CASCADE SYSTEM CALCULATION

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1 Introduction

Different types of collectors and different forms of electricity generation are suitable for different working temperature zones with different costs. A prototype of cascade collection and cascade utilization of solar energy with high efficiency and low cost is presented. Parabolic trough collectors are used to collect low temperature energy with low cost and dish collectors are used to collect high temperature energy with high efficiency. Rankine cycle is used to work in low temperature zone and Stirling cycle is used to work in high 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 produced by Stirling engine.

2 Problem description

To realize the system, calculation of the system must be applied first. The scale of the system and the dimensions of the parameters must be evaluated.

Before detailed model of the system to be created, lots of simplifying assumptions are made:

- Steady state at nominal load
- Pressure losses negligible everywhere in the pressure circuit
- Simplified calculation of processes and equipment

For system 2, the condensation heat of toluene is used to preheat, evaporate, superheat R123. Figure 1 shows the sketch of system 2. Air is heated in dish collectors, then used to heat the hot chamber of Stirling engine, air-toluene heat exchanger and air-R123 heat exchanger successively. Toluene is preheated, evaporated and superheated by trough collectors and then heated by air-toluene heat exchanger and used to work in the toluene turbine, cooled in the superheater, evaporator and preheater of R123. R123 is heated in the cold chamber of Stirling engine, preheater, evaporator, superheater and air-R123 heat exchanger successively, and then used to work in the R123 turbine, cooled in the

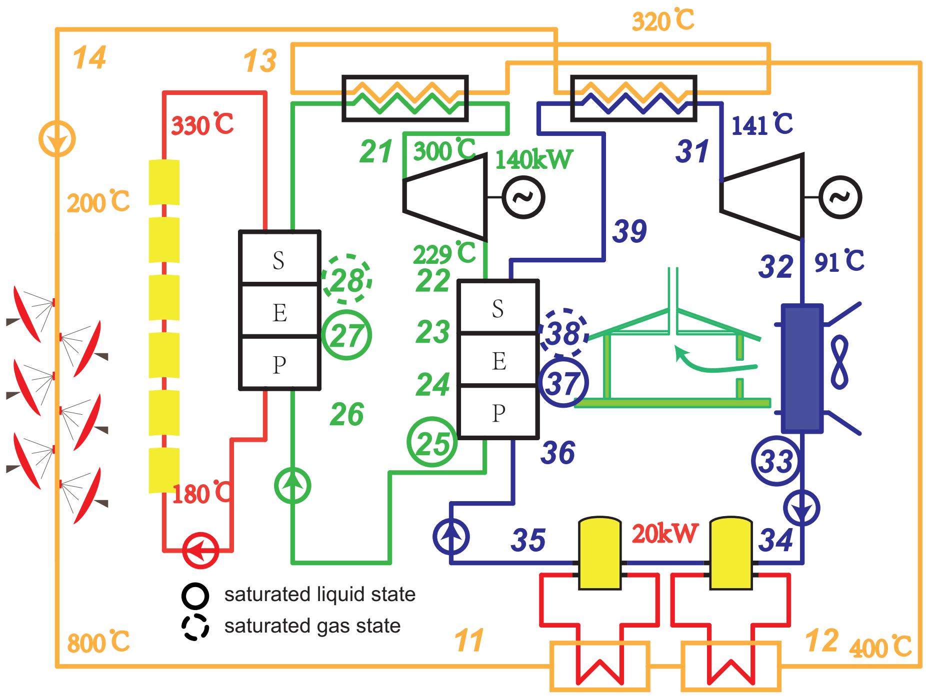

Figure 1: Sketch of system 2

condenser. Pumps are used to change the pressure of fluids. State numbers are marked on the sketch according to its logical position. Numbers with solid circle means saturated liquid states($x = 0$), and with dotted circle means saturated gas states($x = 1$).

