Cascade system using both trough system and dish system for power generation

Nomenclature

$A_{dishCollector}$	Aperture area of each dish collector, m^2
$A_{stirling,1}$	Heat transfer area of Stirling engine at air side, m^2
$A_{stirling,2}$	Heat transfer area of Stirling engine at water side, m^2
$A_{troughCollector}$	Aperture area of each trough collector, m^2
d_{ap}	Aperture diameter of volumetric receiver, m
d_{cav}	Diameter of volumetric receiver cavity, m
$d_{i,air}$	Inner diameter of air tube, m
I_{DNI}	Direct Normal Irradiance, W/m^2
$k_{stirling}$	Specific heat ratio of the working gas in Stirling engine
l_{cav}	Depth of volumetric receiver cavity, m
n	Amount of working gas in each Stirling engine, mol
n_{se}	Speed of Stirling engine, s^{-1}
$n_{stirlingEngine}$	Number of Stirling engines in the Stirling engine array
p_c	Exhaust pressure of turbine, Pa
p_s	Main steam pressure of turbine, Pa
p_{amb}	Ambient pressure, Pa
p_{cp}	Water pressure after condensate pump, Pa
$p_{deaerator}$	Outlet pressure of deaerator, Pa
p_{dish}	Air pressure in dish, Pa
$P_{generator}$	Power of generator, W

p_{trough}	Air pressure in trough, Pa
$q_{cond,tot}$	Total conduction loss
$q_{conv,tot}$	Total convection loss
$q_{dish,air}$	Energy absorbed by air in the dish collector
q_{in}	Solar energy launched into dish receiver aperture, W
$q_{rad,emit}$	Radiation emitted by dish receiver
$q_{rad,reflect}$	Reflected radiation by volumetric receiver, W
T_s	Main steam temperature of turbine
$T_{1,afterstirling}$	Air temperature after heating Stirling engine
T_{amb}	Ambient temperature, K
$T_{dish,inlet}$	Dish inlet temperature, K
$T_{dish,outlet}$	Dish outlet temperature
$T_{s,d}$	Designed mean steam temperature of turbine
$T_{trough,outlet}$	Trough outlet temperature
$U_{stirling,1}$	Overall heat transfer coefficient of Stirling engine at air side, W/(m^2·K)
$U_{stirling,2}$	Overall heat transfer coefficient of Stirling engine at water side, W/(m^2·K)
v_{wind}	Ambient wind speed, m/s
x	Dryness fraction

Abbreviations

EES	Engineering Equation Solver
SAM	System Advisor Model
SES	Stirling Energy System

Greek Symbols

α_{eff}	Effective absorptance
δ_a	Thickness of air tube in volumetric receiver, m
δ_{ins}	Thickness of receiver insulating layer, m

$\Delta T_{oil,water,min}$	Minimum temperature difference between oil and water in the oil-to-water heat exchanger, K
ϵ_{insu}	Emissivity of reciver insulating layer
$\eta_{shading}$	Shading factor
γ	Intercept factor
$\gamma_{stirling}$	Compression ratio of Stirling engine
λ_{ins}	Thermal conductivity of receiver insulating layer, W/(mK)
ρ	Reflectivity
θ_{dish}	Dish aperture angle ($0°$ is horizental, $90°$ is vertically down)

1 Introduction

- Background Information
  1. Why do we need cascade system
  2. What is the advantage of cascade system
  3. What are others' works
  4. What have been done
  5. What to be done
  6. What can we improve
  7. What have we done
- System specification
  1. Environment
  2. Trough collector
  3. Dish collector
  4. Steam turbine
  5. Stirling engine

  1. Air circuit
  2. Water circuit
  3. Oil circuit
  4. System efficiency
- Separate system
- Results

Energy is the crucial part for the infrastructure and maintenance of society. With the increase amount of energy consumption, our quality of life has been improved significantly. However, nowadays the world energy consumption is highly dependent on fossil fuels, which supplied 81.3% of the world's energy consumption in 2012 according to the data of World Bank Group. Using fossil fuels a lot is afflicting the environment, which is sacrificing our quality of life. Environmental pollutions and global warming are becoming serious problem, and it is urgent to find clean and renewable energy to substitute the fossil fuels.

