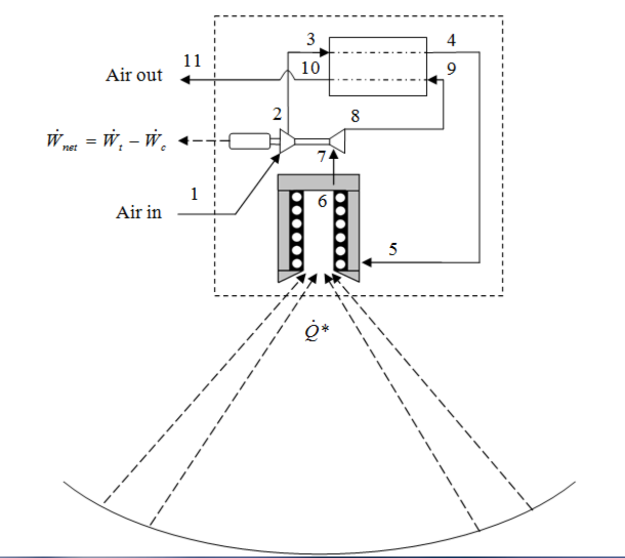
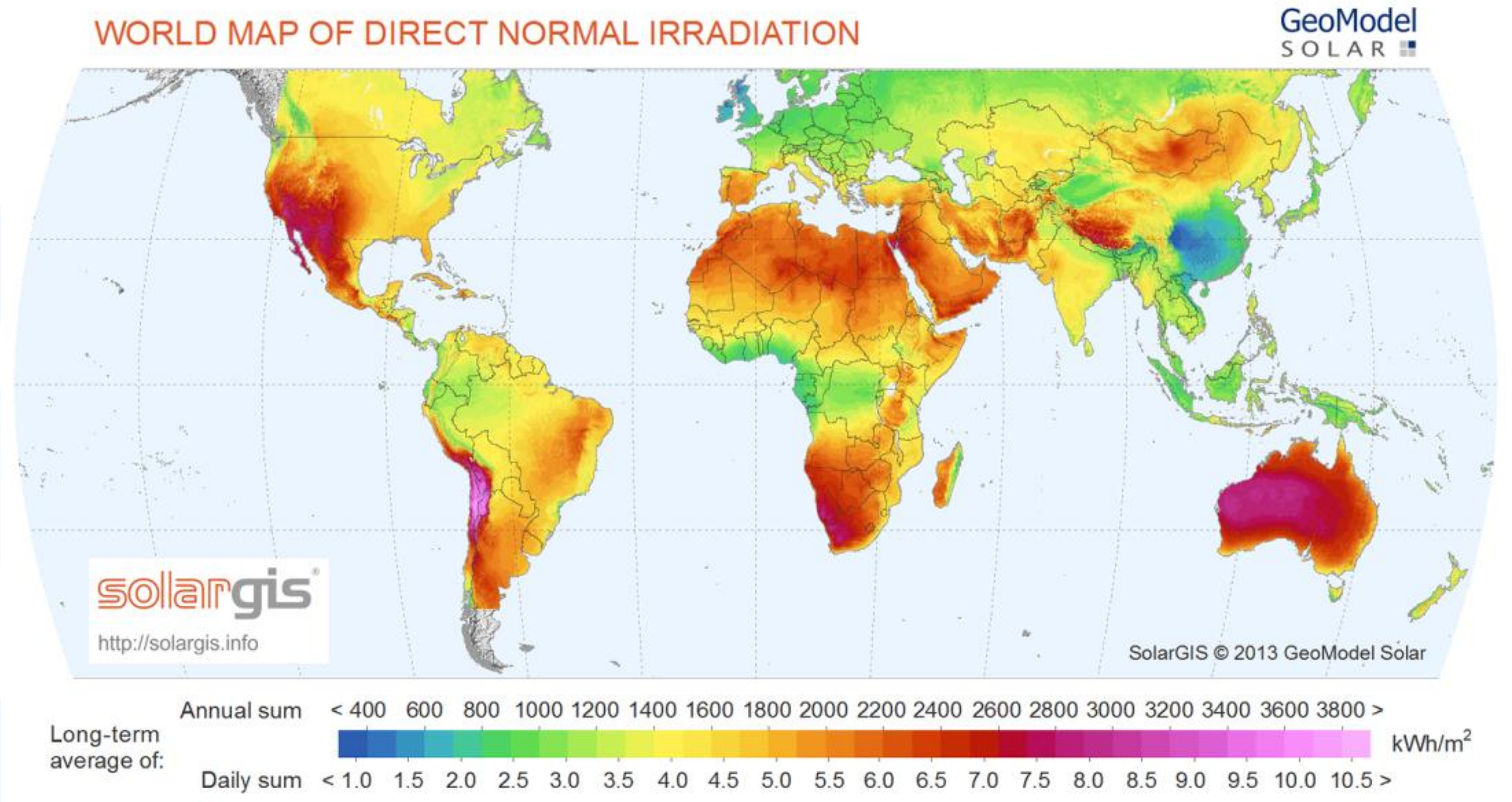
Recuperated solar-dish Brayton cycle with turbocharger and short-term thermal storage

Dr WG Le Roux



Department of Mechanical and Aeronautical Engineering,
University of Pretoria

Background



Long-term average of direct normal solar irradiance on a world map showing the potential of solar power generation in southern Africa (GeoModel Solar, 2014)

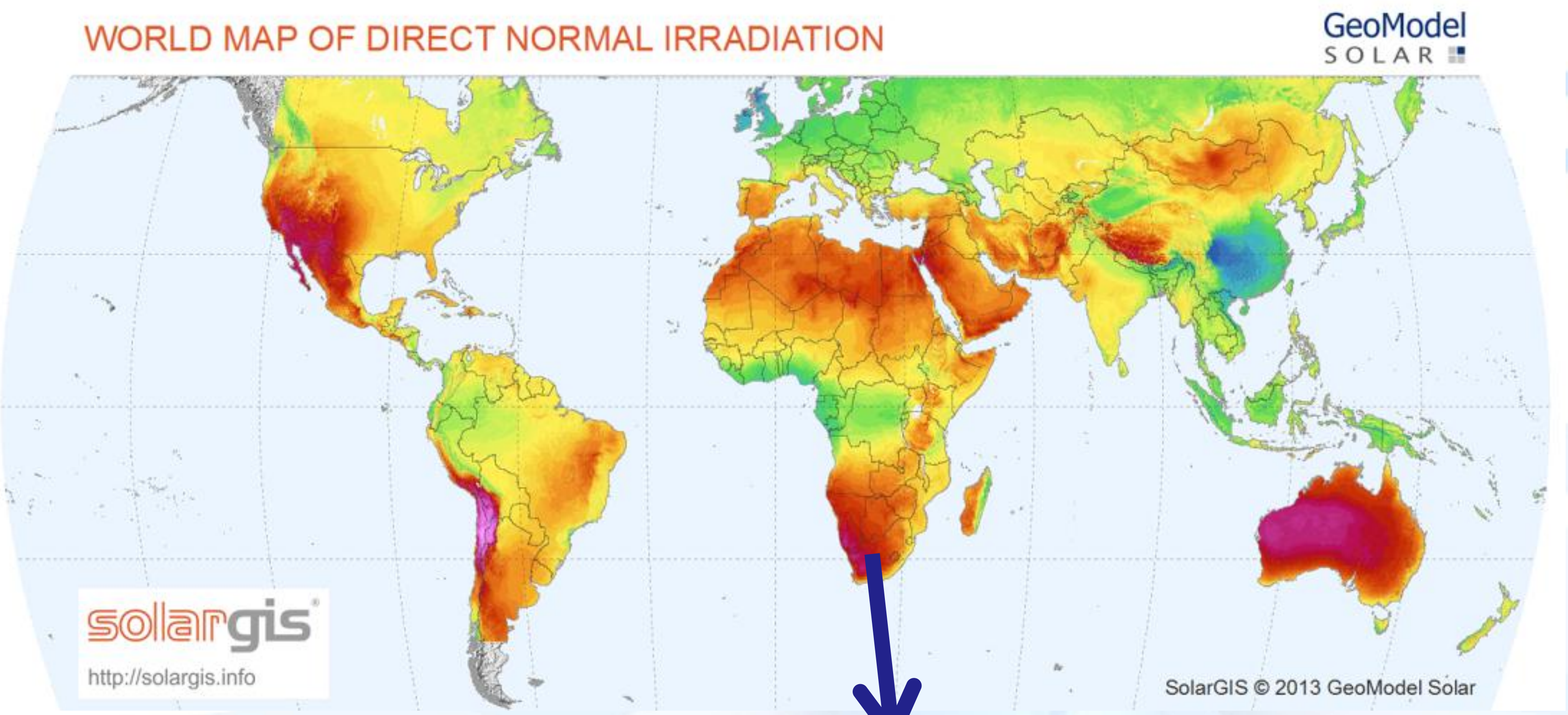
Background

South Africa has one of the ***best solar resources in the world*** *and this resource is free to use and study for all South Africans, who should take the lead in this field in terms of*

- *skills development,*
- *training and*
- *product manufacturing.*

The research and development of ***solar dish technologies is a new and exciting research field*** *in which all South African researchers of all age, race and gender can take the lead.*

Background



1. Power generation
2. Water purification
3. Fuel production

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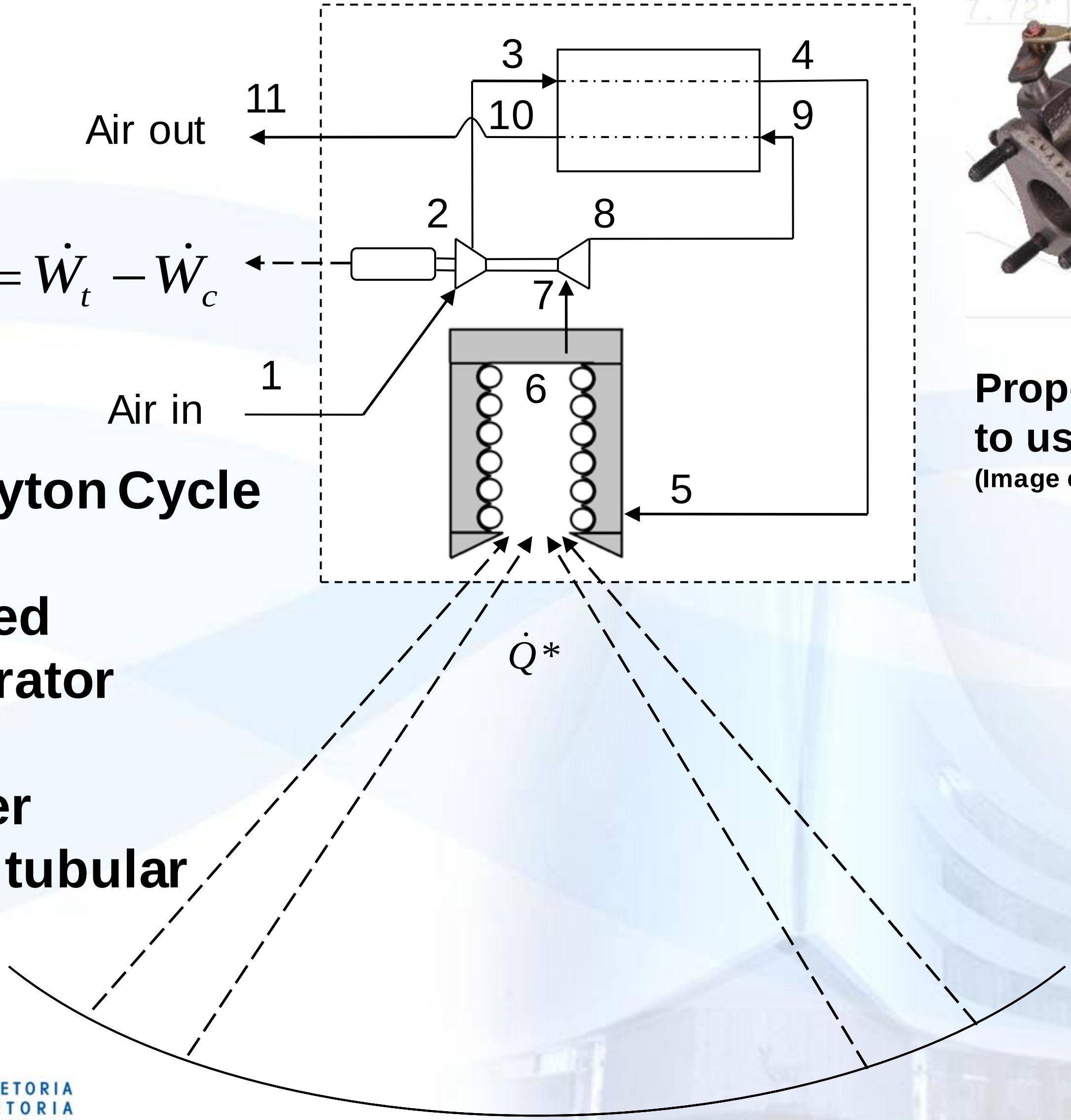
Presentation Outline

1. Introduction and Background
2. Problem and Purpose
3. Methodology
4. Results and Discussion
5. Conclusion

6. Progress to date (Solar@UP)
    - Solar radiation in Pta
    - New dish concept
    - Moonlight testing
    - Receiver testing
    - Recuperator testing

1. Introduction

$$\dot{W}_{net} = \dot{W}_t - \dot{W}_c$$

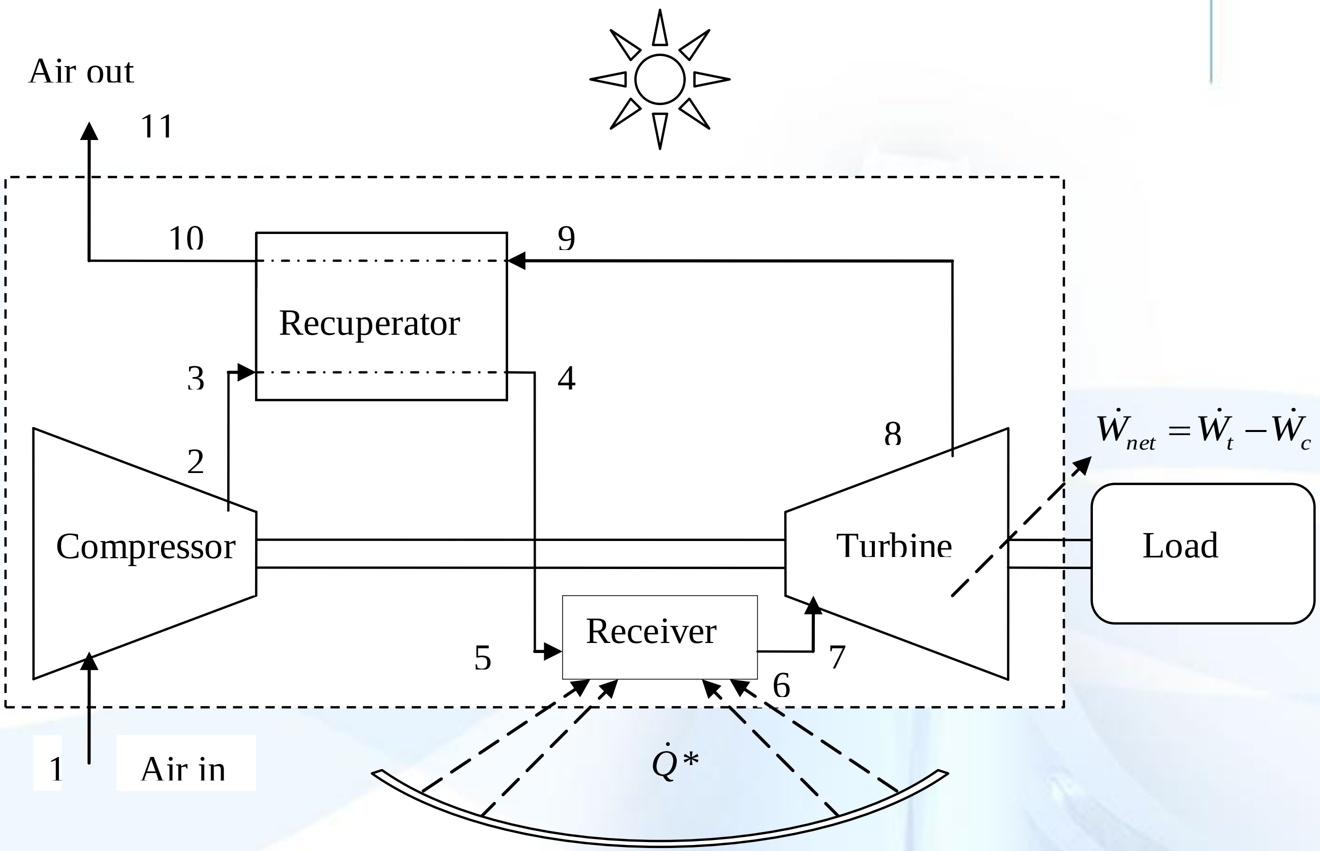


Solar-Dish Brayton Cycle

- **small-scale**
- **dish-mounted**
- **with recuperator**
- **1-20kW**
- **turbocharger**
- **open-cavity tubular receiver**

