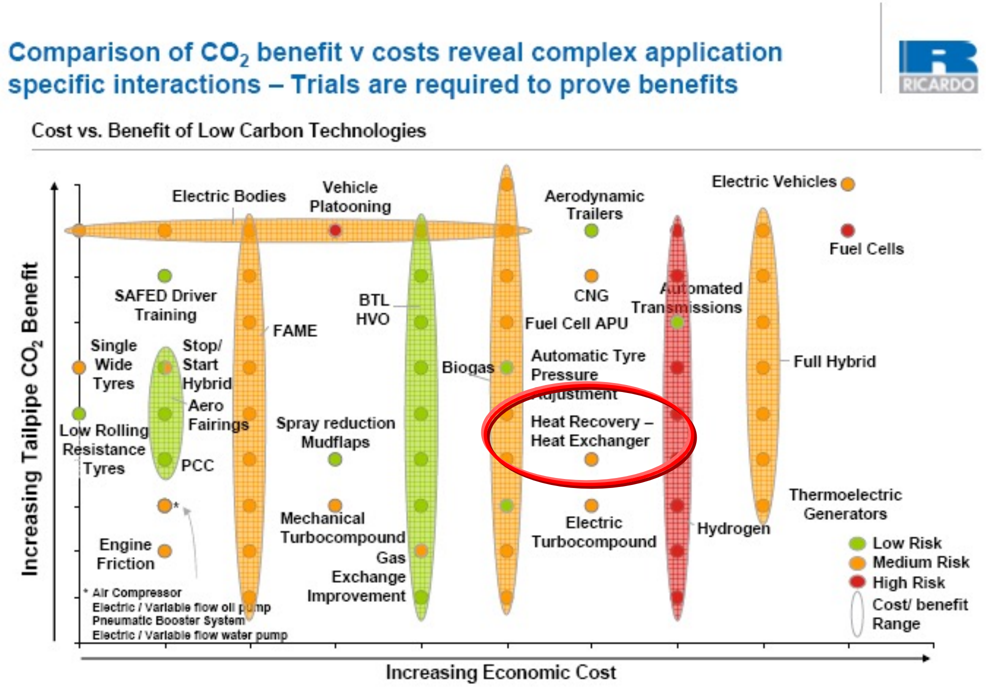
Characteristic	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Auxiliary Load Reduction	0.0%	0.4%	0.7%	1.4%	2.3%	3.3%	4.1%	4.5%	4.7%	4.8%
Idle Hour Reduction	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Engine Efficiency/WHR	0.0%	1.3%	2.6%	4.9%	8.3%	11.9%	14.5%	16.1%	16.9%	17.4%
Parasitics Reduction	0%	0.2%	0.3%	0.6%	1.1%	1.5%	1.9%	2.1%	2.2%	2.3%
Vehicle Weight Reduction	0%	0.1%	0.3%	0.5%	0.9%	1.3%	1.6%	1.9%	2.0%	2.1%
Aerodynamic Load Reductior	0%	0.2%	0.3%	0.6%	1.1%	1.5%	1.9%	2.1%	2.2%	2.3%
Hybrid (Med. Trucks)	0%	0.1%	0.2%	0.5%	1.1%	1.7%	2.4%	3.1%	3.5%	3.7%
Totals:	0%	2%	5%	9%	15%	21%	26%	30%	32%	33%



美国Argonne国家实验室的技术分析预测

- **美国Argonne国家实验室: 内燃机余热能利用具有最大节能潜力; (2013)**

  Argonne National Laboratory: Waste heat energy use in engines has the greatest potential for energy savings; (2013)



英国RICARDO公司关于CO_2减排的技术预测
RICARDO UK's technology forecast on CO_2 reduction

- **英国RICARDO公司: 内燃机余热能利用具有显著的CO_2减排效应; (2013)**

  RICARDO, UK: Waste heat from internal combustion engines can significantly reduce CO_2 emissions; (2013)

1 国内外政府开展内燃机余热回收研究

Various governments conduct research on waste heat recovery from engines

欧盟第七框架行动计划：
“HeatReCar” （2009-2011），汽车发动机余热利用计划。

EU Seventh Framework Action Plan:
“HeatReCar” （2009-2011）

中国973计划:
2010年，高效、节能、低碳内燃机余热能梯级利用基础研究舒歌群教授-首席科学家

China 973 Program:
2010, WHR Basic Research. Prof. Gequn Shu - Chief Scientist

欧盟第七框架行动计划：
“NOWASTE” （2011-2015），车用发动机余热回收再利用计划。

EU Seventh Framework Action Plan:
“HeatReCar” （2011-2015）

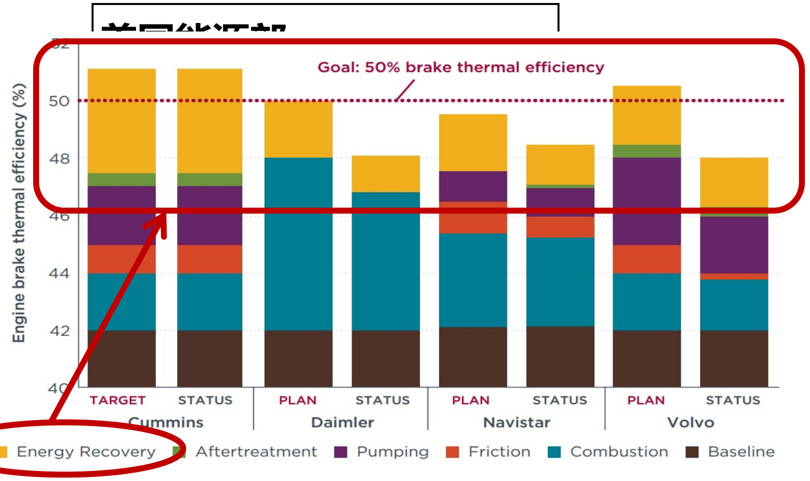
中美卡车联盟：
超级卡车国际合作计划Ⅰ期（2018-2021）：余热回收是研究方向之一。
舒歌群教授-负责人

Supertruck I (2018-2021): waste heat recovery is one of the research directions.

2009 2010 2011 2016 2018 2021 2024

美国能源部：
2010年1月：重型卡车和乘用车效率提高的研究计划（超级卡车计划）-余热能回收利用是技术重点。

US Department of Energy:
January 2010: Waste heat energy recovery is a technology priority.



中美卡车联盟：
超级卡车国际合作计划Ⅱ期（2022-2024）：将继续开展余热回收研究。
舒歌群教授-负责人

Supertruck Ⅱ (2022-2024): waste heat recovery is still one of the research directions.

余热能回收是内燃机效率55%的必然途径！

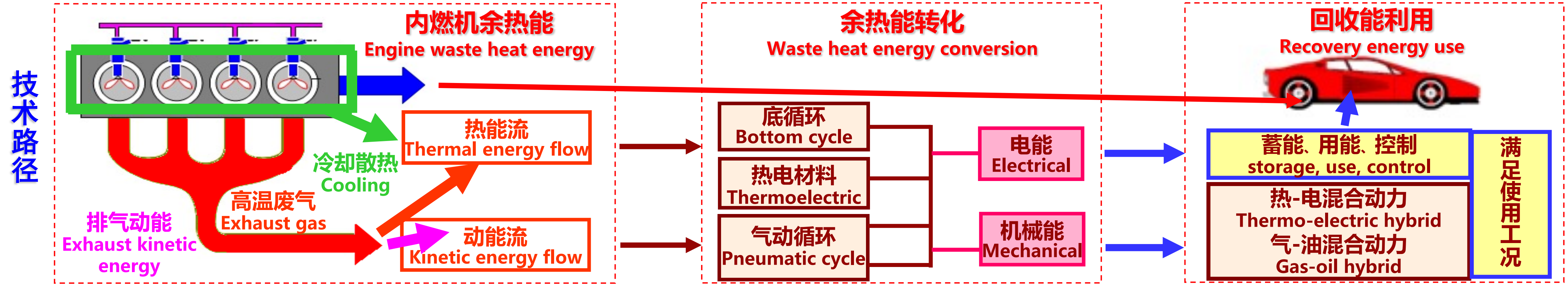
Waste heat energy recovery is the sure way to reach 55% efficiency in engine!

1 我国政府开展内燃机余热回收研究

Chinese government launches research on waste heat recovery from engines

- **中国973计划:** 2010年，高效、节能、低碳内燃机余热能梯级利用基础研究获批。

  China's 973 Program: In 2010, the basic research on efficient, energy-saving and low-carbon engine waste heat energy utilization was approved.



- **中美合作：**2015年9月，新启动一个提高中载至重载卡车能效的技术合作领域。（2018-2020）

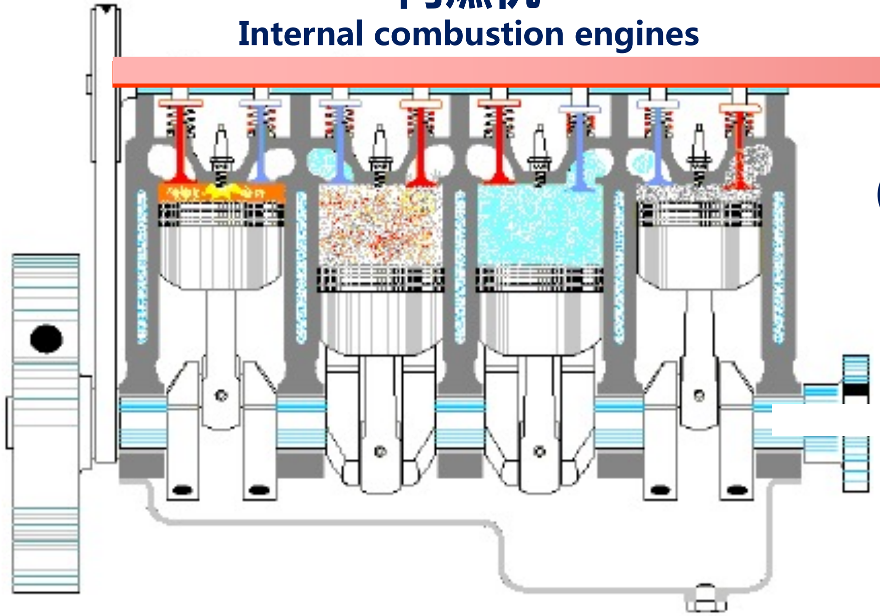
  U.S.-China cooperation: a new area of technical cooperation to improve the energy efficiency of medium- to heavy-duty trucks.

02

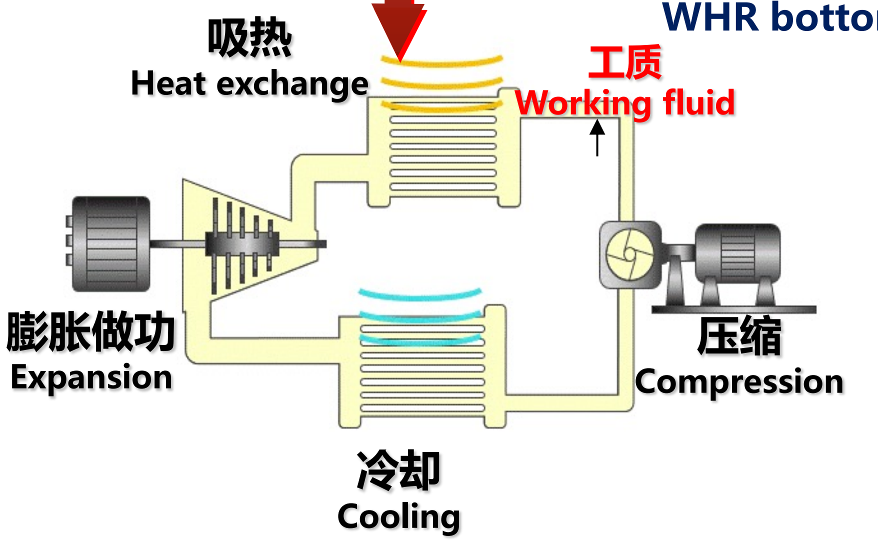
国内外研究现状
Current status of research

2 基本原理

Basic principles



（顶循环）
(top cycle)



内燃机循环复合循环
Combined cycle for internal combustion engines

内燃机顶循环
Engine top cycle
+
余热回收底循环
WHR bottom cycle

（底循环）
(bottom cycle)

nature
International journal of science

Nature, 2012, 488:294-303

内燃机余热能回收可提高效率，特别对重型卡车，方法包括使用**朗肯循环将余热转化为功。**

Approaches include use of the **Rankine cycle** to convert waste heat to work..

