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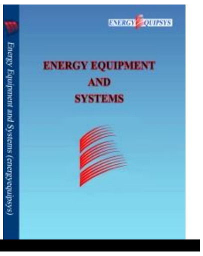

Use of solar radiation to produce cold water for hospital air conditioning system using the combined organic Rankine-vapor compression cycle

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ABSTRACT

In this paper, the optimal combined organic Rankine-vapor compression cycle is proposed to produce cold water for hospital air conditioning using solar energy. The hospital is located in Esfarayen city and the intensity of solar radiation in all months is calculated. The results show that in the five months of May, June, July, August and September, there is the highest solar radiation in Esfarayen city. The possibility of using daily solar radiation to produce cold water during these five months is examined. Simulation is performed using the Engineering Equation Solver (EES) software. Six refrigerants R22, R134a, R600, R143a, R500, and R11 are considered as working fluids for the cycle and based on energy and exergy analysis, suitable fluid is recommended for this system. The effects of solar radiation, refrigerant, and mass flow rate of the refrigerant on the cooling water temperature outlet from the evaporator, cycle performance, organic Rankin cycle efficiency, performance coefficient of the VCC cycle, and exergy efficiency of the ORC-VCC system are investigated. The results show that using the refrigerant R22 is more suitable than other refrigerants because the cycle with this refrigerant reduced the water temperature up to 8 ^{o}C in the evaporator, as well as the cycle performance are obtained 0.72 and organic Rankin cycle efficiency is 13.9%, which will be the highest. The results show that increasing boiler thermal energy (solar radiation) reduces water temperature in the evaporator and exergy efficiency of the system, and increases organic Rankin cycle efficiency and cycle performance.

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1. Introduction

Nowadays, due to global warming, there is a great need for cooling, so, the energy consumption used for cooling has increased significantly. The use of solar energy is one important contribution to cold production and the reduction of energy consumption and harmful emissions to the environment. Solar cooling for air-conditioning is an attractive application of solar energy because cold production on hot days makes it possible. The combined organic Rankine-vapor compression cycle (ORC-VCC) is one of the most common cycles that can produce cooling by receiving thermal energy. The organic Rankin cycle is a cycle that can be launched at low temperatures because the temperature of the liquid-vapor

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phase change in organic working fluids is lower than the water phase change [1]. Various sources of heat can be used to power ORC such as waste heat, geothermal energy, and solar energy. Many researchers have contributed a considerable amount of literate for combined ORC-VCC analysis, some of which will be referred to below.

Aphornratana and Sriveerakul [2] studied a theoretical analysis of a heat-powered refrigeration cycle, a combined Rankine–vapor–compression refrigeration cycle. They used the refrigerants R12 and R134a in the ORC-VCR system. The COP values of the combined cycle calculated by them are between 0.1 and 0.6. Wang et al. [3] investigated the use of low-temperature waste heat to generate cooling, via an Organic Rankine cycle that is combined with a vapor compression cycle. The results show that increasing the pump pressure and boiler temperature increases overall system COP and the efficiency of the first law of thermodynamics. But changing the pump pressure and boiler temperature has no effect on the efficiency of the second law of thermodynamics. Bu et al. [4] utilized a lot of waste energy drained from hot springs for air conditioning. To achieve this goal, the ORC-VCC system is employed and six refrigerants, R123, R134a, R245fa, R600a, R600, and R290 are examined. They showed that refrigerant R600a is more suitable than other refrigerants. Al-Sulaiman et al. [5] examined the three new tri-generation systems, based on the ORC-VCC system consists of solid-oxide fuel cells (SOFC) tri-generation, biomass tri-generation, and solar tri-generation systems. They showed that the solar tri-generation system offers the best thermo-economic performance among the three systems. Mehr and Zare [6] proposed a novel multi-generation system producing power, pure water, cooling and heating. They have analyzed the energy and exergy of the system, and then the system performance is optimized, thermodynamically.

Rawat et al. [7] showed that the overall COP of the combined ORC-VRC system increases with an increase in, boiler exit temperature and evaporator temperature. However, performance decreases with an increase in condenser temperature. The results show that R600 (butane) is the most promising working fluid in the combined ORC-VCR system. Kim and Blanco [8] analyzed the combined organic Rankine cycle and vapor compression cycle for power and refrigeration production, thermodynamically. They investigated the effects of turbine inlet temperature and pressure, and the flow division ratio on system performance for several different working fluids. Their results show that the system has the potential to efficiently utilize low-grade heat sources. Saleh [9] examined the effects of different system parameters such as the evaporator, condenser, and boiler temperatures on the ORC-VCR system performance. He shows that the maximum $\mathrm{COP_S}$ values are attained using the highest boiling candidates with overhanging T-s diagram, i.e. R245fa and R600. Also, R600 is the best candidate for the ORC-VCR system from the perspectives of environmental issues and system performance. Karellas and Braimakis [10] analyzed and verified the tri/co-generation system that capable of combined heat and power production and refrigeration, based on the ORC-VCC system, thermodynamically and economically. The thermal energy required for their system was supplied by biomass and solar energy. Acar and Dincer [11] investigated energy and exergy efficiencies assessment of an integrated solar absorption-cooling and heating system. The desired system is capable of supplying heating and cooling, hot water, electricity, and air conditioning for domestic use. The findings indicated the main sources of exergy destruction rate are the solar collectors and ORC turbines and evaporators.

Dobrovicescu et al. [12] examined the organic Rankine cycle using solar radiation as a heat source analytically. They presented a mathematical model for their cycle considering the Pinch temperature differences in the heat exchangers used in the system. They also performed exergetic analysis of the system for different refrigerants and observed that the use of refrigerant R245fa compared to other refrigerants investigated in the system, would result in the highest exergy efficiency. Popa and Popa [13] investigated the organic Rankine-vapor compression system with a solar heat source and studied the effect of generation and condensing temperatures on the system's overall efficiency. They believed that the choice of working fluids is crucial and important to obtain the appropriate thermodynamic performance cycle. The results show that increasing the generating temperature increases the overall efficiency of the ORC-VCC cycle, while that increasing the condensing temperature decreases the overall efficiency of the combined cycle. Bounefour and Ouadha [14] investigated the theoretically improved combined ORC-VCC system performance to illustrate the feasibility of using such a system in marine applications. They showed that increasing the boiler exit temperature increases exergetic efficiency and COP. Results show that the performance of R600 and R600a has superior performance than R134a.