Proposed turbocharger to use as micro-turbine
(Image extracted from Garrett, 2014)

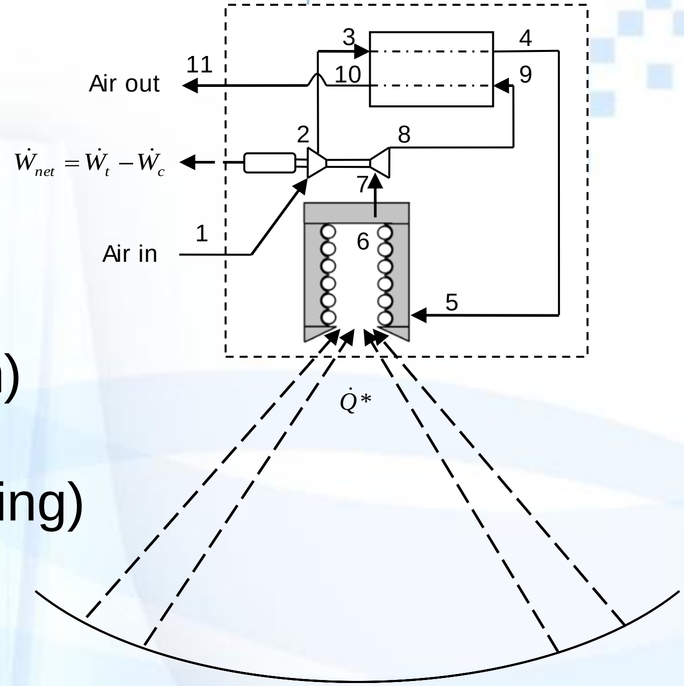
1. Introduction



The small-scale dish-mounted solar thermal Brayton cycle with recuperator (STBC)

1. Introduction

Solar thermal Brayton cycle advantages



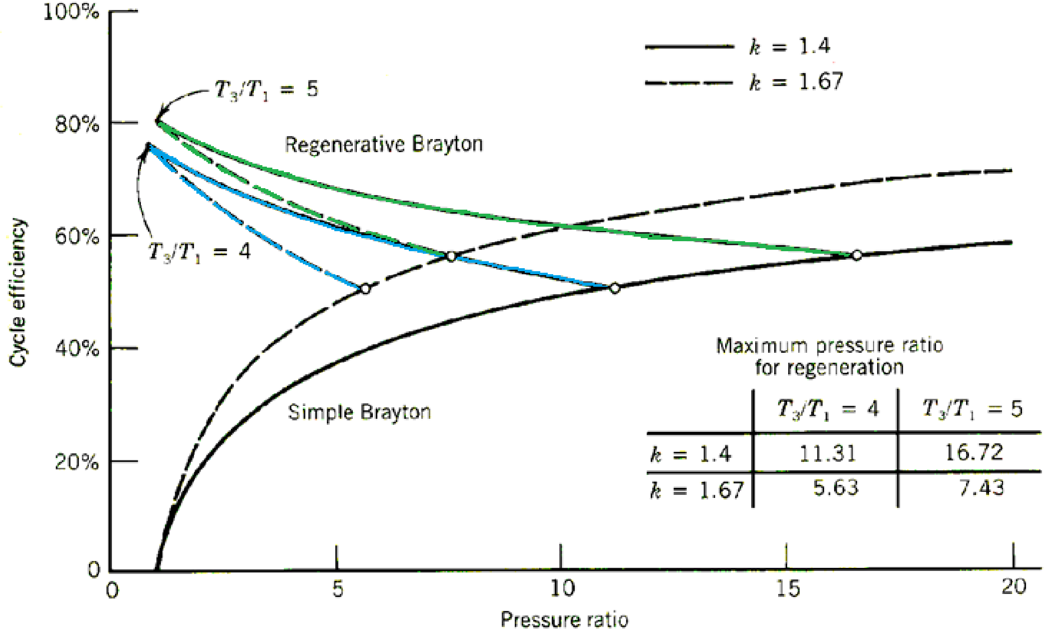
- Air as working fluid
- Turbocharger as micro-turbine
- Can also be powered with gas (hybrid system)
- Water heating (cogeneration)
- High efficiency potential (reheat and intercooling)
- Mobility
- Cost benefits (bulk manufacturing)
- Thermal storage

- Quicker to commercialise (prototyping is quicker and cheaper)
- Large-scale local manufacturing – good for the economy (good for South Africa)
- Micro-grids

1. Introduction

Solar thermal Brayton cycle advantages

- **Recuperator**
  - allows for higher efficiency at lower compressor pressure ratios
  - allows for a less complex receiver (operating at lower pressure and smaller temperature increase)



	$T_3/T_1 = 4$	$T_3/T_1 = 5$
$k = 1.4$	11.31	16.72
$k = 1.67$	5.63	7.43

Image extracted from: Stine, B.S., Harrigan, R.W., 1985, Solar energy fundamentals and design, New York: John Wiley & Sons, Inc.

1. Introduction

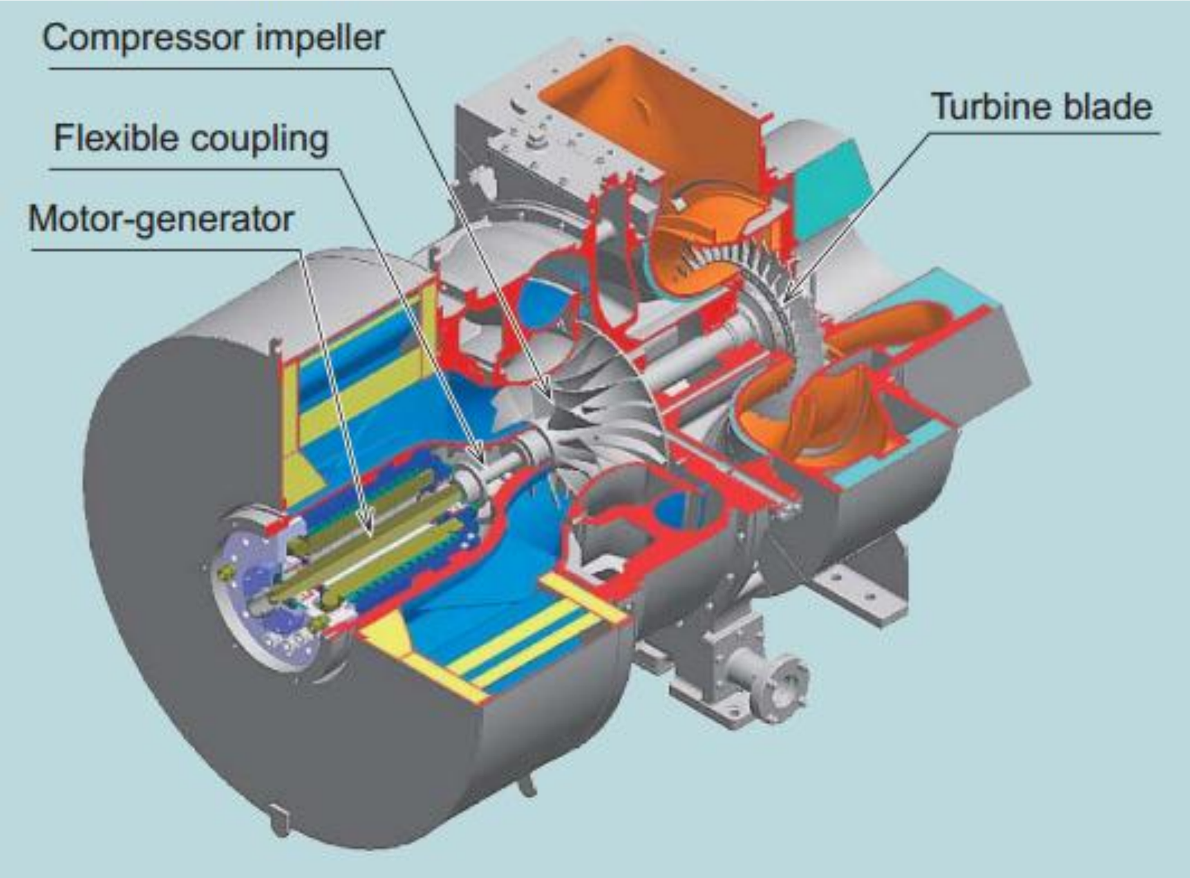
Solar thermal Brayton cycle advantages

- **Turbocharger**
  - The maximum inlet temperature of an off-the-shelf turbocharger is about 1223 K (Garrett, 2014; Shah, 2005) and 1323 K intermittently.

Proposed turbocharger to use as micro-turbine
(Image extracted from Garrett, 2014)

1. Introduction

- Turbocharger
  - Generator coupling



Range extenders in electric vehicles

Generator coupling – simple, robust, easy to maintain

(Image extracted from Shiraishi and Ono, 2007)

1. Introduction

- Turbocharger
  - Generator coupling

Generator coupling – simpe, robust, easy to maintain
(Image extracted from Shiraishi and Ono, 2007)

1. Introduction – Open cavity tubular receiver

Receiver dimensions optimised in a previous work (Le Roux et al., 2014)

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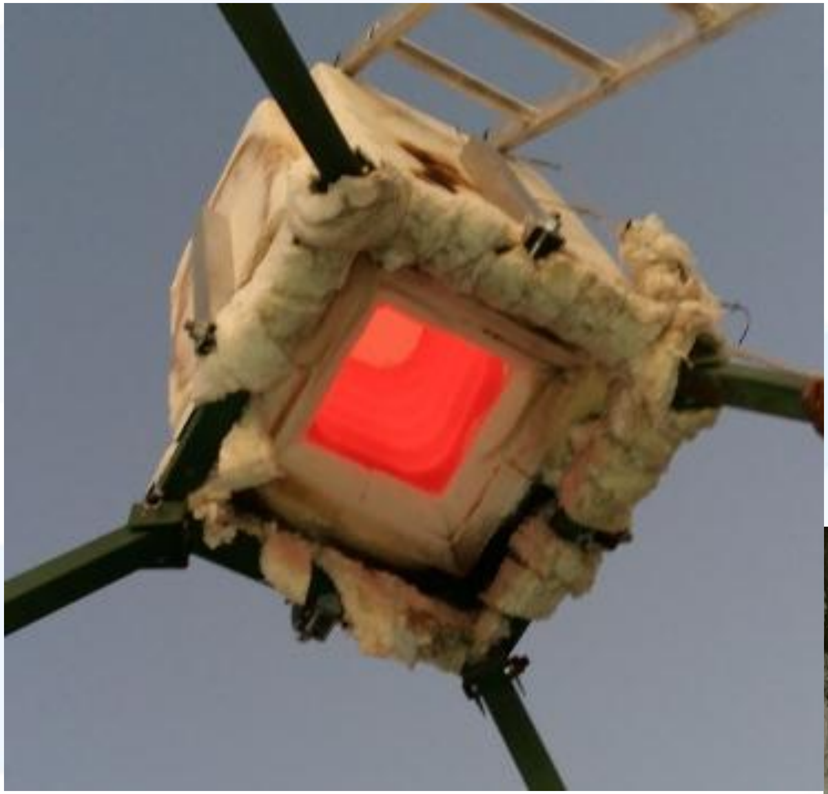
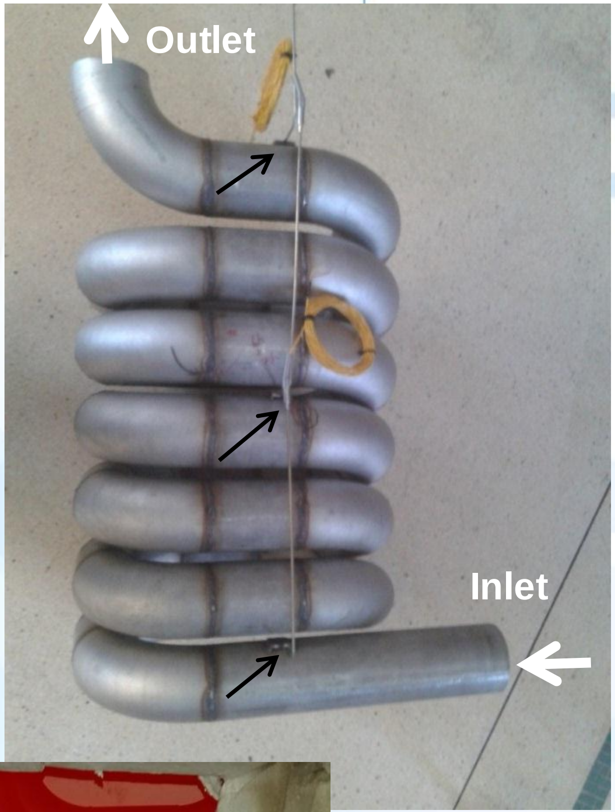
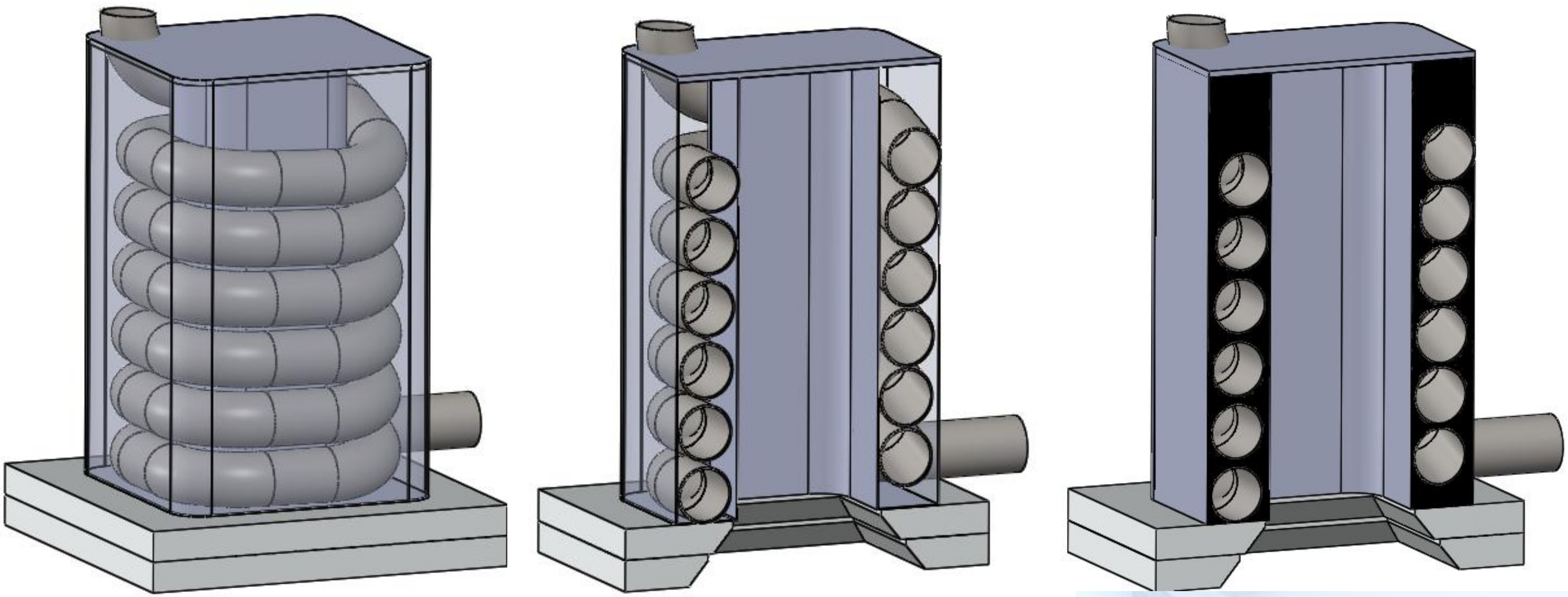
1. Introduction – Open cavity tubular receiver

