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THERMODYNAMIC OPTIMIZATION OF KALINA POWER SYSTEMS SUITABLE FOR LOW, MEDIUM AND HIGH TEMPERATURE HEAT RECOVERIES

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ABSTRACT

Kalina cycle is considered as an efficient power generation cycle in waste heat recovery applications. Three configurations have been examined thermodynamically to highlight the performance potentials at three heat recovery levels for Kalina cycle system (KCS). The operational parameters of all the three cycles vary with separator conditions. The system specifications have been developed at optimized working conditions. The optimum high pressure (HP) and source temperature for three cycles are 35 bar-170 °C, 50 bar-230 °C and 100 bar-550 °C respectively at low, medium and high temperature levels. The output and energy efficiency maximizes at 100 kW-12%, 280 kW-21% and 650 kW-23.5% in the same order at hot climatic conditions. The heat exchangers are sized for all the three plants considered after the thermodynamic rating. The cost estimation also has been performed by suitably assumed heat transfer coefficients. The total plant cost in the order of temperature levels are $ 6093.55/kW, $ 3358.29/kW and $ 2868.30/kW. It shows that the unit cost is reduced with an increase in capacity of the plant.

Keywords: *- Heat recovery, Kalina, power, thermodynamics, vapor absorption.*

I. INTRODUCTION

It is very difficult to erect the power plant without the thermodynamic design and analysis. The present work aims on parametric analysis of a power generating cycle suitable for low, medium and high temperature heat recoveries. The cycle uses binary ammonia-water mixture as the working fluid. The zeotropic mixture due to its distinct feature boils at low temperature. The performance of the Kalina cycle system with different heater setups has been investigated and the heat exchanger sizes of the three recoveries have been evaluated. Kalina cycle has got 15-25% improvement in energy efficiency. This cycle has been considered as a first breakthrough in power generation system. Binary mixture (ammonia-water) is used for running a turbine. The application of this cycle includes bottoming cycles in power station, waste heat recovery in industry etc. The first Kalina plant of output 6.5 MW was implemented in Canoga Park, USA in 1991 followed by countries like Japan, Iceland, Germany, Tibet, China, Taiwan and in 2012, 8.6 MW plant has been started in Pakistan. Kalina cycle is considered as an efficient power cycle than Rankine cycle [1,2]. Parametric analysis of Kalina cycle for various configurations has been reported [3, 4, 5, 6, and 7]. The important parameters considered are separator temperature, turbine concentration, separator concentration, turbine inlet pressure, type of fluid, ammonia fraction, ammonia vapor mass fraction and low pressure. Exergy analyses over Kalina cycle have been evaluated [8,9]. Zhang et al. [10] compared Rankine and Kalina cycles on energy and exergy point. Kalina cycle has got better thermodynamic performances than the Rankine and Organic Rankine Cycle (ORC) with respect to both energy and exergy efficiencies. Rodriguez et al. [11] proposed thermodynamic analysis for ORC and Kalina cycle. They concluded Kalina cycle produces 18% more net power than ORC. Ammonia-water composition, evaporation/condensation pressures and the source temperature have been considered as parameters for providing optimum performance. Singh and Kaushik [12] coupled low temperature Kalina cycle system with steam power plant. Ammonia mass fraction in the mixture and turbine inlet pressure has been considered as key parameters. They concluded that maximum exergy destruction occurs at evaporator. Purevsuren [13] presented a thermo-economic solution for Kalina power plant with a

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focus on energy and exergy with a result of 14% cycle efficiency. Mathew Aneke et al. [21] has compared heat exchanger sizes of dual source ORC with two single ORC systems. The size of the heat exchangers and quantity of working fluid required by dual source ORC is smaller than two single ORC systems. Philippe Roy et al [22] estimated thermodynamic analysis of two Rankine cycles with and without regenerators. The exergetic efficiency is inversely proportional to output, whereas the heat exchanger's surface is directly proportional to output.

Ziegler and Trepp [14] portrayed a new correlation of ammonia-water mixture. Patek and Klomfar [15] developed simple procedure avoiding numerous iterations for calculating thermodynamic properties of mixture suitable up to 2 bar pressure. Xu and Goswami [16] combined the Gibbs free energy method for mixture properties and the bubble and dew point temperature equations for phase equilibrium.

