*Joint 21st International Heat Pipe Conference and*
*15th International Heat Pipe Symposium*
*February 4 - 9, 2023, Melbourne, Australia*

# Heat pipes in Solar Thermal Applications -A review

**Boo, Joon Hong**
**Professor Emeritus**
**Korea Aerospace University**





## Contents

1. Introduction
2. Solar collectors
3. Solar cookers
4. Sokar desalination
5. Solar cooling and heating
6. PVT and CPVT
7. Medium to high temperature solar thermal applications
8. Concentrating solar system and high temperature applications
9. Future scope

# Solar Energy



## Solar energy-general -1



### Background

- Global warming caused by $CO_2$ emission (primarily due to burning of fossil fuels),
- Increase in energy demand while the prices of oil & gas fluctuating,
- Increasing need for environmentally friendly (pollution free), renewable energy,
- Readily available, widespread energy source

### Challenges

- Low heat density (flux): max. 1,000 W/m$^2$ (0.1 W/cm$^2$) in most of the temperate regions on earth.
  [cf. *solar constant*: 1,368 W/m$^2$ when the earth is at its mean distance from the sun (extraterrestrial insolation)]
- Intermittent availability (only during daytime in clear days)
- Low economic viability relative to other energy sources (if not always) ☞

## Solar energy-general -2 Classification of solar energy

- Solar Energy
  - Application
    - Thermal
      - Water heating
      - Air/Space heating
      - Cooker
      - Dryer
      - Power generation
    - Photovoltaic
  - Type of Solar Collector
    - Stationary
      - Flat plate collector (FPSC)
      - Evacuated tube collector (ETSC)
      - Compound parabolic concentrator (CPC)
    - Concentrating
      - Linear Fresnel reflector (LFR)
      - Parabolic trough collector (PTC)
      - Parabolic dish reflector (PDR)
      - Heliostat field collector

From Herez et al., Renewable and Sustainable Energy Reviews 81(1) 2018, 421-432.





## Solar energy-general -3

- **Issues to be elaborated**:
  - Effect of design parameters of solar system (collectors, desalination sys., cookers, etc.) on thermal output,
  - Effect of different **heat pipe types/geometries** (e.g., conventional, PHP, LHP, CTPTS, micro heat pipes..),
  - Effects of different (new/alternative) **working fluids** in HPs,
  - Effects of combined heat pipes and **PCM** (as thermal energy storage material),
  - Effects of different **HTF** (heat transfer fluid) in indirect solar systems. ☞

♠ 'HP' in this material usually denotes 'heat pipe' unless otherwise explained.

# Solar Collectors





## Solar Collectors-1

Solar collectors can be categorized into three groups:

- **Flat plate** collectors (FPC or FPSC): 30-80℃
- **Evacuated tube** collector (ETC or ETSC): 50-120℃
- **Concentrating** collector: may produce heat above 300℃

♠ Heat pipe can be incorporated into each of the above categories.

✓ FPSCs are the most common type in use (esp. for domestic SWH).

✓ IEA (International Energy Agency report) reported that in 2010 more than 50% of total solar collectors installed globally were ETC.

✓ According to recent market scenario (as of 2018), 77.8% of newly installed solar collectors are ETC due to its relatively low cost for high efficiency.

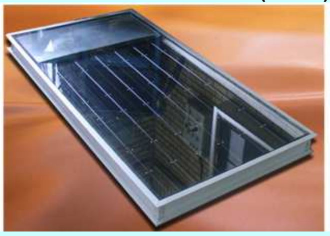
✓ In last 20 years, ETCs overtook the market of flat plate collectors due to the growth of inexpensive sputtering technology for producing twin glass evacuated tubes.

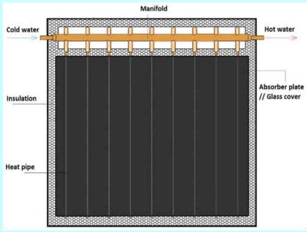
References:
- Allouhi et al., *Energy* 180 (2019).
- Chopra et al., *Applied Energy* 228(2018).
- Pandley and Chaurasiya, *Ren. Sus. Egy. Rev.* 67(2017).

# Solar Collectors-2

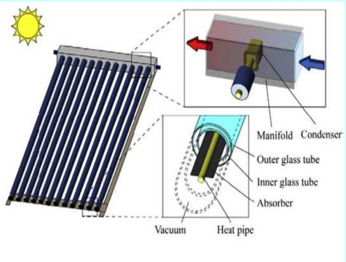
Boo, J.H.

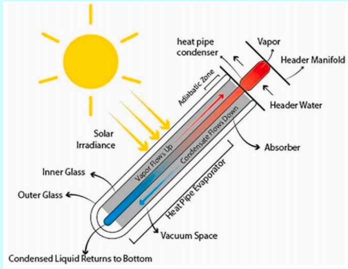
- **Flat Plate Solar Collector (FPSC)**






- **Evacuated Tube Solar Collector (ETSC)**



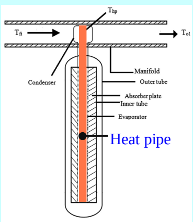


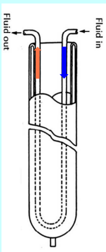

# Solar Collectors-3 Classification of ETSC

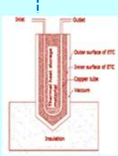
Boo, J.H.

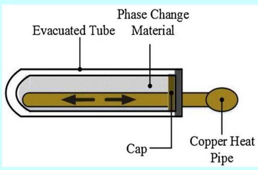
Evacuated Tube Solar Collector (ETSC)

- Adoption of Heat pipe
  - With Heat Pipe
  - Without Heat Pipe
- Adoption of Thermal Energy Storage (TES)
  - With TES
    - Latent Heat Storage
    - Sensible Heat Storage
  - Without TES






From Chopra et al. Applied Energy 228(2018).

## Solar Collectors-4 HP-SC



- **Solutions** that heat pipes brought to problems in conventional solar technologies:
  - Reduced hydraulic resistance (thus pumping power) of the heat transfer fluid (HTF) (by more than ½).
  - Reduced thermal energy loss to surroundings due to thermal diode action.
  - Prevented the freezing and backflow of HTF during night time.
  - Reduced possibility of leak, corrosion, and burst problems in piping.
  - Increased the reliability and life expectancy of the solar systems.
  - Enhanced collector efficiency esp. in medium temperature solar collectors. ($\eta_{col}$ of HP-ETSC: 60-80%, $\eta_{col}$ of HP-FPSC up to 68%)

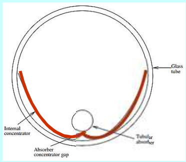
**References**:
- Senthil R et al., *Solar Energy* 227(2021),
- Khairnasov SM & Naumova AM, *Applied Solar Energy* 52(1) (2016).
- Rassamakin B et al., *Solar Energy* 94(2013).
- Riffat SB et al., *Applied Thermal Engineering* 25(2005).



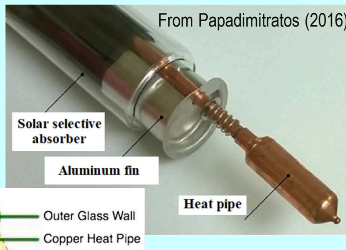
## Solar Collectors-5 HP-ETSC



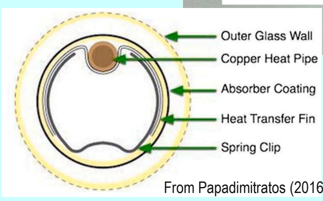
- **Reduction of heat loss and incorporation of PCM**
  - Nkwetta et al. (2013, *ATE* 60): The heat loss coefficients of HP augmented (w/ CPC) evacuated and non-evacuated type solar collectors were 36.01% and 35.17% less than direct flow-based evacuated and non-evacuated solar collectors.
  - Papadimitratos et al. [2016, *Solar Energy* 129] integrated PCMs within ETSC for solar water heaters (SWHs), in which heat pipe was immersed inside two distinct PCMs. Results showed efficiency improvement of 26% for the normal operation and 66% for the stagnation mode, compared with standard solar water heaters that lack PCMs.



From Nkwetta (2013)




From Papadimitratos (2016)




From Papadimitratos (2016)

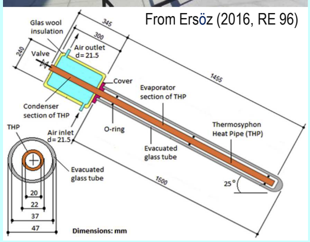
*ATE: Applied Thermal Engineering (A journal)

## Solar Collectors-6 HP-ETSC

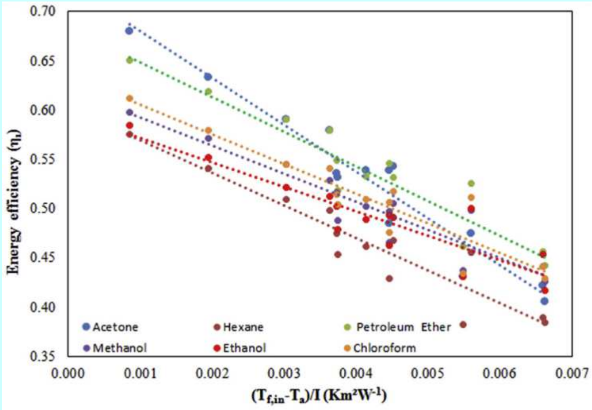


- **Effect of Working fluid (WF) of heat pipe**
  - **Ersöz** [2016, *Renewable Energy* 96] tested 6 WFs (acetone, hexane, methanol, ethanol, petroleum ether, and chloroform) in thermosiphon in ETSC for air heating. Acetone (air vel. 3 m/s or lower) and chloroform (4 m/s) showed best results, hexane had the lowest efficiency.

From Ersöz (2016, RE 96)



From Ersöz (2016, RE 96)



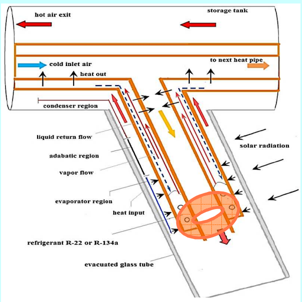

Energy efficiency when air velocity was 2 m/s. [From Ersöz (2016, RE 96)]



## Solar Collectors-7 HP-ETSC



- **Refrigerants as Working fluid of heat pipe**
  - **Esen and Esen** [2005, *Solar Energy* 79(5)] experimentally investigated two-phase closed thermosyphon solar water heater. Their results showed that HP charged with R-410A collected more solar heat compared to R-134a and R-407C.
  - **Kabeel** et al. [2017, *ECM** 138] used coaxial heat pipes constructed using concentric tubes in a twin glass ETSC for air heating. Annular space was charged with refrigerant (worked as HP), and air passed through a inner tube. The system was tested for R-22 and R-134a with FR 30 - 60% and at different tilt angles. Max. 67% increase in the thermal efficiency (compared to the one w/o HP) was observed. The efficiencies for the two refrigerants showed comparable results.




From Kabeel et al. (2017)

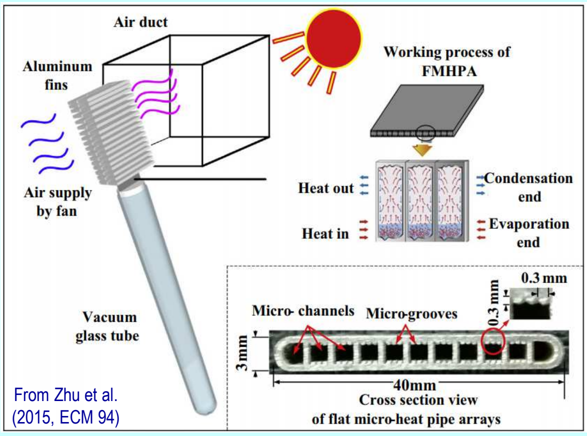
  - **Jayanthi** [2020, *Mat T Proc*** 26] found the avg. efficiency of HPSC with R-134a was 42.95%, which was 37.4% higher than that with distilled water (31.28%). and (relatively 37.4% higher), respectively.

*ECM: Energy Conversion and Management (A journal) **Mat T Proc: Materials Today: Proceedings (A journal)

## Solar Collectors-8 MHPA in ETSC-SAH



- **Micro Heat Pipe Array in solar collectors**
  - **Zhu** et al. (2015, *ECM** 94) conducted experiments on the solar air heater with flat MHPA. In summer, the thermal efficiency of the system reached 73% with a pressure drop of less than 25 Pa when the flow was below 201.6 CMH.



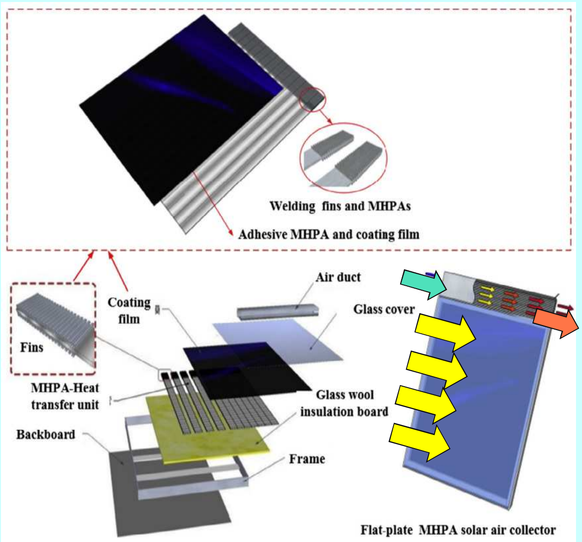

From Zhu et al. (2015, ECM 94)

*ECM: Energy Conversion and Management (A journal)



## Solar Collectors-9 MHPA in FPSC- SAH






Flat-plate solar air heater with MHPA (Zhu et al. 2017 *ATE* 118)

- **Zhu** et al. [2017, *ATE** 118] designed FP solar air collector with MHPA, of which the dimensions were 1750*80*3 mm and the WF was acetone (FR= 20%). The average efficiency increased around 69% at the mass flow rate of 290 CMH.
- **Wang** et al. [2019, *Energy* 177] studied on solar air collector with vacuum glass tube (ET). MHPA (2000*40*3 mm, acetone 20%). Efficiency $\eta_{col}$ = 82.7% with $\Delta p < 20$ Pa.