朱棣文
诺贝尔奖获得者
前美国能源部长

2 欧美发达国家纷纷开展底循环研究

Developed countries have been conducting research on bottom cycle

瑞典 Sweden

Volvo

[2021，WHR-ORC， Improve BTE 3%]

奥地利 Austria

AVL

[2016，WHR-ORC， Improve BTE 1.3%]

德国 Germany

Bosch

[2012，WHR-ORC， Improve BTE 2.25%]

美国 USA

Cummins

[2021，WHR-ORC， Improve BTE 4.3%]

Daimler

[2021，WHR-ORC， Improve BTE 3.6%]

Eaton

[WHR-ORC， Improve BTE 2.7%]

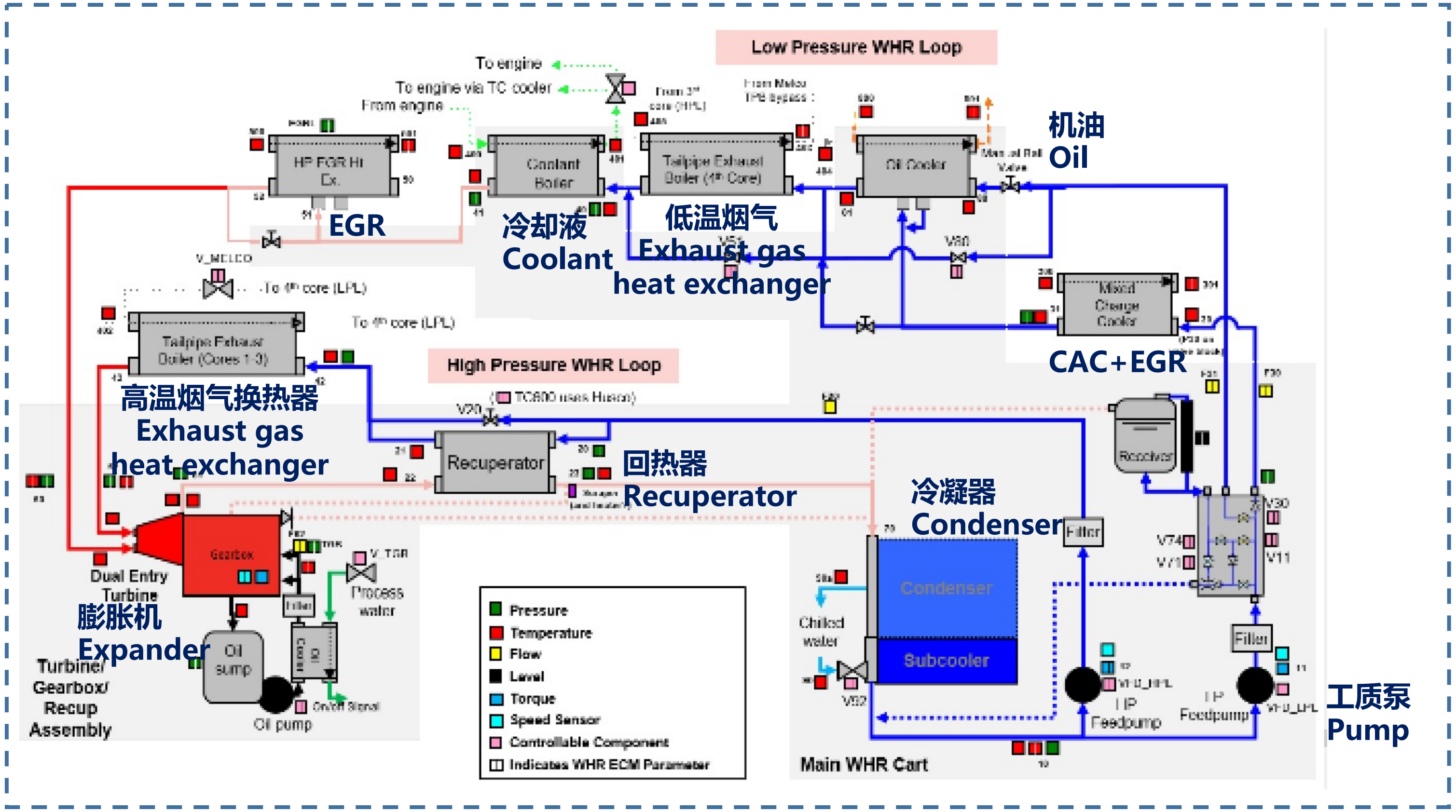
国内外广泛车企投入到内燃机余热回收ORC领域！

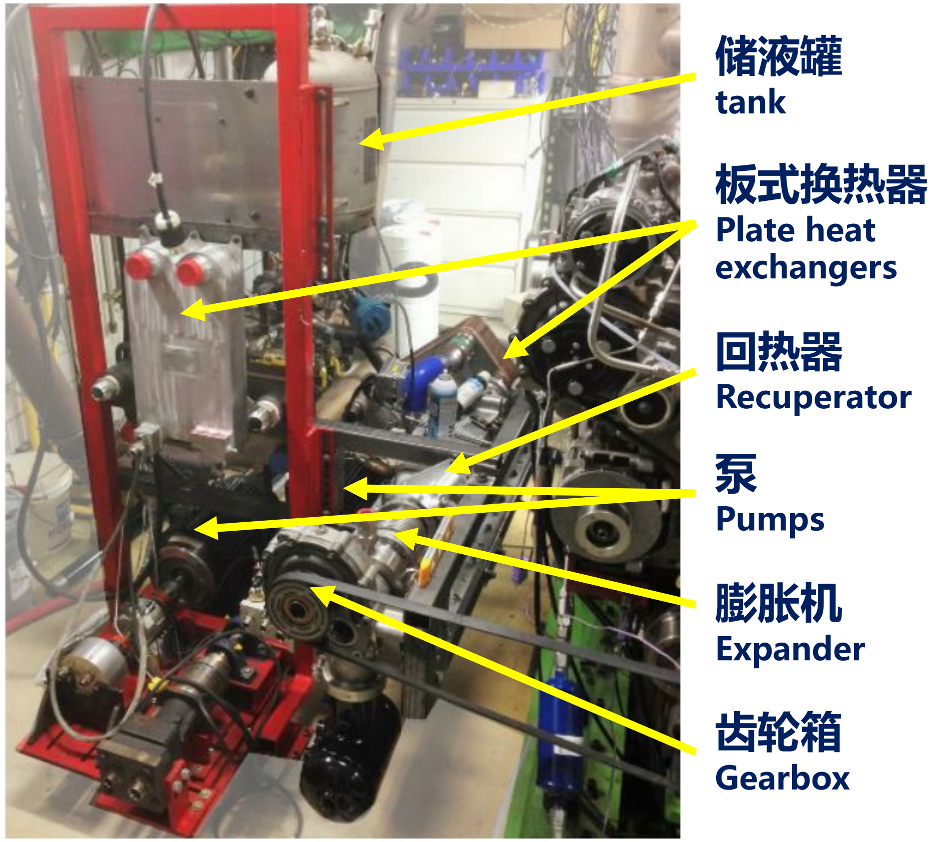
National vehicle companies invest in internal combustion engine waste heat recovery ORC!

2 国内外企业开展内燃机余热回收研究

Companies in various countries conduct research on WHR from engines

□Cummins, USA - SuperTruck II





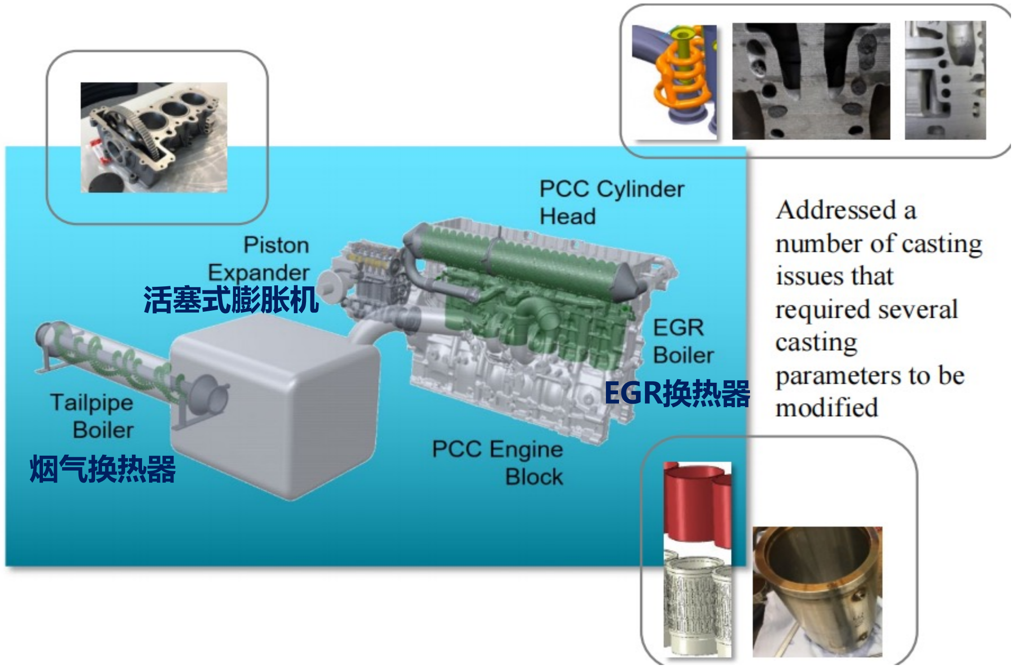
➢ 双压循环台架测试，净输出功19.3kw，**BTE提升4.3%。**

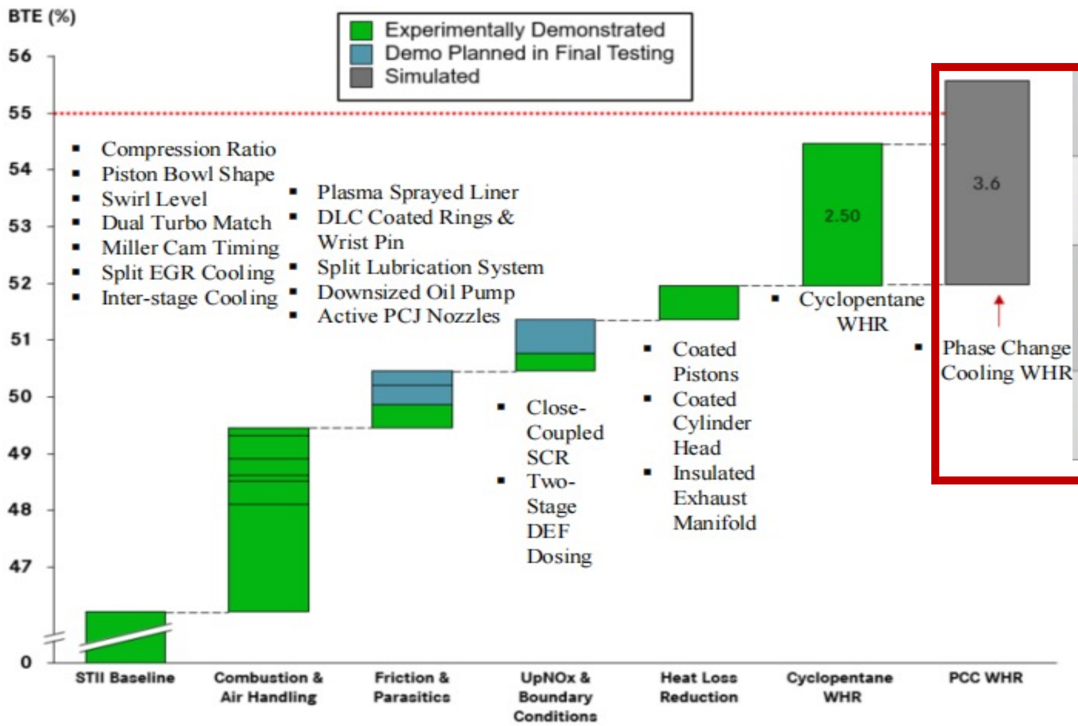
Dual pressure cycle bench, 19.3kw net output power, **4.3% BTE improvement.**

