

塔式太阳能热发电关键部件热性能及 安全可靠研究

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1

塔式太阳能热发电技术

2

塔式太阳能热发电热性能研究

3

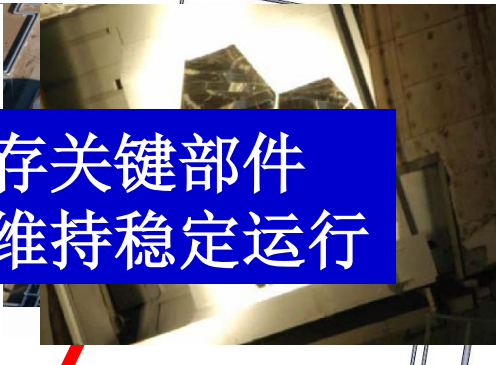
塔式太阳能热发电可靠性研究

4

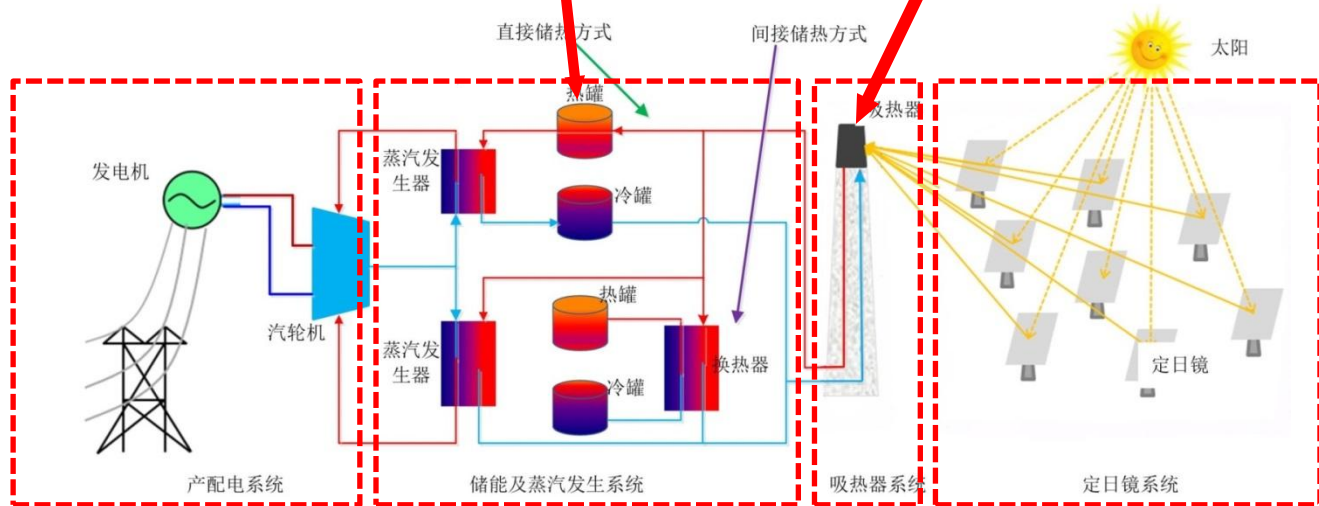
总结及展望

- 1 塔式太阳能热发电技术
- 2 塔式太阳能热发电热性能研究
- 3 塔式太阳能热发电可靠性研究
- 4 总结及展望

1.4 塔式太阳能热发电技术

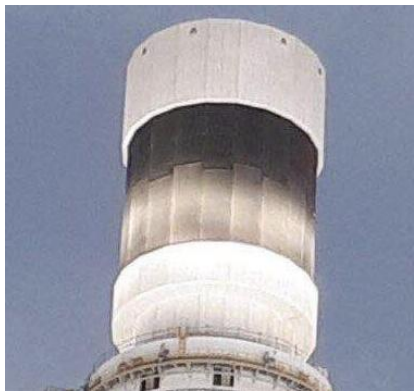


能量转换与储存关键部件
实现光热转换，维持稳定运行



1.5 塔式太阳能热发电技术问题及挑战

➤ 吸热器热效率低

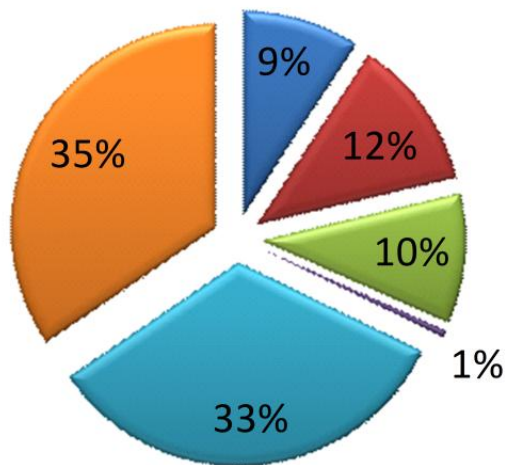


优点：接收阳光面积大，吸热器总功率高；
缺点：吸热面直接暴露在外界环境中，对流及辐射热损失大，温度越高，热损失越大。

优点：吸热面布置在腔体内部，热损失小，热效率高，工作温度更高；
缺点：受开口限制，接收阳光面积小，吸热器总功率低。



➤ 安全可靠性问题严峻



■ 泵阀等辅助设备 ■ 控制系统 ■ 镜场 ■ 管路系统 ■ 吸热器 ■ 其它

Solar two 光热试验电站故障次数占总次数比例

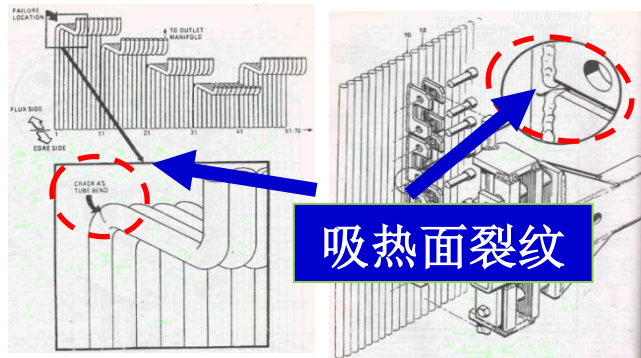
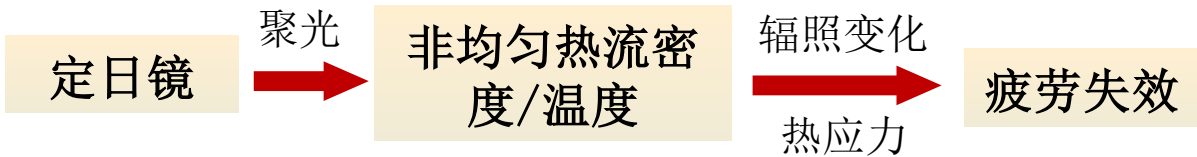
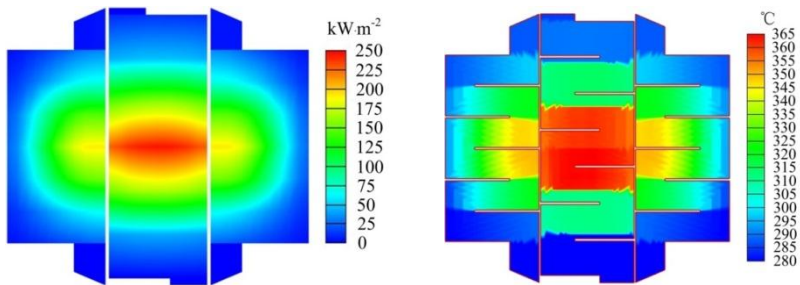
✓ 平均每**2.8**天出现一次故障

表1-2 已报道的储热系统破坏情况

电站名称	储热形式	发生事故
Solar one	单罐 斜温层	储热罐 断裂 、换热器管板 泄露 、法兰密封圈 泄露
CESA-I	双罐	熔融盐 凝固
SEGS-2	双罐	储热罐 爆炸
新月沙丘	双罐	储热罐 泄露
Gemasolar	双罐	储热罐 泄露 （第三次发生）

✓ **非稳态非均匀热流密度**导致设备承受**交变热载荷**，设备**失效问题非常严重**

1.5 塔式太阳能热发电技术问题及挑战



1

塔式太阳能热发电技术

2

塔式太阳能热发电热性能研究

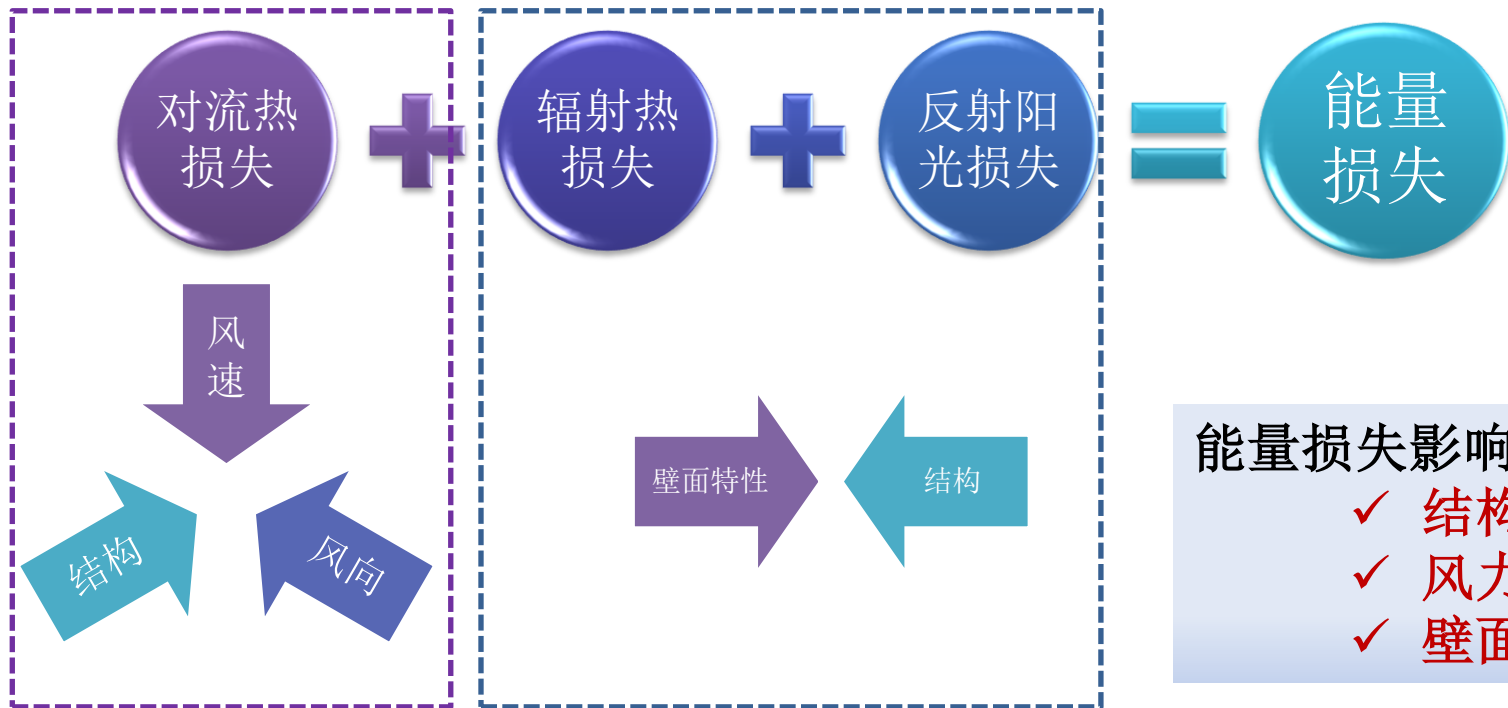
3

塔式太阳能热发电可靠性研究

4

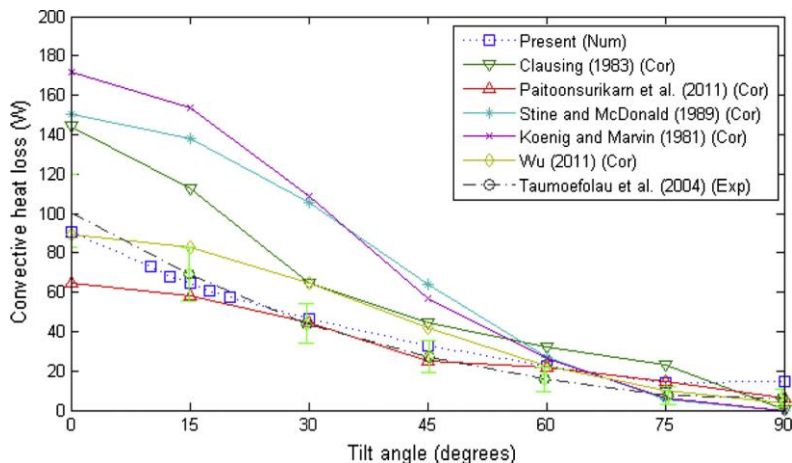
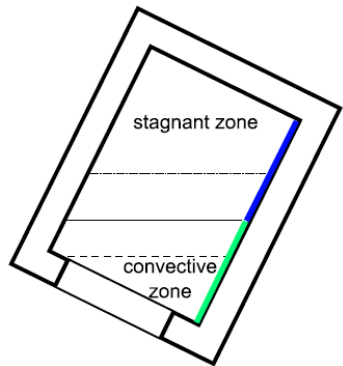
总结及展望

2.1 吸热器能量损失



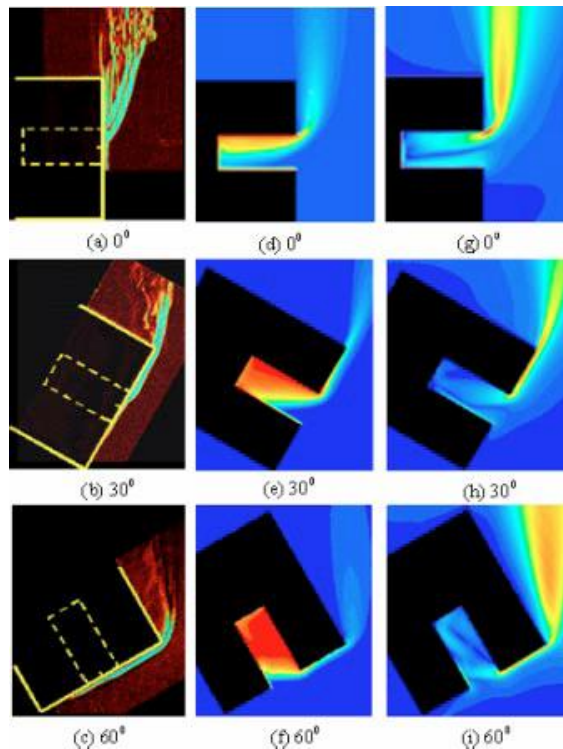
2.2 腔式吸热器热性能研究

➤ 吸热器自然对流热损失



不同倾角下吸热器自然对流热损失
(Lee/2017)

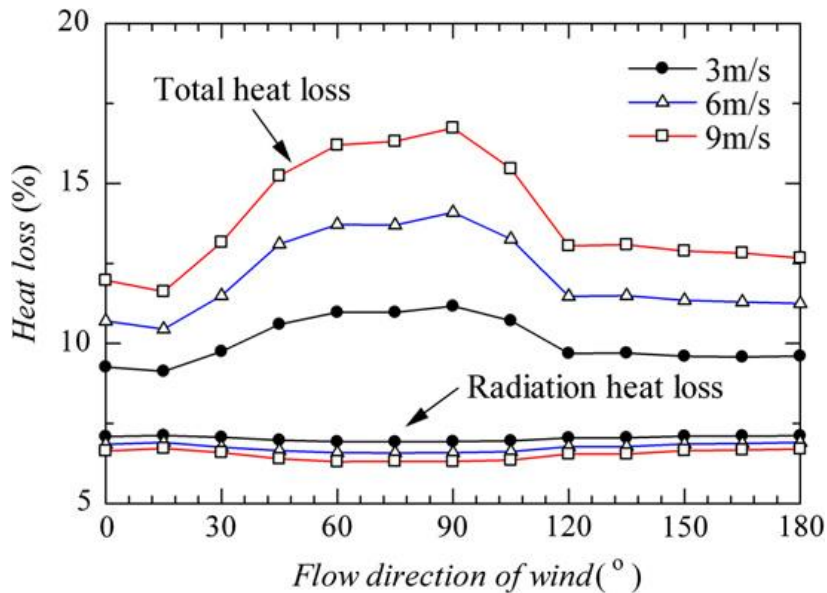
吸热器自然对流
(Flesch/2015)



