CLIMA 2019

26 - 29 May, Bucharest, Romania

重慶大學 CHONGQING UNIVERSITY

Numerical simulation and experiment investigation of phase change energy storage device in the heat pump assisted solar heating system

热泵辅助太阳能系统的相变蓄能装置数值分析与测试研究

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Chongqing University

13TH REHVA WORLD CONGRESS CLIMA 2019

28 May 2019

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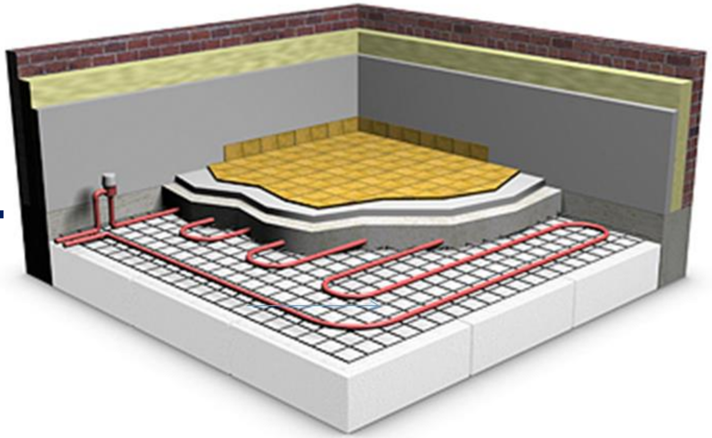
Heat storage tank
水箱蓄热

Energy storage device using Phase change material
相变蓄能罐蓄热



Radiant floor heating terminal
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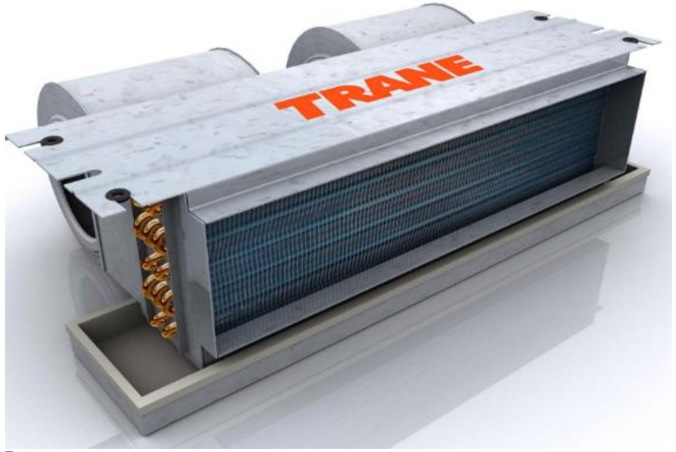
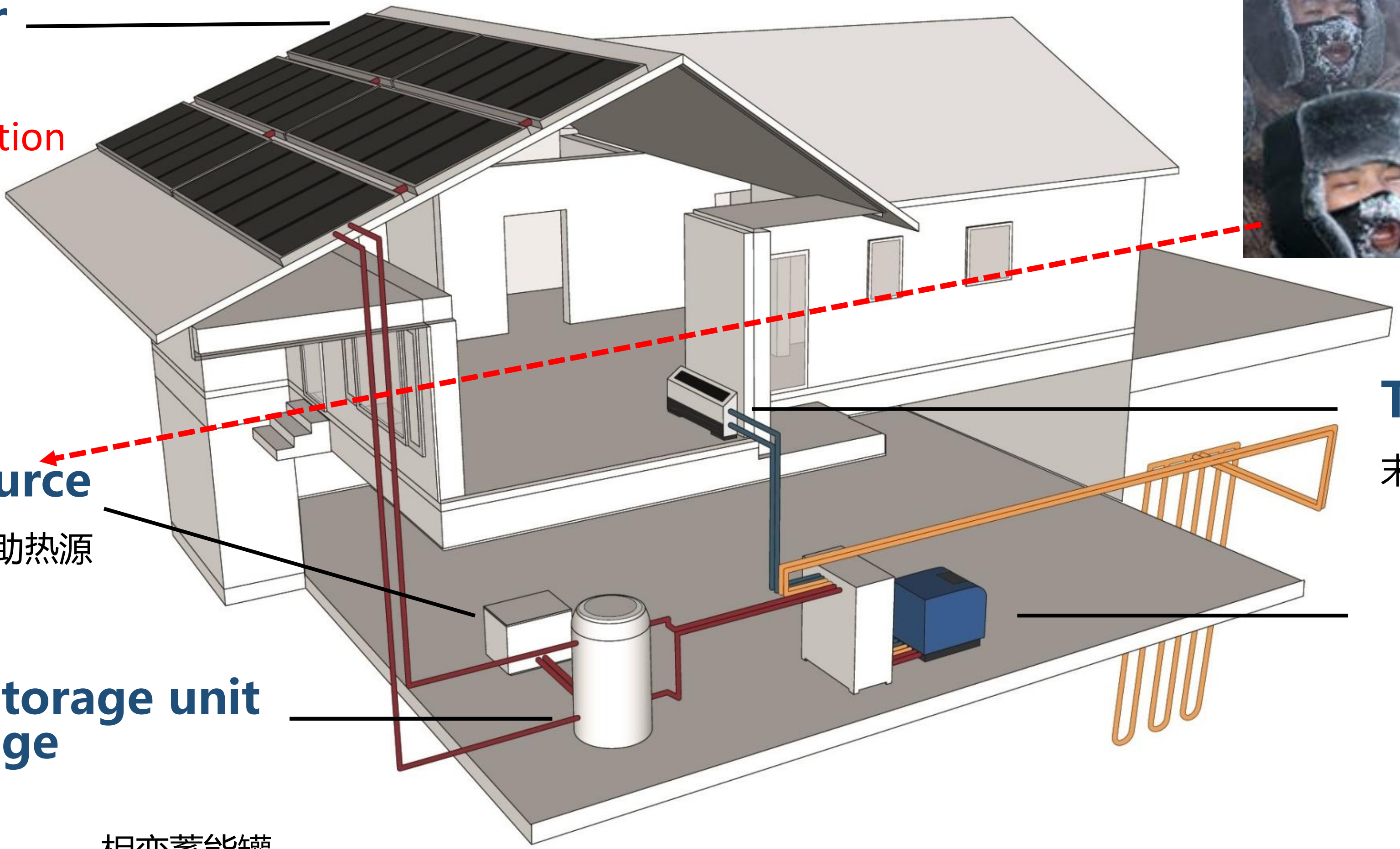


Fan-coil terminal
风机盘管末端

1 Basic form of heating system-- Operating conditions for component

供热系统基本形式–部件运行条件

Under extreme weather conditions



Solar collector

太阳能集热器

intensity of solar radiation

Auxiliary heat source

辅助热源

Thermal energy storage unit using Phase change material(PCM)

相变蓄能罐

Terminal device

末端设备

Heat pump (air source or ground source)

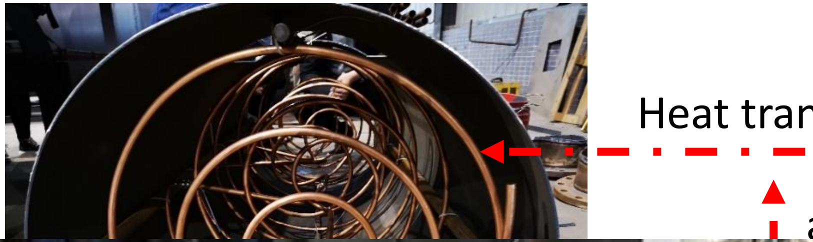
热泵(空气源/地源)

The operation condition is determined by outdoor temperature for air source heat pump

The outdoor temperature should not less than - 35℃ for heating model

Low phase transition temperature. Such as 20~30℃； Solar energy is not abundant. **Preheating outdoor air with a low temperature**

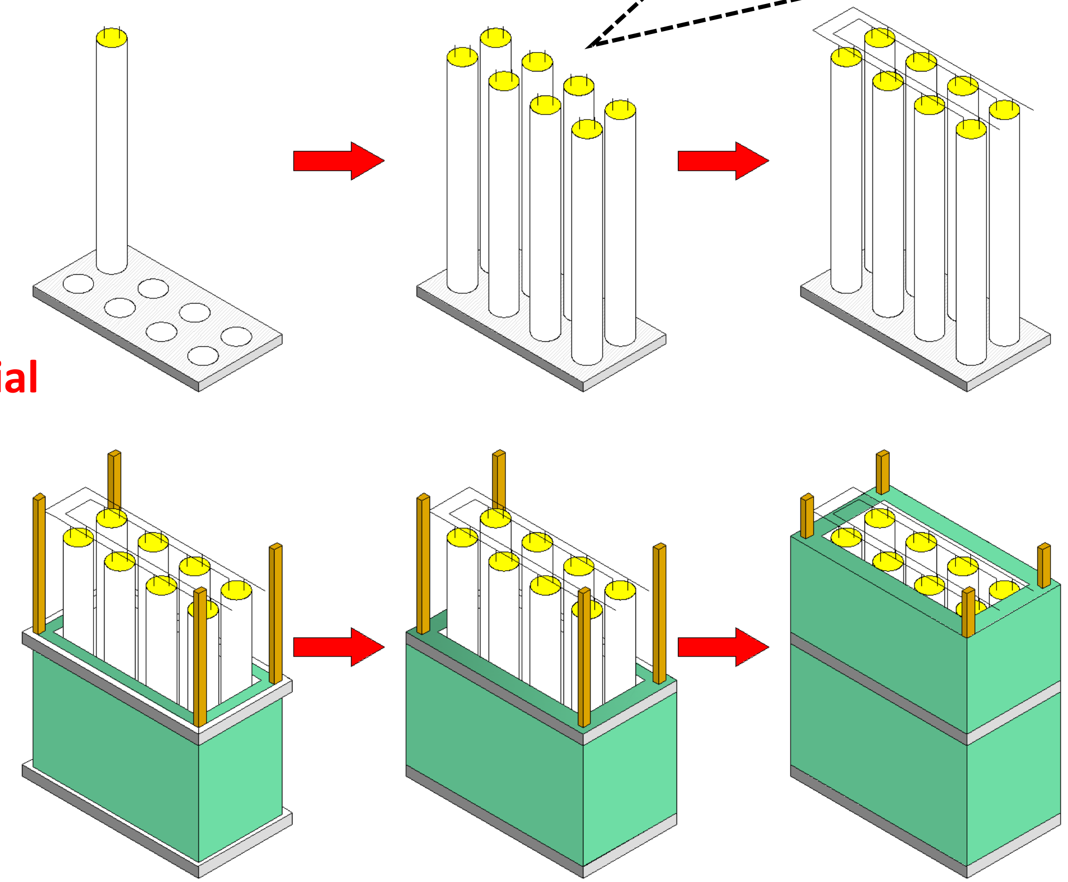
Different PCM should be applied to different situation based on phase transition temperature



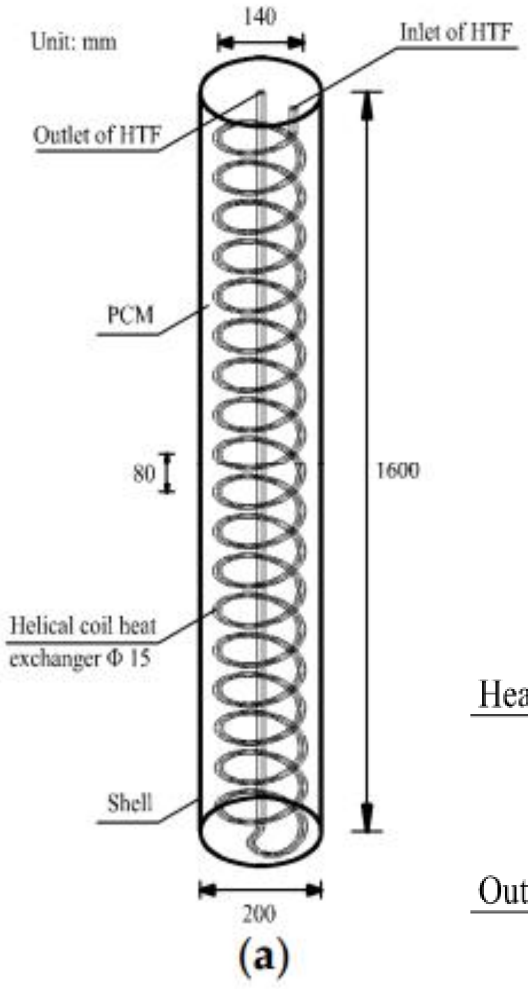
2 Structure & combination form of phase change energy storage device 蓄能罐基本结构与组合形式

The spiral heat exchanger is adopted in the interior of the device to increase the effective heat exchange area
装置内部采用螺旋换热器，增大了有效换热面积

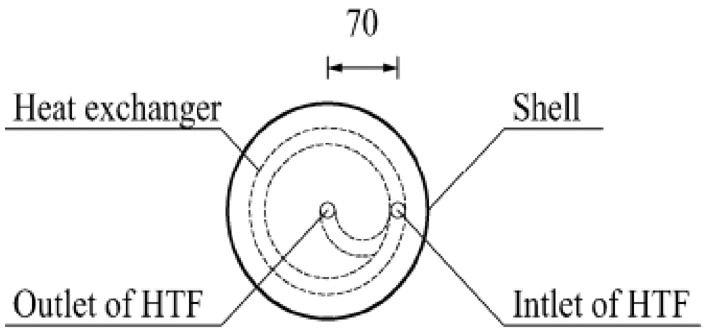
Capacity matching and future expansion are achieved by modular combinations
模块化组合方式实现容量匹配，同时支持未来扩容



3 Numerical calculation model of TES unit-Basic structure
蓄能罐数值模型计算-基本结构



3D view
三维视图



overhead view
俯视图

Basic structure/dimension parameters of TES unit
蓄能罐基本结构尺寸参数

Name 名称	Dimension parameter 尺寸参数	Name 名称	Dimension parameter 尺寸参数
Shell material 外壳材质	Homo-polypropylene 均聚聚丙烯	Material of heat exchanger 换热器材质	Copper 铜
Shell height（mm）外壳高度	1670	Weight of heat exchanger（kg）换热器重量	3
Shell diameter（mm）外壳直径	200	coil pitch（mm）换热器螺距	80
Capacity of TES unit（L）蓄热单元容量	52	coil diameter（mm）换热器直径	140
Weight of TES unit（kg）蓄热单元重量	48	Inner diameter of the helical coil tube（mm）进出水管径	15

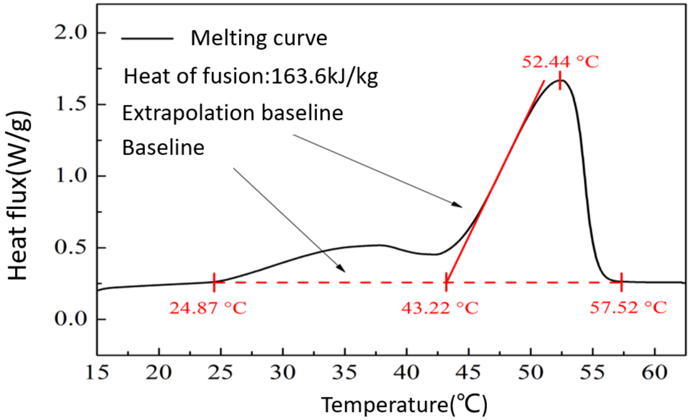
3 Numerical calculation model of TES unit—Measurements of basic parameters（DSC test）and Calculation parameter processing

基本参数测定与边界条件处理

Thermal conductivity coefficient instrument
导热系数测定仪

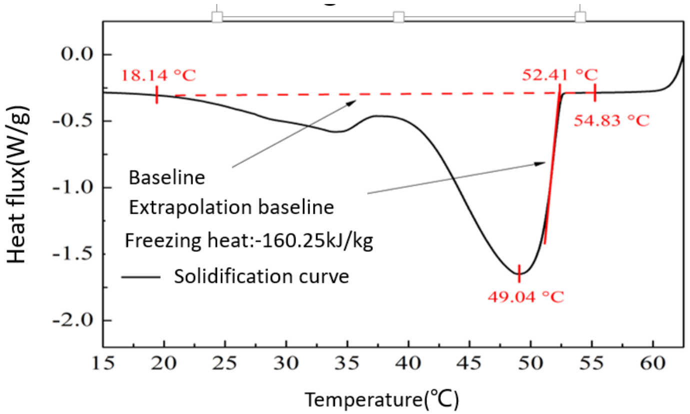
Material thermal conductivity 0.55 W/(m·K)材料导热系数

Fusion / solidification heat tester
熔化/凝固热测试仪



相变材料熔化曲线

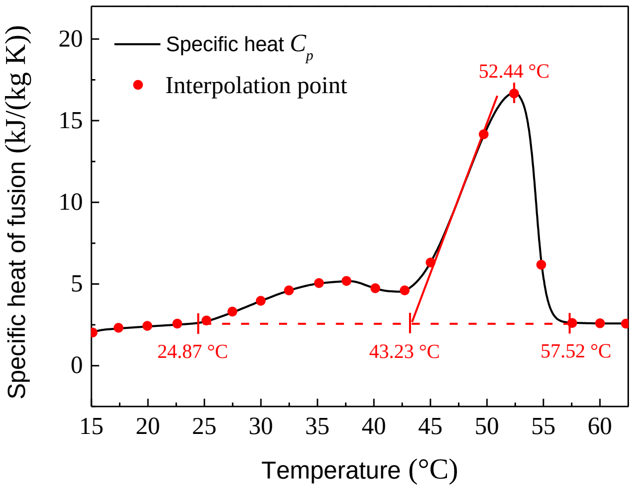
Melting curve of PCM

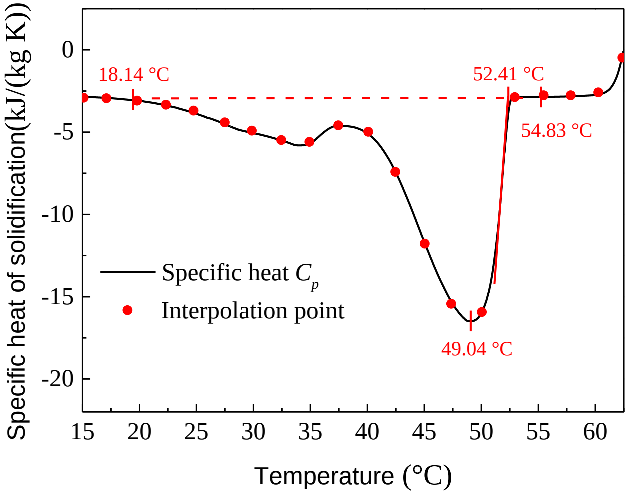


相变材料凝固曲线

Solidification curve of PCM

The melting and solidification specific heat are set as the piecewise linear function of the temperature in the numerical calculation for improving the calculation accuracy of liquid fraction