2 国内外企业开展内燃机余热回收研究

Companies in various countries conduct research on WHR from engines

□Damiler, USA- SuperTruck II





Fluid	Water – ethanol mix (60%/40%)
Pressure	50 bar
Temperature	305°C
Vapor Power	159 kW

➢ 回收烟气余热及EGR余热，经实验测试**可提升BTE3.6%，达到55%的目标。**

Recovery of exhaust gas waste heat and EGR waste heat, **3.6% BTE improvement, Reaching the 55% target.**

2 国内外企业开展内燃机余热回收研究
Companies in various countries conduct research on WHR from engines

□Eaton, USA

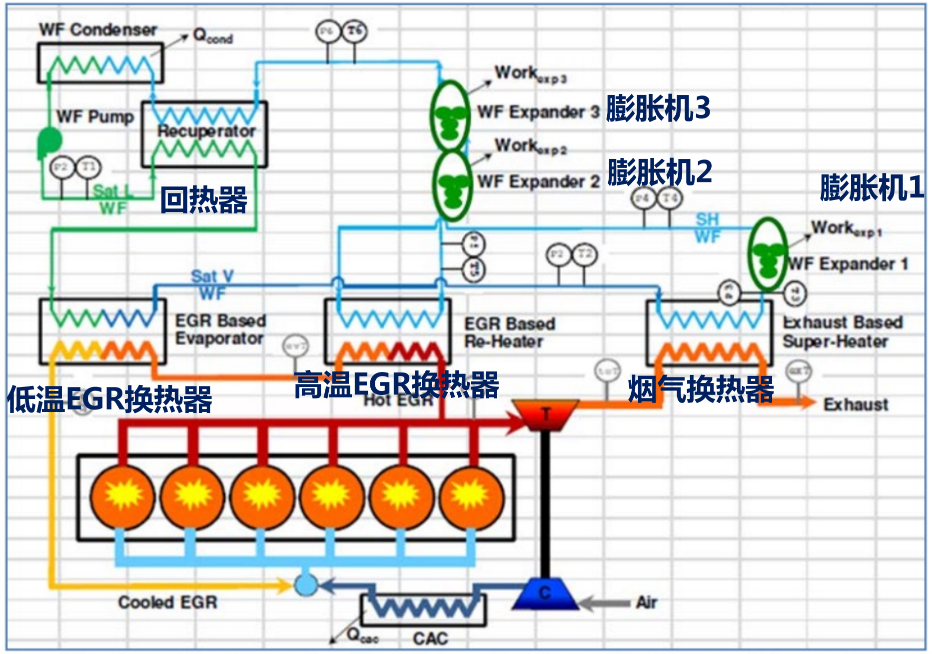


Figure 10: Architecture 4 – Rankine Cycle with Three Stage Expander


烟气换热器
Flue gas heat exchanger

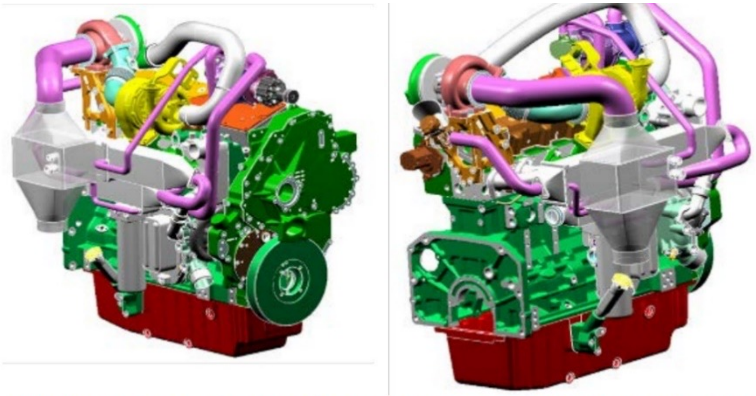

三级膨胀机
Expander


储液罐及工质泵
tank and pump


烟气管路
Flue gas piping


回热器及旁通阀
Regenerator and bypass valve


冷凝器
Condenser

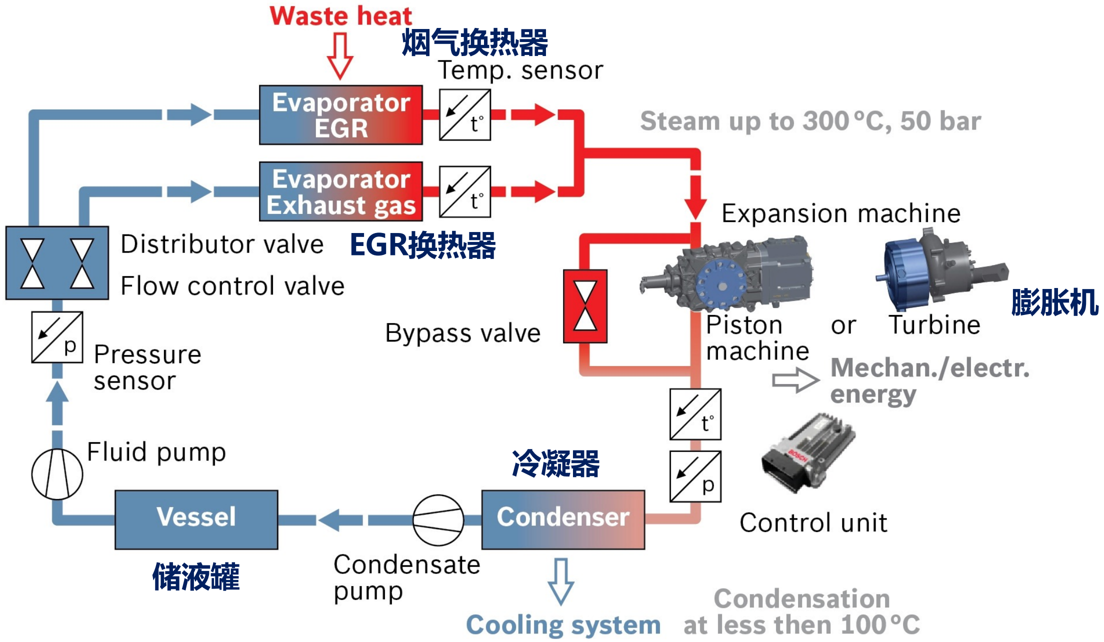

13.5L发动机有机朗肯循环系统三维图
3D view of the organic Rankine cycle for the 13.5L engine

- 回收烟气和EGR余热，采用回热-多级膨胀系统，经实验测试**可提升发动机BTE约2.7%**。
  Recovery of flue gas waste heat and EGR waste heat, reheat - multi-stage expansion system, **2.7% BTE improvement**

国内外企业开展内燃机余热回收研究

Companies in various countries conduct research on WHR from engines

□Bosch, Germany



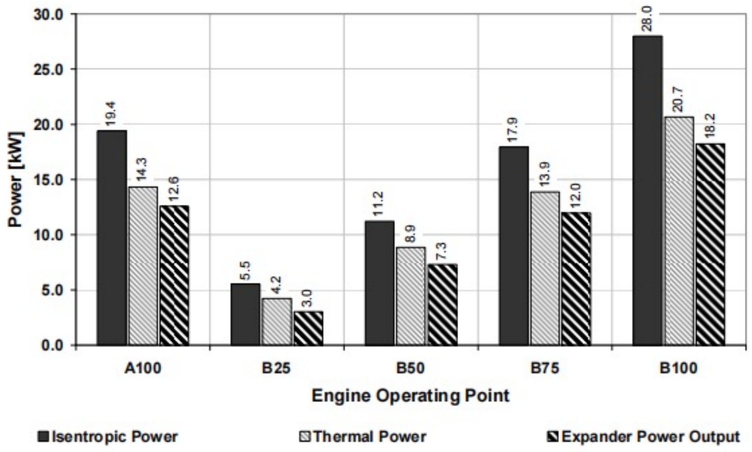


Fig. 5: Calculated power output of the piston machine with water as working fluid

- 烟气和EGR并列为热源，膨胀设备采用活塞式膨胀机；

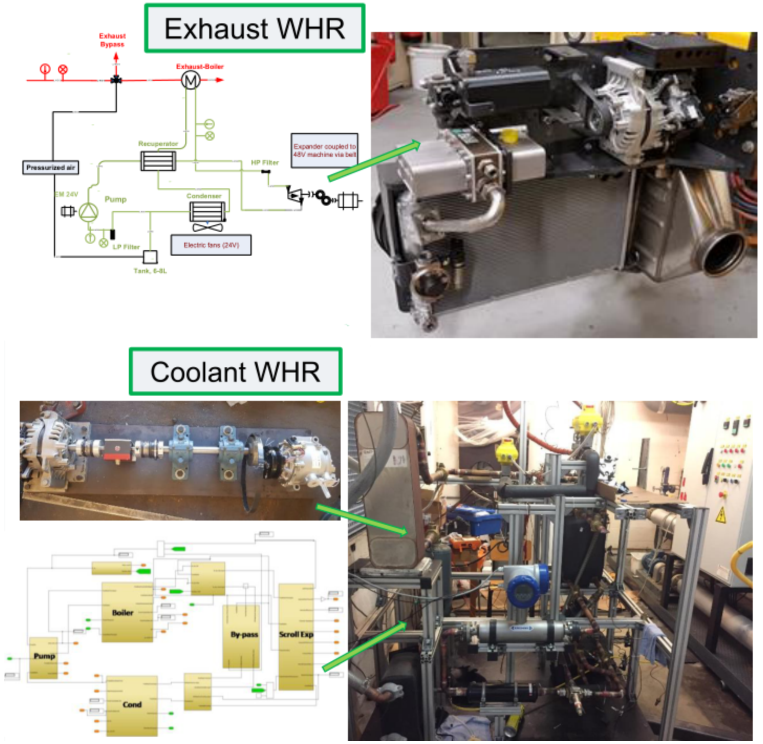
  Recovery of exhaust gas and EGR heat, piston expander.

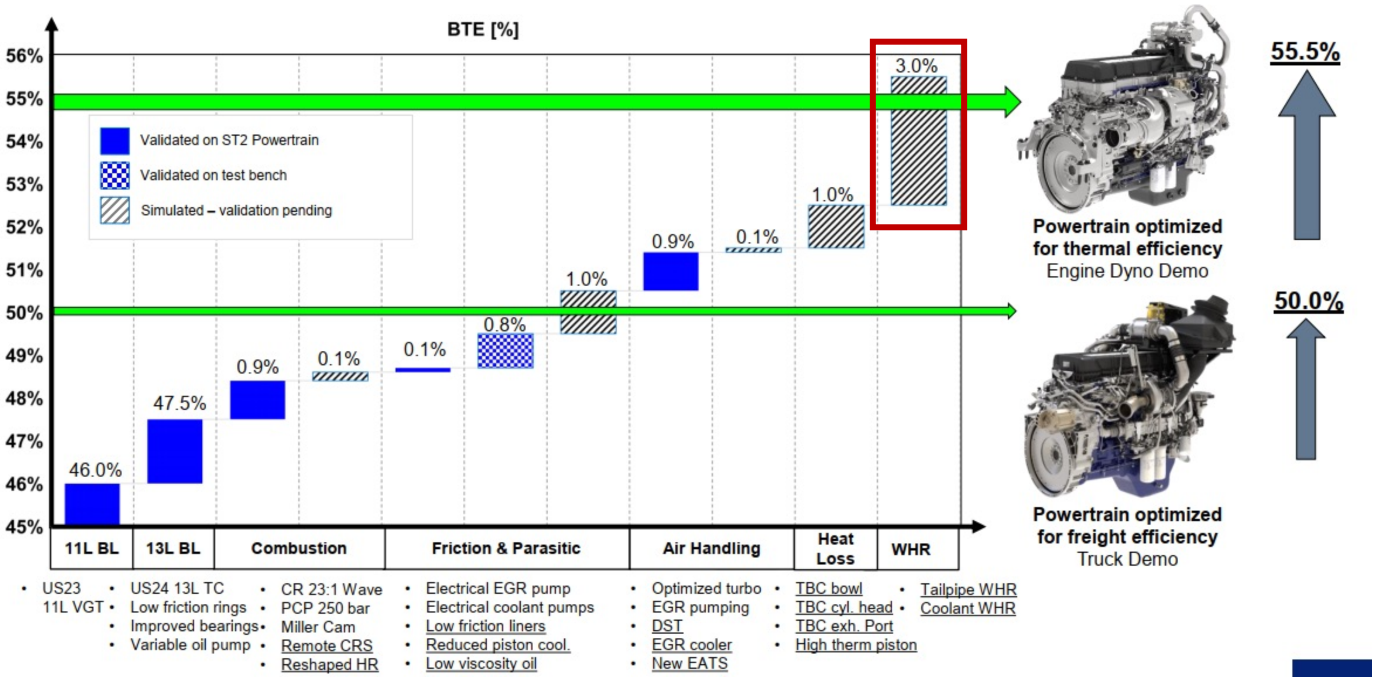
- 活塞式膨胀机的有效输出功率为12 kW，最高可提升BTE约2.25%。

  an effective output of 12 kW and can boost BTE by up to approximately 2.25%.

