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Research Article

Investigation of Kalina Cycle for Power Generation from Heat Dissipation of Tarasht Power Plant

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Abstract

Fuel consumption optimization in thermal power plants is one of the essential topics in the saving energy field in the world. Then; it is necessary to review and provide solutions to increase efficiency. The present manuscript has recovered the heat dissipation from power plant stacks. The Kalina cycle was studied to use exhaust gases to generate power in the Tarasht power plant. Net power output is calculated at about 2080 kW, which increases the total power production of the plant by about 5%. According to environmental analysis, this cycle will cause less damage to the environment due to lowering the temperature of the exhaust gases in the atmosphere and not using additional fossil fuels. Therefore; it is a good solution for using heat dissipation from power plants. The only thing to consider in this solution (based on economic analysis) is the high construction cost compared to other power plant units.

Keywords: *Heat recovery; Kalina cycle; power generation; Tarasht power plant*

1. Introduction

Optimizing fuel consumption in thermal power plants is one of the most critical topics in energy saving in the world. With the increase in oil prices and, consequently, the increase in the share of fuel in the cost price of electricity generated by power plants, the need to study and provide solutions to increase efficiency is well felt. In this regard, and considering the growth of energy consumption in power plants, the limitations and challenges in providing fossil fuels required by power plants, environmental considerations, and rising global prices for fossil fuels, how to meet these challenges for each power plant has been raised as a significant issue. In this regard, the present study deals with the recovery of waste heat from power plant stacks. For this purpose, the Kalina cycle (which is the same Rankine cycle with the difference in working fluid, i.e., water and ammonia with the characteristic feature of creating a variable boiling point at constant pressure), was investigated in the Tarasht power plant. A mixture of water and ammonia was first used in absorption cycles by Maloney and Robertson in 1950 [1]. Kalina proposed another cycle in 1983 with an efficiency of about 30%-60% higher than the steam power generation cycle [2]. L. Side and Terbius showed that when the Kalina and Rankine cycles are placed in the combined cycles, the efficiency of the Kalina cycle increases by about 10%-30% [3]. In 1989, Kalina and Libowitz proposed a cycle for the use of geothermal resources, with the Kalina cycle having a higher net power than the Rankine cycle with the isobutene working fluid [4]. In 1999, a co-production cycle of power and refrigeration was introduced by Goswami, in which the Rankine cycle and the absorption refrigeration cycle were combined [5-6]. In 2004, Ronald Deepipo studied the power cycles of two-component water-ammonia mixtures to use heat energy [7]. Goswami et al. (2004) reported in a theoretical and laboratory study of a designed combined cycle that optimization of the second law of thermodynamics would be most effective if solar heat were used as the heat source [8]. In 2006, Zheng introduced a new water-ammonia cycle for simultaneous power generation and refrigeration [9]. In 2007, Methawa Hitarachchi used Kalina Cycle No. 11 (KCS11), or the Low-Temperature Kalina Cycle, to use