In this work the total plant cost has been estimated for low temperature Kalina cycle system (LTKCS), medium temperature Kalina cycle system (MTKCS) and high temperature Kalina cycle system (HTKCS) using solar thermal energy source at thermodynamic optimized conditions. The operational conditions and specifications have been summarized to provide the base for economic evaluation. The thermo-economic evaluations are discussed using flow charts prepared for all three plants under the consideration.

II. METHODOLOGY

The process flow diagram for LTKCS using solar thermal energy has been depicted in Fig. 1(a). In LTKCS plant, high temperature regenerator (HTRGN), economizer and evaporators are serially connected. It can be operated at a source temperature of 150 °C and a pressure of 35 bars. Similarly Fig. 1(b) shows the schematic material flow details for MTKCS at a source temperature of 230 °C and 50 bar pressure. Since the separator is located at low pressure side, the use of throttle is avoided. MTKCS can be operated at high amount of working fluid compared to the others. The irreversibility in mixing is reduced with pre-heating of the re-circulating stream. HTKCS plant with material flow details is configured in Fig. 1(c). The cycle can be operated at a source temperature of 550 °C and 100 bars. Low pressure depends on absorber temperature and separator concentration. Intermediate pressure is determined from condenser temperature and turbine concentration.

As the boiling and condensation process appear at a variable temperature in the binary mixture, the system approaches a closer match with the source temperatures. The assumptions for the LTKCS are reported in the literature [18]. The energy and exergy formulae for LTKCS and MTKCS are derived and reported in the literature [19, 20].

In modeling, the equations are derived to find the unknown properties and energy values. The performance of the models has been predicted using mass, energy and exergy balances. The key parameters and its operational range influencing the performance of the cycles have been identified and optimized at Indian atmospheric conditions. Finally, the equipment size and total cost of the plants have been solved. Assumptions for analysis of the three systems are tabulated in Table 1. Table 2 summarizes the operational parameters with range for LTKCS, MTKCS, and HTKCS.

Determination of heat transfer performance of either an existing exchanger or an already sized exchanger is referred as rating problem. The rating is also sometimes referred to as the performance or simulation problem [17]. However, in a sizing problem for an extended surface exchanger, the physical size (length, width, height and surface areas on each side) of an exchanger will be determined. The sizing problem is also referred to as the design problem. In the present work, the size of the heat exchangers has been estimated for economic assessment of the KCS plants.

The overall heat transfer coefficients are assumed for recuperator, boiler, and condenser [13]. The LMTD is calculated for all the heat exchangers to find surface area.The cost of the heat exchanger

$$C_{HE} = C_{bs}(size\ of\ HE)^{n} \qquad (1)$$

The size of heat exchanger is determined in m^2.

For calculating the size of the heat exchangers (super heater, economizer, evaporator, HTRGN, LTRGN, condenser, absorber and HE), the value of 'n' in the equation (1) has been considered as 0.8 [13]. The cost for all the heat exchangers has been calculated from equation (1). The cost of turbine and pump has been calculated from the equation (2). The index 'n' for pump and turbine is considered as 0.8 and 0.7 respectively.

$$C_{turbomachine} = C_{bs}(\text{power capacity})^{n} \qquad (2)$$

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$$Q = UAF\Delta T_{lm} \quad (3)$$

The heat exchanger area is calculated from equation (3) For counter flow arrangement, F=1.

$$\Delta T_{lm} = \frac{\Delta T_I - \Delta T_{II}}{\ln\left(\frac{\Delta T_I}{\Delta T_{II}}\right)} \quad (4)$$

$$\Delta T_I = T_{h,i} - T_{c,o} \quad (5)$$

$$\Delta T_{II} = T_{h,o} - T_{c,i} \quad (6)$$

III. RESULTS AND DISCUSSION

The total plant cost which is the sum of heat exchangers, turbo machines and solar collecting system has been worked out and compared at all the temperatures of heat source. Finally, the three plants specifications including cost values have been summarized for thermo-economic comparison.