Toujeni et al. [15] developed a new combined ORC-VCC with the refrigerants isobutene and ammonia for ORC and VCC to generate electrical power and cooling capacity. They studied the influence of the temperature of the boiler and evaporator, and mass flow rate on the performance of the system. The results show that that increasing the boiler temperature led to increased effectiveness of the system and ORC efficiency, while that increasing the boiler temperature decreases the coefficient of performance for VCC. Asim et al. [16] proposed an integrated organic Rankine cycle and organic air conditioning system that combines an organic Rankine cycle and a vapor compression cycle. In this scheme, the waste heat output from the condenser of the air conditioning system is used as a hot source for the ORC. They analyzed the system from energy, exergy, and economic point of view. The results show that the initial COP of the air conditioning subsystem and the combined performance coefficient of the air conditioning-organic Rankine cycle system increase with increasing the cooled return water temperature. Salah [17] investigated the influences of the evaporator, condenser, and boiler temperatures, considering isentropic efficiency for turbine and compressor, on the integrated ORC-VCR system. He studied a cycle analysis in terms of energy and exergy and determined that for better system performance it is advisable to use a working fluid with the uppermost critical temperature. The results show that refrigerant R602 achieves the best performance of the ORC-VCR system. Habibollahzade et al. [18] investigated exergy and economic indicators in the new energy system. The system consisting of solar collectors, a thermoelectric generator, a Rankine cycle, and a proton exchange membrane. They used a thermoelectric generator unit instead of the condenser and showed that this method optimized the performance of the system and reduced total cost. Behzadi et al. [19] proposed a novel solar-based integrated energy system with a thermoelectric generator (TEG) to provide cooling and hydrogen production. The results show that the proposed system with TEG has higher exergy efficiency, higher hydrogen production rate, lower total cost rate, and lower payback period. Ustaoglu et al. [20] designed a new non-imaging concentrator and used it to use solar energy in an organic Rankine cycle. They evaluated the performances of twelve working fluids in terms of cycle efficiency using 2D ray-tracing and thermodynamic analyses. The results disclosed the good efficiency is achieved for the R-141b, methanol, R-113, water, benzene and cyclohexane, respectively. Habibollahzade [21] investigated the use of photovoltaic/thermal panels as a roof of the solar chimney power plants. The results show that the proposed energy system is a promising and applicable method to enhance the power generation and exergy efficiency of the solar chimney power plants. Keshavarzzadeh and Ahmadi [22] proposed a combined, cooling, heating and, power system. They analyzed the exergy efficiency and total cost rate of the combined system and determined the optimal point in multi-objective optimization. The results show that at the lower system exergy efficiency, the influence of the interest rate is more significant. Mortazavi et al. [23] presented a new cycle through the integration of a two-stage compression refrigeration cycle with a combined Rankine power and ejector refrigeration cycle by using the cascade condenser method. They showed the new cycle recorded 11.67 and 16.89 percent improvement in thermal efficiency and exergy efficiency compared to the basic cycle, respectively. Calli et al. [24] presented energy, exergy, and thermoeconomic analyses of three different integrated systems consisting of an organic Rankine cycle. They used biomass burner, solar collector, and a combination of those for heat source of systems. The results show that the biomass-based ORC system has the highest electrical and exergetic efficiencies and the lowest cost.

Alirahmi et al. [25] proposed a multi-generation system for the simultaneous generation of power, cooling, freshwater, hydrogen, and heat. They used a multi-objective-optimization-genetic-algorithm for improving the performance of the combined system from the energy, exergy, and exergoeconomic points of view. Karimi et al. [26] investigated biomass-based combined heat and power plant integrating a downdraft gasifier, a solid oxide fuel cell, a micro gas turbine and an organic Rankine cycle. The results show that current density plays the most important role in achieving a tradeoff between system exergy efficiency and cost rate. Khanmohammadi et al. [27] proposed a novel integrated system consisting of a geothermal system, organic Rankine flash cycle, Proton exchange membrane fuel cell, and thermoelectric generator (TEG) modules. They analyzed the new system and compared it with the conventional system, thermodynamically. The results show that with employing TEG modules an increase of 2.7% and 2.8%, for the first and second law efficiencies can be obtained respectively. Keshavarzzadeh et al. [28] proposed a novel energy system to produce fresh water and electricity. The new energy system included a Brayton cycle, a heliostat field, an organic Rankine cycle, and a multi-effect desalination-thermal vapor compression unit. Ahmadi et al. [29] investigated a gas turbine power plant coupled with a multi-effect desalination system with thermal vapor compression. They used genetic algorithm-based multi-objective optimization to determine the best decision variables. Decision variables include compressor pressure ratio, combustion temperature, compressor isentropic efficiency, gas turbine isentropic efficiency, top brain temperature, last effect temperature, and ejector compression ratio.

Previous studies have never used the ORC-VCC system, with a solar power source, to produce cold water in a hospital's air conditioner. Also, in previous research, the selection of a suitable refrigerant for the cycle by considering the three parameters of ORC cycle efficiency parameters, total cycle performance coefficient, and evaporator outlet water temperature was not studied simultaneously. In this paper, solar energy is used to produce cold water for air conditioners. Coldwater is produced by a combined ORC-VCC cycle and is used in the hospital's cooling in Esfarayen (Northeastern Iran). Based on the climatic conditions of the area, the intensity of solar radiation is calculated daily and hourly. To model the desired cycle, a program was developed in Engineering Equation Solver (EES) to perform the energy and exergy analysis in the cycle. To validate, the results of the program written in EES are compared with the results of Saleh [9]. Six working fluids are being investigated and, based on energy and exergy analysis, a suitable fluid is recommended for this system. Also, the effects of solar radiation intensity, refrigerant type, and mass flow rate of the refrigerant on the cooling water temperature outlet from the evaporator, cycle performance, ORC efficiency, COP of the VCC cycle, and exergy efficiency of the ORC-VCC system are investigated.

Nomenclature

a	Coefficients of the Angstrom model
b	Coefficients of the Angstrom model
I	Daily solar radiation intensity (W)
I_0	Atmospheric daily solar radiation intensity (W)
I_{SC}	world solar constant (W/m^2)
S	Being sunny hours (hour)
S_0	Maximum sunny hours (hour)
T	Temperature (^oC)
Ex	Exergy rate (kW)
$\dot{Q}$	Heat rate (kW)
$\dot{W}$	Net work (kW)
$\dot{m}$	Mass flow rate (kg/s)
h	Specific enthalpy (kJ/ kg)
n	number of days from January

Greek symbols

β	Cycle performance (%)
η	Thermal efficiency (%)
ω_s	Sun's angle (deg)
δ	The angle of deviation of the sun (deg)
φ	Latitude (deg)

Abbreviation

ORC	Organic Rankine Cycle
VCC	Vapor Compression Cycle
COP	Coefficients of Performance
PMR	Pump Compression Ratio
CMR	Compressor Compression Ratio
TEG	Thermo Electric Generator

2. Combined ORC-VCC system descriptions

In this paper, a refrigeration cycle, activated by solar radiation energy is investigated for the production of cold water. The refrigeration cycle used an organic Rankine cycle (ORC) coupled with a vapor compression cycle (VCC). The schematic diagram of the combined cycle is shown in Fig.1.

The main components of this system include pump, boiler, expander, condenser, expansion valve, an evaporator and compressor. Specifications and assumptions of this system include: (1) In both cycles, the same working fluid is used; (2) Compressor and expander are connected to one shaft, therefore, it is assumed that all expander power is given to the compressor; (3) a reciprocal condenser is used for both cycles; (4) This system is considered under steady-state; (5) The pressure drops in heat exchangers (boiler, condenser, and evaporator) is assumed 10%; (6) The isotropic efficiency of the expander, pump, and compressor is assumed to be 85%, 90%, and 85%, respectively; (7) The working fluid is exited from the condenser at saturated liquid state; (8) The expansion process in an expansion valve is assumed to be adiabatic; (9) As mentioned before, boiler heating is provided by solar collectors. It is assumed that 90% of the solar radiation absorbed by the collectors is transferred to the working fluid. Figure 2 shows the diagram of the temperature against entropy (T-s) for the ORC-VCC systems.