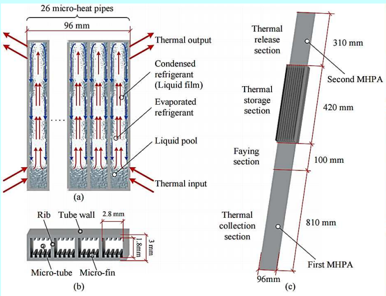
☞

*ATE: Applied Thermal Engineering (A journal)

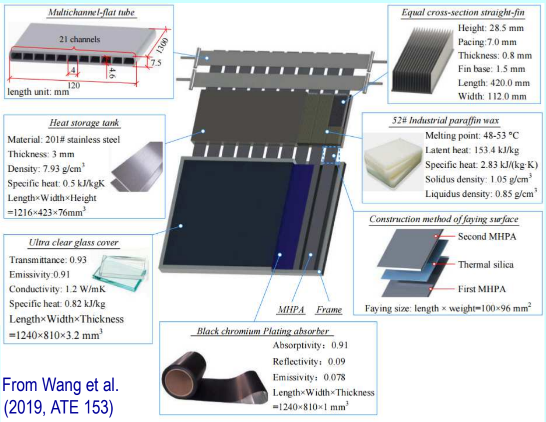
# Solar Collectors-10 Use of MHPA & PCM-SWH

Boo, J.H.

- **Wang** et al. [2019, *ATE* 153] tested *integrated collector–storage* solar water heater (ICSSWH) based on MHPA and PCM. Max. eff. reached 61.5% and the avg extraction power and avg outlet temp. reached 1323.3 W and 42.1°C, respectively.




From Wang et al. (2019, ATE 153)




From Wang et al. (2019, ATE 153)

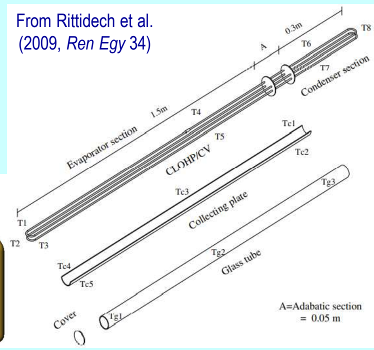


# Solar Collectors-11 Use of OHP(PHP)

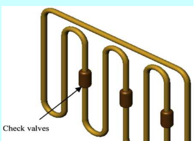
Boo, J.H.

- **Rittidech & Wannapakne** (2007, *ATE* 27) investigated a SC with closed-end oscillating heat pipe (*CLOHP*), which was made of 3 mm ID copper tubing and R-134A as working fluid. The collector efficiency of 62% was achieved.

From Rittidech et al. (2009, *Ren Egy* 34)



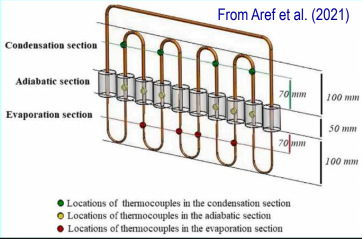

- **Rittidech** et al. (2009, *Renewable Energy* 34) used a CLOHP with check valve in ET solar collector and observed an *enhanced* efficiency of 76%.




From Rittidech et al. (2009)

- **Aref** et al. (2021, *Energy* 230) proposed and tested a CLOHP with a dual-diameter configuration for FPSC application. Max. efficiency of 72.4% was achieved corresponding to the conditions of 60% FR and 1030 W/m$^2$ direct normal irradiance (DNI).

From Aref et al. (2021)



## Solar Collectors-12 Review

Boo, J.H.

- **Thermal Energy Storage** (TES) [esp. **PCM**] enhanced overall performance of SCs (regardless of spec. types) primarily by **lengthening the operating time** and **preventing system overheat**. PCMs can be selected according to desired temperatures. (Refer to Naghavi et al. [2015, *ECM* 105] for a review of hybrid HP latent heat storage systems).

✓ PCMs usually have very low thermal conductivity: incorporation with **HP**s can enhance heat transfer thus reduce transient response time. In some cases, mixing with additive materials with high thermal conductivity may be necessary.

  - *M. S. Naghavi, K.S. Ong, M. Mehrali, I.A. Badruddin, H.S.C. Metselaar, A state-of-the-art review on hybrid heat pipe latent heat storage, Energy Conversion and Management 105 (2015) 1178-1204.*

- **Nanotechnology** is not treated in this review though many studies in recent years reported beneficial aspects of using various nanofluids as WF or HTF in HP and solar systems. (Refer to Hussein [2016, *RSER** 62] for a review). However, studies based on long-term operation results are desired to identify any possible degenerative effects.

  - *A. K. Hussein, Applications of nanotechnology to improve the performance of solar collectors – recent advances and overview, RSER*., 62 (2016), 767-792.*

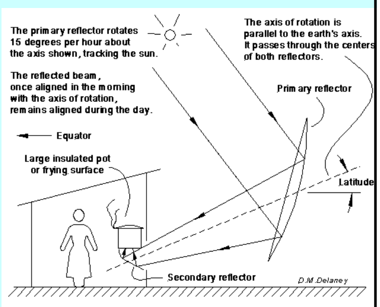
☞

**RSER*: Renewable and Sustainable Energy Reviews (A journal)



Boo, J.H.

# Solar Cookers



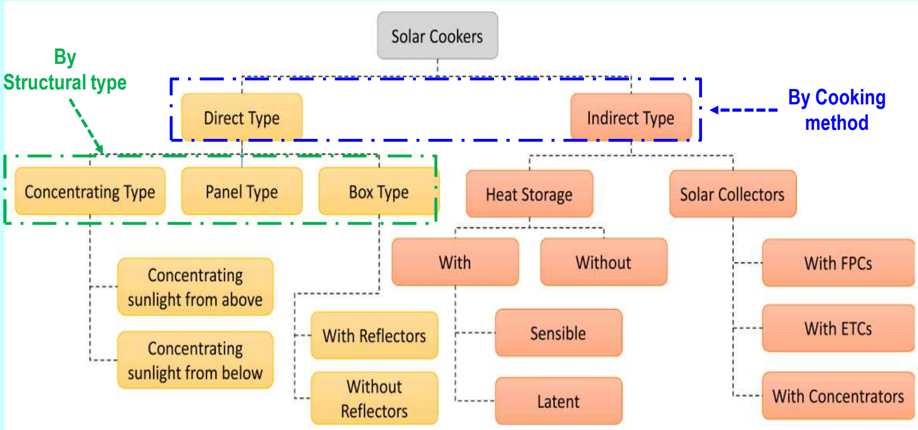

How a Scheffler reflector used for cooking keeps its focus on the cooking place as the sun moves.

Egypt's first ***Scheffler Community Kitchen*** at El Sherouk Farm near Alexandria.
(https://solarcooking.fandom.com/wiki/Scheffler_Community_Kitchen)

# Solar cookers -1 Classification

Boo, J.H.

* Recent review paper on R&D of (concentrating) solar cookers:
**Gorjian** et al. [2022, *Solar Energy* 245], A comprehensive study of research and development in concentrating solar cookers (CSCs): Design considerations, recent advancements, and economics



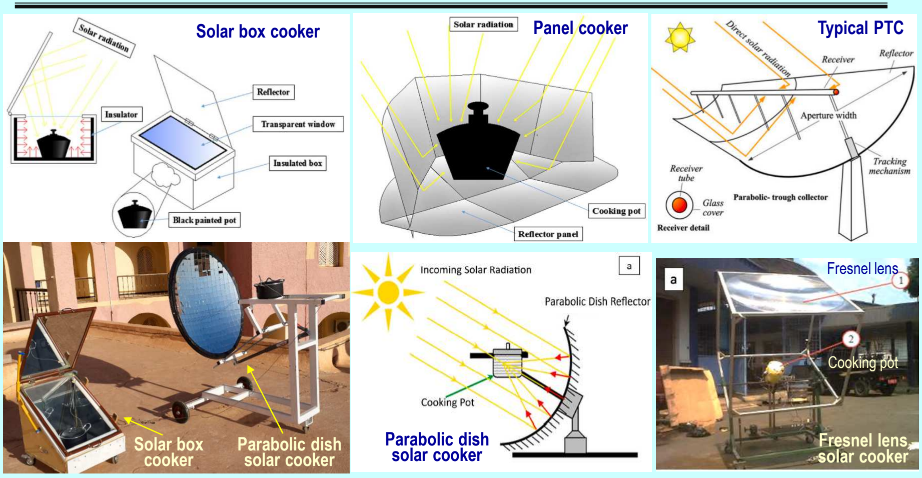

From Gorjian et al. [2022, Solar Energy 245]

☞



# Solar cookers -2 Various solar cookers

Boo, J.H.




♠ **Solar Cooker International (SCI):** one of the prominent non-governmental organizations worldwide keeping an eye on all emerging designs and over 350 non-governmental organizations from various locations in the world working for the dissemination of these useful appliances that play an important role in eco-friendly sustainable development.
https://www.solarcookers.org

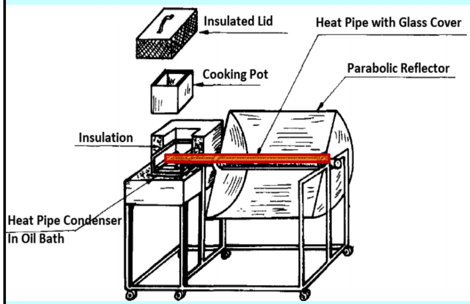
☞

# Solar cookers -3

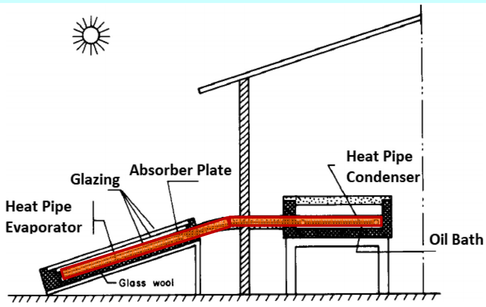
Heat pipes in solar cookers

Boo, J.H.

**Khalifa et al**. [1986, *Applied Energy 24(2)*] developed and tested two heat pipe solar cookers. The first cooler (Mecca-1) employed a parabolic trough collector (Aperture area Ap = 1 sqm.). The second cooker (Mecca-2) was a flat-plate heat-pipe cooker in which a single copper-ethanol heat pipe in each cooker absorbed the energy at the collector, and transported it to an insulated oven at the condenser end in the kitchen. It was found that the Mecca-2 cooker with triple glazing had a utilization efficiency of up to 19 % and could boil 1 L of water in 27 min for a solar insolation of 900 W/m$^2$.




Mecca-1 heat pipe solar cooker with PTC.




Mecca-2 heat pipe solar cooker with a FPSC.



# Solar cookers -4

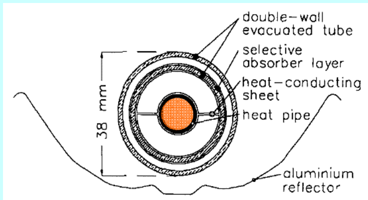
HP in solar cookers-2

Boo, J.H.

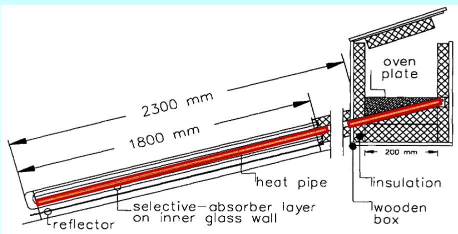
**Balzar et al**. [1996, *Solar Energy 58(1-3)*] tested solar cooking system which consisted of a collector ($A_p$ = 0.95 sqm., L = 1.8 m, tilt 15°, no tracking) with 6 vacuum-tubes mounted on AL concentrating reflector with integrated heat pipes connected to hot plate.

HPs: **copper-water** (as working fluid, **FR > 5%)** and had 75 axial grooves with 0.2 mm depth.

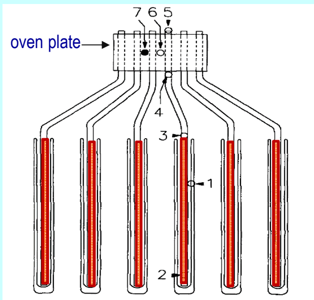
HPs are differently bent and lead directly to the oven unit via an insulated adiabatic section of about 0.5 m. On clear days in Marburg (latitude 51°), the stainless steel pot (9 L capacity and 2.3 kg mass) containing 5 L of edible oil reached maximum temperature of 252℃.