3 Data

Table 1 shows the basic data of the system 2, such as the nominal electric power of Stirling engine and generator, temperatures of inlet and outlet of dishes, design parameters of turbine. According to these data, some important parameters of the system, such as mass flow rate, temperature of a state, system efficiency, can be obtained by calculation. To calculate the system, the model must be built first. EES is used for the model construction and calculation.

Table 1: System characteristics of System 2

Nominal electric power		
$P_{stirling} = 50\text{kW}$	$P_{2,generator} = 140\text{kW}$	$\eta_{2,generator} = 0.975$
$\eta_{3,generator} = 0.975$		
Solar data		
$DNI = 0.657\text{kW/m}^2$		
Dish		
$T_{dish,inlet} = 200°\text{C}$	$T_{dish,outlet} = 800°\text{C}$	$p_{dish} = 0.5\text{MPa}$
$\eta_{dish} = 0.85$		
Trough		
$\eta_{trough} = 0.6$		
Stirling engine		
$T_{1,afterstirling} = 400°\text{C}$	$T_{environment} = 30°\text{C}$	$\Delta T_{stirling,hot} = 30°\text{C}$
$\Delta T_{stirling,cold} = 25°\text{C}$	$\eta_{co} = 0.5$	$p_{3,stirling} = 0.3\text{MPa}$
Main steam and condensation of fluid2(toluene)		
$T_{2,s} = 300°\text{C}$	$p_{2,s} = 2.8842\text{MPa}$	$T_{2,c} = 228.85°\text{C}$
$p_{2,c} = 0.3605\text{MPa}$		
Main steam and condensation of fluid3(R123)		
$T_{3,s} = 141.152°\text{C}$	$p_{3,s} = 1\text{MPa}$	$T_{3,c} = 91.35°\text{C}$
$p_{3,c} = 0.167\text{MPa}$		
Median temperature of air		
$T_{1,mid} = 320°\text{C}$		
Isentropic efficiency of organic turbines		
$\eta_{2,turbine} = 0.75$	$\eta_{3,turbine} = 0.75$	

4 Model of the system

The system is built in several blocks. These blocks are made of circulations and efficiency calculation. Three circulations, air circulation, toluene circulation and R123 circulation, are built in some specific states and in some components. Known parameters of the states, efficiency of the system and the overall efficiency of separated systems can be achieved.

4.1 Air circulation

For state 11,

$$\left.\begin{array}{l} p_{11} = p_{dish} \\ T_{11} = T_{dish,outlet} \end{array}\right\} \Rightarrow h_{11} \tag{1}$$

For state 12,

$$\left.\begin{array}{l} p_{12} = p_{11} \\ T_{12} = T_{1,afterstirling} \end{array}\right\} \Rightarrow h_{12} \tag{2}$$

For Stirling engine,

$$\begin{array}{l} T_{hot} = T_{12} - \Delta T_{stirling,hot} \\ T_{cold} = T_{35} + \Delta T_{stirling,cold} \\ \eta_{stirling} = \eta_{co} \cdot (T_{hot} - T_{cold})/T_{hot} \\ Q_{stirling} = P_{stirling}/\eta_{stirling} \\ Q_{stirling} = m_1(h_{11} - h_{12}) \\ \left.\begin{array}{l} Q_{stirling,cold} = Q_{stirling} - P_{stirling} \\ Q_{stirling,cold} = m_3(h_{35} - h_{34}) \end{array}\right\} \Rightarrow h_{35} \end{array} \tag{3}$$

For state 13,

$$\left.\begin{array}{l} p_{13} = p_{12} \\ T_{13} = T_{1,mid} \end{array}\right\} \Rightarrow h_{13} \tag{4}$$

For state 14,

$$\left.\begin{array}{l} p_{14} = p_{13} \\ T_{14} = T_{dish,inlet} \end{array}\right\} \Rightarrow h_{14} \tag{5}$$

For dish,

$$\begin{array}{l} Q_{dish} = m_1(h_{11} - h_{14}) \\ Q_{dish} = DNI \cdot A_{dish} \cdot \eta_{dish} \end{array} \tag{6}$$