不同倾角下吸热器自然对流流场
(Taumoefolau/2004)

2.2 腔式吸热器热性能研究

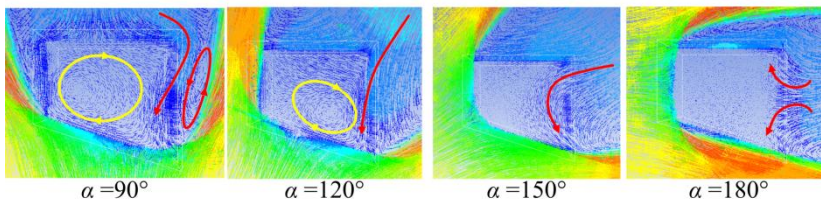
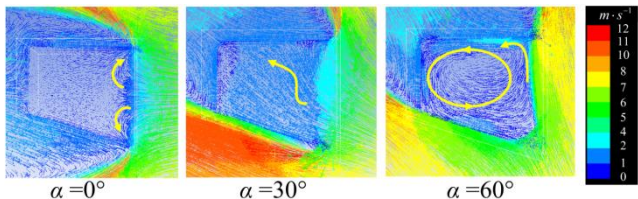
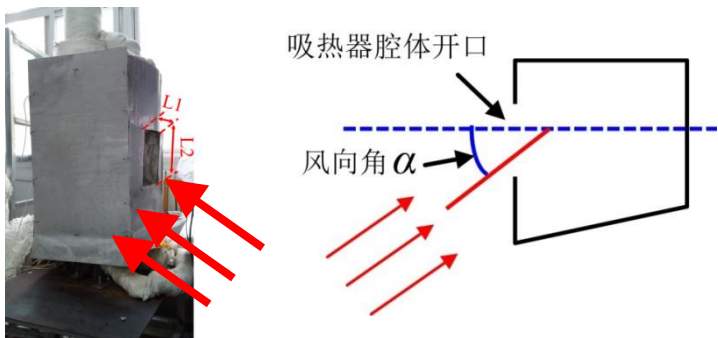
➤ 风力作用对吸热器对流热损失影响



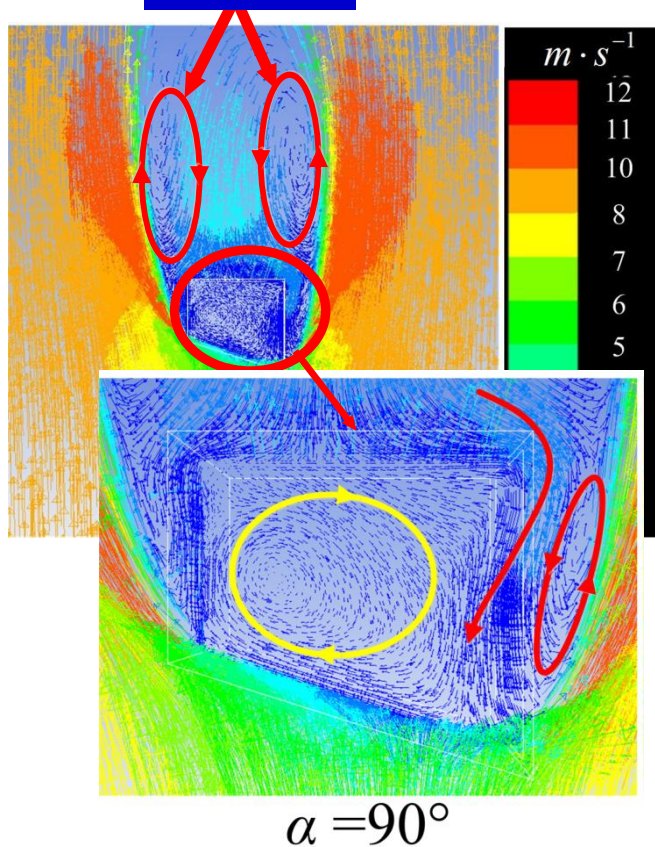
风速及风向对吸热器对流热损失影响
(Jinjia Wei/2011)

2.2 腔式吸热器热性能研究

➤ 风力作用下吸热器对流热损失产生机理

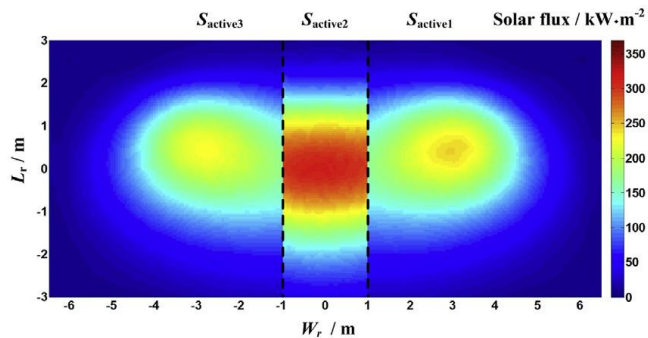


对称涡

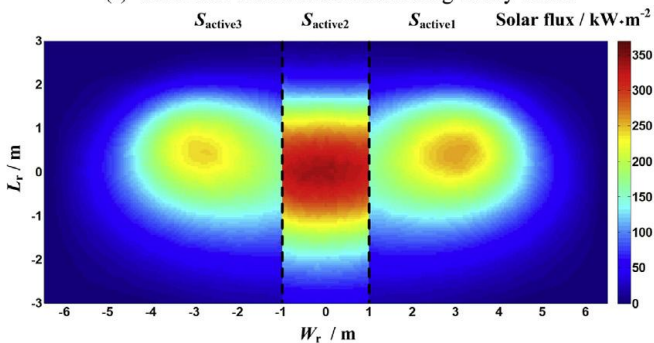


2.2 腔式吸热器热性能研究

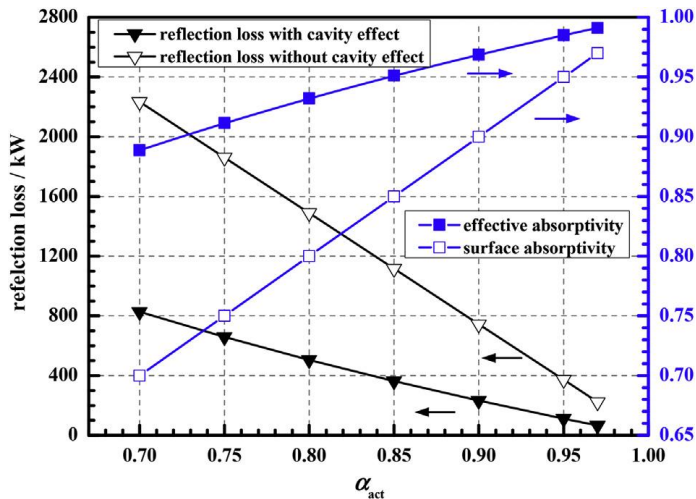
➤ 腔体效应影响



(a) Solar flux distribution considering cavity effect



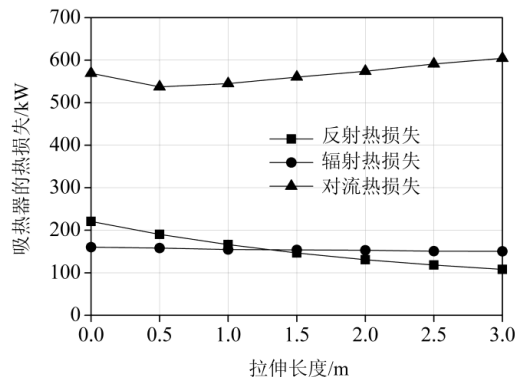
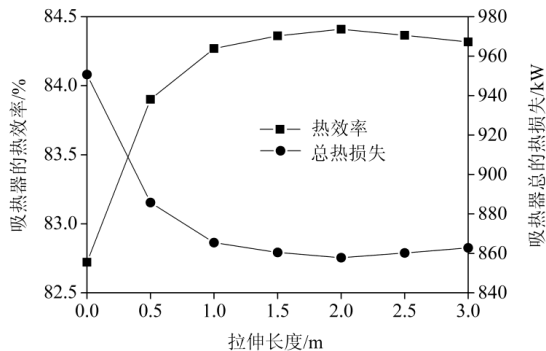
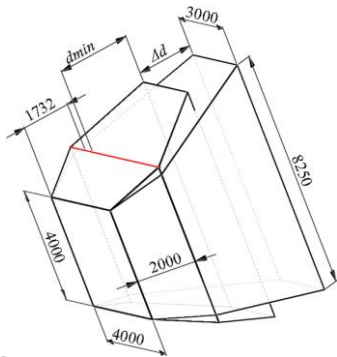
(b) Solar flux distribution ignoring cavity effect



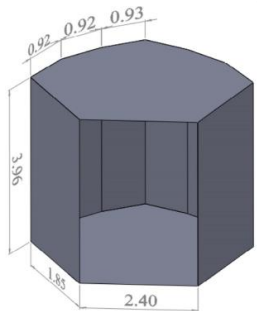
- ✓ 腔体效应在一定程度上可以提高内部热流密度分布的均匀性
- ✓ 腔体效应可以显著降低吸热器反射损失

2.2 腔式吸热器热性能研究

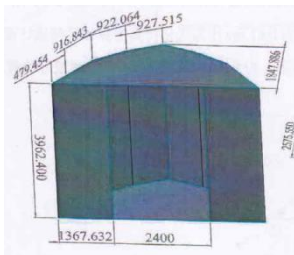
➤ 腔体结构影响



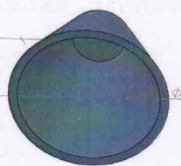
拉伸对吸热器性能影响 (Tu/2015)



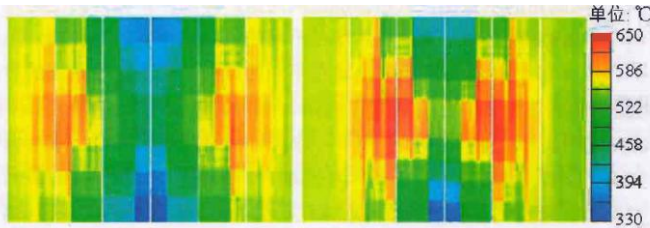
MSEE结构



Modified结构

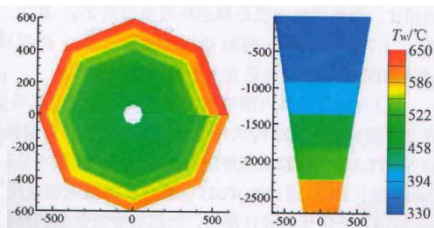


螺旋管结构



温度分布 (MSEE)

热效率: 88%



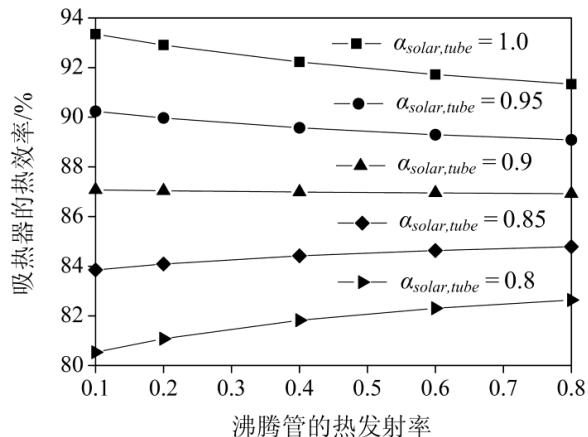
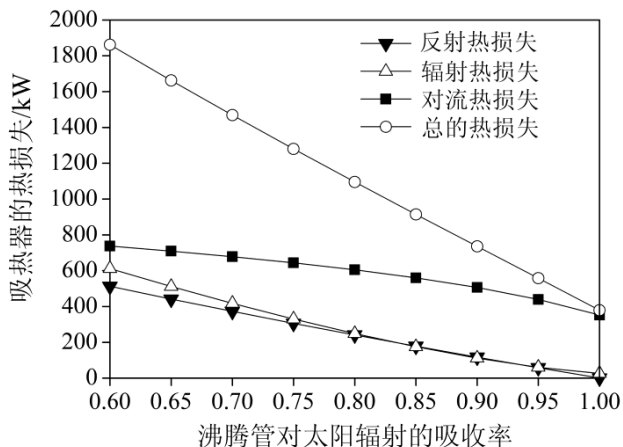
温度分布 (螺旋管结构)

热效率: 91.8%

腔体结构对吸热器性能影响 (张莉/2015)

2.2 腔式吸热器热性能研究

➤ 壁面特性对吸热器性能影响



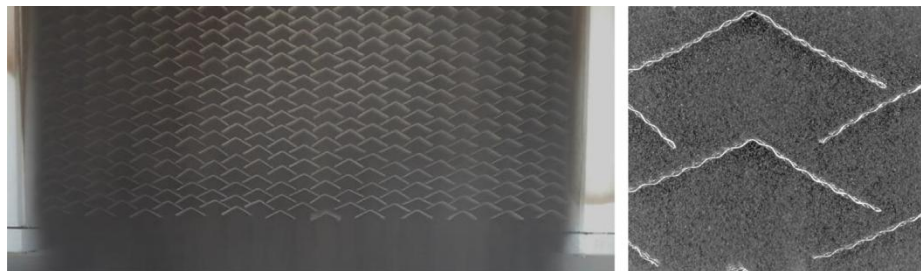
蒸发管壁面特性对吸热器性能影响 (屠楠/2015)

- ✓ 吸热表面对太阳辐射的吸收率会显著影响吸热器的热性能
- ✓ 红外热辐射在腔体内部的宏观传递方向是判断吸热表面热发射率对其热性能影响规律的关键

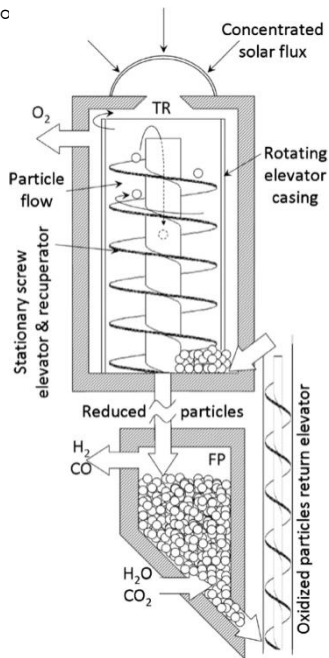
2.2 腔式吸热器热性能研究

➤ 颗粒吸热器性能

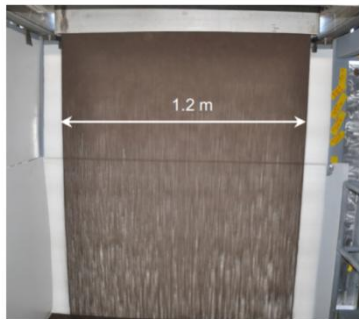
- ✓ 直接式：颗粒直接吸收聚焦阳光能量。



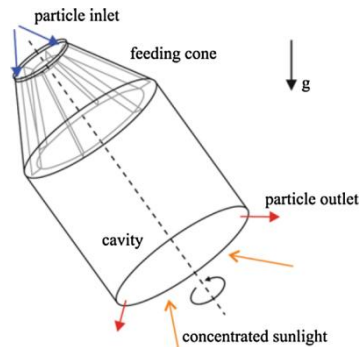
延时颗粒吸热器 (Ho/2015)