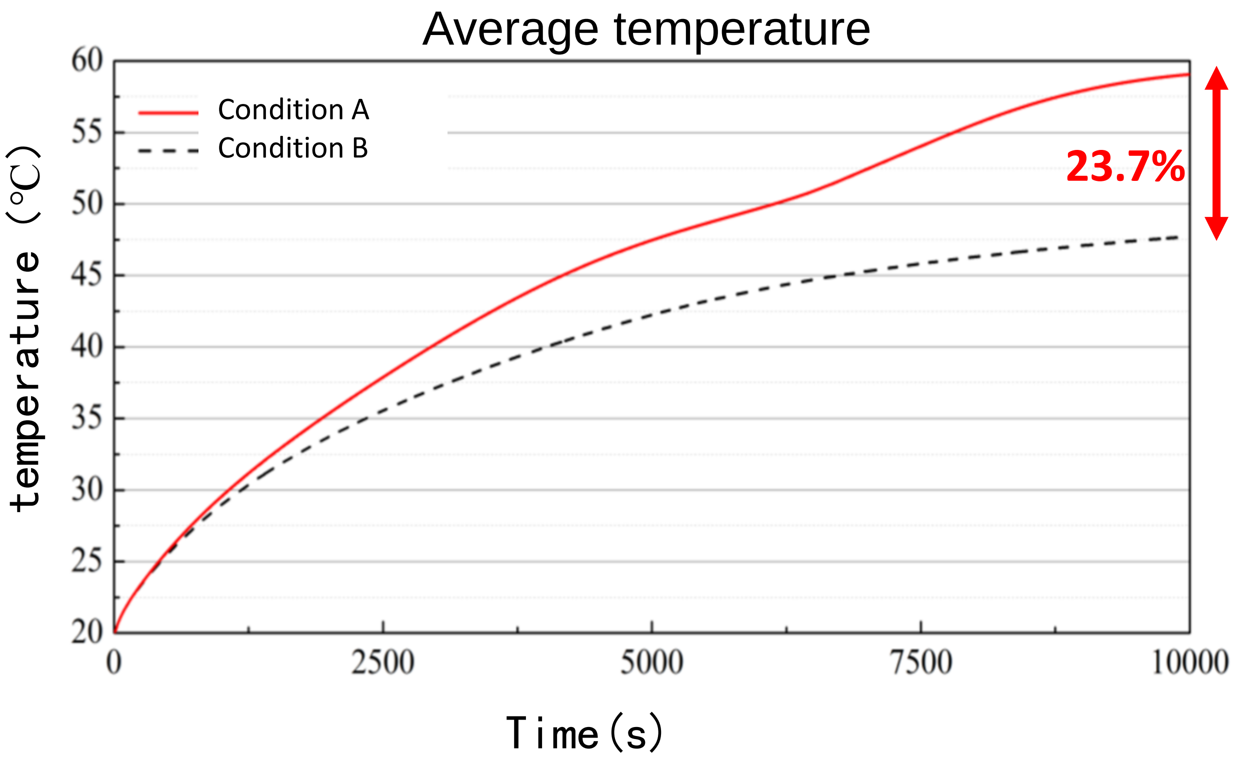
3 Numerical calculation model of TES unit—Natural convection

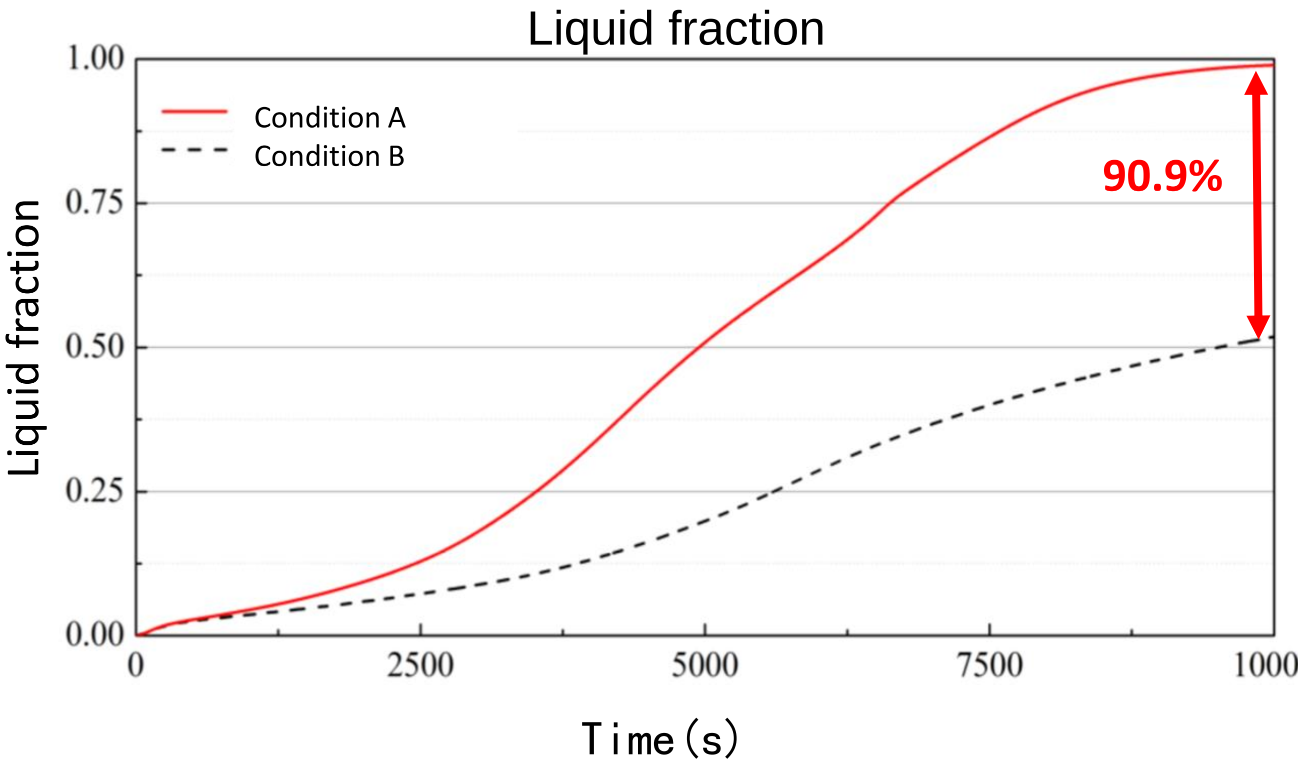
蓄能罐数值模型计算-模型需要考虑自然对流

- Natural convection
- Density varies with the temperature based on Boussinesq assumption

—— Condition A: Thermal conductivity with natural convection

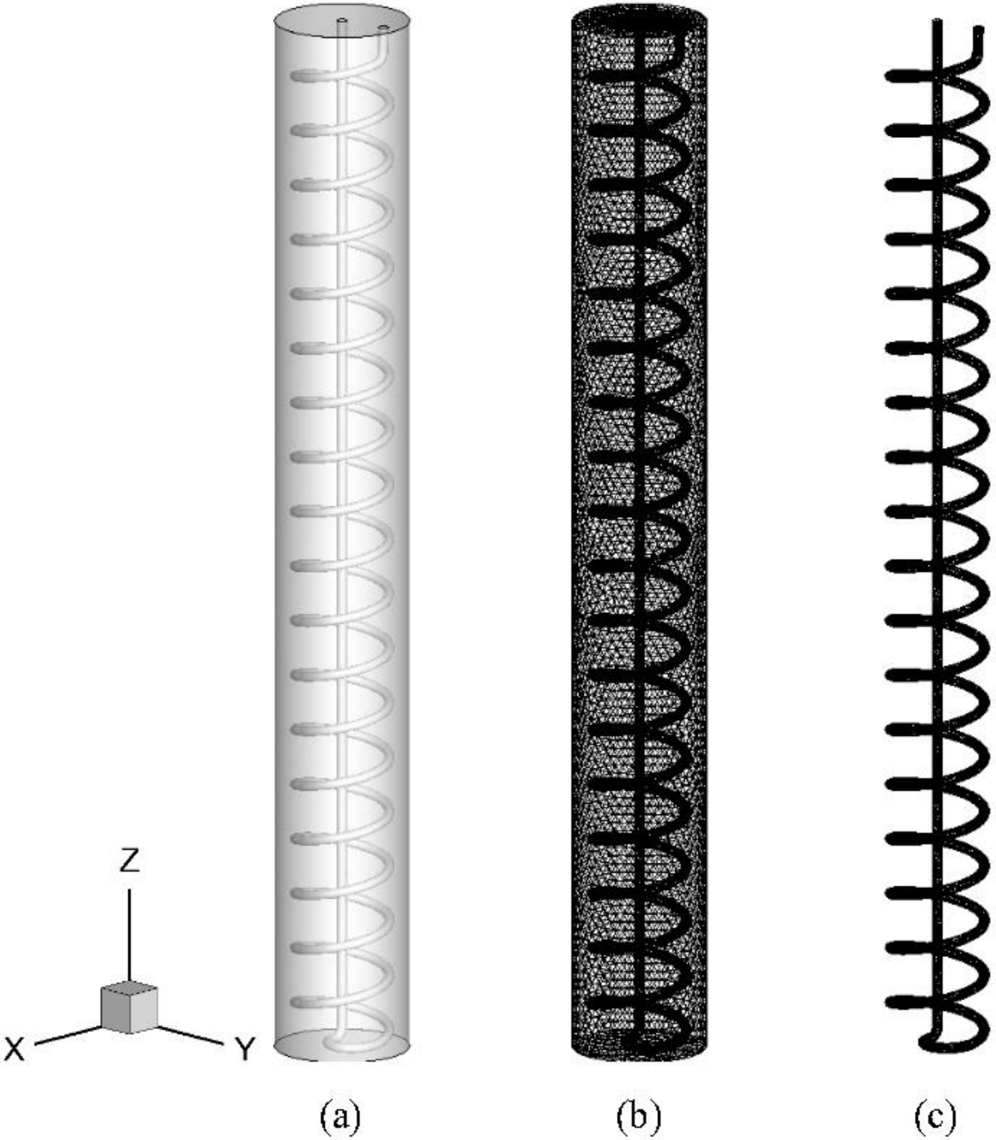
-·-·- Condition B: Thermal conductivity

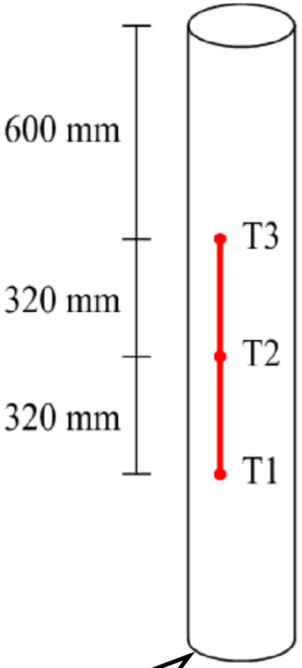




3 Numerical calculation model of TES unit—Geometric and computational mesh models and arrangement of measured points

几何和计算网格模型及测点

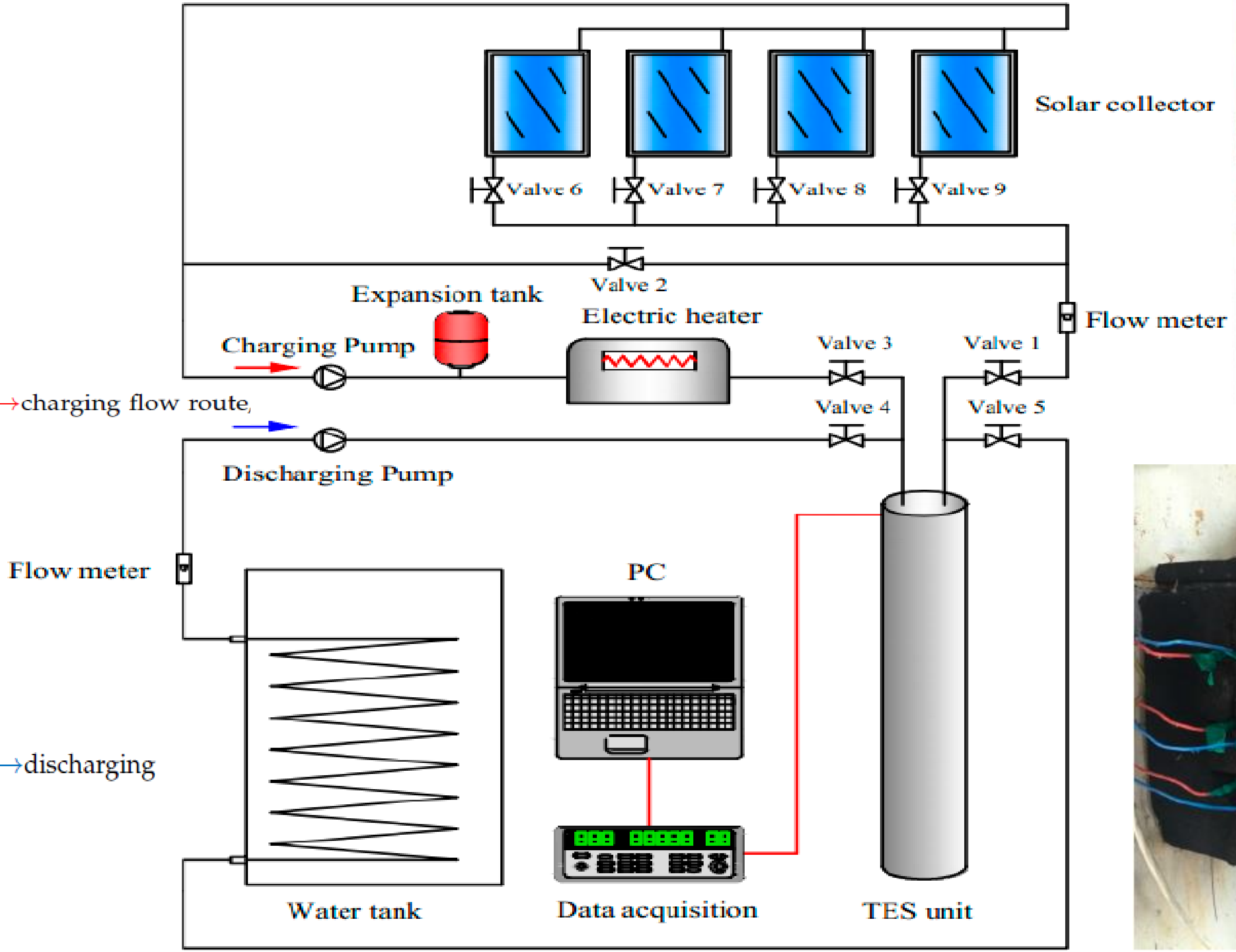




The thermocouples are embedded in TES unit for further verifying the reliability of the numerical model

蓄能罐内部埋入热电偶温度测点用于后续验证数值模型的可靠性

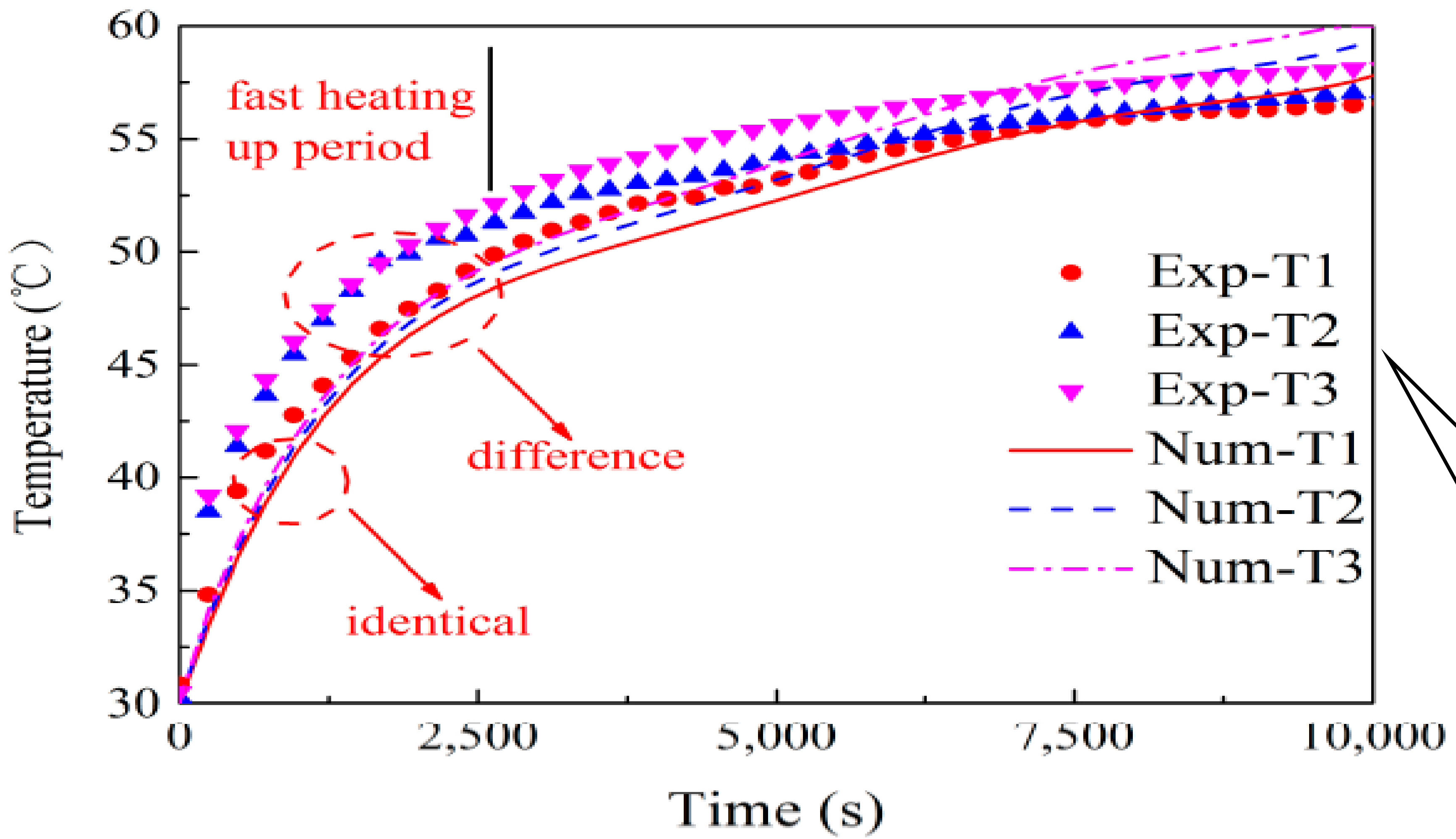
Validation -calculation and results
Schematic diagram of experimental platform
测试平台流程图

