# Experimental Study of a Single Quartz Tube Solid Particle Air Receiver

Fengwu Bai*, Zhiying Cui, Fangzhou Wang

**Key Laboratory of Solar Thermal Energy and Photovoltaic System of Chinese Academy of Sciences, Institute of Electrical Engineering**

**Beijing, China**

**E-mail: baifw@mail.iee.ac.cn**

# Outline

1. Brief introduction of IEECAS
2. Background and motivation
3. Experiments
4. Summary and future work
5. Acknowledgements

# Brief Introduction of IEECAS

- Founded in 1958, focused on the basic knowledge and high-tech. R&D in the field of electrical engineering, one of 113 research institutes in CAS.
- 431 employees (375 are scientists, engineers, research assistants)

| IEECAS | Research Dept. | Research Group |
|---|---|---|
| | 1、Lab. of Renewable Energy | Wind &PV G.<br>Solar Thermo G.<br>Solar Cell<br>Ocean Wave G.<br>Testing center |
| | 2、Lab. of New Power Equipment Technology | Evaporative cooling tech. |
| | 3、Lab. of Power Electronics & Energy Conversion | EV Drives<br>PE &LM Drives<br>EV Energy M.<br>HV Tech. |
| | 4、Lab. of Superconductors and New Materials | SP Power Tech.<br>SP Magnetics Tech<br>HT SP Materials<br>Nano Tech. |
| | 5、Lab. of Bioelectromagnetics and Electromagnetic Detection | Bioelectromagnetic Theory<br>EM Signal Detection Tech.<br>EM Theory |
| | 6、Laboratory of Smart Grid | Smart Grid |

**Web: http://www.iee.ac.cn**

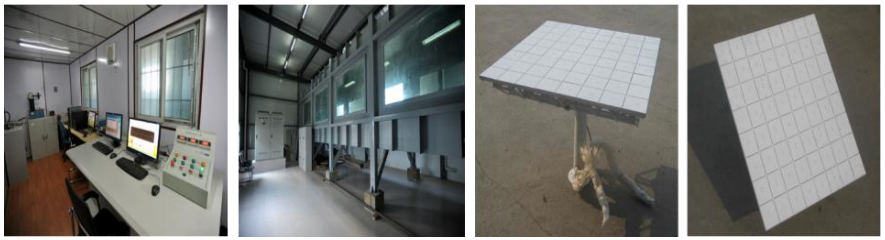
# Solar Thermal Power of IEECAS

**33 staffs with 3 professors, 20 of them with doctor degree. 10 Ph.d students and 3 master students**

- ✓ **Solar thermal power technology（tower、 parabolic trough、 dish Stirling）**
  - ☐ **System optimization of CSP plant**
  - ☐ **Solar concentrator**
  - ☐ **Receiver**
  - ☐ **Thermal energy storage**
  - ☐ **Solar thermal power materials**
  - ☐ **Control technology**
- ✓ **Solar desalination**
- ✓ **Solar integrated building**
- ✓ **Solar collector/heater thermal performance testing technology**

- ☐ **Tower: 119m, three apertures，Turbine: 1.5MW,**
- ☐ **HTF: Water/steam and molten salt, Solar field:10000㎡**

## Badaling Platform of Solar Thermal Power



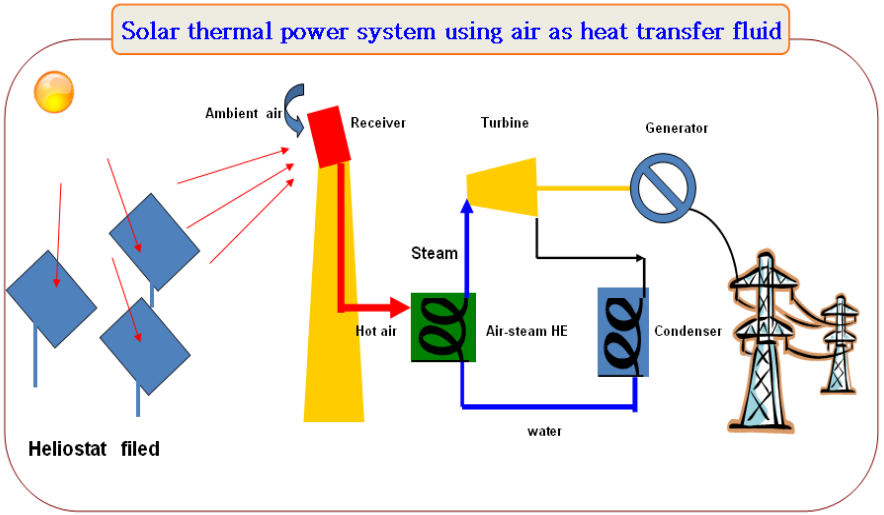
**Wind tunnel： testing section 2.5m×3m, Speed:0-30m/s**

- ☐ **Three loops，HTF: thermal oil of 293-393℃**
- ☐ **Solar field: 9900㎡，Turbine: 1.5MW**

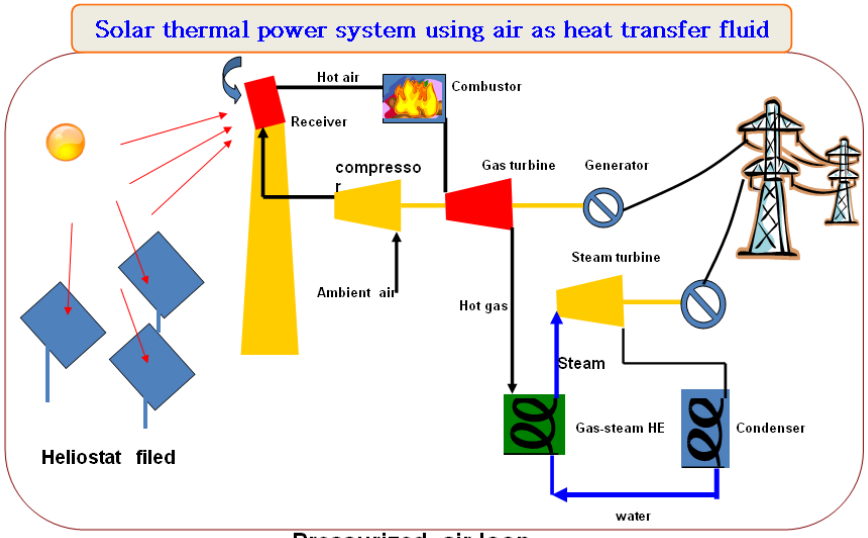
# Motivation： air is a good heat transfer fluid for CSP plant

**Free and environmentally friendly**

- **High temperature， single phase**（101.3 kPa， condense point 81.7K ）
- **To achieve higher efficiency （30-35%， combined cycle）**
- **Low water consumption（suitable to desert area）**




Open air loop

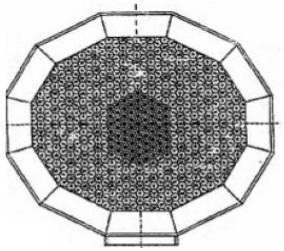



Pressurized air loop

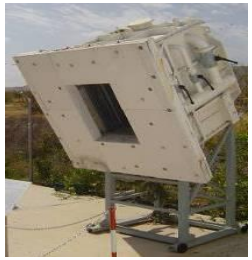
# Motivation： air receiver is the key component

Problems：

- Hot spot destroy
- Small unit connection for large scale
- Uneven heat transfer

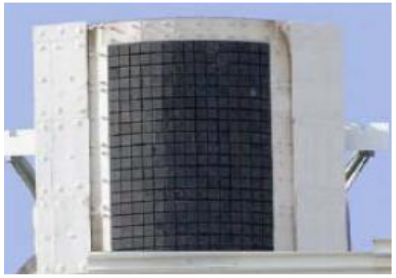


PHOEBUS project，1988—1989
Metal mesh

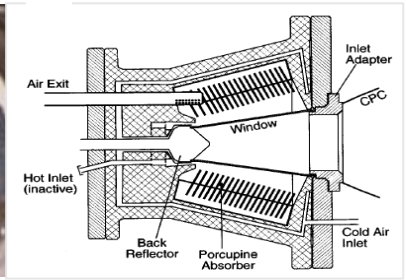


PSA，Spain，1989-1993
Ceramic tube

REFOS project，1998
815℃，400kW，1.5MPa，SIC
ceramic foam



PSA，Spain， 1997-2000
SIC honeycomb ceramic



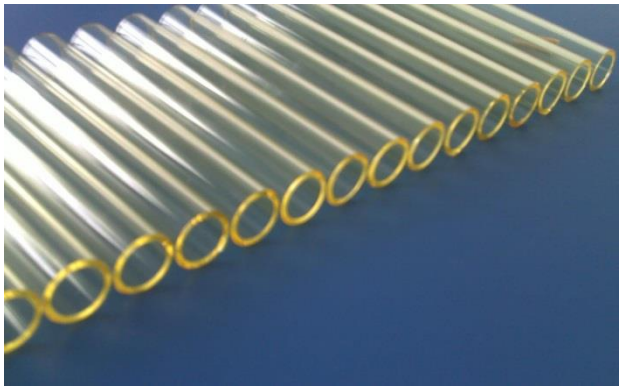

DIAPR project, Israel，2001
（50kWt, 1200℃，20bar） Ceramic tube

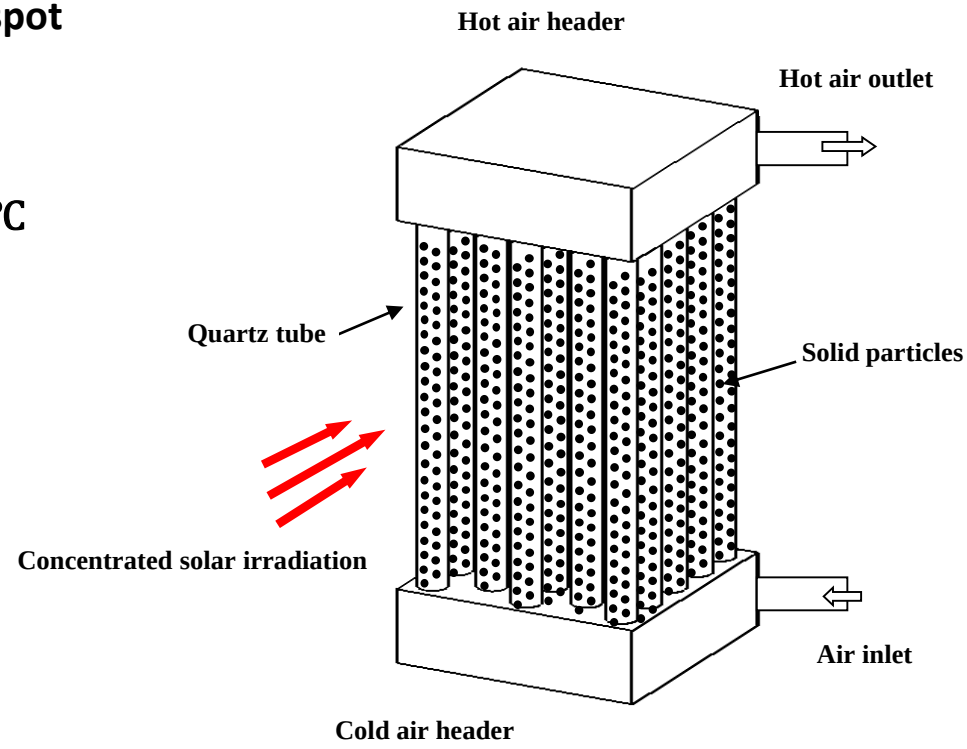
China，2011
SIC ceramic foam

# Motivation： using solid particles as absorber

## Merits:

- Low temperature difference between particles and air
- Low risk of absorber destroy by hot spot
- Pressurized air
- Quartz tube
  - ✓ Working temperature： ≤1100℃
  - ✓ Length ≤6m
  - ✓ Diameter： 5mm-200mm
- Suitable to large scale receiver