Sectional view of an ETC tube with integrated HP and heat conducting sheet (Balzar et al., 1996)




Side view of the solar cooker (not to scale)(Balzar et al., 1996)




Solar cooker (Balzar et al., 1996)

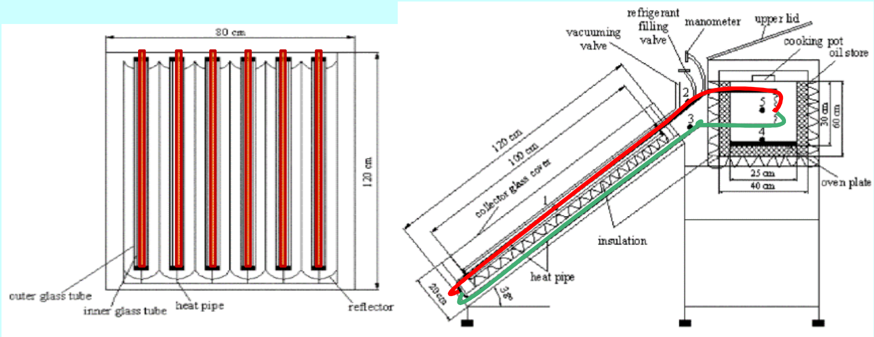
# Solar cookers -5

Refrigerants as HP WF in solar cooker



**Esen** [2004, *Solar Energy 76(6)*] fabricated and conducted experiments on indirect solar cooker with **HP-ETSC** and parabolic concentrating chrome-nickel reflectors, all enclosed in flat glazed box (Ap = 0.96 m2) (Fig. 8) and checked viability of **refrigerant (R-134a, R-407C, R-22) as HPs working fluid**. The condenser section of the coiled HP is immersed in HTF (9 L, Mobiltherm 605) and aluminum oven plate is mounted on it.

Time variation of temperature was monitored and achieved a temperature of 175℃ for 7 L edible oil. Among tested refrigerants, R-407C showed much shorter cooking time than others. This system cooked various foods in 27 to 70 min. They observed that the useful thermal power was much higher when the system is preheated.




(a) (b)





# Solar cookers -6

PCM in HP Solar cookers

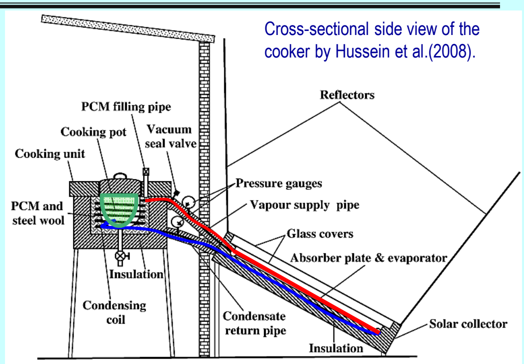


**Hussein et al**. [2008, *ECM** 49] designed and tested indirect solar cooker with a FPSC, **a closed thermosyphon (TS) loop**, and indoor cooking pots (3 L and 4 L cap.) surrounded by **PCM** (magnesium nitrate hexahydrate, $T_m$ = 89℃). Two plane reflectors enhanced the insolation by 24%.

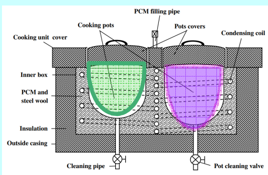
Evaporator section (in outdoor collector): 15 parallel copper tubes of 16 mm OD and 0.75 m length. (The tubes deformed to have elliptical cross sections of 22× 14 mm.)

Condenser section (in the indoor PCM cooking unit): copper tube of 9.5 mm OD and about 7 m length in the form of a helical coil. WF: water with filling ratio of 15% (based on total volume).

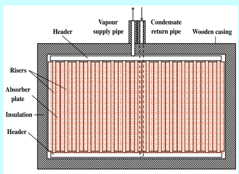
The solar cooker was tested in Giza, Egypt and demonstrated cooking different kinds of meals at noon, afternoon and evening times, while it can be used for heating or keeping meals hot at night and early morning.




Cross-sectional side view of the cooker by Hussein et al.(2008).



Indoor PCM cooking unit surrounded by HP condenser



Wickless HP evaporator in FPSC.

**ECM*: Energy Conversion and Management (A journal)

# Solar cookers -7

Future scope

## Summary

- Solar cooking is an environmentally benign and sustainable solution to replace or supplement traditional cooking methods (anywhere solar resource is available).
- Many disadvantages of solar collectors in indirect solar cooking system were able to be eliminated employing HP and PCM.
  - Low cooking speed/ Exposure to serious solar radiation, etc.
- By using proper reflector/concentrator with absorbing means (as in ETSC w/ CPC), cooking is possible even under low insolation, without tracking.

## Future Scope

- More appropriate HP designs of a solar collector are subject to development for enhanced performance of indirect solar cooking system.
- Selecting and optimizing (in meaningful respect, e.g. sizing, cooking time, cooking temp., economy) the quantity of PCM in thermal storage unit of a solar cooking system is desired based on their thermo-physical properties.
- Selection/development of proper/better HTF (heat transfer fluid) is desired to enhance cooking performance at higher temperature.
- Minimizing the heat losses from the cooking chamber and utilizing thermal storage will improve cooking efficiency.

☞





# Solar Desalination

Boo, J.H.

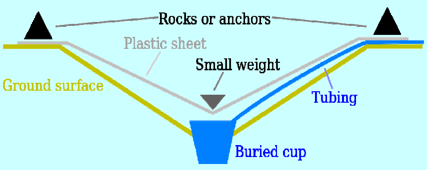
## Desalination -1 General

Desalination: a method to convert brackish water to fresh water.

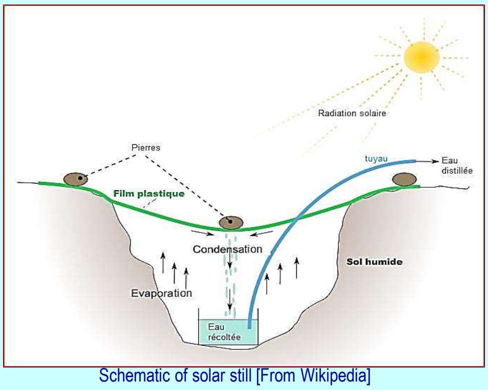
Desalination can be done by using economical and ecofriendly renewable energy resources.

direct system: solar still,

Indirect system: those using solar collectors based on temperature requirement in desalination processes




Schematic of solar still [From Wikipedia]




Schematic of solar still [From Wikipedia]



Boo, J.H.

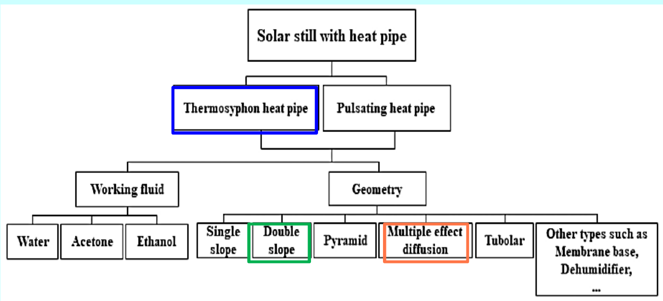
## Desalination -2 HP systems

**Shoeibi** et al. [2022, *Desalination* 540], A comprehensive review on performance improvement of solar desalination with applications of heat pipes,

The lowest CPL (Cost per liter) was achieved in solar desalination w/ HP-ETSC (HPET), which was about 0.0092 $/L.

The highest improve in productivity was in solar desalination w/ THP*-ETSC and external condenser, which was 2.13 times more than conventional ones.

*THP: Thermosyphon HP



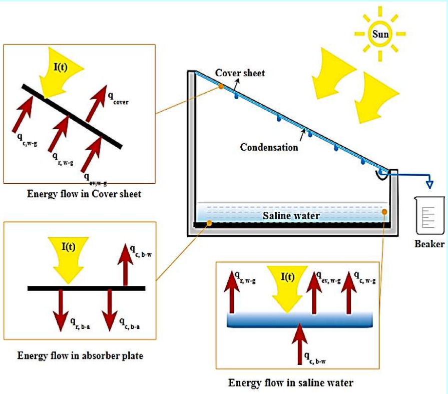

Classification of solar desalination using heat pipes. [From Shoeibi et al., 2022, Desalination 540]

**Ref.**: S. Shoeibi, S.A.A. Mirjalily, H. Kargarsharifabad, M. Khiadani, H. Panchal, A comprehensive review on performance improvement of solar desalination with applications of heat pipes, Desalination 540 (2022) 115983.

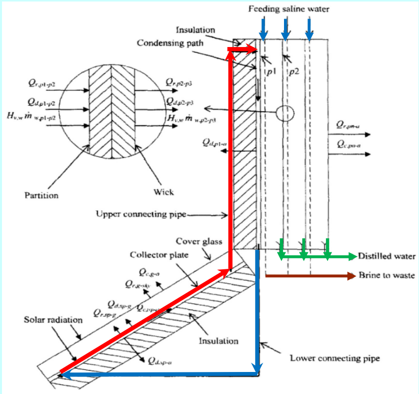
# Desalination -3

Principles

Boo, J.H.




Energy flow in the various components of a solar desalination system. [From Shoeibi, 2022]




Multiple-effect diffusion of solar desalination using heat pipe. [From Tanaka, 2004]

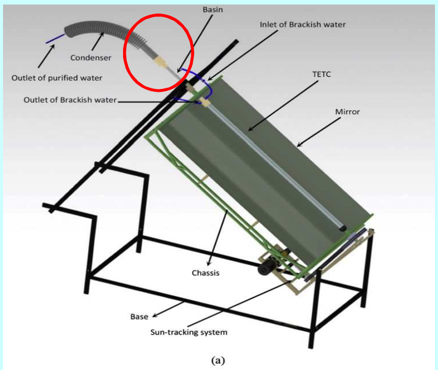


# Desalination -4

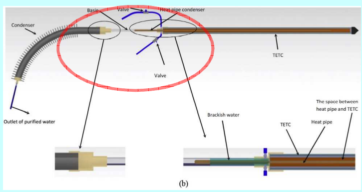
Single slope type

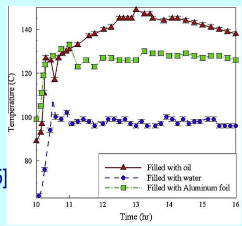
Boo, J.H.

**Mosleh** et al. [2015, *ECM* 99] used ethanol **HP** in **ETSC** located at the focus of **PTC** ($A_p$* = 1.8 $m^2$, CR = 6.77) and investigated production rate and efficiency. With AL conducting sheet (foil) inserts within a space btw HP and ECT, output and efficiency found as 0.27 kg/($m^2$-h), 22.1%. With oil (no details) btw HP and ECT, output and efficiency as 0.93 kg/($m^2$-h), 65.2%.

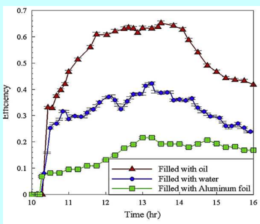



TETC (twin-glass evacuated tube collector)[Mosleh, 2015]




Temperature



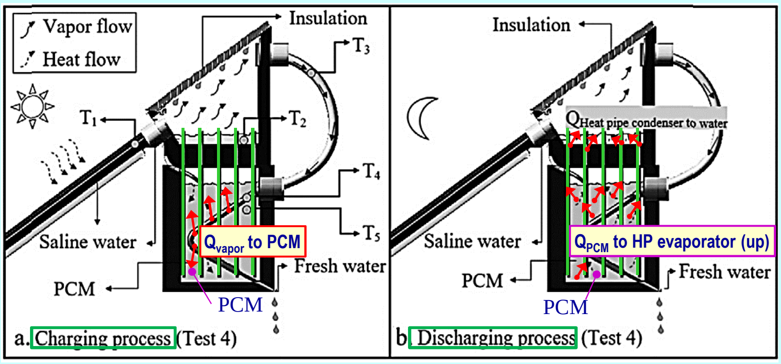

Efficiency

*$A_p$ : collector aperture area

Boo, J.H.

# Desalination -5 With PCM

**Faegh and Shafii** [2017, *Desalination* 409] devised a solar still with ETSC, PCM and HP. The external condenser was filled with PCM. Wasted latent heat of vapor condensation during the daytime was stored in PCM (Paraffin) and used during the evening time for continued desalination. The system yield increased by 86% without affecting the daytime yield. The maximum yield and daily efficiency obtained are 6.555 kg/m$^2$-day and 50%, respectively.
HP: copper-acetone (FR 15%), OD 10 mm, L= 0.4 m (Le= 0.3 m, Lc= 0.02 m).




Schematic of the processes in the system with external condenser containing PCM and HP (From Faegh and Shafii, 2017]

M. Faegh, M.B. Shafii, Experimental investigation of a solar still equipped with an external heat storage system using phase change materials and heat pipes, Desalination 409 (2017) 128–135,

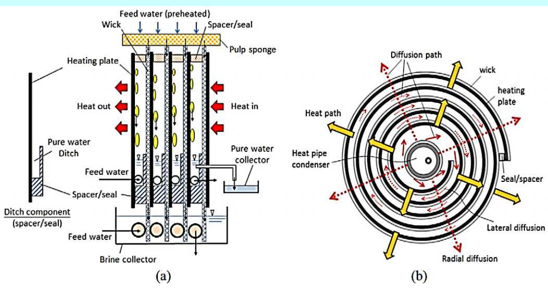
☞ 33



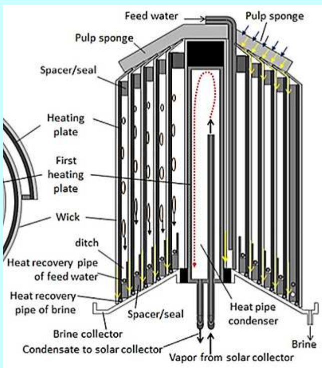
Boo, J.H.