3. Solar radiations

The relationships used to calculate solar radiation are always dependent on meteorological variables. These variables include sunshine hours, ambient temperature, cloudiness, rainfall, relative humidity, composition, concentrations and particle size of the atmosphere. These variables are used alone or in conjunction with each other. In this research, the Angstrom model is used to calculate the solar radiation intensity. According to this model, solar radiation can be obtained [30]

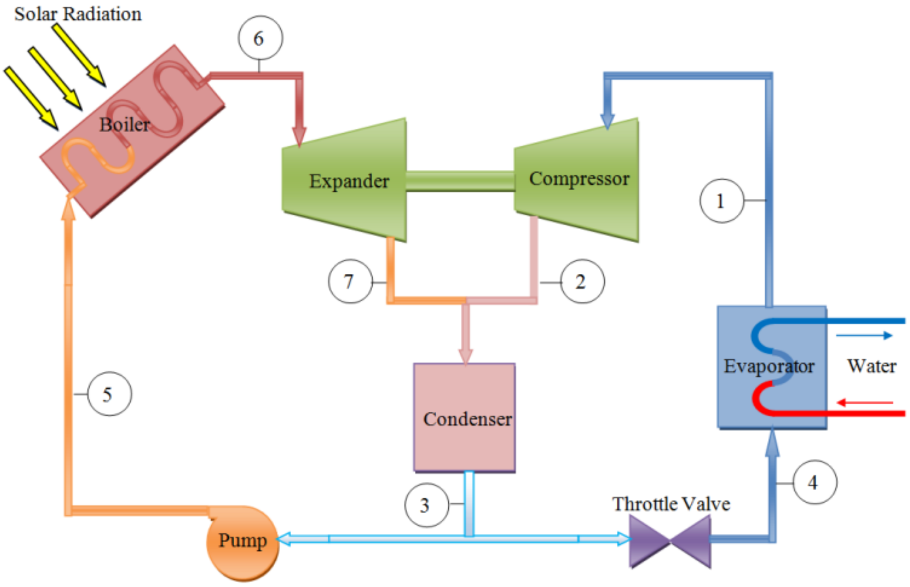


Fig.1. The schematic diagram of the ORC–VCC system

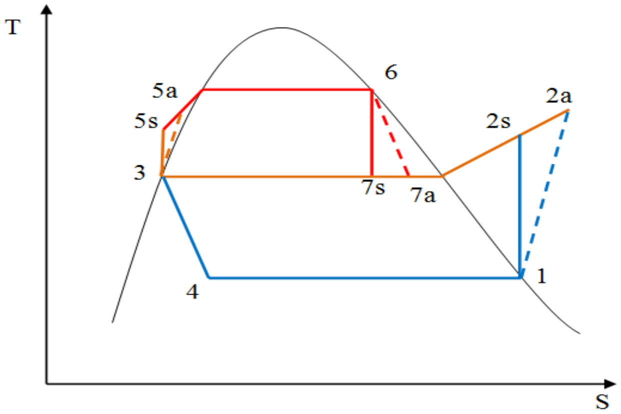


Fig. 2. The diagram of the temperature against entropy (T-s) for the ORC-VCC systems

$$\frac{I}{I_0}=a+b\frac{S}{S_0} \tag{1}$$

where I is the intensity of daily solar radiation, I_o is the intensity of the daily radiation outside the atmosphere, 'a' and 'b' are the experimental coefficients of the Angstrom model that must be chosen according to the location and weather conditions, S being sunny hours and S_o is maximum sunny hours.

The 'a' and 'b' coefficients are calculated by using Ferrer's method, given by [31]

$$a=-0.27+1.75\frac{S}{S_0}-1.34\left(\frac{S}{S_0}\right)^2 \tag{2}$$

$$b=1.32+2.90\frac{S}{S_0}+2.30\left(\frac{S}{S_0}\right)^2 \tag{3}$$

The intensity of the daily radiation outside the atmosphere can be calculated using [30]

$$I_0=\frac{24\times3600}{\pi}I_{SC}\left(1+0.033\cos\left(\frac{360n}{365}\right)\right)\left[\cos j\cos\delta\sin\omega_S+\frac{2\pi\omega_S}{360}\sin j\sin\delta\right] \tag{4}$$

where I_{sc} is set to 1367 W/m^2 according to the world radiation center, n is the number of days starting from January first, ω_s is the sun's angle at the moment of astronomical sunset, φ is the latitude and δ is the angle of deviation of the sun.

Based on the climate of Esfarayen during six years (from 2011 to 2016) and applying the above relations, the amount of solar radiation is calculated monthly. In Fig.3, the average intensity of solar radiation in one hour is shown for days of every month of the year.

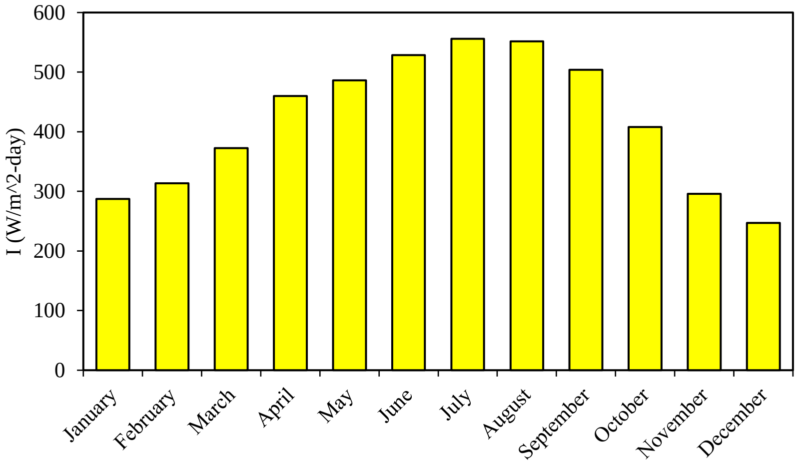


Fig.3. Daily solar radiation averages in one hour for all months

Five months of May, June, July, August, and September are observed with the highest intensity of solar radiation. These months seem to be the perfect solar energy to launch a combined ORC–VCC system; also air conditioners are used extensively. Using this high-power solar energy led to energy efficiency and reduces environmental pollution from fossil fuels. Therefore, the hourly solar radiation intensity during the day is calculated for these months. Figure 4 shows the intensity of hourly solar radiations during the day in May, June, July, August, and September. Since solar radiation is unsteady, solar radiation is calculated hourly per day. This takes into account the unsteady effects of solar radiation in one day.

Considering the solar collectors with a total surface area of 160 m^2 and thermal efficiency of 70%, the heat energy delivered to the boiler is calculated. The solar energy transferred to the boiler for five months warm of the year during a day is shown in Figure 5. In these months, from 8:00 am to 16:00, 60 to 125 kilowatts of thermal energy are given to the working fluid in the boiler. This amount of energy is suitable for cooling production using a combined ORC-VCC system.