国内外企业开展内燃机余热回收研究
Companies in various countries conduct research on WHR from engines

□Volvo, Sweden





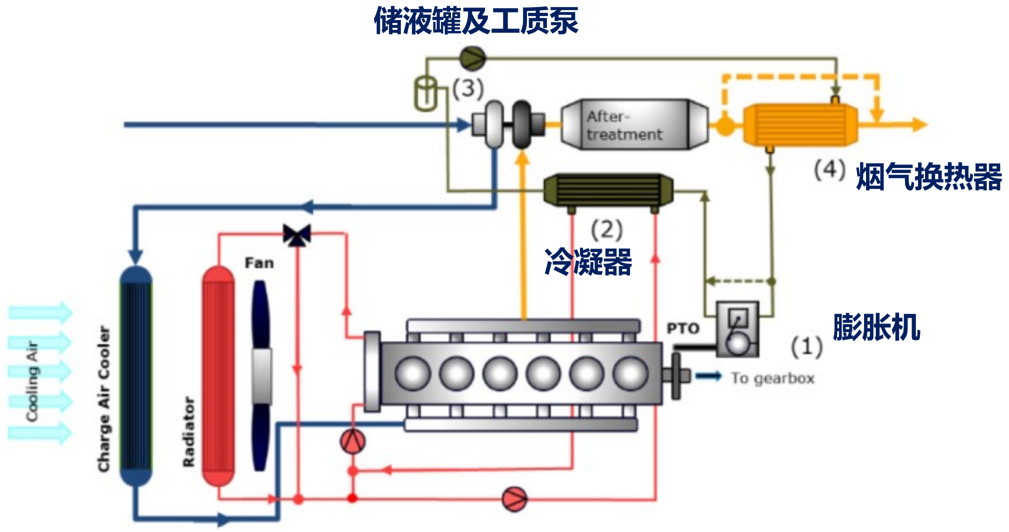
➢ **采用双回路余热回收ORC系统，余热回收系统整体实现BTE提升3%，助力实现55%。**

Dual loop ORC-WHR system, 3% BTE improvement, Engine BTE up to 55%

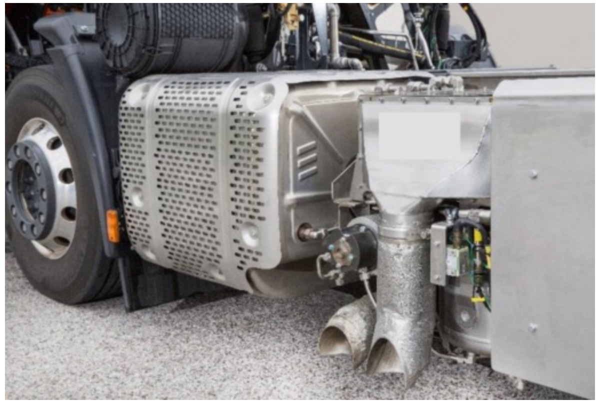
2 国内外企业开展内燃机余热回收研究

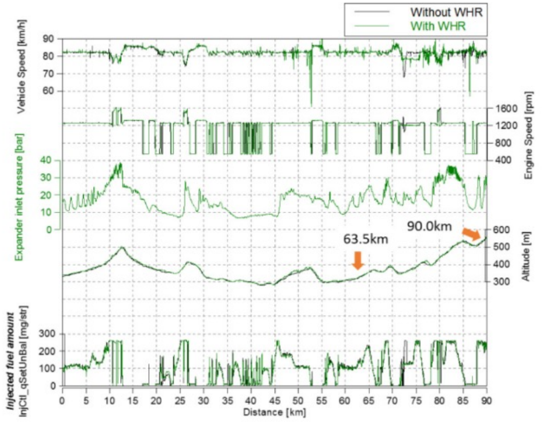
Companies in various countries conduct research on WHR from engines

□AVL, Austria



Piston Expander with bypass (1)
Condenser (2)
Reservoir and pump (3)
Exhaust Evaporator with bypass (4)
Expander mechanically connected to Power Take-off (PTO)





- ➢ **该系统仅回收烟气余热，测试结果表明：余热回收系统实现BTE提升约1.3%。**

  Test results show that the waste heat recovery system achieves a BTE improvement of approximately 1.3%.

03

主要研究进展
Research Progress

3 主要进展

Research Progress

主要进展1 低压蒸发单级有机朗肯循环（Relay evaporation single stage ORC）

以高效回收、小型化与集成化为目标，提出低压蒸发单级有机朗肯循环系统

主要进展2 双级多分流有机朗肯循环技术（Two-stage multi-flow ORC）

以多余热源高效回收为目标，提出按质用能的思想， 构建双级多分流ORC系统

主要进展3 热源匹配跨临界CO_2分流循环（Trans-critical CO_2 split-flow power cycle ）

以高效回收、小型化与集成化为目标构建跨临界CO_2分流型动力循环

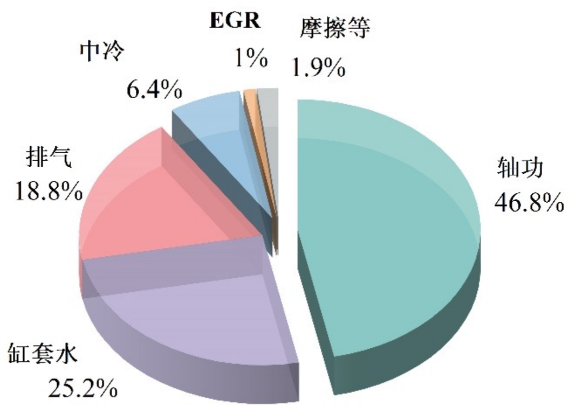
主要进展4 多热源匹配跨临界CO_2双分流循环（Trans-critical CO_2 dual-split power cycle ）

以进一步提高多余热源回收效率为目标， 构建跨临界CO_2二次分流型动力循环

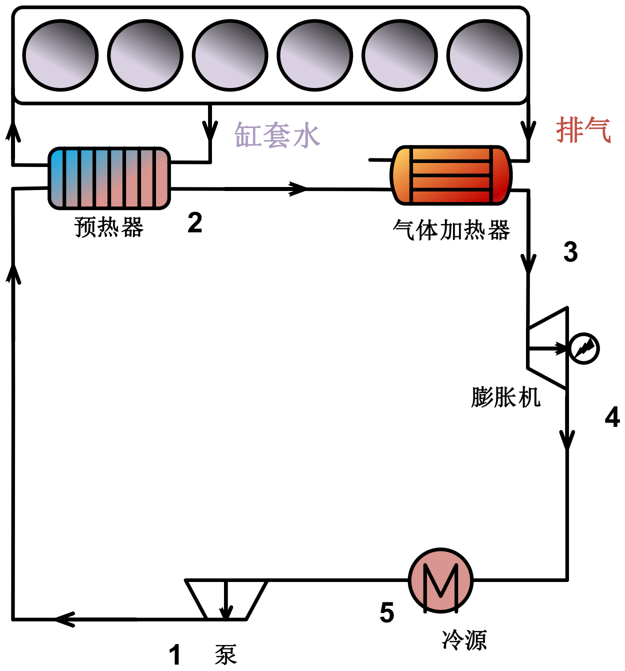
主要进展1-低压蒸发单级ORC技术
Progress 1 - Relay evaporation single stage ORC technology

复合热源适配系统和工质
Compound heat source adaptation system and working fluid

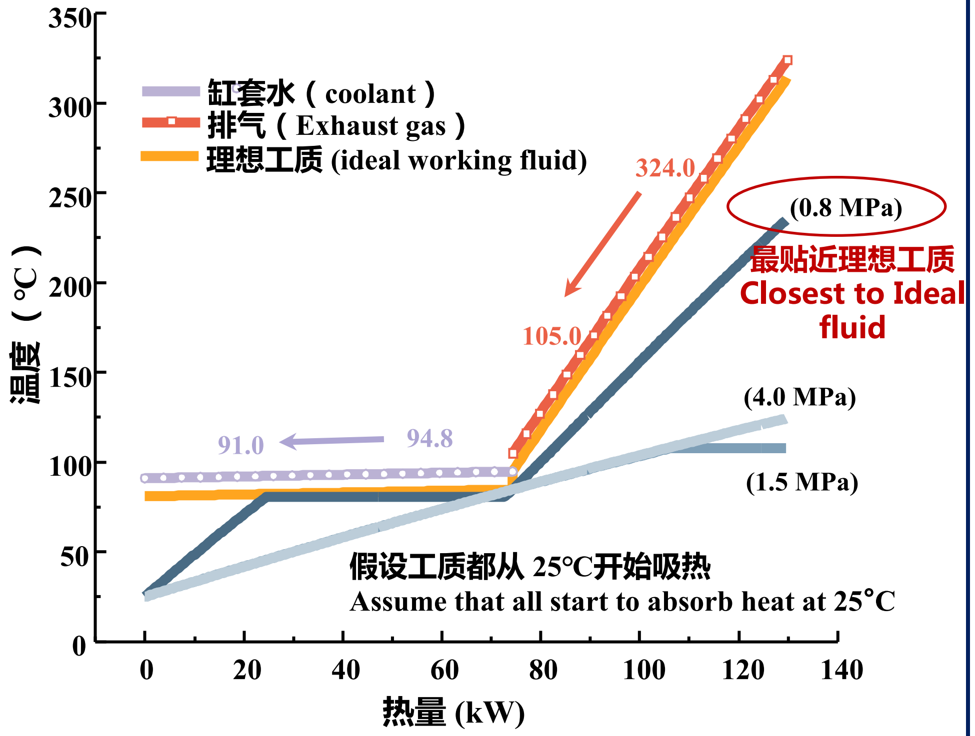
□ 低压蒸发吸热曲线更加贴近理想工质
The heat absorption curve of R245fa under low pressure evaporation is closer to the ideal working fluid