low-temperature geothermal resources [10]. In 2007, Zhang and Lu designed a new hybrid cycle capable of simultaneously generating power and refrigeration using an external heat source, such as industrial waste heat or gas turbine exhaust. Another feature of the designed system was the replacement of the absorber with a condenser in the Rankine cycle [11]. Zhang and Lever presented several systems with water-ammonia base working fluid. Important and basic parameters for combining refrigeration and power systems to create optimal exergy efficiency by reducing exergy loss were investigated [12]. In 2007 Rouvas and Kerneus tested a Kalina cycle powered by steam and concluded that electricity generated from such a system was in a better position economically and environmentally than coal-fired and diesel-fired power generation systems [13]. In 2008, the Kalina cycle was studied by Ying Zang et al. According to the first law of thermodynamics and the adoption of the Peng Robinson equation as the general equation for the properties of ammonia mixtures in water; thermodynamic analysis was presented in a Kalina cycle distillation step [14]. In 2008, Jiang Feng et al. Proposed a hybrid power-refrigeration cogeneration cycle that combines the Rankine cycle with the absorption refrigeration cycle [15]. In 2009, Ogrisk introduced the Kalina cycle process in a combined heat and power system to maximize heat generation with heat recovery without needing additional fuels [16]. In 2009, Lolos and R. Dakis used solar energy to provide the heat needed for the Kalina cycle. They concluded that using these heat sources would increase the cycle efficiency by about 5 to 10 percent [17]. In 2010, Philippi used the organic Rankine cycle with water-ammonia working fluid for heat recovery of boilers, examined the organic Rankine cycle with recovery (heat exchanger) and without recovery, and performed an exergy analysis on its cycle. It also determined the area required for the heat exchanger [18]. In 2012, a solar Kalina cycle was studied by Faming Sun and Yasuki Ekigami [19]. In 2013, Jiang Fengwag and Zhouyan Yang introduced a solar cycle. In this system, a storage system was used to store solar radiation energy as a heat source. Solar cycle simulations were also performed based on an extended mathematical model to evaluate system performance over a while [20]. In 2014, Anish Maddie and Frederic Haglind studied a Kalina cycle with a high-temperature source at 450 ° K and a pressure of 100 bar using a solar system. They compared the cycle in terms of efficiency and exergy with a simple Rankine cycle. [21]. In 2017, Anhua Wang and his colleagues studied the sliding density pressure method according to the previous study on the adjustment of ammonia mass to improve the efficiency of the Kalina cycle and considering that a local constant temperature was considered for the maximum operating point of the Kalina cycle [22]. In 2018, Shaubu Zhang et al. analyzed the modified Kalina cycle with parallel power generation and refrigeration (PPR-KC) [23]. In 2018, Hyung Hoon Kim et al. analyzed the Kalina Flash Cycle (KCF) and compared it to the Kalina cycle. This cycle is a new mode that has recently been proposed and operates using a low-temperature heat source [24]. In 2020, Gholamreza Salehi et al. evaluated the thermodynamic and economic analysis of heat recovery of Shahid Hasheminejad Gas Refinery steam network known as Khangiran by Kalina cycle and Rankine organic cycle with different fluids such as isobutane, cyclohexane, isopentane, hexane, isohexane and hexane [25].