Table 3 results the size and cost details for LTKCS. The sizing of heat exchangers has been carried out at an assumed heat transfer coefficients. The total cost of the system results $ 522826.63. The size of the components is function of temperature gradient and heat duty. Dorj [13] reported the results for the plant located at Tsetserleg, Mangolia with 1860 kW capacity, at 120 °C and 30 bar pressure, with 5 °C sink temperature and 80 kg/s mass flow rate of hot geothermal source. The reported sizes for vaporizer, condenser, high temperature recuperator and low temperature recuperator are 1410 m^2, 1923 m^2, 44 m^2 and 208 m^2 respectively. The heat load for vaporizer, condenser, high temperature recuperator and low temperature recuperator are respectively 13508 kW, 11648 kW, 868 kW and 1800 kW. Rodriguez et al. [21] reported the sizes of vaporizer, condenser, high temperature recuperator and low temperature recuperator as 455.14 m^2, 940.18 m^2, 50.45 m^2 and 144.65 m^2 respectively for 930 kW output, at 140 °C and 25 bar pressure, with 25 °C sink temperature and 100 kg/s mass flow rate of hot geothermal source. Austin Reid [23] resulted in a Rankine cycle using heptafluoropropyl methyl ether or HFE 7000 as working fluid, the boiler, condenser, turbine and pump costs as $ 800, $ 800, $ 4500 and $ 1200 at 3 kW output with turbine inlet temperature and pressure of 100 °C, 6bar. In the present LTKCS, the sizes of the boiler for the same output are $ 850, $ 400, $ 3355 and $ 2091 at turbine inlet temperature and pressure of 130 °C, 35bar. *Ventosa i Capell and Victòria [24] gave* the cost estimation details for various power plants. The unit manufacturing cost of a typical Kalina cycle suitable for low temperature heat recovery located at Hawaii in 2003 is $ 1678.95/kW. In Husavik Iceland for low temperature geothermal power plant, the estimated capital cost is $ 1590.44/kW. At Unterhaching Kalina power plant in Germany with 135 °C source temperature, the capital cost is about $ 3056.41/kW. At Bruchsal power plant in Germany utilizing Kalina cycle for power generation, the capital cost is $ 13525.66/kW. The Kalina cycle power plant capital cost of the Thedki report presents $ 3194.71/kW. On average basis the capital cost of the Kalina cycle projects claims $ 2380.13/kW. In the present work the estimated cost details of the Kalina power plant is $ 1777.55/kW. As per Denzel Hankinson [25] results, the estimated power plant cost of the Kalex, ORC cycles with 110 °C, 130 °C turbine inlet temperatures and pressures 27.6 bar, 18 bar is proposed to be $ 4218/kW and $ 3384/kW. The current LTKCS results with power plant cost of $ 6093.55/kW at 130 °C turbine inlet temperature and 35bar pressure. The present system claims higher plant cost as a result of solar collector. The estimated specific cost of the ORC cycle utilizing 1,1,1,2-Tetrafluoroethane, R-134a as working fluid with 75 °C turbine inlet temperature is proposed to be $ 7988/kW as reported by Bertrand Fankam [26]. The system considered isentropic turbine efficiency of turbine and pump as 70% and 90%. Solar irradiation considered as 600 W/m^2. The current LTKCS power plant specific cost is proposed to $ 93.55/kW at turbine inlet temperature of 130 °C, isentropic turbine efficiency of turbine and pump as 75%, Solar irradiation considered as 650 W/m^2. Aliabadi and Wallace [27] showed the cost of the solar collector, turbine, boiler, condenser and pump of solar thermal power plant suitable for low temperature applications as $ 12000/kW, $ 700/kW, $ 350/kW, $ 300/kW, $ 400/kW respectively at turbine inlet temperature and pressure of 140 °C, 13 bar. The same for the present LTKCS is $ 4316/kW, $ 1118/kW, $ 283/kW, $ 134/kW and $ 745/kW at turbine inlet temperature and pressure of 135 °C, 35 bar.

Table 4 results the sizing and cost estimation for the solar collector, heat exchangers, turbine and pump in MTKCS. The specific cost of the solar collecting system is a function of output. The cost of the solar collecting system is high compared to the other components. The total cost of the heat exchangers are $ 48,753.5. The total cost for the turbine is $ 2072778.44 and pump is $ 8470.49. The maximum cost of heat exchanger is $ 16455.99 for HE_2 and the minimum heat exchanger cost is $ 804.61 for super heater. The total cost of the equipments of MTKCS is $ 3358.39/kW. Robert L. Fuller [28] reported at 270 °C turbine input temperature the cycle efficiency of ORC is 23% with total heat exchanger costs $ 16900.00. The present LTKCS claims the heat exchanger costs of $ 21383.00 with 20% cycle efficiency at 230 °C turbine input temperature. Tony Ho et al. [29] showed the total cost of equipments for medium temperature system of 1 kW ORC system as $ 1289 and an OFC (organic flash cycle) system as $ 1225. For Kalina system the total cost is $ 1162 with a reduction of 10% total cost of ORC and 5% total cost of OFC.