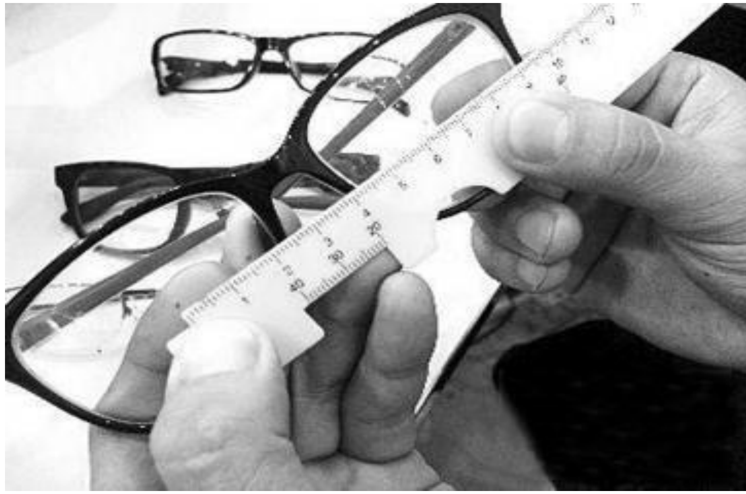


Validation -calculation and results

Temperature comparison between calculated and measured points

计算与测点温度对比



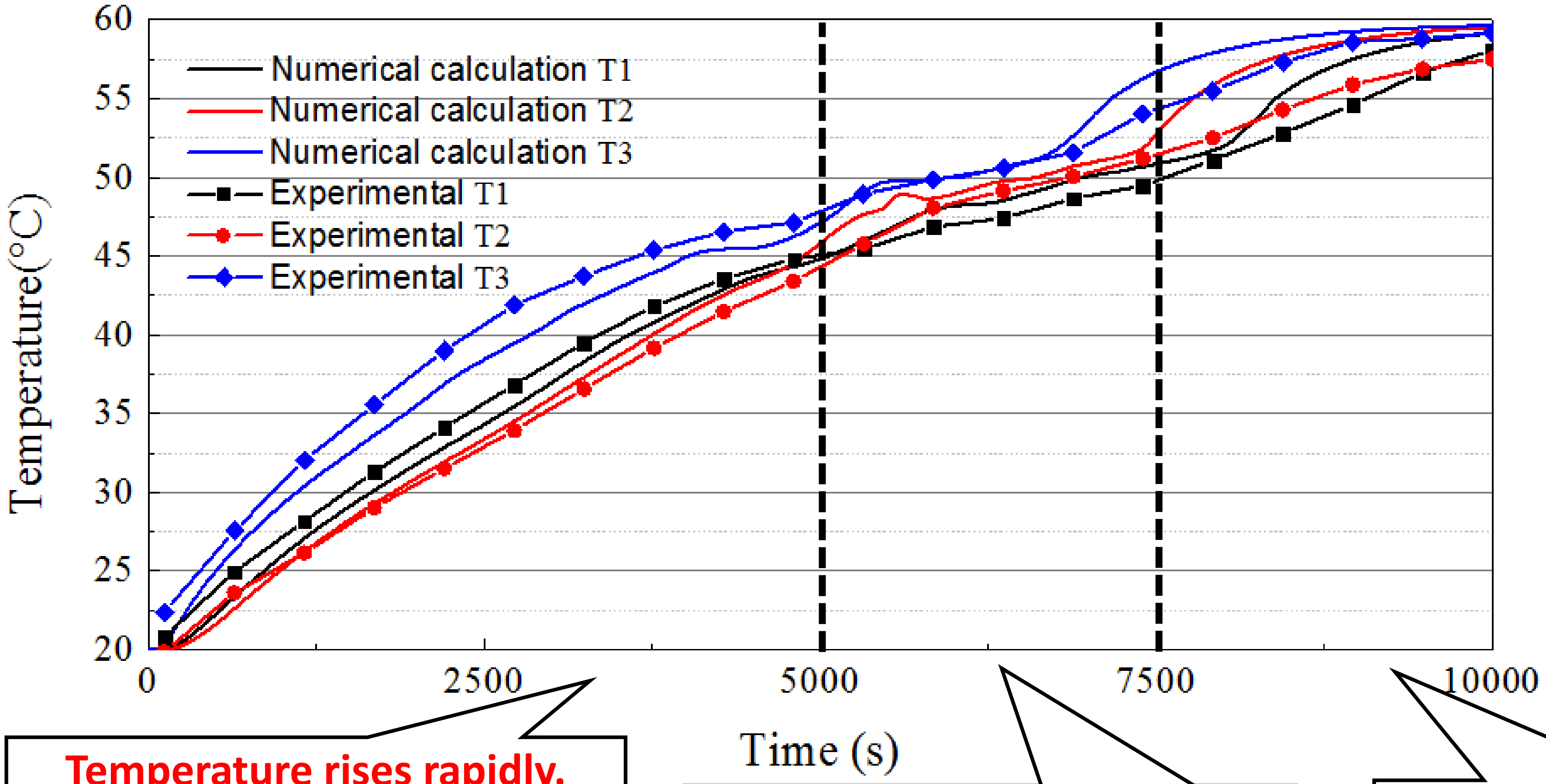


maximum error is less than 8%

The numerical results are in good agreement with the experimental results, which verified the reliability of the numerical model

数值与实验结果吻合较好
验证了数值模型的可靠性

4 Validation -calculation and results： Analysis of the model calculation results
模型计算结果分析



T Xiong， X Yang， Y Wang *
Investigation of the Dynamic Melting Process in a Thermal Energy Storage Unit Using a Helical Coil Heat Exchanger. Energies, 2017(10):1-17

Temperature rises rapidly. Sensible heat storage is dominant.
快速升温阶段
显热蓄热为主

Temperature rises slowly . Latent heat storage is dominant.
缓慢升温阶段
潜热蓄热为主

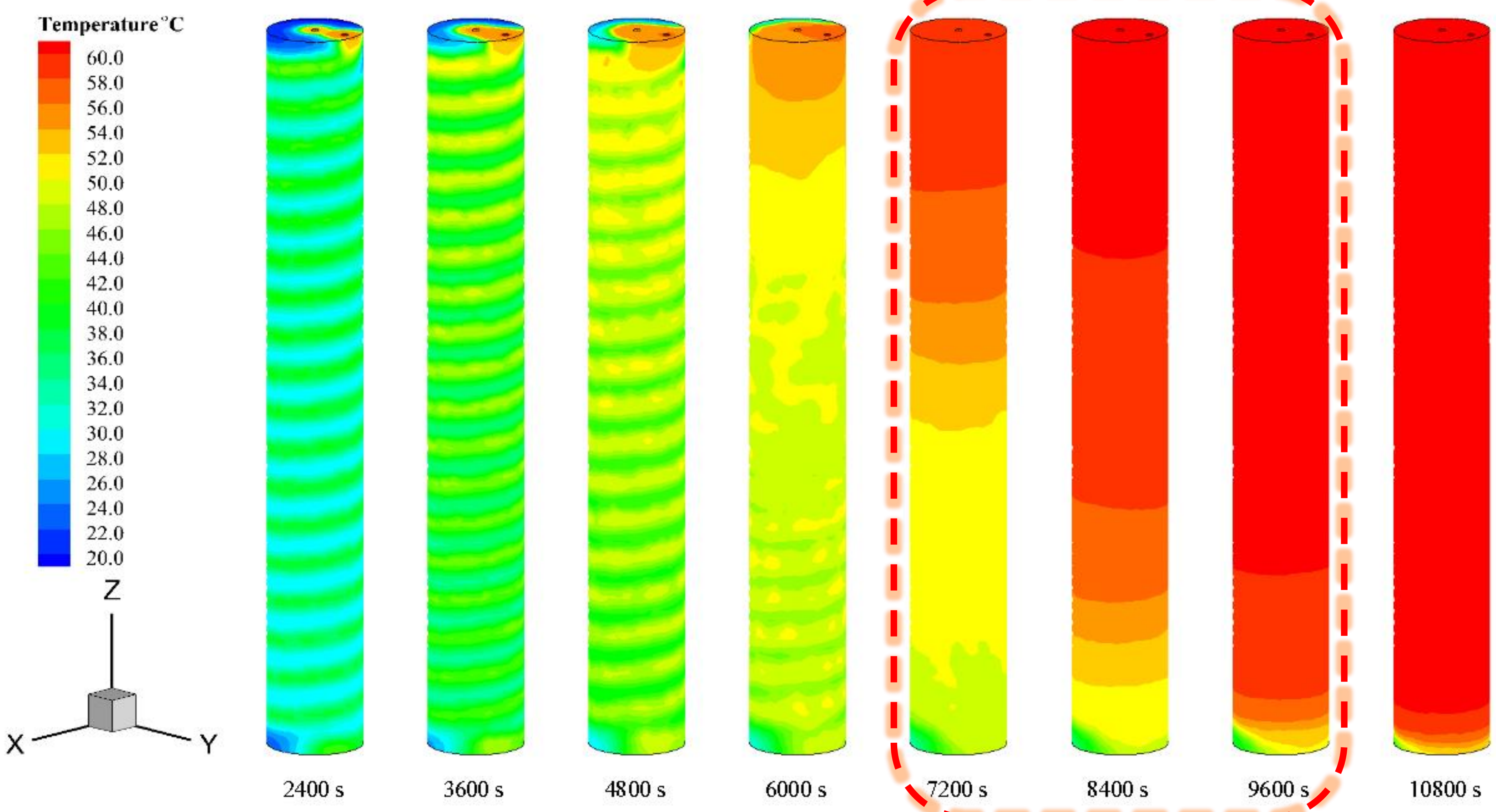
Temperature rises steadily. Sensible heat storage is dominant.
稳定升温阶段
显热蓄热为主

4 Analysis of the model calculation results-- Temperature profile of external surface of PCM

模型计算结果分析–相变材料外表面温度云图

Conditions: The initial temperature is 20℃. The inlet temperature is 60℃, and the influent flow rate is 0.25m³/h.

基本条件：初始温度20℃，进水温度60℃，进水流量0.25m³/h



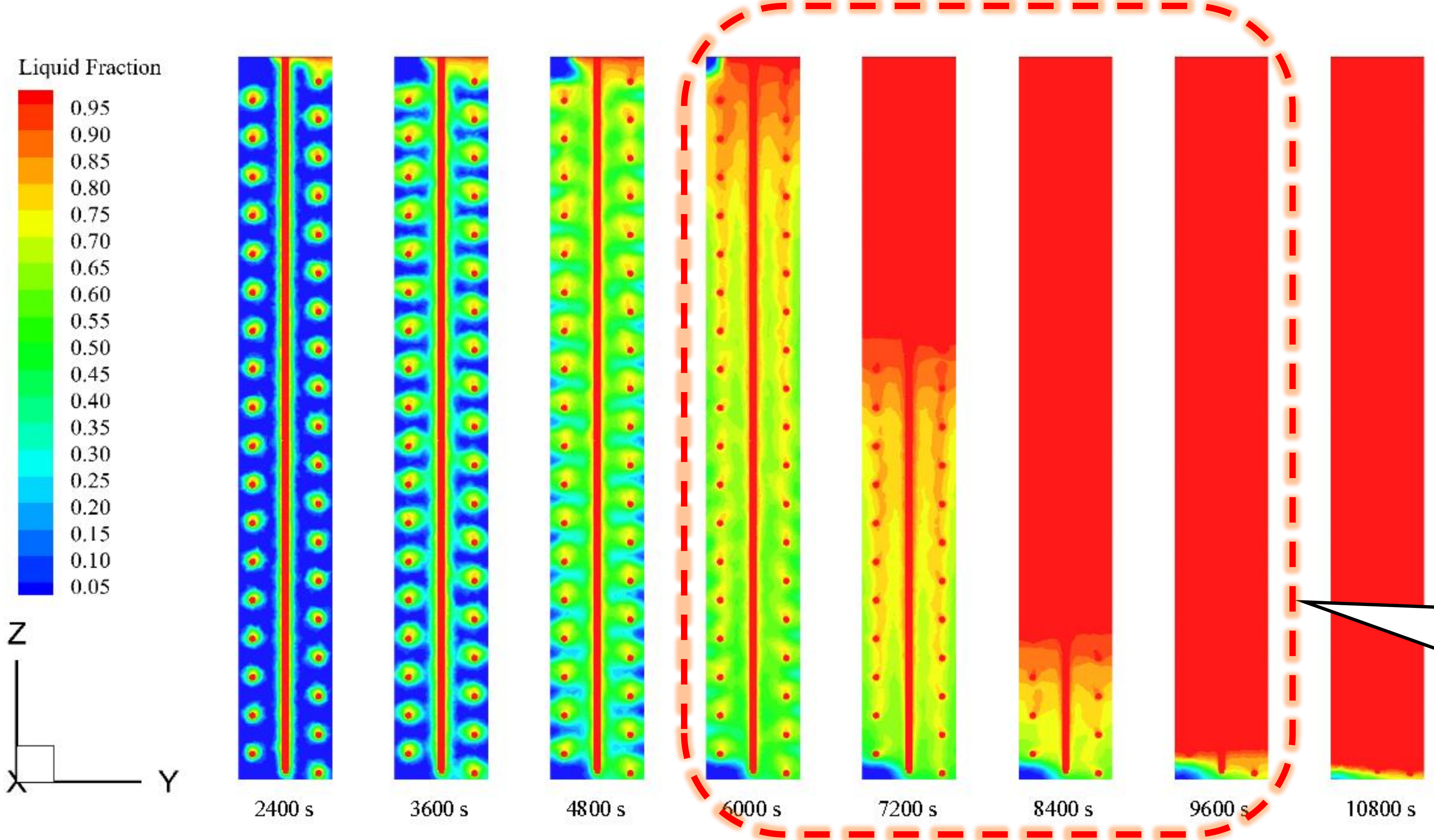
The surface temperature is stratified over time

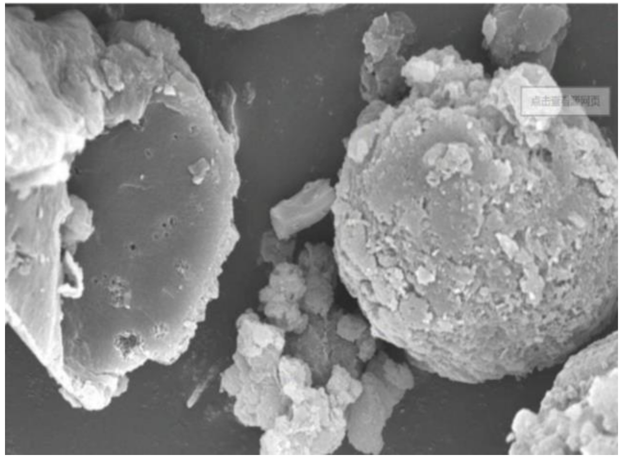
外表面温度随时间发生分层

4 Analysis of the model calculation results--Liquid fraction of the vertical section of the TES unit

模型计算结果分析–蓄热罐纵剖面液相率云图

Conditions: The initial temperature is 20℃. The inlet temperature is 60℃, and the influent flow rate is 0.25m^3/h.
基本条件：初始温度20℃，进水温度60℃，进水流量0.25m^3/h



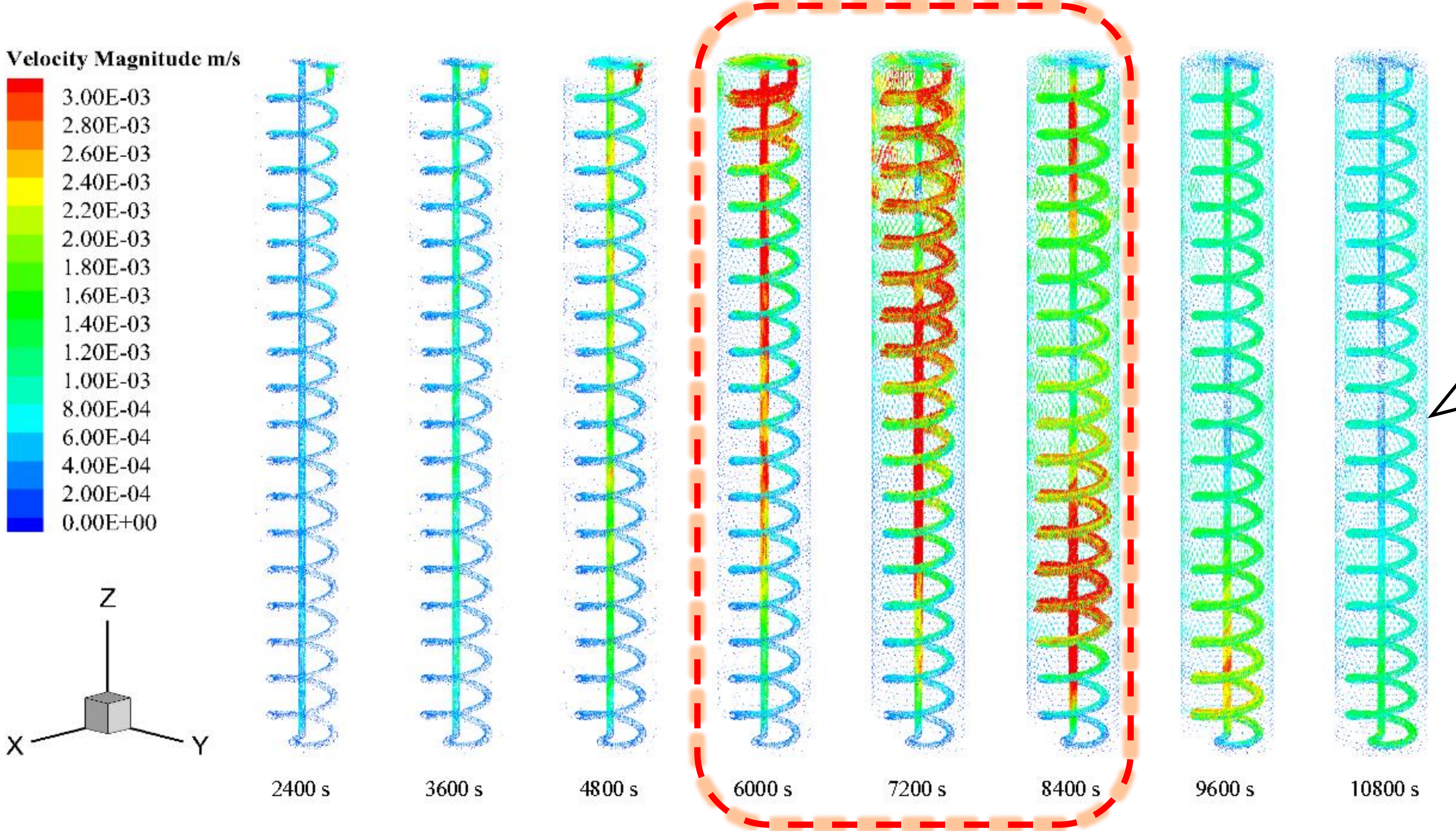


The PCM melts from top to bottom gradually
相变材料的熔化由上至下逐渐进行.