In this study, the possibility of using the waste heat of the Tarasht power plant in the form of the Kalina cycle was evaluated. The analysis tool used is one of the modules of Thermoflow commercial software called Thermoflex [26], which calculates the outputs based on continuity equations and conservation of mass and energy. A unit of the Tarasht power plant was modeled, and the calculation results were compared with the available accurate information, and validation was performed. Exhaust gas specifications have been used as a hot source for the Kalina cycle.

2. Modeling

2.1 *Introduction of Tarasht Power Plant*

In 1955, Tehran Electricity Company signed a contract with the French company Alstom to purchase a 50,000 kW factory consisting of 4 units of steam power plants with a nominal power of 12.5 MW for $ 3.6 million with a 10-year repayment and a 5% profit. In October 1959, this power plant was put into operation, providing more than 50% of the electricity required by Tehran. The height of this power plant is 1260 meters above sea level, and its practical power is 10 MW [27]. Table 1 provides general information about the Tarasht power plant.

Table 2. General Information of the Tarasht Power Plant.

Number of units	4
Nominal power per unit (MW)	12.5
Average Summer Operating Power (MW)	10
Average Winter Operating Power (MW)	10
Design efficiencies (%)	30
Current efficiency (%)	17.5
Generator voltage (kV)	11.5
Power plant output voltage (kV)	63
Manufacturer	Alstom
Boiler Manufacturer	Stein Industry
Turbine Manufacturer	Alstom
Generator Manufacturer	Alstom

2.2 Technical Specifications of the Power Plant

The steam turbines of Tarasht power plant are single cylinder and produce 12.5 MW of power in nominal conditions. The steam entering the turbine has a pressure of 40 bar and a temperature of 420 °C. There are three extracted steam flow in each turbine introduce steam into the heaters to heat the feed water. The cycle of the Tarasht power plant does not have a high-pressure feed water heater and only has two low-pressure heaters and a separator. The diffuser in these units does not have an air outlet and does not play the role of removing oxygen. Instead, a heat exchanger called a recuperator is located in the feed water path after the condenser, which is responsible for this task. Of course, between the recuperator and heater No. 1, there is another heat exchanger called an auxiliary heater. The auxiliary heater heats the feed water slightly with the help of recurrent saturated water from the shells of heaters No. 1 and 2, as well as part of the low-pressure flow of the turbine [27]. The boiler of the Tarasht power plant has natural circulation. Under normal conditions, the feed water enters the boiler at a temperature of 177 ° C, and the steam leaves at a temperature of 460 ° C and a pressure of 43 bar with a mass flow of 65 tons/hr. Tarasht power plant boiler is also capable of producing 91 tons/hr of steam. The boiler has no re-heater and has two superheaters. The boiler furnace of the Tarasht power plant is under vacuum in such a way that the two blowing and suction fans create these conditions. It should be noted that there is no air preheater in the units of this power plant. Four cooling towers are provided for each unit. The generator of the units is also cooled by water [28].

2.3 Power Plant Modeling

In this power plant, three extracted steam flow systems are installed for the turbine, through which some of the steam flow enters the heaters and causes the initial heating of the feed water, which has an effect on improving the efficiency of the steam power plants. The turbine output flow, after passing through the condenser, passes through the blower and is then pumped to the heaters. Figure 1 shows the placement of equipment and connections in the software. The inputs used in modeling are described in Table 2.

3. Results and Discussion

The results of power plant modeling are included in Table 3. They show that the net power of each unit is 10047 kW, which is being used with an efficiency of 21.15%. The characteristics of the exhaust gas are described in Table 4. The temperature of the exhaust gas is equal to 257 °C. The modeling results of the Tarasht power plant are compared with the reference [29] in Table 5, and the relative power error calculated in the practical conditions of the power plant 3.48%.

Table 2. Input Data for Power Plant Modeling.

Equipment name attribute	Input characteristic	value
Main site	Site height (m)	1260
	Ambient temperature (°C)	37
	Relative humidity (%)	40
	Ambient wet bulb temperature (°C)	25.06
	Ambient pressure (bar)	0.8708
Boiler	Inlet fuel	Natural gas
	Inlet fuel pressure (bar)	1.724
	Outlet steam temperature (°C)	450
	Outlet steam flow (kg/s)	16.4
Turbine	Inlet steam pressure (bar)	40
	Number of shafts	1
	Shaft speed (rpm)	3000
	Mechanical efficiency (%)	99.8
Condenser	Design pressure (bar)	0.0689
	Increase in water cooling temperature (°C)	10
	Low condenser temperature (°C)	2
Condenser water source	Pressure (bar)	1.014
	Temperature (°C)	15
Blowdown	Temperature (°C)	15
Pump after Blowdown	Efficiency (%)	100
	Pressure increment (bar)	5.859
First heater	Outlet water temperature (°C)	74.25
Second heater	Outlet temperature (°C)	108.5
	Design pressure (bar)	3.904
De-aerator	Output temperature (°C)	142.8
Pump after de-aerator	Efficiency (%)	100
	Pressure increment (bar)	41.21
Third heater	Outlet temperature (°C)	177
Stack	Outlet temperature (°C)	257

The Kalina model proposed by Ogrisk has a primary path and a secondary path. In the main path, the mixture is pumped after the condenser to the low-temperature recuperator, which is charged by the ammonia source. Next, the ammonia-water mixture is passed through a high-temperature recuperator and then an evaporator to reach the liquid-vapor separator because the working conditions of the Kalina cycle are at low temperatures. In the present modeling, to use the power plant exhaust heat with the characteristics of the exhaust gas, including temperature, pressure, and percentage of compounds, has been used as a low-temperature source. The heat exchange of this source with the evaporator plays an essential role in heating the water-ammonia mixture path. In the separator, the mixture with the separated steam phase goes to a special water-ammonia turbine to produce power. At the same time, the mixture with the liquid phase passes along the side path, during which it acts as a hot fluid in the high-temperature recuperator. It then combines with the expanded steam mixture from the turbine and passes from the low-temperature recuperator to the condenser.