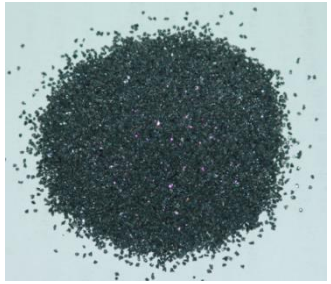
# Concept of five tubes

**Quartz tube**

- ✓Inner diameter： 40mm
- ✓Thickness： 3mm
- ✓Length： 500mm

**Solid particles**

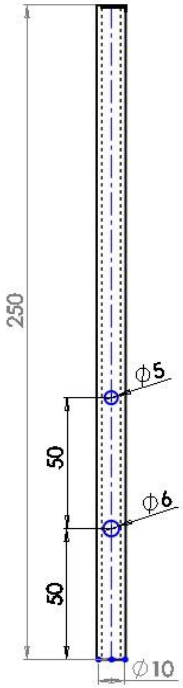
- ➢silicon carbide
- ➢Diameter： 1mm

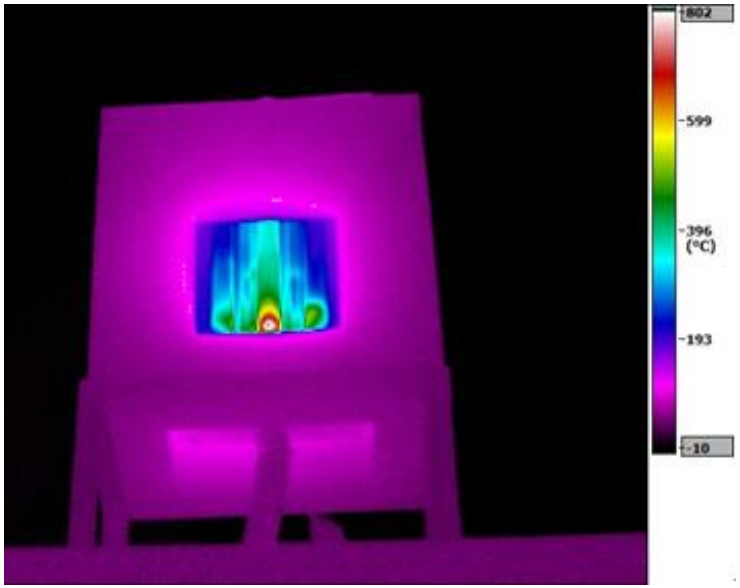


The maximum outlet air temperature is obtained as 624.1℃

**Five tubes receiver was well tested**

**Further research is needed.**






**Stainless steel entrance duct**

# Key points of such receiver

**Physical characteristic of particles**

- Size
- Thermal conductivity
- Specific heat
- Density
- Absorptance
- High temperature stability
- Hardness

**Cost and availability**

**Now the candidate is Silicon carbide(SiC)**

**Physical characteristic of quartz tubes**

- Diameter
- Thickness
- Thermal conductivity
- Transmissivity in wavelength range of concentrated solar irradiation
- High temperature stability
- Hardness

**Cost and availability**

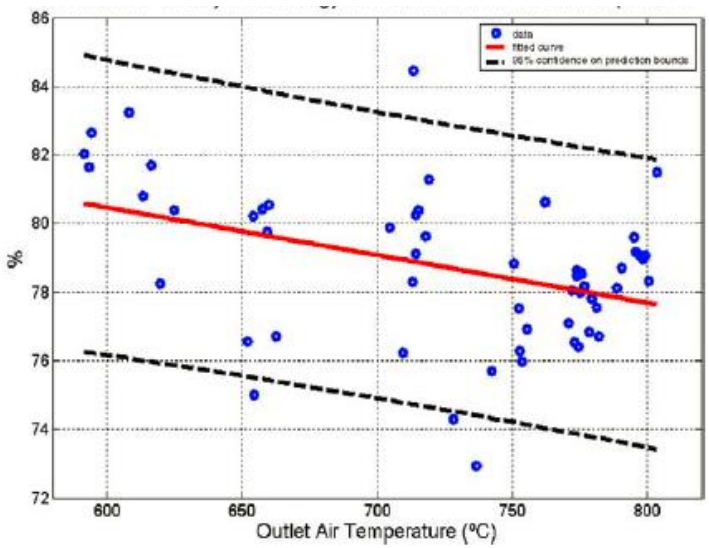
**Receiver**

- Structure including the connection of tubes and metal
- Air entrance duct to ensure well solid fluidization

**Cost and lifetime**

**Design point**

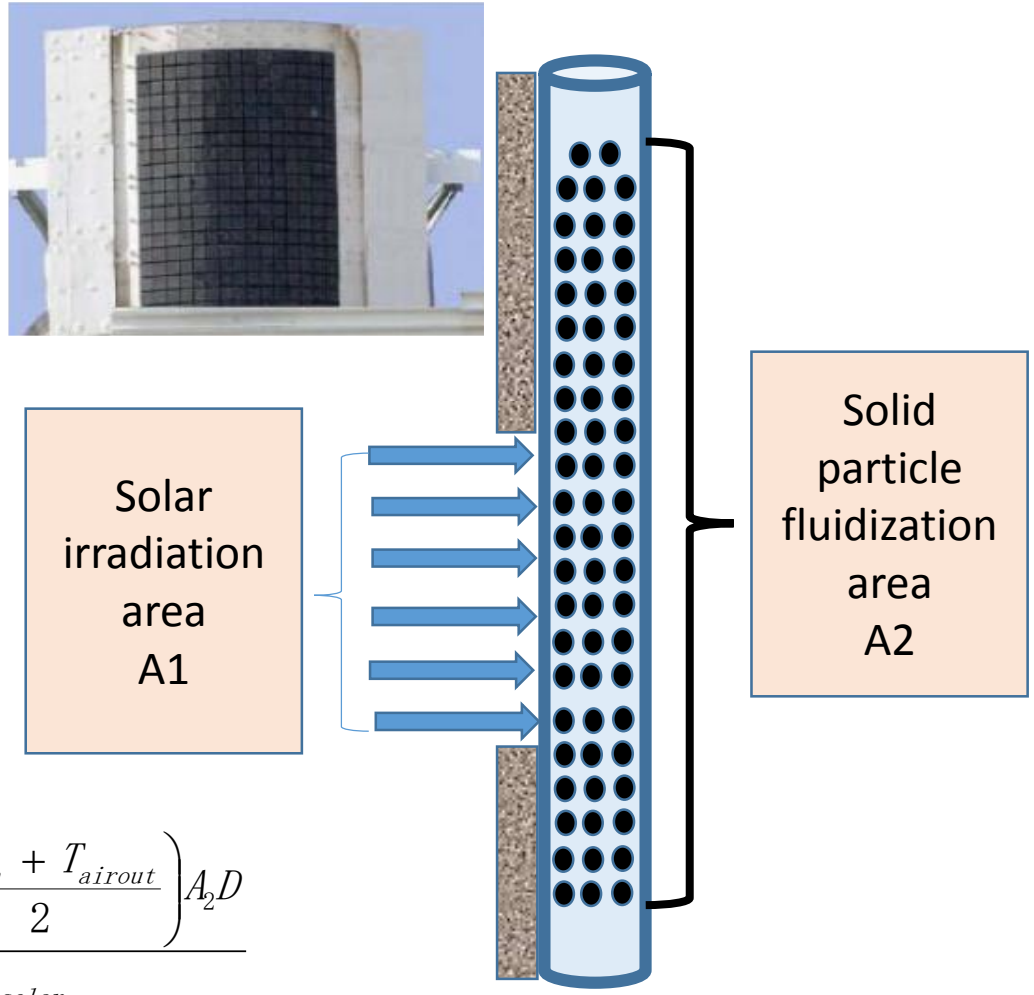
- Outlet air temperature
- Efficiency




**From: Peter Heller, Markus Pfander, Thorsten Denk.Test and evaluation of a solar powered gas turbine system. Solar Energy 80 (2006) 1225–1230**

# Basic description of the problem

- At the same time, only some particles absorb solar energy , while most of them transfer heat to air or store heat.
- The ratio of solar penetration area to the fluidization area will take effect on the outlet air temperature and thermal efficiency.
- Compare to the volumetric receiver, in operation, this ratio is dependent on the fluidization state, is kept variable.




$$\eta = \frac{\dot{m}c_p\left(T_{airout} - T_{airin}\right)}{A_1 q_{solar}} = \frac{h_v\left(\bar{T}_S - \frac{T_{airin} + T_{airout}}{2}\right)A_2 D}{A_1 q_{solar}}$$

# Working procedure

$$\eta = \frac{\dot{m}c_p\left(T_{airout} - T_{airin}\right)}{A_1 q_{solar}}$$

- Input solar flux distribution measurement
- Experiments of thermal performance of receiver by measure the outlet air temperature