- Heat up insulated receiver to 857 °C
  - using 86 kW LPG flame from Sievert burner

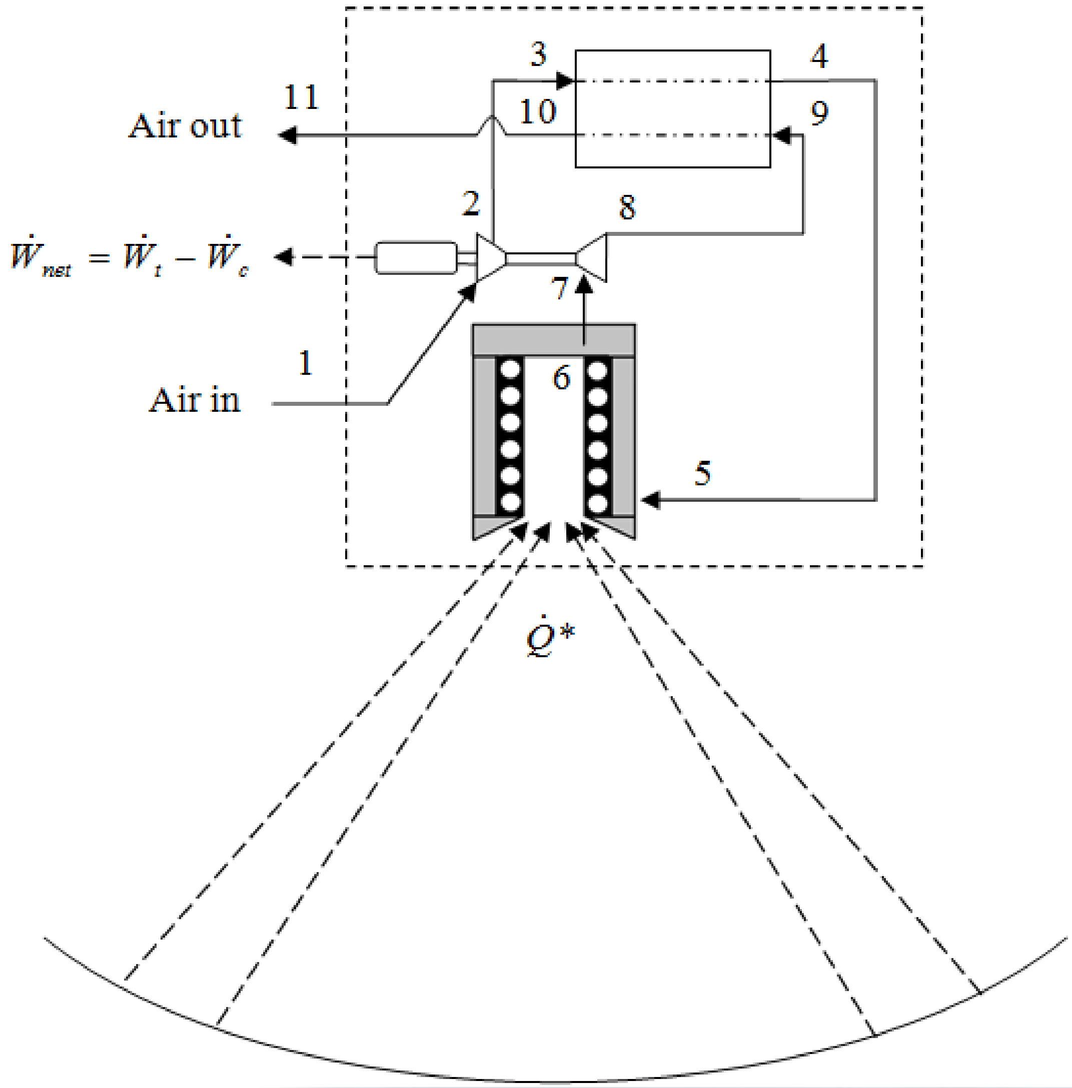




1. Introduction – Brayton cycle thermal storage



1. Introduction – Brayton cycle thermal storage



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1. Introduction

Thermal storage

- Lithium fluoride (Cameron et al., 1972; Asselman, 1976)
- Packed rock beds (Allen, 2010; Ozturk et al., 2019),
- Encapsulated sodium sulphate (Klein, 2016)

- **Phase-change materials** can be used to provide a stable turbine inlet temperature;
  - however, most phase-change materials have a **low thermal conductivity** of around 0.5 W/mK (Liu et al., 2012).
  - **metallic phase-change materials** have higher thermal conductivities.
  - Other materials such as salt composites and inorganic salts have limited applications because of large volume changes during melting as well as **corrosion issues** (Liu et al., 2012).

1. Introduction (Solar-dish Brayton cycle) – Metallic phase-change materials (Liu et al. 2012)

Phase-change material	Composition (wt%)	Melting temperature (K)	ρ (kg/m³)	$c_{p,solid}$ (J/kgK)	$c_{p,liquid}$ (J/kgK)	k (W/mK)	Latent heat, L_f (kJ/kg)
Mg		921	1740	1270	1370		365
Al		933	2700	900	1100	186	397
Zn–Cu–Mg	49/45/6	976	8670	420			176
Cu–P	91/9	988	5600				134
Cu–Zn–P	69/17/14	993	7000				368
Cu–Zn–Si	74/19/7	1038	7170				125
Cu–Si–Mg	56/27/17	1043	4150	750			420
Mg–Ca	84/16	1063	1380				272
Mg–Si–Zn	47/38/15	1073					314
Cu–Si	80/20	1076	6600	500			197
Cu–P–Si	83/10/7	1113	6880				92
Si–Mg–Ca	49/30/21	1138	2250				305
Si-Mg	56/44	1219	1900	790		70	757

2. Problem and Purpose

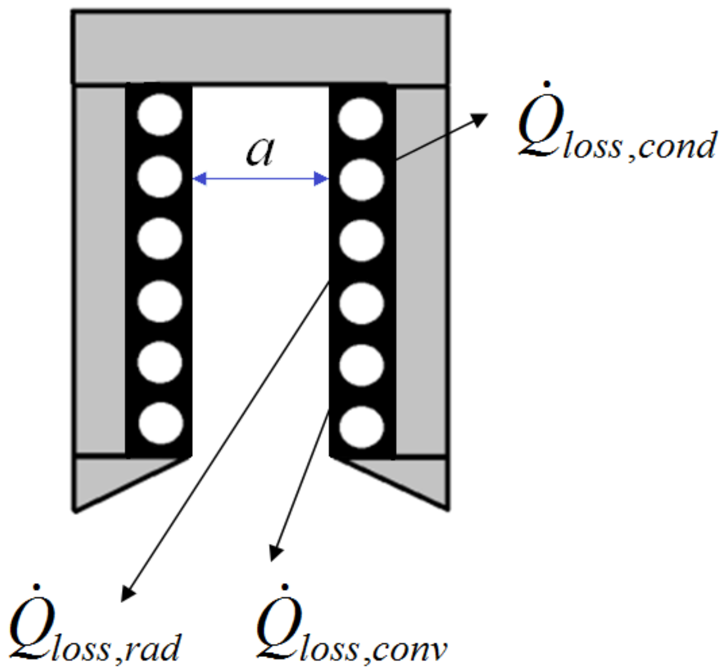
Problem

- the phase-change temperature affects the solar conversion efficiency

Purpose of the study

- Determine maximum thermal efficiency of the cycle for
  - an off-the-shelf turbochargers
  - various recuperator geometries
  - fixed receiver geometry
  - Metallic phase-change material at different solar receiver temperatures

3. Methodology - Receiver



Assumptions for receiver:

- **Constant surface temperature tube, at steady state (T_s = PCM temperature**
- **Koenig and Marvin heat loss model for cavity receiver**

$$T_e = T_s - \left(T_s - T_i\right)e^{-h_{rec}A_s / \dot{m}c_p}$$

$$\Delta P = \frac{8\dot{m}^2}{\rho \pi^2 d^4}\left(f\frac{L}{d} + \sum_y K_y \right)$$

$$\dot{Q}^* = \dot{Q}_{loss,cond} + \dot{Q}_{loss,conv} + \dot{Q}_{loss,rad} + \dot{Q}_{net}$$

$$\dot{Q}_{net} = h_{rec}A_s \frac{\left(T_i - T_e\right)}{\ln\left[\left(T_s - T_e\right)/\left(T_s - T_i\right)\right]}$$

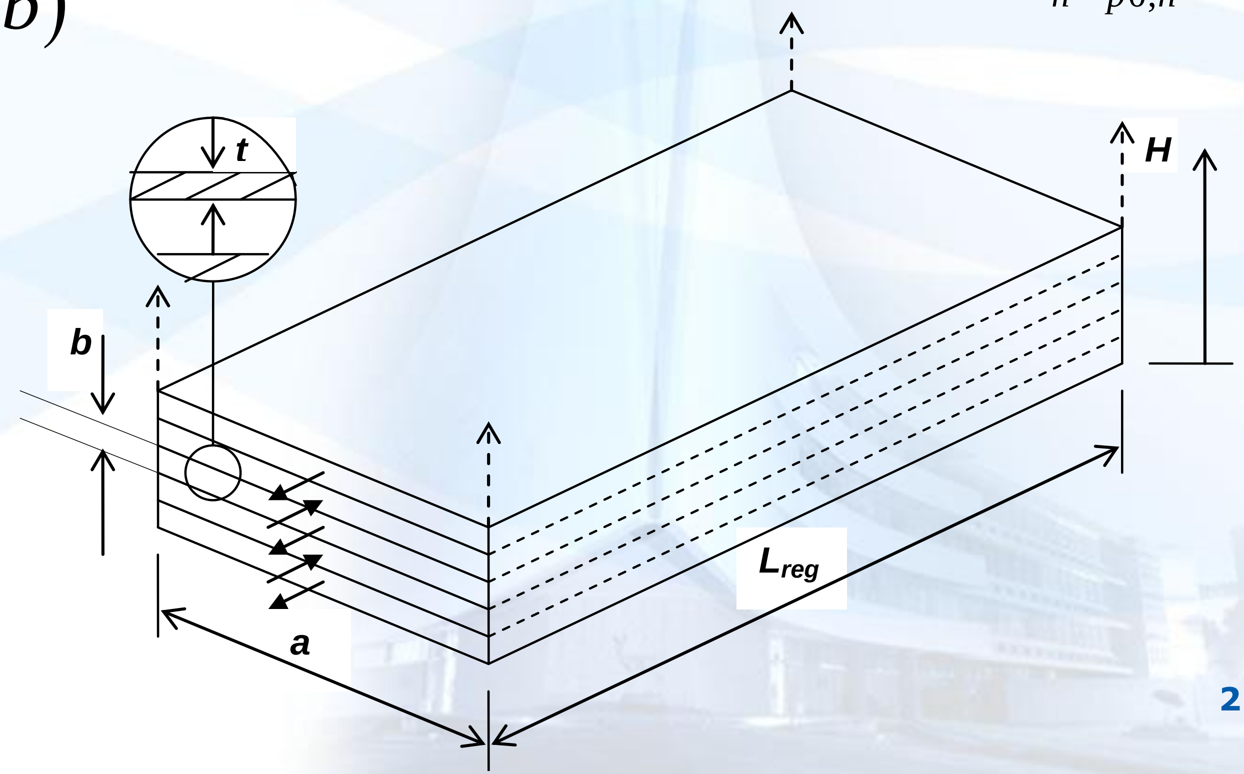
3. Methodology - Recuperator

Assumptions for recuperator:

- **Effectiveness-NTU model including heat loss to the environment (Nellis and Pfotenhauer, 2005)**

$$\Delta P = \frac{f L_{reg} \left(\dot{m}/n\right)^2 \left(a+b\right)}{4\rho\left(ab\right)^3}$$

$$NTU_h = \frac{UaL_{reg}\left(2n-1\right)}{\dot{m}_h c_{p0,h}}$$



3. Methodology - Turbocharger

Assumptions for turbocharger:

- **Determine mass flow rate and pressure ratios from the compressor map and turbine map (GT2052)**

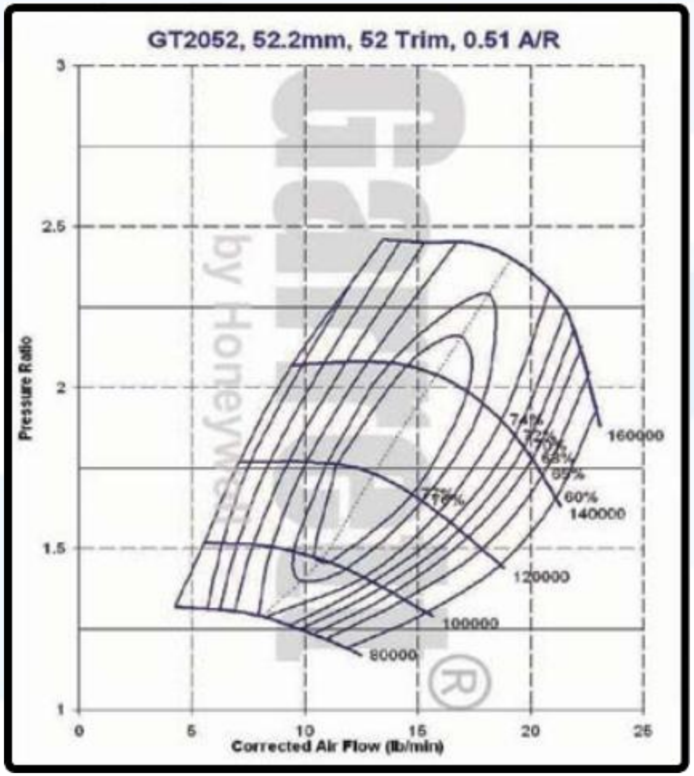
3. Methodology - Turbocharger

Assumptions for turbocharger:

- **Determine mass flow rate and pressure ratios from the compressor map and turbine map**

$$BSR = \frac{\frac{2\pi N}{60}\left(\frac{D_t}{2}\right)}{\left[2h_{in}\left(1 - r_t^{\frac{1-k}{k}}\right)\right]^{1/2}}$$

$$\eta_t = \eta_{t,\max}\left(1 - \left(\frac{BSR - 0.6}{0.6}\right)^2\right)$$



3. Methodology – Parameters

Power output calculation:

The MATLAB program has the following stucture:

- **For Ts = 900:100:1200,**
  - **For each turbine pressure ratio (rt) in the operating range of the turbine,**
    - **For each recuperator design (625 different combinations),**
      - **Find net power output and efficiency of cycle.**

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3. Methodology – Net power output

Entropy generation minimisation to optimise geometries of components for a common goal

$$\dot{W}_{net} = -T_\infty \dot{S}_{gen,\text{int}} + \left(1 - \frac{T_\infty}{T^*}\right)\dot{Q}^* + \dot{m}c_{p0}\left(T_1 - T_{11}\right) - \dot{m}T_\infty c_{p0} \ln\left(\frac{T_1}{T_{11}}\right)$$

$$\dot{S}_{gen,\text{int}} = \left[-\dot{m}c_{p0}\ln\left(T_1/T_2\right) + \dot{m}R\ln\left(P_1/P_2\right)\right]_{compressor}$$