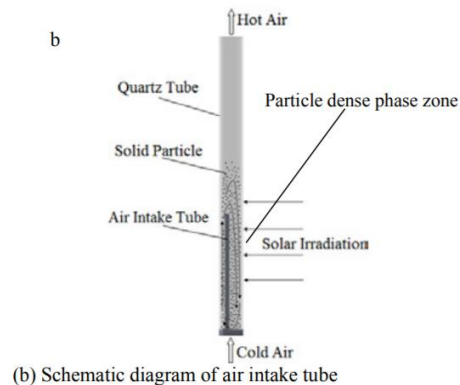
延时颗粒吸热器
(Ermanoski/2015)



直接下落颗粒吸热器
(Ho/2015)



回转炉/离心颗粒吸热器
(Wu/2014)



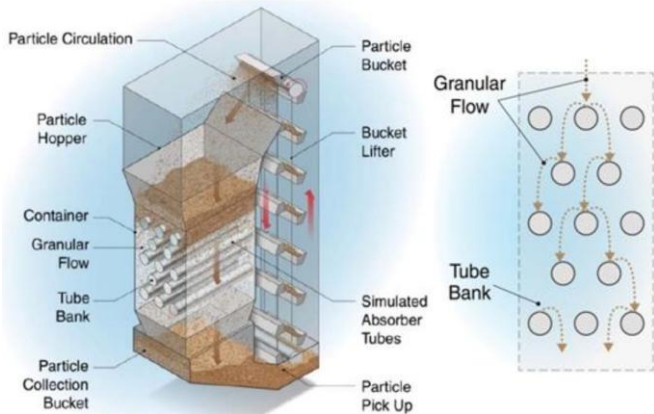
(b) Schematic diagram of air intake tube

石英管固体颗粒吸热器
(Zhang/2015)

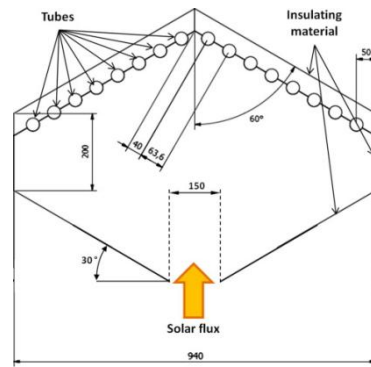
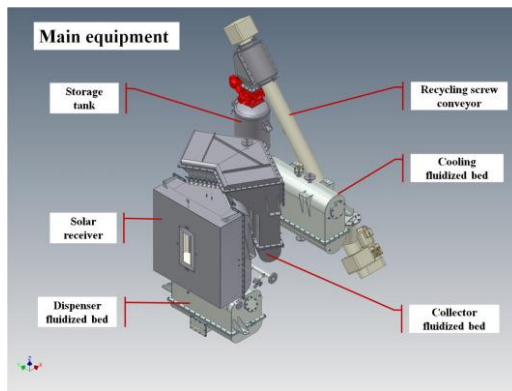
2.2 腔式吸热器热性能研究

➤ 颗粒吸热器性能

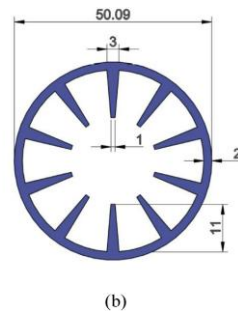
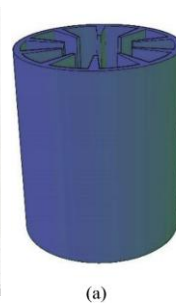
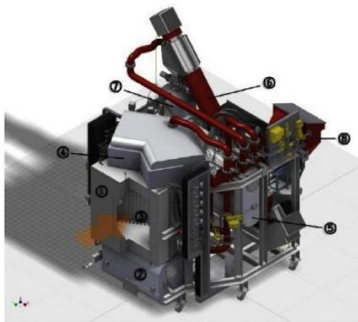
- ✓ 间接式：聚焦阳光加热吸热体（管道等），颗粒与吸热器换热。



间接式颗粒吸热器
(Martinek/2015)



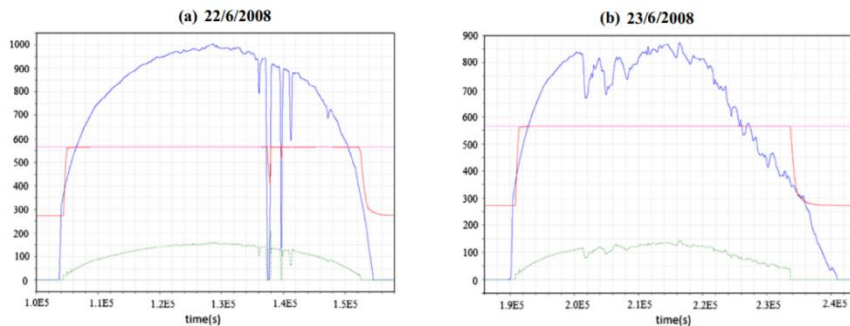
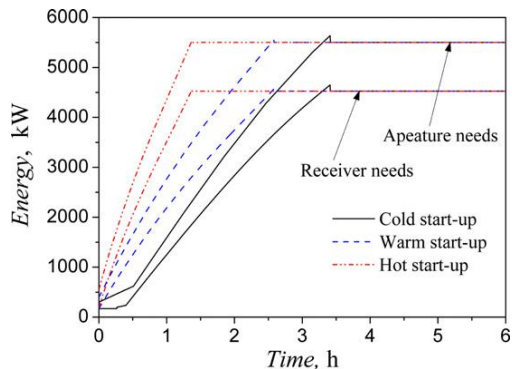
间接颗粒吸热器 (Perez Lopez/2016)



间接颗粒吸热器 (Zhang/2017)

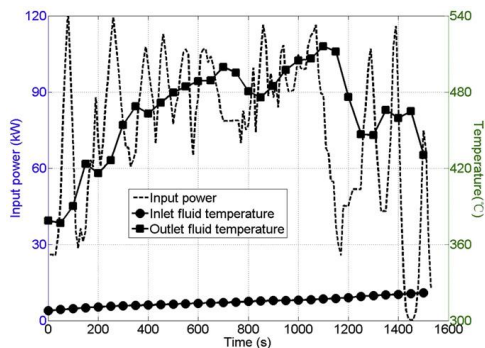
2.2 腔式吸热器热性能研究

吸热器动态性能

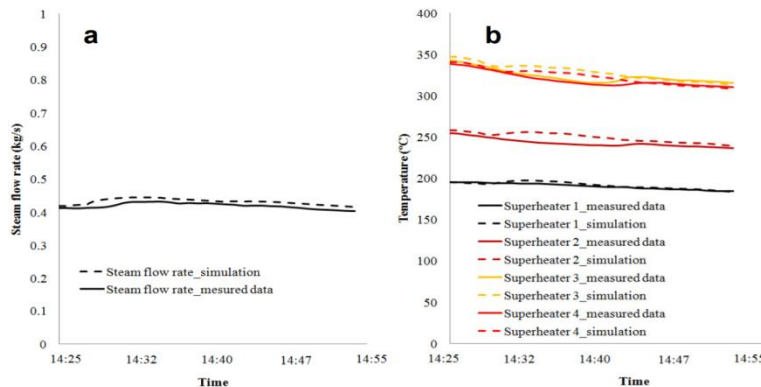


DNI变化时吸热器性能变化 (Samanes/2014)

不同启动方式下吸热器所需能量 (Fang/2013)



熔融盐吸热器动态试验温度变化 (Zhang/2013)

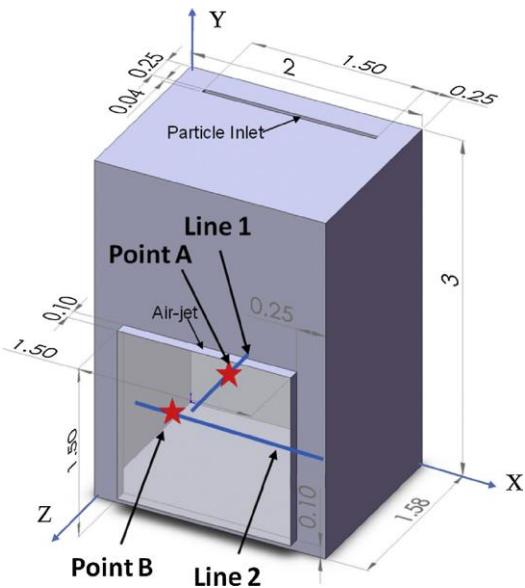


吸热器动态仿真 (Zhang/2014)

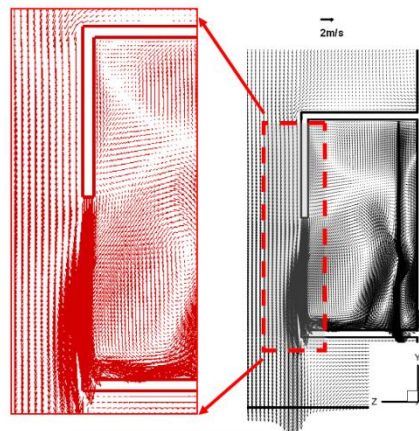
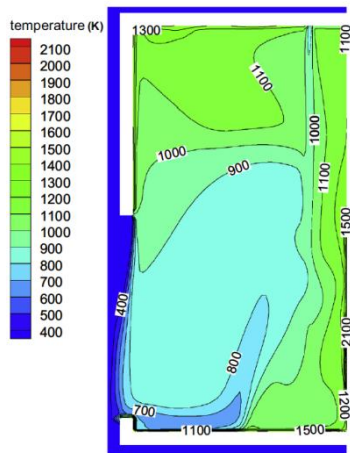
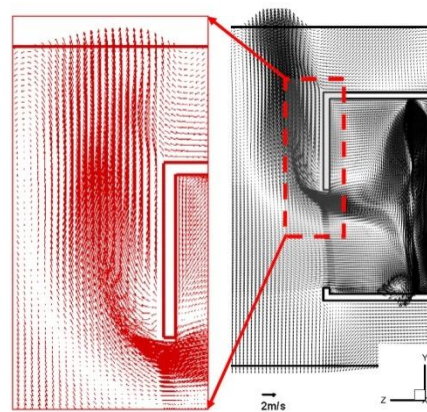
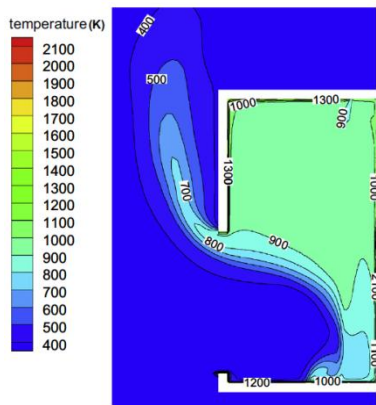
2.2 腔式吸热器热性能研究

➤ 高效吸热器设计技术

✓ 空气帘幕对吸热器性能影响



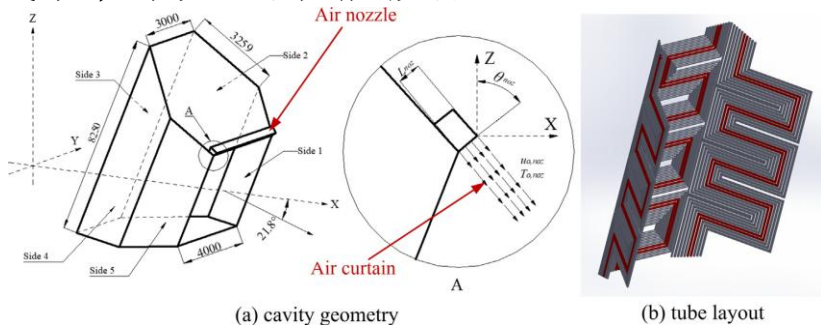
空气帘幕对吸热器影响 (Tan/2015)



2.2 腔式吸热器热性能研究

➤ 高效吸热器设计技术

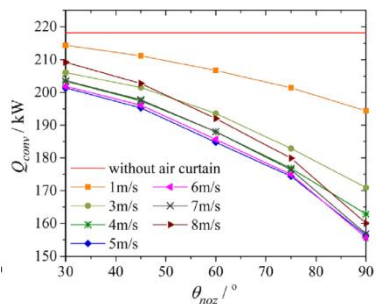
✓ 空气帘幕对吸热器性能影响



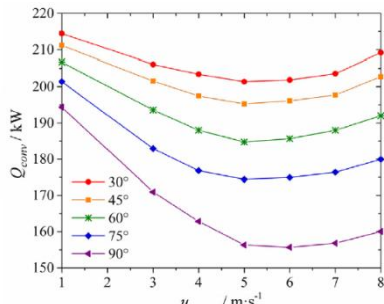
(a) cavity geometry

(b) tube layout

空气帘幕对吸热器影响 (Fang/2019)

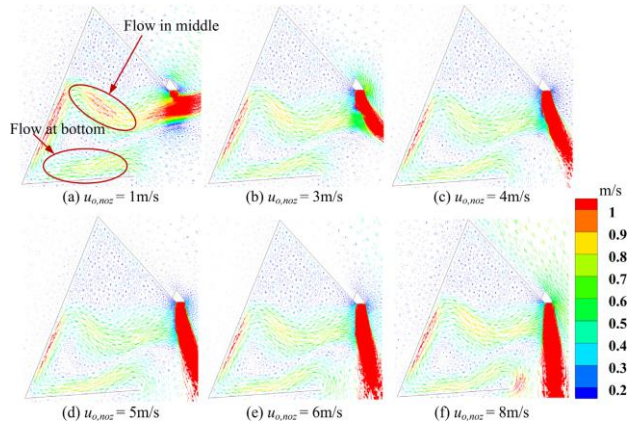
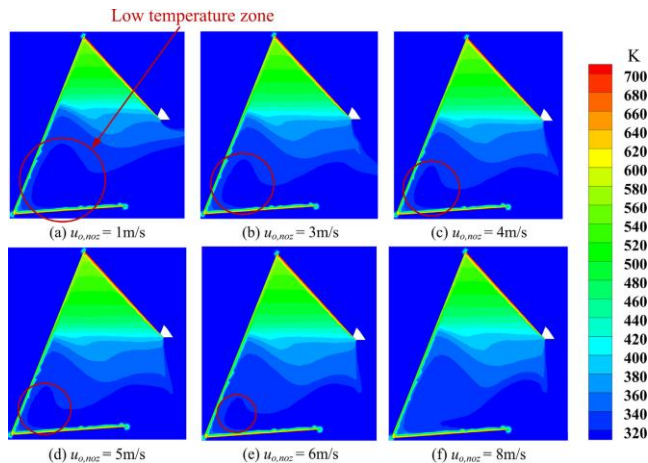