4.2 Toluene circulation

For state 21,

$$\left.\begin{aligned} p_{21} &= p_{2,s} \\ T_{21} &= T_{2,s} \end{aligned}\right\} \Rightarrow h_{21} \tag{7}$$

For state 22,

$$\left.\begin{aligned} T_{22} &= T_{2,c} \\ p_{22} &= p_{2,c} \end{aligned}\right\} \Rightarrow h_{22} \tag{8}$$

For state 23,

$$\left.\begin{aligned} &p_{23} = p_{22} \\ &m_2(h_{22} - h_{23}) = m_3(h_{39} - h_{38}) \end{aligned}\right\} \Rightarrow \begin{cases} h_{23} \\ T_{23} \end{cases} \tag{9}$$

For toluene Rankine cycle,

$$\begin{aligned} &P_{2,generator} = \eta_{2,generator} P_{2,turbine} \\ &P_{2,turbine} = \eta_{2,turbine} E_{2,rankine} \\ &E_{2,rankine} = \eta_{2,rankine} Q_{2,total} \\ &Q_{2,total} = m_2(h_{21} - h_{25}) \\ &\eta_{2,rankine} = (h_{21} - h_{22})/(h_{21} - h_{25}) \\ &\eta_{2,total} = \eta_{2,rankine}\eta_{2,turbine}\eta_{2,generator} \end{aligned} \tag{10}$$

For state 24,

$$\left.\begin{aligned} &p_{24} = p_{23} \\ &m_2(h_{23} - h_{24}) = m_3(h_{38} - h_{37}) \\ &m_2(h_{24} - h_{25}) = m_3(h_{37} - h_{36}) \end{aligned}\right\} \Rightarrow \begin{cases} h_{24} \\ T_{24} \end{cases} \tag{11}$$

For state 25,

$$\left.\begin{aligned} p_{25} &= p_{24} \\ x_{25} &= 0 \end{aligned}\right\} \Rightarrow \begin{cases} h_{25} \\ T_{25} \\ s_{25} \end{cases} \tag{12}$$

For state 26,

$$\left.\begin{aligned} p_{26} &= p_{2,s} \\ s_{26} &= s_{25} \end{aligned}\right\} \Rightarrow \begin{cases} T_{26} \\ h_{26} \end{cases} \tag{13}$$

For state 27,

$$\left.\begin{aligned} p_{27} &= p_{26} \\ x_{27} &= 0 \end{aligned}\right\} \Rightarrow \begin{cases} T_{27} \\ h_{27} \end{cases} \tag{14}$$

For state 28,

$$\left.\begin{aligned} p_{28} &= p_{27} \\ x_{28} &= 1 \end{aligned}\right\} \Rightarrow \begin{cases} T_{28} \\ h_{28} \end{cases} \tag{15}$$

For air-toluene heat exchanger,

$$m_1(h_{12} - h_{13}) = m_2(h_{21} - h_{29}) \Rightarrow h_{29} \tag{16}$$

For state 29,

$$\left.\begin{aligned} p_{29} &= p_{28} \\ h_{29} & \end{aligned}\right\} \Rightarrow T_{29} \tag{17}$$

For trough,

$$\begin{aligned} Q_{trough} &= m_2(h_{29} - h_{26}) \\ Q_{trough} &= DNI \cdot A_{trough} \cdot \eta_{trough} \end{aligned} \tag{18}$$

4.3 R123 circulation

For state 31,

$$\left.\begin{aligned} p_{31} &= p_{3,s} \\ T_{31} &= T_{3,s} \end{aligned}\right\} \Rightarrow h_{31} \tag{19}$$

For state 32,

$$\left.\begin{aligned} T_{32} &= T_{3,c} \\ p_{32} &= p_{3,c} \end{aligned}\right\} \Rightarrow h_{32} \tag{20}$$