# Desalination -6 Multiple effect diffusion-1

**Huang** et al. [2015, *Desalination* 362] developed a solar still with spiral-shape multiple-effect diffusion unit (MDU or MED) which could produce 40.6 kg/(m$^2$-day) of pure water (based on the absorber area), when 14 MDUs coupled with ETSC ($A_p$ = 1.08 m$^2$) were used. The performance was much higher than the published results. The measured solar distillation efficiency** is 2.0–3.5. The improved production rate was due to spiral still cell of MDU enhancing diffusion process by facilitating lateral as well as radial diffusion.
HP (Loop TS): Evaporator (Vapor tube)- Copper tube OD 10mm, Condenser- OD 80 mm, H= 0.7 m (Effective heating height 0.68 m)




Design concept of MDU (MED) [From Huang et al. 2015]

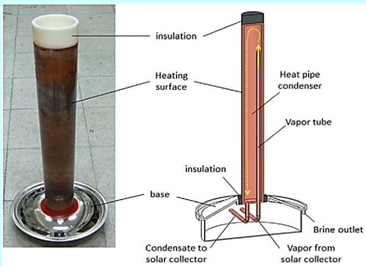



Schematic of MDU prototype [From Huang et al. 2015]

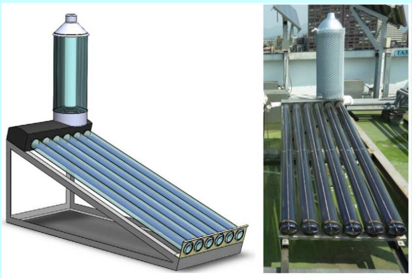
** solar distillation efficiency (usu. Denoted by 'R") is defined as
R = $h_{fg}$*M/$H_T$, where M is yield rate (kg/h-m2 or kg/day-m2), $H_T$ is daily total insolation. Depending on how the unit area (glass cover, collector, evaporator, etc) is specified, M and R have corresponding suffices.

☞ 34

## Desalination -7 Multiple effect diffusion-2




Condenser section of HP in sMDU [From Huang et al. 2015]



Prototype of MEDS-sp [From Huang et al. 2015]

Selected references for Multiple-Effect Diffusion solar still:


- B.J. Huang, T.L. Chong, P.H. Wu, H.Y. Dai, Y.C. Kao, Spiral multiple-effect diffusion solar still coupled with vacuum-tube collector and heat pipe, Desalination 362 (2015) 74–83.
- T.L. Chong, B.J. Huang, P.H. Wu, Y.C. Kao, Multiple-effect diffusion solar still coupled with a vacuum-tube collector and heat pipe, Desalination 347 (2014) 66-76.
- H. Tanaka, Y. Nakatake, M. Tanaka, Indoor experiments of the vertical multiple-effect diffusion-type solar still coupled with a heat-pipe solar collector, Desalination 177 (2005) 291-302.
- H. Tanaka, Y. Nakatake, A vertical multiple-effect diffusion-type solar still coupled with a heat-pipe solar collector, Desalination 160 (2004) 195–205.
- Tanaka, H., Thermal distillation system utilizing biomass energy burned in stove by means of heat pipe, Alexandria Engineering J. 55(3) 2016, 2203-2208.






## Desalination -8 Summary/Review

- The major issue of solar desalination is the low water production rate, compared to other intensive desalination process.
- Direct solar still has its own advantages:
  - Eco friendly
  - Direct desalination based on simple principle and structure
  - However, the productivity (yield rate) is the lowest among various solar desalination methods.
- For higher productivity of fresh water, **indirect** methods are generally preferred. However, the productivity should be improved considerably.
  - For efficient heat supply with high temperature, most of recent R&D employ ETSC. HP proved to be beneficial for performance enhancement.
  - Use of solar concentrator may supply even higher heat flux to the desalination process. Cylindrical geometry of ETSC can easily adopt PTC and CPC concentrators.
  - Selection of proper PCM (to prolong the operating time) and HTF (thermal transport) need to be carefully reviewed.
  - Desalination system performance can be evaluated by yield rate and efficiency.

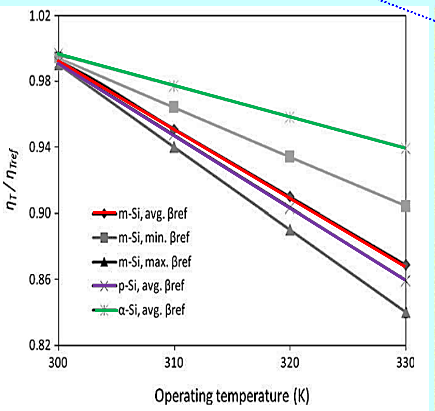
# PVT systems





## PVT systems-1 Background

- **Skoplaki & Palyvos** [*Solar Energy 83(2009)*]: On the basis of data in Table 1 for $T_{ref}$ = 25℃, avg. $\eta_{ref}$ = 0.12 and avg. $\beta_{ref}$ = 0.0045℃$^{-1}$. Fig. shows the effect of the temp. coeff. upon the efficiency of various silicon-based PV module types.




The ratio [ $\eta_T / \eta_{Tref}$ ] as predicted by the Evans-Evans–Floschuetz eff. correlation for typical silicon-based PV module types. [From Skoplaki & Palyvos, 2009]

From Skoplaki and Palyvos (2009).

Table 1
Evans-Florschuetz PV efficiency correlation coefficients $\eta_T = \eta_{T_{ref}}[1 - \beta_{ref}(T - T_{ref})]$.

| $T_{ref}$ (°C) | $\eta_{T_{ref}}$ | $\beta_{ref}$ (°C$^{-1}$) | Comments | References |
|---|---|---|---|---|
| 25 | 0.15 | 0.0041 | Mono-Si | Evans and Florschuetz (1977) |
| 28 | 0.117 (average) (0.104–0.124) | 0.0038 (average) (0.0032–0.0046) | Average of Sandia and commercial cells | OTA (1978) |
| 25 | 0.11 | 0.003 | Mono-Si | Truncellito and Sattolo (1979) |
| 25 | 0.13 | 0.0041 | PV/T system | Mertens (1979) |
| | | 0.005 | | Barra and Coiante (1993) |
| 20 | 0.10 | 0.004 | PV/T system | Prakash (1994) |
| 25 | 0.10 | 0.0041 | PV/T system | Garg and Agarwal (1995) |
| | | | | Agarwal and Garg (1994) |
| | | | | Garg et al. (1994) |
| 20 | 0.125 | 0.004 | PV/T system | Hegazy (2000) |
| 25 | | 0.0026 | a-Si | Yamawaki et al. (2001) |
| 25 | 0.13 | 0.004 | Mono-Si | RETScreen (2001) |
| | 0.11 | 0.004 | Poly-Si | |
| | 0.05 | 0.0011 | a-Si | |
| 25 | 0.178 | 0.00375 | PV/T system | Nagano et al. (2003) |
| 25 | | 0.005 | Mono-Si | Tobias et al. (2003) |
| 25 | 0.12 | 0.0045 | Mono-Si | Chow (2003) |
| 25 | 0.097 | 0.0045 | PV/T system | Zondag et al. (2003) |
| 25 | | 0.0045 | PV/T system | Radziemska (2003) |
| 25 | 0.0968 | 0.0045 | | Bakker et al. (2005) |
| | | 0.005 | UTC/PV system | Naveed et al. (2006) |
| 25 | 0.09 | 0.0045 | PV/T system | Tiwari and Sodha (2006a) |
| 25 | 0.12 | 0.0045 | PV/T system | Tiwari and Sodha (2006b) |
| 25 | | 0.0045 c-Si 0.0020 a-Si | PV/T system | Zondag (2007) |
| 25 | 0.12 | 0.0045 | PV/T system | Tiwari and Sodha (2007) |
| 25 | 0.12 | 0.0045 | PV/T system | Assoa et al. (2007) |
| 25 | 0.127 | 0.0063 | PV/T system | Tonui and Tripanagnostopoulos (2007a) |
| 25 | 0.127 unglazed 0.117 glazed | 0.006 | PV/T system | Tonui and Tripanagnostopoulos (2007b) |
| 25 | | 0.0054 | PV/T system | Othman et al. (2007) |

*Notes:*
- At $T_{ref}$ = 25 °C, average $\eta_{ref} \approx 0.12$ and average $\beta_{ref} \approx 0.0045$ °C$^{-1}$.
- The same correlation has been adopted in Hart and Raghuraman (1982), Cox and Raghuraman (1985), Sharan and Kandpal (1987), and Sharan et al. (1987), although no numerical values are given for the parameters.

# PVT systems-2 General issues

Boo, J.H.

◆Objective: To enhance electrical efficiency of PV cells (by cooling) while utilizing the wasted thermal energy simultaneously

◆A significant amount of R&D work on the photovoltaic/thermal (PVT or PV/T) technology has been done since the 1970s [*Chow, Applied Energy 87(2010)*].

◆Options in PVT integration

- Collector medium: Air, water or evaporative
- Collector type: flat plate or concentrator
- Glazing: glazed (single, double) or unglazed panels
- Driving of HTF: natural or forced flow
- Stand-alone or building integrated
- Solar cells: monocrystalline/ polycrystalline/ amorphous silicon (m-Si/ p-Si/ a-Si) or thin-film

◆Design decision factors:

- Collector type
- Thermal-to-electric yield ratio
- Solar fraction for optimizing the overall benefits

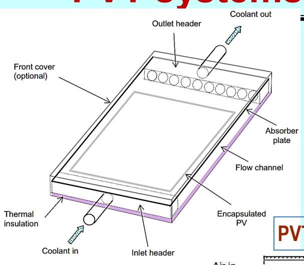
◆To incorporate HP into PVT, the operating conditions (e.g. HTF and/or air flow rate) and system design parameters associated with HP (pitch, gap, spacing, covering factor, etc) should be carefully reflected.

☞



# PVT systems-3 Common layouts

Boo, J.H.

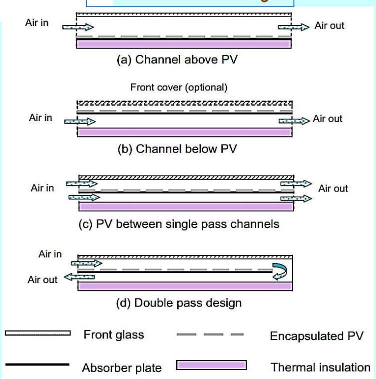



❖ Conventional cooling method (air/water) in PVT had difficulties in

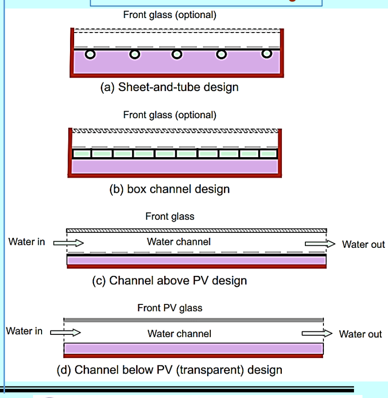
- achieving uniform temp. distribution across the panel
- integration in roof installations
- using water in cold regions (due to freezing)

❖ Heat pipes proved to be solutions to many challenges in PVT systems.

PVT/Air collector designs




PVT/Water collector designs




[From Chow, Applied *Energy* 87(2010)].

## PVT systems-4

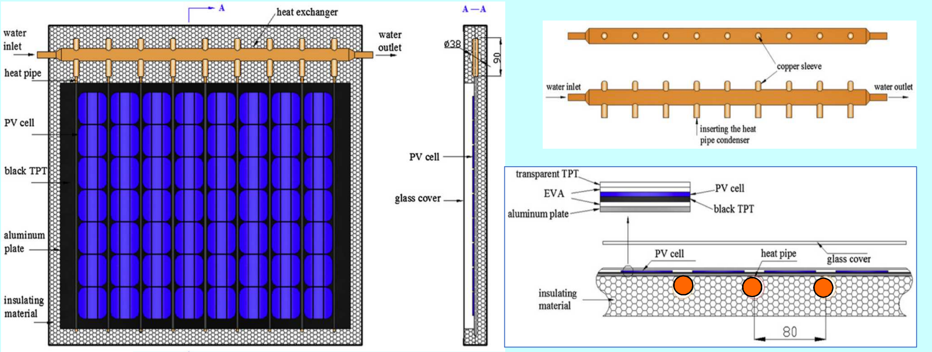
PVT system w/ HPs

Boo, J.H.

- The focus of the research was to operate the PV panels at low temperatures (e.g. ≤ 35℃), cooling it with a HP sys and using the excess water in different app.
- The design types: mainly cylindrical HP and flat HP.

**Gang et al.** [*Energy 37(2012)*] developed a flat plate HP-PV/T panel. 9 HPs joined together at the back of AL plate, using water as working fluid. HP: copper-water combination, axial grooves inside. Evapr: OD 8 mm, Le= 1.3 m, Condr: OD 24 mm, Lc= 90 mm. Spacing btw HPs: apprx 80 mm.