(f) $L_{noz}=600\text{mm}$, $T_{o,noz}=400\text{K}$



(f) $L_{noz}=600\text{mm}$, $T_{o,noz}=400\text{K}$

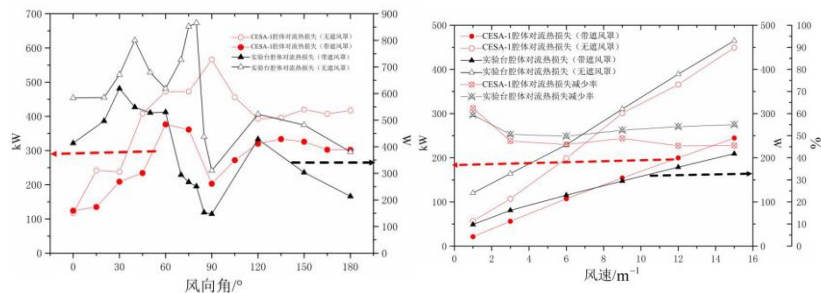
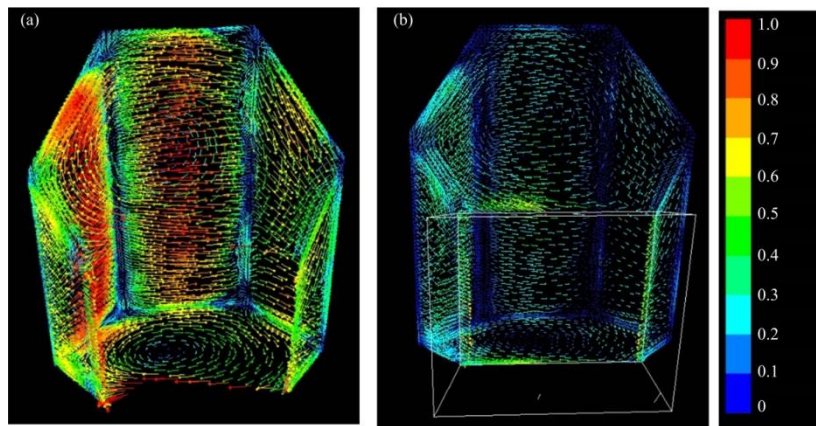
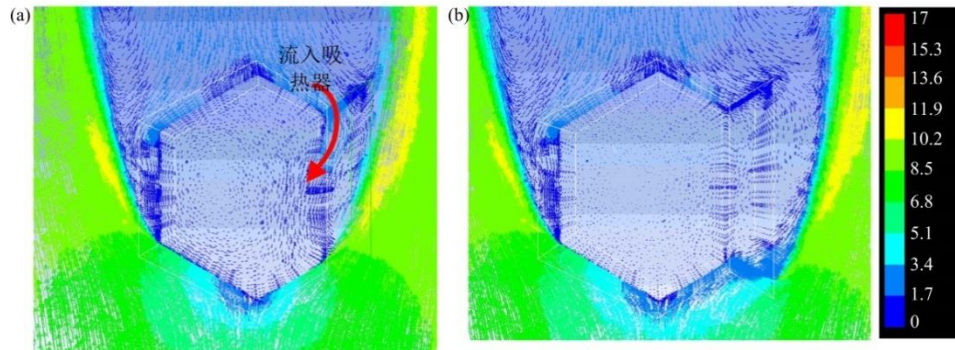
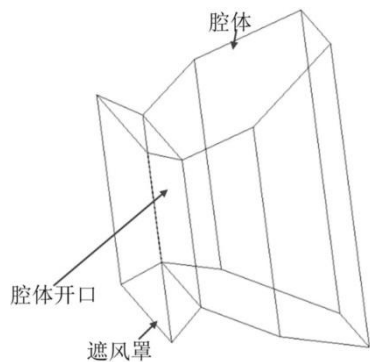
喷嘴角度及气流对吸热器影响



2.2 腔式吸热器热性能研究

➤ 高效吸热器设计技术

✓ 多孔介质遮风罩对吸热器性能影响

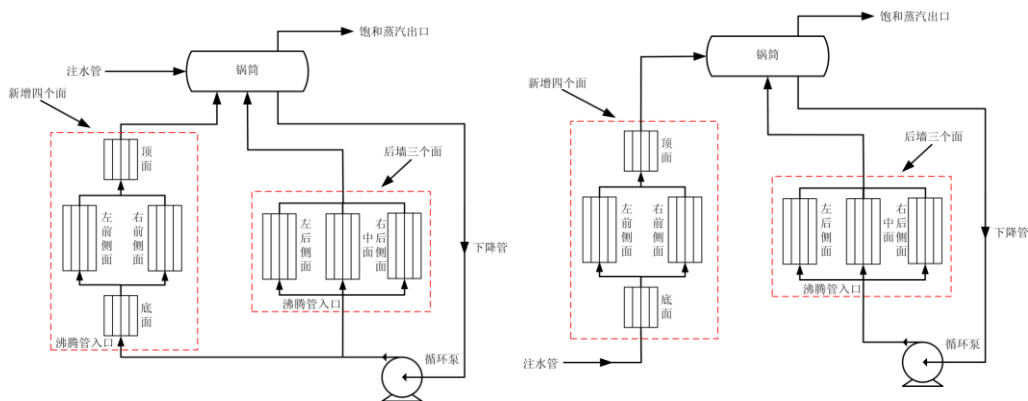
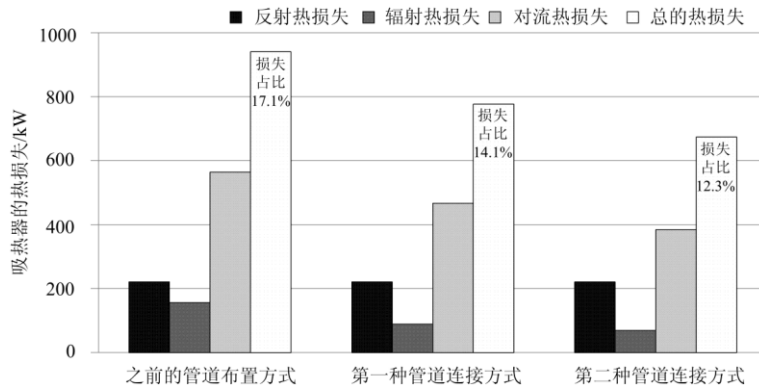
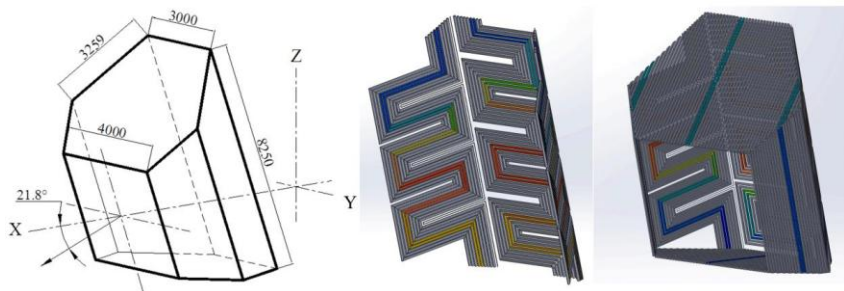


多孔介质遮风罩对吸热器影响 (Wei)

2.2 腔式吸热器热性能研究

➤ 高效吸热器设计技术

✓ 管道布置对吸热器性能影响



2.4 储热系统形式

➤ 储热系统的形式

储能系统

显热储能

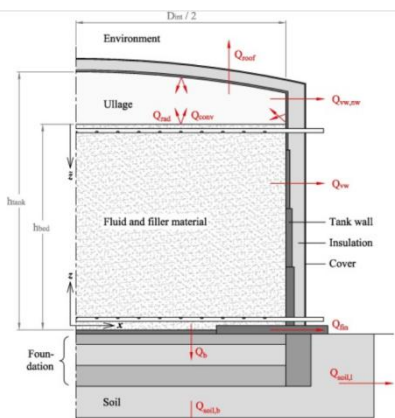
✓ 储能总量受制于材料物理特性，如温度。

潜热储能

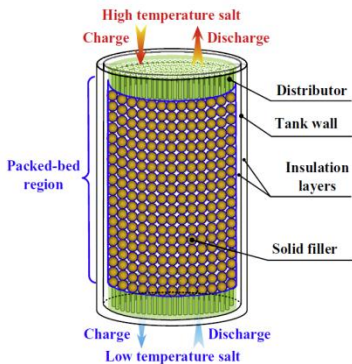
✓ 热导率很低，充放电过程很慢。

热化学储能

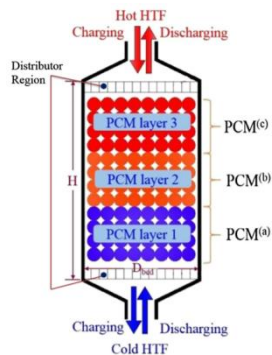
✓ 传热及传质能力弱。



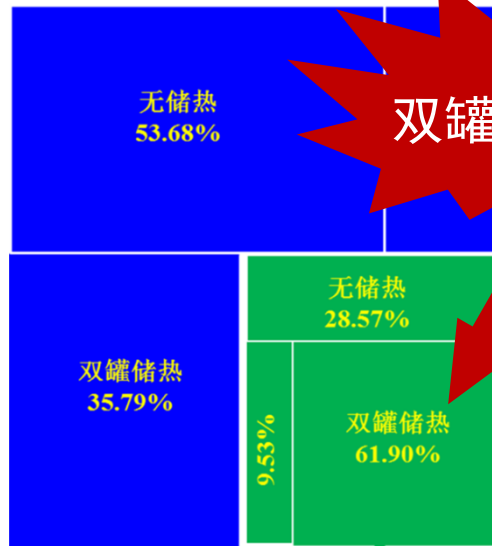
储能形式（储热罐）



Packed-bed填料



相变填料



双罐储热为主

运行中 95座

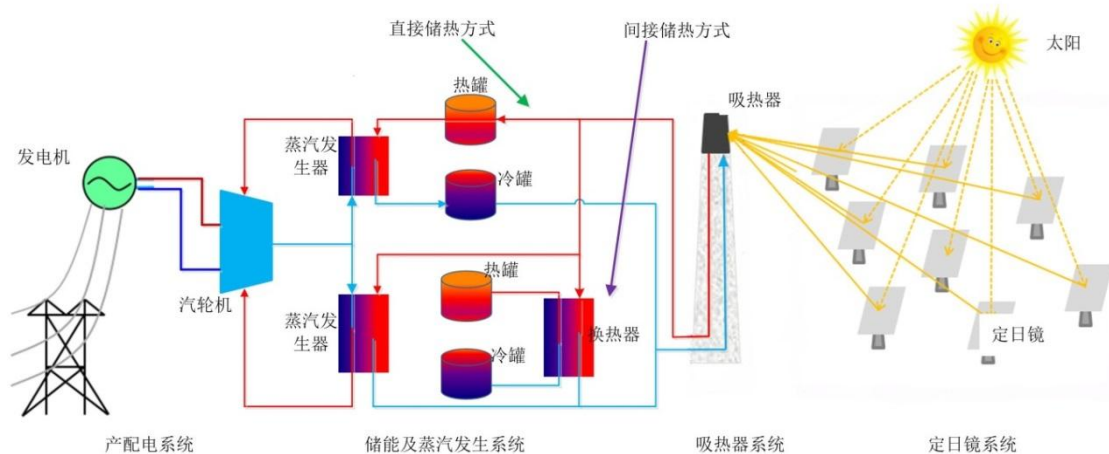
在建 21座

运行及在建热发电电站储热系统形式

2.4 双罐储热技术

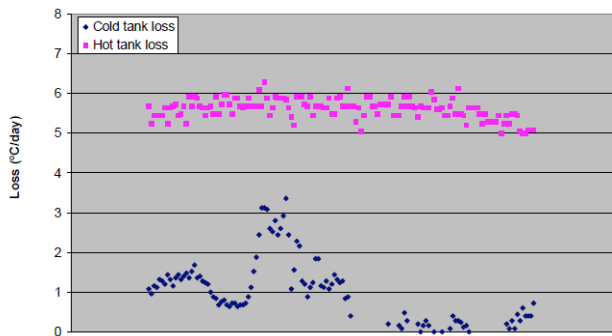
➤ 双罐储热技术

- ✓ 熔融盐为储热介质
- ✓ 直接式/间接式两种技术路线
- ✓ 熔融盐在冷热储热罐循环，实现充放热



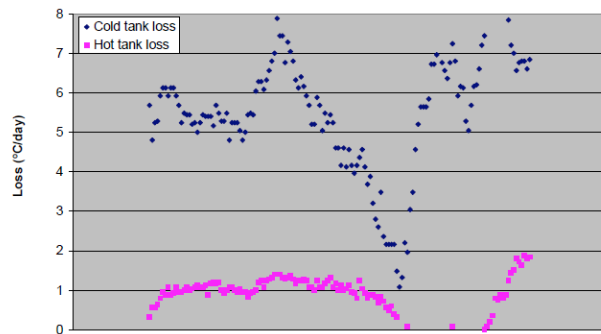
2.4 双罐热性能研究

实际罐体热损失



冷罐充满/热罐排空时每天热损失

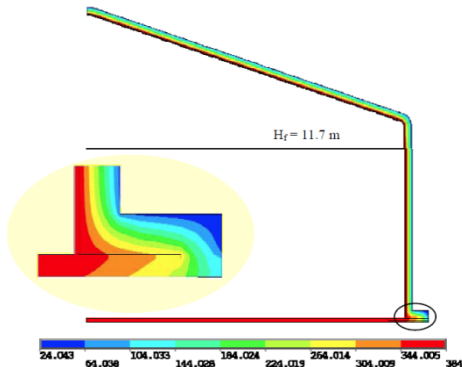
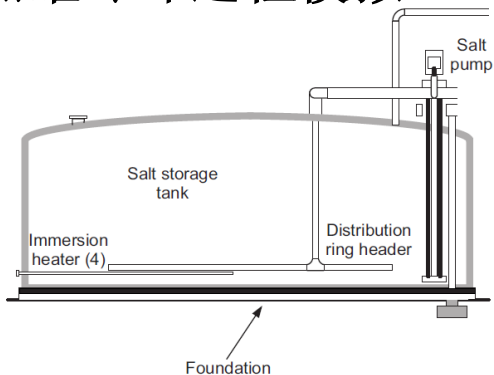
Parameter	Value
Number of tanks	2
Tanks height	14 m
Tanks diameter	38.5 m
Number of oil-to-salt heat exchangers	6
Number of salt pumps	3 units per tank + 1 spare unit in cold tank
Salt mass	28500 tonnes
Nitrate molten salt composition	60% NaNO ₃ + 40% KNO ₃
Cold tank temperature	292°C
Hot tank temperature	386°C
Input power for storage charge	131 MW _{th}
Output power for storage discharge	120 MW _{th}
Thermal capacity	1010 MW _{th} = 7.7 equivalent hours



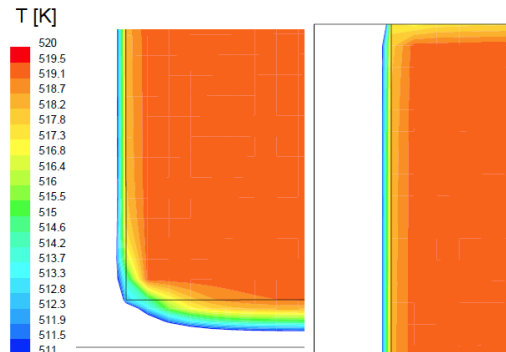
冷罐排空/热罐充满时每天热损失

2.4 双罐热性能研究

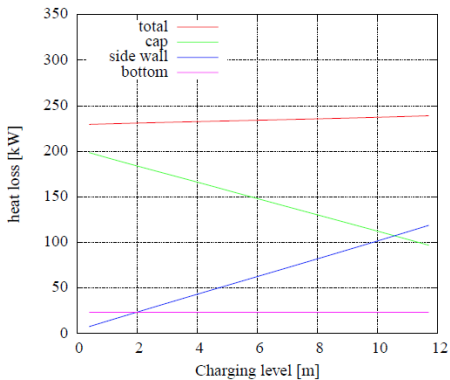
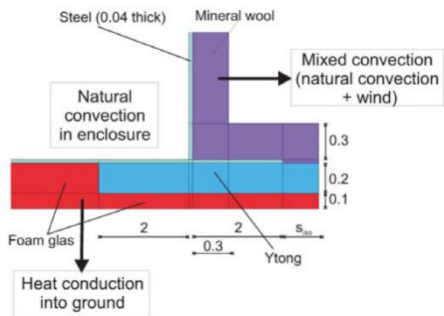
➤ 储热罐冷却过程模拟



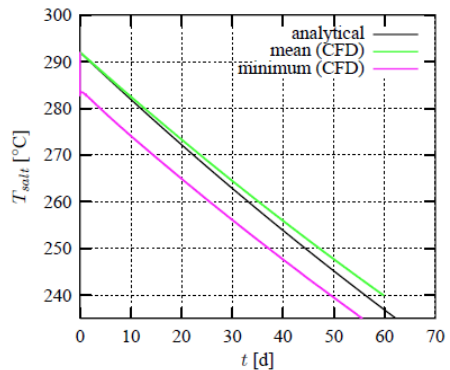
壁面温度分布



局部熔融盐温度分布



不同储液高度热损失



冷却过程温度变化

2.4 双罐热性能研究

➤ 外界环境对储热罐影响

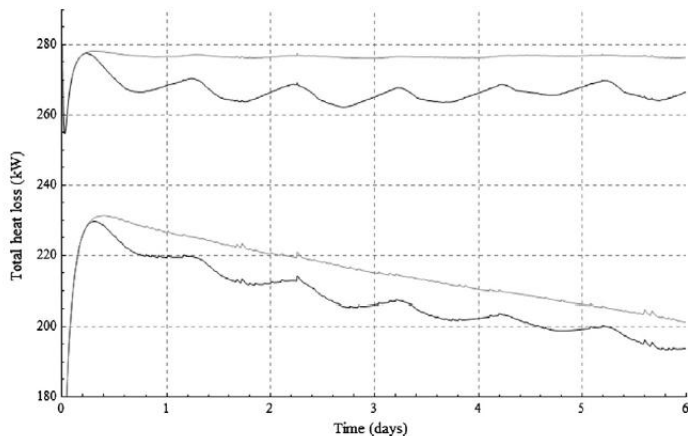


Fig. 18. Total molten salt inventory heat loss for the hot tank with 386 °C simulation start temperature and reference day set I – gray lines: solar irradiation not considered – black lines: solar irradiation considered – upper lines: charged – lower lines: discharged.