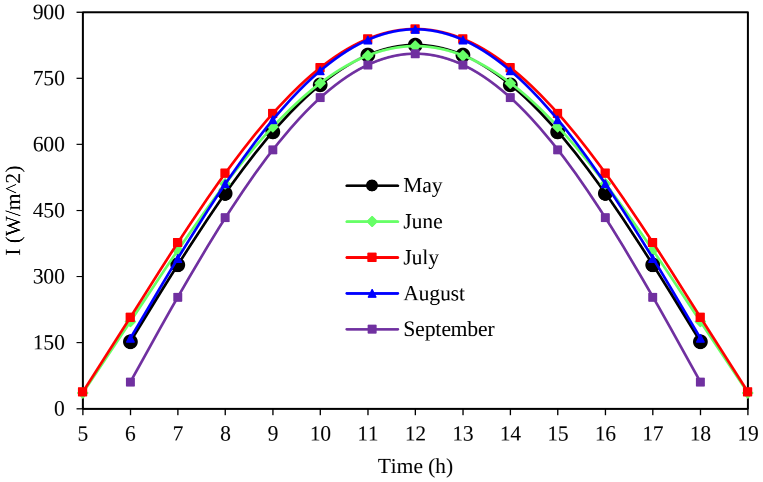


Fig.4. Hourly solar radiations during the day in May, June, July, August, and September

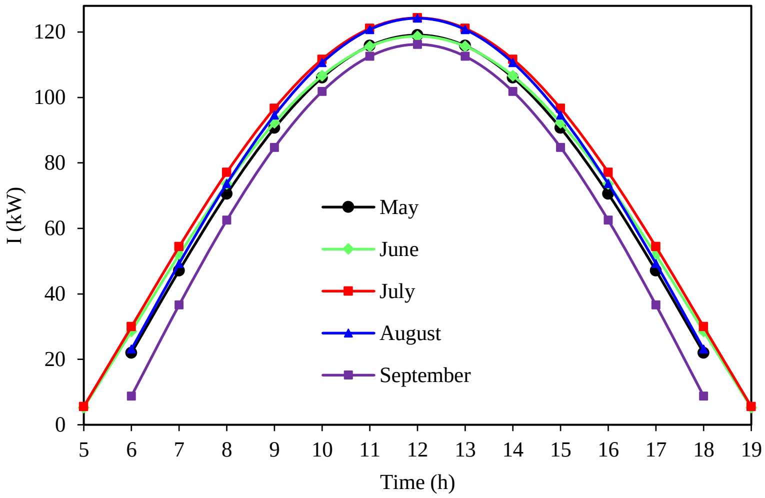


Fig.5. Heat energy transferred to the boiler during a day for the months of May, June, July, August, and September

4. Thermodynamic analyses

The analysis of thermodynamic cycles based on energy analysis is not very appropriate, because this method cannot provide the user with an accurate understanding of the quality and efficiency of the cycle. But by analyzing the exergy for a system, the quality of the system can be well studied. Exergy is considered as a criterion for determining the distance of systems from overall equilibrium. In this paper, the thermodynamic cycle is investigated in terms of energy and exergy analysis methods which are based on the first and second laws of thermodynamics.

Assuming that, negligible kinetic, chemical and potential energy changes; the mass, energy and exergy balances for any control volume at steady state can be expressed, respectively, by the following relationships [14].

$$\sum \dot{m}_{in} = \sum \dot{m}_{out} \tag{5}$$

$$\dot{Q} + \dot{W} = \sum \dot{m}_{out} h_{out} - \sum \dot{m}_{in} h_{in} \tag{6}$$

$$\dot{E}x_{heat} + \dot{W} = \sum \dot{E}x_{out} - \sum \dot{E}x_{in} + \Delta\dot{E}x \tag{7}$$

where *m* is the mass flow rate, subscriptions *in* and *out* signify inlet and outlet states, *Q* is the net heat input, *W* is the network, *h* is the enthalpy, *Ex* is the rate of exergy, and Δ*Ex* is the rate of exergy losses.

By applying these equations for each of the components of the cycle, energy and exergy balances equations are obtained. The thermodynamic mathematical model for the ORC-VCC system consists of two parts, ORC and VCC. Based on assumptions and referring to the ORC–VCC system presented in Fig.1 and Fig.2, the mathematical model for the system is given in Table 1.

The process of modeling and thermodynamic analysis of the cycle is done in EES software. To validate, the simulation results obtained from the developed EES code are compared with the values has obtained by Saleh [9]. Table 2 shows the results of the EES development code and Saleh's [9] results. This comparison shows that the EES development code can accurately calculate the thermodynamic properties and energy of the combined ORC–VCC cycle.

Table 1. Balances of energy and exergy for cycle components [14]

Component	Energy Balance	Exergy Balance
Compressor	$\dot{W}_{Comp} = \dot{m}_1 (h_2 - h_1)$	$\Delta\dot{E}_{Comp} = \dot{E}x_1 - \dot{E}x_2 + \dot{W}_{Comp}$
Condenser	$\dot{Q}_{Cond} = \dot{m}_7 h_7 + \dot{m}_2 h_2 - \dot{m}_3 h_3$	$\Delta\dot{E}_{Cond} = \dot{E}x_7 + \dot{E}x_2 - \dot{E}x_3 - \left(\frac{h_3 - h_7 - h_2}{T_3}\right)$
Throttling valve	$h_4 = h_3$	$\Delta\dot{E}_{Thrott} = \dot{E}x_3 - \dot{E}x_4$
Evaporator	$\dot{Q}_{Evap} = \dot{m}_4 (h_4 - h_1)$	$\Delta\dot{E}_{Evap} = \dot{E}x_4 - \dot{E}x_1 + \dot{Q}_{Evap}\left(1 - \frac{T_0}{T^*_{Evap}}\right)$
Pump	$\dot{W}_{Pump} = \dot{m}_5 (h_5 - h_3)$	$\Delta\dot{E}_{Pump} = \dot{E}x_3 - \dot{E}x_5 + \dot{W}_{Pump}$
Boiler	$\dot{Q}_{Boiler} = \dot{m}_5 (h_6 - h_5)$	$\Delta\dot{E}_{Boiler} = \dot{E}x_5 - \dot{E}x_6 + \dot{Q}_{Boiler}\left(1 - \frac{T_0}{T^*_{boiler}}\right)$
Expander	$\dot{W}_{Expand} = \dot{m}_6 (h_6 - h_7)$	$\Delta\dot{E}_{Expand} = \dot{E}x_6 - \dot{E}x_7 - \dot{W}_{Expand}$
ORC–VCC cycle	$\eta_{ORC} = \frac{\dot{W}_{Expan} - \dot{W}_{Pump}}{\dot{Q}_{Boiler}}$ $COP_{VCC} = \frac{\dot{Q}_{Evap}}{\dot{W}_{Comp}}$ $\beta_{ORC\text{-}VCC} = \eta_{ORC} \times COP_{VCC}$	$\eta_{exergy} = 1 - \frac{\Delta\dot{E}_{total}}{\dot{E}x_{in}}$