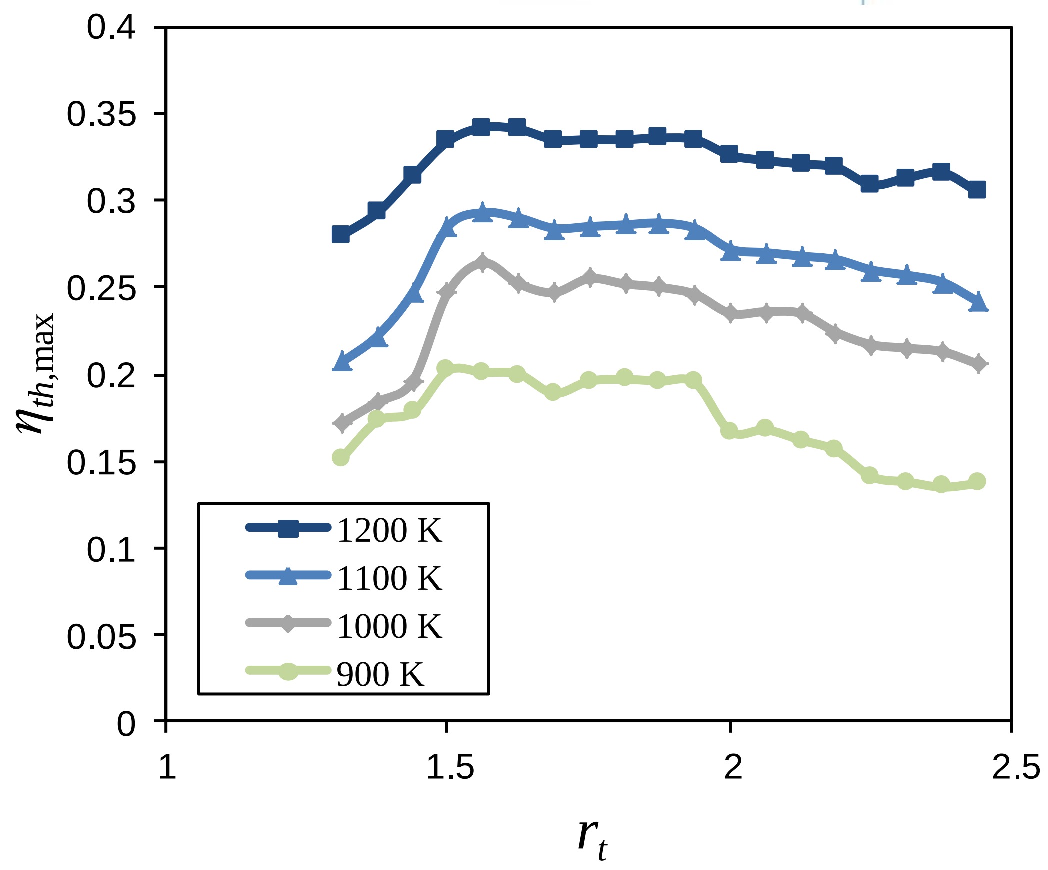
$$+\left[\dot{m}c_{p0}\ln\left[\frac{T_{10}T_4}{T_9T_3}\left(\frac{P_{10}P_4}{P_9P_3}\right)^{-R/c_{p0}}\right] + \dot{Q}_{loss,reg}/T_\infty\right]_{recuperator}$$

$$+\left[-\frac{\dot{Q}^*}{T^*} + \frac{\dot{Q}_{loss}}{T_\infty} + \dot{m}c_{p0}\ln\left(T_6/T_5\right) - \dot{m}R\ln\left(P_6/P_5\right)\right]_{receiver}$$

$$+\left[-\dot{m}c_{p0}\ln\left(T_7/T_8\right) + \dot{m}R\ln\left(P_7/P_8\right)\right]_{turbine}$$

4. Results and discussion- thermal efficiency

Maximum thermal efficiencies of 20.2% to 34.2%



Maximum thermal efficiency of the cycle for different turbine pressure ratios and receiver tube surface temperatures (for *GT2052*).

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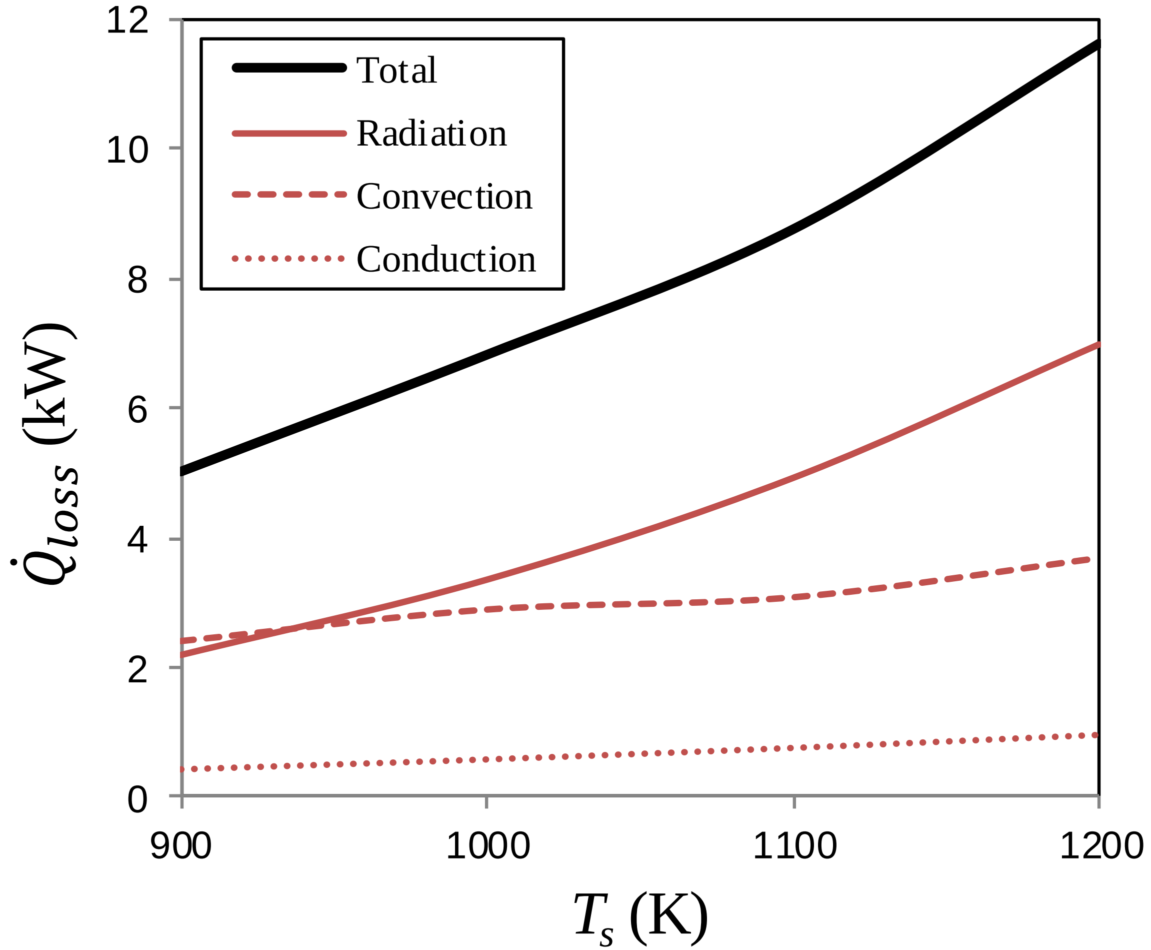
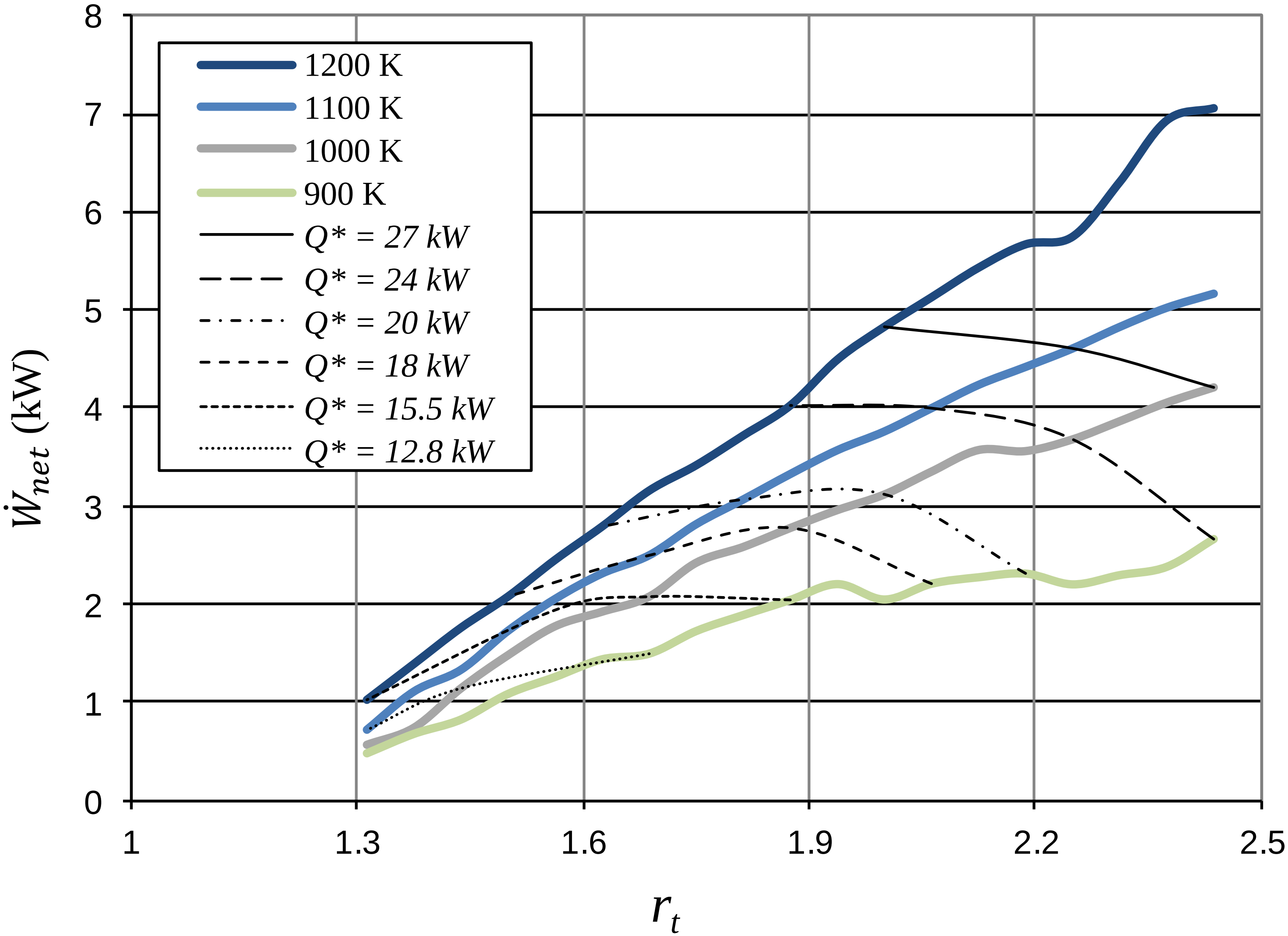
4. Results and discussion – receiver heat loss



Heat loss rate from the solar receiver as a function of tube surface temperature.

4. Results and discussion – performance map



Net power output at maximum thermal efficiency for *GT2052* as a function of dish size

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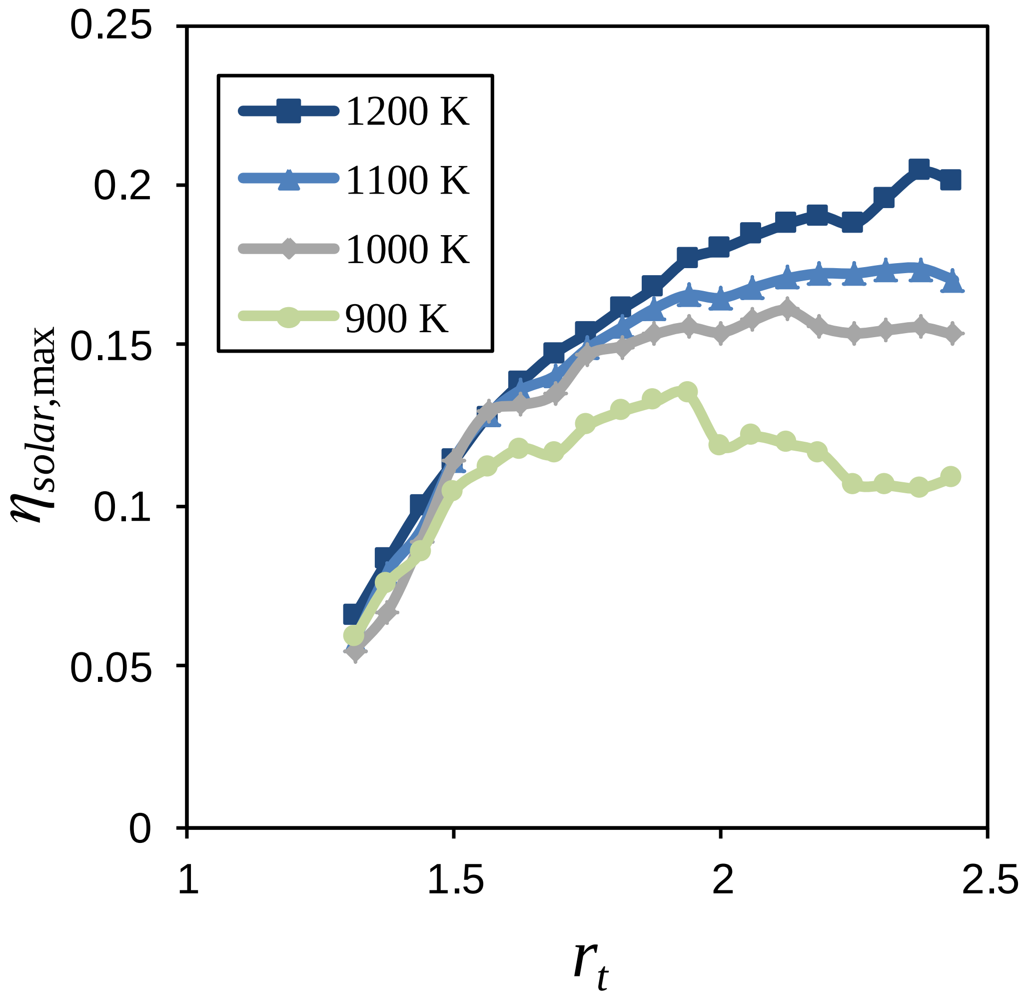
4. Results and discussion – solar conversion efficiency



Maximum solar conversion efficiencies of **13.5% to 21%** can be achieved at receiver temperatures of between 900 K and 1200 K.

Maximum solar conversion efficiency for *GT2052*.