4 Analysis of the model calculation results--Velocity vector diagram of phase change region

模型计算结果分析–相变区域速度矢量图

Conditions: The initial temperature is 20℃. The inlet temperature is 60℃, and the influent flow rate is 0.25m³/h.基本条件：初始温度20℃，进水温度60℃，进水流量0.25m³/h



The variation of internal flow field indicates the intensity of convection heat transfer

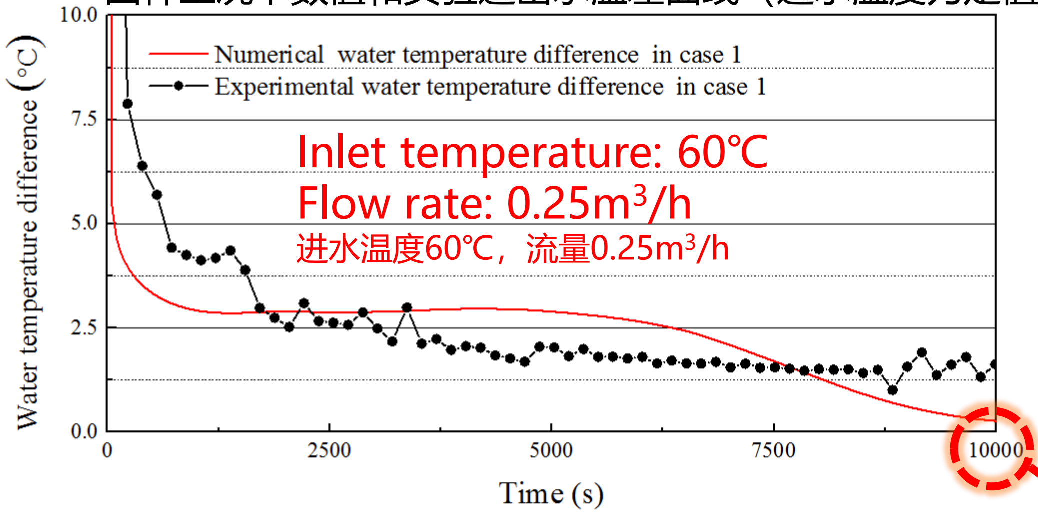
内部流场的变化表征对流换热强度

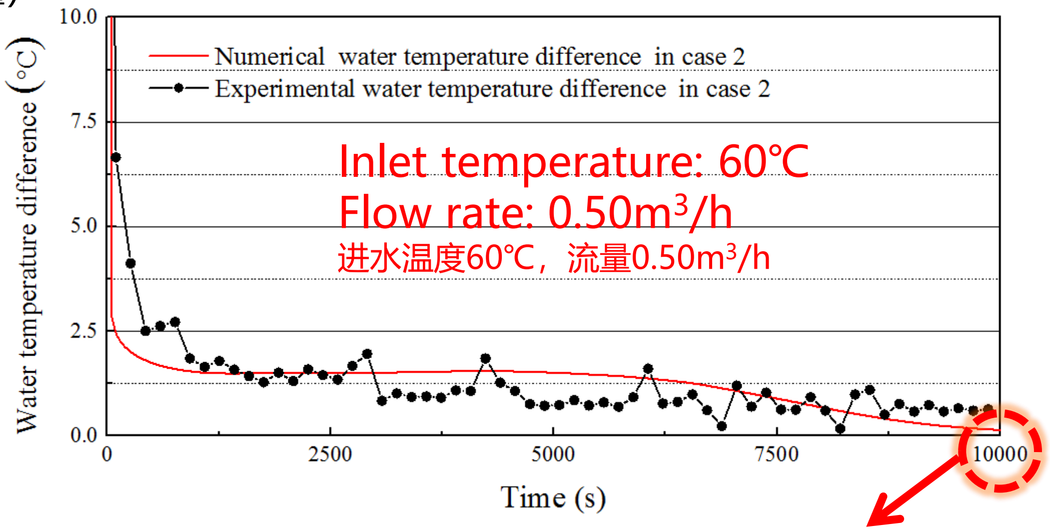
5 Thermal storage characteristics--The influence of heat transfer fluids

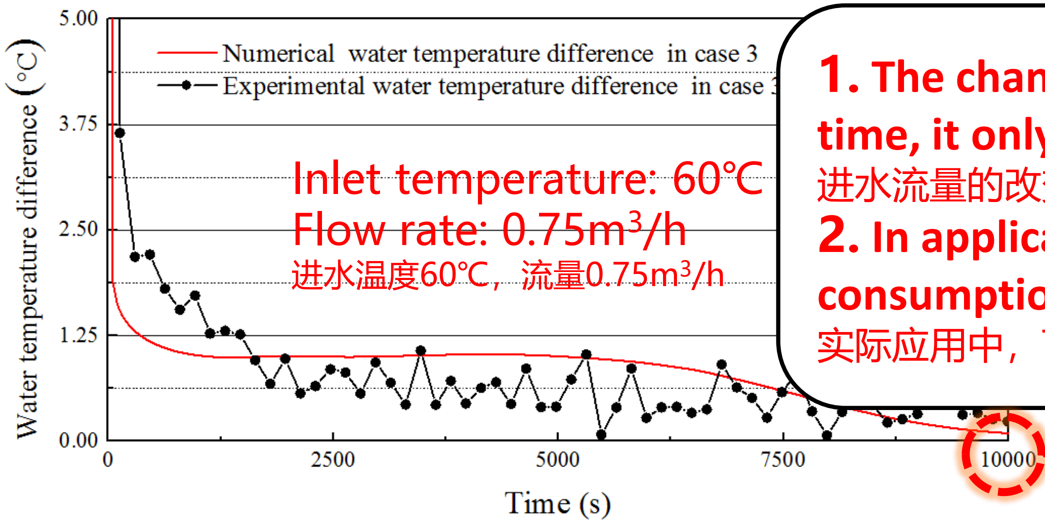
蓄热特性–传热流体的影响

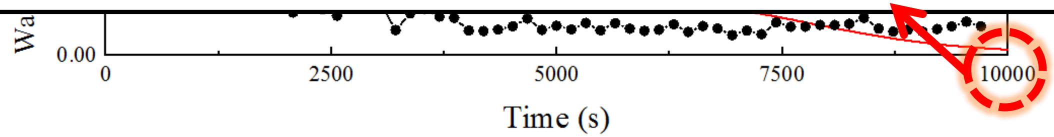
The numerical and experimental water temperature difference between the inlet and outlet in four conditions are shown as follows (the inlet temperature is fixed and the water flow is changed)

四种工况下数值和实验进出水温差曲线（进水温度为定值，改变进水流量）









1. The change of inlet flow rate has no significant influence on the heat storage time, it only changes the temperature difference between inlet and outlet.

进水流量的改变对蓄热时间无显著影响，其只改变了进出水温差。

2. In application, low flow heat storage can be reduced the heat storage power consumption.

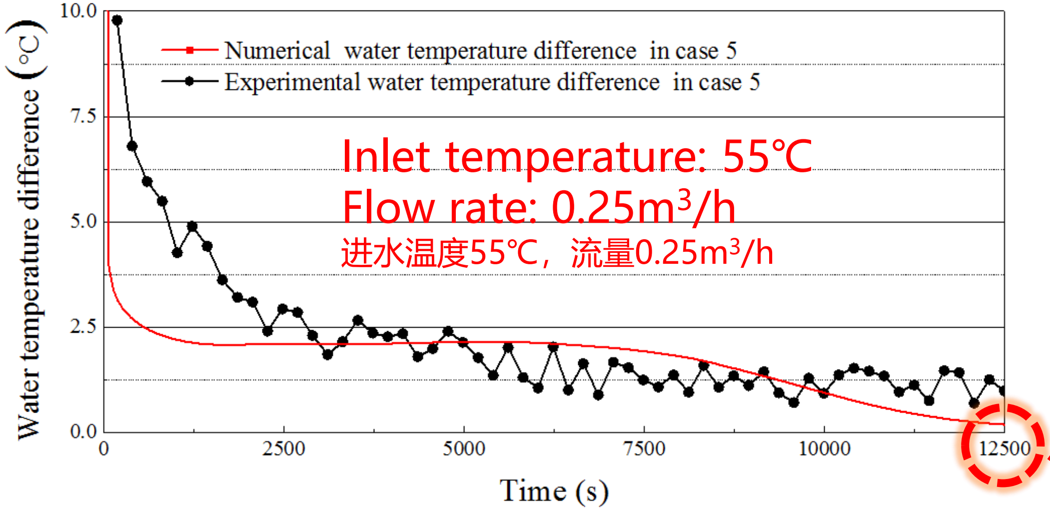
实际应用中，可考虑小流量蓄热以减少蓄热功耗。

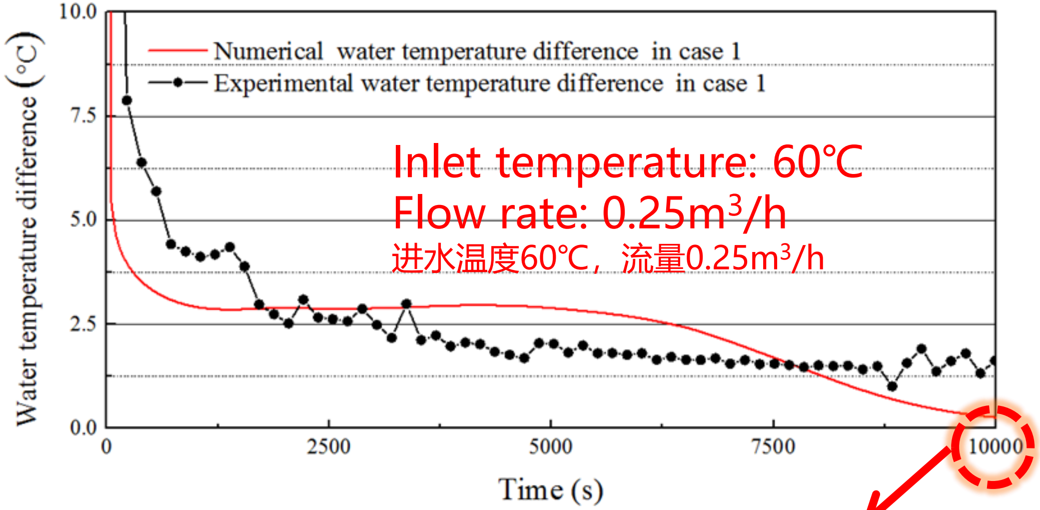
5 Thermal storage characteristics-- The influence of heat transfer fluids

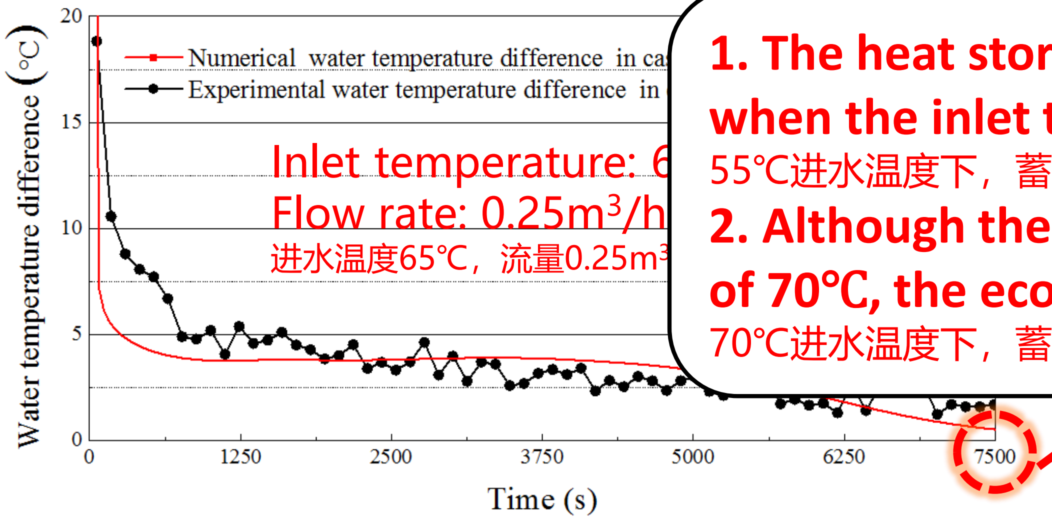
蓄热特性–传热流体的影响

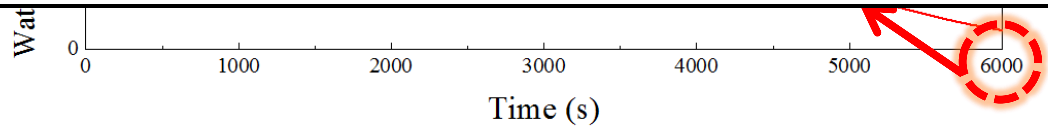
The numerical and experimental water temperature difference between the inlet and outlet in four conditions are shown as follows (the water flow is fixed and the inlet temperature is changed)

四种工况下数值和实验进出水温差曲线（进水流量为定值，改变进水温度）









1. The heat storage time is long and the PCM is not melted completely when the inlet temperature is 55℃

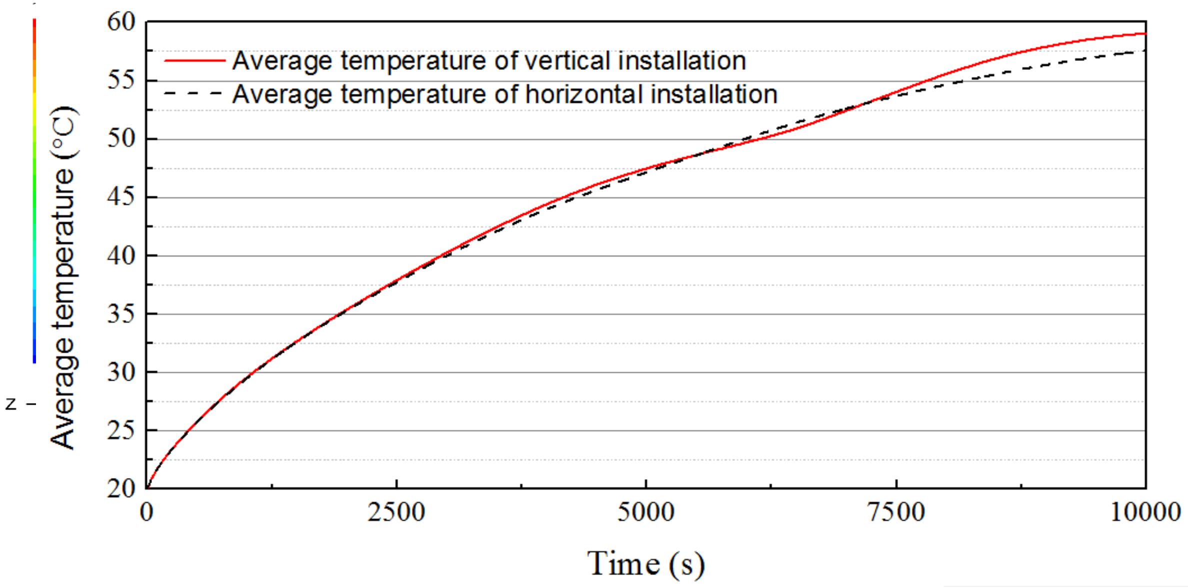
55℃进水温度下，蓄热时间长且相变材料熔化不完全。

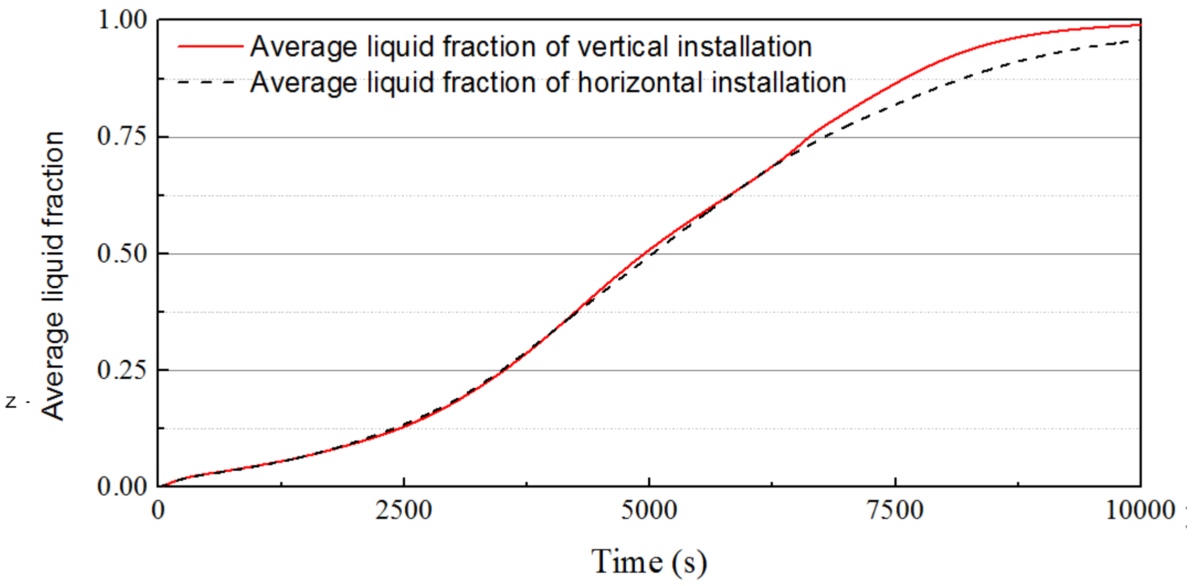
2. Although the thermal storage time is short under the inlet temperature of 70℃, the economy of heat pump for energy storge is poor.