# Experiment system

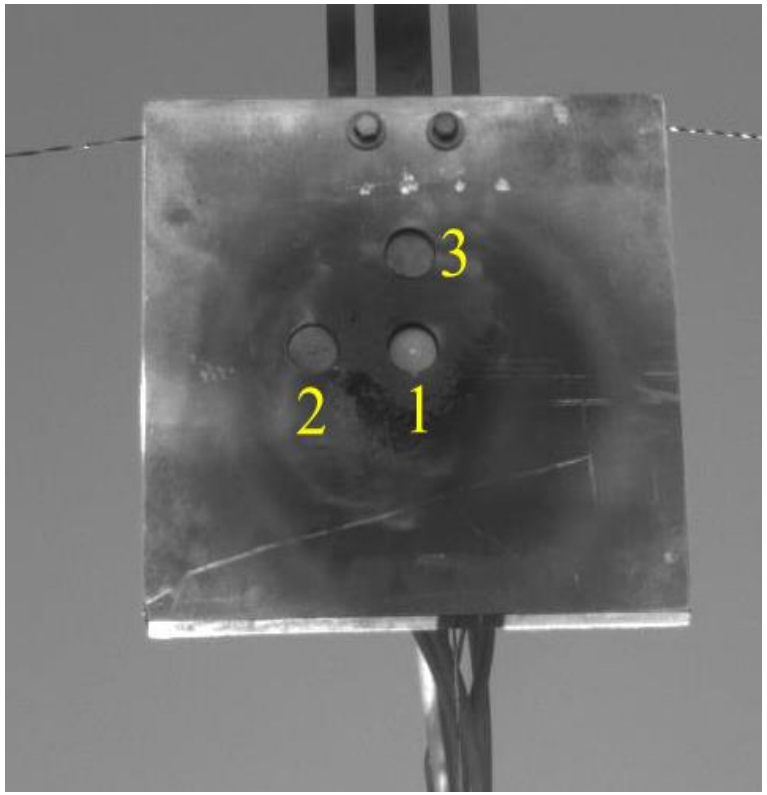
## Solar furnace to provide heat

- Heliostat area: 35.3m$^2$
- Focal area diameter: 200mm

# Experiment system

## Moving bar method to measure the solar flux distribution

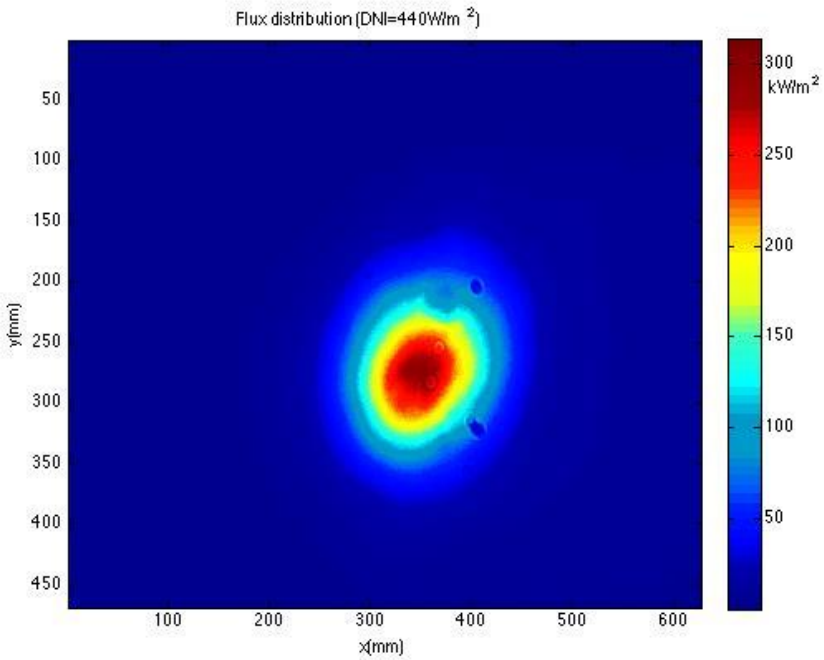
The instrument for measuring solar flux distribution

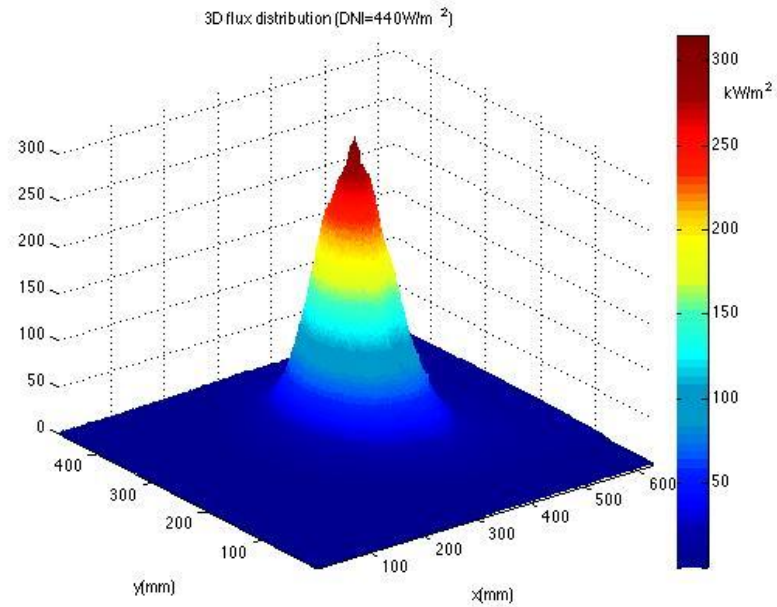



Heat flux sensor

# Experiment system

## Typical measured result of heat flux distribution



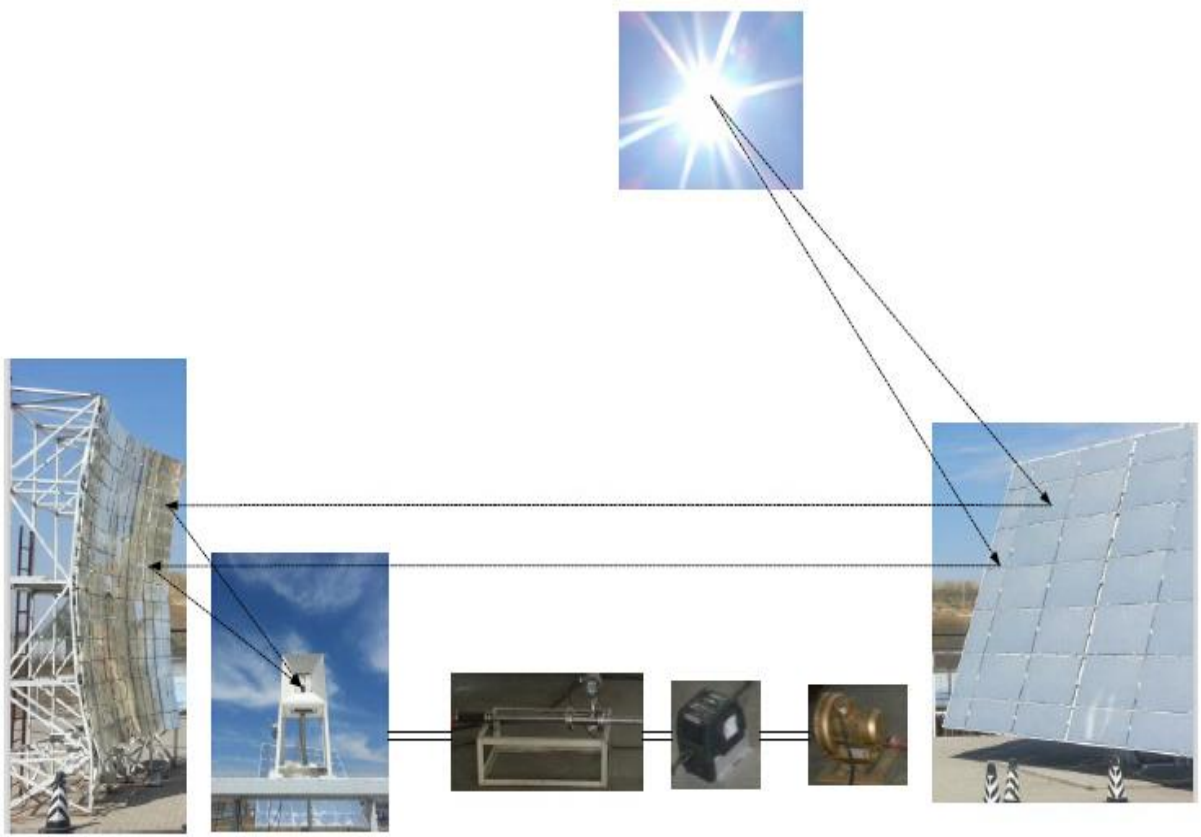



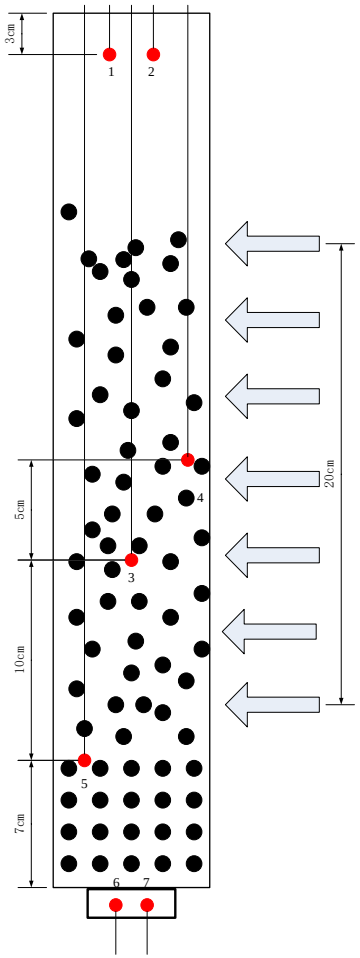

**Two dimensional distribution of concentrated heat flux on solar furnace**

**Three dimensional distribution of concentrated heat flux on solar furnace**

**The distribution of heat flux on solar surface is consistent with Gauss distribution. The average diameter of solar spot is about 215mm.**