某柴油机常用工况能流分布
Energy flow distribution of a engine



简单单级有机朗肯循环系统结构
Simple single-stage ORC system construction



不同工质吸热曲线
Heat absorption curves for different working fluids

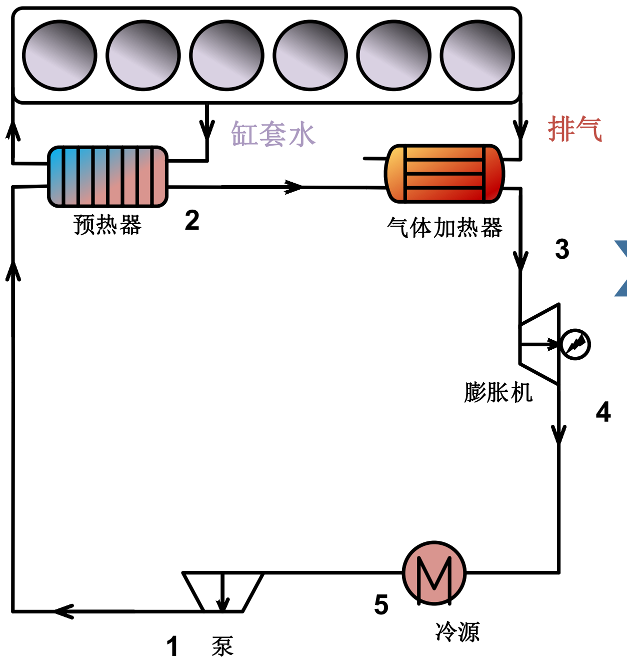
3 主要进展1-低压蒸发单级ORC技术

Progress 1 - Relay evaporation single stage ORC technology

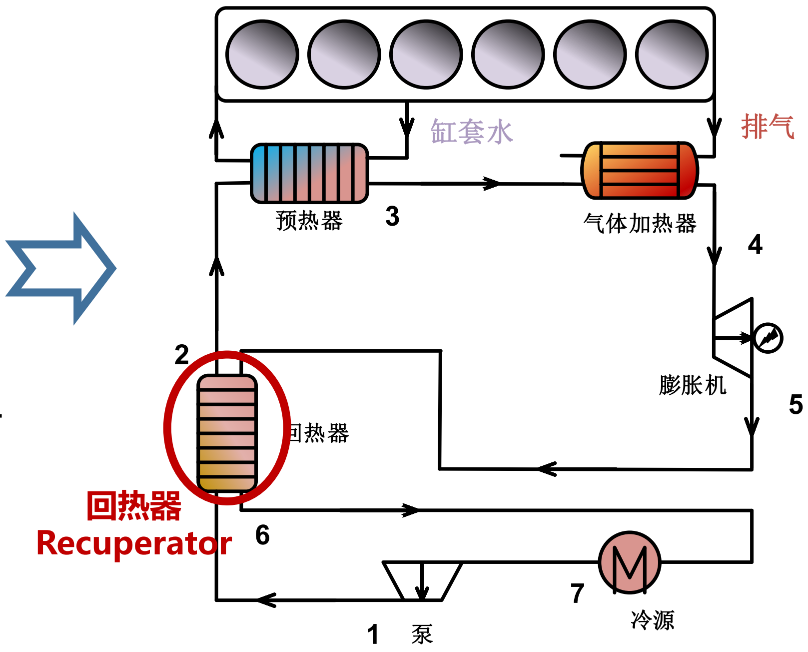
系统方案优化
Optimize system configuration

□ 回热设置进一步提升系统热效率

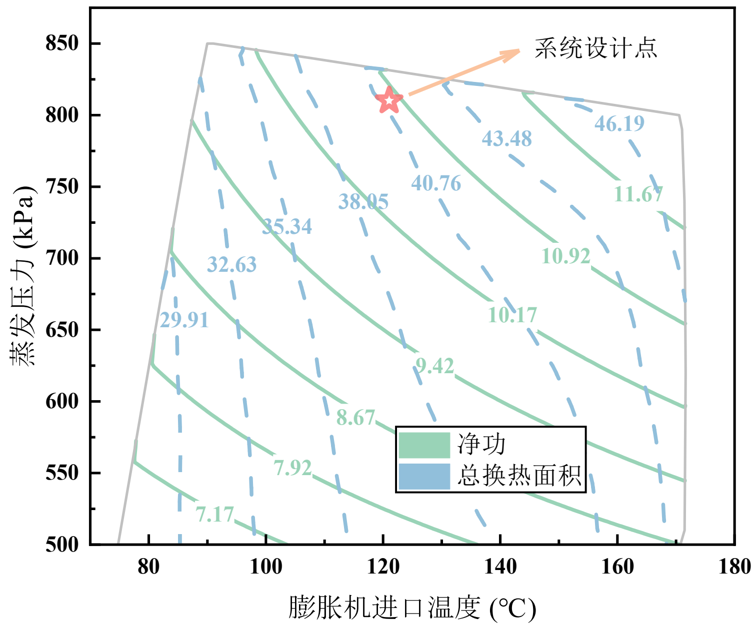
Regenerator further improves the thermal efficiency of the system



简单单级有机朗肯循环系统结构
Simple single-stage ORC system construction



带有回热器的单级有机朗肯循环系统结构
Single-stage ORC system construction with recuperator



净功和换热面积协同优化确定系统设计点
Synergistic optimisation of W_{net} and A to determine system design point

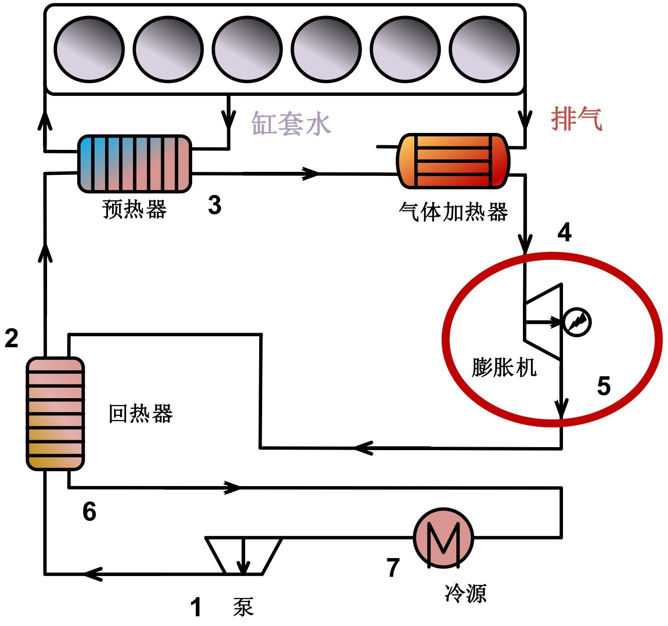
3 主要进展1-低压蒸发单级ORC技术

Progress 1 - Relay evaporation single stage ORC technology

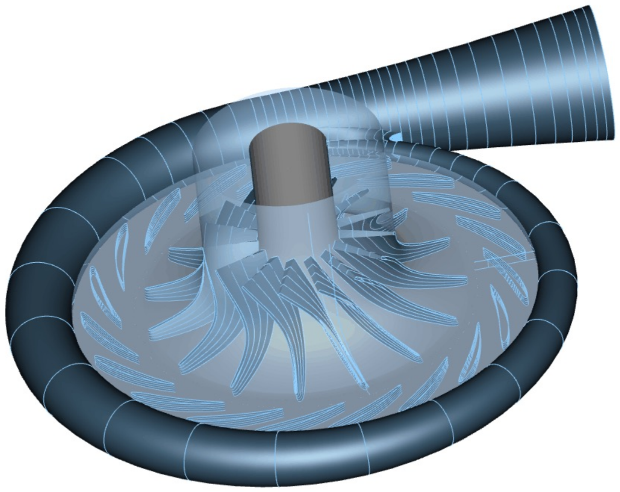
关键部件优化设计
Optimised design of key components

ロ对系统关键部件——透平膨胀机进行优化设计及样机加工

Design and process the key component turbine



单级有机朗肯循环系统结构
Single-stage ORC system construction



建立ORC径流式高速透平膨胀机三维设计方法
Establishing three-dimensional design method for ORC turbine

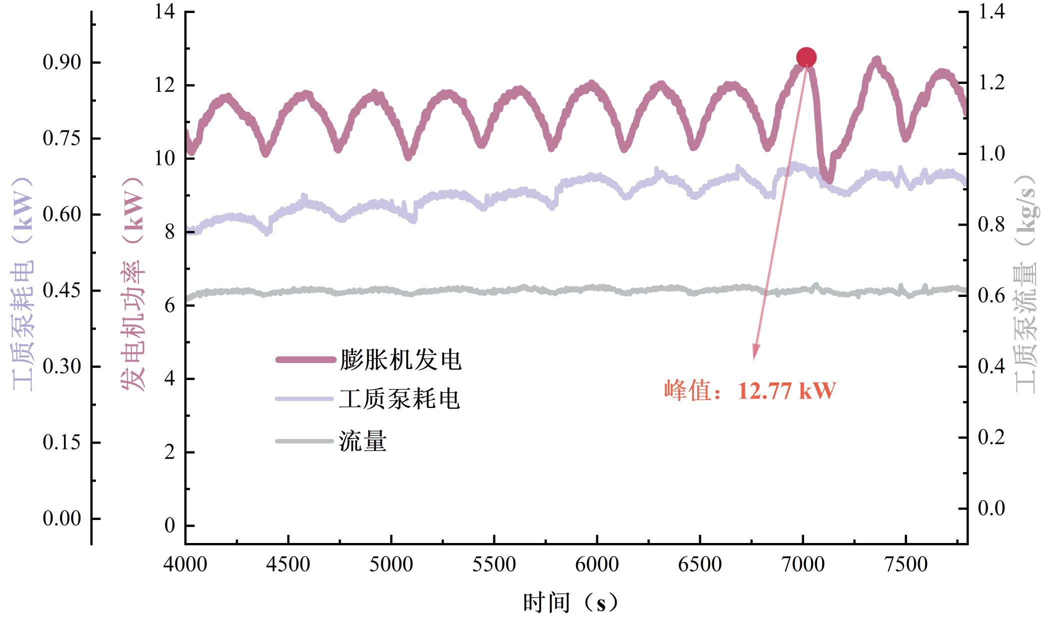
ORC向心透平样机，轻量化程度高，约35kg
Production of a 10kW ORC turbine, 35kg

3 主要进展1-低压蒸发单级ORC技术
Progress 1 - Relay evaporation single stage ORC technology

样机搭建及测试
Test bench construction and testing

- 系统最高发电量12.7kW，可提升发动机BTE3.7%。
  System power generation of 12.7kW, which improves engine BTE by 3.7%.

低压蒸发单级有机朗肯循环样机测试平台
Low pressure evaporation single stage ORC system bench



初步测试结果
Preliminary test results

3 主要进展

Research Progress

主要进展1 低压蒸发单级有机朗肯循环（Relay evaporation single stage ORC）

以高效回收、小型化与集成化为目标，提出低压蒸发单级有机朗肯循环系统

主要进展2 双级多分流有机朗肯循环技术（Two-stage multi-flow ORC）

以多余热源高效回收为目标，提出按质用能的思想， 构建双级多分流ORC系统

主要进展3 热源匹配跨临界CO_2分流循环（Trans-critical CO_2 split-flow power cycle ）

以高效回收、小型化与集成化为目标构建跨临界CO_2分流型动力循环

主要进展4 多热源匹配跨临界CO_2双分流循环（Trans-critical CO_2 dual-split power cycle ）

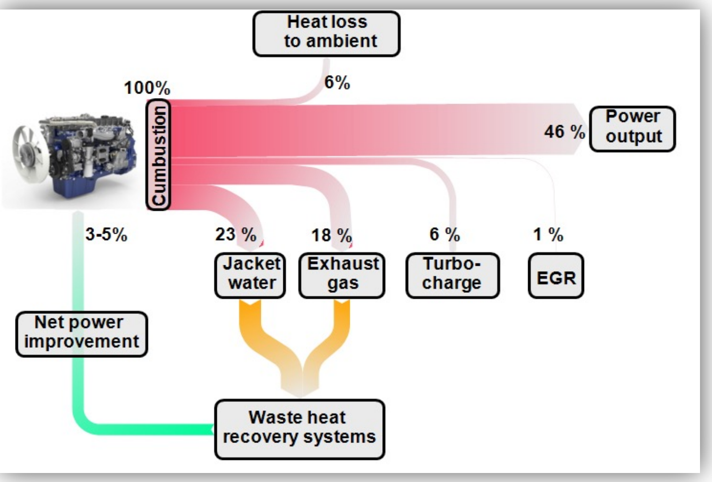
以进一步提高多余热源回收效率为目标， 构建跨临界CO_2二次分流型动力循环

3 主要进展2-双级多分流ORC技术

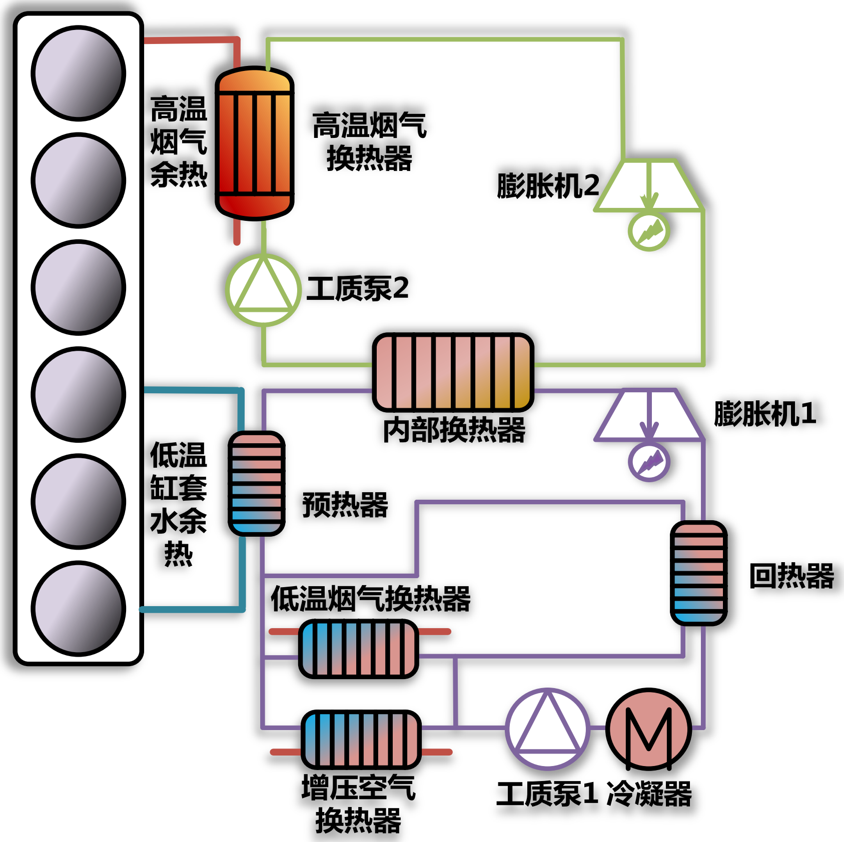
Progress 2 - Two-stage multi-flow ORC

首次提出使用双级多分流ORC动力循环
First proposal to use two-stage multi-flow ORC power cycle

□ **针对内燃机余热按品位分级设计循环，实现按质用能。**
The cycle is designed according to the quality of the waste heat to achieve energy use according to quality.