太阳辐照对罐体热损失影响

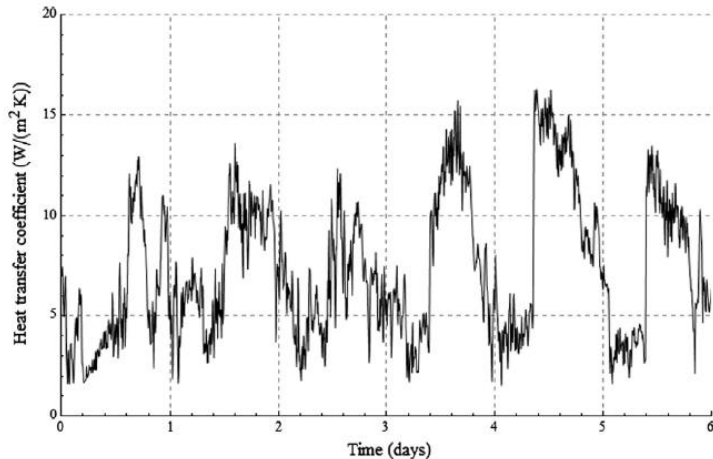


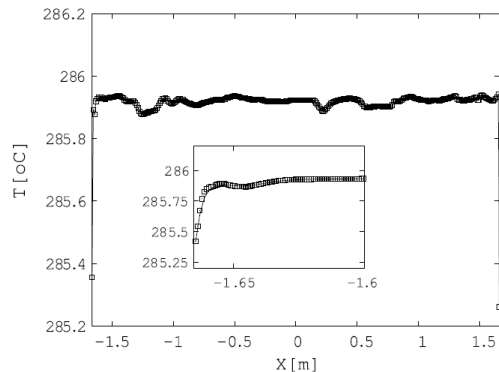
Fig. 19. Convective heat transfer coefficient between the ambient air and the exterior roof surface – reference day set I.

罐体外侧对流换热系数变化

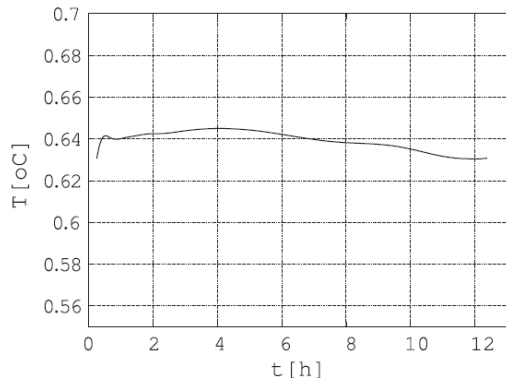
储热罐瞬态性能模拟 (Zaversky/2013)

2.4 双罐热性能研究

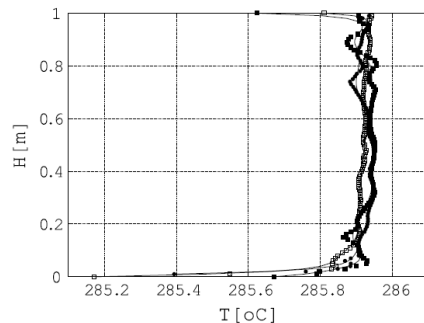
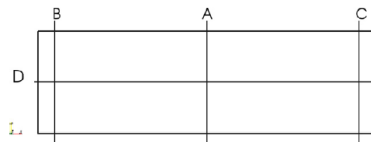
罐体内部熔融盐流动传热特性



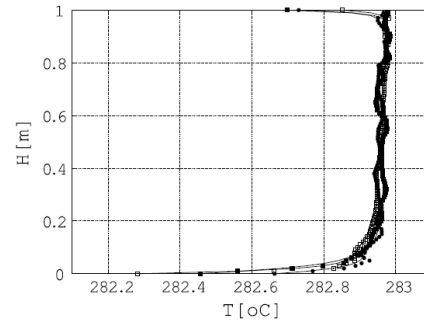
4h后罐体中心高度 (D截面) 温度分布



熔融盐与罐壁温差



(a)



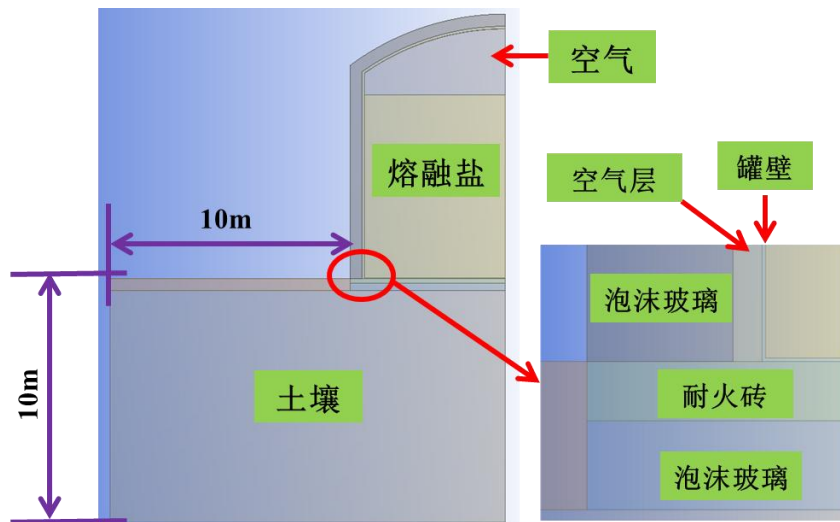
(b)

4h后 (a) 及8h后 (b) 不同位置 (A\B\C) 竖直方向温度分布

- ✓ 在接触面温度波动较大
- ✓ 其它位置熔融盐温度分布较为均匀

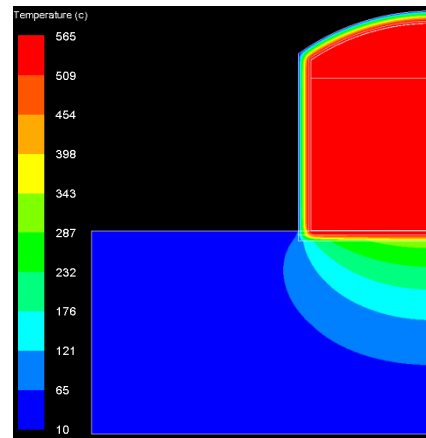
2.4 双罐热性能研究

➤ 储热罐热损失产生机理

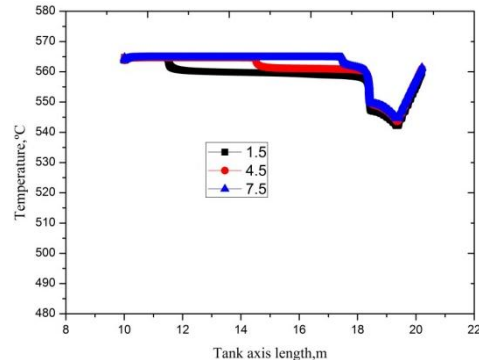


模型: Solar Two 高温储热罐
储热量: 110 MWh
高温熔融盐容量: 1400 T
罐体直径: 11.6m
罐体高度: H=8.4m

实际液面高度: $H_a = 7.5m$
罐体壁厚12mm
轴对称模型



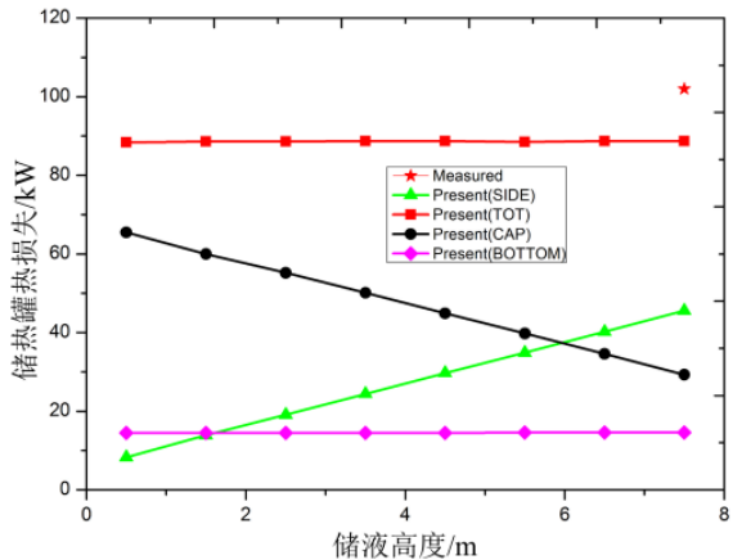
储热罐温度分布



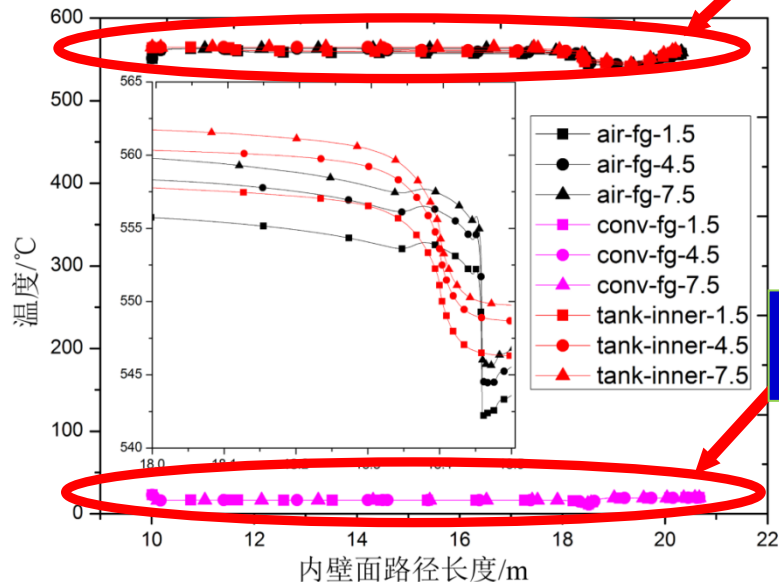
不同储液高度下罐体内壁温度

2.4 双罐热性能研究

➤ 储热罐热损失产生机理



不同储液高度下罐体热损失



不同储液高度下罐体不同位置温度分布

- ✓ 罐体运行过程中，内壁面温度基本不变，因而总热损失基本不变
- ✓ 太阳辐照/风力等外界作用影响罐体绝热层外壁温，导致总热损失波动

1

塔式太阳能热发电技术

2

塔式太阳能热发电热性能研究

3

塔式太阳能热发电可靠性研究

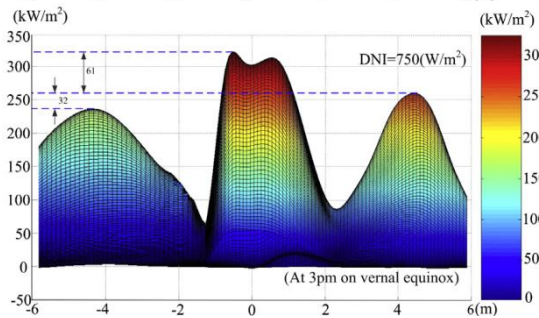
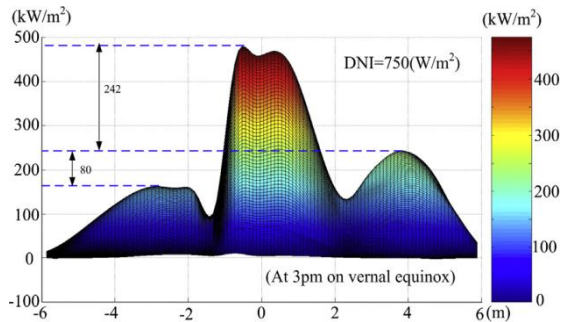
4

总结及展望

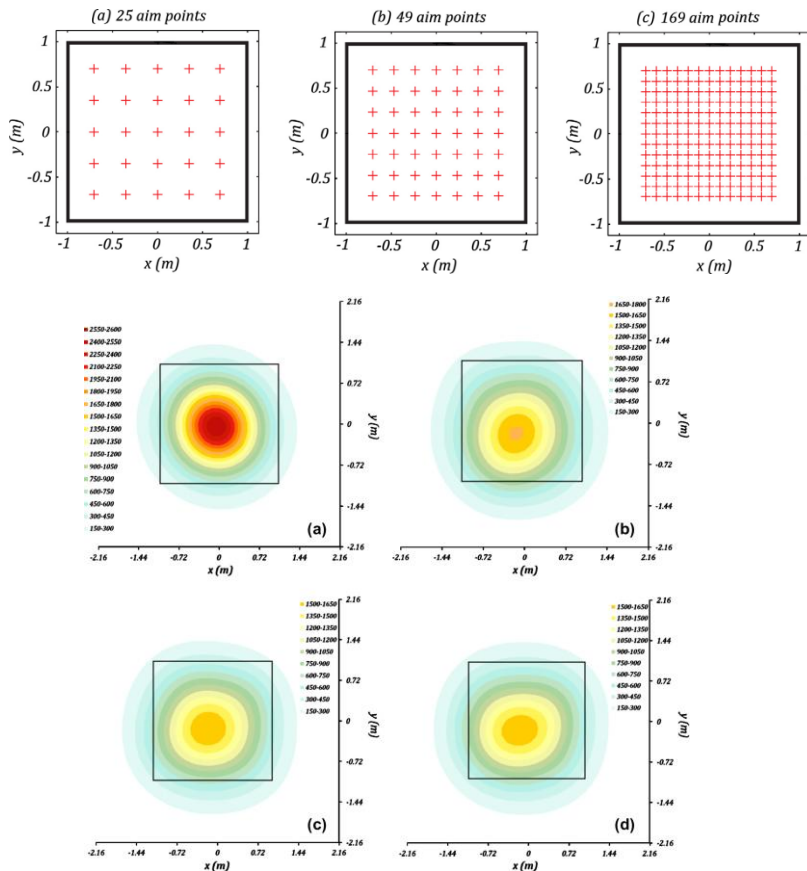
3.1 吸热器安全可靠运行研究

➤ 热流密度均匀化提升技术

✓ 镜场多点聚焦方式



多点聚焦方式优化热流密度分布 (Yu/2014)