# Experiment system



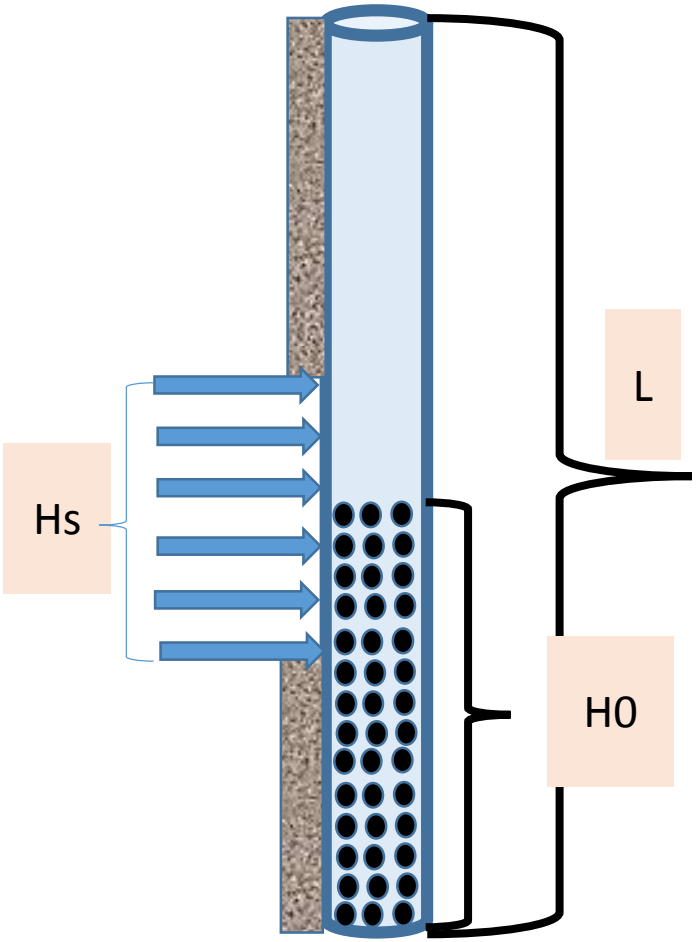



**Experiment system**

**Thermocouples layout**

# Experiments list

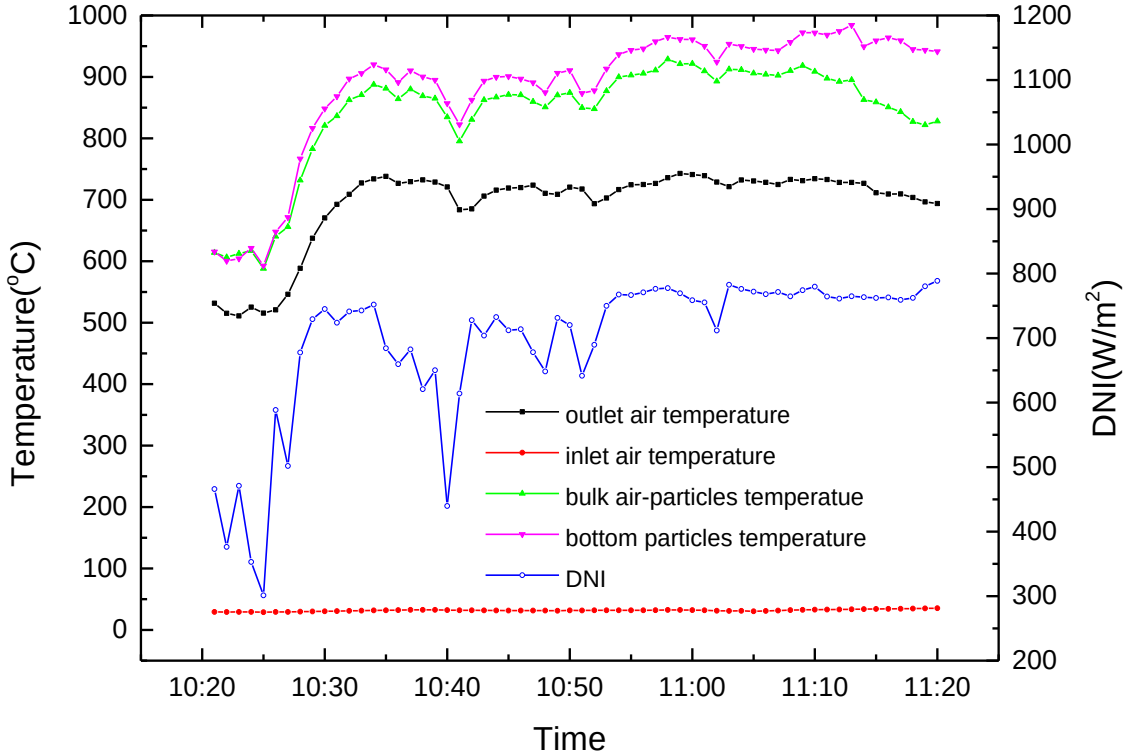
| Case | Particle size(mm) | Height of penetration Hs (mm) | Relative Packed height σ |
|---|---|---|---|
| 1 | 1.0 | 200 | 0.35 |
| 2 | 1.0 | 150 | 0.35 |
| 3 | 1.0 | 100 | 0.35 |
| 4 | 1.0 | 50 | 0.35 |
| 5 | 0.5 | 200 | 0.4 |
| 6 | 0.5 | 150 | 0.4 |
| 7 | 0.5 | 100 | 0.4 |
| 8 | 0.5 | 50 | 0.4 |
| 9 | 2.0 | 150 | 0.4 |
| 10 | 2.0 | 100 | 0.4 |
| 11 | 2.0 | 50 | 0.4 |
| 11 | 1.0 | 200(Steel tube) | 0.35 |