For HTKCS the cost details of the equipment is shown in Table 5. The maximum heat exchanger cost is $ 19891.28 for absorber and the minimum heat exchanger cost is $ 326.86 for HE_1. The total cost of the heat exchangers is $ 71602.43 which is comparably higher than low temperature and medium temperature cycles. The turbine and pump cost depends on the capacity of the plant. In HTKCS, the cost of turbine and pump increases with the increased capacity. McKellar et al. [30] reported the total cost of equipment for a Rankine cycle with cycle efficiency of 39% demands $ 928.48/kW. The high temperature and pressure in the system results 593 °C and 240 bar. For the present HTKCS the total equipment cost demands $ 868/kW at an efficiency of 23% and 500 °C, 100 bar high temperature and pressure. Ulrik Larson et al. [31] stated the estimated purchase cost of the condenser, evaporator, superheater for the high temperature Kalina cycle and Split cycle with turbine inlet pressure and temperature of 110 bar, 346 °C is reported as $ 36/kW, $ 201/kW, $ 82/kW and $ 39/kW, $ 285/kW, $ 139/kW. For the present system the cost details of the components are $ 31.31/kW, $ 16/kW and $ 10.83/kW at pressure of 100 bar. The cycle efficiency of the present system is 23.6% against 20.8% of the reported Kalina cycle and 22.1% of the split cycle.

The turbine cost of the reported Kalina cycle and Split cycle is $ 485/kW, $ 477/kW with the assumed turbine polytropic efficiency of 70%. The present work results $ 667/kW with isentropic turbine efficiency of 75%. Maria Jonsson [32] reported the specific investment cost of the Kalina cycle components using Trent and GTX100 gas turbines as $ 603/kW and $ 665/kW at turbine inlet pressure of 115 bar and turbine base cost of $ 110/kW. The present work results specific investment cost of the equipments as $ 828/kW at the turbine inlet pressure of 100 bar and turbine base cost of $ 4405/kW. The estimated power plant cost of the Flash cycle with 300 °C turbine inlet temperatures and 12 bar turbine inlet pressure is proposed to be $ 1684/kW. The HTKCS power plant cost of the present work results $ 2868/kW.

Table 6 summarizes the performance details of LTKCS, MTKCS and HTKCS. The source temperature for the three cycles optimizes at 170 °C, 230 °C and 550 °C. In the LTKCS, at a maximum temperature of 150 °C the power maximizes at 130 kW. The corresponding plant and cycle efficiencies are 4.5% and 11.50% respectively. In MTKCS, at the optimized conditions the cycle efficiency, plant efficiency and specific power have been found as 20%, 7.5% and 280 kW. In the HTKCS, the cycle efficiency, plant efficiency and specific power have been found as 23.5%, 7.5% and 675 kW. The output increases with the increase in temperature levels from LTKCS to HTKCS. At high temperatures the collector efficiency decreases with thermal losses, convection losses of air over the collector.

IV. CONCLUSIONS

Three different configurations of Kalina cycle have been considered for thermodynamic evaluation. The operating temperature and pressure levels are increased with increase in heat recovery temperature. This work will be useful for the developers of KCS plants at the experimental stage. The rating and sizing of the total plant have been presented after the thermal optimization of the total system. The specific area of collector is 32.50 m^2/kW for LTKCS, 16.50 m^2/kW for MTKCS and 16 m^2/kW for HTKCS. The total cost of equipments is $ 6093.55/kW for LTKCS, $ 3358.29/kW for MTKCS and $ 2873.70 /kW for HTKCS. There is no much improvement in plant efficiency due to increased losses at solar collectors with increase in temperature from medium to high temperature heat recovery. Among three plants, the MTKCS proves by resulting higher performance.