充分利用
Full use

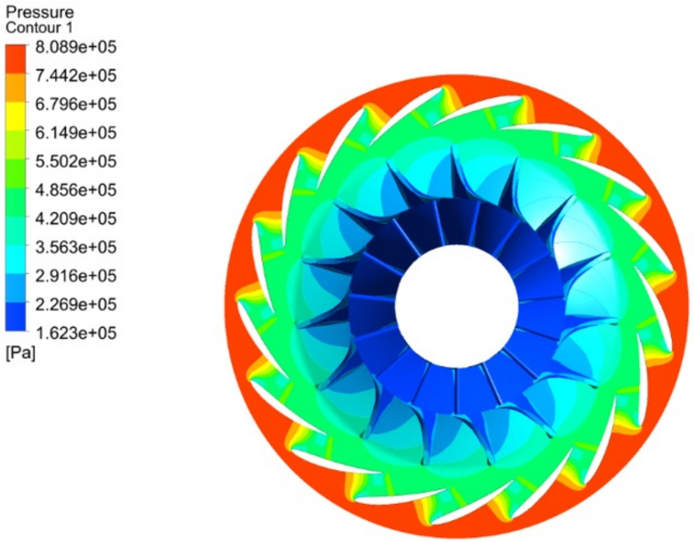


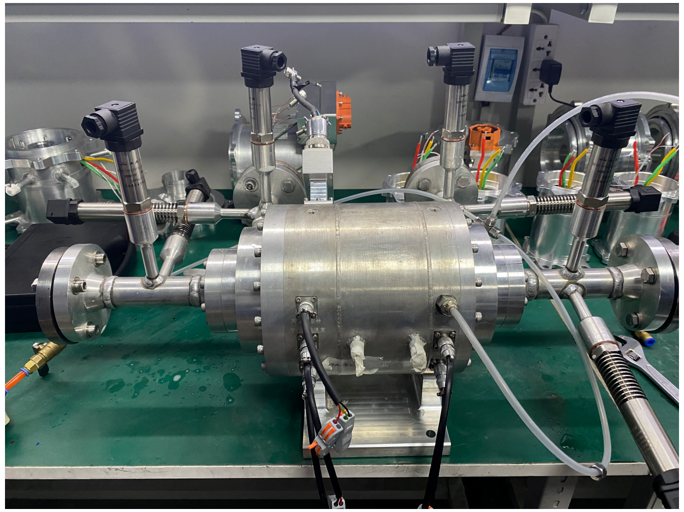
内燃机余热源 Waste heat source			
缸套水热源温区 Coolant temperature	70~90℃	排气热源温区 Exhaust gas temperature	200~500℃
增压空气温区 Charge air temperature	180~200℃	EGR温区 EGR temperature	300~500℃

3 主要进展2-双级多分流ORC技术
Progress 2 - Two-stage multi-flow ORC

关键部件优化设计
Optimised design of key components

□ 对系统关键部件——高参数透平进行优化设计。
Optimised design of the system's key component, **the turbine**





透平需要满足的要求：
Requirements to be met by the turbine:

- ✓ **高效率** high efficiency
- ✓ **大压比** large pressure ratio
- ✓ **高焓降** high enthalpy drop
- ✓ **小流量** small flow rates
- ✓ **小体积高参数** High operating parameters

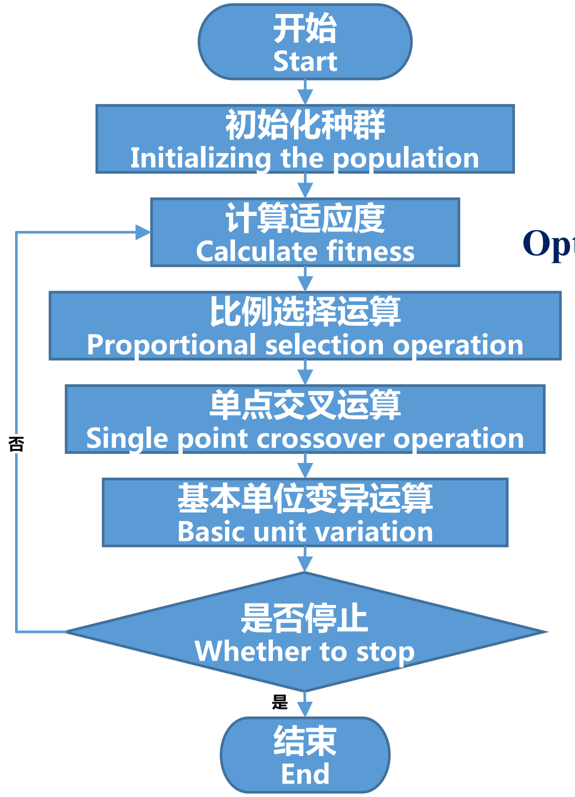
高参数ORC径流式高速透平膨胀机全流程设计方法
ORC run-off high speed turbine expander full flow design approach

3 主要进展2-双级多分流ORC技术

Progress 2 - Two-stage multi-flow ORC

基于机器学习-遗传耦合优化算法的参数优化
Parameter optimization based on a machine learning-genetic coupled optimization algorithm

□ 系统最大输出功34.5kW，BTE提升5.82%。Maximum output power 34.5kW, 5.82% BTE improvement



遗传算法流程图 Genetic algorithm flow chart

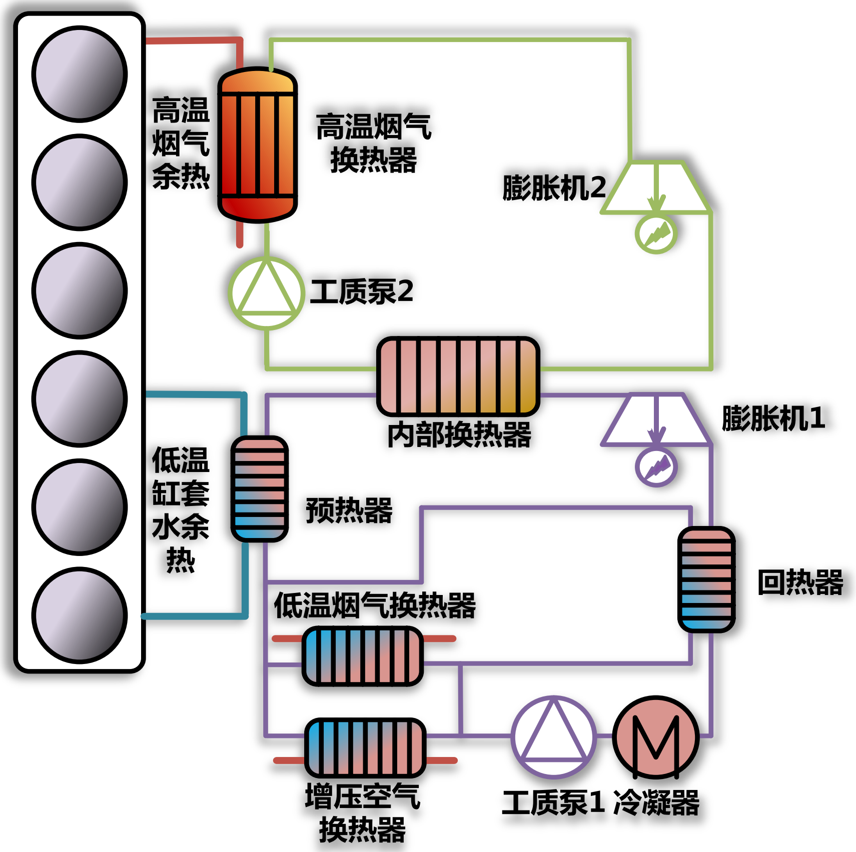
优化结果
Optimisation results

工质泵等熵效率 Isentropic efficiency of working medium pump	60%	膨胀机等熵效率 Isentropic efficiency of expander	70%
总输出功率 Total output power	34.5KW	总体热效率 Overall thermal efficiency	14.97%
BTE提升 BTE lift	5.82%		

3 主要进展2-双级多分流ORC技术
Progress 2 - Two-stage multi-flow ORC

试验台搭建
Test bench construction

□ 搭建双级多分流ORC实验样机 Build the two-stage multi-flow ORC test bench.



正在吊装的发动机
Engine being lifted

3 主要进展

Research Progress

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以进一步提高多余热源回收效率为目标，构建跨临界CO_2二次分流型动力循环

3 主要进展3-热源匹配跨临界CO_2分流循环

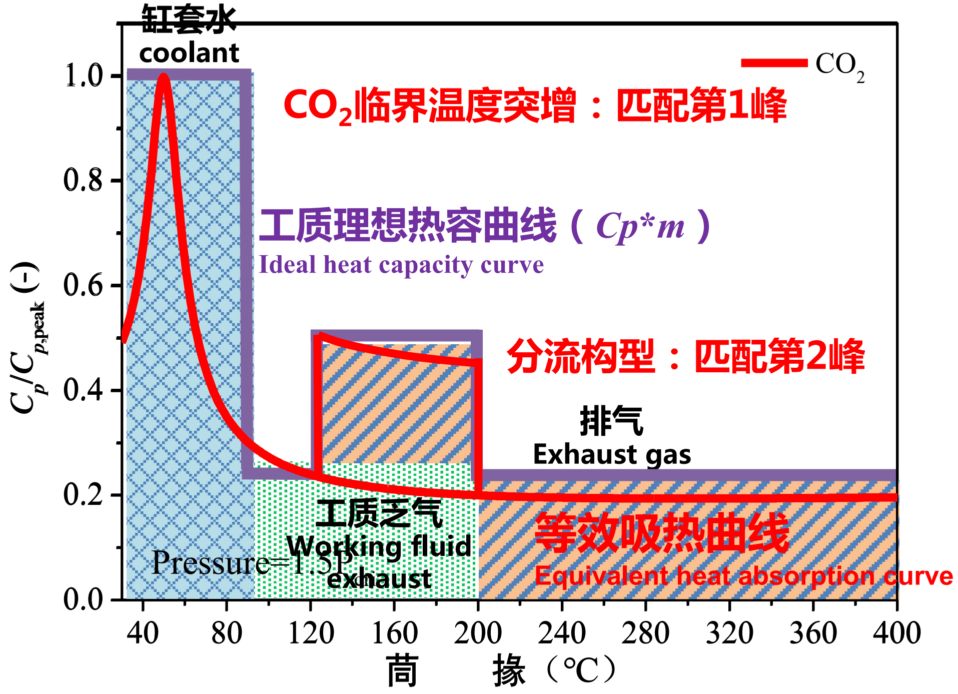
Progress 3 - Trans-critical CO_2 split-flow power cycle