$$\delta = \frac{H_0}{L}$$

# Results-Case 1

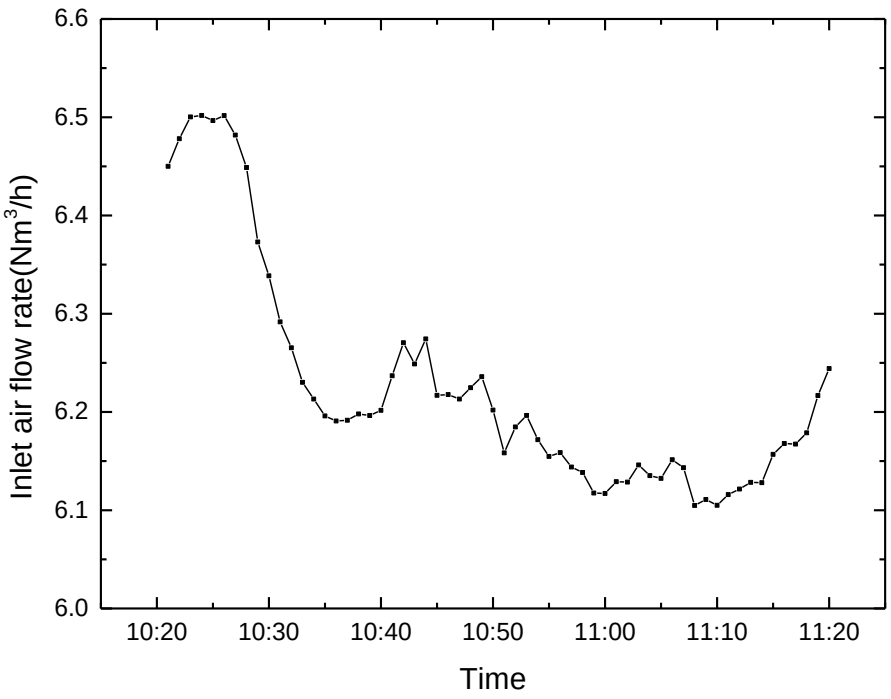
**Hs=200mm**



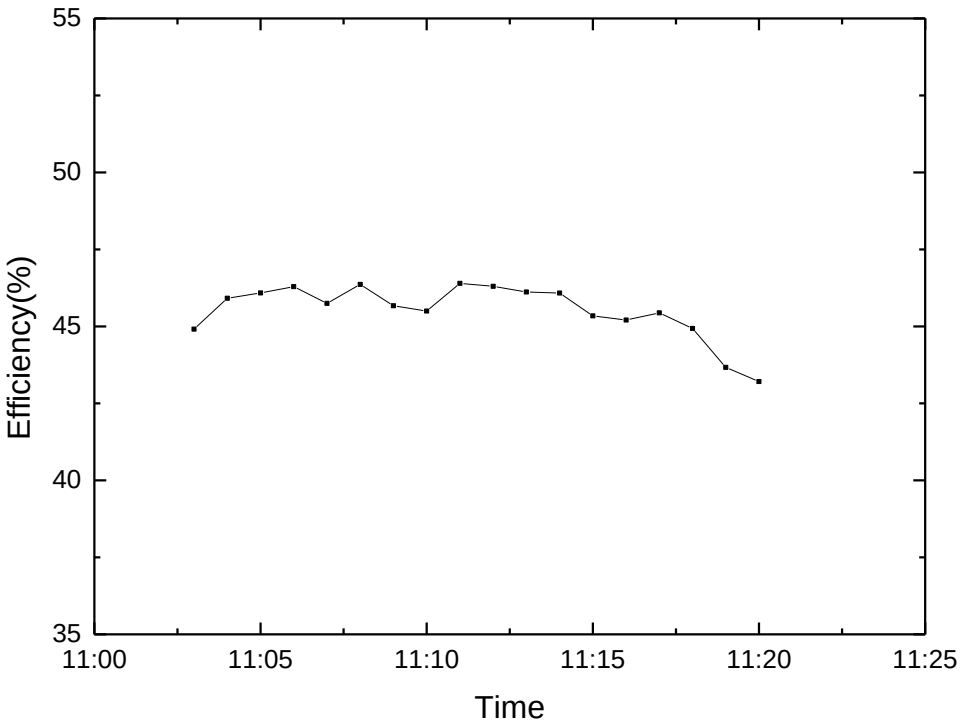

**Temperatures & DNI**

**DNI changes greatly， but outlet air temperature keeps stable, the highest is 742.8°C**

# Results–Case 1




**Inlet air flow rate**



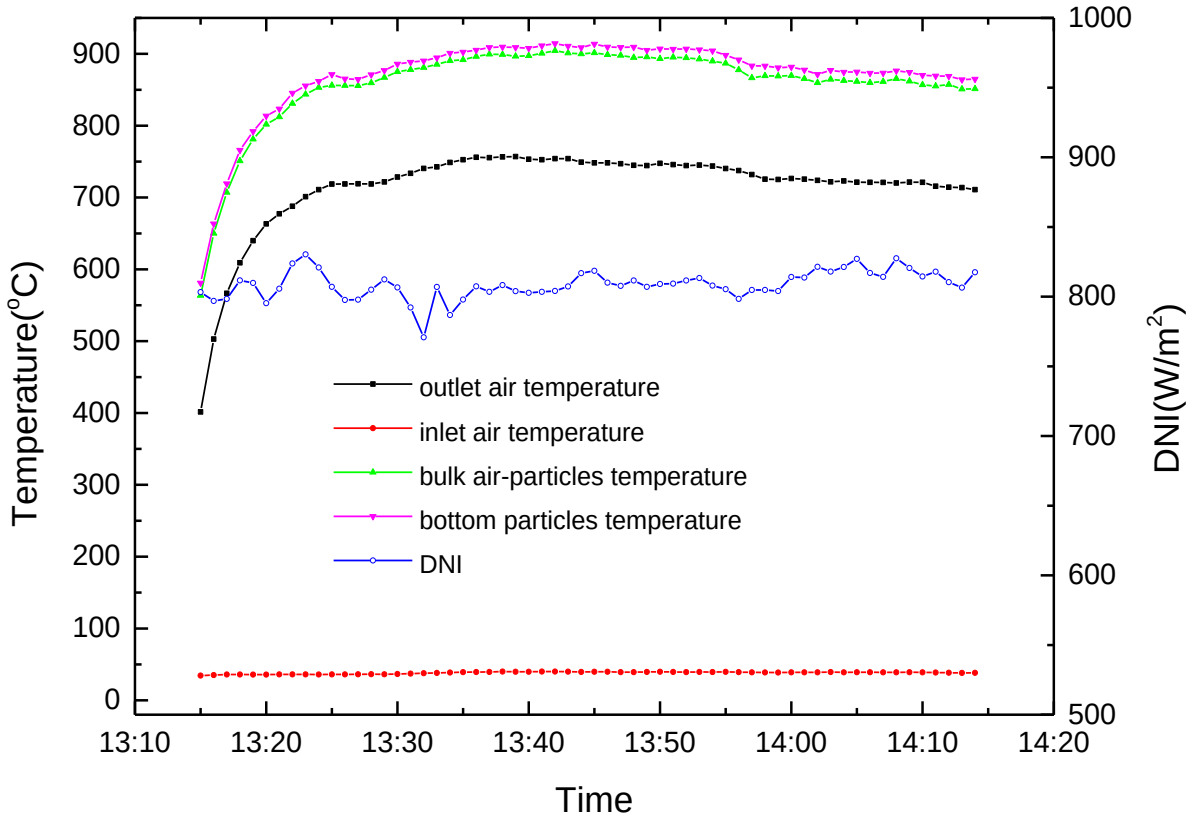

**Transient thermal efficiency**

**Thermal efficiency is low**

**45.5%**

# Results–Case 2

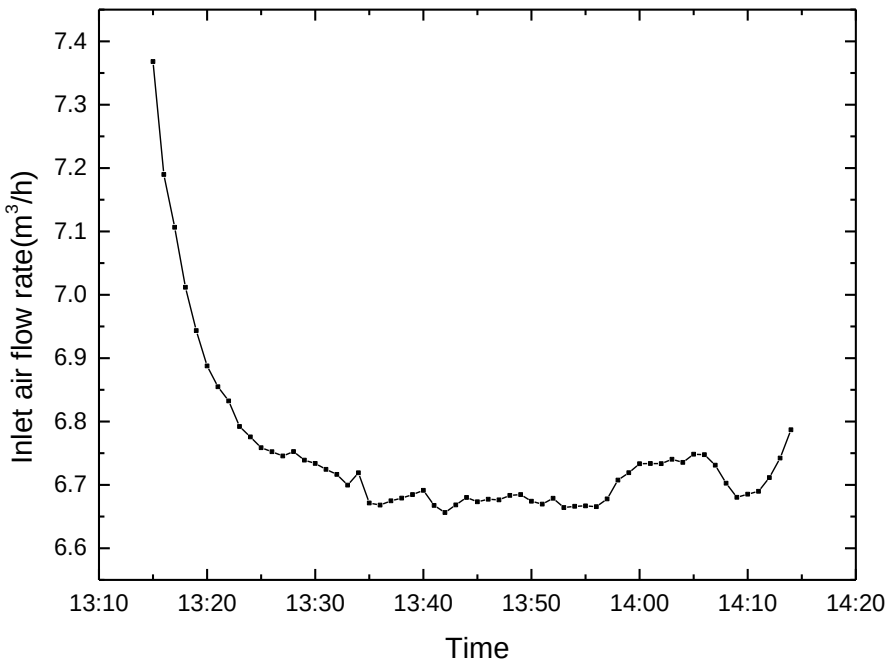
**Hs=150mm**



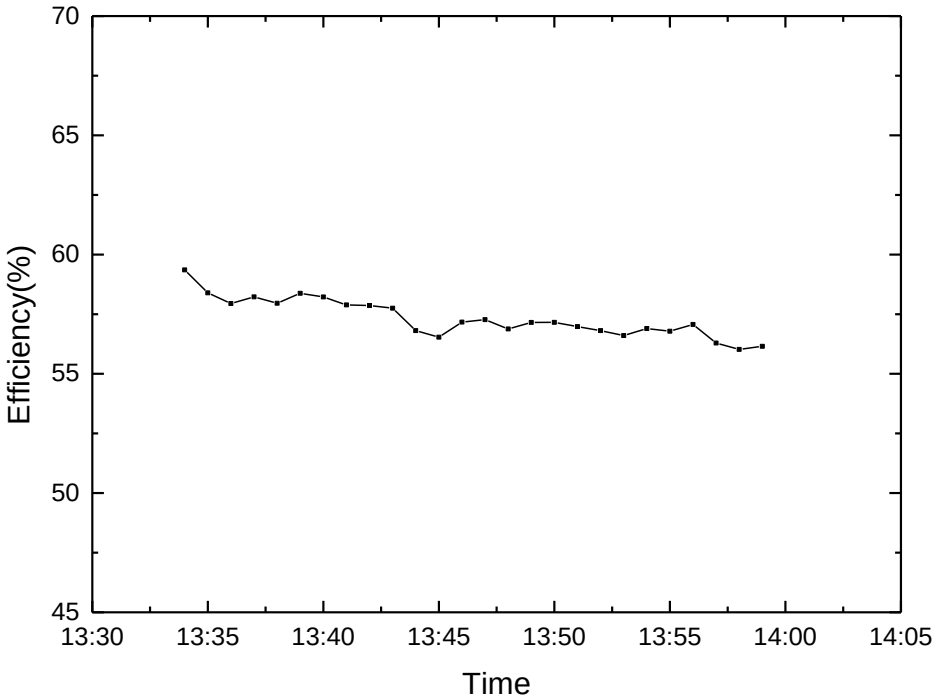

**Temperatures**

**The highest outlet air temperature: 756.9°C**

# Results–Case 2




**Inlet air flow rate**

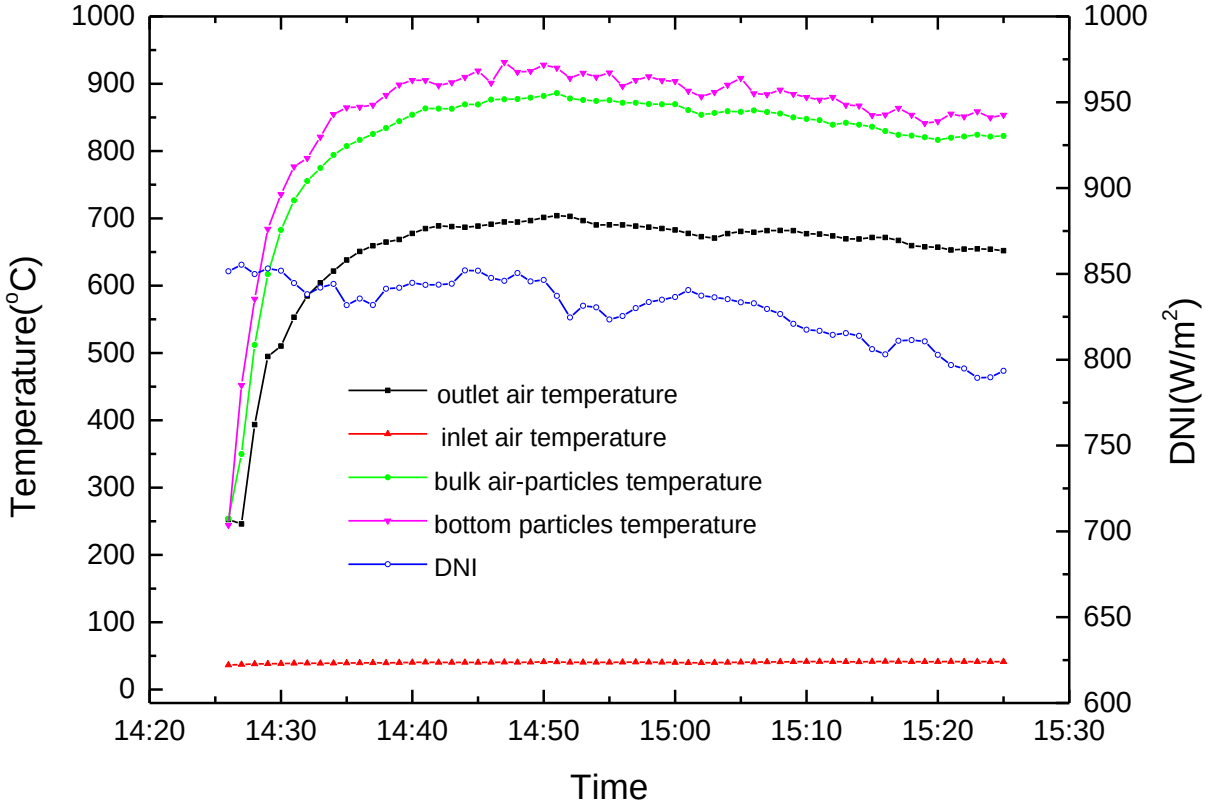