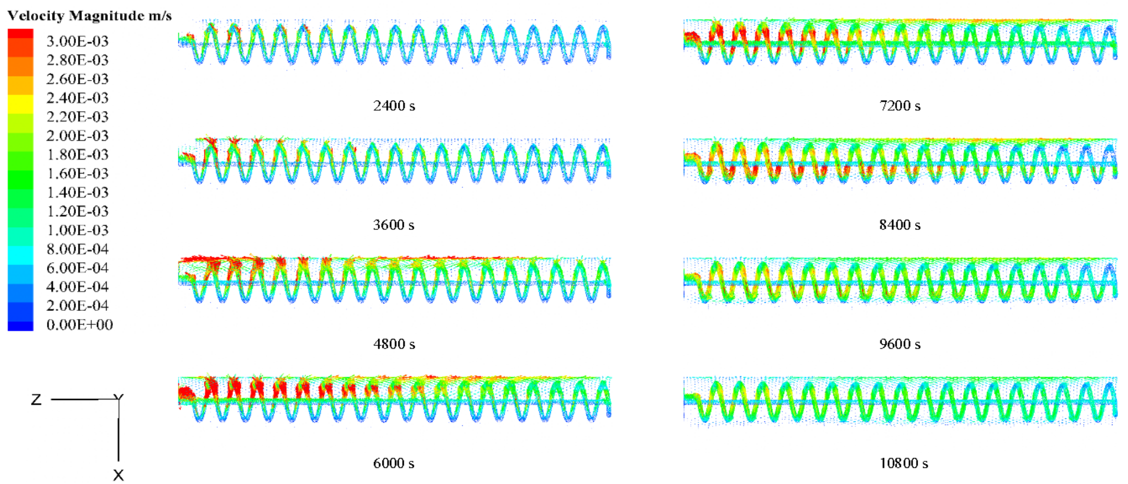
70℃进水温度下，蓄热时间虽然很短，但用热泵蓄热时的经济性差。

5 Thermal storage characteristics-- Influence of different installation forms/angle

蓄热特性–不同安装形式的影响







Velocity vector diagram of the phase change region

相变区域速度矢量图

Basically, The horizontal installation form are in line with vertical installations based on temperature changes and melting trends .

卧式安装下的温度变化和熔化趋势与立式安装基本一致。

The installation form can be freely chosen according to actual installation conditions

5

Thermal storage characteristics-Reasonable temperature for energy storage
耦合特性–蓄热温度要求

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Inlet temperature at 55℃ 55℃进水温度	Inlet temperature at 60℃ 60℃进水温度	Inlet temperature at 65℃ 65℃进水温度	Inlet temperature at 70℃ 70℃进水温度

Thermal storage time is too long and the PCMs cannot melt completely.
蓄热时间过长
相变材料无法完全熔化

Thermal storage time is short and the PCMs can completely melt.
蓄热时间短
相变材料完全熔化

Poor economy
经济性差

Good compatibility with heat sources
与热源的兼容性好

Fitting the matching thermal storage capacity of a single TES unit
拟合单个蓄热罐的匹配蓄热功率

$$W_1 = 0.63351 + 8.95721 \times 0.99398^t$$

$$W_2 = 0.96565 + 9.72376 \times 0.99745^t$$

W_1 ——The matched heating power with the inlet temperature of 60℃， kW；
进水温度为60℃时的匹配制热功率；

W_2 ——The matched heating power with the inlet temperature of 65℃， kW；
进水温度为65℃时的匹配制热功率；

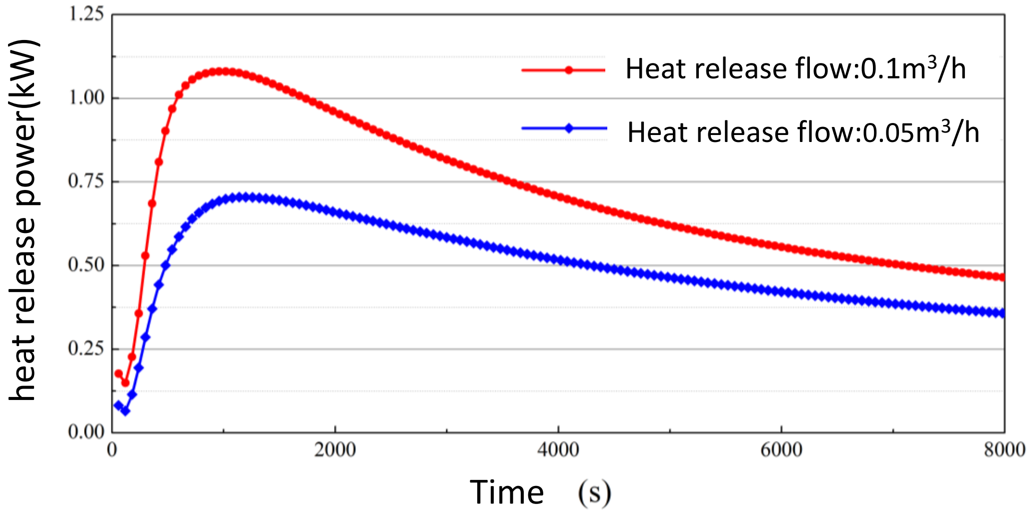
t ——time（时间）， s。

5 characteristics of heat release process

耦合特性–释热过程

The water tank is used to simulate heat release
利用水箱模拟末端散热

Heat release experiments of the TES unit are carried out
进行蓄热罐的释热实验



The variation of heat release power under different flow rates
不同流量下的释热功率变化曲线

1. The heat release rate of the TES unit can be adjusted by the water flow rate, which is different from the thermal storage process.
与蓄热过程不同，蓄热罐的释热速率可通过进水流量进行调节。

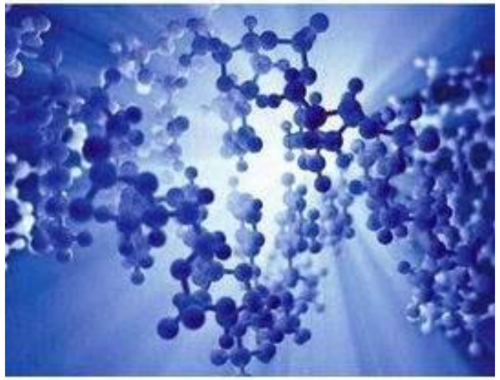
2. The matching of number of TES units and the thermal load of the room can be got in design process base on the variation of heat release power.
通过释热功率变化曲线，在选型设计时可对蓄热罐个数与末端房间的热负荷进行匹配计算。

Results of numerical simulation with nanoparticle-enhanced
纳米增强材料数值计算结果

Thermophysical properties

Physical parameters		Nano-enhanced paraffin	Pure paraffin
ρ	kg/m^3	1122.2	880
C_p	J/kg·K	2457 (solid) 3750 (liquid)	3110 (solid) 4810 (liquid)
λ	W/m·K	0.288 (solid) 0.245 (liquid)	0.2
μ	kg/m·s	0.033	0.031
h	J/kg	1.59×10^5	1.84×10^5
T	K	289~296	288~300

Pure PCM



NEPCM（add nanoparticle-enhanced to PCM）

Listen

Original Articles

Study of a U-tube heat exch
stabilized phase change ba

Xiangli Li, Cang Tong, Lin Duanmu & Liangkan Liu

Pages 430-440 | Received 08 Apr 2016, Accepted 21 Sep 2016, Accepted author v

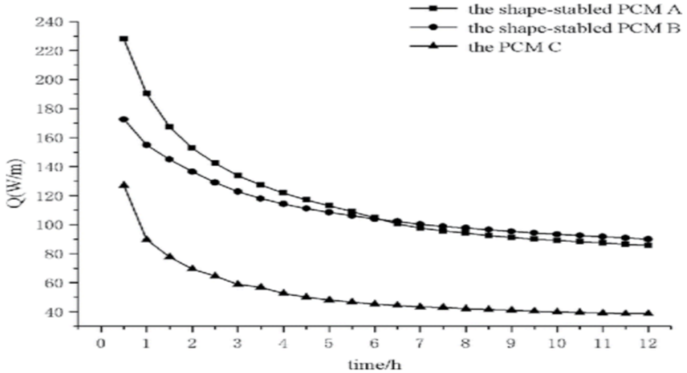
Table 4 of 4

Table 4. The physical parameters of three PCMs.

Journal
Science and
Volume 23, 201
Climate HVAC (

Material	Density, kg/m³	Thermal conductivity, w/(m·k)	Sp
The shape-stabled PCM A	790	1.528	
The shape-stabled PCM B	790	1.528	
The PCM C	790	0.235	

Fig. 11. The heat exchange for a unit borehole depth of three kinds of phase change backfill material.



6 Results of numerical simulation with nar
纳米增强材料数值计算结果

Thermophysical properties

Physical parameters		Nano-enhanced paraffin	Pure paraffin
ρ	kg/m³	1122.2	880
C_p	J/kg·K	2457 (solid) 3750 (liquid)	3110 (solid) 4810 (liquid)
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Results of numerical simulation with nanoparticle-enhanced
纳米增强材料数值计算结果

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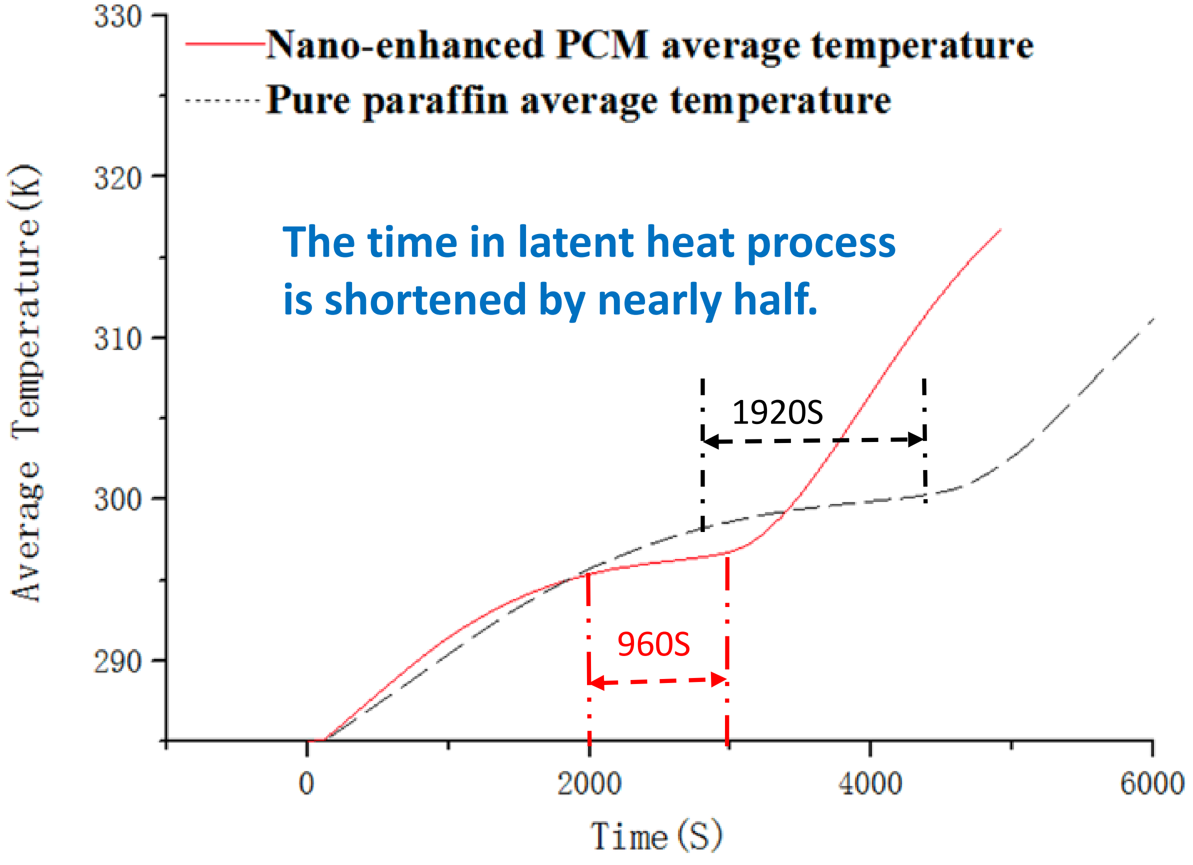
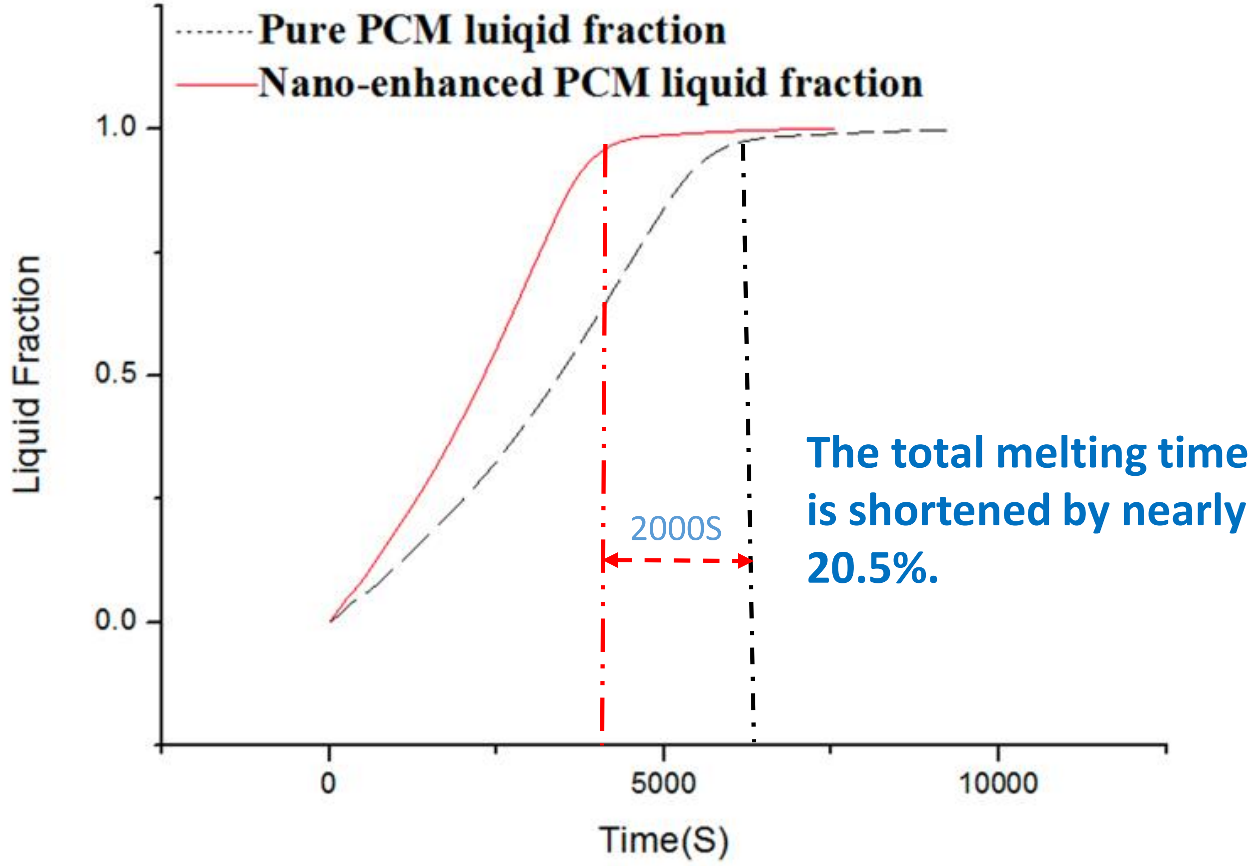