Table 2. Results of EES development code and Saleh [9] results

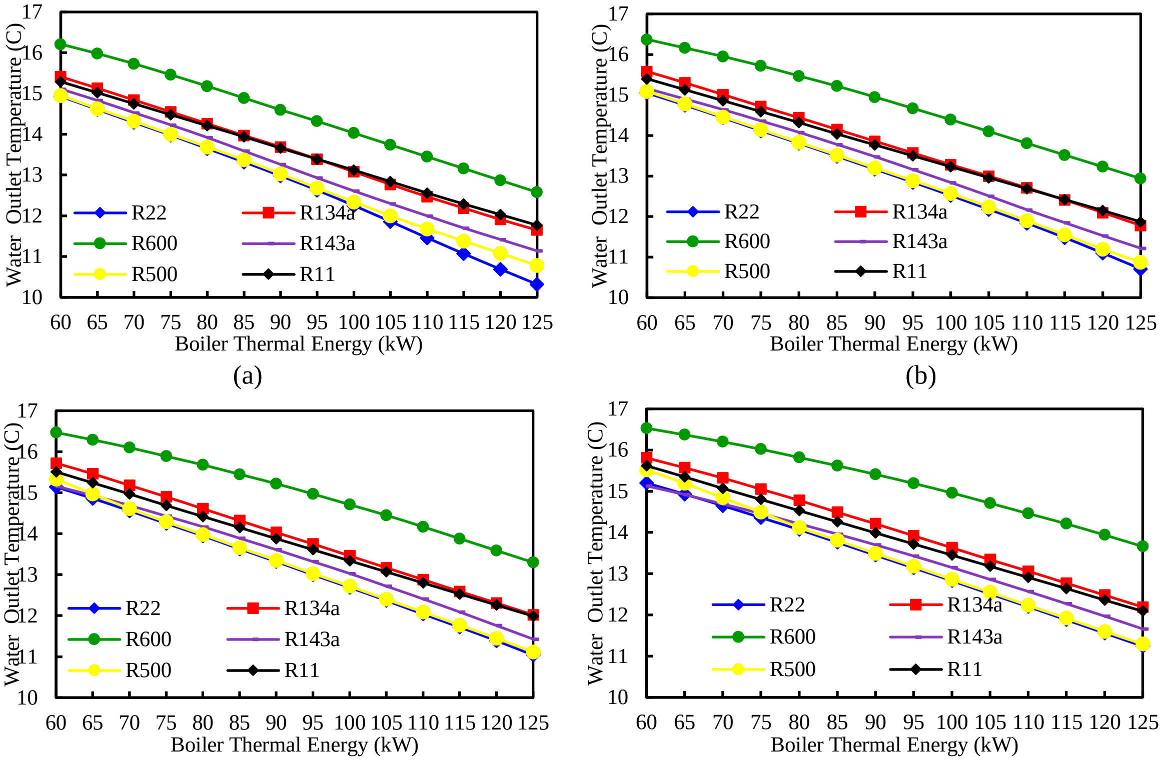
Substance	**Saleh**			**EES development code**		
	η_{ORC} (%)	**COP_{VCR}**	**COP_S**	**η_{ORC} (%)**	**COP_{VCR}**	**COP_S**
R290	6.90	4.81	0.332	6.899	4.815	0.332
RC318	6.94	4.58	0.318	6.954	4.576	0.3182
R600	7.76	5.12	0.398	7.759	5.112	0.3967
R600a	7.57	5.01	0.380	7.427	4.961	0.3684

5. Results and Discussion

Simulation results have been obtained based on the 4.5 pump compression ratio (PMR) in the ORC cycle. The boiler receives 60 to 125 kilowatts of thermal energy, which is supplied by the collector (70% efficiency) from solar radiation. This energy range is based on the hourly solar radiant energy in June, July, August and September. The inlet water temperature of the evaporator is 18 °C and the water mass flow rate is 2.52 kg/s (40 GPM). The six working fluids R22, R134a, R600, R143a, R500, and R11 are considered for the cycle, and the effect of solar energy given in the boiler on the outlet water temperature from the evaporator for air conditioner, the performance of the cycle (β), the ORC efficiency, Coefficient of performance for VCC, and the efficiency of the thermodynamics second law of the cycle are examined.

The main purpose of this research is to provide cold water for the cooling system of a hospital unit using solar energy. Solar energy is given to the working fluid through the boiler and the working fluid cools the water in the evaporator for the hospital cooling system. Figure 6 shows the effect of boiler heating (Q_{boiler}) on the outlet water temperature (T_{wo}) from the evaporator for four different mass flow rates in ORC. The results are shown for four mass flow rates 0.5, 0.6, 0.7, and 0.8 in the ORC cycle. The results show that with increasing boiler heat, the outlet water temperature decreases. It seems that the use of R22 and R500 in the combined ORC-VCC cycle is more suitable for cold water production. In this case, the 18°C water entering the evaporator comes out with a temperature of about 10°C. While refrigerant R600 cannot provide a good cooling compared to other refrigerants. By increasing the mass flow rate of the refrigerant from 0.5 to 0.8, the water existed from the evaporator becomes warmer. The results indicate that for more than 90 kW boiler heating, the study cycle can produce a temperature difference of 4 to 8 degrees Celsius in the evaporator outlet water with all refrigerants except refrigerant R600. It's also worth noting that the chiller device currently used in the Esfarayen hospital creates a temperature difference of 4 to 5 degrees Celsius. Therefore, the system can properly provide the needs of the cold water in the cooling system of the desired hospital.

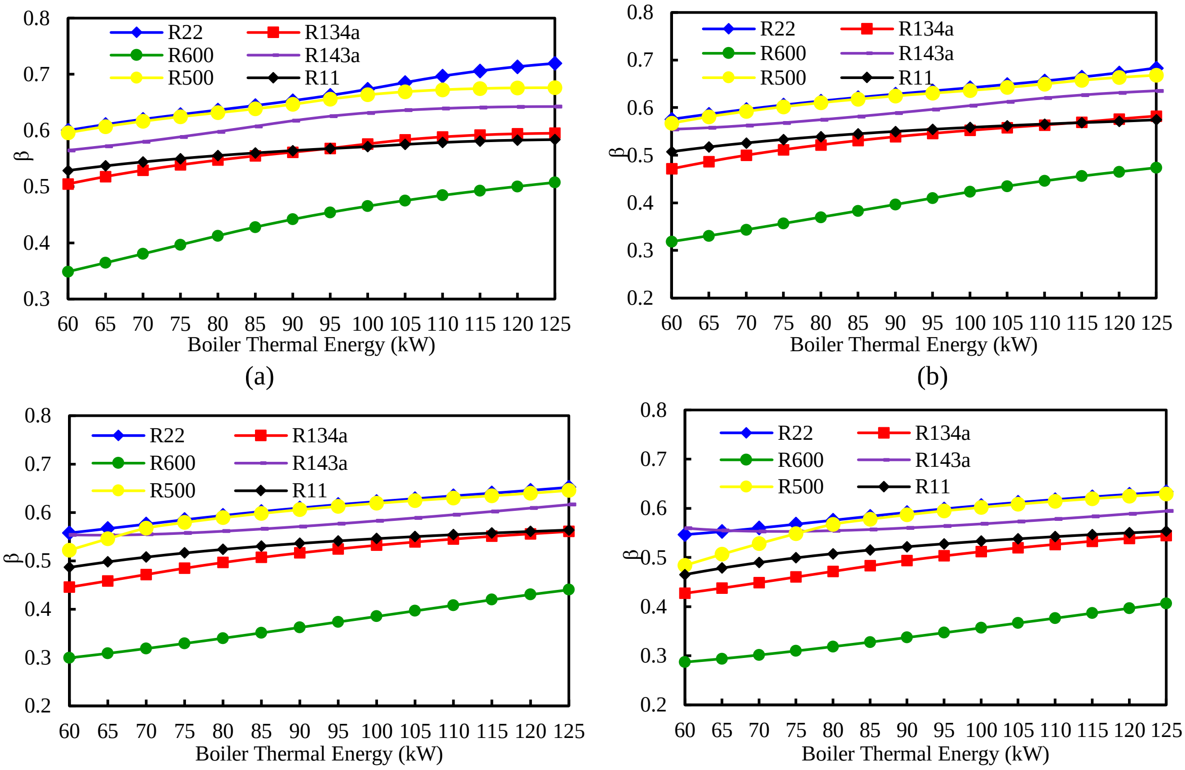
The coefficient of performance is one of the parameters determining the quality and performance of a cycle. The effect of boiler heating (Q_{boiler}) on the cycle performance (β) for each of the working fluids is investigated. The results of this study are presented in Fig.7. The results of Fig.7 show that increasing boiler heat leads to increased cycle performance. When using two refrigerants R22 and R500 in the combined ORC-VCC cycle, the cycle has the highest performance coefficient. The refrigerant R600 has the lowest performance coefficient for the cycle. The results show that by increasing the mass flow rate of the refrigerant in the cycle, the performance coefficient decreases. The curve slope of the refrigerant R600 is higher than other refrigerants. This means that the cycle performance coefficient for this refrigerant is more affected by boiler energy than other refrigerants. The highest cycle performance for all refrigerants occurs in mass flow rate 0.5 kg/s and boiler thermal energy 125 kW. In this case, the highest cycle performance is equal to 0.72, 0.68, 0.64, 0.59, 0.58, and 0.51 for refrigerants R22, R500, R143a, R134a, R11, and R600, respectively.