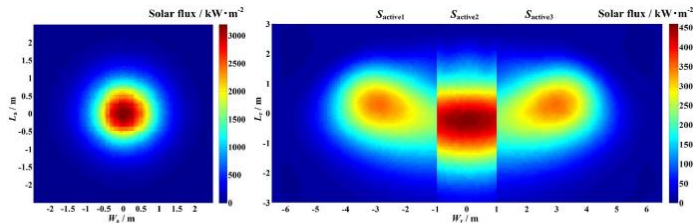
多点聚焦对热流密度影响 (Salome' /2013)

3.1 吸热器安全可靠研究

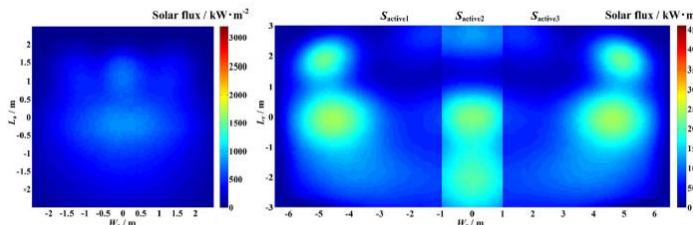
➤ 热流密度均匀化提升技术

✓ 镜场多点聚焦方式

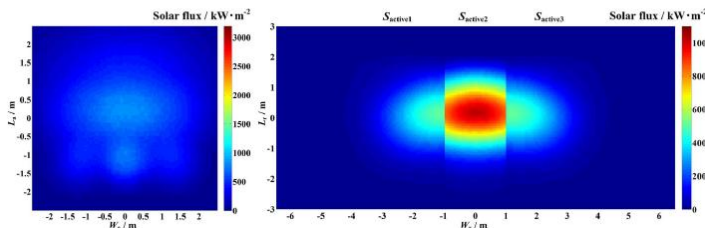
- ✓ 镜场多目标瞄准策略在提高吸热器接收聚焦阳光热流密度分布均匀性、降低最大热流密度的同时，会引起镜场光学损失增大
- ✓ 吸热器开口面积一定时，存在最优聚焦目标点数量及位置
- ✓ 对于腔式吸热器，开口接收阳光流密度均匀性的提高并不一定能够腔体内部壁上聚焦阳光热流密度分布均匀性的提高



(a) Solar flux distribution on the aperture (left) and on the inner surfaces (right) with single point aiming strategy ($PF_a=320\text{kW}\cdot\text{m}^{-2}$, $PF_{in}=456\text{kW}\cdot\text{m}^{-2}$, $\sigma_1=1.03$, $\eta_{\text{loss}}=23.08\%$)



(b) Solar flux distribution on the aperture (left) and on the inner surfaces (right) with multi-point aiming strategy-A ($PF_a=838\text{kW}\cdot\text{m}^{-2}$, $PF_{in}=228\text{kW}\cdot\text{m}^{-2}$, $\sigma_1=0.539$, $\eta_{\text{loss}}=29.22\%$)



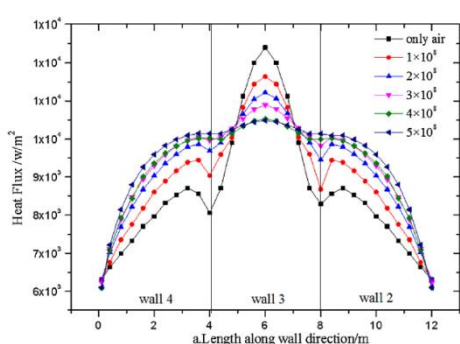
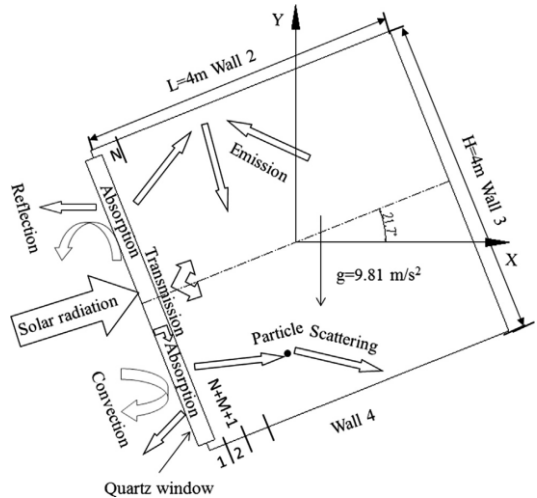
(c) Solar flux distribution on the aperture (left) and on the inner surfaces (right) with multi-point aiming strategy-B ($PF_a=851\text{kW}\cdot\text{m}^{-2}$, $PF_{in}=1025\text{kW}\cdot\text{m}^{-2}$, $\sigma_1=1.80$, $\eta_{\text{loss}}=27.34\%$)

不同聚焦方式对吸热器开口及腔体内部热流密度分布影响 (Wang/2017)

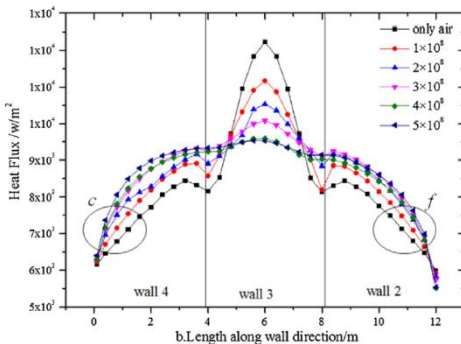
3.1 吸热器安全可靠研究

➤ 热流密度均匀化提升技术

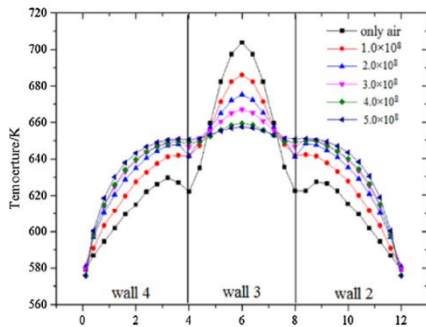
- ✓ 内部充填颗粒方式



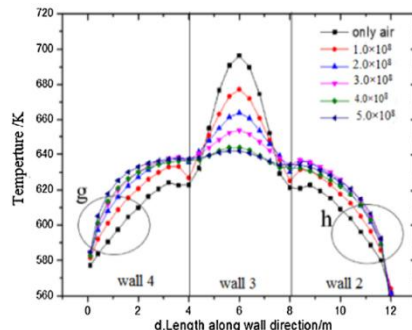
(a). Radiation condition



(b). Radiation-flow conditions



(c). Radiation condition

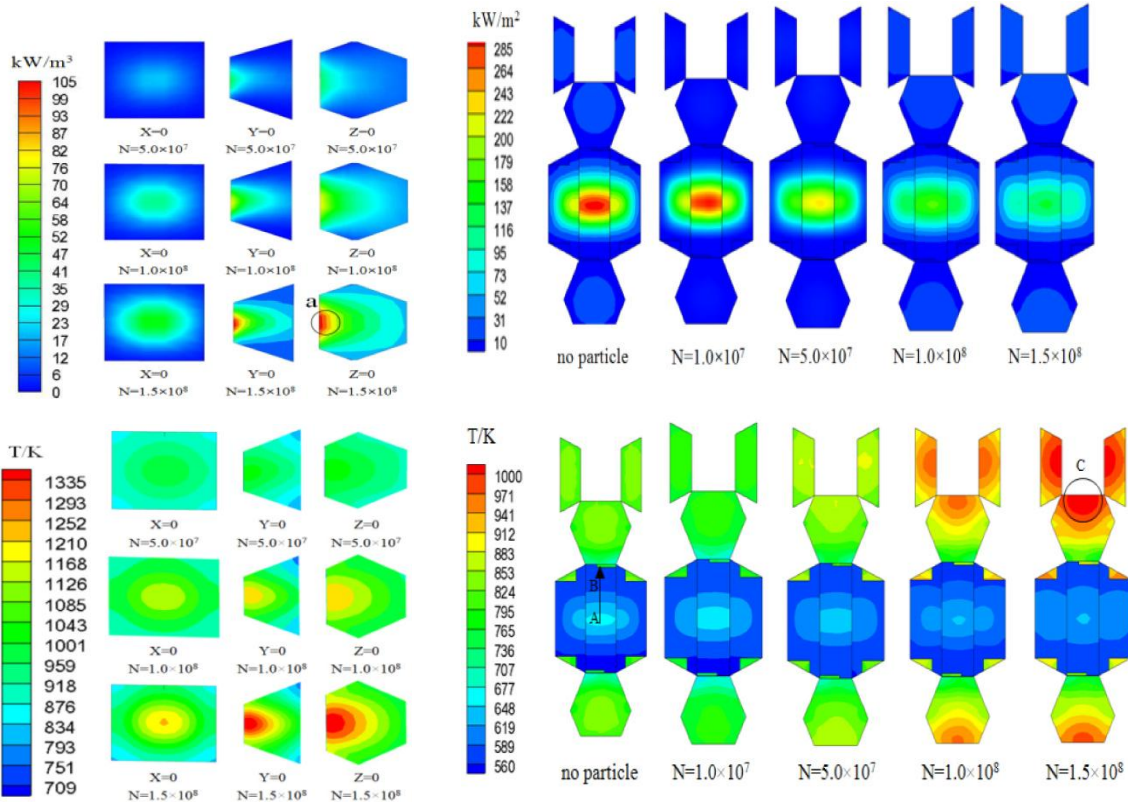
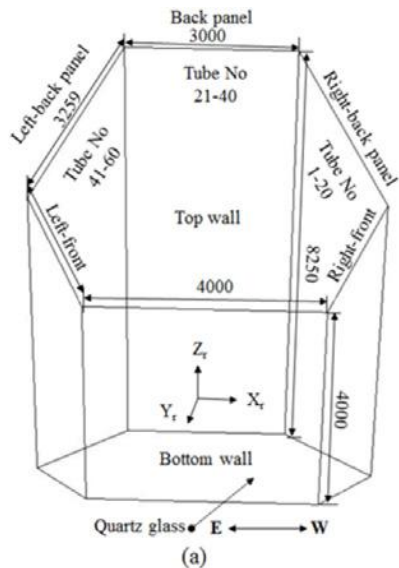


(d). Radiation-flow conditions

3.1 吸热器安全可靠研究

➤ 热流密度均匀化提升技术

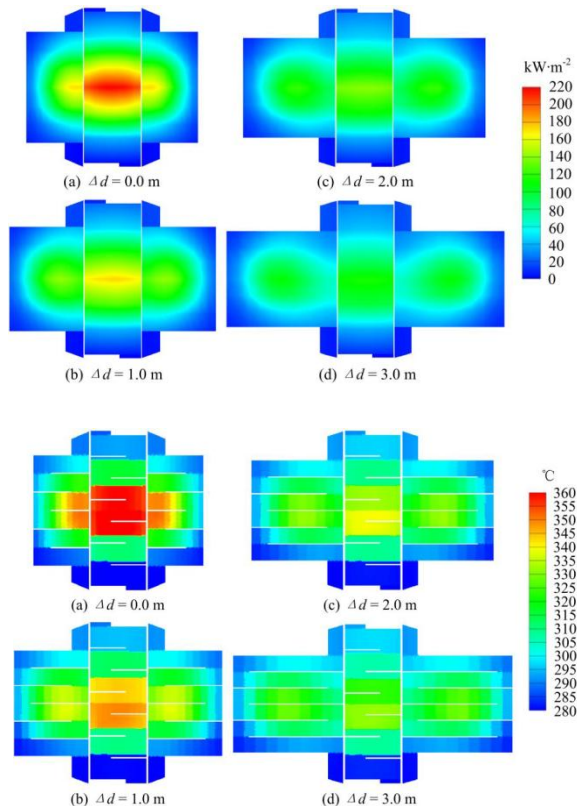
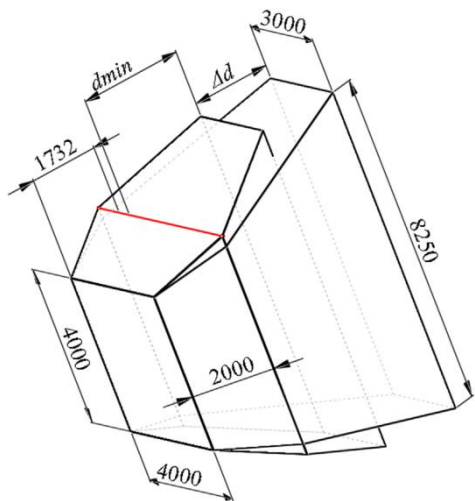
✓ 内部充填颗粒方式



3.1 吸热器安全可靠性能研究

➤ 热流密度均匀化提升技术

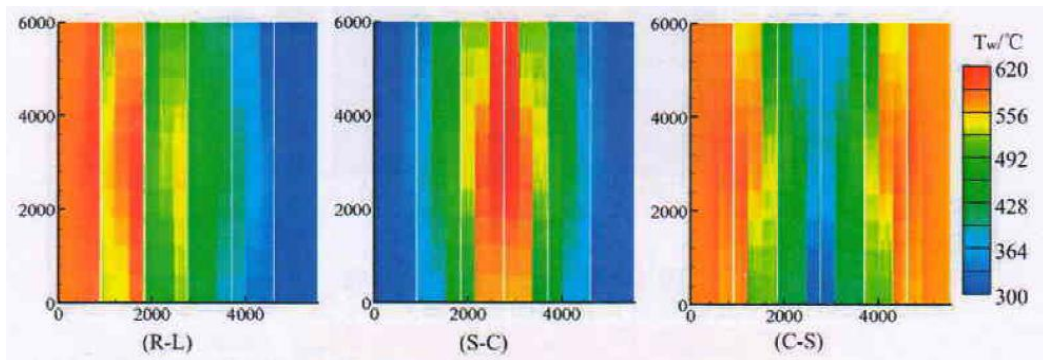
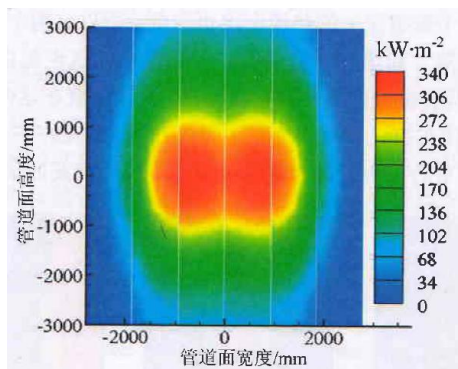
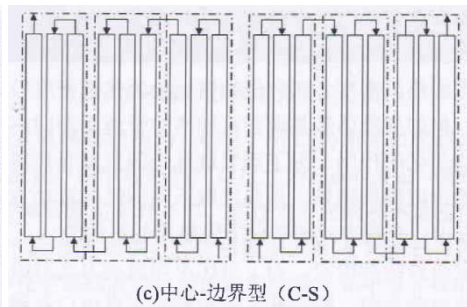
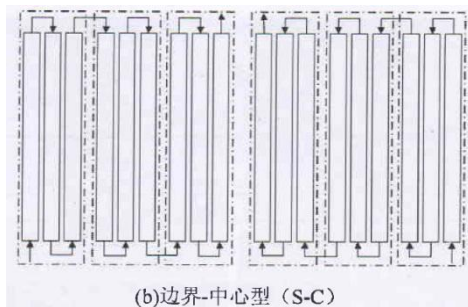
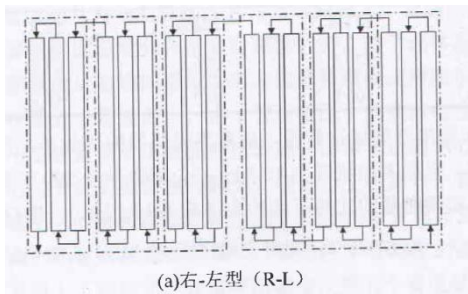
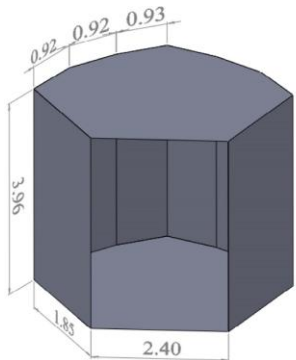
- ✓ 改变腔体深度方式