(a) volume-average temperature



(b) volume-average liquid fraction

Results of numerical simulation with nanoparticle-enhanced
纳米增强材料数值计算结果

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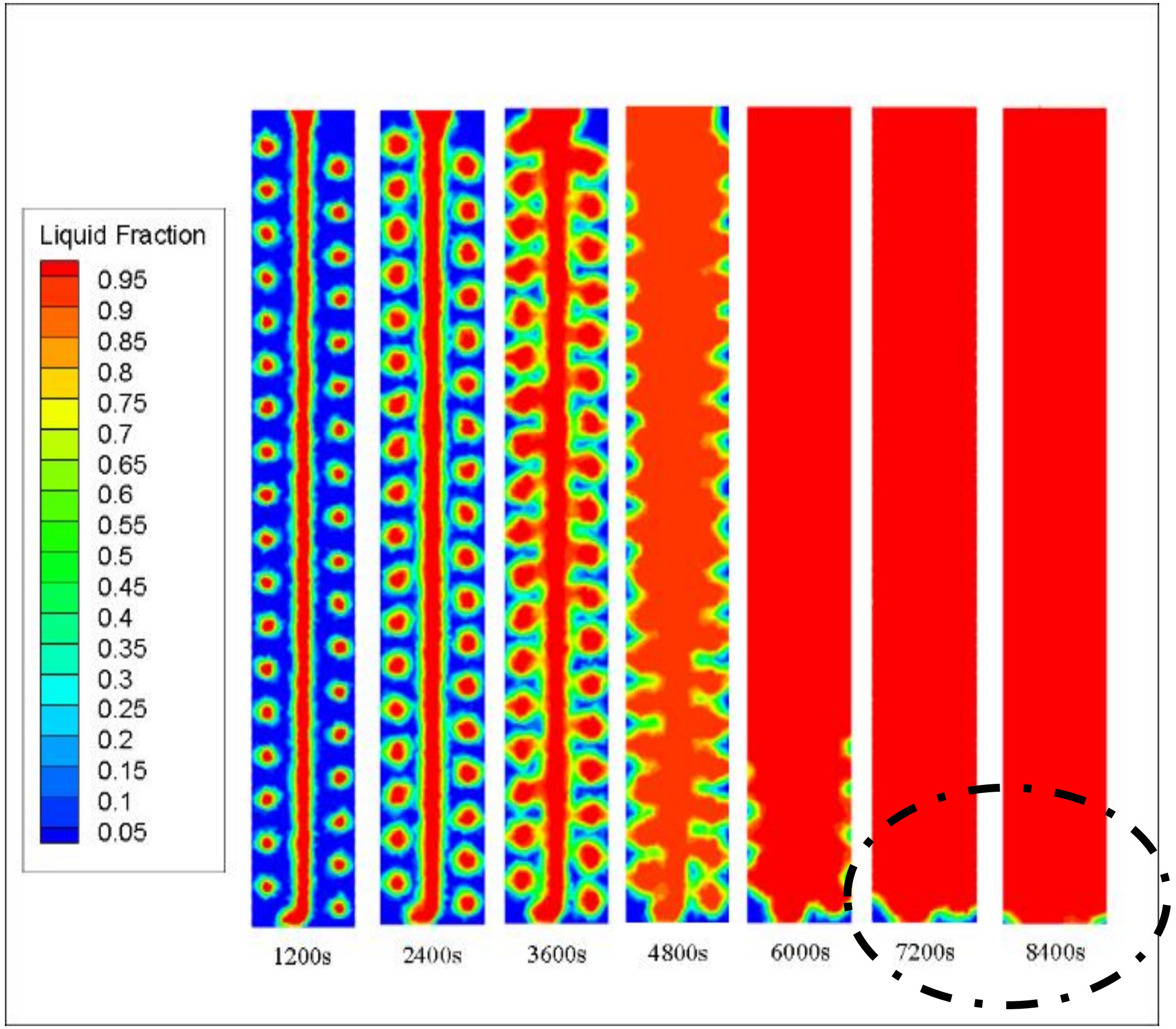
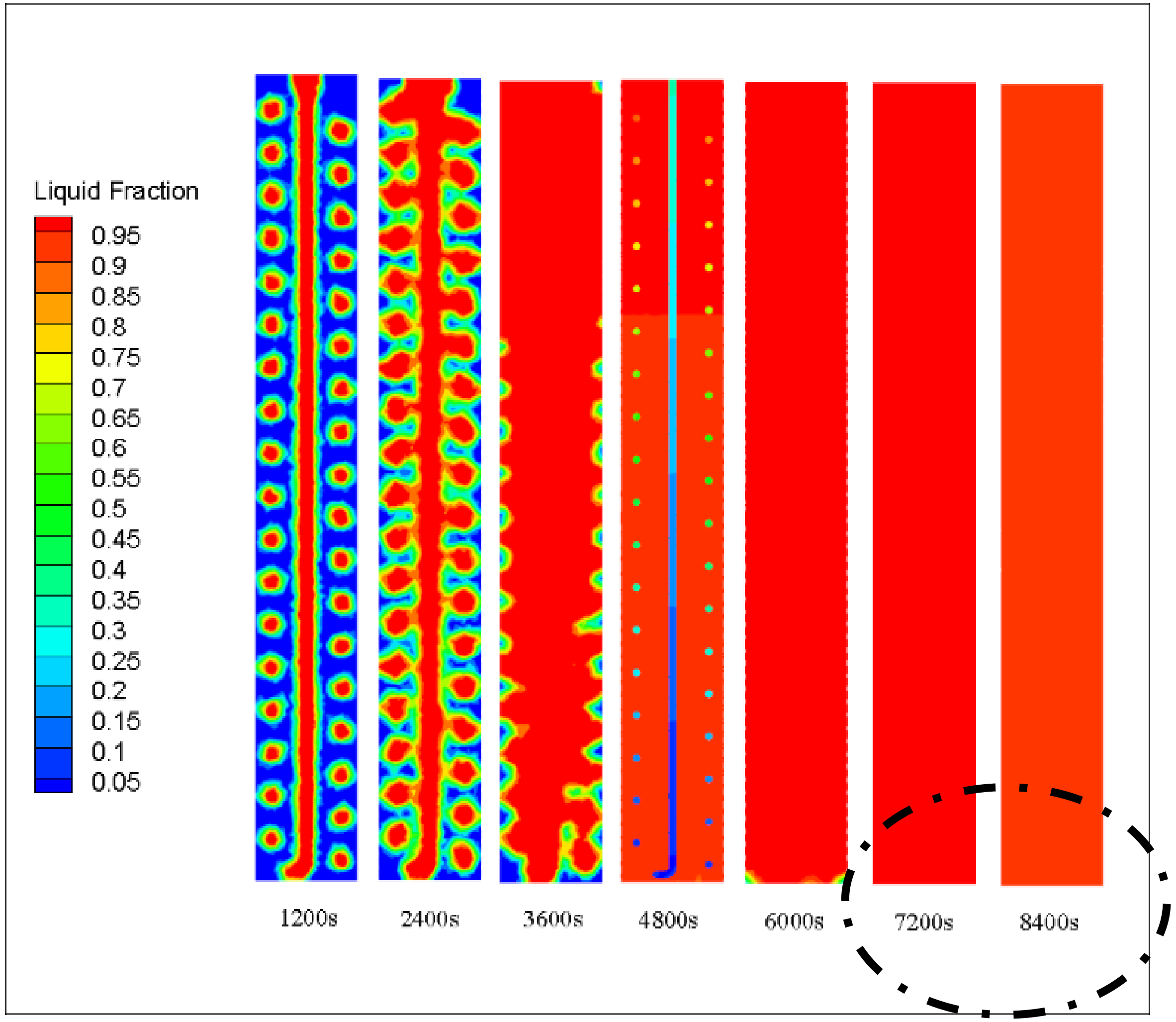
（a）Pure PCM



(b)NEPCM



Not completely melted at bottom of unit!

Melted completely

6 Results of numerical simulation with nanoparticle-enhanced
纳米增强材料数值计算结果

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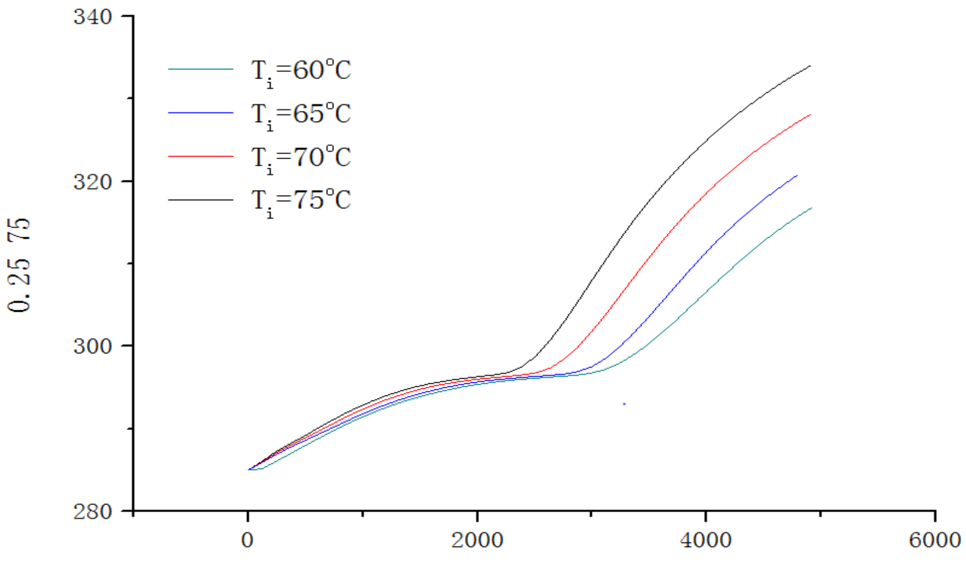
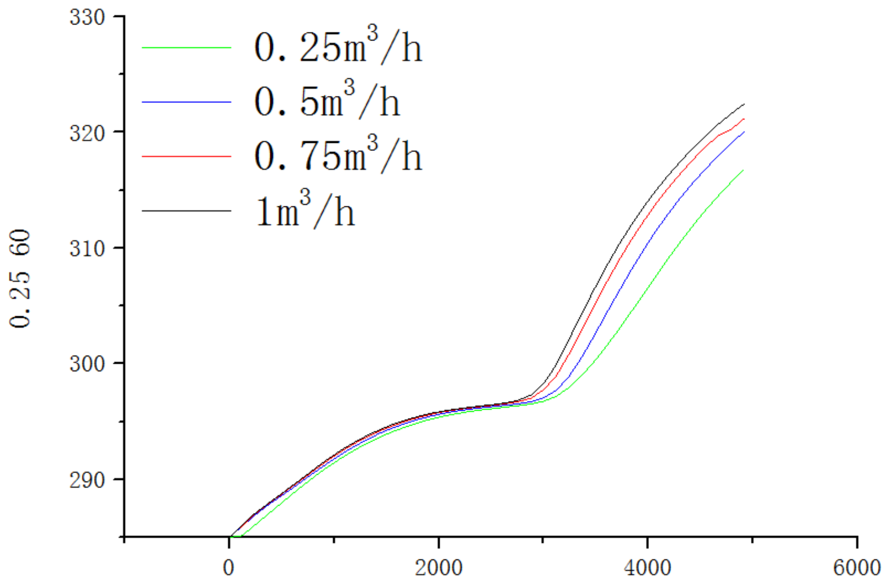
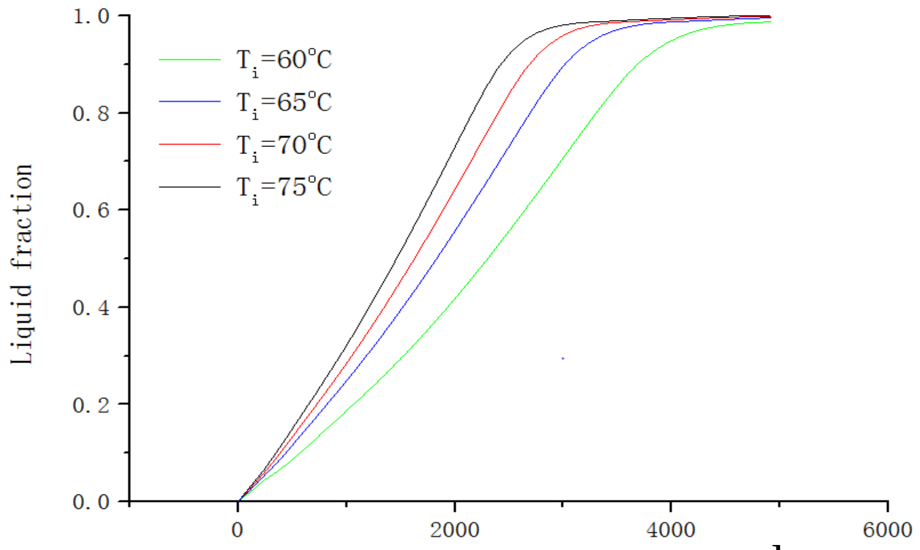
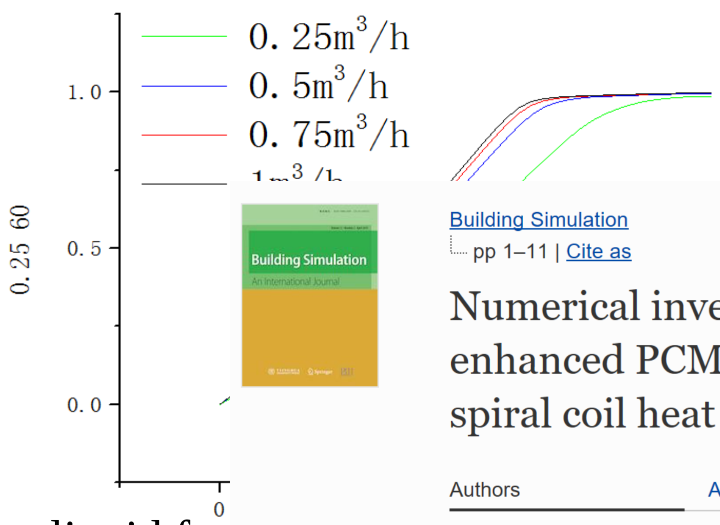




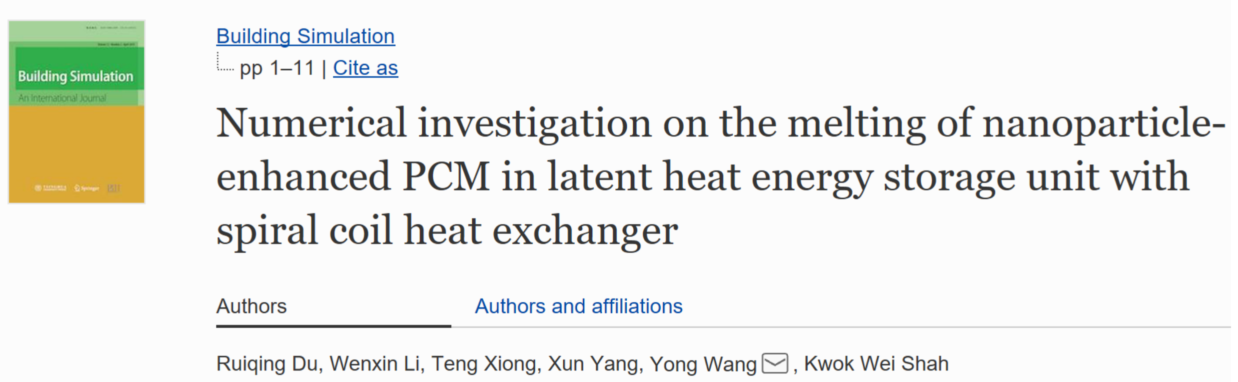
volume-average temperature





volume-average liquid fra

The change regulation of nanoparticle-enhanced and pure PCM under the action of inlet temperature and flow rate are the similar.


Building Simulation
pp 1–11 | Cite as

Numerical investigation on the melting of nanoparticle-enhanced PCM in latent heat energy storage unit with spiral coil heat exchanger

Authors Authors and affiliations

Ruiqing Du, Wenxin Li, Teng Xiong, Xun Yang, Yong Wang, Kwok Wei Shah

7 Coupling characteristic- Performance evaluation approach for thermal storage matching
耦合特性–蓄热匹配评价计算方法

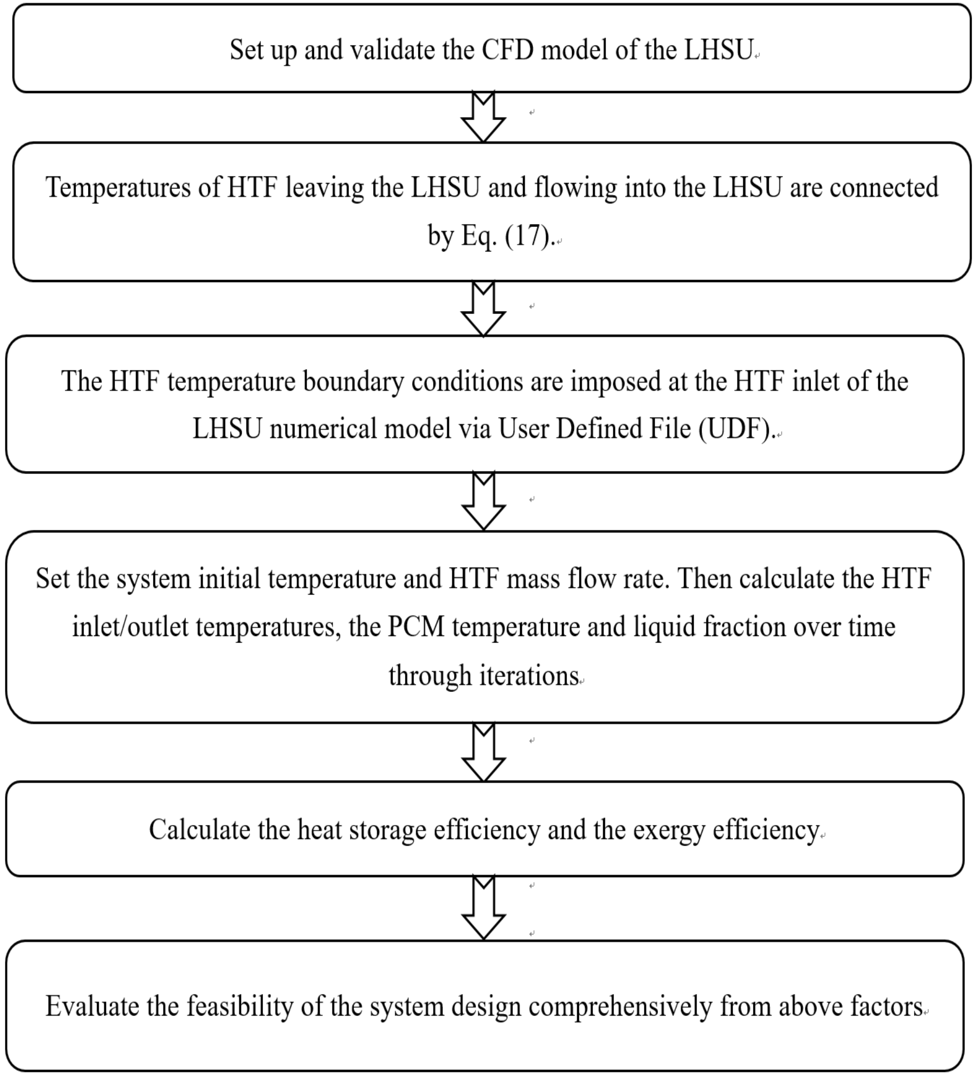
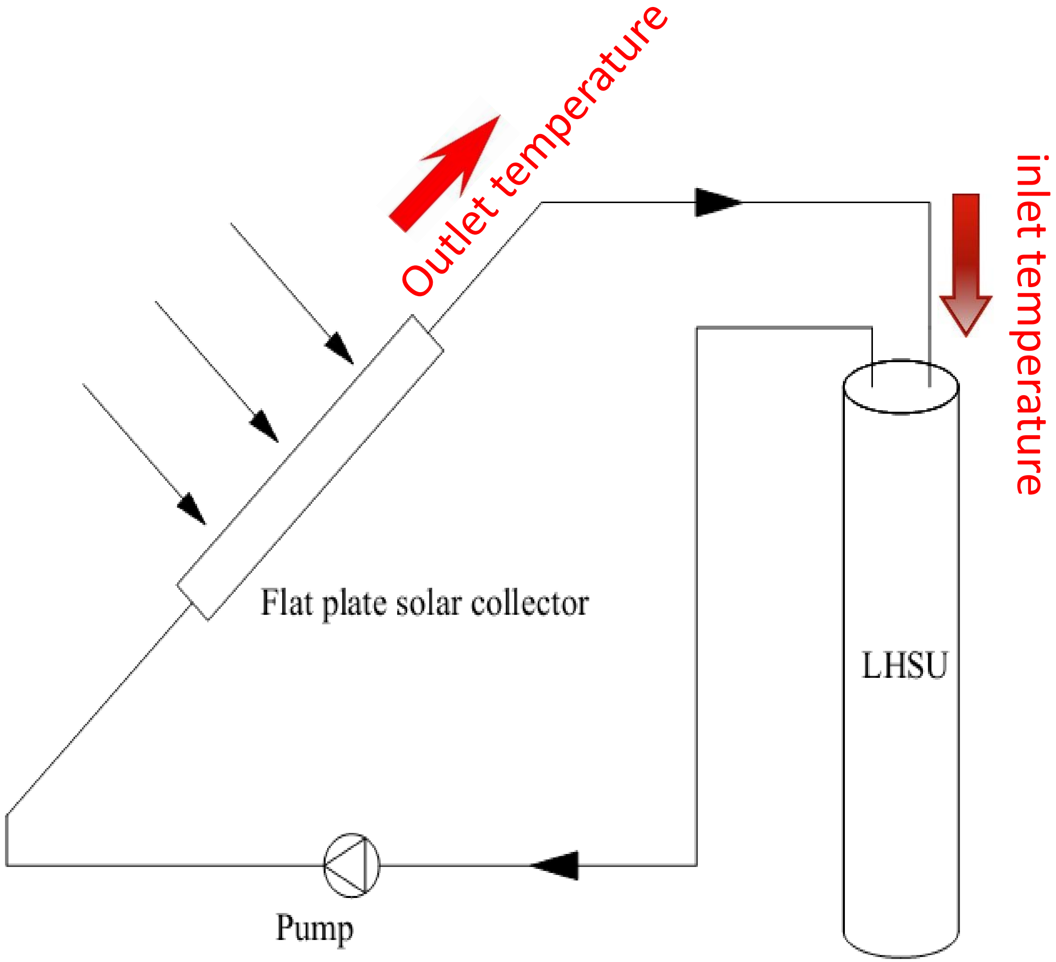
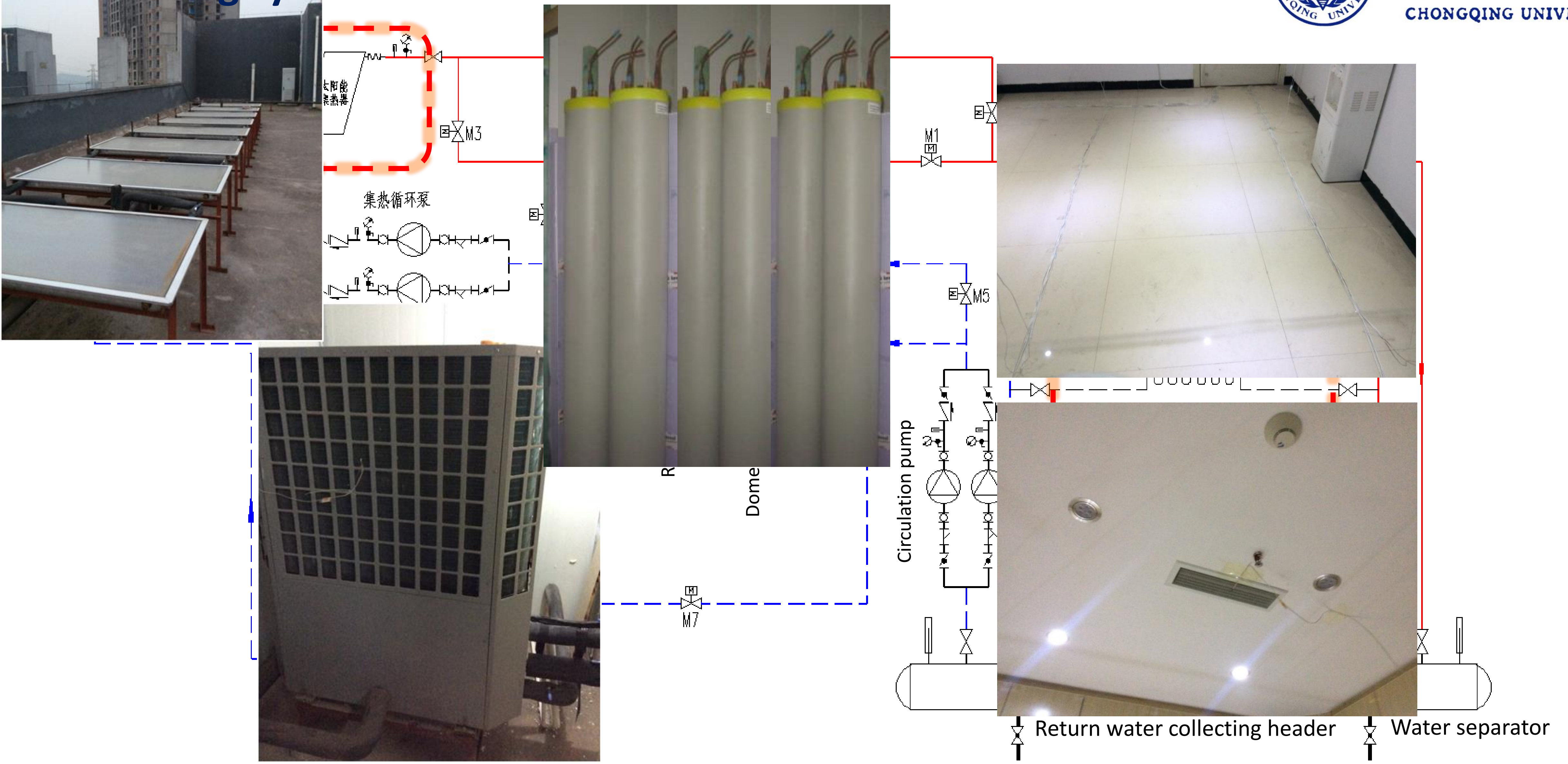