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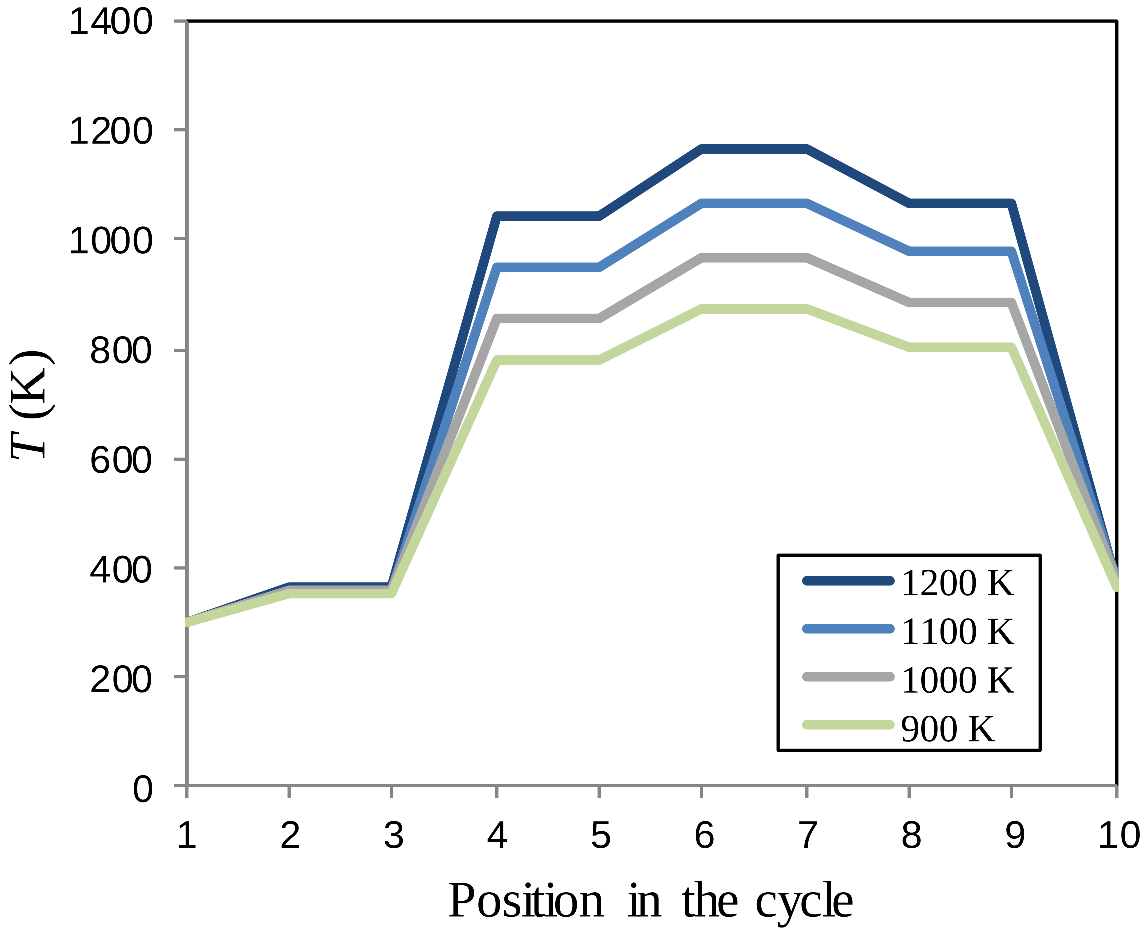
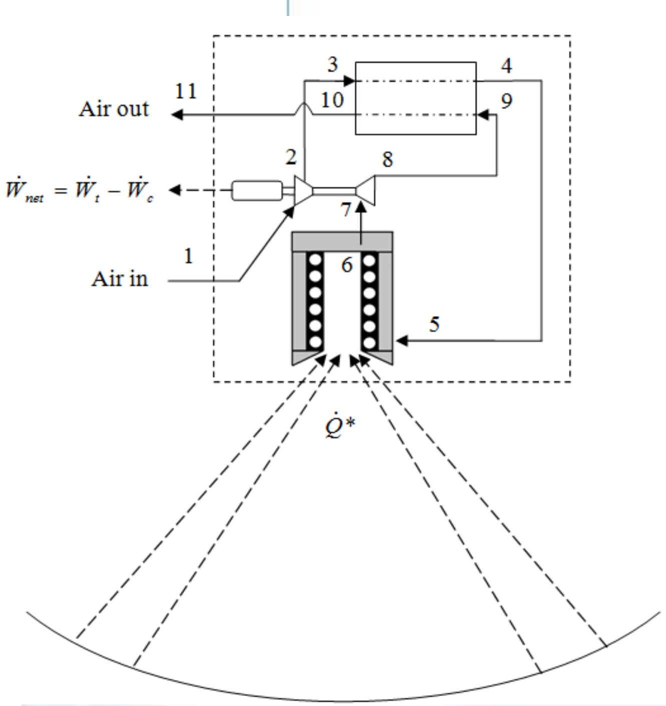
4. Results and discussion





Temperature in the cycle at different receiver surface temperatures for maximum thermal efficiency (for *GT2052*).

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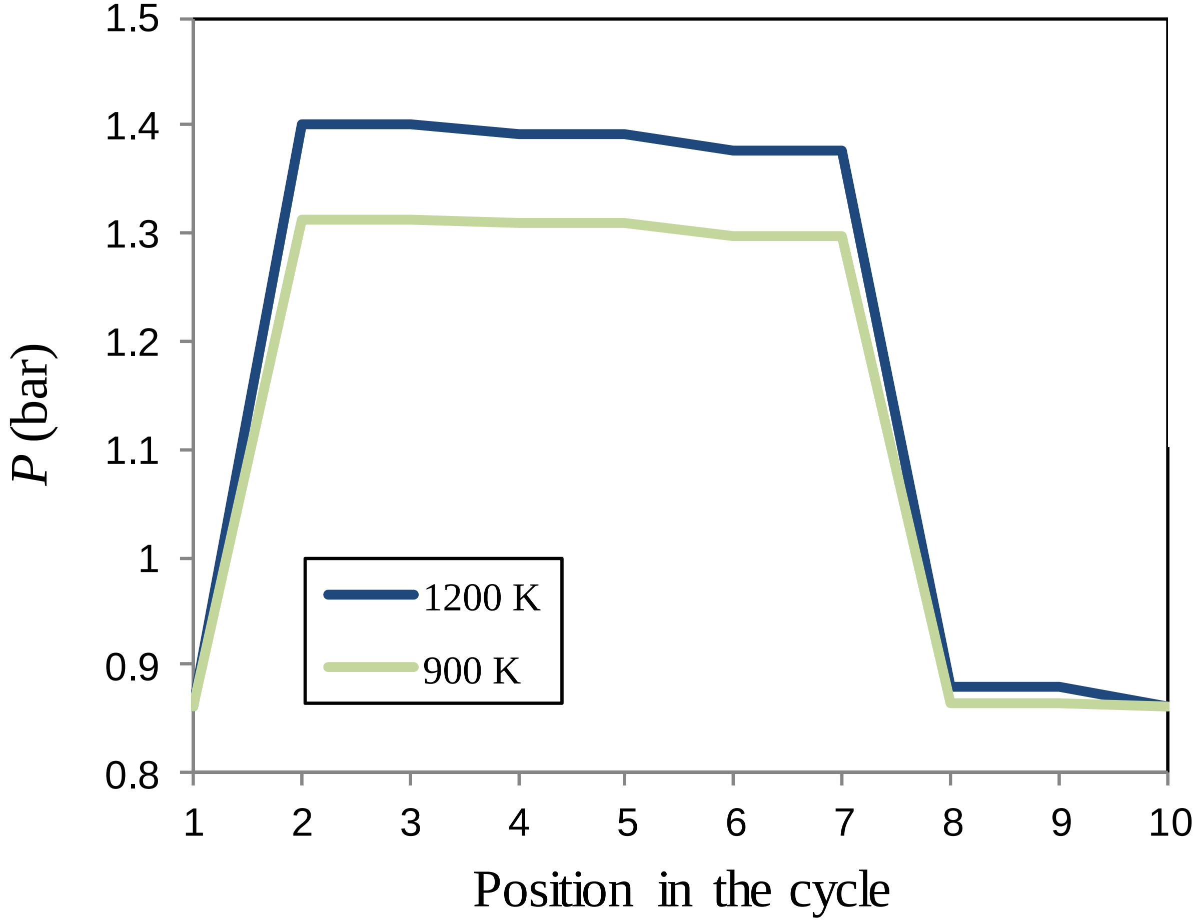
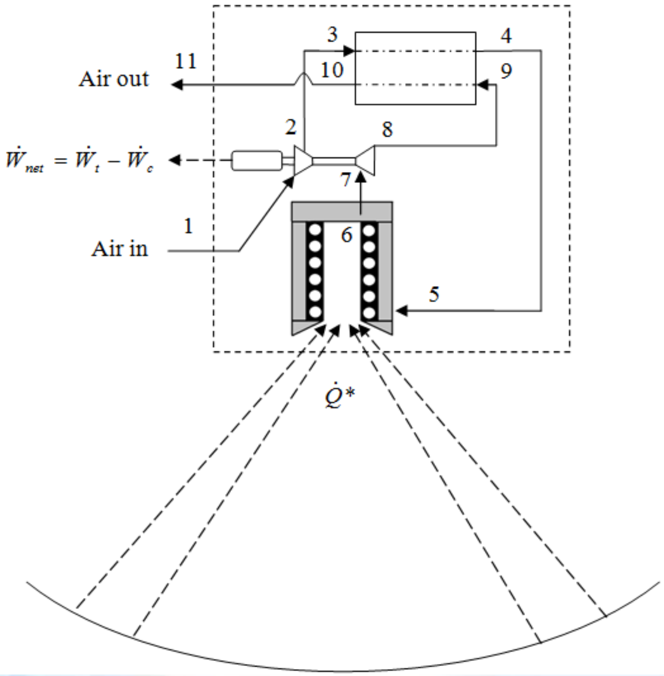
4. Results and discussion

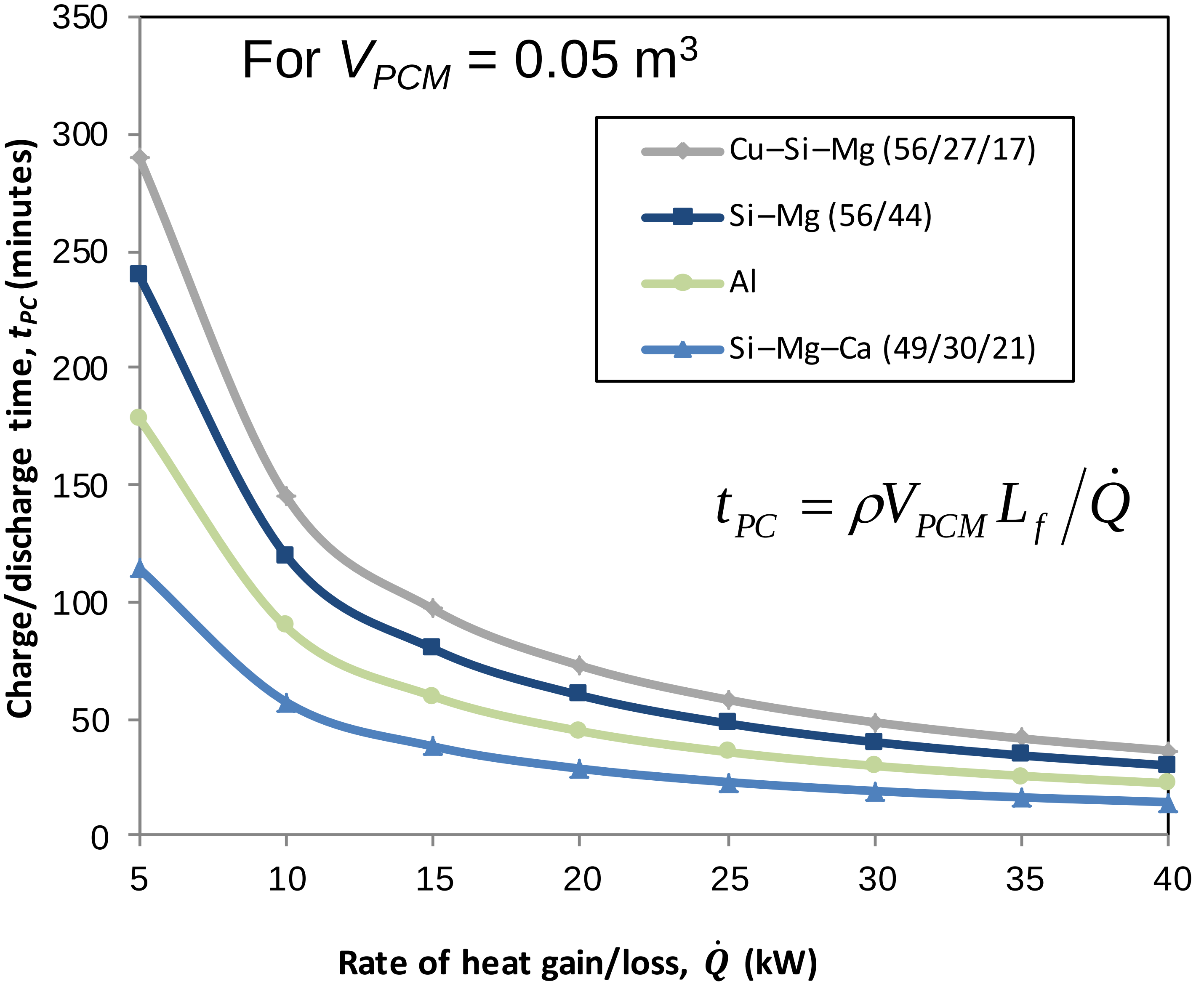




Pressure in the cycle at different receiver surface temperatures for maximum thermal efficiency (for *GT2052*).

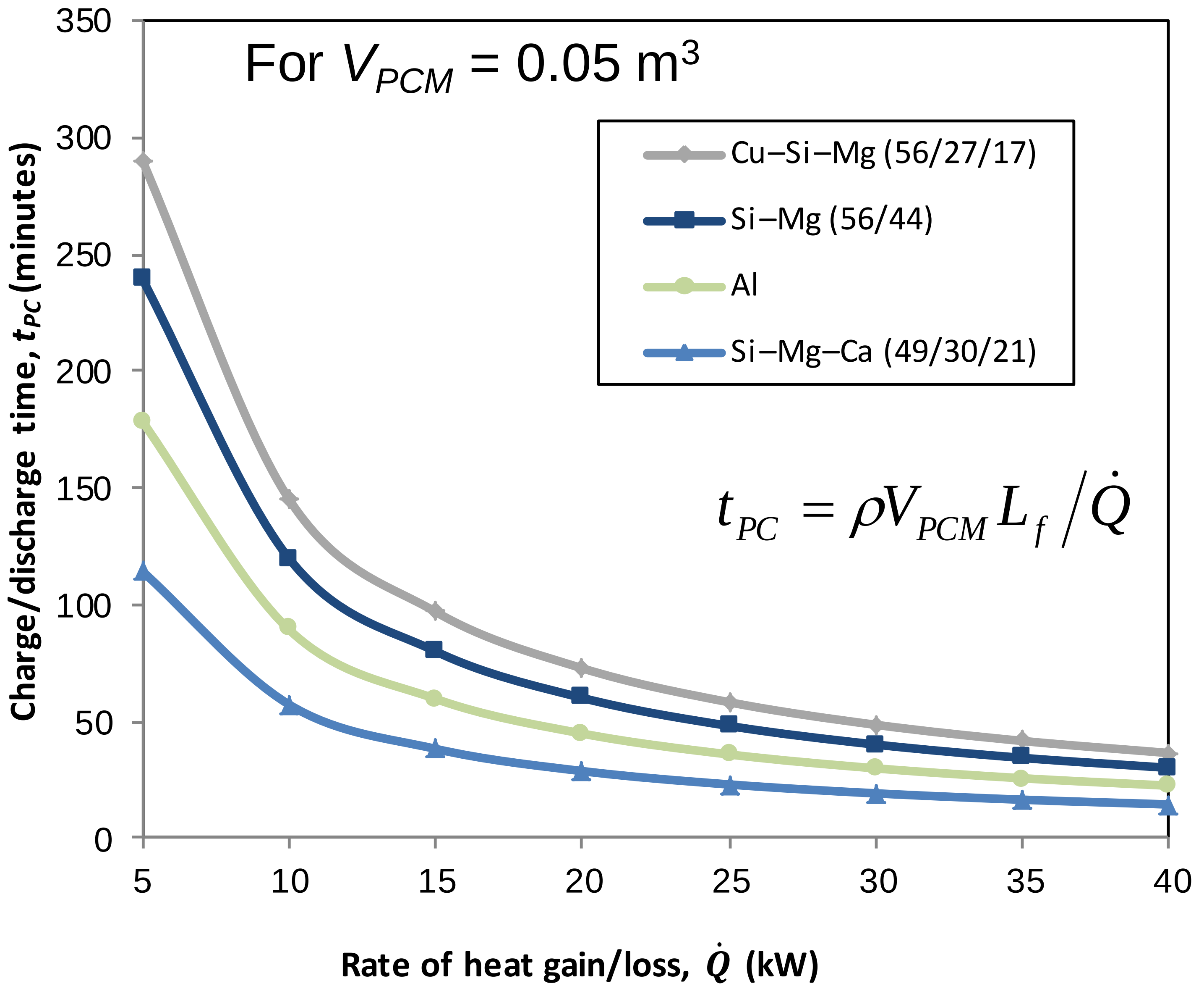
4. Results and discussion – storage time

Thermal storage time available at the phase-change temperature.