Table 3. Results of Power Plant Modeling.

Gross Power (kW)	10653
Gross electric efficiency (%)	22.42
Gross heat rate (LHV)(kJ/kWh)	16057
Net Power (kW)	10047
Net electric efficiency (LHV) (%)	21.15
Net heat rate (LHV)(kJ/kWh)	17025
Net electric efficiency (HHV) (%)	19.1
Net heat rate (HHV)(kJ/kWh)	1848

Table 4. Specifications of Power Plant Exhaust Gas.

Temperature (°C)		257
Mass flow (kg / s)		74.6
Gas composition (Mole, %)	Oxygen	2.237
	Carbon dioxide	8.43
	Water vapor	18.72
	Nitrogen	69.78
	Argon	0.837

Table 5. Verification.

Parameter	Quantity (unit)	Present modeling	Reference
Power	P (kW)	10047	10410
efficiency	η (%)	21.15	21.44

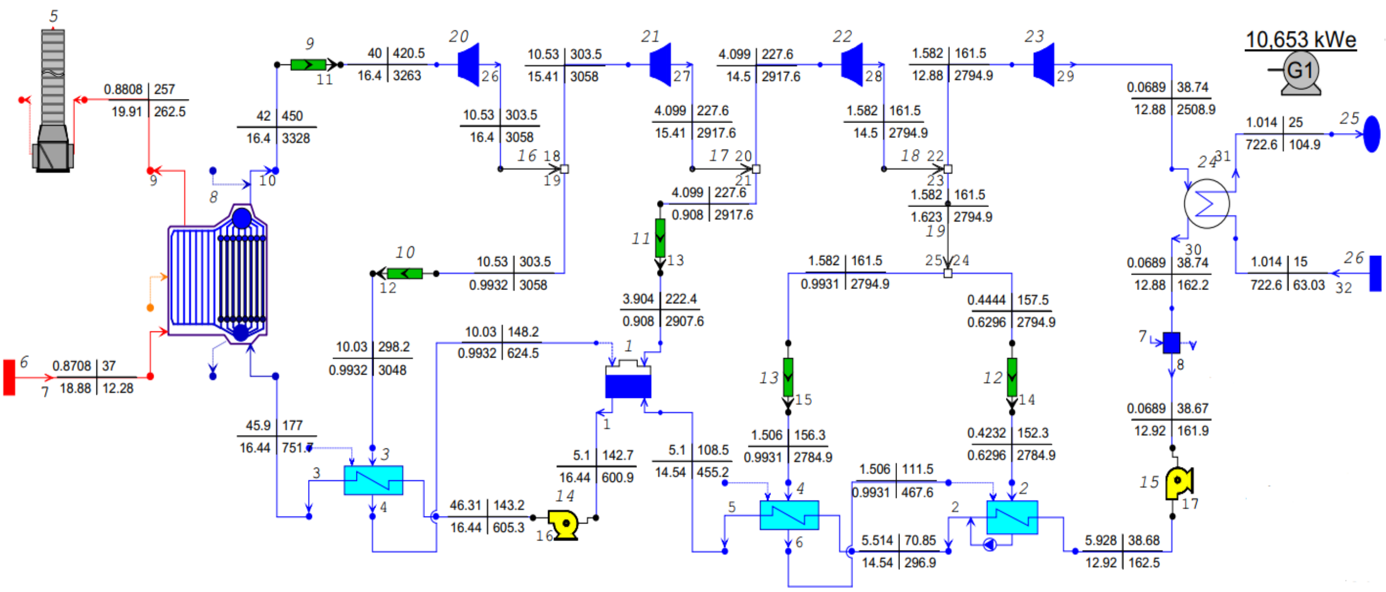

Figure 1. Schematic of Tarasht Power Plant Modeling.