** Similar study found in Solar Energy 85(2011).*



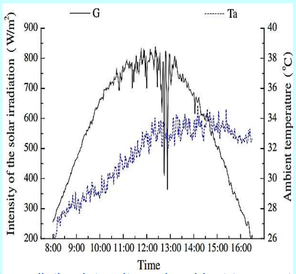

From Gang P, Huide F, Huijuan Z, Jie J. Performance study and parametric analysis of a novel heat pipe PV/T system, *Energy* 37(2012).



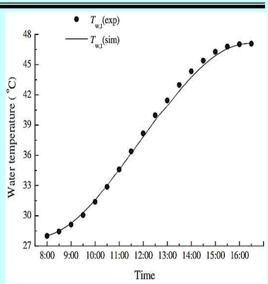
## PVT systems-5

Gang et al. [*Energy 37(2012)*]

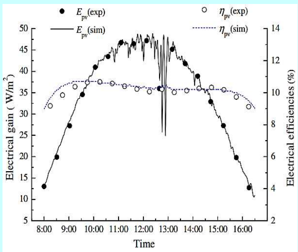
Boo, J.H.



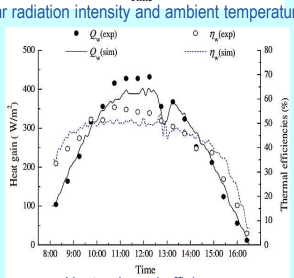

Solar radiation intensity and ambient temperature.




Temperature of water in the storage tank.




Electrical gain and efficiency




Heat gain and efficiency

From Gang P, Huide F, Huijuan Z, Jie J. Performance study and parametric analysis of a novel heat pipe PV/T system, *Energy* 37(2012)

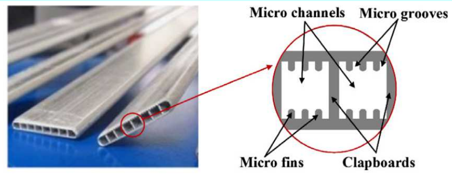
# PVT systems-6

## PVT system w/ MHPA

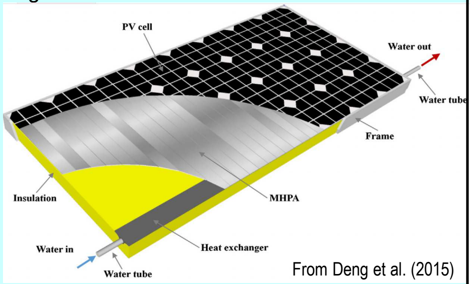
*Boo, J.H.*

**Deng et al.** [*ECM* 106(2015)*]: PVT system with a micro-heat-pipe array (MHPA).

- A flat AL strip (800*60*3 mm) consisted of multiple parallel micro HPs which operate independently. Each HP (WF: acetone, FR= 20%) had many microgrooves for extended surface area to enhance the heat transfer performance.
- Test results (for 4 typical days in different seasons): avg. electrical effs were 11.92-14.65%; avg. thermal effs were 17.24-33.07%; and the avg. total effs were 31.89-45.38%.

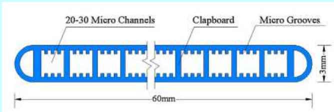



From Deng et al. (2015)




From Deng et al. (2015)

- Other references on PVT studies with MHPA:
  Hou L, Quan Z, Zhao Y, Wang L, Wang G. An experimental and simulative study on a novel photovoltaic-thermal collector with micro heat pipe array (MHPA-PV/T). *Energy Build* 2016;124:60-9.




MHPA in Hou et al. [2016, Energy and Buildings 124]

**ECM*: Energy Conversion and Management (A Journal)

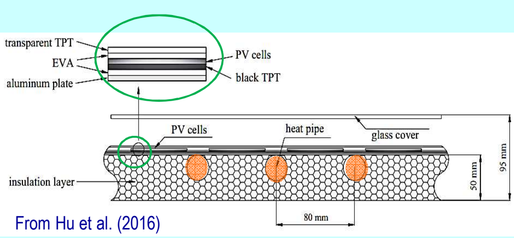


# PVT systems-7

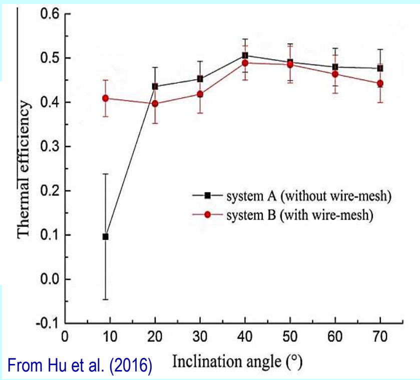
## HP inclination

*Boo, J.H.*

**Hu et al.** [*ATE* 106(2016)*] experimentally investigated the effect of inclination angles on wicked (wire-mesh) and wickless HPs for a PV/T system with monocrystalline silicon cells. The thermal performance of wickless HPs was sensitive at lower inclination angles, while both types of heat pipes exhibited optimum performance 40° inclination. The wickless HP PV/T system was recommended at latitudes higher than 20°, whereas the wicked HP was suggested at latitudes lower than 20°.




From Hu et al. (2016)



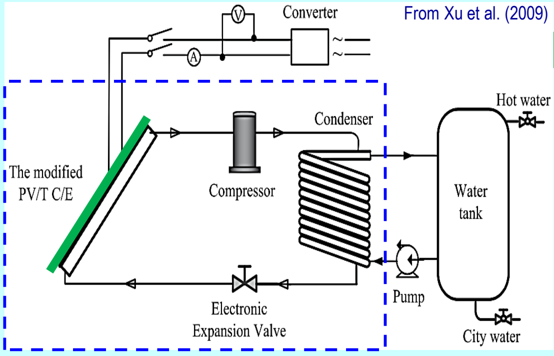

From Hu et al. (2016)

**ATE*: Applied Thermal Engineering (A Journal)

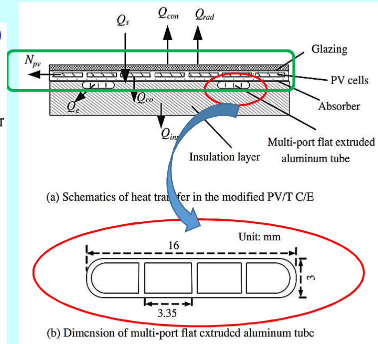
## PVT systems-8 PVT-heat pump

- <u>**Xu** et al. [*2009, Solar Energy 83*] used multi-port flat extruded aluminum tubes</u> in the modified C/E (collector/evaporator), which resulted in a better performance. The COP and thermal efficiency were enhanced by 7% and 6%, respectively, compared to conventional C/E.

From Xu et al. (2009)




Heat pump cycle




Detail configuration and heat transfer process of the modified PVT C/E (From Xu et al. 2009)

Reference: Xu G, Deng S, Zhang X, Yang L, Zhang Y. Simulation of a PV/T heat pump system having a modified collector/evaporator, Solar Energy 83(2009).





## PVT systems-9 Reviews

- According to the literature, the followings can be stated on **HP-PVT** performance.
  - The performance of the **HP-PVT** is influenced by different factors such as
    - <u>inlet temperature</u> and <u>mass flow rate</u> of the cooling fluid,
    - PV cell <u>covering factor</u>* (*ratio of the cell area and total area)
    - <u>spacing</u> btw HPs, <u>gap</u> btw PV cell and HP.
    - <u>inclination</u> of the HPs.
  - By increasing the <u>flow rate of the cooling fluid</u>, the efficiency and the energy gain of the PV/T panel are enhanced.
  - The increase of the <u>covering factor</u> results in higher electrical gain and enhanced total efficiency, while the thermal efficiency of the system decreases.
  - The thermal efficiency, electrical efficiency and exergy efficiency varied between the following ranges: $\eta_{th}$ = 41.9 to 63.6%, $\eta_e$ = 9.4 to 15.1%, and $\varepsilon_{PVT}$ = 6.8% to 10.3%.
  - PV efficiency ($\eta_e$) could increase by 15 - 30% compared to the sole PVs, if its surface temperature is controlled to around 40℃ [*Zhang et al. RSER* 16(2012), Jouhara et al. Energy 108(2016)*].
- Combination of **PCM with HP** in PVT systems is recommended that may further enhance the performance (with a prolonged operating time).
  - Refer to <u>*Carmona et al. [Renewable Energy 172(2021)]*</u> for supporting experimental results on PVT-PCM (w/o HP): e.g. a 7% increase in daily electrical efficiency.

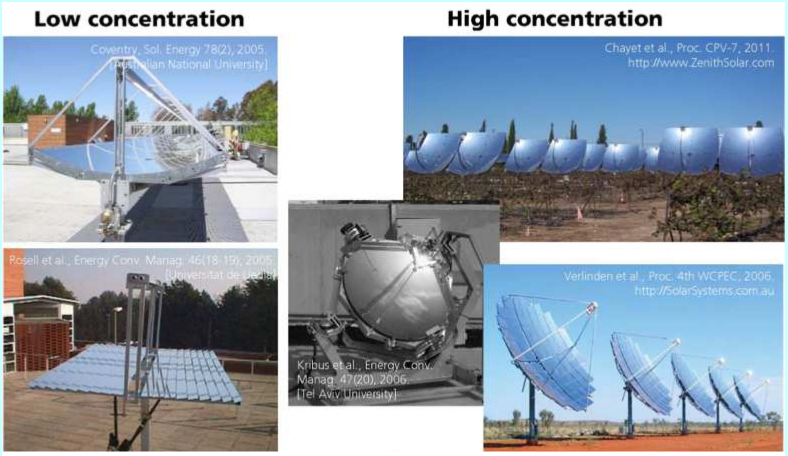
☞

**RSER*: Renewable and Sustainable Energy Reviews (A Journal)

## PVT systems-10 CPVT-1

Boo, J.H.

CPVT requires CPV, concentrating device, and thermal energy utilization method.




From ISES Hybrid CPVT Webinar material (2014.3)

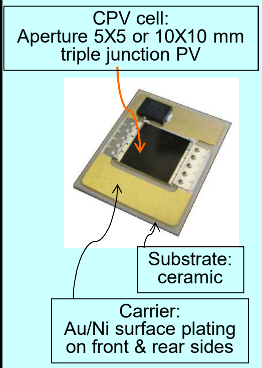
Direct utilization: Domestic water heating (40 - 80℃), Industrial process heating (40 - 200℃).
Cogeneration (Polygeneration): Solar cooling & A/C (50 -175℃), Solar desalination (60 - 110℃).



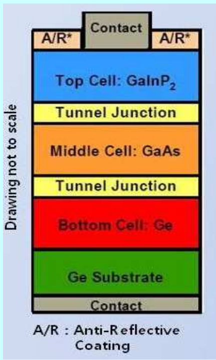
## PVT systems-11 CPVT-2

Boo, J.H.

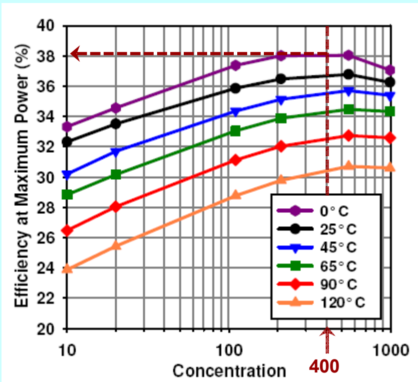
Typical CPV cell




♠ Specs. may differ by manufacturers/models.




Multi-junction (MJ) PV




CPV eff. vs. CR and cell temperature (example)

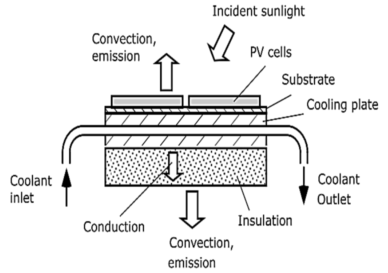
Max. cell operating temp. (long term)~120℃

- As of 2014, the best lab cell efficiency for concentrator III-V MJ-cells has improved to 46% (4-junctions) at research-scale production levels.
- The rate of annual CPV installations peaked in 2012 and has fallen to near zero since 2018 with the faster price drop in crystalline silicon photovoltaics.
- Still, R&Ds on CPV are ongoing in USA (50% by mid-2020s), Europe, Australia etc. for higher cell eff.

## PVT systems-12 CPVT-3

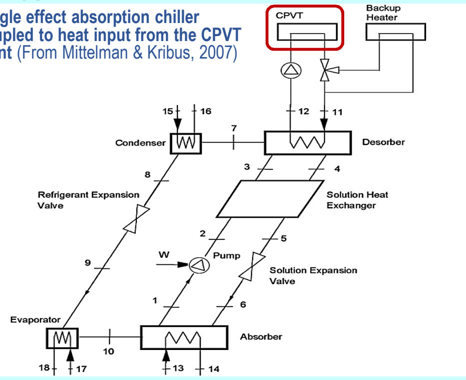
Boo, J.H.