拉伸腔体对热流密度及温度分布影响 (Tu/2014)

3.1 吸热器安全可靠性的研究

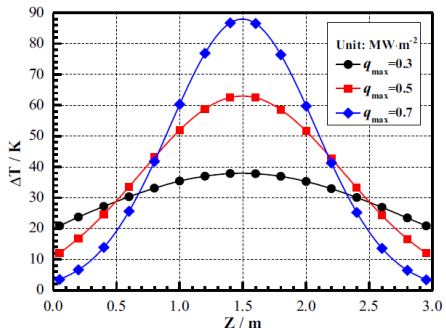
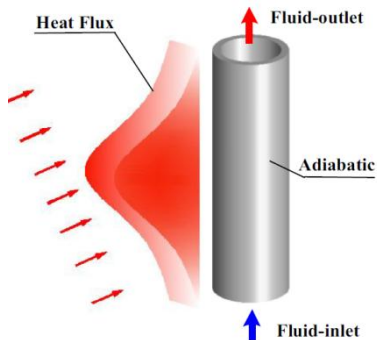
➤ 流动方式对壁面温度均匀性



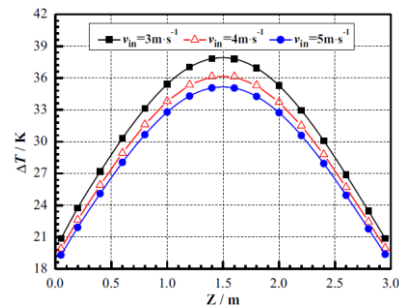
不同流动方式对壁面温度影响 (Zhang/2018)

3.1 吸热器安全可靠研究

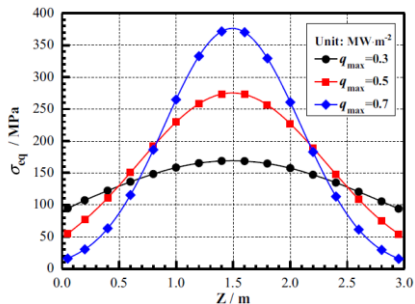
➤ 吸热管应力及寿命研究



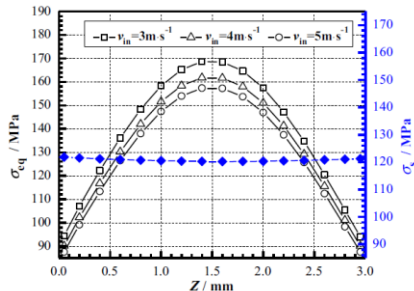
热流密对温差影响



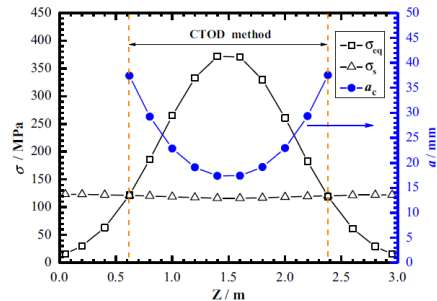
入口流速对温差影响



热流密对应力影响



入口流速对应力影响

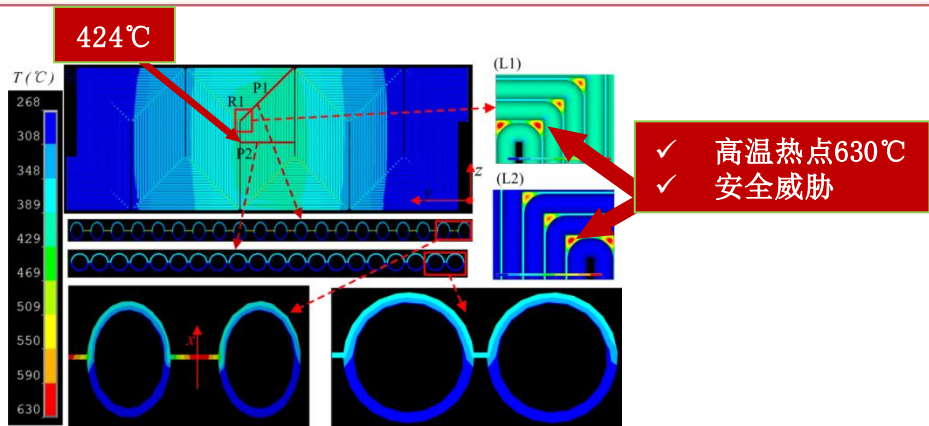
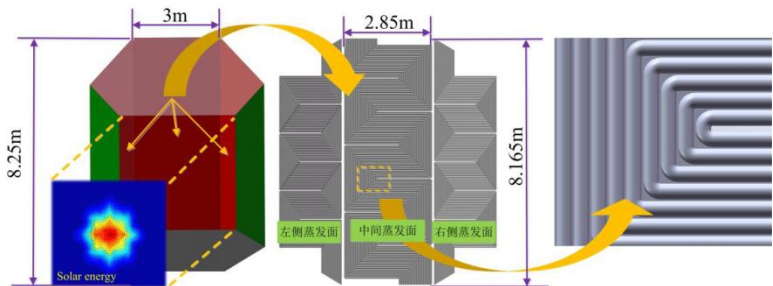


外壁面临界裂纹长度及等效应力

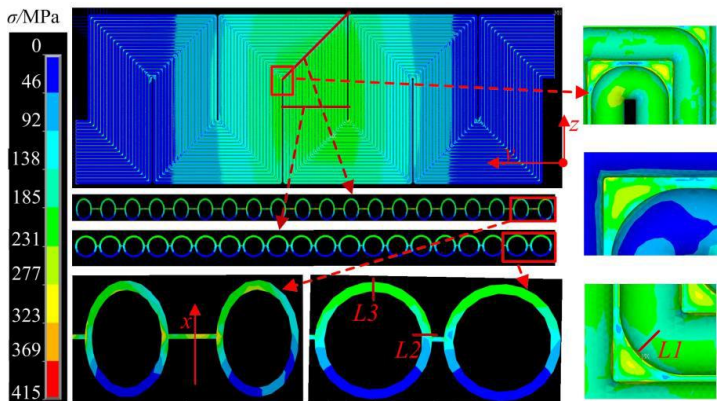
吸热管热应力及临界疲劳裂纹 (Du/2016)

3.1 吸热器安全可靠研究

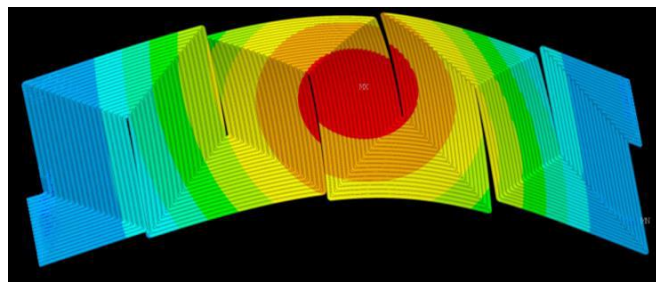
➤ 吸热管应力及寿命研究



蒸发面温度分布



蒸发面热应力分布

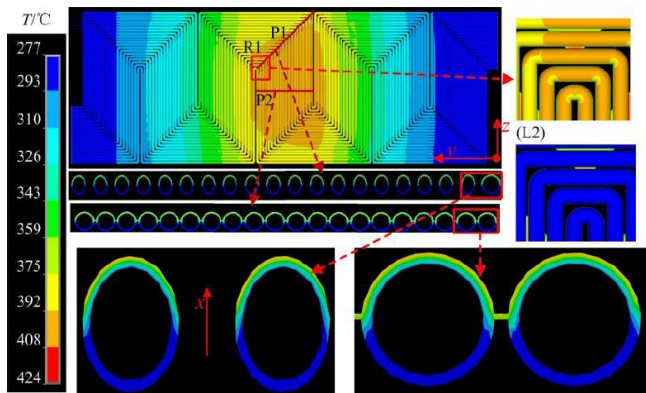


蒸发面热变形

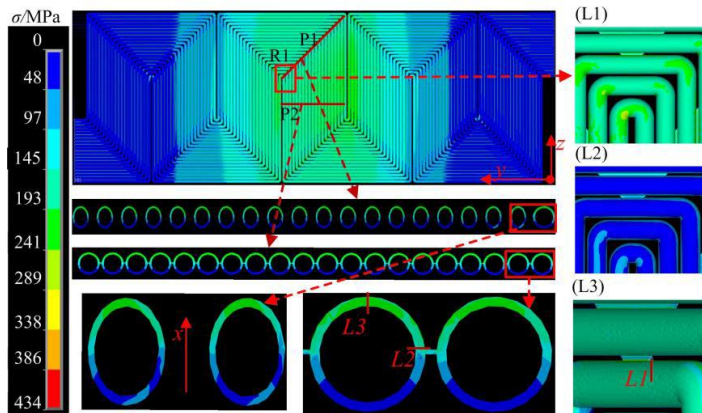
蒸发面热应力及疲劳寿命 (Wei/2018)

3.1 吸热器安全可靠研究

➤ 吸热管应力及寿命研究



剪切膜式壁面温度分布



剪切膜式壁面温度分布

- ✓ 高温热点消除
- ✓ 最大热应力增大19 MPa

蒸发面热应力及疲劳寿命 (Wei/2018)

3.1 吸热器安全可靠研究

➤ 吸热管应力及寿命研究

膜式壁面及剪切膜式壁面疲劳寿命对比



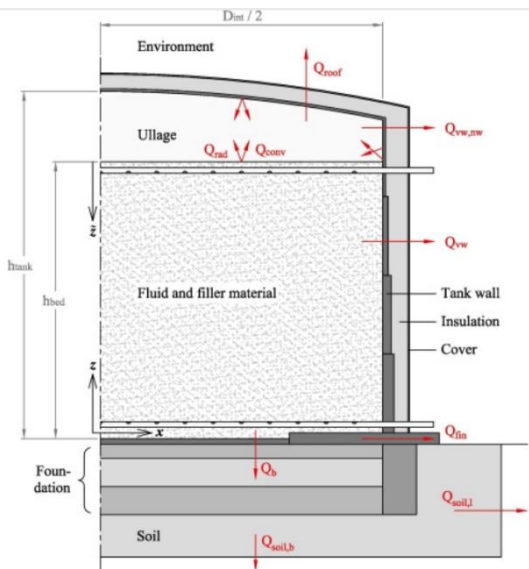
项目	路径	ΔS_p /MPa	疲劳寿命(循环次数)			
			$K_f=1.0$	$K_f=1.7$	$K_f=2.5$	$K_f=4$
膜式壁面	L1	415	4.67×10^4	7102	1907	520
	L2	233	6.88×10^5	5.57×10^4	1.32×10^4	2714
	L3	228	7.82×10^5	*	*	*
剪切膜式壁面	L1	434	3.94×10^4	6087	1657	465
	L2	238	6.08×10^5	5.15×10^4	1.23×10^4	2527
	L3	238	6.08×10^5	*	*	*

焊缝相关

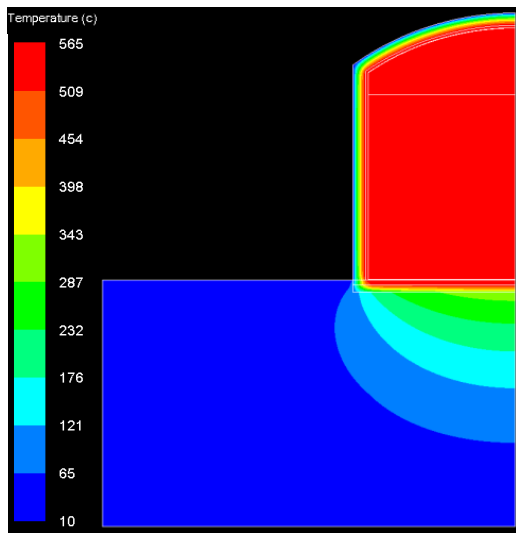
- ✓ 研究结果与Baker等对Solar one及CESA-I系统吸热器测试结果相符，即吸热器换热管的泄露总是与吸热面焊缝有关
- ✓ Solar one换热管在投入运行18~20个月出现泄露；CESA-I吸热器数月内出现弯曲泄露
- ✓ 除最大热应力位置外，剪切膜式壁面疲劳寿命高于膜式壁面

3.2 储热罐安全可靠研究

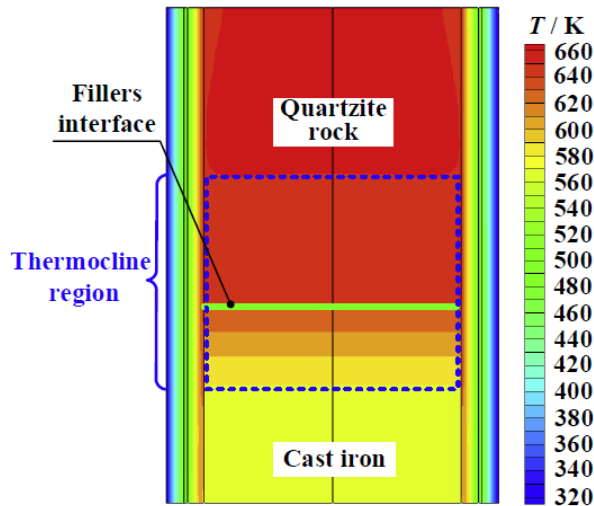
➤ 共性问题——工况复杂、无运行设计规范



储热罐结构



熔融盐储热罐温度分布

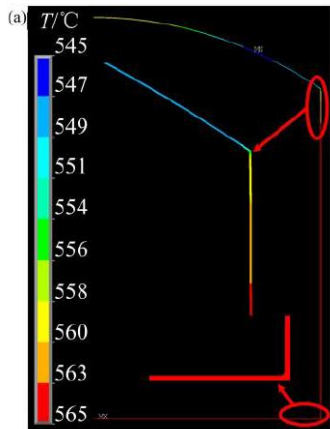


单罐斜温层储热温度分布

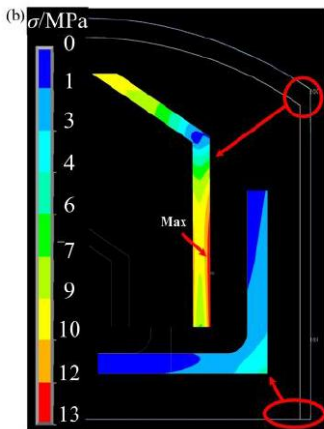
- ✓ 罐体尺寸大、储热介质温度高
- ✓ 尚无设计标准。设计依照储油罐标准，储热介质工作温度远超石油储罐设计最高温度（220°C）