Figure 2. Performance evaluation procedure of a typical SLHSS



Yong Wang*,Xun Yang,Teng Xiong et al.Performance Evaluation Approach for Solar Heat Storage Systems Using Phase Change Material, **Energy and Buildings ,155(2017) 155-127**

Application for evaluation approach- System scheme of hybrid heating system 评价方法应用：某工程联合供热系统原理图



TES using PCM+ solar collector + air source heat pump--hybrid heating system

相变蓄热+太阳能集热+空气源热泵联合供热系统

Test analysis - Current situation of the system
工程实例-系统安装现状图

Main functions：
主要功能包括：

1. **Solar heat collection**
   太阳能集热
2. **Thermal energy storage by heat pump**
   热泵集热
3. **Supply heat by TES unit**
   蓄热罐供热
4. **Supply heat by heat pump and Solar collector**
   热泵和太阳能供热
5. **Supply domestic hot water**
   制取生活热水

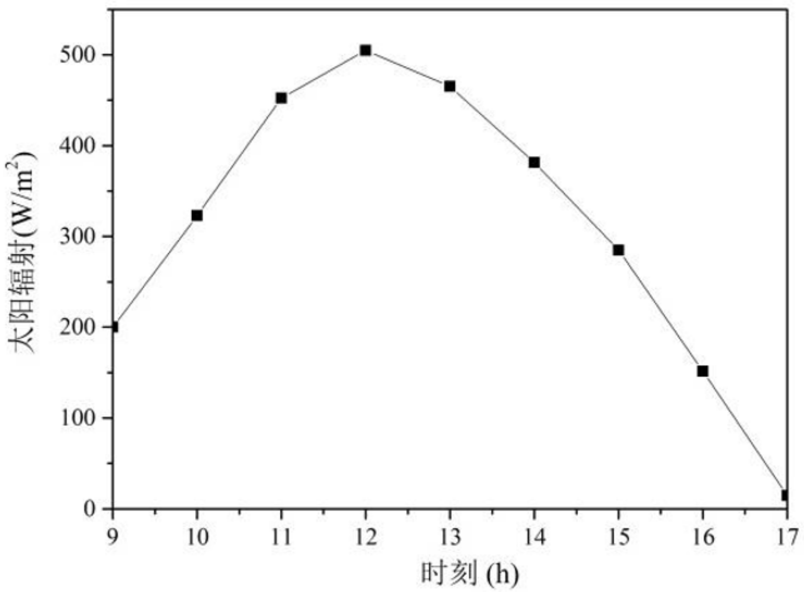
Six TES units inside

Heat pump

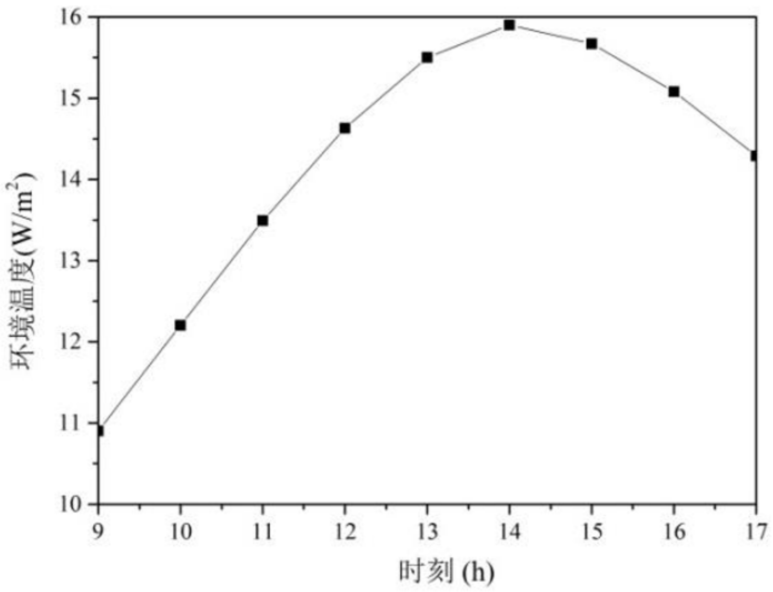
Evaluation – TES Units

评价方法的应用—蓄热单元检验

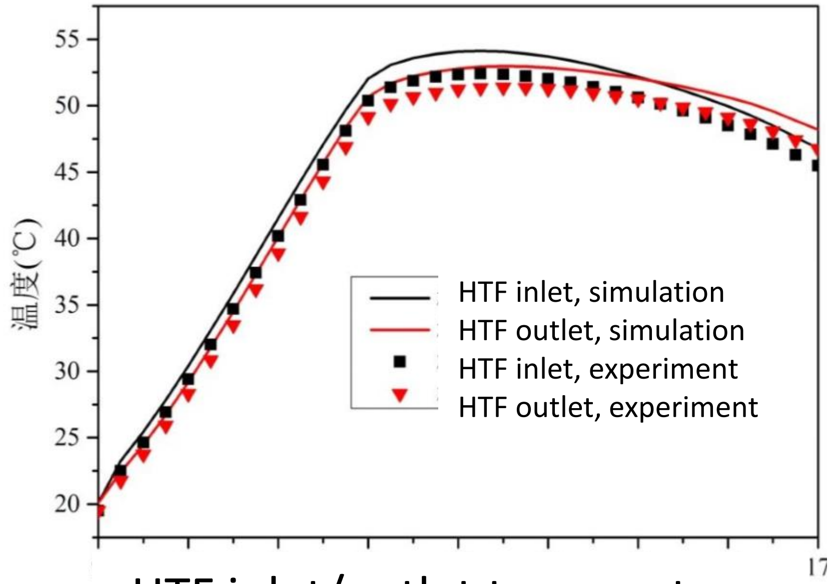
- Experiment time: 9:00~17:00 Dec. 8 2016
- 8 solar collectors (total collection area: 13.7m^2) 平板集热器运行 8 块，总集热面积13.7m^2
- Flow rate of the heat pump: 1.2m^3/h 集热泵流量 1.2m^3/h
- 6 TES units, initial temperature: 20.1℃ 6个相变蓄热单元全部开启, 蓄热初始温度 20.1℃
- Daily solar radiation 10MJ/m^2 实验日太阳辐射良好，日辐射量约为 10MJ/m^2。



Solar radiation on the horizontal plane



Ambient temperature



HTF inlet/outlet temperatures of the LHTES unit

Evaluation – Solar collector area & TES Units
集热器面积与蓄热单元个数的匹配

Calculation condition 计算基本条件

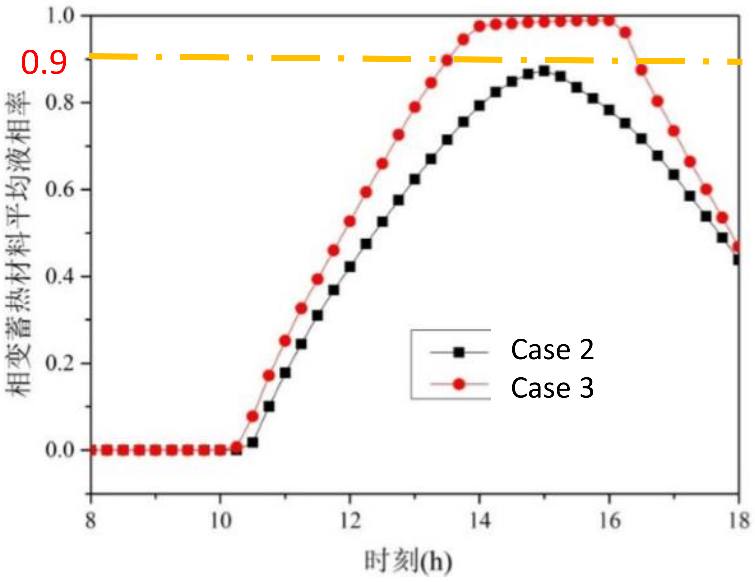
Cases	Solar collection area (m^2) 总集热面积	Heat flow rate kg/s (m^3/h) 总集热流量	Number of the TES units 相变蓄热单位数量	Collection area of a single TES unit 单个相变蓄热单位匹配集热面积 A_c (m^2)	Heat flow rate of a single TES unit 单个相变蓄热单位匹配集热流量 m_f (V_f), kg/s (m^3/h)
1	13.7	0.66 (2.28)	6	2.3	0.11 (0.38)
2	13.7	0.66 (2.28)	4	3.4	0.16 (0.57)
3	13.7	0.66 (2.28)	3	4.5	0.22 (0.76)

conditions in the original design

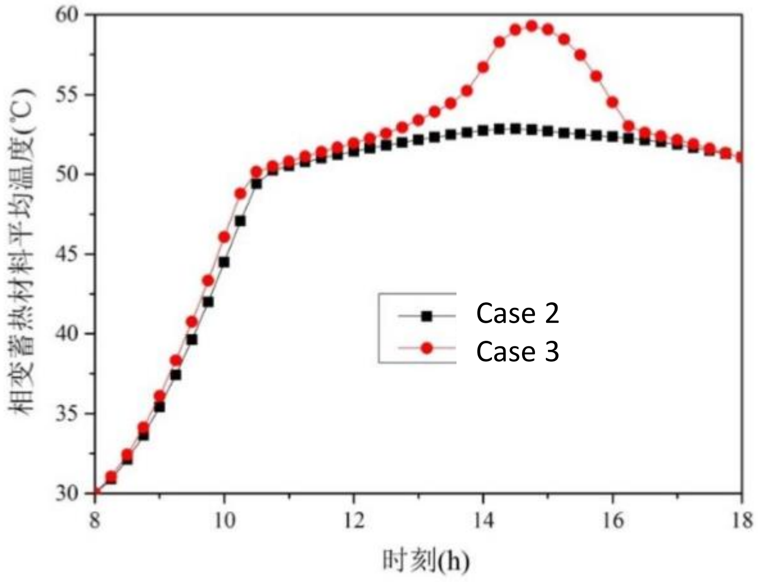
7 Calculation results – Solar collector area & TES Units

集热器面积与蓄热单元个数的匹配

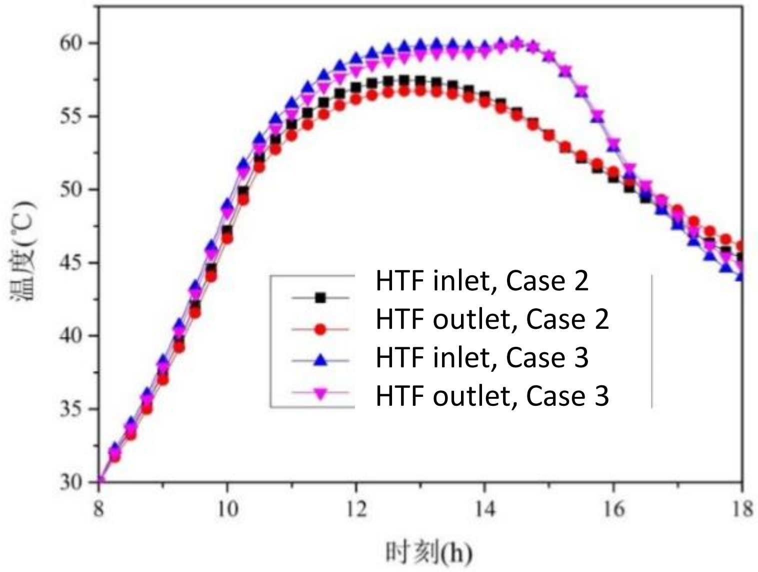
Average liquid fraction of PCM



Average temperature of PCM



HTF temperatures



- Case 2: Not melt completely, a larger storage capacity

不能实现相变蓄热装置的完全熔化，相变蓄热容量偏大，匹配不合理。

- Case 3: Melt completely

完全熔化，满足蓄热要求，匹 配合理。

- Number of TES Units: 3, collection area of single TES unit: 4.5 m^2

合理的设计匹配：相变蓄热单元的数量可减少为 3 个，单个相变蓄热单元的集热面积为4.5m^2

Evaluation – Flow rate range
集热流量的范围确定

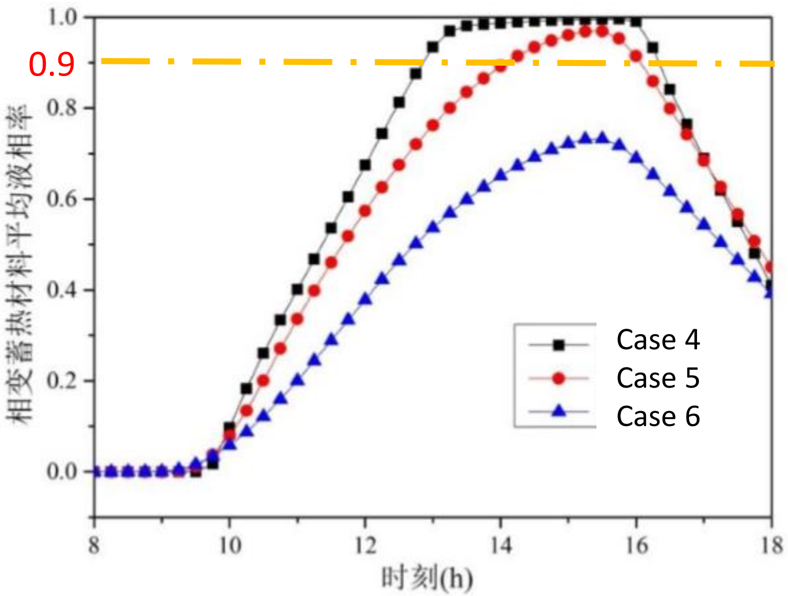
Calculation condition 计算基本条件

Cases	Solar collection area (m^2) 总集热面积	Heat flow rate kg/s (m^3/h) 总集热流量	Number of the TES units 相变蓄热单位数量	Collection area of a single TES unit 单个相变蓄热单位匹配集热面积 A_c (m^2)	Heat flow rate of a single TES unit 单个相变蓄热单位匹配集热流量 m_f (V_f), kg/s (m^3/h)
4	13.7	0.167 (0.6)	3	4.5	0.056 (0.2)
5	13.7	0.017 (0.06)	3	4.5	0.006 (0.02)
6	13.7	0.009 (0.03)	3	4.5	0.003 (0.01)