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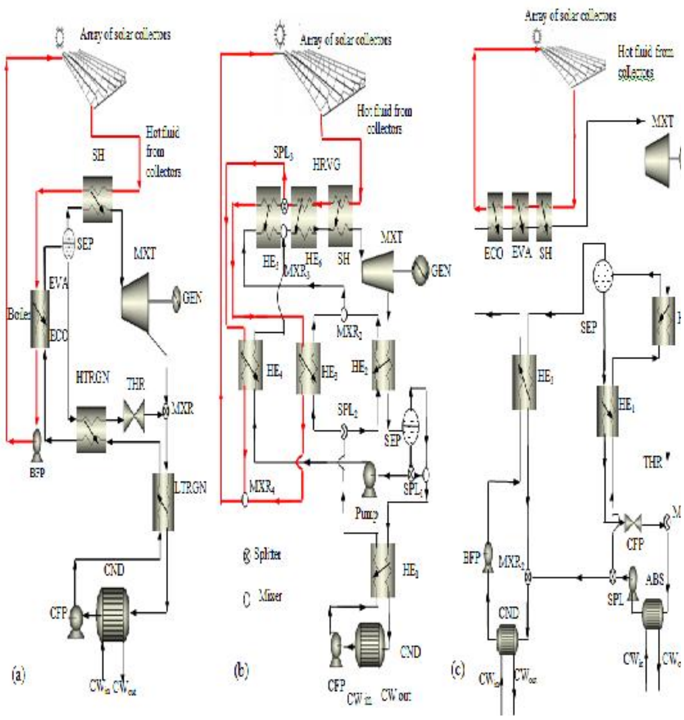

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Table 1 Assumptions made for thermodynamic evaluation of Kalina cycles

Atmospheric condition	25 °C and 1.01325 bar
Terminal temperature difference (TTD) at heat recovery Vapor generator (boiler) inlet with respect to the collector's hot fluid	10 K
Pinch point (PP) in boiler	5 °C
Approach point (AP) in the boiler	10 °C
Degree of superheat	10 °C
The cooling water inlet temperature	30 °C
The cooling water temperature difference	10 K
The isentropic efficiency of solution pump and mixture turbine is considered as	75%
The mechanical efficiency of the solution pump ($\eta_{m,p}$) and mixture turbine ($\eta_{m,t}$) is taken as	96%
The condensate leaving the condenser is assumed as saturated liquid	
Pressure drop and heat loss in the pipelines are neglected	

Table 2 KCS operational parameters and ranges

Sr. No.	Name	Operational Parameters	Range
1	LTKCS	Vapor fraction	20-80%
		Separator temperature	110-150 ºC
		Turbine concentration	0.85-0.97
		Beam radiation	400-800 W/m^2
2	MTKCS	Strong solution concentration	0.86-0.94
		Separator temperature	70-100 ºC
		Turbine concentration	0.77-0.86
		Turbine inlet pressure	25-60 bar
		Beam radiation	400-800 W/m^2
3	HTKCS	Concentration difference	4-20 %
		Separator temperature	60-100 ºC
		Turbine concentration	0.50-0.80
		Turbine inlet pressure	50-100 bar
		Collector outlet temperature	250-600 ºC
		Beam radiation	400-800 W/m^2

Table 3 Sizing and cost results of equipment for LTKCS

Sl. No.	**Components**	**Particulars**					**Cost, US$**
1	Solar collecting system	Area = 2788 m^2, Specific cost = $ 4316 / kW					370312.00
		Hot fluid inlet and outlet temperature, °C	**Cold fluid inlet and outlet temperature, °C**	**Flow rate for hot and cold fluids, kg/s**	**Heat duty, kW**	**Size, m^2**	
2	Evaporator	143.70 85.77	80.77 125.00	3.82 1.00	914.38	80.03	19587.52
3	Economizer	85.77 78.17	56.51 80.77	3.82 1.00	121.33	10.67	3907.58
4	Superheater	145.00 143.70	125.00 135.00	3.82 0.65	21.00	1.51	821.92
5	HTRGN	125.00 88.05	43.45 56.45	0.35 0.78	63.00	1.13	648.69
6	LTRGN	71.79 69.08	36.87 43.45	1.00 1.00	35.00	1.15	661.05
7	Condenser	69.08 35.00	25.00 33.00	1.00 27.51	920.00	41.14	11504.56
		Total cost ($ 432.77 /kW)					37131.62
		Capacity, kW					
8	Turbine	96.5					107923.25
9	Pump	10.7					7459.76
					Total		522826.63