Based on the modeling results (Figure 1) of a steam unit of the Tarasht power plant in the previous section, the available gas flow rate is obtained as 19.1 kg/s. According to the four available steam units in Tarasht power plant, the amount of gas flow rate available as a heat source in the Kalina cycle will equal 76.4 kg/s. Results are shown in Table 6, and the final schematic of the Kalina cycle with flow characteristics is in Figure 2. The net power output is calculated to be 2080.8 kW.

Table 6. Results of Kalina Modeling.

Gross Power (kW)	2205.6
Gross electric efficiency (%)	13.4
Gross heat rate (LHV)(kJ/kWh)	26864
Net Power (kW)	2080.8
Net electric efficiency (LHV) (%)	12.64
Net heat rate (LHV)(kJ/kWh)	28475

Table 7. The Energy Equations for Each Device.

Device	Equation
Separator	$\dot{m}_{10} = \dot{m}_1 + \dot{m}_2$
Turbine	$\dot{w}_T = \dot{m}_1(h_1 - h_3)$
Mixer after turbine	$\dot{m}_{12} = \dot{m}_3 + \dot{m}_9$
Condenser	$\dot{m}_7(h_7 - h_4) = \dot{m}_{14}(h_5 - h_{14})$
Pump	$\dot{w}_P = \dot{m}_4(h_{13} - h_4)$
LT recuperator	$\dot{m}_{17}h_{17} + \dot{m}_{12}h_{12} = \dot{m}_6h_6 + \dot{m}_7h_7$
HT recuperator	$\dot{m}_6h_6 + \dot{m}_2h_2 = \dot{m}_8h_8 + \dot{m}_9h_9$
Evaporator	$\dot{m}_8(h_{10} - h_8) = \dot{m}_{15}(h_{15} - h_{11})$

For the economic analysis of the Kalina cycle, the cost is estimated according to the power generation [30-31].

$$C_{inv} = C_{PC} + C_{land} + C_{cnt} \tag{1}$$

The following equation is used to estimate the cost of the power cycle:

$$C_{PC} = C_{PC.eqp} + C_{PC.misc} \tag{2}$$

The cost function of power cycle equipment is as follows:

$$C_{PC.eqp} = C_{tur} + C_{gen} + C_{Pu} + \sum C_{re} + C_{sep} \tag{3}$$

The cost of purchasing turbines, pumps, and generators is calculated based on the following equations:

$$C_{tur} = 4405 \times \dot{W}_{tur}^{0.7} \tag{4}$$

$$C_{Pu} = 1120 \times \dot{W}_{Pu}^{0.7} \tag{5}$$

$$C_{gen} = 10 \times 10^6 \times \left(\frac{W_{gen}}{160\times10^3}\right)^{0.7} \tag{6}$$

The cost of heat exchangers is obtained based on the following equation:

$$C_{hx} = 32800 \times \left(\frac{A_{hx}}{80}\right)^{0.8} \times f_{pres} \times f_{temp} \tag{7}$$

In the heat exchanger cost equation, A_{hx} is the amount of heat transfer area, which is obtained by dividing the heat capacity of each exchanger by the heat transfer coefficient, which according to the reference [32] for the evaporator $1.1(kW/m^2K)$, for recuperator $0.7(kW/m^2K)$and for condensers $0.5(kW/m^2K)$. f_{temp} and f_{pres} are temperature correction coefficient and pressure correction coefficient, respectively, obtained from the reference [33] according to the characteristics of the heat exchanger. In this analysis, due to the low temperature of the cycle, the temperature correction coefficient is equal to 1 and considering that the maximum pressure in the recuperator and evaporators is 30 bar, the pressure correction coefficient is equal to 1.3, and for the condenser is equal to 1. The separator cost function is calculated using the following equation:

$$C_{sep} = f_{pres} \times 10^{f_{s1} + f_{s2}\times\log H_{sep} + f_{s3}\times(\log H_{sep})^2} \tag{8}$$