4. Results and discussion – storage time

Molten aluminum in the receiver at 933 K, could be worth investigating further as a simple and low-cost solar-dish Brayton cycle configuration.



5. Conclusion

- Solar-dish Brayton cycle advantages:
  - air as working fluid
  - cogeneration
  - hybridisation
  - thermal storage
  - cost benefits, benefits for the economy

- Problem - the phase-change temperature affects the solar conversion efficiency

- Purpose
  - Determine maximum thermal efficiency of the cycle for
    - off-the-shelf turbocharger
    - various recuperator geometries
    - fixed receiver geometry
    - metallic phase-change material at different solar receiver temperatures

5. Conclusion

- **Maximum thermal efficiencies of 20.2% to 34.2%**
- **Maximum solar conversion efficiencies of 13.5% to 21%** can be achieved at **receiver temperatures of between 900 K and 1200 K.**
- Overall, the results show that an open-cavity tubular solar receiver with metallic phase-change thermal storage material can be used together with an off-the-shelf turbocharger for power generation in a recuperated solar-dish Brayton cycle.
- The *GT2052* operating with molten aluminium in the receiver is recommended for further analytical and experimental investigation.

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Solar@UP

Dr WG Le Roux

TIA funded project:

Building a prototype:

Recuperated solar-dish Brayton cycle with turbocharger

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University of Pretoria

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Solar @ UP – Very good DNI (SAURAN)

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Solar @ UP – old dish

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Solar @ UP – old dish

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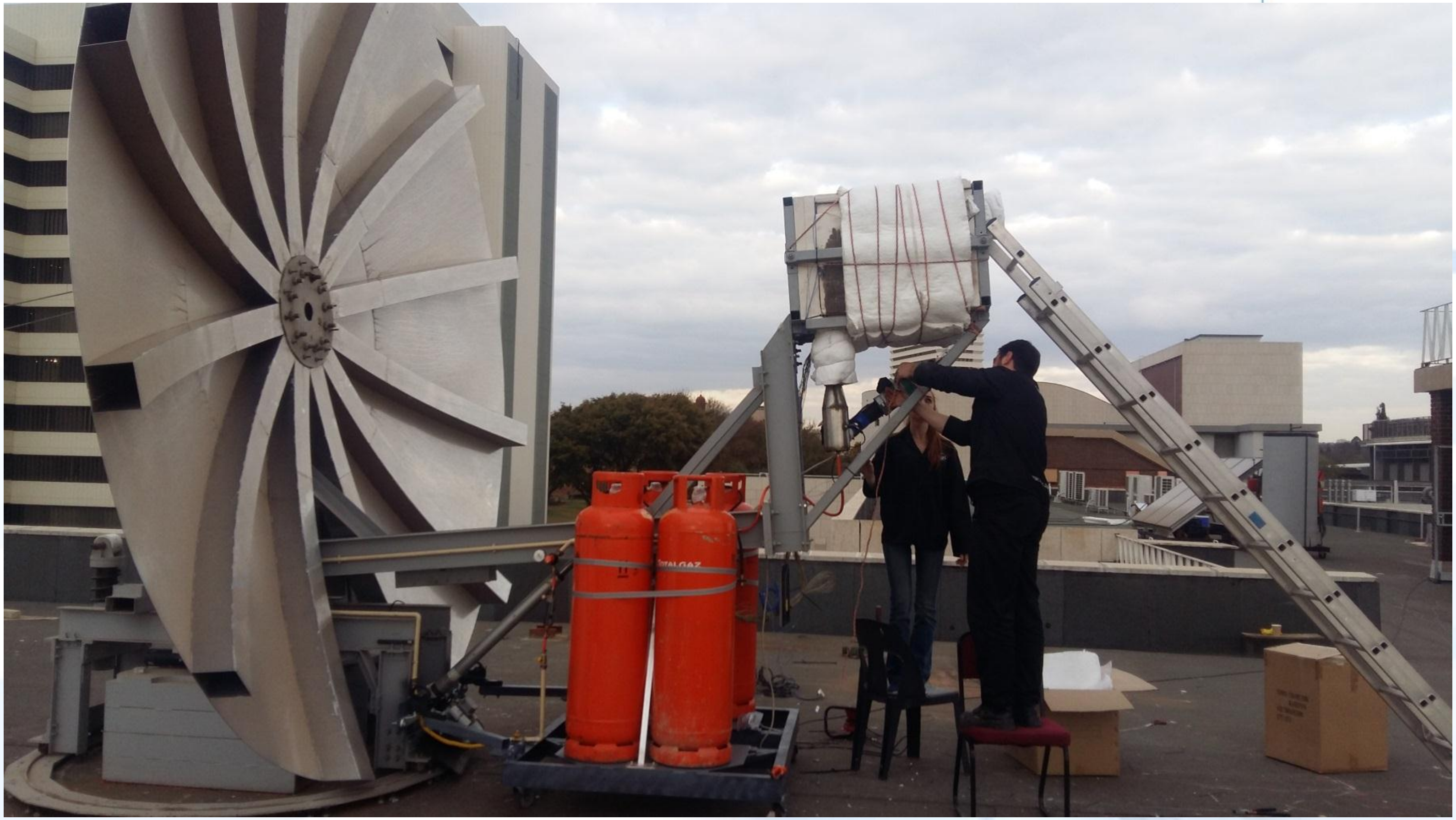
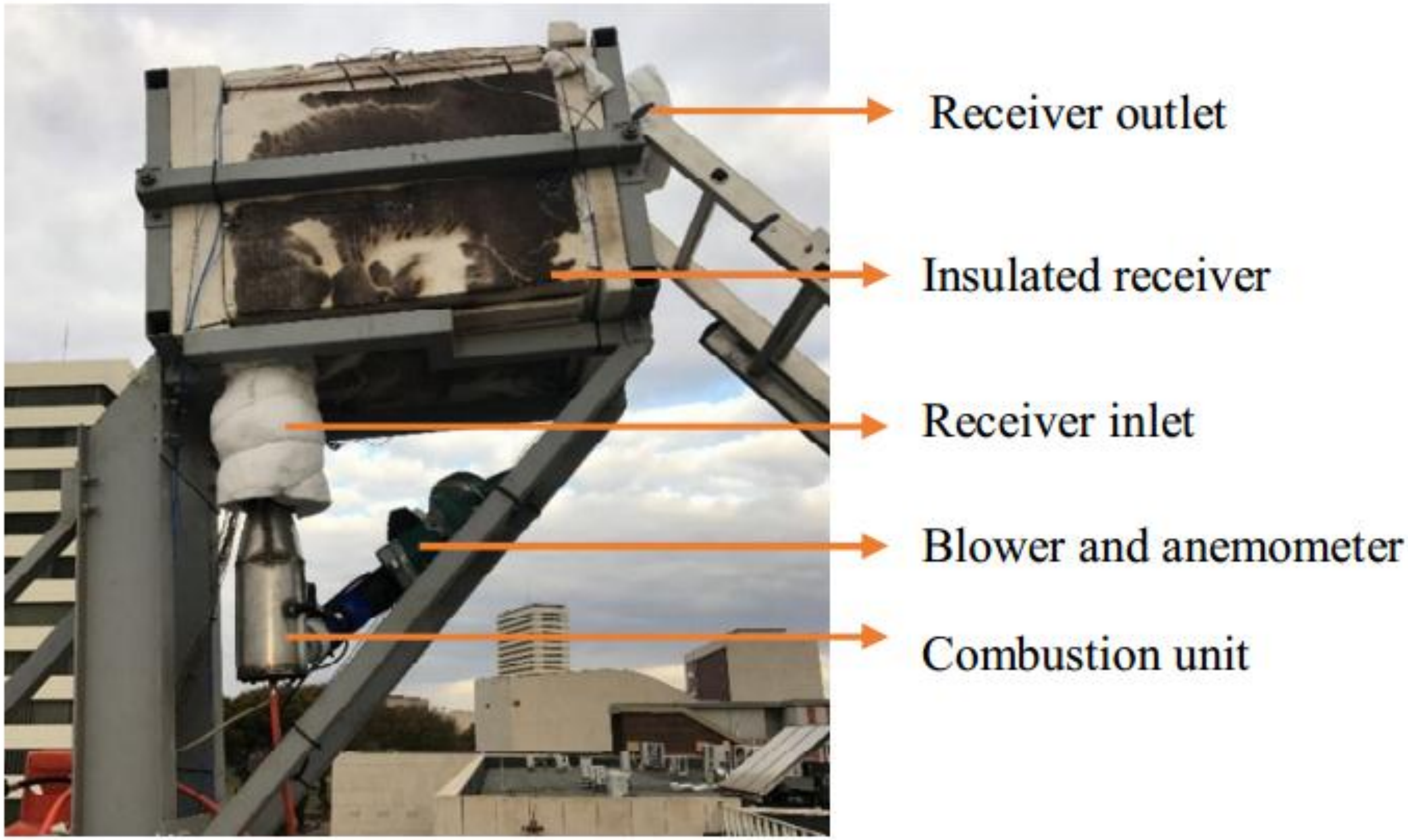
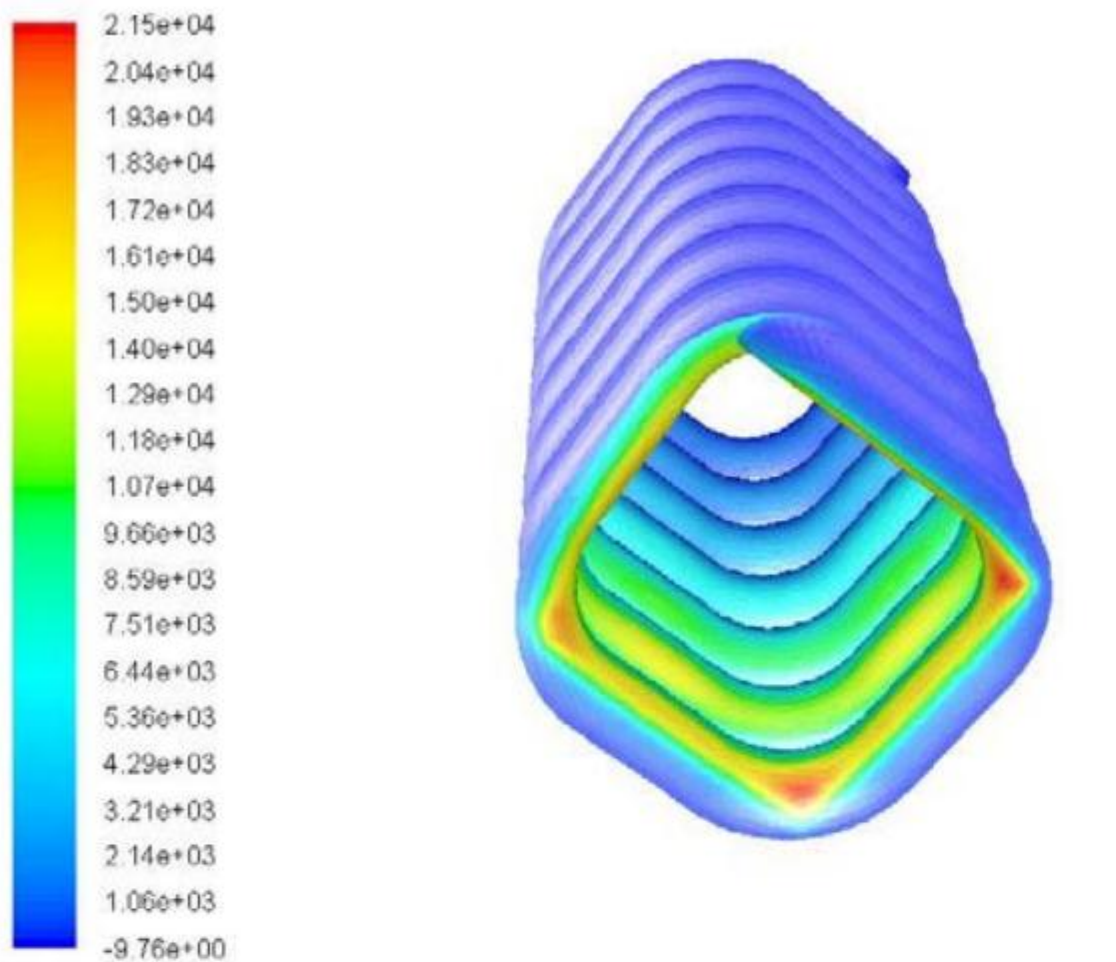


Solar @ UP – Solar receiver testing



Solar @ UP – CFD (Prof. Ken Craig)



Solar @ UP – new dish

Solar @ UP – new dish

Solar @ UP – new dish

Solar @ UP - new dish

Solar @ UP – new dish

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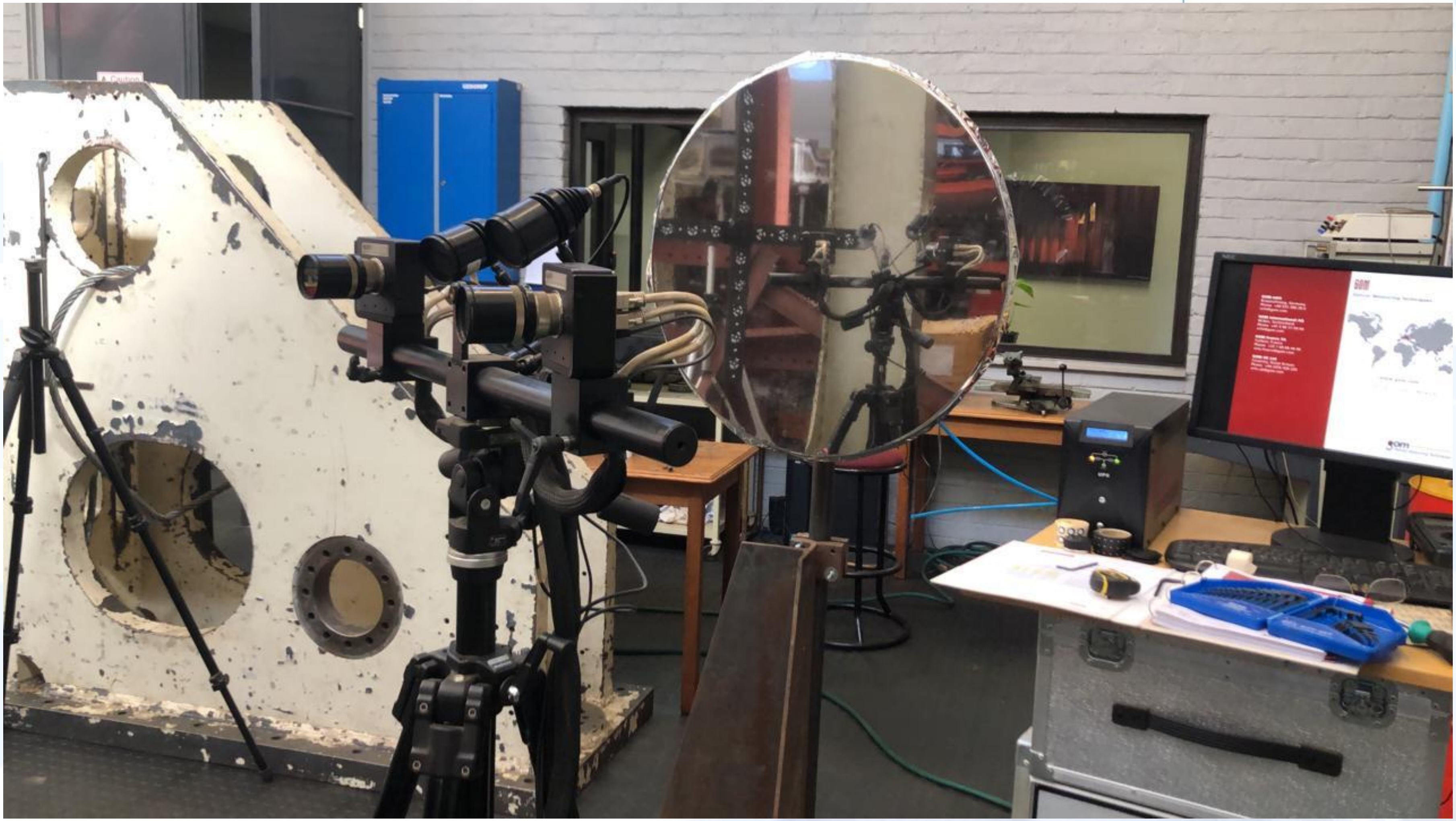
Solar @ UP – new dish (photogrammetry)