**Transient thermal efficiency**

**Thermal efficiency is 57.3%**

# Results–Case 3

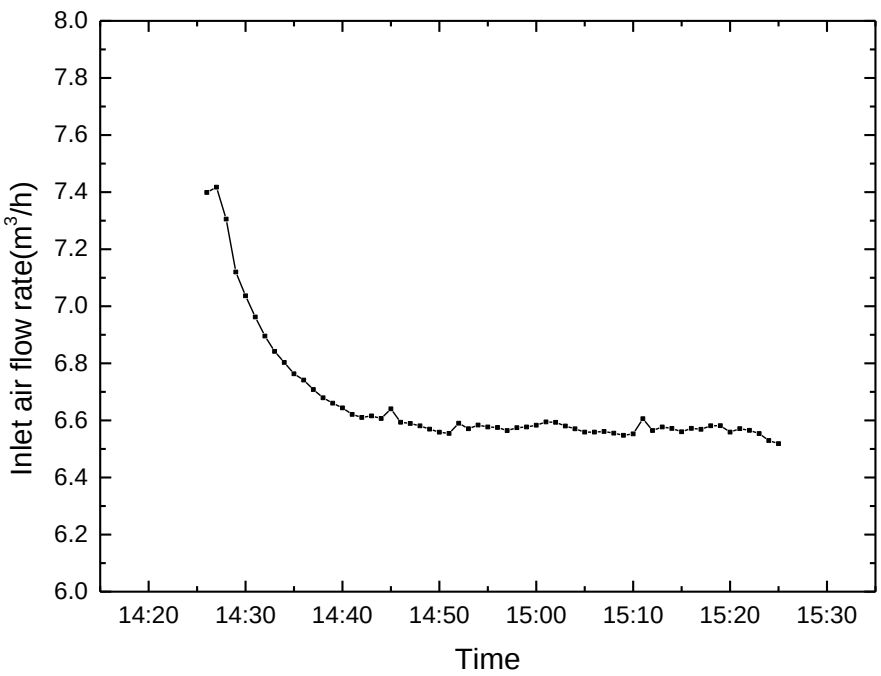
**Hs=100mm**



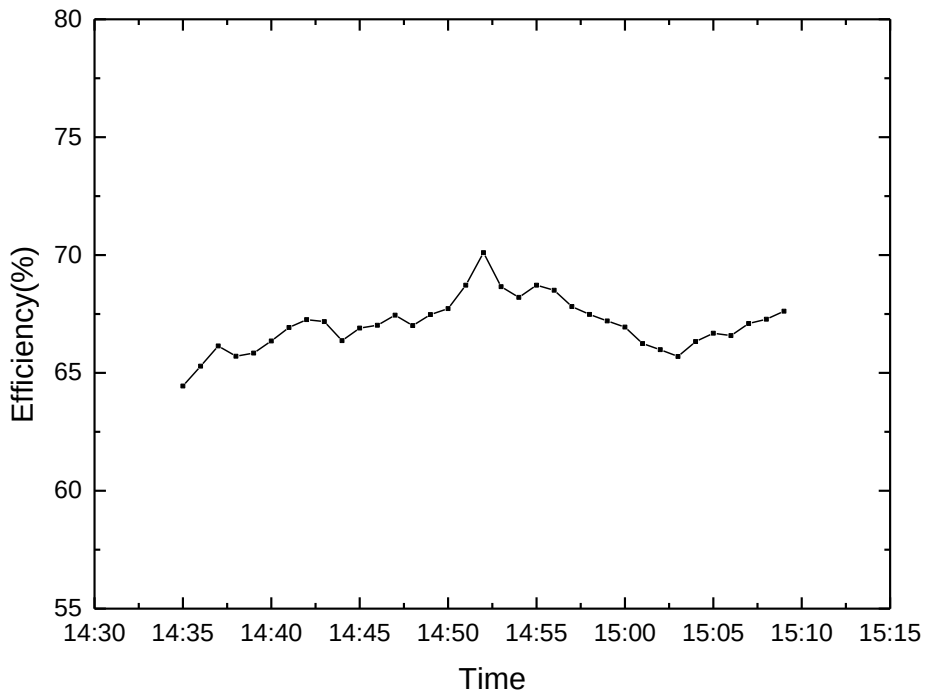

**Temperatures &DNI**

**The highest outlet air temperature: 704°C**

# Results–Case 3




**Inlet air flow rate**

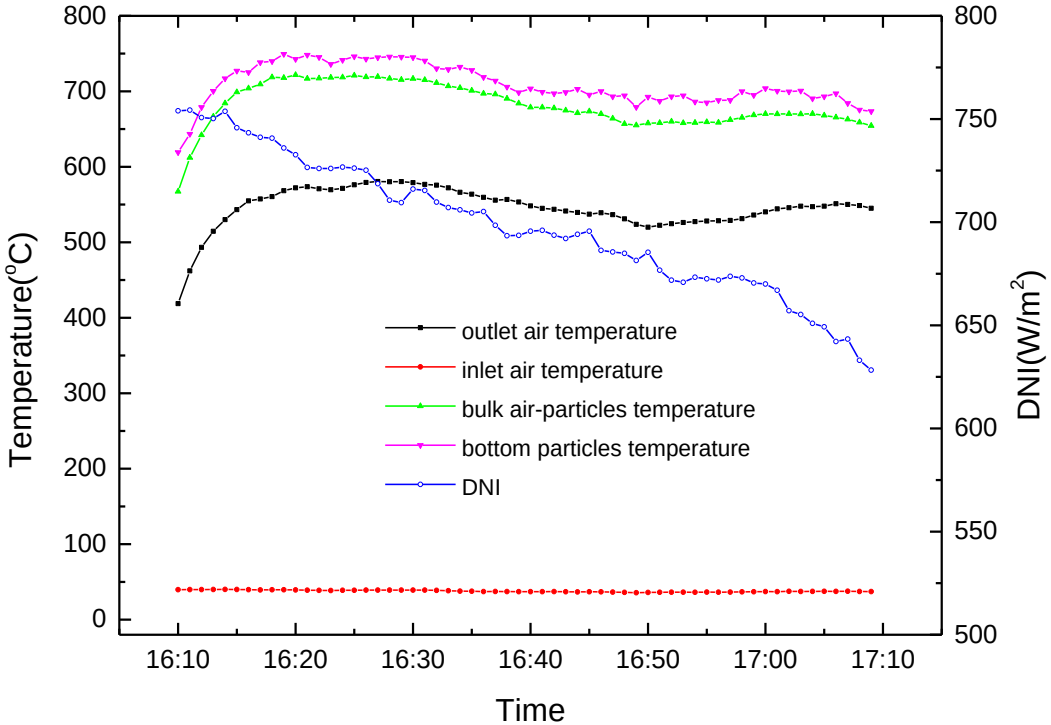



**Transient thermal efficiency**

**Thermal efficiency is 67 %**

# Results–Case 4

**Hs=50mm**

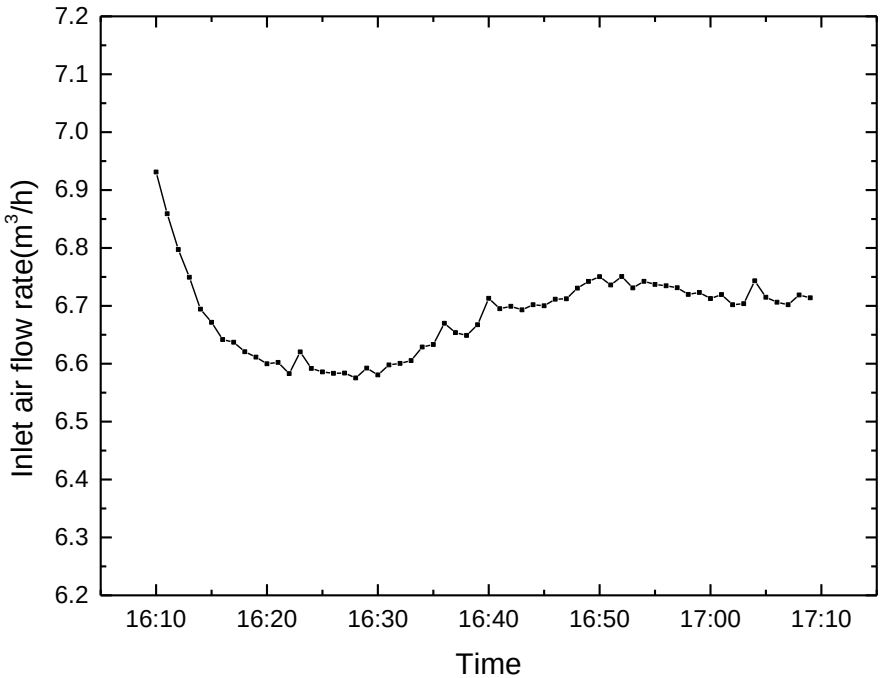



**Temperatures &DNI**

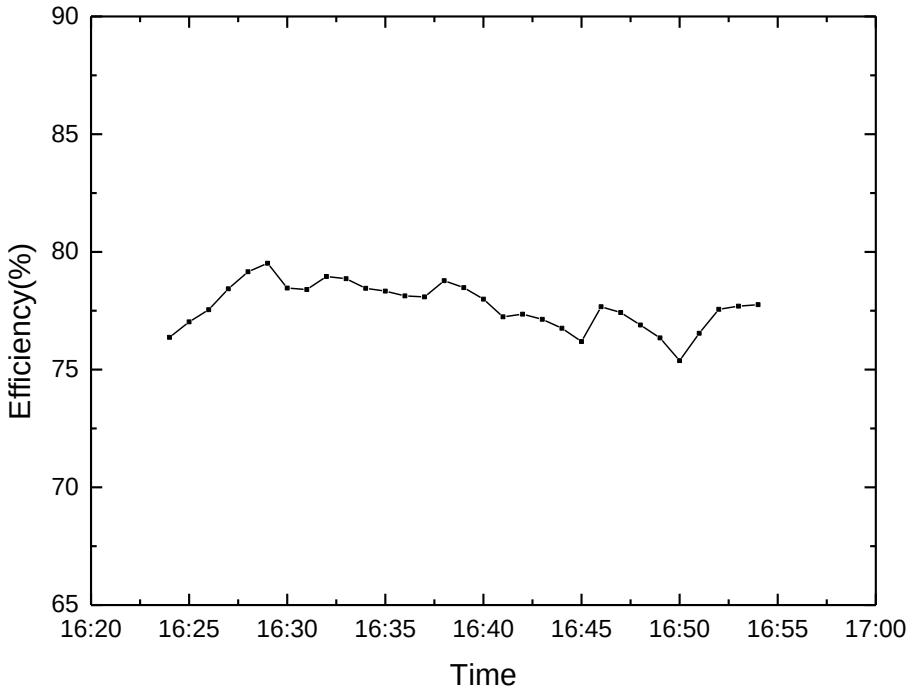
**The highest outlet air temperature: 580.6°C**

**DNI drops down，but outlet air temperature keeps stable. Solid particles in the opaque area can be served as heat storage media.**