In this function, H_{sep} is the height of the liquid inside the separator from the inlet nozzle in the first 3 minutes of the process, is considered 0.5 m. The coefficientsf_{s1}, f_{s2} and f_{s3} are correction coefficients that depend on the geometric dimensions.

In the power miscellaneous cost function: $C_{PC.pip}$ is the cost of piping, $C_{PC.insc}$ the cost of control systems and instrumentation, $C_{PC.el}$ the cost of electrical equipment and materials, and $C_{PC.inst}$ the cost of installation. Their amount includes 66%, 10%, 10%, and 45% of the cost amount of cycle equipment.

The cost of land purchase is considered to be 1200 dollars per kilowatt of gross output power. In this analysis, the amount of contingent costs are 20% of the total amount of cycle costs and land purchase.

The value of the total investment cost function is written with the criteria of 2010. To convert it into daily units, an equation is needed to perform this conversion using the correction factor. Marshall and Swift's cost index [34] is one of the most reliable indices for converting costs in different years and this index has been used in this analysis.

$$C = C_{CF} \times f_{M\&S}^{2018} / f_{M\&S}^{CF.Y} \tag{9}$$

In the above function, C_{CF} is the sum of the cost functions, $f_{M\&S}^{CF.Y}$ is the Marshall and Swift coefficient in the year when the cost functions were written, which is 1.13 in 2010, and $f_{M\&S}^{2018}$ is the new coefficient Marshall and Swift, which is considered equal to 1.

The concept of irreversibility in the thermodynamic analysis is necessary. This approach is related to the exergy concept as the available work from certain input energy. The system deviation of the environment is called exergy. The exergy calculation can be expressed as it follows:

$$e_f = (h - h^*) - T_0(s - s^*) + \sum_{i=1}^{n}(\mu_i^* - \mu_i^0) \tag{10}$$

The first two terms present the physical exergy, and the third term presents the chemical exergy. The temperature, pressure, and concentration of the environment (T_0, P_0, w_0) can be called the global dead state that the related properties can be shown with 0 symbols. In the restricted dead state (*), in which only the temperature and pressure are changed to the environmental values [35]. The exergy destruction in each component can be evaluated based on fuel and product exergy [36]