- CPV (Concentrating photovoltaic) may operate at temperatures above 100℃, and the thermal energy can drive processes such as refrigeration, desalination and steam production. Electrical efficiency of CPV cell is well above 40% nowadays.
- **CPVT** (Concentrating photovoltaic-thermal) systems were proposed and theoretically reviewed in a few studies. [*Mittelman & Kribus, ECM* 48 (2007); Mittelman et al., Solar Energy 83(8) (2009)*] **← No HP adoption**
- Experimental studies on a prototype or actual CPVT systems are hardly found in literature. However, **CPVT is a potential application area of HPs.**




Thermal model of the PV module includes transfer to the coolant and heat losses from the front and back surfaces (From Mittelman & Kribus, 2007, *ECM* 48)

**Single effect absorption chiller coupled to heat input from the CPVT plant** (From Mittelman & Kribus, 2007)



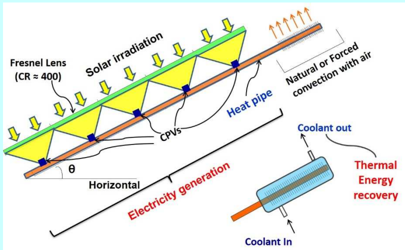

**ECM*: Energy Conversion and Management (A Journal)



## PVT systems-13 CPVT: Case study

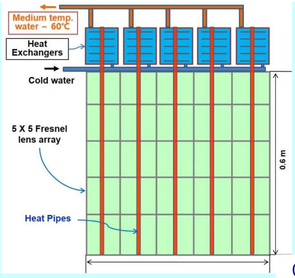
Boo, J.H.

CPVT-HP with Fresnel lens [Boo, 2013, HPST]




Concept of CPVT-HP using Fresnel lens (Boo, 2013)

Photograph of CPVT-HP using Fresnel lens (Boo, 2013)




Under 1 SUN (1000 W/m$^2$), 0.6 X 0.6 m area receives max. 360 W from the sun.

The system can generate
1) 108 W electricity (30%) and
2) 180 W thermal energy (50%) at the same time.

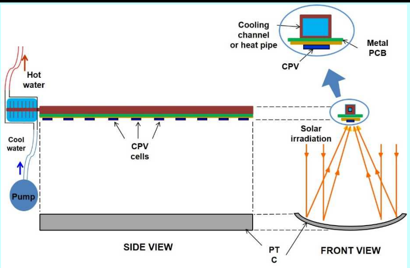
Combined efficiency
(108+180)/360 = 80%

Configuration of CPVT-HP w/ Fresnel lens (Boo, 2013)

# PVT systems-14

## CPVT: Case study

Boo, J.H.




Increased CR up to 4 times (400) using secondary reflector (Boo, 2013)

**CPVT system with PTC & LFR**

Under 1 SUN (1000 W/m$^2$),
1 X 1 m area receives
max. 1000 W from the sun.
The system can generate
1) 280 W electricity and
2) 470 W thermal energy (with high temp)
3) Combined efficiency
(280+470)/1000 = 75%

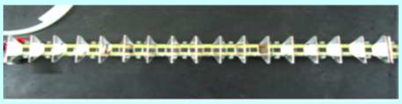
*21st IHPC and 15th IHPS*

KOREA AEROSPACE UNIVERSITY

# PVT systems-15

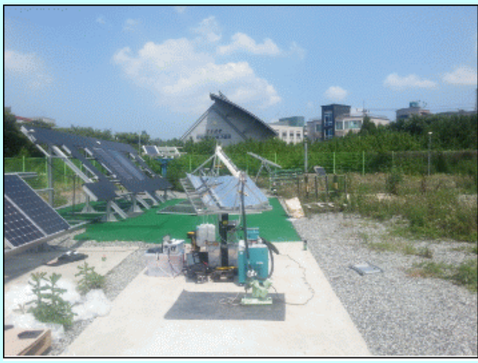
## CPVT: Case study

Boo, J.H.



CPV module with secondary reflectors
KAU-CPV300LFR

**Performance test by a 3rd party- TÜV Rheinland Korea**



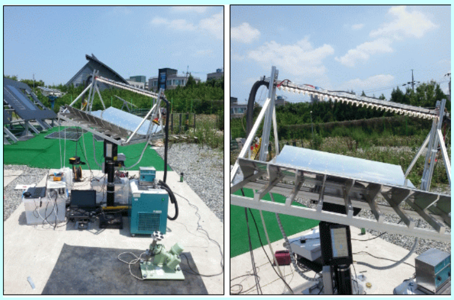

*21st IHPC and 15th IHPS*

KOREA AEROSPACE UNIVERSITY

Boo, J.H.

# PVT systems-16

## CPVT: Case study



KAU-CPV300LFR: 300X Concentration using PTC(LFR)

KAU-FLCPV5-L / –HP: Fresnel lens, CR~500

21st IHPC and 15th IHPS

KOREA AEROSPACE UNIVERSITY

Boo, J.H.

# PVT systems-17

## CPVT: Case study

9 / 22

Test report no.: 13014152 001

TÜVRheinland® Precisely Right.

5. KAU-CPV400LFR

| 유량 (cc/min) | 직달일사 조사율 (W/m²) | 전 조사율 (W/m²) | 전압 (V) | 전류 (A) | 모듈 전기출력 (W) | 집광기 직달일사 조사량 (W) | 모듈 전기 변환효율(%) (직달일사) | 냉각수 입구온도 (℃) | 냉각수 출구온도 (℃) | 열 회수 열량 (W) | 열 회수율 (%) | 복합 효율 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 300 | 625.8 | 1017.0 | 28.3 | 3.4 | 95.4 | 491.8 | 19.4 | 21.4 | 32.0 | 222.2 | 45.2 | 64.6 |
| 300 | 616.7 | 1013.0 | 28.4 | 3.4 | 95.1 | 484.6 | 19.6 | 21.4 | 32.1 | 223.6 | 46.1 | 65.8 |
| 300 | 595.0 | 977.0 | 28.3 | 3.2 | 89.8 | 467.5 | 19.2 | 21.3 | 32.1 | 224.2 | 48.0 | 67.2 |
| 200 | 614.1 | 1018.0 | 28.2 | 3.3 | 93.5 | 482.5 | 19.4 | 22.0 | 38.7 | 232.3 | 48.1 | 67.5 |
| 200 | 623.2 | 1010.0 | 28.2 | 3.4 | 96.2 | 489.7 | 19.6 | 21.9 | 38.6 | 232.3 | 47.4 | 67.1 |
| 200 | 617.4 | 1003.0 | 28.2 | 3.3 | 94.4 | 485.2 | 19.5 | 21.9 | 38.5 | 230.3 | 47.5 | 66.9 |
| 100 | 614.9 | 1003.0 | 27.8 | 3.3 | 91.7 | 483.2 | 19.0 | 23.3 | 58.1 | 241.9 | 50.1 | 69.0 |
| 100 | 609.5 | 998.0 | 27.8 | 3.3 | 92.1 | 479.0 | 19.2 | 23.3 | 58.3 | 243.5 | 50.8 | 70.1 |
| 100 | 605.1 | 992.0 | 27.8 | 3.3 | 90.6 | 475.5 | 19.1 | 23.3 | 58.2 | 242.6 | 51.0 | 70.1 |

Electrical efficiency

Thermal efficiency

Summary Test results

| Sample # | Remarks / constructional characteristics | DNI [W/m²] | 전기변환효율 (%) | 열회수율 (%) | 복합효율 (%) |
|---|---|---|---|---|---|
| 1 | KAU-FLCPV5-L (액체냉각식) | 733.6 | 31.2 | 64.7 | 95.5 |
| 2 | KAU-FLCPV5-HP (히트파이프 냉각식) | 737.4 | 29.1 | 54.8 | 83.8 |
| 3 | KAU-CPV200LFR (CPV-LFR, CR200) | 585.8 | 19 | 58.4 | 77.4 |
| 4 | KAU-CPV300LFR (CPV-LFR, CR300) | 679.6 | 22.4 | 53.9 | 76.4 |
| 5 | KAU-CPV400LFR (CPV-LFR, CR400) | 613.5 | 19.3 | 48.2 | 67.6 |

HP-CPVT

- Electrical efficiency ranged 19 to 31.2%,
- Thermal efficiency ranged 48.2 to 64.7%.
- $\eta_{th}$ = 48~65% in this study is better than existing flat-plate type solar collector
- **HP-CPVT system** with Fresnel lens showed lower performance than the Liquid-cooled CPVT system. Still, it showed the second best electrical eff. (29.1%) and combined eff.(83.8%).

21st IHPC and 15th IHPS

KOREA AEROSPACE UNIVERSITY

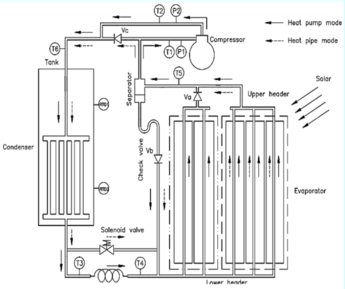
# Solar Heating and Cooling
# Solar TEG





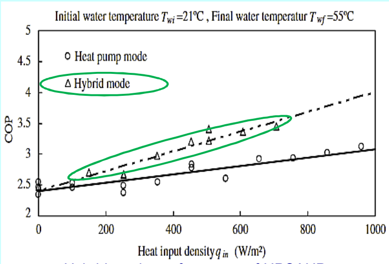
## Solar heating and cooling    Heat pump

- **Huang et al**. [*2005, Solar Energy* 78] studied a heat-pipe enhanced solar-assisted heat pump water heater (HPSAHP), which combined heat pump and HPSC. HPSAHP can thus achieve high-energy efficiency by operating in heat-pump mode when solar radiation is low and in heat-pipe mode without electricity consumption when solar radiation is high. In a test of prototypes, COP of the hybrid-mode operation reached 3.32, an increase of 28.7% as compared to the heat-pump mode COP (2.58).
  - Collector: tube-in-sheet type, using copper tube (6 mm diameter). Copper tubes were soldered on the copper sheets (110 cmX110 cm). → Integrated *Loop thermosyphon*



Schematic of the HPSAHP
(From Huang et al. 2005)


Prototype of the HPSAHP
(HPSAHP-B was for outdoor)



Hybrid-mode performance of HPSAHP
(From Huang et al (2005)

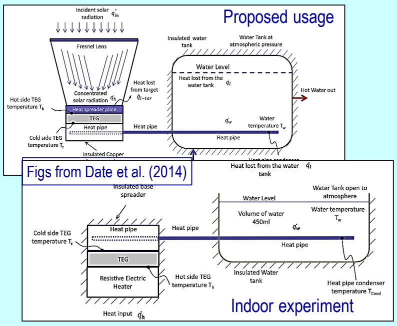
They observed that the heat-pipe mode had better be operated at the water temperature < 30°C (proposed switching temp.) and at the heat input density > 400 W/m$^2$.

# Solar TEG-1

Thermo-Electric Generator (Cooler)

Boo, J.H.

**Date** et al. [2014, *Solar Energy 105*] studied HP-TEG system for water heating by concentrated solar thermal energy. HP: copper-fiber wick (OD 6 mm, L = 0.2 m). Indoor experiment was conducted using electric heater to simulate solar concentration.
For 180 W max. thermal input, $\Delta T$= 150℃ (across TEG) and $P_{electric}$ = 3.5 W. TEG eff. ranged 1.94 to 2.1%. Water heating eff.(thermal) was 53.8-61.3% (for $T_{water}$ = 73℃ and 98℃, respectively)





A. Date, A. Date, C. Dixon, A. Akbarzadeh, Theoretical and experimental study on heat pipe cooled thermoelectric generators with water heating using concentrated solar thermal energy, Solar Energy 105 (2014) 656-668.

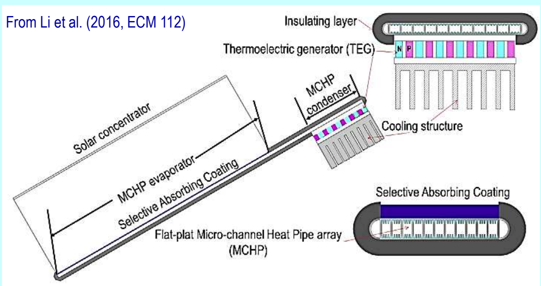


# Solar TEG-2

TEG with MCHP array

Boo, J.H.

**Li** et al. [2016, *ECM 112*] conducted mathematical modelling of solar TEG systems with micro channel HP array (MCHP). Performance analyses presented for the areas of selective coating, concentration ratios, ambient temperatures, wind speed.
MCHP: t= 3mm, L=0.75 m (selective coating on evpr. surf.), $k_{assumed}$ = 23000 W/m-K.
CR= 4 for Fresnel lens concentrator.
For a system with 12 TEGs (CR=8, V= 8 m/s), *electric eff. was max. 0.8 %.*



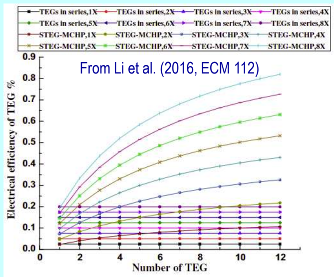




Fig. 12. Electrical efficiency of TEG with the wind speed of 8 m/s.

Source: G. Li, G. Zhang, W. He, J. Ji, S. Lv, X. Chen, H. Chen, Performance analysis on a solar concentrating thermoelectric generator using the micro-channel heat pipe array, *Energy Conversion and Management* 112 (2016) 191-198.

♠ The electric efficiencies of HP-TEG systems proposed thus far were very low (< 3%), an innovative approach is desired for a competitive performance.