For state 33,

$$\left.\begin{aligned} p_{33} &= p_{32} \\ x_{33} &= 0 \end{aligned}\right\} \Rightarrow \begin{cases} h_{33} \\ T_{33} \\ s_{33} \end{cases} \tag{21}$$

For R123 Rankine cycle,

$$\begin{aligned} P_{3,generator} &= \eta_{3,generator} P_{3,turbine} \\ P_{3,turbine} &= \eta_{3,turbine} E_{3,rankine} \\ E_{3,rankine} &= \eta_{3,rankine} Q_{3,total} \\ Q_{3,total} &= m_3(h_{31} - h_{33}) \\ \eta_{3,rankine} &= (h_{31} - h_{32})/(h_{31} - h_{33}) \\ \eta_{3,total} &= \eta_{3,rankine} \eta_{3,turbine} \eta_{3_generator} \end{aligned} \tag{22}$$

For state 34,

$$\left.\begin{aligned} s_{34} &= s_{33} \\ p_{34} &= p_{3,stirling} \end{aligned}\right\} \Rightarrow \begin{cases} h_{34} \\ T_{34} \end{cases} \tag{23}$$

For state 35,

$$\left.\begin{aligned} &p_{35} = p_{34} \\ &h_{35} \end{aligned}\right\} \Rightarrow \begin{cases} T_{35} \\ s_{35} \end{cases} \tag{24}$$

For state 36,

$$\left.\begin{aligned} p_{36} &= p_{3,s} \\ s_{36} &= s_{35} \end{aligned}\right\} \Rightarrow \begin{cases} T_{36} \\ h_{36} \end{cases} \tag{25}$$

For state 37,

$$\left.\begin{aligned} p_{37} &= p_{36} \\ x_{37} &= 0 \end{aligned}\right\} \Rightarrow \begin{cases} T_{37} \\ h_{37} \end{cases} \tag{26}$$

For state 38,

$$\left.\begin{aligned} p_{38} &= p_{37} \\ x_{38} &= 1 \end{aligned}\right\} \Rightarrow \begin{cases} T_{38} \\ h_{38} \end{cases} \tag{27}$$

For air-R123 heat exchanger,

$$m_1(h_{13} - h_{14}) = m_3(h_{31} - h_{39}) \Rightarrow h_{39} \tag{28}$$

For state 39,

$$\left.\begin{aligned} &p_{39} = p_{38} \\ &h_{39} \end{aligned}\right\} \Rightarrow T_{39} \tag{29}$$

4.4 System efficiency calculation

$$\begin{aligned} &E_{total} = DNI \cdot (A_{dish} + A_{trough}) \\ &\eta_{system} = (P_{stirling} + P_{2,generator} + P_{3,generator})/E_{total} \\ &T_{cold,separate} = T_{environment} + \Delta T_{stirling,cold} \\ &\eta_{stirling,separate} = \eta_{co} \cdot (T_{hot} - T_{cold,separate})/T_{hot} \\ &\eta_{separate} = (Q_{dish}\eta_{stirling,separate} + Q_{trough}\eta_{2,total})/E_{total} \end{aligned} \tag{30}$$

5 Results

Figure 2 shows main results of the system. From the results, we can see that the overall of the cascade system $\eta_{system} = 0.1278$ is higher than that of separated system $\eta_{separate} = 0.08532$. The separated system uses the same collectors of the cascade system and recirculated cooling water with the same temperature of the environment is used to cool cold chamber of Stirling engine.

Figure 3 shows array table results of the system. The array shows the enthalpy, pressure, entropy, temperature and dryness of states.