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Table 4 Sizing and cost results of equipment for MTKCS

Sl. No.	Components	Particulars					Cost, US$
1	Solar collecting system	Area = 3762 m^2, Specific cost =$ 2196/kW					500688
		Hot fluid inlet and outlet temperature, °C	**Cold fluid inlet and outlet temperature, °C**	**Flow rate for hot and cold fluids, kg/s**	**Heat duty, kW**	**Size, m^2**	
2	Evaporator (HE_6)	214.30 173.00	148.00 182.30	3.43 1.31	594	19.04	6211.18
3	Super heater	217.30 214.30	182.30 192.30	3.43 1.31	42	1.48	804.61
4	HE_1	75.00 69.10	37.50 48.90	1.00 1.00	56	1.94	1001.59
5	HE_2	118.60 75.00	48.90 113.60	1.31 0.84	822	64.37	16455.99
6	HE_3	140.00 128.00	48.90 113.60	3.09 0.16	155	3.22	1501.12
7	HE_4	173.00 82.10	77.10 148.00	0.34 0.31	130	10.46	3845.94
8	HE_5	173.00 140.00	113.60 148.00	3.09 1.00	426	16.57	5559.34
9	Condenser	69.10 35.00	25.00 33.00	1.00 33.22	1111	49.67	13373.73
		Total cost ($ 213.83 /kW)					48753.5
		Capacity, kW					
10	Turbine	246					207778.44
11	Pump	18					8470.49
	Total						765690.43

Table 5 Sizing and cost results of equipment for HTKCS

Sl. No.	Components	Particulars					Cost, US$
1	Solar collecting system	Area = 8400 m^2, Specific cost =$ 2000/kW					1050000
		Hot fluid inlet and outlet temperature, °C	**Cold fluid inlet and outlet temperature, °C**	**Flow rate for hot and cold fluids, kg/s**	**Heat duty, kW**	**Size, m^2**	
2	Evaporator	358.74 148.36	143.36 224.84	1.46 1.00	1286.04	29.81	8889.28
3	Economizer	358.74 73.57	57.81 143.36	1.46 1.00	457.17	48.77	13179.51
4	Superheater	500.00 358.74	224.84 490.00	1.46 1.00	863.54	18.08	5958.48
5	HE_1	80.00 74.51	36.13 39.50	0.83 1.25	19.00	0.48	326.86
6	HE_2	249.69 90.20	39.50 80.00	1.00 1.25	830.00	8.42	3233.15
7	HE_3	80.00 44.29	37.99 57.81	0.42 1.00	93.00	7.36	2903.21
8	Condenser	46.68 35.00	25.00 33.00	1.83 14.95	500.00	68.13	17220.66
9	Absorber	78.06 35.00	25.00 33.00	1.00 45.21	1512.00	59.01	19891.28

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		Total cost ($ 136.38 / kW)	71602.43
		Capacity, kW	
10	Turbine	555	367240
11	Pump	30	17018
		Total	1505860.43

Table 6 Performance details of LTKCS, MTKCS and HTKCS plants (area and cost from the specification developed at optimum conditions)

Description	LTKCS	MTKCS	HTKCS
Source temperature ºC	130-170	190-230	250-550
Solar input W/m2	600.00	600.00	600.00
Heat input in boilers	1035.00	1347.00	2606.00
Heat rejection in condensers	920.00	1111.00	500.00
Turbine output	96.50	246.00	555.00
Pump input, kW	10.70	18.00	30.00
Net output, kW	85.80	228.00	525.00
Net specific power (max), kW	130.00	280.00	675.00
Cycle energy efficiency (max), %	11.50	20.00	23.50
Plant energy efficiency (max), %	4.50	7.50	7.50
Cycle exergy efficiency (max), %	71.00	80.00	64.00
Area of collectors, m^2/Kw	32.50	16.50	16.00
Cost of solar collecting system, $/kW	4316.00	2196.00	2000.00
Cost of heat exchangers, $/kW	432.77	213.83	141.79
Cost of vapor turbine, $/kW	1257.84	911.30	699.50
Cost of vapor turbine, $/kW	1257.84	911.30	699.50
Cost of feed pump, $/kW	86.94	37.15	32.41
Total cost of equipments, $/kW	6093.55	3358.29	2873.70

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