# Concentrated Solar Power

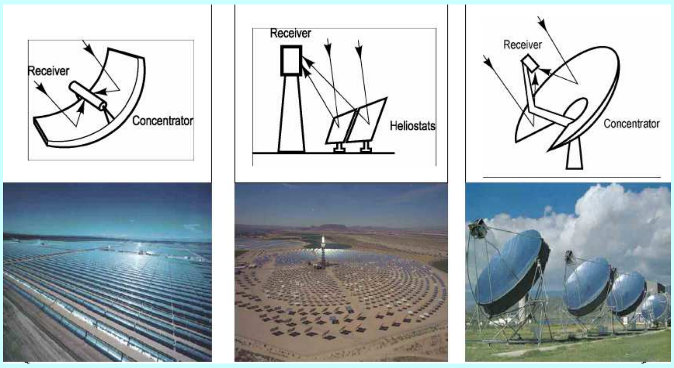

**Solar tower power station in Almería, Spain**
(Source: DLR homepage, https://www.dlr.de/content/en/articles/energy/programme-topics/solar-energy.html)

**References**:
- C.K. Ho and B.D. Iverson, Review of high-temperature central receiver designs for concentrating solar power, *Renewable and Sustainable Energy Reviews* 29 (2014) 835–846. Ren Sus ER 23(2013)
- O. Behar, A. Khellaf, K. Mohammedi, A review of studies on central receiver solar thermal power plants, *RSER* 23 (2013)





## Large-scale Solar Concentration



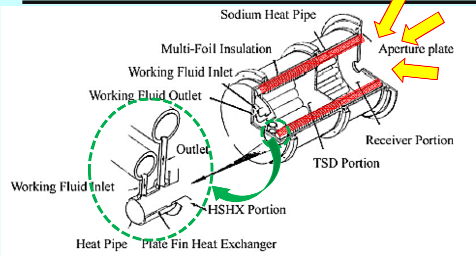

**Trough** **Tower** **Dish**

- Odeillo solar furnace (France): max **3500℃ with 10,000 suns**.
- Synlight (artificial sun, **CR 10,000**) (DLR, Germany) can produce temperatures up to **3000℃**.

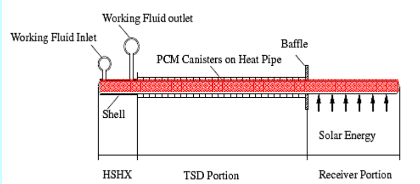
[Appl Egy 188(2017)]-(**PSI, Swiss**)…Solar tests carried out with the nominal 10 kW reactor prototype subjected to a peak solar concentration above **3500 kW/m$^2$** proved the low thermal inertia of the reactor system – ZnO surface temperatures of **2000 K** were reached in 2 s – and its resistance to thermal shock.

## Heat Pipe Receivers — General/Typical

Boo, J.H.




Brayton heat pipe configuration (Stumpf and Coombs, 1988)
Copied from Cui et al. (2006, Solar Energy 80)




The unit tube of heat pipe receiver (From Cui et al. [2006])

♠ Heat pipe receivers can supply high-T solar heat to Brayton cycle, Rankine cycle, AMTEC etc. for power generation, or to solar furnace for chemical processes.

**Solar Fuel**: a synthetic chemical fuel produced from solar energy. (Hydrogen, organic compounds (e.g. alcohols), or metals. Can be produced from water, fossil fuels, or CO2 )
The production methods :

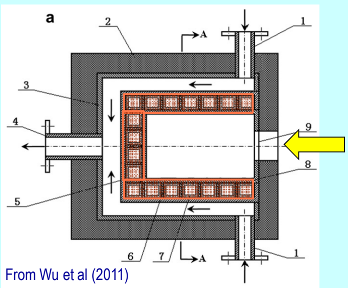
- Photochemical
- Electrochemical
- Thermochemical
  - Involves endothermic chemical transformation
  - Concentrated solar radiation as a source of high-T process heat ☞



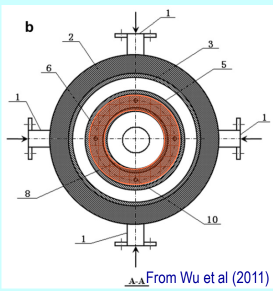
## Heat Pipe Receiver — Cavity

Boo, J.H.

**Wu** et al. [2011, *ATE* 31] analyzed the effect of aperture position/size in a new configuration of heat-pipe receiver to realize the isothermal light-heat conversion for middle- and high-temperature solar dish system. The impact of aperture position on the natural convection heat loss is closely related to tilt angle, while the aperture size has similar effect for different tilt angles. WF: Sodium. Aimed usage: Stirling cycle, Rankine cycle, AMTEC etc.
Outer cylinder- OD 280, depth 320; Inner cylinder- OD 70, depth 150 (units: mm )




From Wu et al (2011)




From Wu et al (2011)

A scheme of heat-pipe receiver: (a) elevation view and (b) plane view of A-A (1-heated fluid inlet; 2-insulation; 3-outer wall of the annular channel; 4-heated fluid outlet; 5-outer cavity wall; 6-annular metal fins; 7-capillary wick; 8-inner cavity wall; 9-aperture; 10-circular hole).

S.Y. Wu, L. Xiao, Y-R Li, Effect of aperture position and size on natural convection heat loss of a solar HP receiver, ATE 31(2011) 2787-2796.

## Heat Pipe Receiver — Flat/rectangular

Boo, J.H.

**Yang** et al. (2016, *ATE* 109): High-T 2-phase flat heat pipe receiver (FHPR) in a solar power tower plant to achieve the uniform heat flux distribution and remove heat spots.
Vapor chamber: Sodium+ STS 310S. Two flat plates with t = 3 mm and a frame.
Dimension: 530 *200 *12 mm with Le= 200 mm, La= 130 mm, Lc= 200 mm.
condenser section is composed of water jackets.

For $Q_{in}$ = 3 kW, Min. R= $4.57\times10^{-3}$ K/W, $k_{eff,max}$ = $8.27\times10^{5}$ W/m-K , $T_{E,max}$~540 ℃ ($T_{furnace}$~ 824℃).

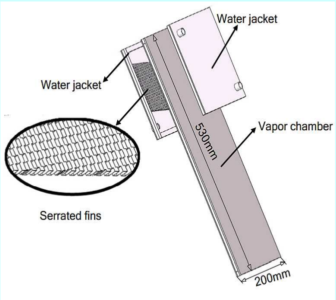



Fig. 1. The structure of solar receiver.

From Yang et al. (2016).

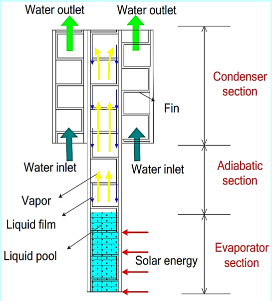



Fig. 3. The working principal of solar receiver.

From Yang et al. (2016).

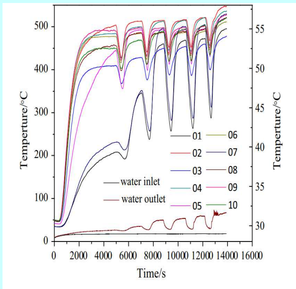



Fig. 13. Temperature variations of evaporator and condenser for $Q_{in}$ from 1 kW to 3 kW steppedly increased indicated with incline angle is 45°.

From Yang et al. (2016).

Yang L, Zhou RW, Ling X, Peng H., Experimental investigate on thermal properties of a novel high temperature flat heat pipe receiver in solar power tower plant, ATE 109 (2016) 662-666.



## Heat Pipe Receiver — Conical array/molten salt

Boo, J.H.

**Liao and Faghri** (2016, *ATE* 102) theoretically analyzed a heat pipe solar central receiver for a molten salt solar power tower. HP WF: sodium.
The reflector redirects concentrated sunlight from the heliostats field onto the evaporator section of the HP. The condenser section is inserted into the receiver tube, and is cooled by a cross flow of the heat transfer fluid inside the receiver tube. In the proposed concept, the receiver tube is free from direct irradiation by the sunlight and therefore can be kept warm by electrical heating.

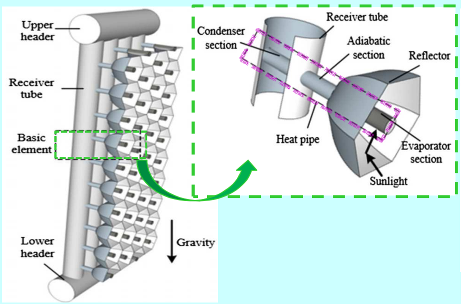
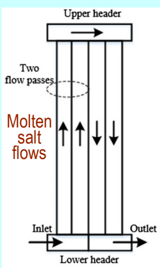
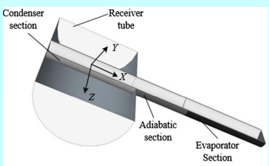



Fig. from Liao and Faghri (2016))




From Liao and Faghri (2016))




From Liao and Faghri (2016))

Liao Z, Faghri A. Thermal analysis of a heat pipe solar central receiver for concentrated solar power tower. *ATE* 102 (2016).

# High-T Heat Pipe Thermal Energy Storage System

**Mahdavi** et al. (2015, *ATE* 81) numerically investigated a complex geometry high-T HP (sodium-STS) which was specially configured for TES (thermal energy storage) in CSP (concentrated solar power) system. The heat transfer limits due to heat pipe geometry, working fluid, wick structure, and operational temperature were calculated.

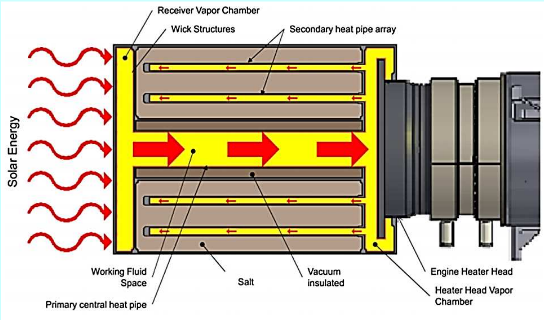
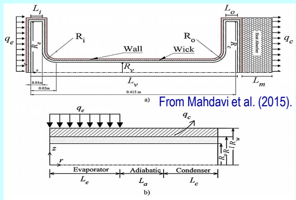



Fig. 1. Heat pipes and thermal energy storage module [38].

From Mahdavi et al. (2015).




From Mahdavi et al. (2015).

Fig. 2. Heat pipes schematics. a) The complex heat pipe b) Conventional cylindrical heat pipe.

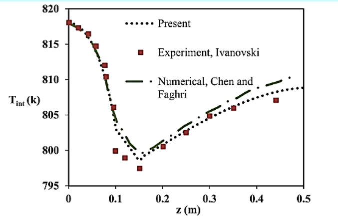



Fig. 4. Comparison of present result with experimental data and previous numerical predictions [11,42].

From Mahdavi et al. (2015).





# Medium-T HP TES System — General

- Medium-temperature range Heat Pipe: 550 to 750 K (280 to 480℃)
  - ✓ Often encountered in subsystems of solar thermal power (esp. for CR > 1,000)
  - ✓ Typical HP WFs for Med-T range
    - Mercury (toxic), Naphthalene
    - Synthetic fluids: Flutec PP9 (<160℃), PP2 (< 225℃, dielectric)
    - Dowtherm-A* (Thermex): 150-400℃ *a eutectic mixture of diphenyl & diphenyl ether
- Molten salts as PCM for Medium-T range TES (Thermal Energy Storage)
  - ➢ Reduction of system volume/weight (due to latent heat)/ Less operating cost
  - ➢ Difficulties
    - Very low thermal conductivity of molten salts (order of $10^{-1}$ W/m-K)
    - Large T-gradient (ΔT)in the system
    - Long response time due to low heat transfer
- Challenge
  - ➢ Enhance the heat transfer performance of the system using Heat Pipes

Typical molten salts as PCM

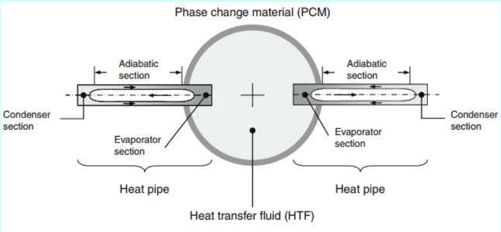
| T-range | Med-High T | Med.-T | Ref. |
|---|---|---|---|
| Name | Potassium Nitrate | Lithium Nitrate | Sodium Nitrate |
| Chemical formula | $KNO_3$ | $LiNO_3$ | $NaNO_3$ |
| Melting point | 334℃ | 253℃ | 308℃ |
| Density, kg/m³ | 2,110 | 2,380 | 2,257 |
| Latent heat of Fusion, kJ/kg | 95 | 387 | 178 |
| Thermal Conductivity, W/m-K | 0.5 | 0.5 | 0.2 |
| Specific heat, kJ/kg-K | 0.95 | 0.93 | 1.095 |

'**Solar salt**': Eutectic mixture of 60 wt.% sodium nitrate ($NaNO_3$) and 40 wt.% potassium nitrate ($KNO_3$), [ M.P. 220℃, $C_p$ = 1517 J/kg-K, ρ = 1817 kg/m³, k= 0.49 W/m-K ].