Solar @ UP – New dish (Moonlight testing)

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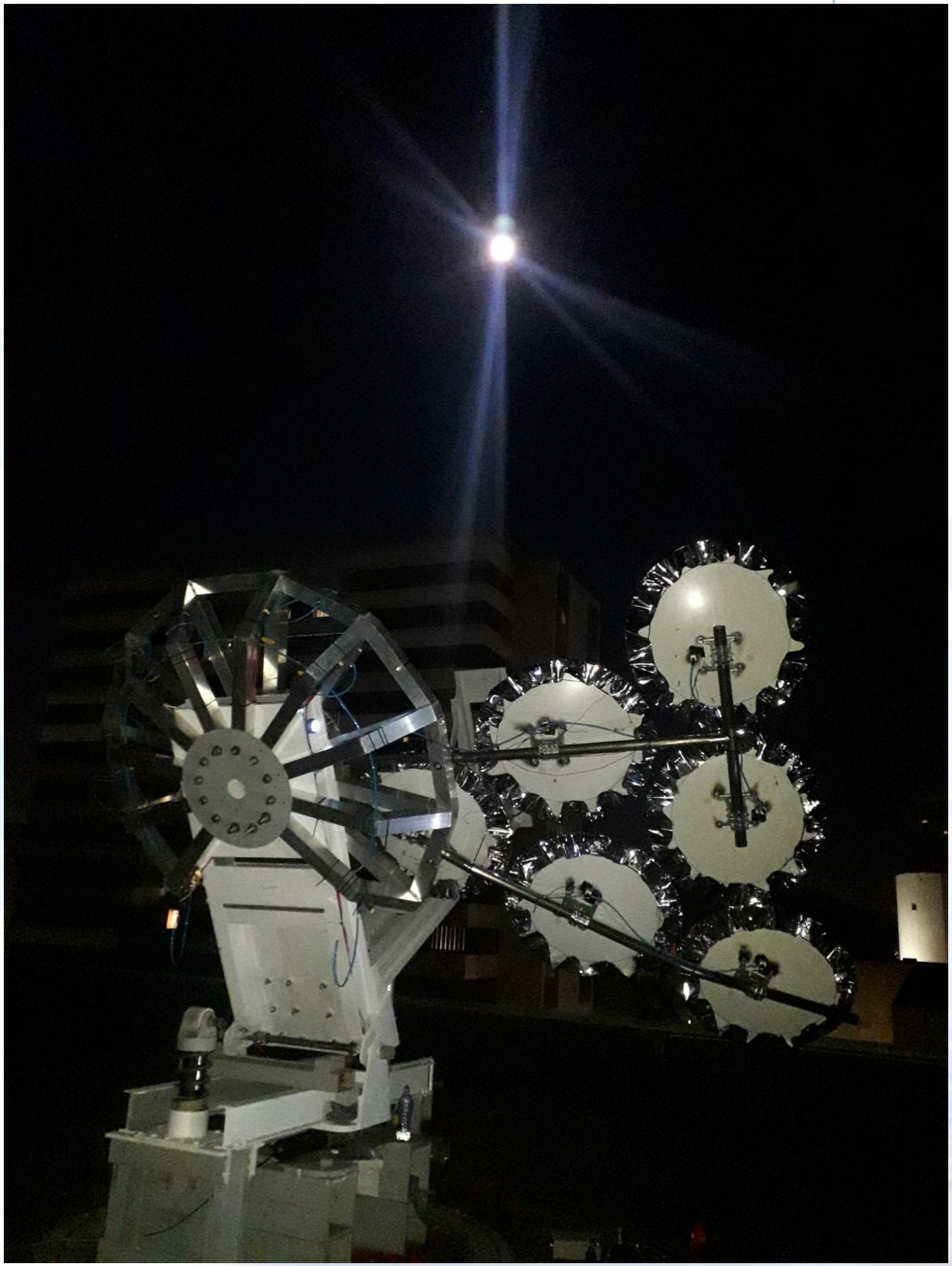

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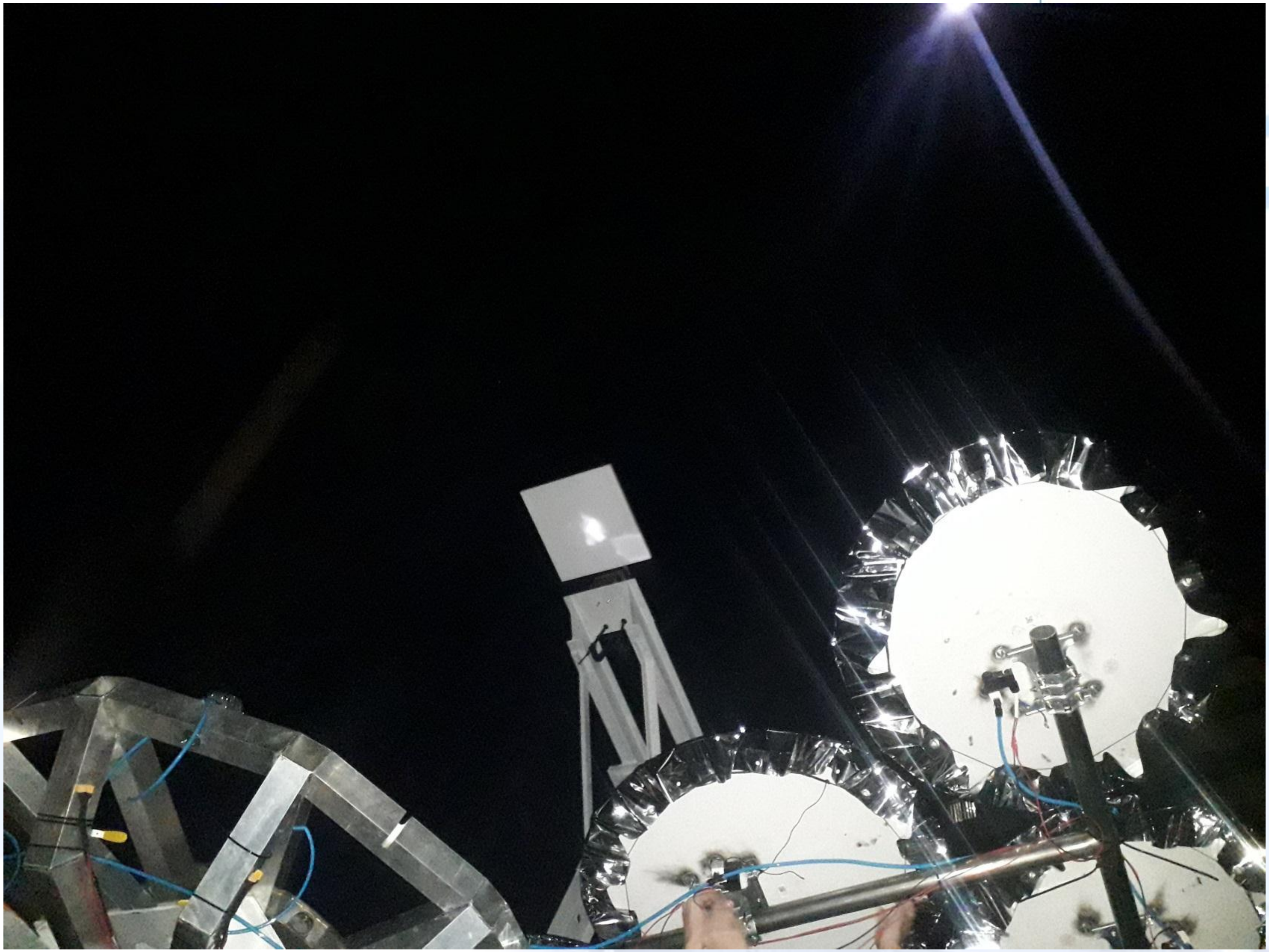
Solar @ UP



Solar @ UP – New dish (Moonlight testing)

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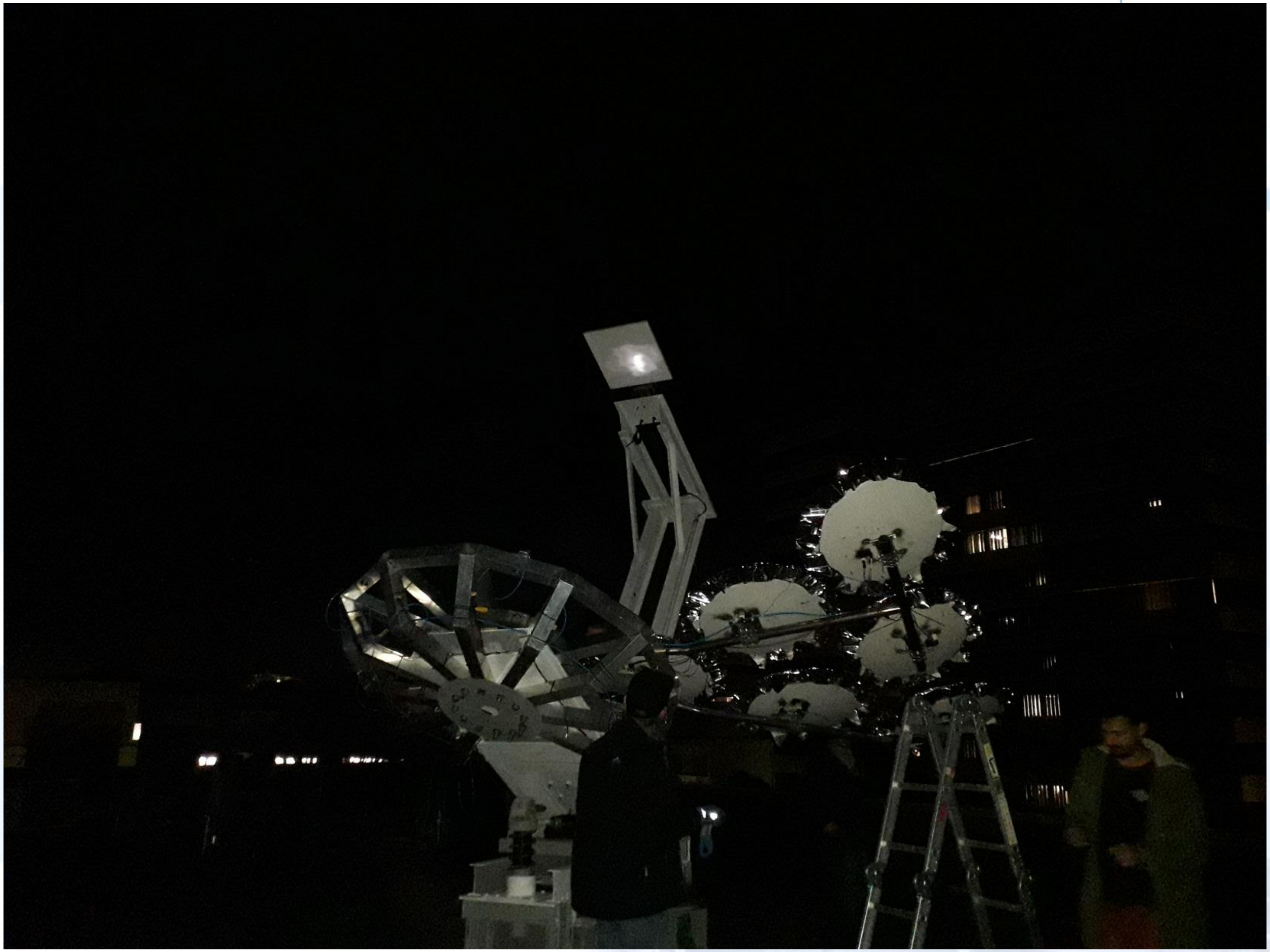

Solar @ UP – New dish (Moonlight testing)

Solar @ UP – Smaller dish setup (moonlight testing)

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Solar @ UP – Smaller dish setup (moonlight testing)