提出解决热源温区干涉的方案

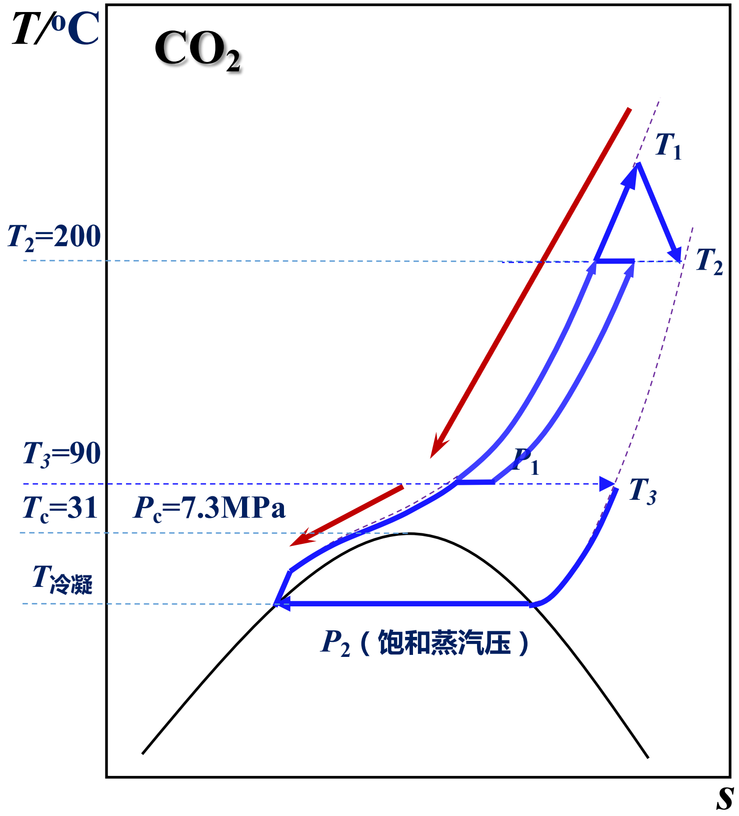
Propose solutions to address heat source temperature zone interference

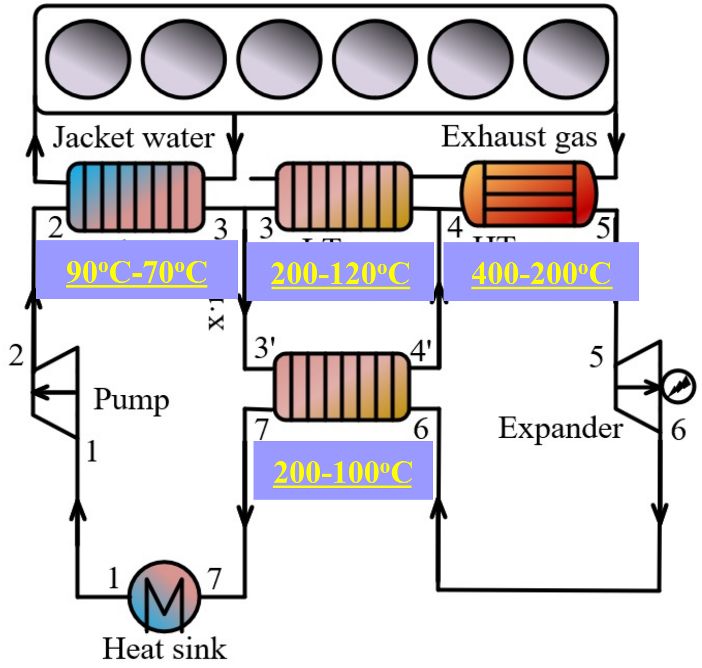
□提出**分流型CO_2动力循环构型**，逼近理想热容曲线"双峰"特征，进一步匹配大温跨热源。

Proposed **trans-critical CO_2 split-flow power cycle**， matching large temperature span heat sources.



CO_2物性匹配热源原理
CO_2 physical property matching heat source principle





CO_2跨临界分流型循环构型
Trans-critical CO_2 split-flow power cycle configuration

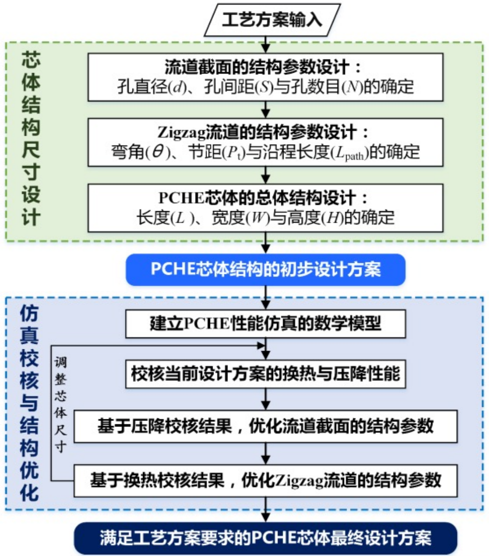
3 主要进展3-热源匹配跨临界CO_2分流循环

Progress 3 - Trans-critical CO_2 split-flow power cycle

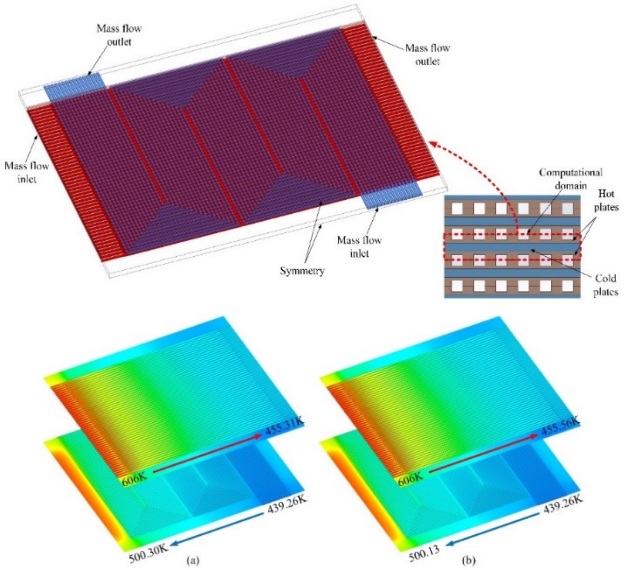
关键换热部件烟气换热器设计加工
Design and processing of flue gas heat exchanger

□ 开发了同时满足耐高温高压、高效换热和低压降的**新型印刷板式烟气换热器（PCHE）**。

New **printed circuit heat exchanger (PCHE)** developed.

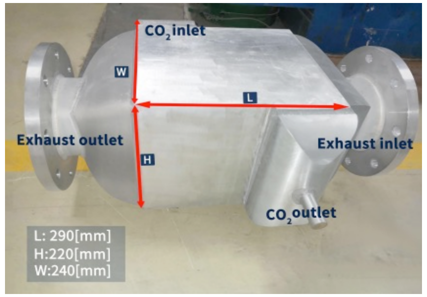


PCHE设计流程
PCHE Design Process



PCHE仿真优化
PCHE simulation optimization

中温PCHE烟气换热器（50-90℃）
Medium temperature PCHE (50-90°C)



高温PCHE烟气换热器（100-400℃）
High temperature PCHE (100-400°C)

关键参数达到国内外先进水平
Key parameters reach international advanced level

单位体积换热量274.5W/cm³
heat transfer per unit volume 274.5W/cm³

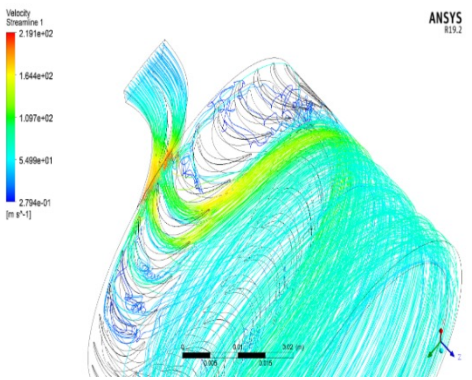
3 主要进展3-热源匹配跨临界CO_2分流循环

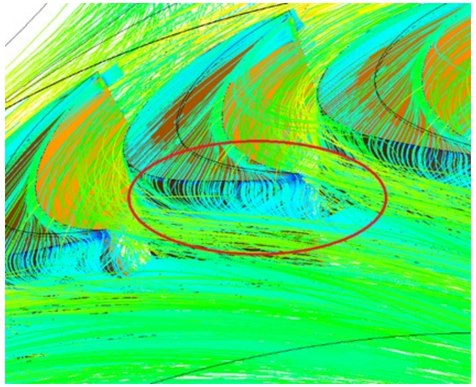
Progress 3 - Trans-critical CO_2 split-flow power cycle

关键做功部件透平膨胀机设计加工
Design and processing of flue gas heat exchanger

□开发了系列化膨胀机样机，填补了小型高速CO_2透平膨胀机的国际空白。

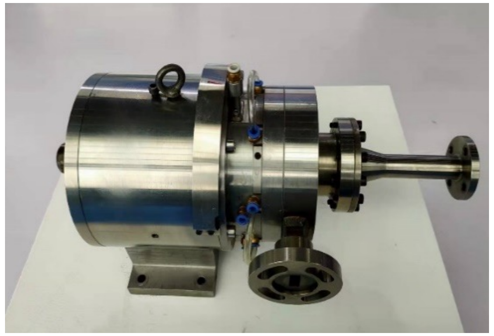
Developed a series of expanders, filling an international gap in small high-speed CO_2 turbine expanders.



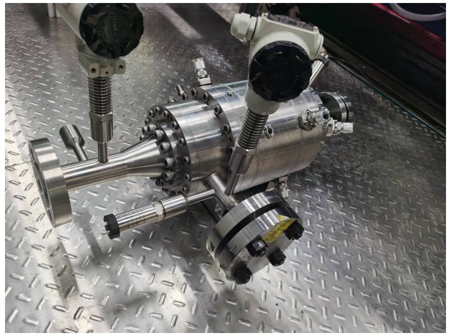


sCO_2轴流式高速透平膨胀机全流程设计方法，基于CO_2真实气体模型的CFD仿真方法

sCO_2 axial flow high speed turbomachinery full flow design method, CFD simulation method based on CO_2 real gas model



5kW级sCO_2轴流透平(半封闭)
5kW sCO_2 axial flow turbine (semi-enclosed)



15kW级sCO_2轴流透平(全封闭)
15kW class sCO_2 axial turbine (fully enclosed)

关键参数达到国内外先进水平

Key parameters reach international advanced level

单位体积发电量近88kW/m^3

power generation per unit volume nearly 88kW/m3

3 主要进展3-热源匹配跨临界CO_2分流循环

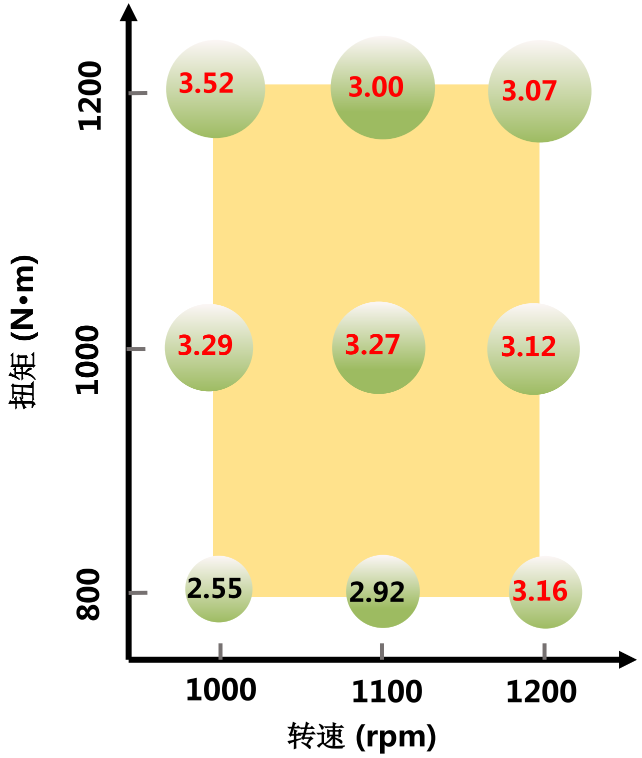
Progress 3 - Trans-critical CO_2 split-flow power cycle