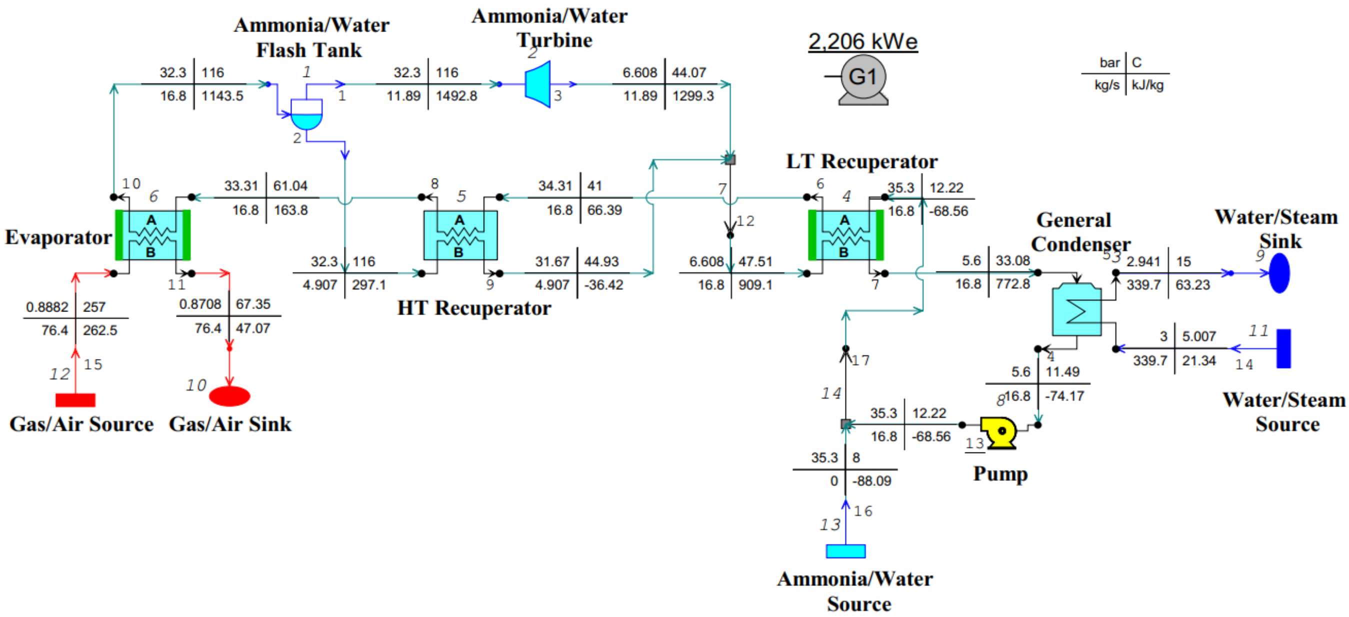

Figure 2. Schematic of Kalina Cycle Modeling.

$$E_D = E_{fuel} - E_{product} \quad (11)$$

Exergetic efficiency is one of the important parameters for irreversibility evaluation that defined based on the fuel-product definition as below [36]:

$$\varepsilon = product/fuel \quad (12)$$

The amount of net power was obtained from the modeling of the power plant for one unit of 10.047 kW and all four units 40.188 kW and from the modeling of the Kalina cycle 2080 kW, which shows that the production power of the power plant has increased by 5.18%. If the temperature of the exhaust gas is less than 257°C; the amount of net production power and heat transfer will decrease, the results are shown in Table 8.

Table 8. The Effect of Temperature on Power Generation.

Temperature (℃)	230	240	250	257
Net power (kW)	1819	1972	1995	2080
Gross power (kW)	1969	2097	2182	2205
Heat transfer (kW)	15314	16060	16270	16459

The results show that if the inlet temperature of the evaporator in the Kalina cycle increases, the amount of power production will increase, which is shown in Figure 3.

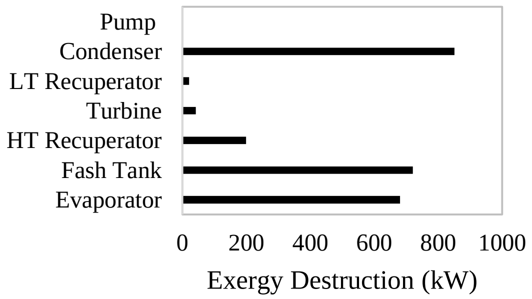

Figure 3. Comparison of Kalina Cycle Net Power for Different Evaporator Inlet Temperatures.

The final cost according to the availability of land in the vicinity of the Tarasht Power Plant with and without considering the land purchase cost is compiled in Table 9.

Exergy analysis results show that the general condenser has the highest unit exergy destruction and thus this component is the most inefficient component. The exergetic efficiency of the Kalina cycle is calculated as 45.24 %. The Exergy destruction in the different components are presented in Figure 4.

Table 9. Investment Cost Results.