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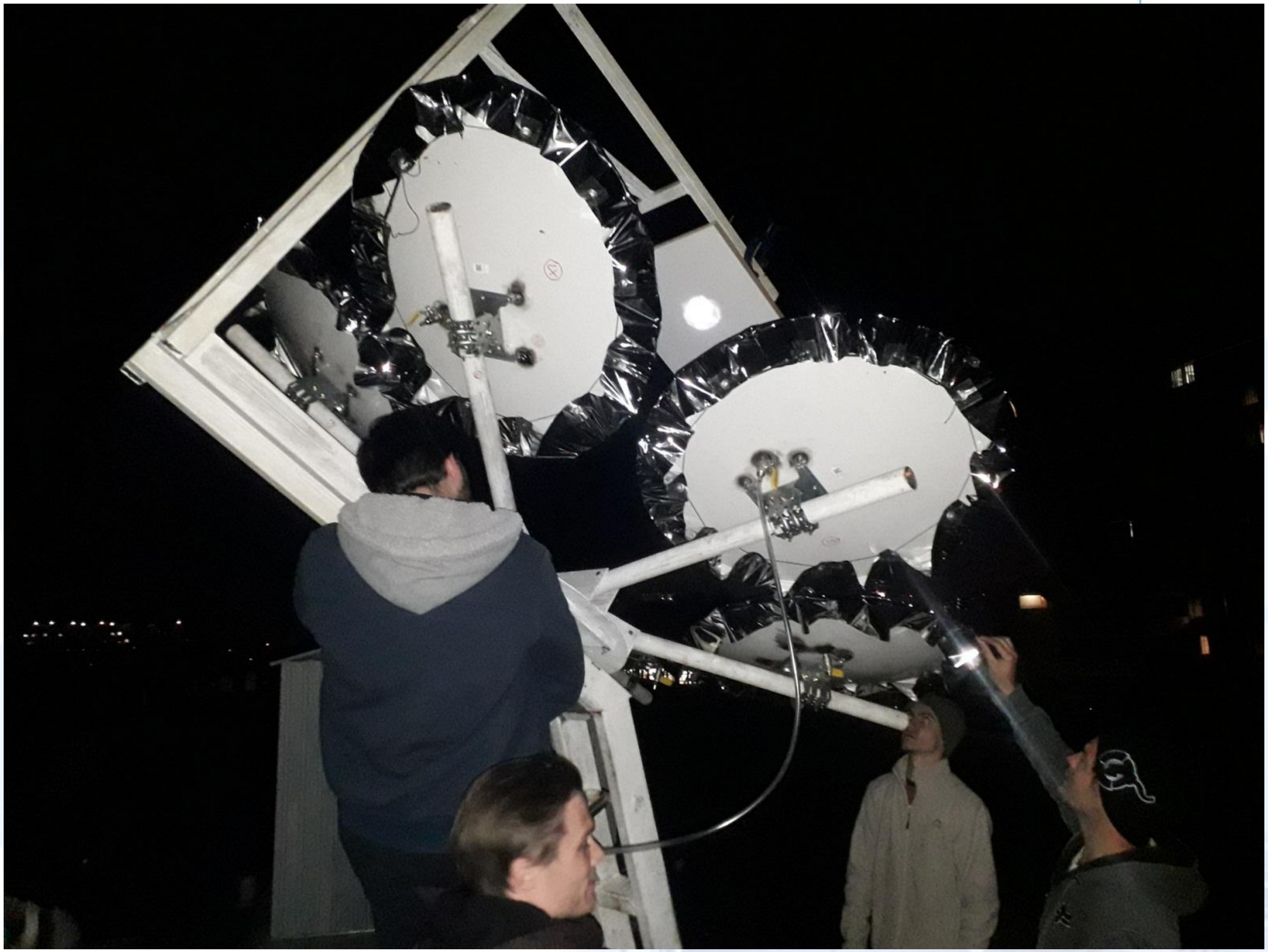
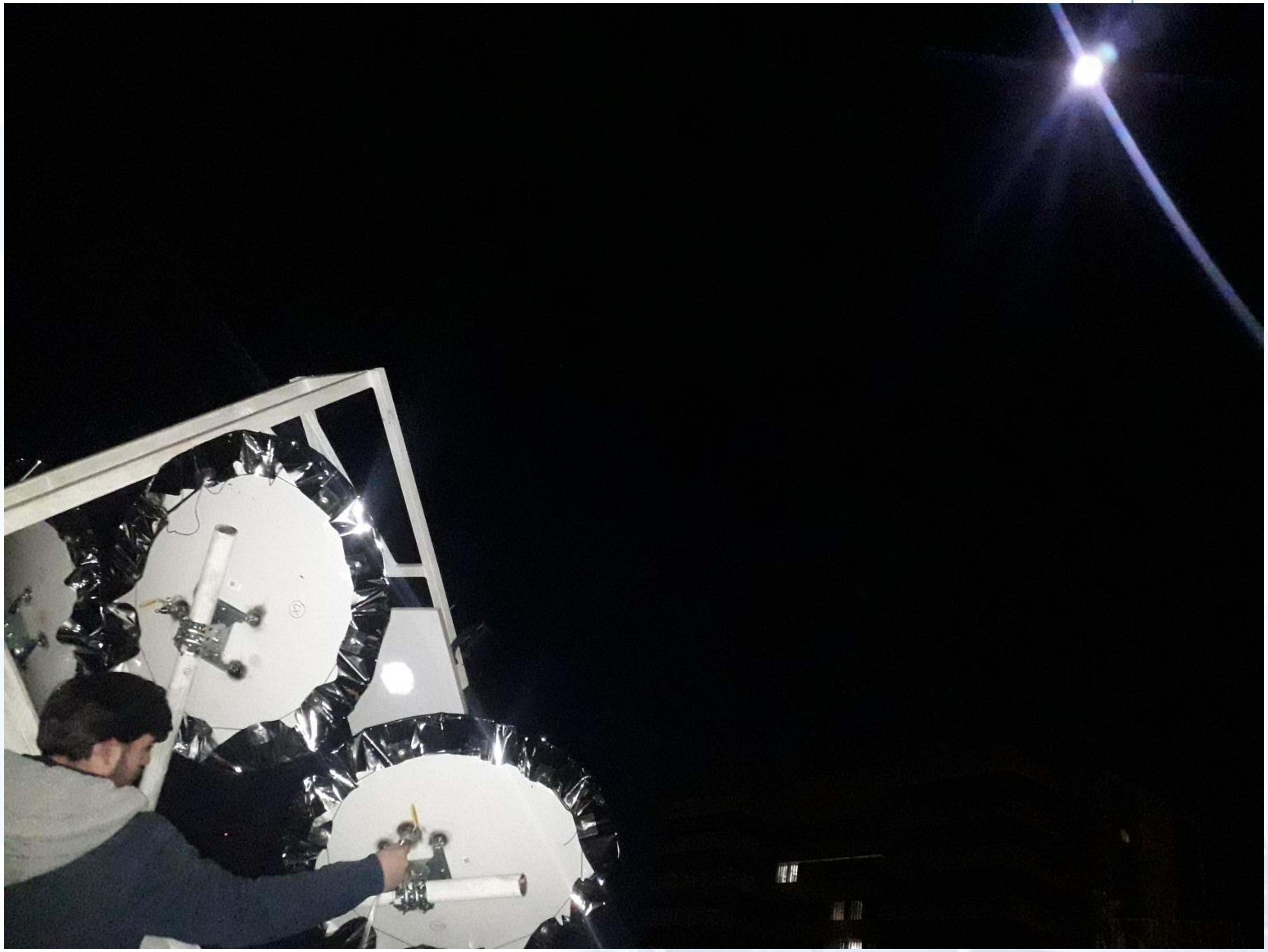
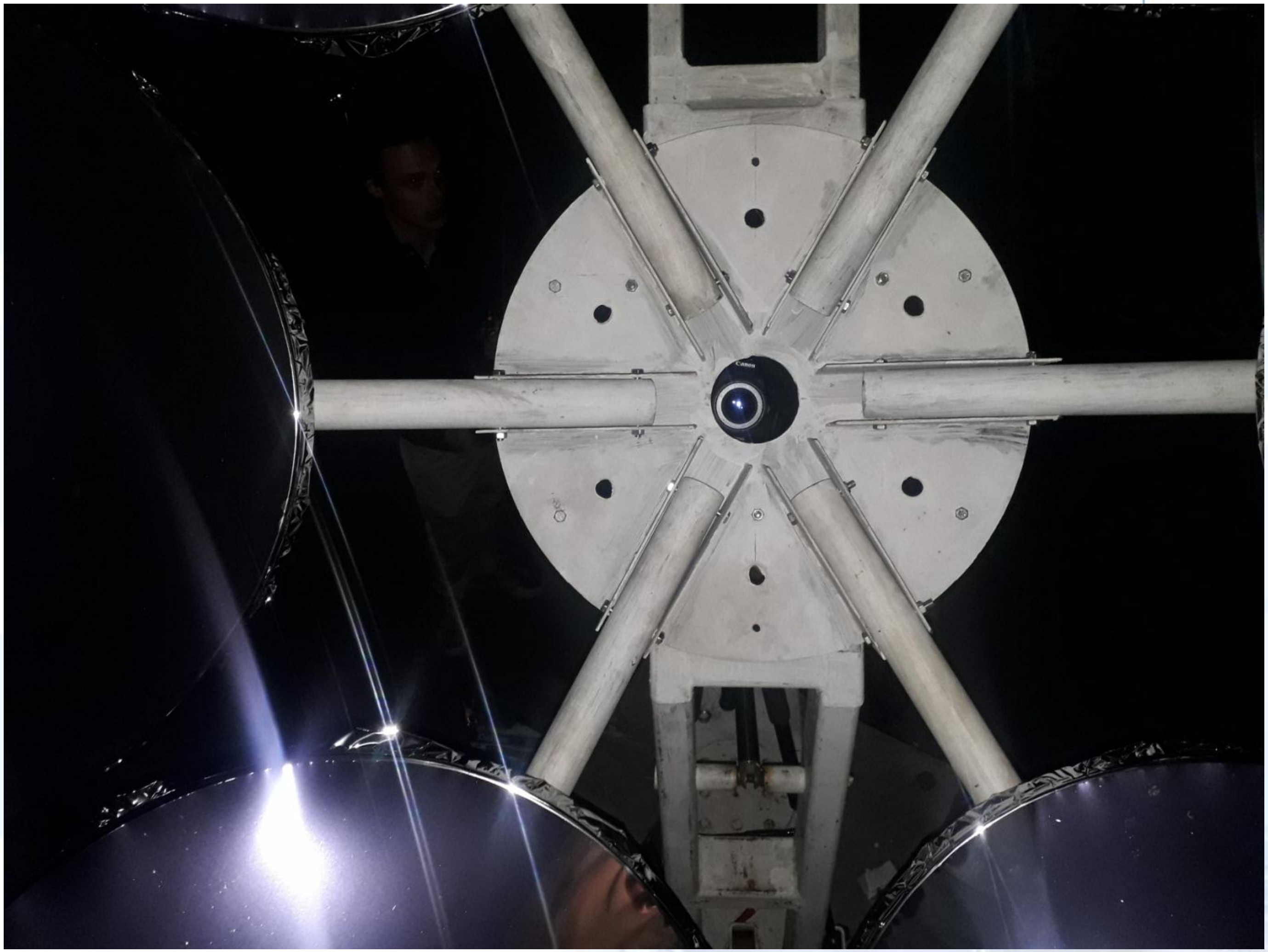


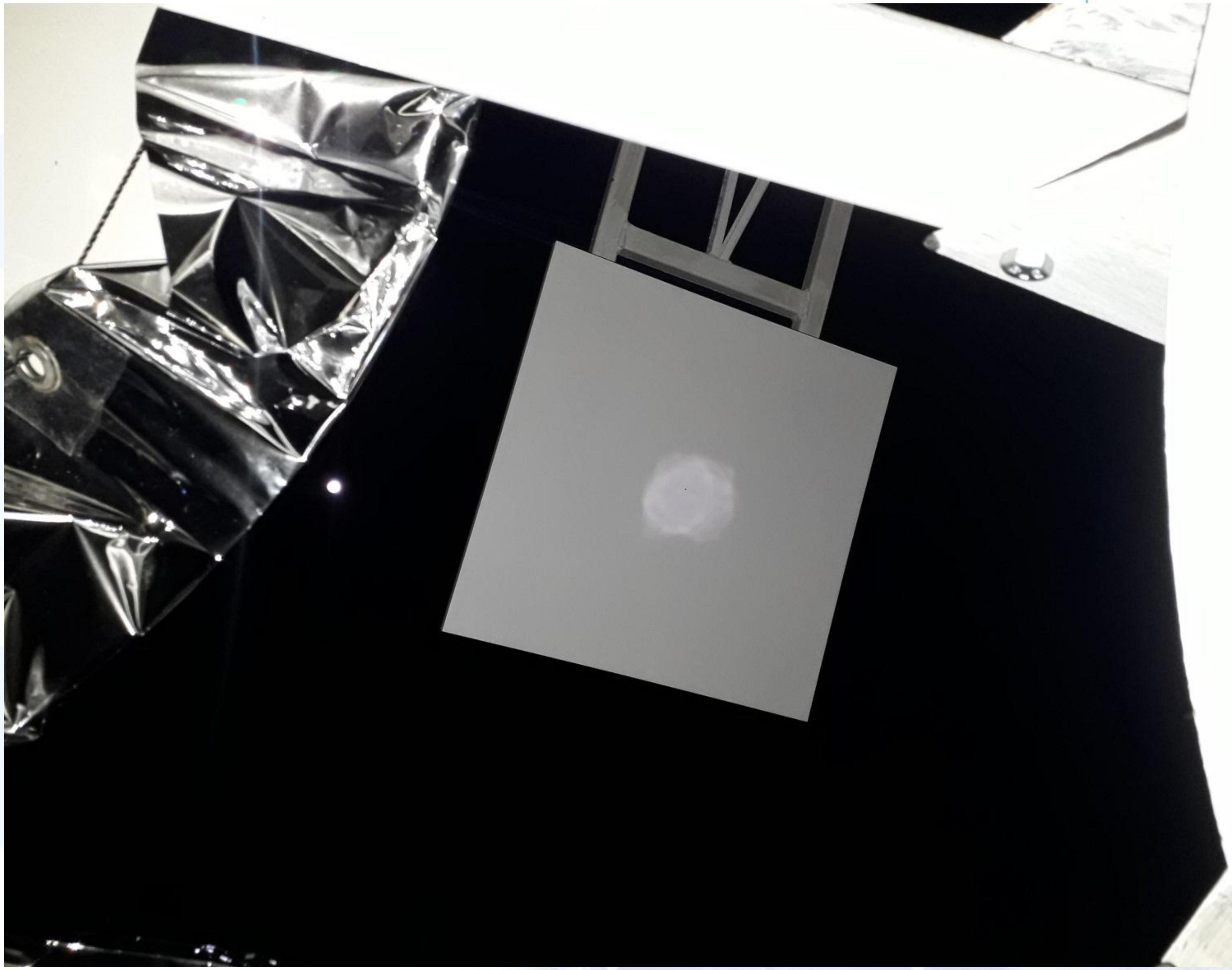
Solar @ UP – Smaller dish setup (moonlight testing)



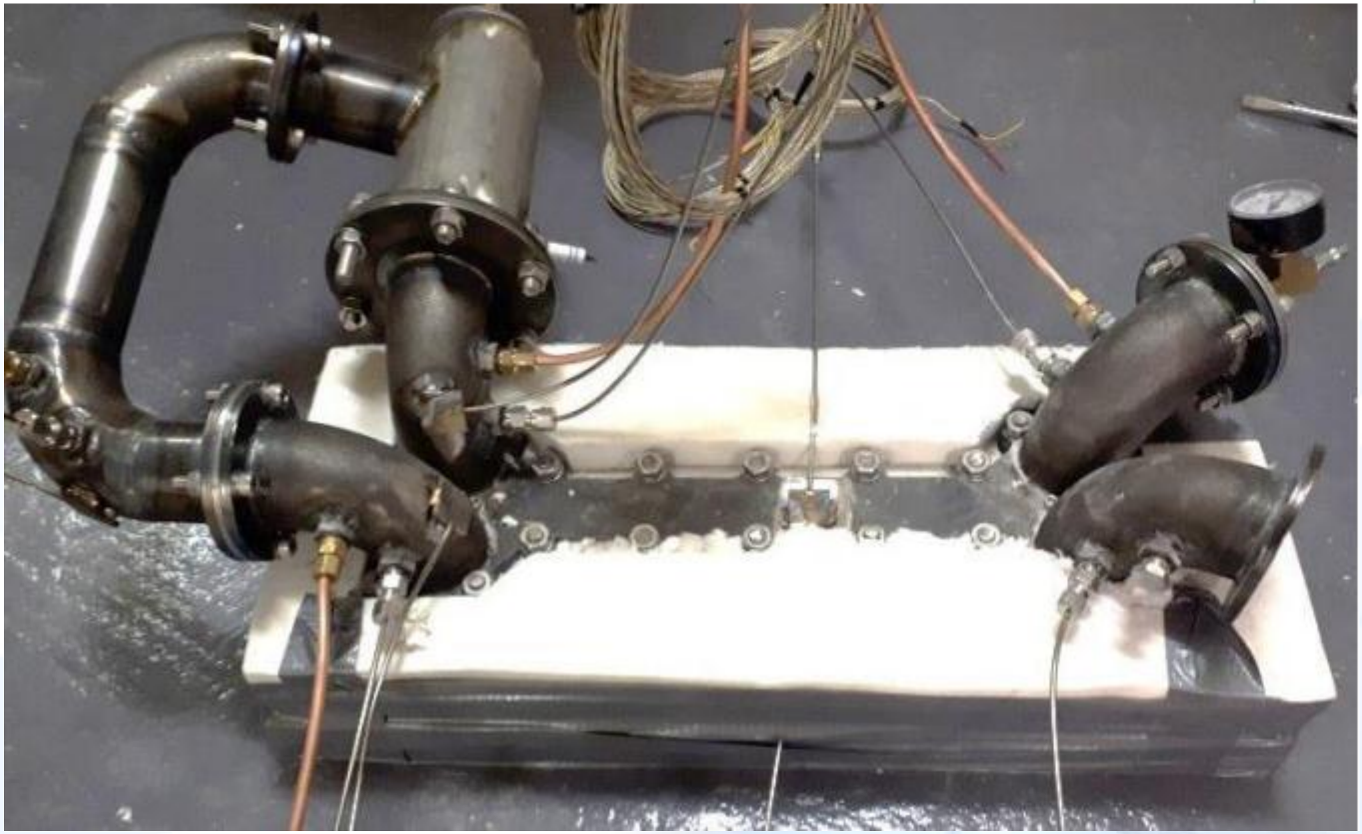
Solar @ UP
– Moonlight testing for flux mapping



Solar @ UP
– Moonlight testing for flux mapping



Solar @ UP – Recuperator testing



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Thank you

Questions?

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