(a) (b)

(c) (d)

Fig.6. The effect of boiler thermal energy on the outlet water temperature for ORC mass flow rate (a) 0.5 kg/s (b) 0.6 kg/s (c) 0.7 kg/s (d) 0.8 kg/s



(a) (b)

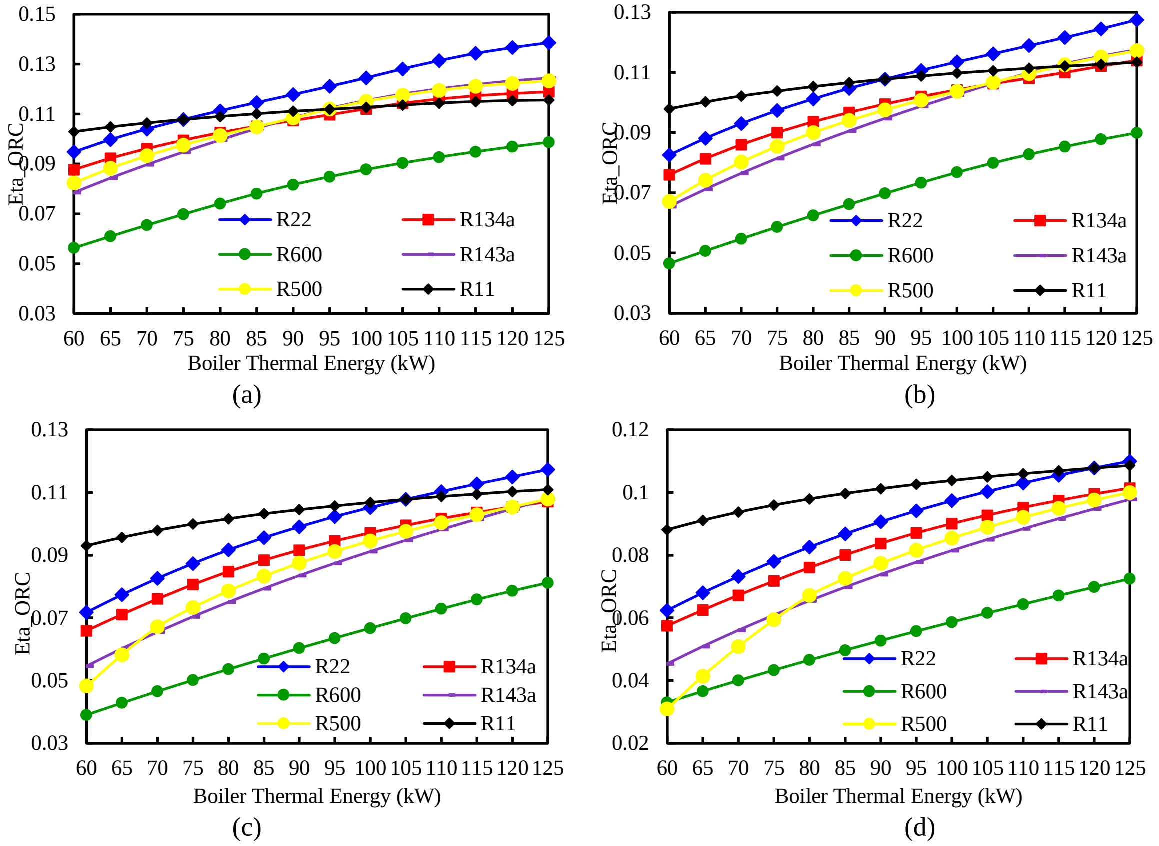
(c) (d)

Fig.7. The effect of boiler thermal energy on the performance coefficient of the ORC-VCR cycle for mass flow rate (a) 0.5 kg/s (b) 0.6 kg/s (c) 0.7 kg/s (d) 0.8 kg/s

Figure 8 shows the effect of boiler heating on the Organic Rankin Cycle efficiency (η_{ORC}) for different working fluids. Generally, the refrigerant R22 has the highest efficiency and the refrigerant R600 has the lowest efficiency. As can be seen, increasing the boiler's thermal energy increases ORC efficiency. The process of increasing the efficiency of the refrigerants is similar except for refrigerant R11 and R500. Refrigerant R11 has a slower growth rate than other refrigerants so that with energy changes in the boiler, the ORC efficiency changes only up to 0.01. ORC efficiency for refrigerant R500 is strongly affected by boiler heat. Increasing the mass flow rate of the refrigerant in the cycle reduces ORC efficiency. The highest ORC efficiency is 13.9%, which occurs in the mass flow rate of 0.5 kg/s and the boiler thermal energy 125 kW, for the refrigerant R22.

The results show that the mass flow rate of the refrigerant in the ORC-VCC cycle and boiler thermal energy does not affect the COP of the VCC cycle. But the refrigerant used in the combined cycle has a much effect on the performance coefficient of the VCC cycle. The effect of the refrigerant on the performance coefficient of the VCC cycle is shown in Fig.9. The results show that the R11 refrigerant has the highest COP with 4.98. R143a refrigerant has an efficiency of 4.285, which is the lowest value compared to other refrigerants.