Unit Settings: SI K MPa kJ mass rad

A_{dish} = 597.4 [m^2]	A_{trough} = 3260 [m^2]	C2K = 273.2 [K]
$\Delta T_{stirling,cold}$ = 25 [K]	$\Delta T_{stirling,hot}$ = 30 [K]	DNI = 0.657 [kW/m^2]
$\eta_{2,generator}$ = 0.975	$\eta_{2,rankine}$ = 0.1432	$\eta_{2,total}$ = 0.1047
$\eta_{2,turbine}$ = 0.75	$\eta_{3,generator}$ = 0.975	$\eta_{3,rankine}$ = 0.1316
$\eta_{3,total}$ = 0.09627	$\eta_{3,turbine}$ = 0.75	η_{co} = 0.5
η_{dish} = 0.85	$\eta_{separate}$ = 0.08532	$\eta_{stirling}$ = 0.2203
$\eta_{stirling,separate}$ = 0.2449	η_{system} = 0.1278	η_{trough} = 0.6
$E_{2,rankine}$ = 191.5 [kW]	$E_{3,rankine}$ = 183.1 [kW]	E_{total} = 2534 [kW]
F1$ = 'air_ha'	F2$ = 'toluene'	F3$ = 'R123'
m_1 = 0.5091 [kg/s]	m_2 = 2.576 [kg/s]	m_3 = 5.985 [kg/s]
$p_{2,c}$ = 0.3605 [MPa]	$P_{2,generator}$ = 140 [kW]	$p_{2,s}$ = 2.884 [MPa]
$P_{2,turbine}$ = 143.6 [kW]	$p_{3,c}$ = 0.167 [MPa]	$P_{3,generator}$ = 133.9 [kW]
$p_{3,s}$ = 1 [MPa]	$p_{3,stirling}$ = 0.3 [MPa]	$P_{3,turbine}$ = 137.3 [kW]
p_{dish} = 0.5 [MPa]	$P_{stirling}$ = 50 [kW]	$Q_{2,total}$ = 1337 [kW]
$Q_{3,total}$ = 1391 [kW]	Q_{dish} = 333.6 [kW]	$Q_{stirling}$ = 227 [kW]
$Q_{stirling,cold}$ = 177 [kW]	Q_{trough} = 1285 [kW]	$T_{1,afterstirling}$ = 673.2 [K]
$T_{1,mid}$ = 593.2 [K]	$T_{2,c}$ = 502 [K]	$T_{2,s}$ = 573.2 [K]
$T_{3,c}$ = 364.5 [K]	$T_{3,s}$ = 414.3 [K]	T_{cold} = 359.8 [K]
$T_{cold,separate}$ = 328.2 [K]	$T_{dish,inlet}$ = 473.2 [K]	$T_{dish,outlet}$ = 1073 [K]
$T_{environment}$ = 303.2 [K]	T_{hot} = 643.2 [K]	

Click on this line to see the array variables in the Arrays Table window

No unit problems were detected.

Calculation time = .1 sec.

Figure 2: Main results of system 2

Sort	1 h_i [kJ/kg]	2 p_i [MPa]	3 s_i [kJ/kg-K]	4 T_i [K]	5 x_i
[11]	1131	0.5		1073.15	
[12]	685.1	0.5		673.15	
[13]	600.2	0.5		593.15	
[14]	475.6	0.5		473.15	
[15]					
[16]					
[17]					
[18]					
[19]					
[20]					
[21]	628	2.884		573.15	
[22]	553.7	0.3605		502.00	
[23]	512.4	0.3605		480.02	
[24]	218.3	0.3605		435.37	
[25]	108.8	0.3605	0.2649	435.37	0
[26]	112.3	2.884	0.2649	436.47	
[27]	435	2.884		563.04	0
[28]	595.5	2.884		563.04	1
[29]	611.2	2.884		567.56	
[30]					
[31]	476.7	1		414.30	
[32]	446.2	0.167		364.50	
[33]	244.4	0.167	1.15	315.49	0
[34]	244.5	0.3	1.15	315.55	
[35]	274	0.3	1.24	334.80	
[36]	274.7	1	1.24	343.34	
[37]	321.8	1		384.22	0
[38]	448.4	1		384.22	1
[39]	466.1	1		402.96	

Figure 3: Array table results