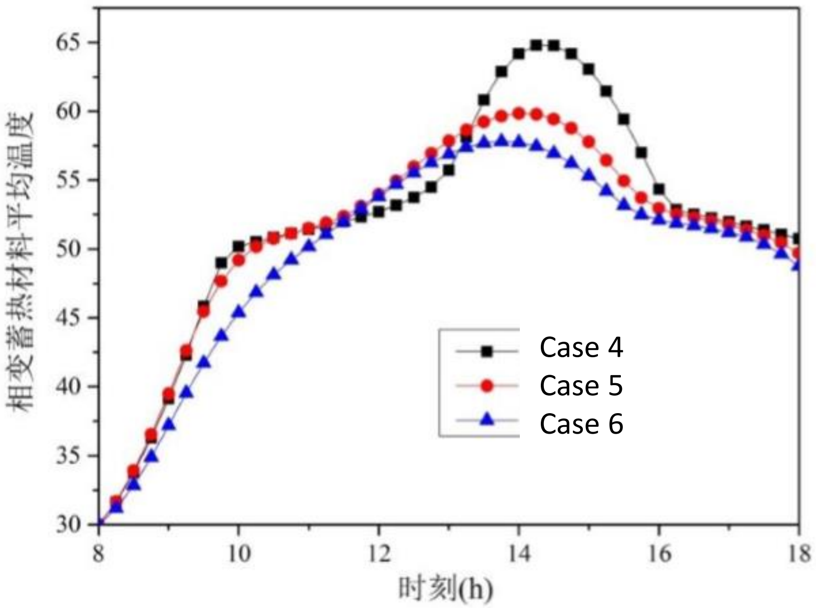
7 Calculation results– Flow rate range

流量匹配计算结果

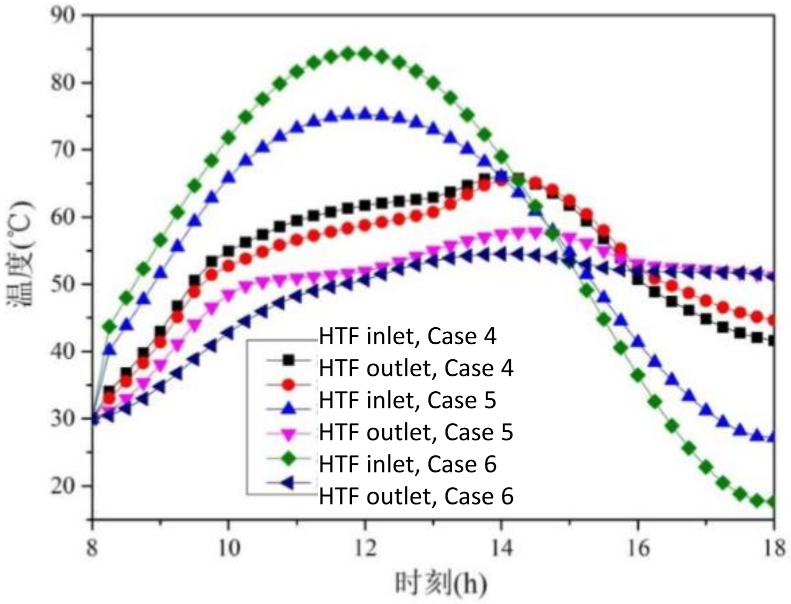
Average liquid fraction of PCM



Average temperature of PCM



HTF temperatures



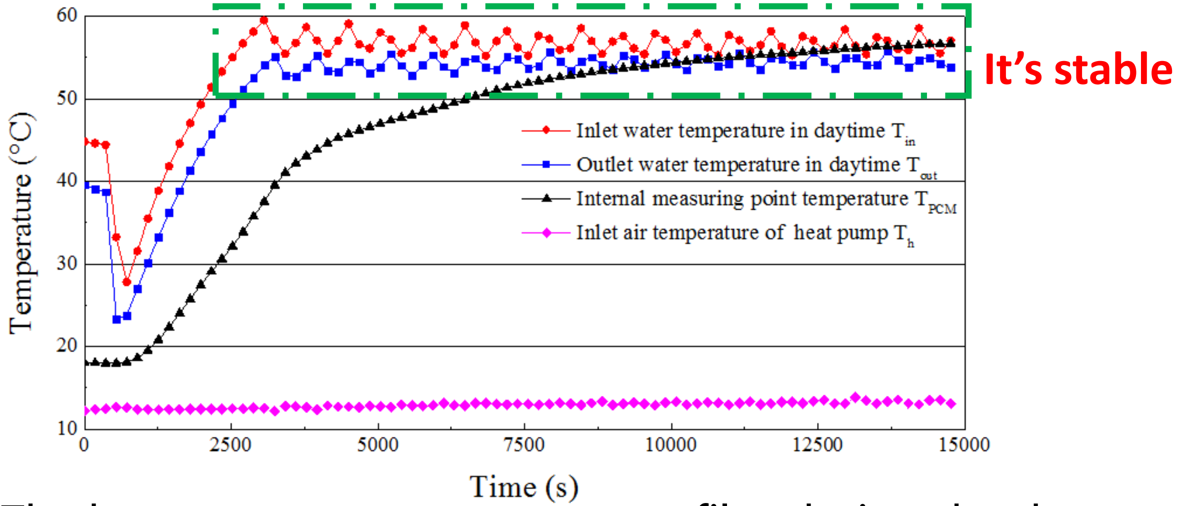
- Max liquid fraction: Case 4 > Case 5 > Case 6

最大液相率: Case 4 满足设计匹配要求， Case 5 刚好处于临界点(0.9)，Case 6 不能满足要求

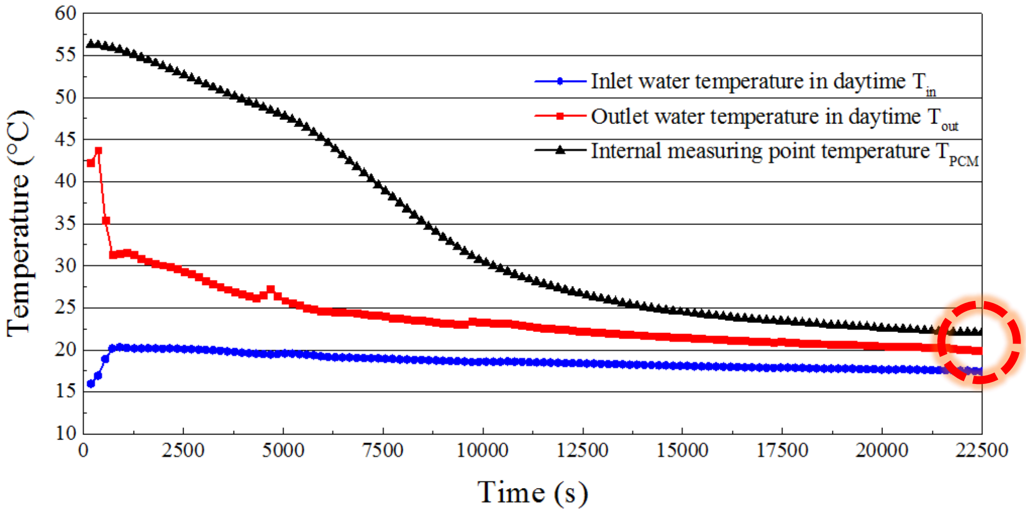
- Max inlet temperature increased with the decreasing of the flow rate (0.2 ~ 0.02 m^3/h), incomplete melting occurs when flow rate decreased to 0.01 m^3/h.

集热流量在0.2~0.02 m^3/h内减小时，相变蓄热装置最大进口温度升高，未超过汽化温度，相变材料均能完全熔化，相变蓄热装置匹配合理。但当集热流量降低到 0.01 m^3/h 时，相变材料最大液相率就迅速下降，不能完全熔化。单个相变蓄热单元匹配的集热流量并不是越小越好

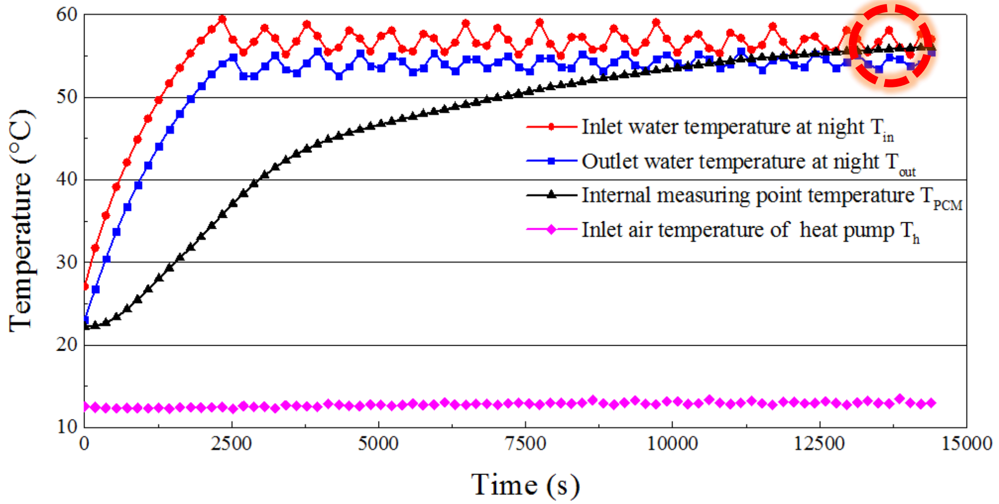
Coupling heat storage and heat release characteristics of the heat pump and TES unit using PCM - Application Case
工程实例–热泵与相变蓄能罐的耦合蓄热与放热特性



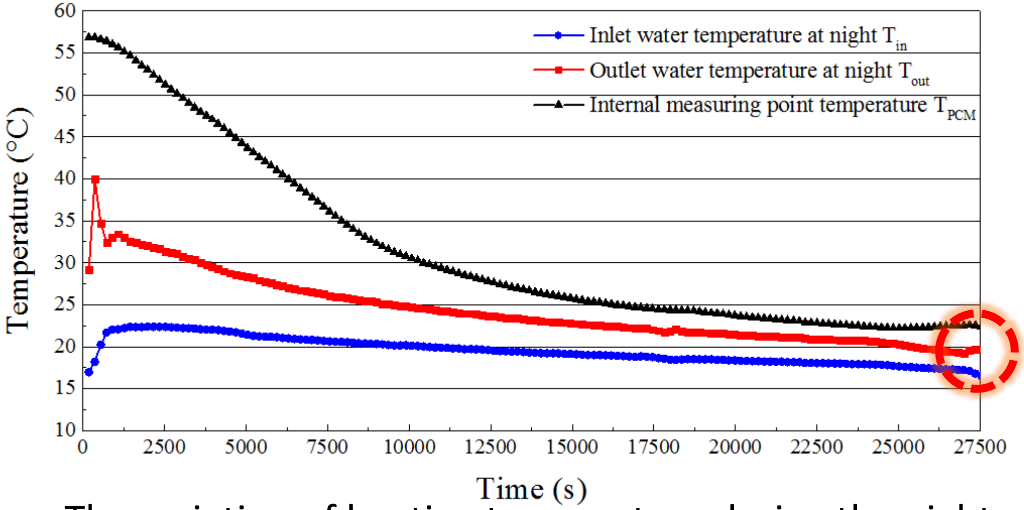
The heat storage temperature profiles during the day
白天蓄热温度变化曲线



The variation of heating temperature during the day
白天供热温度变化曲线



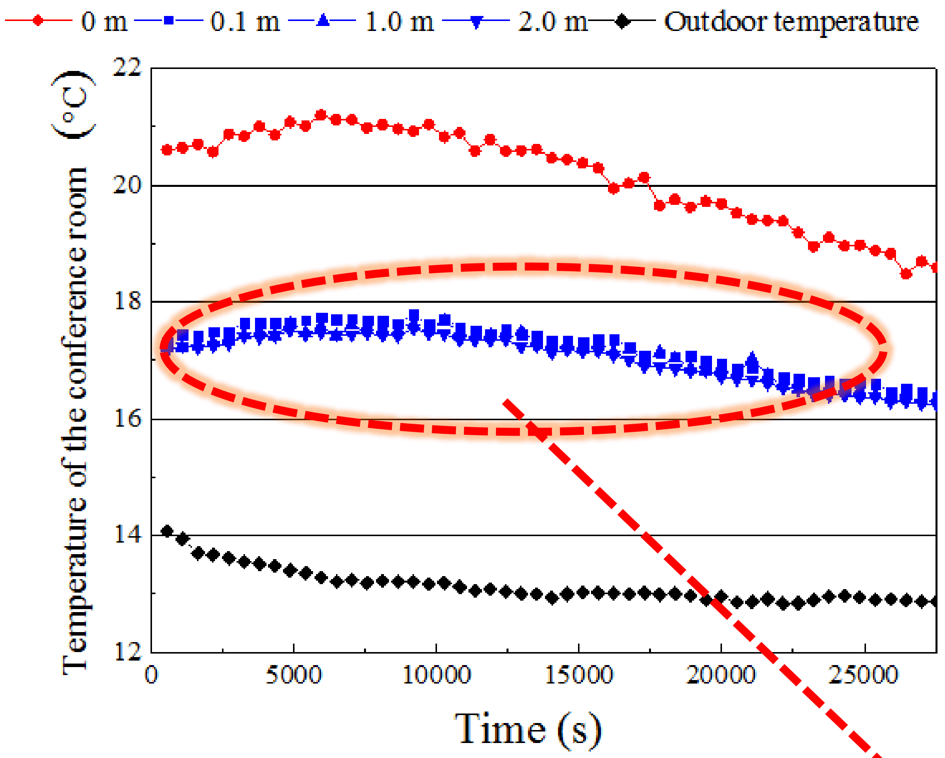
The heat storage temperature profiles during the night
夜间蓄热温度变化曲线



The variation of heating temperature during the night
夜间供热温度变化曲线

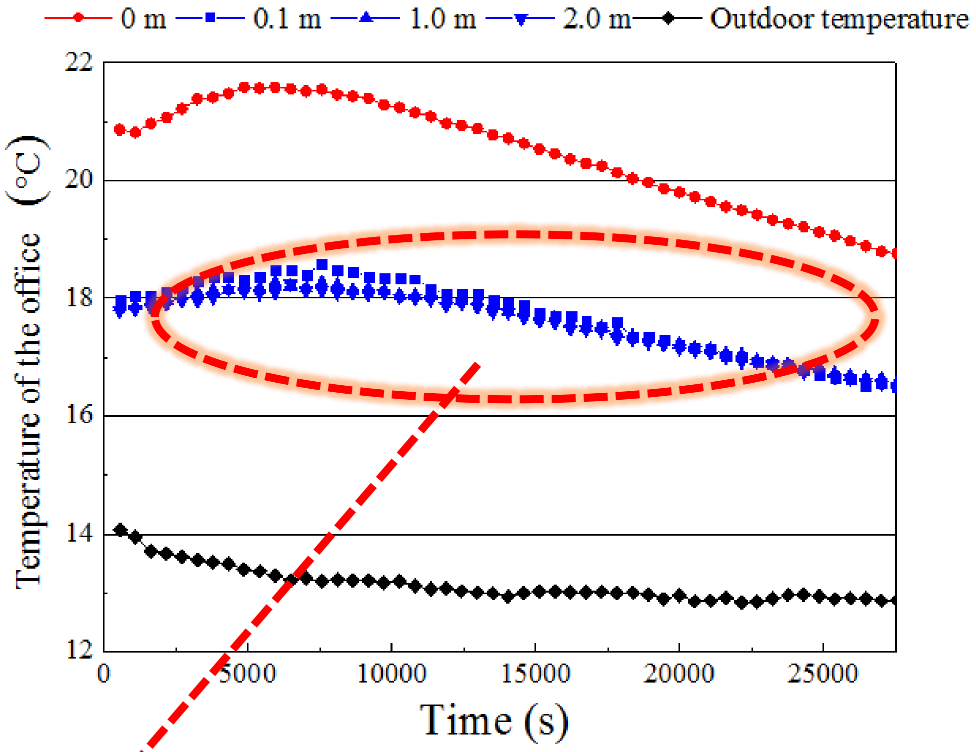
7 The indoor temperature variation of room during the night- Application Case

工程实例–夜间末端房间的温度变化



The temperature variation in the meeting room (area of 25.5m²) at night

夜间会议室（25.5m²）温度变化



The temperature variation in the office room (area of 9.3m²) at night

夜间办公室（9.3m²）温度变化

The indoor temperature can keep above 16 ℃ for about 7.5 hours at night when the heat release rate is 0.6 m^3/h.

在0.6 m^3/h的释热流量下，夜间室内房间可维持16℃以上约7.5小时

8 Conclusion 结论

CHONGQING UNIVERSITY 重慶大學

Influence of heat transfer fluid on the characteristics of thermal energy storage

传热流体对蓄热特性的影响

1. When the inlet water temperature(T_{in}) is constant, the influent flow rate(Q_{in}) has no significant influence on the heat storage time(T_m). Thus **the heat storage with small flow should be adopted to reduce the thermal energy consumption in application** .

在进水温度T_{in}=const的情况下，进水流量Q_{in}对蓄热时间T_m的影响不显著，实际工程应采用小流量蓄热以减少蓄热能耗。

2. When the inlet water flow (Q_{in}) is constant, the heat storage time(T_m) can be reduced by increasing the inlet water temperature(T_{in}). **It is worth noting that the inlet water temperature(T_{in}) should be controlled in a certain range**, and the economy of heat storage should be considered simultaneously.

在进水流量Q_{in}=const的情况下，进水温度T_{in}↑有利于蓄热时间T_m↓，但要控制在一定范围内，并考虑蓄热的经济性。

Influence of natural convection heat transfer on the characteristics of thermal energy storage and release

自然对流换热对蓄释热特性的影响

1. The numerical results show that **the natural convection heat transfer** in heat storage process has a great influence on the accuracy of the numerical calculation, and **it should be taken into account in the model**. However, the natural convection heat transfer can be ignored in the solidification (or heat release) process.

数值结果表明，蓄热过程中的自然对流换热对数值模型的计算精度有较大影响，在模型中应予以考虑，但凝固（释热）过程影响较小，可以忽略自然对流。

2. The numerical results show the vertical installation and horizontal installation of the TES unit both have little influence on its performance. **The installation form can be freely chosen according to actual installation conditions**.

数值结果表明，蓄热罐的立式安装与卧式安装对其使用性能造成的影响较小，可根据实际安装条件自由选择。

8

Conclusion 结论

Application of the evaluation method 评价方法的应用

1. The evaluation method is proposed to optimize the design of the solar collectors and TES units.

   利用评价计算方法，可以有效实现集热器与蓄能罐的设计匹配评价。

2. Further research on the operation of practical system.

   实际的运行评价还有待探索。

Practical application of the PCMs 相变蓄能能够有效应用于实际工程

1. Practical applications of the energy storage device using Phase change material is entirely feasible.

   相变蓄能罐能够在工程上实施。

2. Approaches to optimize the performance of TES device: innovative materials(PCM)， nanomaterial, structure optimization

   新型相变材料、纳米材料、结构优化等措施可进一步提高其性能。

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Discussion？

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