Understanding energy and exergy efficiency are crucial for designing, analyzing, optimizing, and improving energy systems through a variety of measures and strategies for sustainable development [32]. Exergy analysis is intended to determine the maximum workability of the system, and given that different types of energy are directly considered in exergy terms. Therefore, it is clear that exergy analysis is essential for energy systems and exergy efficiency is an objective and rigorous



(a) (b) (c) (d)

Fig.8. The effect of boiler thermal energy on the Organic Rankin Cycle efficiency for mass flow rate (a) 0.5 kg/s (b) 0.6 kg/s (c) 0.7 kg/s (d) 0.8 kg/s

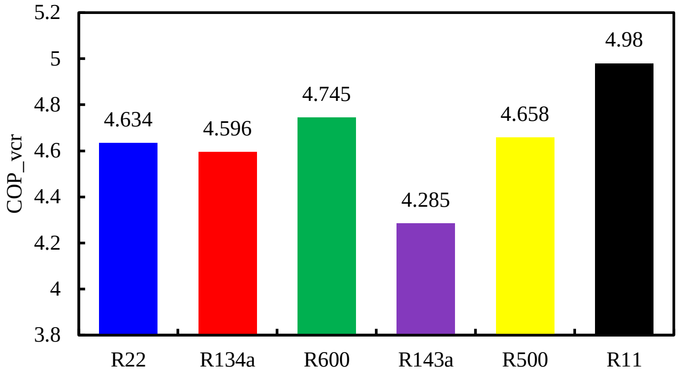
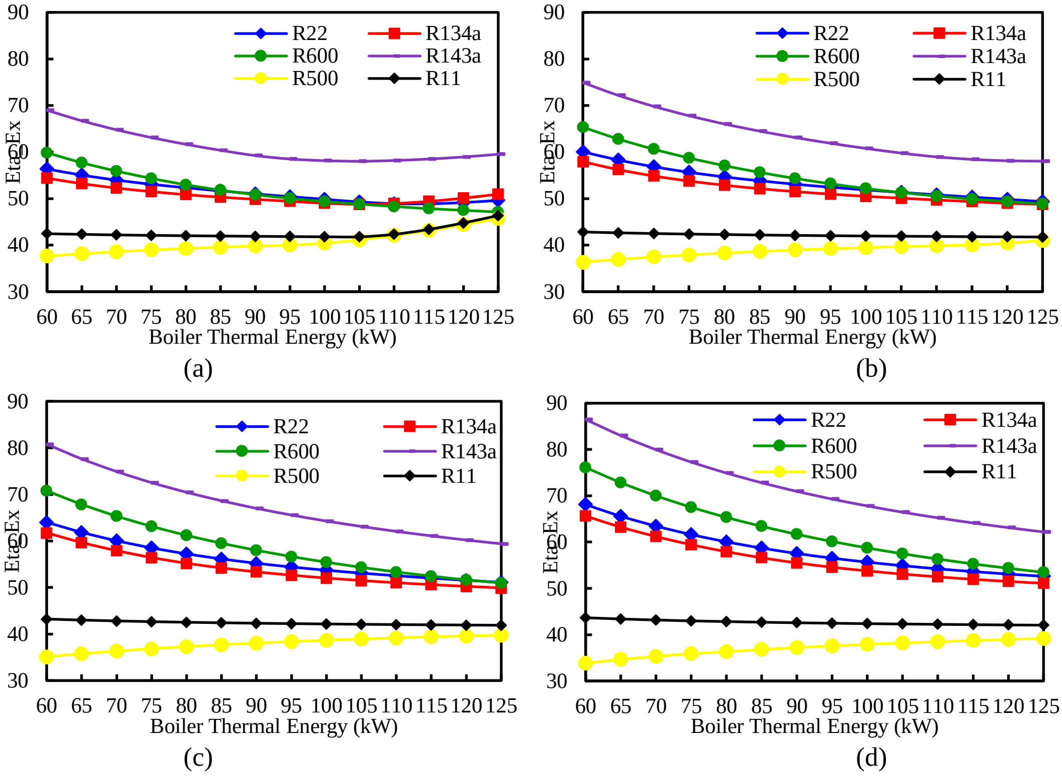


Fig.9. The effect of refrigerant on the performance coefficient of the VCC cycle

criterion for evaluating thermodynamic systems.

In this paper, the exergy is calculated in each part of the cycle and then the exergy efficiency of the cycle is calculated. Variation of exergy efficiency (η_{Ex}) of various working fluids with the boiler thermal energy for four mass flow rates 0.5, 0.6, 0.7, and 0.8 in the ORC cycle is shown in Fig.10. It is seen that the exergy efficiency of the combined cycle decreases with an increase in boiler thermal energy but increases with an increase in the mass flow rate of the ORC cycle. Of course, the behavior of both refrigerants R11 and R500 are slightly different from that of other refrigerants. Exergy efficiency for refrigerant R11 is almost always constant .In other words, for this refrigerant, there is no change in exergy efficiency due to changes in the mass flow rate of the ORC cycle and boiler energy. By increasing boiler energy, the exergy efficiency increases for refrigerant R500. The changes in exergy efficiency with increasing boiler heat for refrigerants R143a and R600 are greater than other refrigerants. Generally, the refrigerant R143a has the highest exergy efficiency and the refrigerant R500 has the lowest exergy efficiency.



(a) (b)

(c) (d)

Fig.10. The effect of boiler thermal energy on the exergy efficiency of ORC-VCC cycle for mass flow rate (a) 0.5 kg/s (b) 0.6 kg/s (c) 0.7 kg/s (d) 0.8 kg/s

Exergy destruction is investigated in each component of the cycle to determine the role of each component in the exergy changes. The results show that the amount of energy destruction changes with the change in the mass flow rate of the refrigerant and the boiler temperature for each refrigerant. However, in all cases, the greatest exergy destruction occurs in the boiler and then in the condenser.

Figure 11 shows the contribution of each component of the cycle to exergy destruction. These results are for refrigerant R22, mass flow rate 0.5 kg/s, and boiler thermal energy 95 kW. The highest percentage of exergy destruction is in the boiler with 56.93% and the lowest in the evaporator with 0.004%.

The results showed that most exergy destruction and changes occur in the boiler. On the other hand, the effect of the solar radiation intensity on the exergy is in the boiler. Therefore, the rate of exergy losses in the boiler is investigated. Figure 12 shows the effect of solar radiation intensity on the rate of exergy losses in a boiler. In all cases, refrigerant R500 has the highest rate of exergy losses, while refrigerant R600 has the lowest. The upward trend in exergy losses is observed with increasing temperature for all refrigerants and mass flow rates. Studies have shown that the maximum amount of exergy losses that occur in the boiler is 21.27 kW, which occurs in the mass flow rate of 0.5 kg/s and boiler thermal energy 125 kW.

With the negotiations, this project can be implemented in Esfarayen Hospital. Therefore, it is necessary to consider a suitable pump and compressor for project implementation. One of the parameters of pump and compressor selection is the pressure ratio. In this project, the pump compression ratio (PMR) 4.5 is considered. But the compressor pressure ratio (CMR) is calculated for different refrigerants. The results show that the CMR is constant for all mass flow rate and boiler thermal energy and only changes with the change of refrigerant type. The CMR for refrigerators R22, R500, R143a, R134a, R11, and R600 is 3.36, 3.42, 3.2, 3.84, 4.88, and 4.08, respectively.