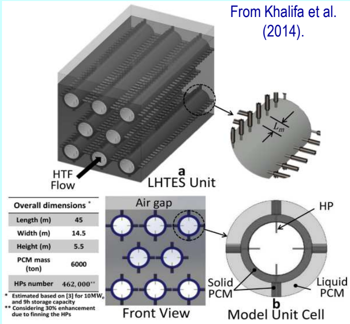
# Medium-T HP TES System

**Shabgard** et al. (2010, *IJHMT* 53) numerically investigated the benefits of inserting multiple HPs (mercury-STS) btw HTF (Therminol VP-1) and PCM($KNO_3$) and demonstrated that adding HP enhances thermal performance (quantified in terms of dim'less HP effectiveness).

**Khalifa** et al. (2014, *ATE* 70) numerically and experimentally investigated HP-TES and quantified the advantages of utilizing axially finned HPs. In the numerical study, HP WF (mercury), PCM and HTF were the same as in Shabgard et al. (2010). The results have shown the energy extracted increased by 86% and the HP effectiveness increased by 24%. In experiments, copper-water HPs were used and the results included temperatures below 83℃ during PCM solidification process.




From Shabgard et al. (2010).




From Khalifa et al. (2014).

♠ While the m.p. of the PCM is 335℃, medium-T data were not presented in both of the above articles.

☞



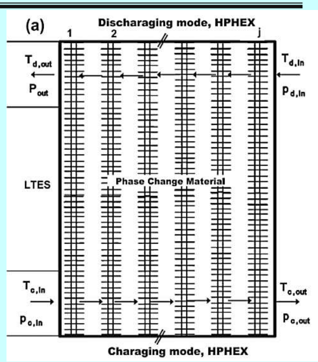


# Medium-T HP TES System

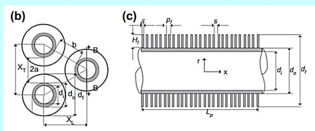
## HPHEX

**Jung and Boo** (2014, *Solar Energy* 102) developed an analytical model to predict the transient thermal behavior of a sodium HP-LTES system for concentrated solar power (CSP). $KNO_3$ (m.p. 335℃) was used as PCM. Thermal model was used to estimate the heat transfer rate and the transient temperature variation in the PCM contained in each row of the HPHEX. Both melting (charging) and solidification (discharging) were simulated assuming pure conduction. The discrepancy btw the prediction by model and valid previous experimental results were less than 8%.

**Jung and Boo** (2014, *Applied Energy* 135) numerically modeled heat transfer of an air-to-air heat pipe heat exchanger (HPHEX) with counter flow and a high-T range as encountered in a solar receiver. The HPHEX was constructed from sodium-STS HPs using a staggered configuration. The model was developed by the nodal approach, and the junction temperature and thermal resistance of the HP and heat transfer fluid of each row were defined. The simulation results agreed with experimental data to within 5% error for normal operation (T > 450℃) of the sodium HPs.



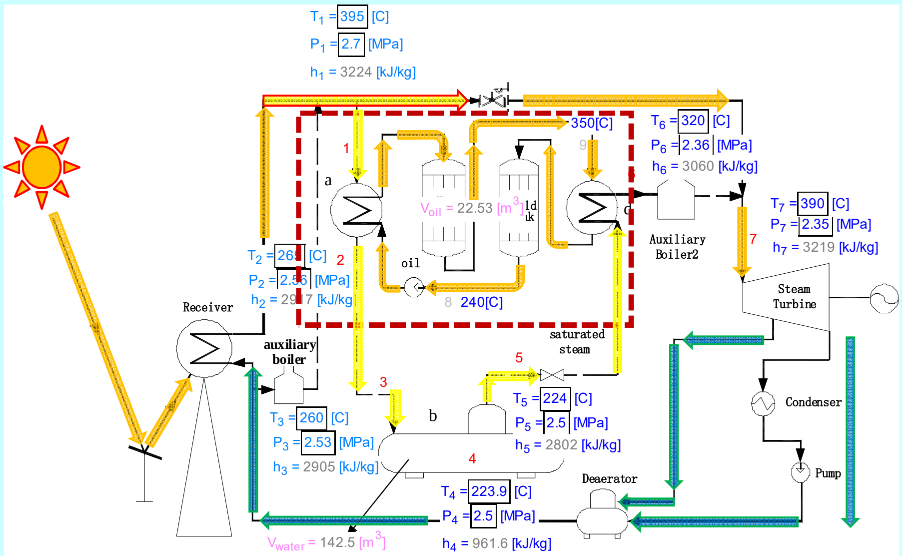

Jung and Boo (2014, Sol Egy 102)




HPHEX: (a) top view showing geometry of the HP arrangement, (b) unit of the HP arrangem

## Medium-T HP TES System    Case Study

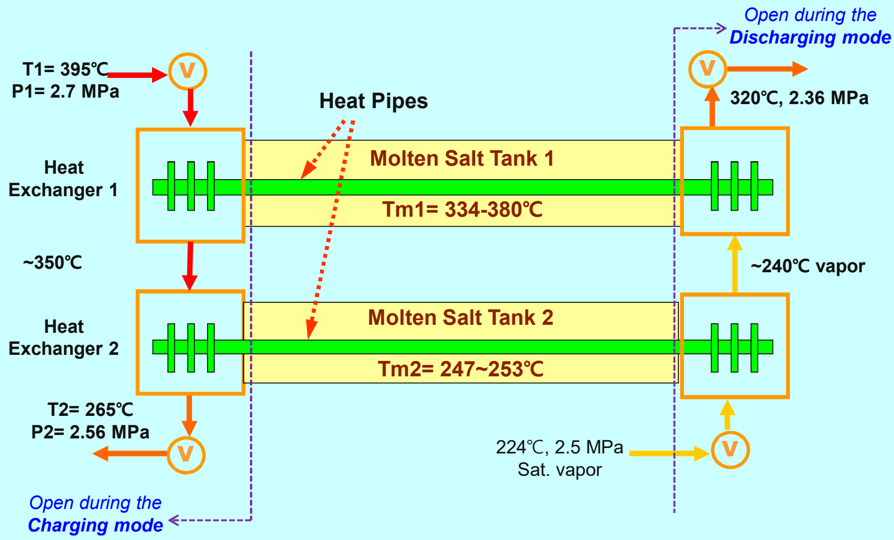
Boo, J.H.






## Medium-T HP TES System    Case Study

Boo, J.H.

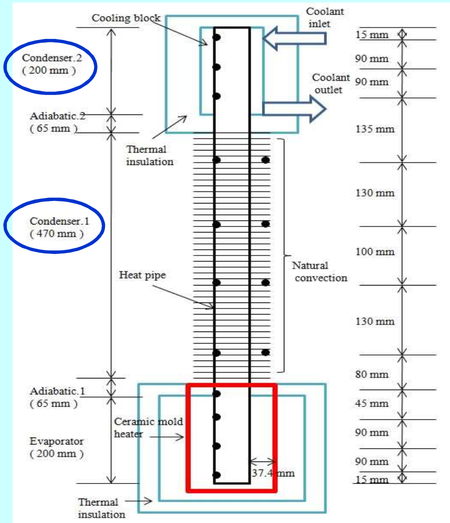


## Medium-T HP TES System

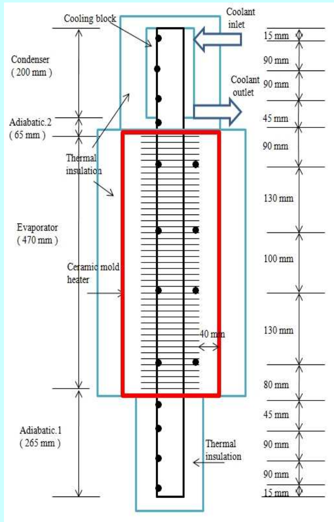
Case Study

*Boo, J.H.*

**(Charging mode)**




**(Discharging mode)**

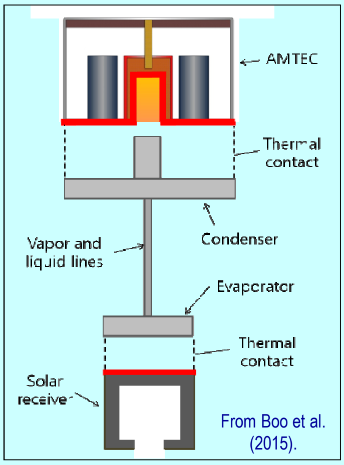




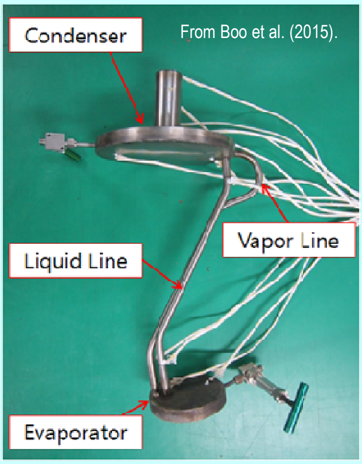

## High-temperature AMTEC application

*Boo, J.H.*

**Boo** et al.[2015, Egy Proc. 69] designed and experimentally investigated a loop-type sodium heat pipe for **high-T solar receiver** for AMTEC application.




From Boo et al. (2015).




From Boo et al. (2015).

J. H. Boo, S. M. Kim, Y. H. Kang, An experimental study on a sodium loop-type heat pipe for thermal transport from a high-temperature solar receiver, Energy Procedia 69 ( 2015 ) 608 – 617

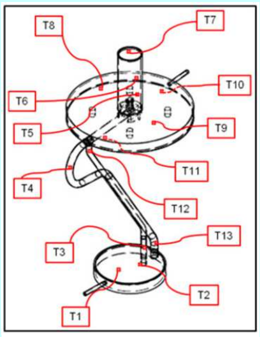
# High-temperature solar application -2

Boo, J.H.

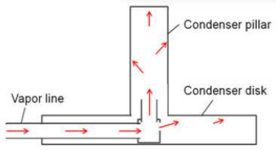
The container wall and transport lines of the loop-type HP were made of stainless steel 304, and the WF was sodium. The geometry was complex reflecting thermal interface in AMTEC. The evaporator and condenser were disk-type containers with diameters of 122 and 216 mm, respectively, though both had a height of 20 mm. The diameters of the vapor and liquid lines were 12.7 and 9.53 mm, respectively. The total length of the loop was approximately 1.4 m. Screen wicks were attached to inner wall of condenser to enhance isothermal characteristics.

Table 1. Sectional dimensions of the heat pipe

| Section | Outer diameter (mm) | Wall thickness (mm) | Volume ($cm^3$) | Length (L) or height(H) (mm) |
|---|---|---|---|---|
| Evaporator | 122 | 3 | 148 | (H) 20 |
| Vapor line | 12.7 | 1 | 66.3 | (L) 738 |
| Liquid line | 9.53 | 1 | 21.4 | (L) 582 |
| Condenser disk | 216 | 3 | 510.2 | (H) 20 |
| Condenser pillar | 42.7 | 2.8 | 119.6 | (H) 130 |




Locations of temperature measurement (Boo et al. 2015).




Vapor injection in the condenser (Boo et al. 2015).

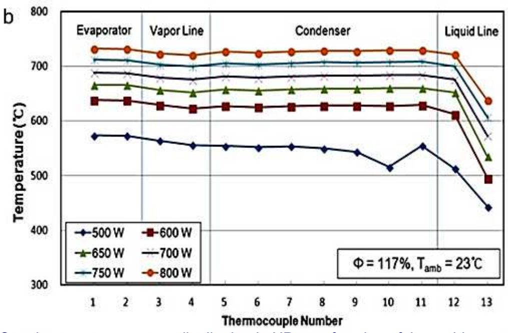




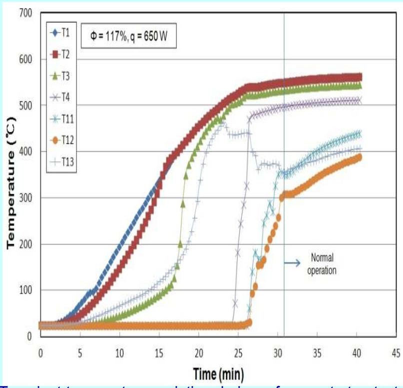
# High-temperature solar application -3

Boo, J.H.

The performance of the sodium loop-type HP varied considerably with WF FR. During the experiment the condenser surface was cooled by natural convection. However, the condenser surface was insulated in an experiment to compare temp. uniformity on the surface. Results showed generally optimum performance was exhibited for FR=117% based on wick void volume (32% of evpr. vol). The HP was capable of transporting an 800 W load with discharge T in the condenser higher than 750℃.




Steady-state temperature distribution in HP as a function of thermal input for a specified WF FR (Boo et al. 2015).




Transient temperature variation during a frozen startup test (Boo et al. 2015).

# Future scope



- From low-T to high-T range, exploration of new solar thermal applications for HPs are desired, considering that solar energy share shall increase as important new and renewable energy source.
- Usage of HPs with flat geometry having multi-channel or array type is expected to expand in various solar thermal application. Design optimization of these HPs should be reviewed, as they are rarely seen in the literature.
- PVT area will continue to grow as new and more efficient PVs are being developed. HPs are expected to contribute accordingly to their performance enhancement and waste energy utilization.
- Development and investigation of new heat pipe materials is desired to deal with challenging areas that have not been explored.
  - New container materials: especially for reliability and extended life in harsh environment, such as high-T and contaminated fluids,
  - New HP working fluids: to meet environmentally friendly requirements, such as GWP and ODP.
- Cost-effective manufacturing technologies/processes should be developed further for HPs for solar thermal applications to provide economic competitiveness. In addition, a life expectancy of 20 years+ is desired, in general solar thermal devices.