# Results–Case 4




**Inlet air flow rate**

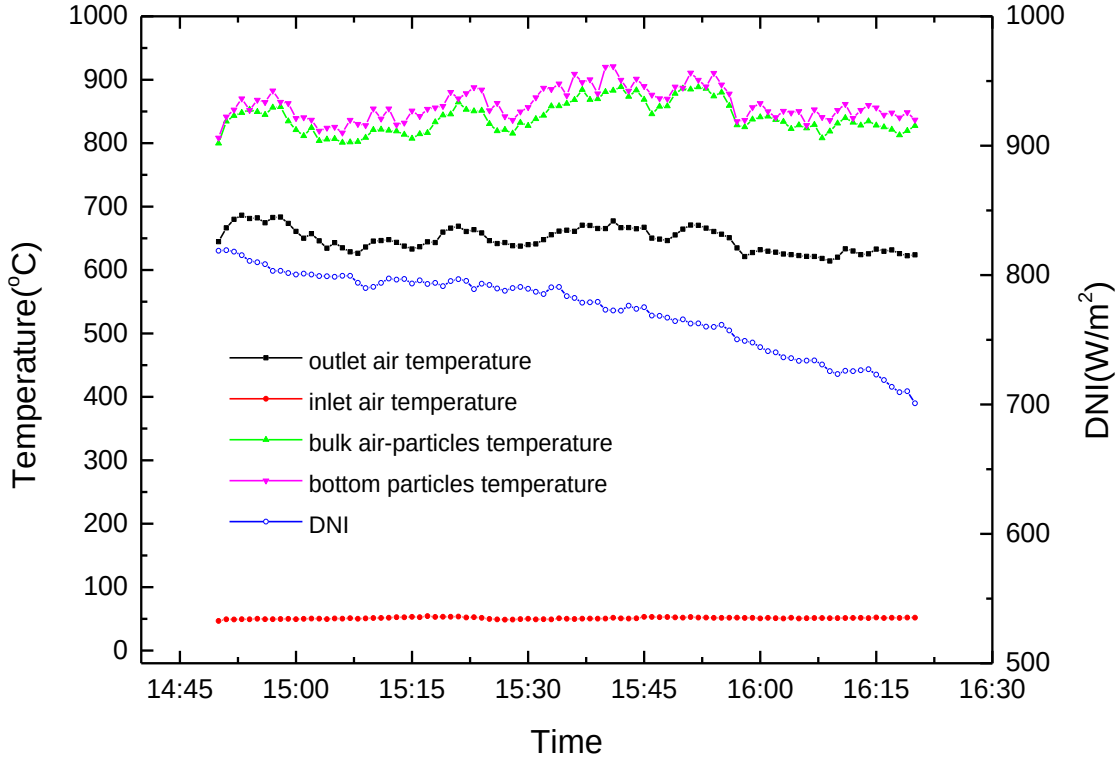



**Transient thermal efficiency**

**Thermal efficiency is 77.7%**

# Results–Case 5

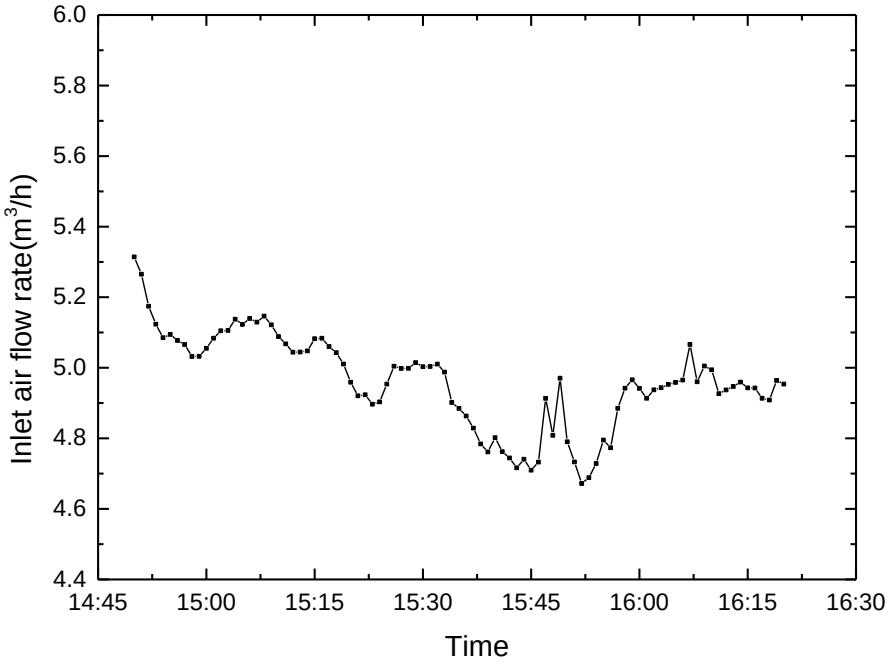
**Hs=200mm**



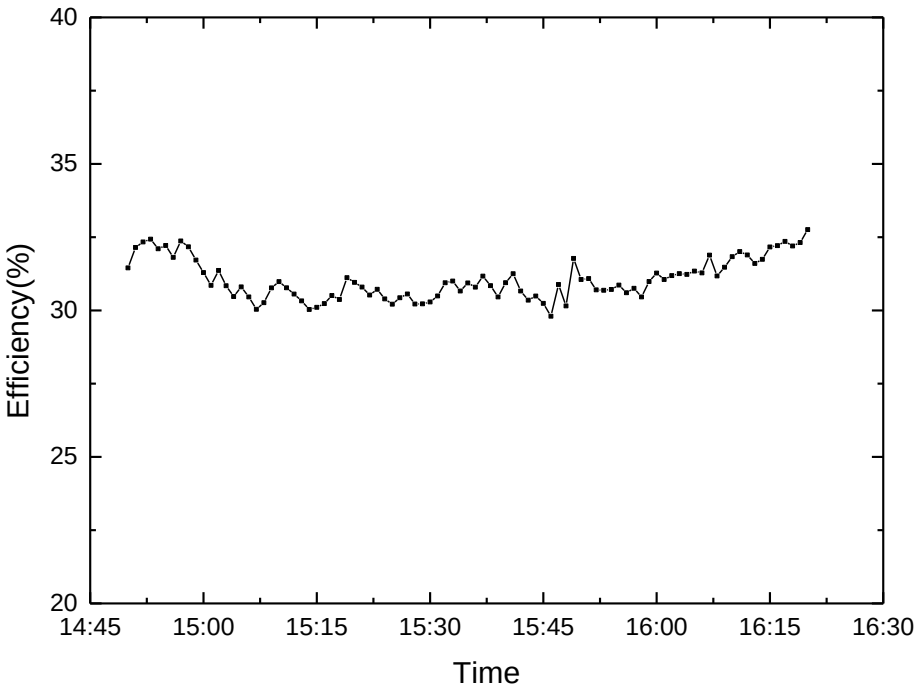

**Temperatures & DNI**

**Outlet air temperature is stable and the highest is 686.4°C**

# Results–Case 5




**Inlet air flow rate**

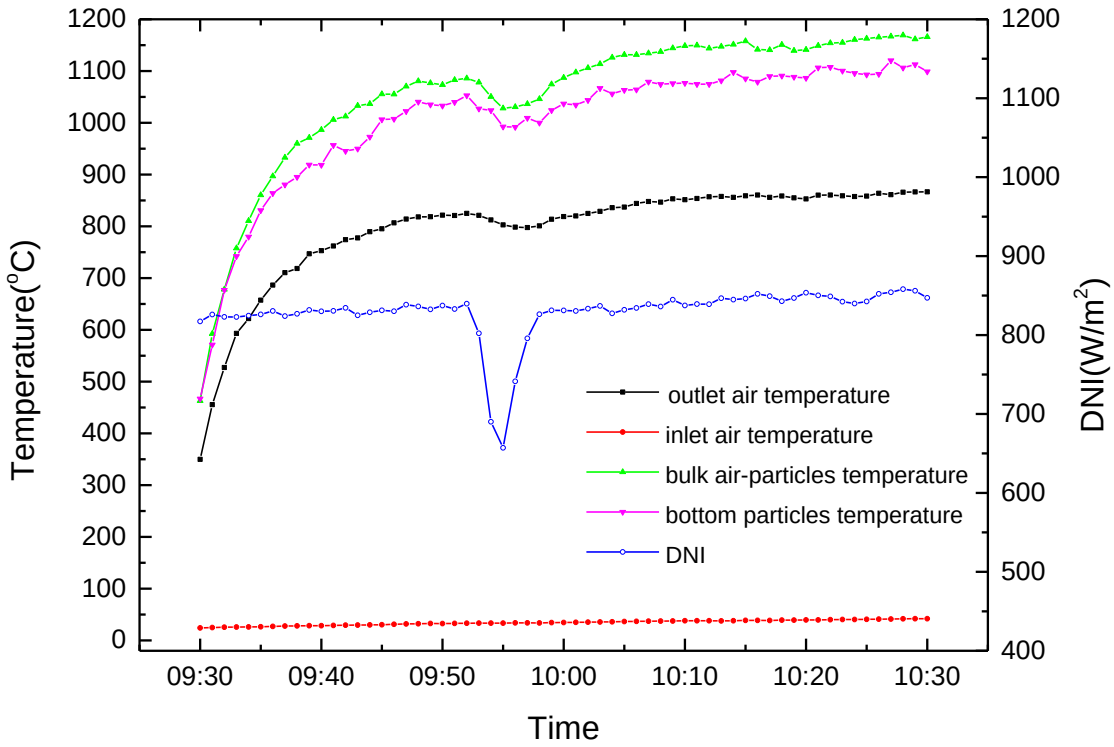



**Transient thermal efficiency**

**Thermal efficiency is low**
**31.1%**

# Results–Case 6

**Hs=150mm**



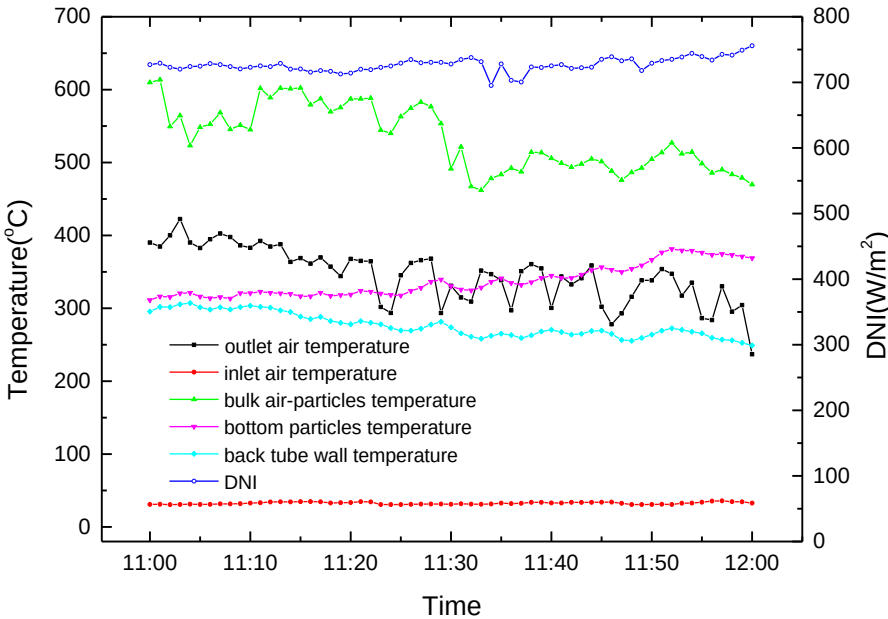

**Temperatures in the receiver of Case 2**

**The highest outlet air temperature: 866.6°C.**

**Inlet air flow rate cannot be measured as it is beyond the flowmeter range.**

# Results–Case 12

**Hs=200mm**

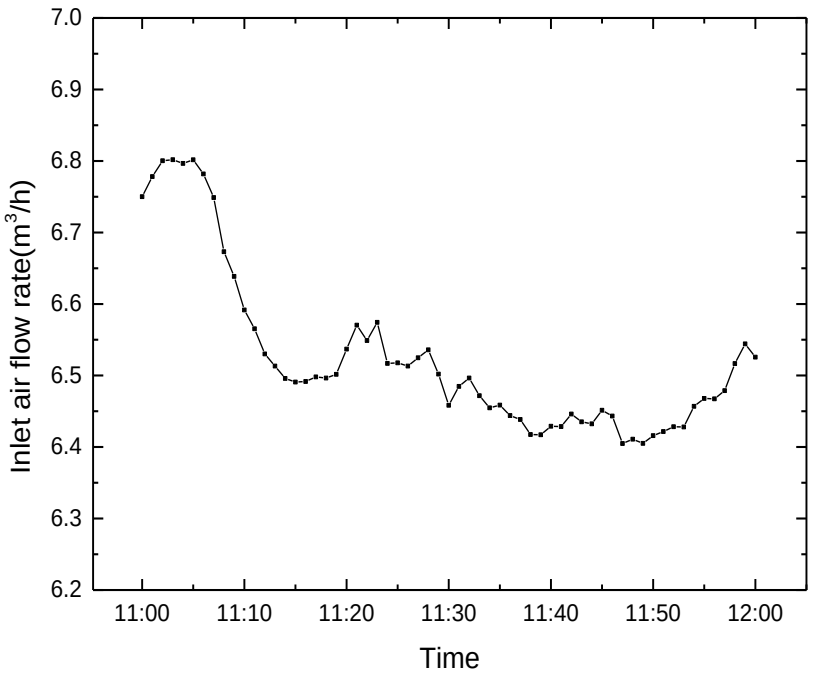



**Temperatures &DNI**

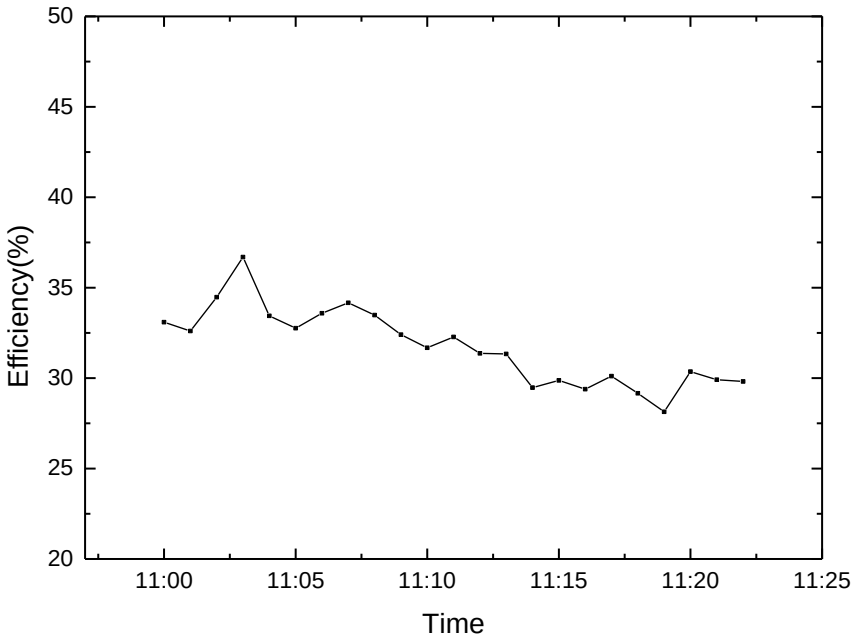
**The highest outlet air temperature: 422.3°C**

**Part of the tube wall is melt, lower outlet air temperature**

# Results–Case 12




**Inlet air flow rate**




**Transient thermal efficiency**

**Thermal efficiency is 31.8%**

# Results–comparison

| Case number | Highest outlet air temperature (℃) | Thermal efficiency (%) |
|---|---|---|
| 1 | 742.8 | 45.5 |
| 2 | 756.9 | 57.3 |
| 3 | 704.0 | 67.0 |
| 4 | 580.6 | 77.7 |
| 5 | 686.4 | 31.1 |
| 6 | 866.6 | N/A |
| 7 | 692.6 | N/A |
| 8 | 567.3 | N/A |
| 9 | 702.2 | 50.5 |
| 10 | 703.9 | 68.4 |
| 11 | 593.7 | 77.1 |
| 12 | 422.3 | 31.8 |

# Summary

**1 The ratio of solar penetration area to the fluidization area affects the outlet air temperature and thermal efficiency.**

- **The solid particles in the covered area have heat storage capacity, which can stabilize outlet air temperature and be beneficial for receiver operation.**
- **Case 3 can meet the requirement of receiver operation as the outlet temperature is over 700℃ and thermal efficiency is close to 70%.**

2 Using transparent quartz tube performs better than the one with opaque tube