Solar energy is a clean, sustainable, wide-distributed energy. The total amount of solar energy is very huge. The amount of sunlight striking the earth's atmosphere continuously is 1.75×10^5 TW, even if 1% of it could be converted into electric energy with a 10% efficiency, it would produce 175 TW, much larger than the total global energy needs predicted to be 25?30 TW in 2050[1]. But at the same time, solar energy has some disadvantages for its low flux density and large fluctuation due to daily and seasonal variations exacerbated by variations owing to weather. Concentrated solar power (CSP) technology has the ability to overcome these disadvantages and believed to be the future power generation technology.

There are 4 common forms of CSP technologies, parabolic trough, dish Stirlings, concentrating linear Fresnel receiver, and solar power tower. Different types of collectors and different technologies for electricity generation are suitable for different working temperature zones with different costs.

Cau, G. and D.Cocco[2] reported a comparative performance analysis of CSP plants using parabolic trough and linear Fresnel collectors, thermal oil as heat transfer fluid and an Organic Rankine Cycle (ORC) power generation unit. A two-tank direct thermal storage system are included and in the Rankine cycle, regenerator, 4 6 steam extractions and air-cooler condenser are used. The performance analysis of the two types of system shows that CSP plants based on linear Fresnel collectors lead to higher values of electrical energy production per unit area of land and CSP plants based on parabolic troughs gives better values of energy production per unit area of collector.

In this paper, an idea of cascade collection and cascade utilisation of solar energy with higher efficiency is presented. Parabolic trough collectors are used to collect lower temperature energy with lower cost and dish collectors are used to collect higher temperature energy with higher efficiency. Rankine cycle is used to work in lower temperature zone and Stirling cycle is used to work in higher temperature zone. Furthermore, effective topological structures are considered to take full advantages of thermodynamic characters of different components of the system. The cold chamber of Stirling engine is cooled by condensed fluid of Rankine cycle to use the heat released by Stirling engine.

2 System description

An EES model was used to study the characteristics of the cascade system. Figure 1 shows the sketch of the cascade system. Dish collectors are used to provide heat for Stirling engines and air-to-water heat exchanger. Trough collectors are used to provide heat for preheating, evaporating and superheating in the Rankine cycle. Water is used as the working fluid of Rankine cycle, which is heated in the cold chamber of Stirling engines, preheater, evaporator, superheater, and air-to-water heat exchanger successively, and then expand in turbine, condense in condenser. Pumps are used to change the pressure of fluids. Stirling engines are used for power generation and cooled by feed water of the Rankine cycle. State number pairs of different fluids are marked on the sketch. The first number of a number pair indicates the fluid type, the second number of a number pair indicates the state point of the fluid. Number pairs with solid circle indicate saturated liquid states ($x = 0$), and with dotted circle indicates saturated gas states ($x = 1$).

To build the cascade system model, several simplifying assumptions are made:

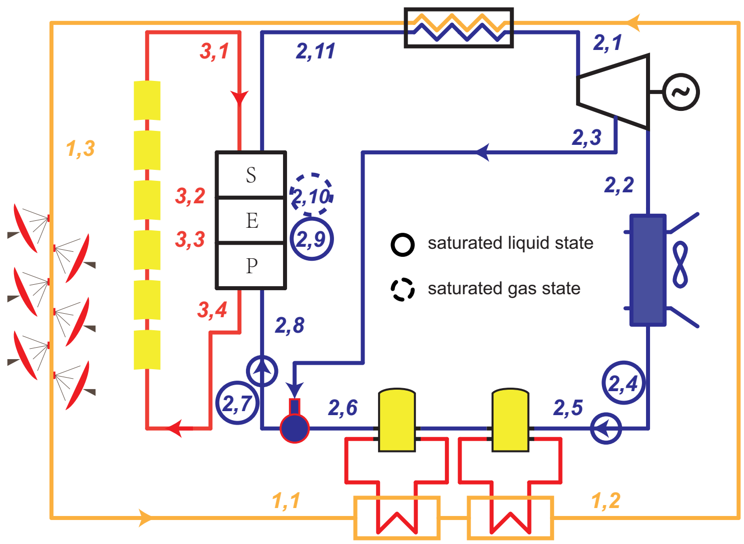

Figure 1: Sketch of the cascade system

- Steady state at nominal load of the system is analyzed
- Pressure drop due to flow is negligible
- The leak of working fluid in the pipes is neglected
- Same isentropic efficiency of steam turbine with different loads and in different stages
- Heat loss that occurs from the tube to the atmosphere is not considered
- There is no heat loss to the environment for Stirling engines
- Simple models are used of some processes and equipments
- A symmetrical regenerator behaviour is assumed so that a single effectiveness can be defined as $e = \dfrac{T_R - T_L}{T_H - T_L}$ [3, 4]

3 System specification

Table 1 shows the basic design parameters of the cascade system.