3.2 储热罐安全可靠研究

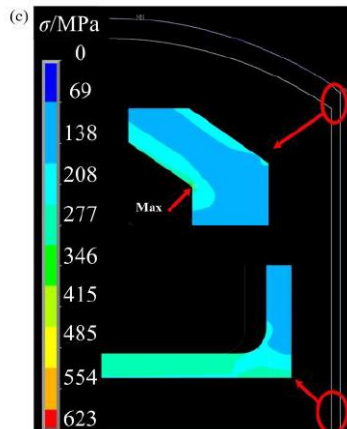
➤ 储热罐热应力



(a) 罐壁温度分布

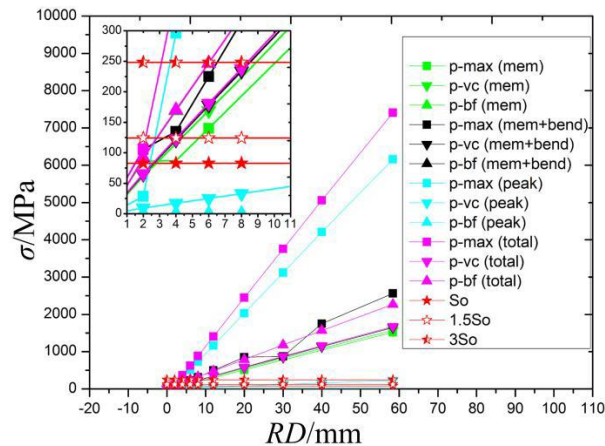


(b) 自由膨胀热应力



(c) 径向约束 6mm 时热应力

罐体温度分布及不同约束时热应力分布

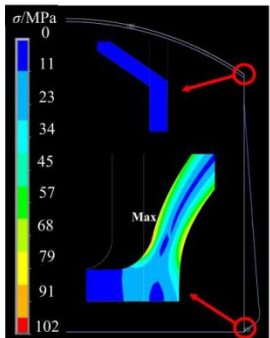


不同径向约束时罐体热应力

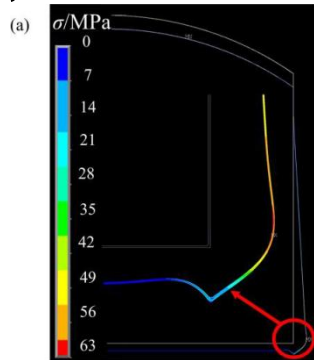
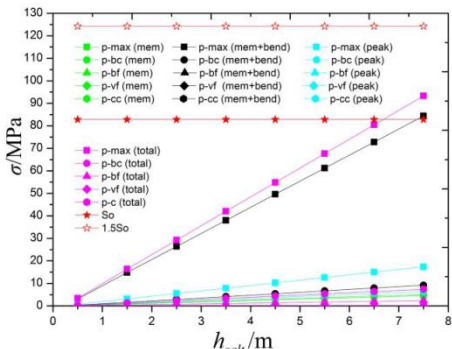
- ✓ 储热罐**温度梯度**引起热应力很低，最大热应力仅为**13.0 MPa**
- ✓ 热应力与径向约束量存在线性关系
- ✓ 径向约束对罐体热应力影响极大，很小约束量就可以引起热应力急剧升高。**储热罐设计及运行过程中严禁约束热变形**

3.2 储热罐安全可靠研究

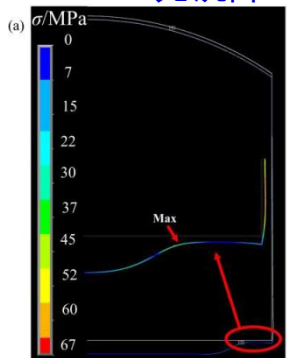
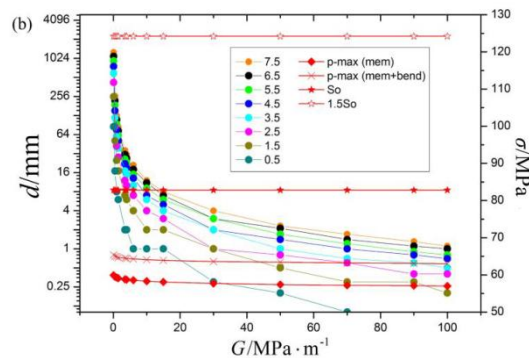
罐体沉降及其对储热罐安全运行影响



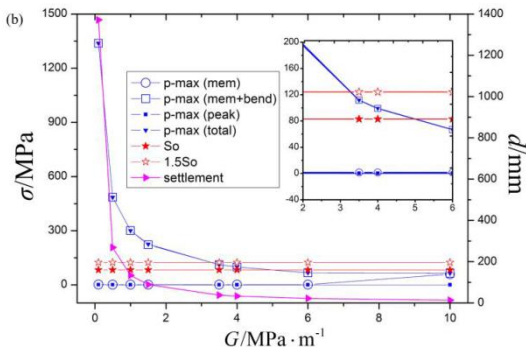
无沉降时罐体应力分布及变化



基础刚度对罐体应力及沉降影响



填料刚度对罐体应力及沉降影响



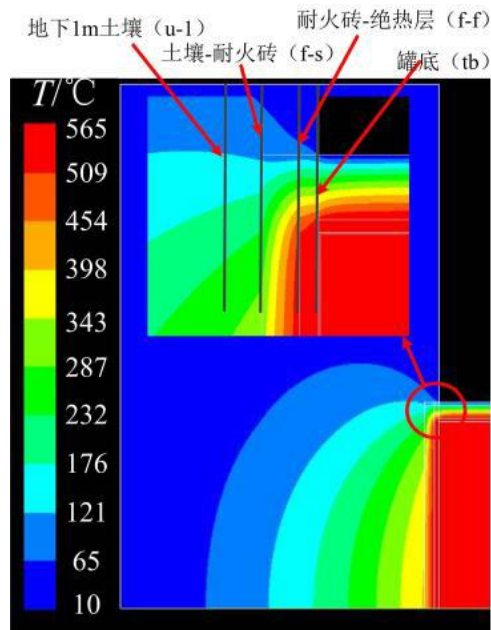
储热罐安全可靠研究 (Wei/2018)

- ✓ 适度沉降可降低充/放热引起罐体应力变化幅值
- ✓ 罐底基础刚度对沉降影响极大，应高于30.0 MPa m⁻¹
- ✓ 罐底基础填料刚度对罐体应力水平影响极大，应高于3.5 MPa m⁻¹

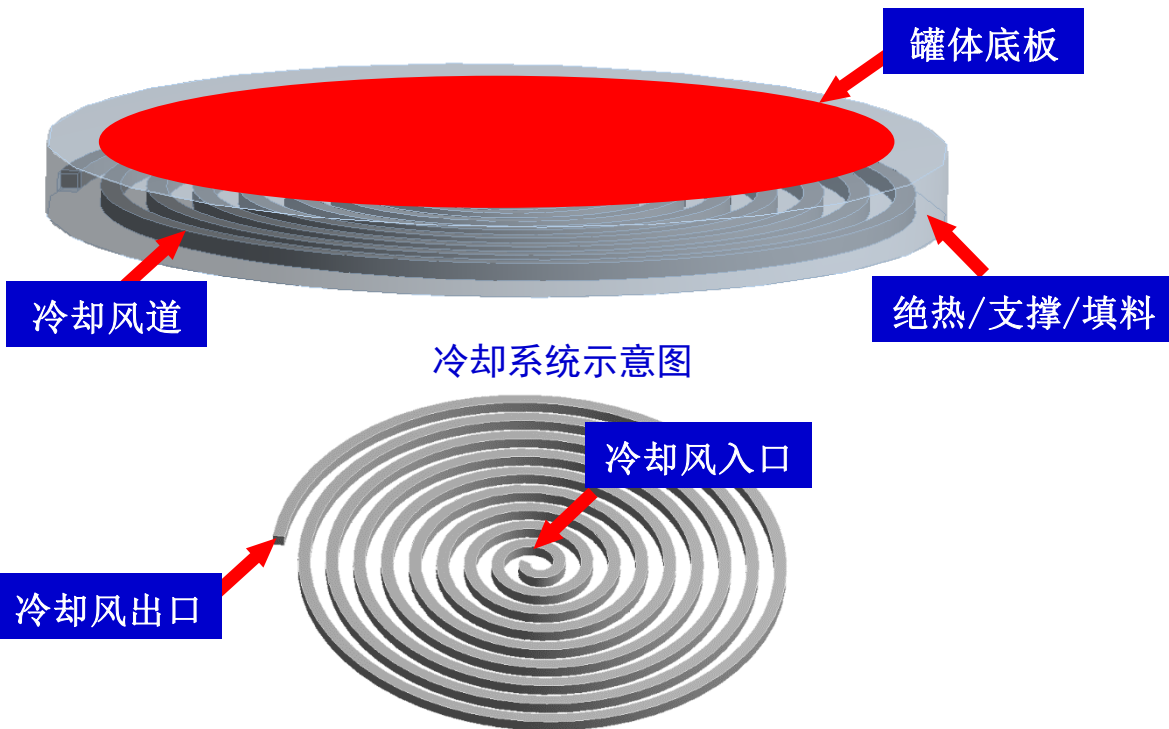
3.2 储热罐安全可靠性的研究

罐低冷却系统设计

基础非均匀温度分布 → 基础非均匀变形 → 罐体底板沉降



无冷却系统时罐底基础温度分布



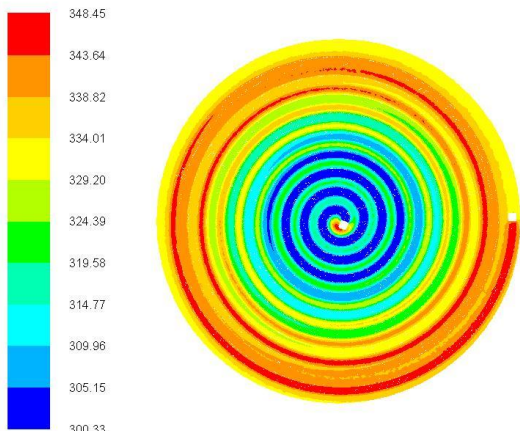
冷却系统示意图

冷却风道示意图

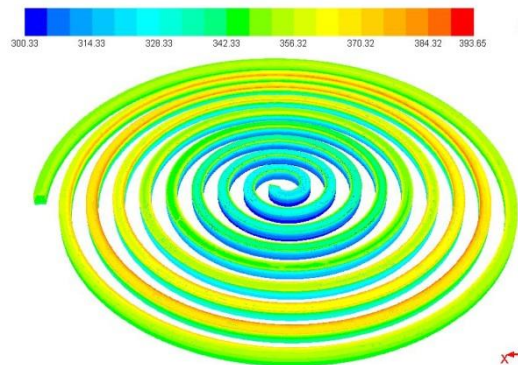
3.2 储热罐安全可靠性的研究

罐底冷却系统设计

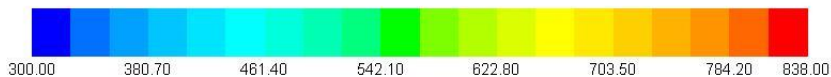
温度监测面F



F面温度分布 (单位: K)



冷却风道温度分布 (单位: K)



基础横截面温度分布 (单位: K)

1

塔式太阳能热发电技术

2

塔式太阳能热发电热性能研究

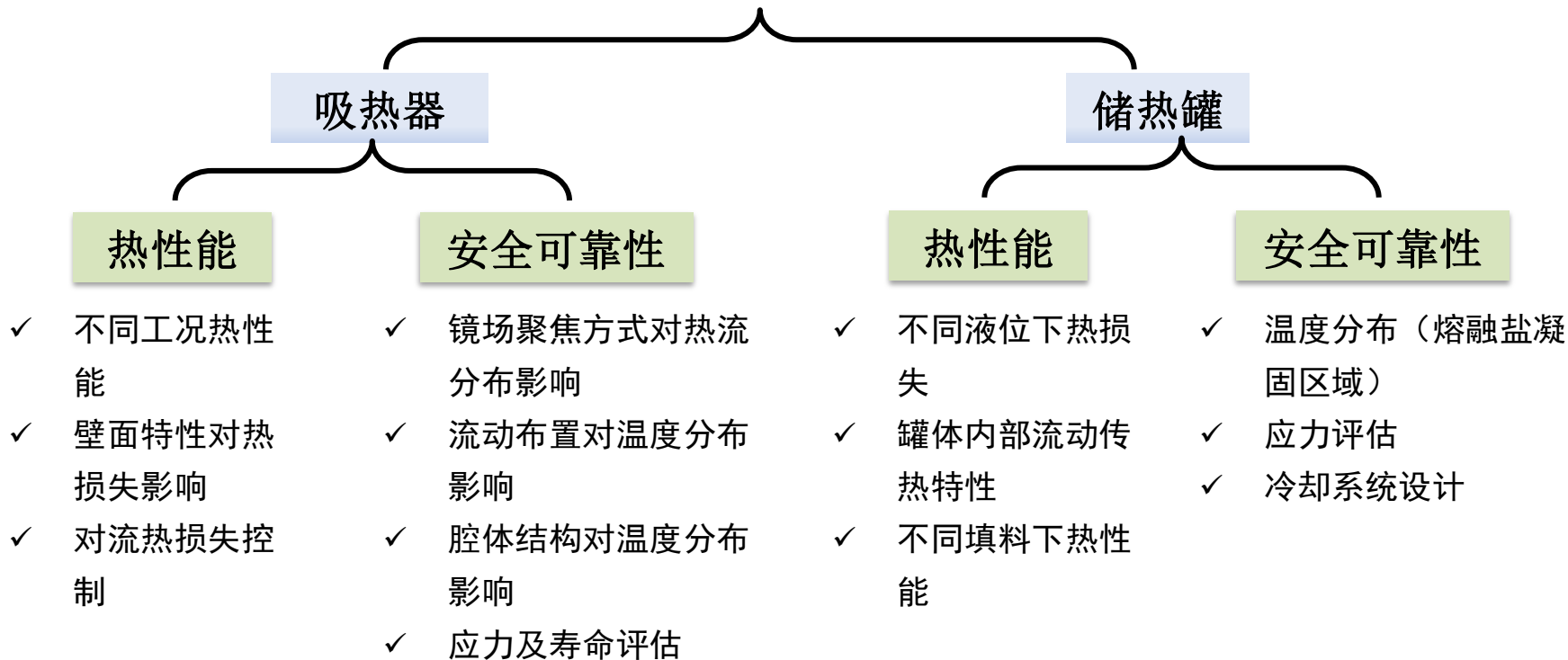
3

塔式太阳能热发电可靠性研究

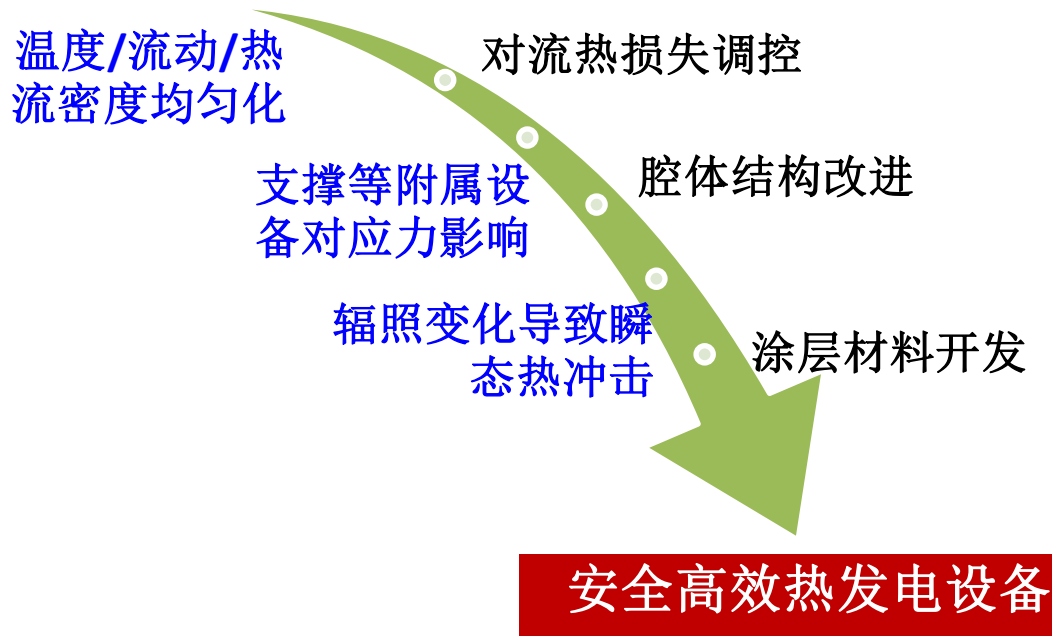
4

总结及展望

塔式太阳能热发电关键部件研究现状



总结及展望





谢谢!