	Investment cost per unit of net power ($/kW)	Investment cost ($)
with considering the cost of land purchase	3749	7798121
without considering the cost of land purchase	2574	5354995

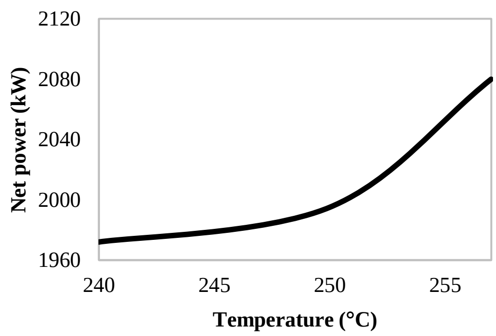

Figure 4. Exergy Destruction.

In power plants, increasing the temperature of water and producing wastewater are essential issues. In the Kalina cycle, the water used for cooling in the condenser enters with a temperature of 5 °C and leaves with a temperature of 15 °C, But there is no change in the nature of the water and only its temperature increases, according to the specifications of the condenser of the Tarasht power plant, whose inlet temperature is 15 degrees, it is possible to use the output water of the Kalina cycle condenser and avoid excess water consumption. . The distinctive feature of this cycle is the production of electricity without the consumption of fossil fuels, the most important environmental effect of which is the saving of non-renewable resources.

The investment cost with/without considering the cost of the land purchase that was calculated earlier, the current cost with approximately 1.5% of the investment cost and the annual income of selling electricity to the grid with an electricity sale price of 1,000 Rials per kilowatt hour (each dollar is equivalent to 450,000 Rials), the system will not be profitable in the life cycle during (Assuming a life cycle of 30 years). The details of the calculation are included in Table 10.

Table 10. Cost Results.

	Investment cost (&)	Current expense ($)	Income ($)	Return period
with land purchase cost	7798121	116971.815	34417.07	>30 (Yr)
without land purchase cost	5354995	80324.925		

4. Conclusions

To recover the waste heat from the stacks of the Tarasht power plant, the Kalina cycle (which is the same as the Rankine cycle with a difference in the working fluid i.e., water and ammonia with the distinct feature of creating a variable boiling point at constant pressure) was studied. Using Thermoflex, a unit of the Tarasht power plant was modeled, and the calculation results were compared with the available information, and validation was done. The calculation results for exhaust gas have been used as the heat source of the Kalina cycle. The results of this modeling show the production of net power of about 2080 kilowatts, which increases the net power of the entire power plant by about 5%. Exergy analysis results show that the general condenser has the highest unit exergy destruction and thus this component is the most inefficient component. The exergetic efficiency of the Kalina cycle is calculated as 45.24 %. According to the environmental analysis, this cycle will cause less damage to the environment due to the temperature reduction of the exhaust gas to the environment and the non-use of additional fossil fuel. Therefore, it is a suitable solution for using waste heat from power plants. The only point to consider in this solution (based on the economic analysis) is the high cost of startup compared to other power plant units. Therefore, by using the Kalina cycle for heat recovery in the Tarasht power station, it is possible to extract about 2 megawatts of power.

Nomenclature

h	Enthalpy (kJ/kg)
C_{inv}	Total investment cost ($)
C_{PC}	Cost of The Power Cycle ($)
$C_{PC.eqp}$	Cost of Power Cycle Equipment ($)
C_{tur}	Cost of Purchasing Turbines ($)
C_{gen}	Cost of Purchasing Pumps ($)
C_{Pu}	Cost of Purchasing Generators ($)
C_{re}	Cost of Heat Exchangers (Recuperator, Evaporator, Condenser) ($)
C_{sep}	Separator Cost Function ($)
$C_{PC.misc}$	Power Miscellaneous Cost Function ($)
C_{land}	Cost of Land Purchase ($)
C_{cnt}	Contingent Cost ($)
E_D	Exergy Destruction (kW)
$\dot{m}$	Mass flow (kg/s)
T	Temperature (°C)
W	Power (kW)
w	Concentration (ppm)
ε	Exergetic efficiency (%)
μ	Chemical Potential (J/kg)

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