# Future Work

**(1) Experiment of single long(>4m) quartz tube receiver**

- **Air intake duct design**
- **Diameter of tube**
- **Solid particles**
- **Fluidization parameters**

**(2) Simulation work of the receiver**

- **Performance analysis based on CFD**
- **Connection of tubes**
- **Air flow rate distribution**

# Acknowledgements

**The present work was supported by National Natural Scientific Foundation of China**

**(Gran No. 51376176)**

**Thanks to SolarPACES for the workshop**

Thank you!

# Experiment system

## Heat flux distribution

## Optical concentrating ratio

$$\beta_0 = \frac{A\cos\theta}{A'\cos\gamma} \approx \frac{E'/\cos\gamma}{E_0}$$

Excluding actual flux losses generated by the atmosphere, shadowing and blocking effects, or limited dimensions of the receiver aperture

$$\bar{\beta}_0 = \frac{\bar{E}'/\cos\gamma}{E_0} \approx \frac{\bar{E}'}{E_0}$$

Assuming that the incidence is normal to the receiver surface

$$\bar{\beta} = \bar{\beta}_0 \frac{k_1 k_2}{k_1' k_2'}$$

k is the average reflectivity of heliostat and concentrator

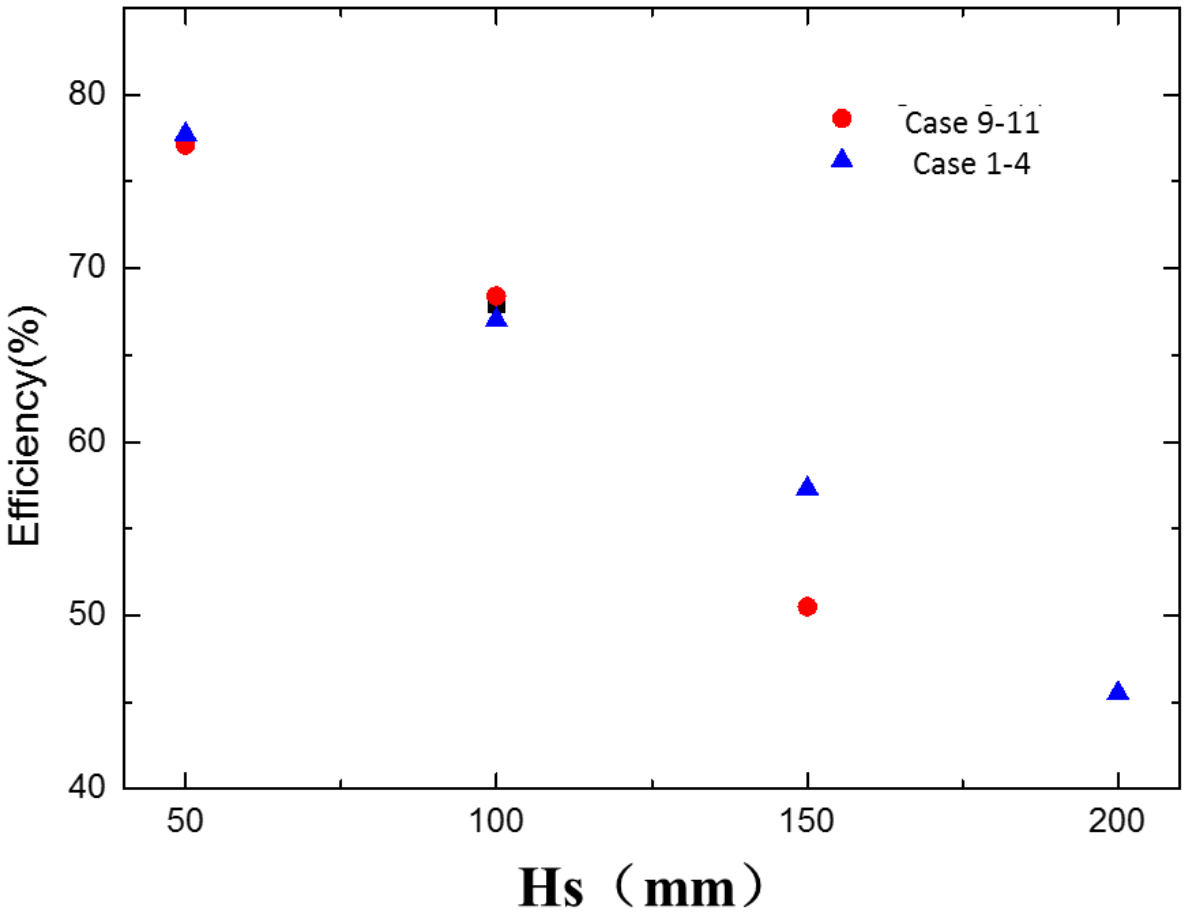
## Table 1 Reflectivity of both heliostat and parabolic mirrors

| Mirror | Reflectivity(%) | | | | | | | | | | | | Average (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Heliostat** | **83.4** | **87.6** | **81.3** | **90.5** | **93.2** | **84.7** | **78.9** | **82.4** | **87.1** | **81.6** | **83.4** | **87.6** | **85.1** |
| **Concentrator** | **93.5** | **92.7** | **90.1** | **91.3** | **88.5** | **89.1** | **87.3** | **91.9** | **89.2** | **94.1** | **93.5** | **92.7** | **90.7** |

## Table 2 Average optical concentrating ratio of experimental cases

| Hs(mm) | 200 (Case 1, 5, 12) | 150 (Case 2, 6, 9) | 100 (Case 3, 7, 10) | 50 (Case 4, 8, 11) |
|---|---|---|---|---|
| $\beta$ | 590.2 | 661.6 | 735.0 | 1029.0 |

# Results-comparison




**Less area of receiving solar radiation can improve receiver thermal efficiency.**