系统样机搭建及测试
Test bench construction and testing

□ 开发了sCO_2动力循环样机。**发电量11.5kW，热效率绝对值提升3.52%。**

The sCO_2 power cycle test bench. **Power generation of 11.5kW, with an increase in BTE of 3.52%.**

sCO_2跨临界动力循环样机
The sCO_2 power cycle test bench



3 主要进展
Research Progress

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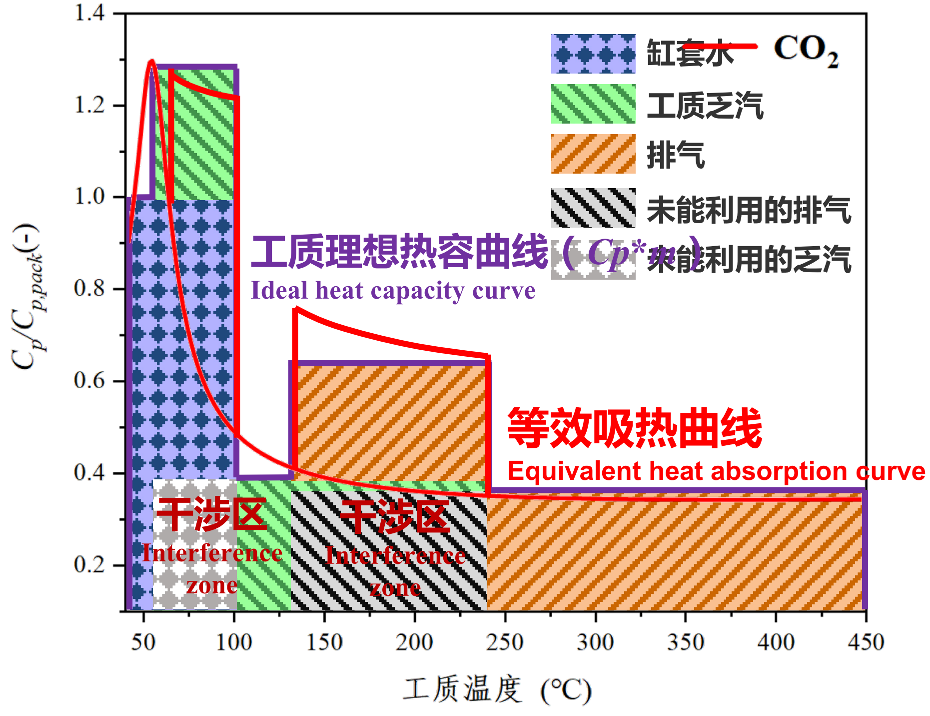
以进一步提高多余热源回收效率为目标， 构建跨临界CO_2二次分流型动力循环

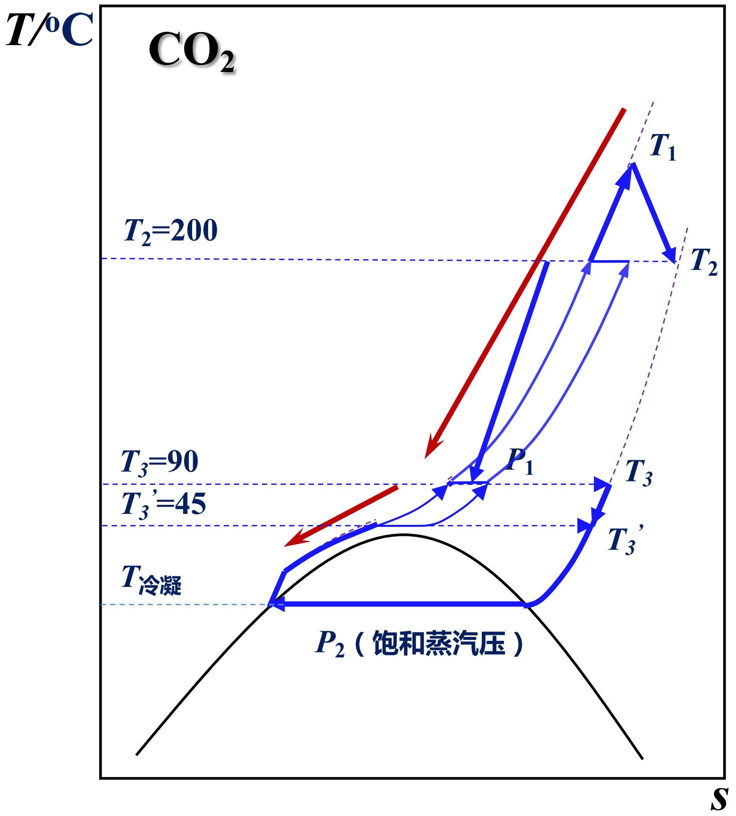
3 主要进展4-跨临界CO_2双分流循环
Progress 4 - Trans-critical CO_2 dual-split cycle

提出多热源匹配的CO_2动力循环构型
Proposing CO_2 power cycle with matched multiple heat sources

- 提出**二次分流型CO_2动力循环构型**，进一步提高乏汽回收率，降低冷却损失。
  Trans-critical CO_2 dual-split cycle. Increase in spent steam recovery and reduction in cooling losses.



CO_2物性匹配热源原理
CO_2 physically matched heat source principle



3 主要进展4-跨临界CO_2双分流循环

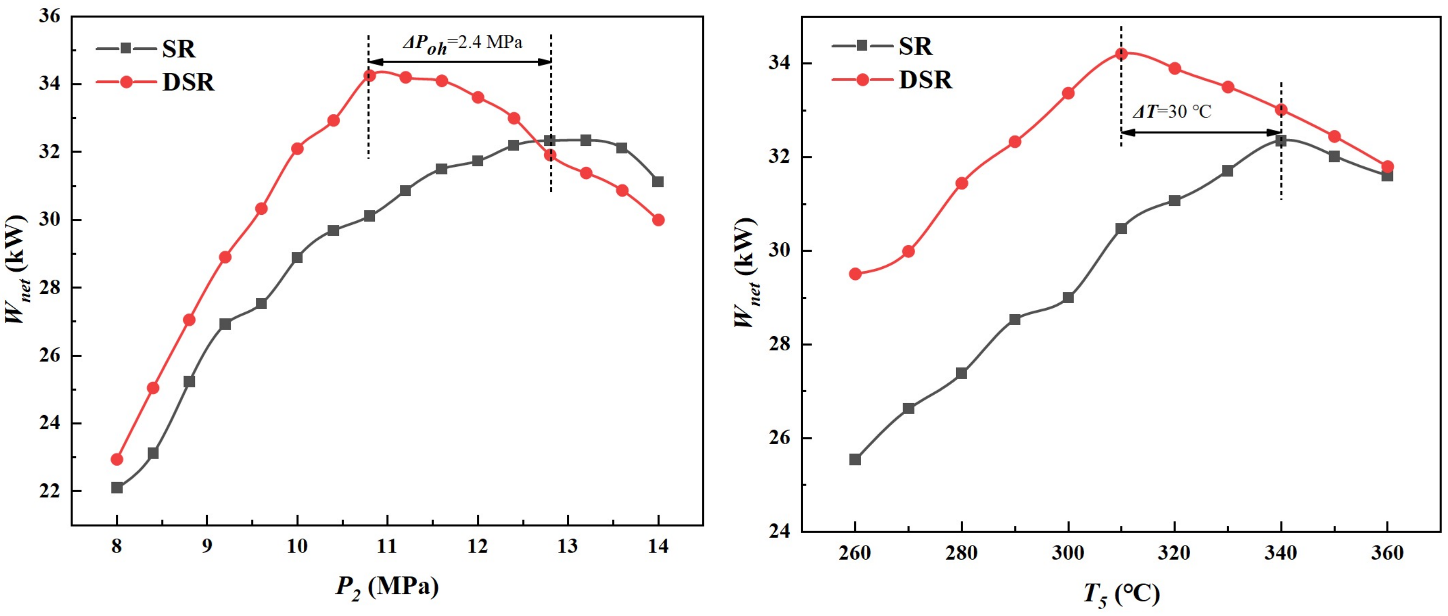
Progress 4 - Trans-critical CO_2 dual-split cycle

循环构型性能对比
Cycle configuration performance comparison

- **相较分流型动力循环效果，循环输出净功提高5.5%，最佳操作压力和最佳温度降低。**

  Compared to trans-critical CO_2 split-flow cycle, **the net power output of the cycle is increased by 5.5% and the optimum operating pressure and optimum temperature are reduced.**

	二次分流型 Dual-split	分流型 Split
净功* /kW Net output power	34.3	32.5
工质乏气热利用率 Ur of WF exhaust gas	92%	70%
排气余热回收率 Ur of exhaust gas	100%	100%
缸套水余热回收率 Ur of coolant	100%	100%
工质泵等熵效率 efficiency of pump	50%	50%
膨胀机等熵效率 efficiency of expander	75%	75%



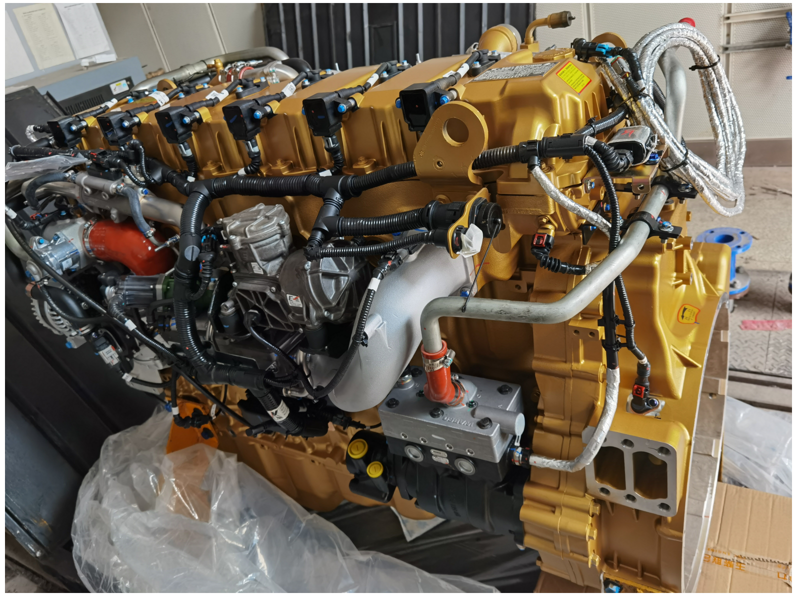
最佳操作压力和最佳温度对比
Comparison of optimum operating pressure and optimum temperature

3 主要进展4-跨临界CO_2双分流循环
Progress 4 - Trans-critical CO_2 dual-split cycle

系统样机开发
Test bench construction

- 正开发**二次分流型sCO_2动力循环样机**，可应用于重载卡车余热回收

  Develop a **Trans-critical CO_2 dual-split cycle test bench**, which can be applied to WHR of trucks



发动机台架搭建
Engine being lifted

- 目标：与发动机联测，最低油耗点**BTE提升>4.5%**

  Objective: Minimum oil consumption point **BTE improvement >4.5%**

- 研究特色：

  Research features:

1. 稳态设计、动态仿真能力
   Steady state design and dynamic simulation capability
2. 高温回热器和烟气微通道换热器开发
   Development of high-temperature regenerator and PCHE
3. 50kW级高速sCO_2透平膨胀机开发
   Development of 50kW high-speed sCO_2 turbine expander
4. 测控系统开发
   development of control system

04

结论与展望
Conclusion and outlook

- 共识：WHR是内燃机热效率>55%的必然途径；需重视
  Consensus: WHR is the inevitable way for the thermal efficiency of engine to be>55%; Needs attention

- 现状：WHR目前对内燃机热效率提升1.5%-4.3%；需提高
  Current situation: WHR can improve the thermal efficiency engine by 1.5% - 4.3%; Needs to be improved

- 方向：单级ORC(BTE>3.7%)，双级ORC(>5.5%)；CO_2单分流(>3.5%) ;CO_2双分流(>4.5%)；有效性
  Direction: single cycle(BTE>3.5%); Two-stage multi-flow ORC (BTE>5.5%); Trans-critical CO_2 dual-split cycle (BTE>4.5%); Effectiveness

- 未来：关键部件和系统高强化、集成化，整车集成；需攻关
  Future: key components and systems are highly strengthened and integrated; Needs to be tackled

天津大学
Tianjin University

感谢各位专家批评指正！
Thank you for your criticism and correction!

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