4 System model

The system is built in several blocks. These blocks are made of circuits and efficiency calculations. Two circuits, air circuit and water circuit, are built in

Table 1: Parameters of the cascade system

Nominal electric power			
$P_{generator}$	6×10^6 W		
Environment			
I_{DNI}	700 W/m^2	T_{amb}	293 K
p_{amb}	1×10^5 Pa	v_{wind}	4 m/s
Dish collector			
$T_{dish,inlet}$	623K	$T_{dish,outlet}$	1073 K
p_{dish}	5×10^5 Pa	$A_{dishCollector}$	87.7 m^2
Trough collector			
$\Delta T_{oil,water,min}$	15 K	$T_{trough,outlet}$	623 K
p_{trough}	2×10^6 Pa	$A_{troughCollector}$	545 m^2
Stirling engine			
$T_{1,afterstirling}$	673 K	n_{se}	10 s^{-1}
$U_{stirling,1}$	30 W/(m^2·K)	$U_{stirling,2}$	150 W/(m^2·K)
$A_{stirling,1}$	8 m^2	$A_{stirling,2}$	8 m^2
$k_{stirling}$	1.4	$\gamma_{stirling}$	3.375
n	7.73×10^{-2} mol	$n_{stirlingEngine}$	100
Steam turbine			
T_s	340°C	p_s	2.35×10^6 Pa
p_c	1.5×10^4 Pa	$T_{s,d}$	390°C
$p_{c,p}$	1×10^6 Pa		
Deaerator			
$p_{deaerator}$	1×10^6 Pa		

some specific states and in some components. Known parameters of the states, we can get the efficiency of the system and the overall efficiency of separated systems.

4.1 Air circuit

In air circuit, efficiency of dish collectors needs to be calculated. Fraser, in his dissertation[5], built a performance prediction model of Stirling dish system, which has detailed description of the dish collector model. The model is also used in the software SAM, which provides performance and financial models for facilitate decision in the renewable energy industry.

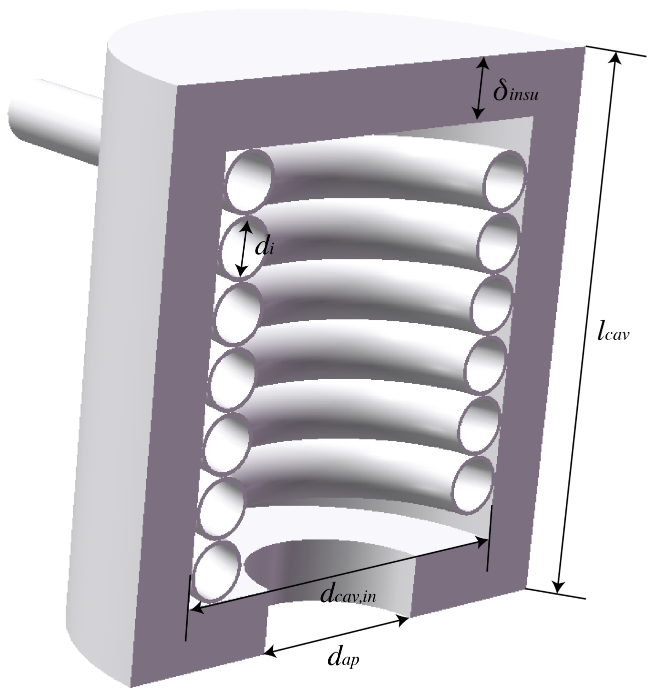

Figure 2: Structure of the dish receiver

In our cascade system, the structure of the dish receiver is as shown in Figure 2. The dish receiver model concerns the losses includes: collector losses due to mirror reflectivity, receiver intercept losses, losses due to shading, and thermal losses. Thermal losses take the largest portion of all those losses, which are due to conduction, convection and radiation. Figure 3 shows the heat network of dish receiver, which concerns the losses:

- Radiation losses reflected off of the receiver cavity surfaces and out of the receiver through the aperture. ($q_{rad,reflect}$)
- Conductive losses through the receiver insulating layer. ($q_{cond,tot}$)
- Free convection from the cavity in the absence of wind. ($q_{conv,free}$)
- Forced convection in the presence of wind. ($q_{conv,forced}$)
- Emission losses due to thermal radiation emitted from the receiver aperture. ($q_{rad,emit}$)

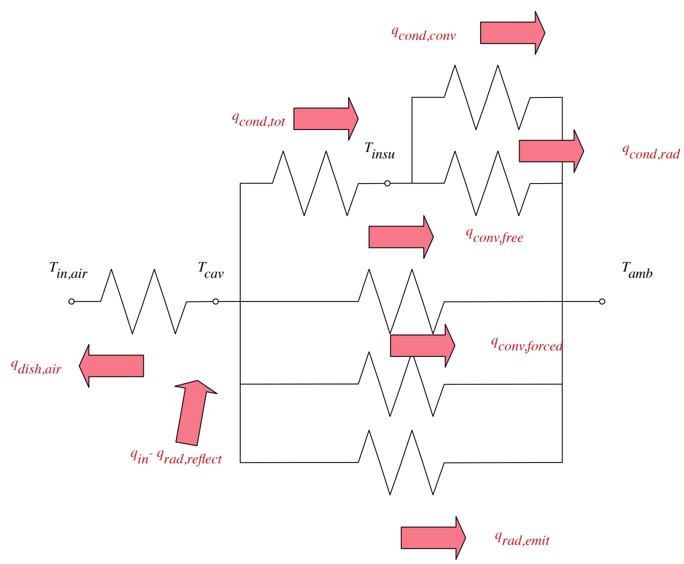

Figure 3: Heat network of dish receiver

$$q_{in} = q_{rad,reflect} + q_{dish,air} + (q_{cond,tot} + q_{conv,tot} + q_{rad,emit}) \tag{1}$$

A dish collector product of SES used in Fraser's paper, which is also used in this system, and its parameters are listed in Table 2 [5].

q_{in} can be obtained by

$$q_{in} = I_{DNI} \cdot A_{dishCollector} \gamma \eta_{shading} \rho \tag{2}$$

4.1.1 Reflected loss of dish receiver

To determine the reflected loss of the cavity surfaces of the dish receiver, the effective absorptance of the cavity receiver α_{eff} is required to determine the

Table 2: Parameters of the dish receiver

Parameters	Value
d_{cav}	0.46 m
δ_{insu}	0.075 m
l_{cav}	0.23 m
d_{ap}	0.184 m
λ_{insu}	0.06 W/(m·K)
ϵ_{insu}	0.6
α_{cav}	0.87
δ_a	0.005 m
$d_{i,air}$	0.07 m
θ_{dish}	45°
γ	0.97
$\eta_{shading}$	0.95
ρ	0.91

fraction of energy reflected out of the receiver. The effective absorptance of a cavity receiver without a receiver aperture cover is given by Equation (3) where α_{cav} is the cavity surface absrptance, A_a is the cavity aperture area, and A_{cav} is the total inner surface area of the cavity [6]. Sandra National Laboratories gave an estimate value of the absorptance of the cavity surface α_{cav} of an existing Stirling dish receiver to be 0.87 [7]. To achieve higher effective absorptance, a smaller ratio of the two surface area should be used. But the ratio is constrained by the concentration ratio of the receiver.

$$\alpha_{eff} = \frac{\alpha_{cav}}{\alpha_{cav} + (1 - \alpha_{cav})\,(A_{ap}/A_{cav})} \tag{3}$$

$$q_{rad,reflect} = q_{in}(1 - \alpha_{eff})$$

4.1.2 Conduction loss of dish receiver

4.1.3 Convection loss of dish receiver

Ma conducted tests to determine the free convection losses from the receiver for six alternative setups, and the data were consistent with Stine and McDonald's free convection correlation[8]. It is assumed that forced convection is independent of free convection in the receiver, so the total convection losses can be represented as the sum of the free and forced convection losses as shown in Figure 3.

$$q_{con,tot} = q_{con,free} + q_{con,forced} \tag{4}$$

4.2 Stirling engine array

4.3 Water circuit

4.3.1 Oil-Water heat exchangers

4.3.2 Steam turbine

4.3.3 Condensor

4.3.4 deaerator

5 Separate system model

6 Result and Conclusion

References

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