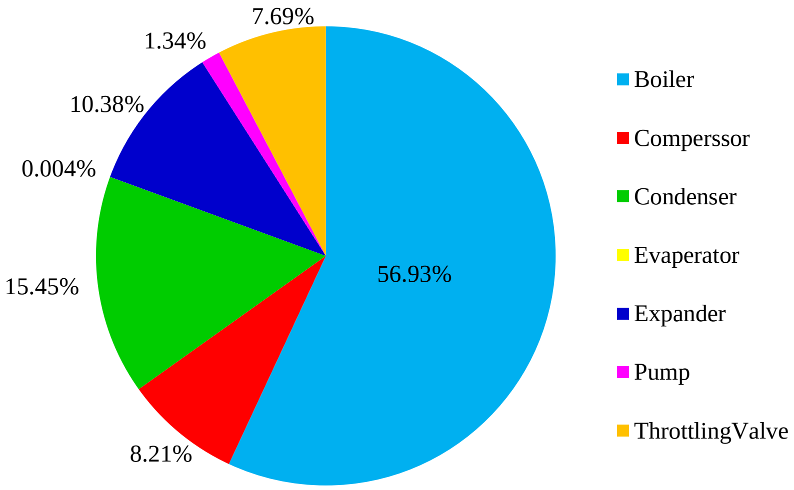
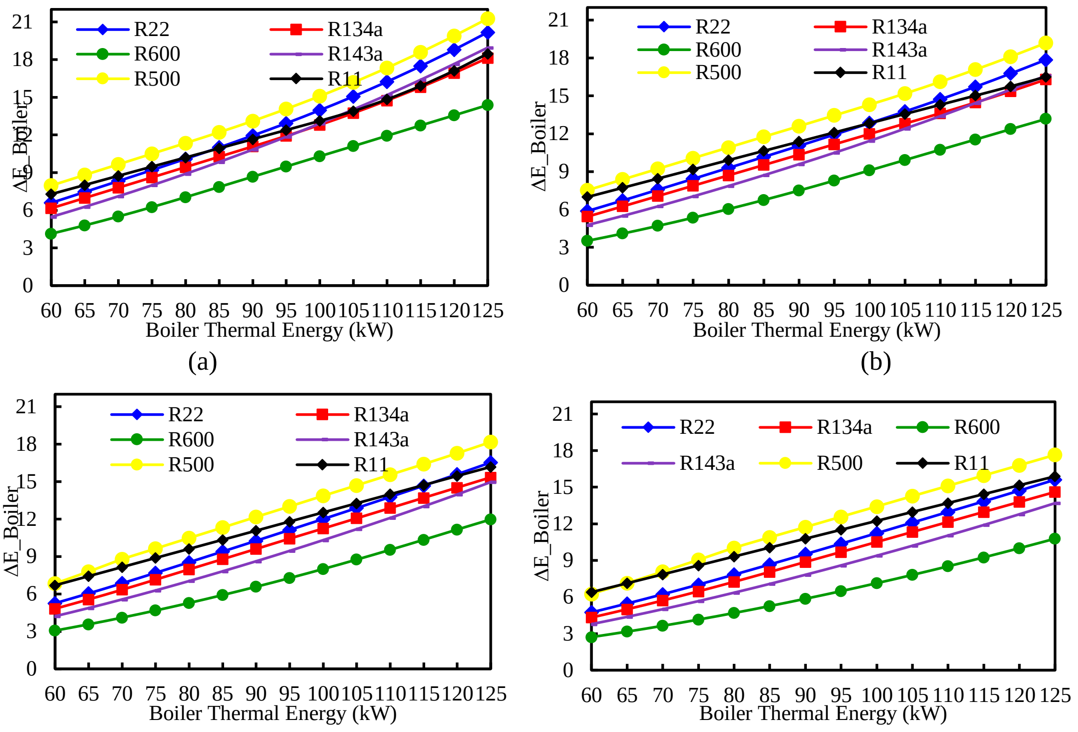


Fig.11. The contribution of each cycle component to the exergy destruction



(a) (b)

(c) (d)

Fig.12. The effect of boiler thermal energy on the rate of exergy losses in the boiler for mass flow rate (a) 0.5 kg/s (b) 0.6 kg/s (c) 0.7 kg/s (d) 0.8 kg/s

6. Conclusions

In this paper, a combined organic Rankine-vapor compression cycle is proposed and optimized to produce cold water. The optimally combined cycle produced cold water for hospital air conditioning using solar energy. The hospital is located in Esfarayen city, so the amount of solar energy in this city was calculated monthly, daily and hourly. Optimization is based on the selection of the appropriate refrigerant according to the cycle simulation and energy and exergy analysis. Simulation is performed using the Engineering Equation Solver (EES) software. To validate, simulation results were compared with Saleh's results. The analysis led to the following results. Simulation results have been obtained based on the 4.5 pump compression ratio. The boiler receives 60 to 125 kilowatts of thermal energy. The inlet water temperature of the evaporator is 18 °C and the water mass flow rate is 2.52 kg/s. The six working fluids R22, R134a, R600, R143a, R500, and R11 are considered for the cycle.

- The intensity of hourly solar radiations during the day in May, June, July, August, and September more than 500 watts per square meter. By using solar collectors, 60 to 125 kilowatts of thermal energy are given to the working fluid in the boiler of combine ORC-VCC.
- By increasing boiler thermal energy, the water temperature of the outlet from the evaporator decreases. Also using refrigerators R22 and R500 in the combined ORC-VCC cycle is more suitable for cold water production compared to other refrigerants. If the mass flow rate of the refrigerant used in the ORC cycle is lower, cooler water is produced in the evaporator.
- Increasing boiler thermal energy leads to increased cycle performance, while by increasing the mass flow rate of the refrigerant in the ORC cycle, the performance coefficient decreases. The refrigerants R22 and R500 have the highest performance coefficient and the refrigerant R600 has the lowest performance coefficient for the cycle.

- The refrigerant R22 has the highest ORC efficiency and the refrigerant R600 has the lowest ORC efficiency. With an increase in boiler thermal energy, from 60 to 125 kW, the ORC efficiency for refrigerant R22 is increased by 4.4% for a mass flow rate of 0.5 kg/s.
- The refrigerant used in the combined cycle has a much effect on the performance coefficient of the VCC cycle. The refrigerant R11 has the highest COP and the refrigerant R143a has the lowest COP, which is 4.980 and 4.285, respectively.
- By changing the boiler thermal energy and the mass flow rate of the refrigerant, different behaviors are observed in the exergy efficiency of the refrigerants. There was almost no change in the exergy efficiency due to an increase in boiler heat and mass flow rates for refrigerant R11. Increased boiler heating reduced the exergy efficiency for the four refrigerants R22, R134a, R600, and R143a .While increasing the boiler's heat leads to an increase of the exergy efficiency for refrigerant R500.
- By using solar energy to cool the Esfarayen hospital, two chillers with a total capacity of 320 refrigeration tons will be removed. The amount of electrical energy used by these two chillers is 280 kW. Since most of the electricity in Iran is from fossil power plants, reducing the amount of energy consumption can reduce the environmental pollution from the plants.

Although the results showed that this cycle can be used to save energy, there is still heat loss in the condenser and the pump needs to receive energy. Therefore, it is recommended that the use of a thermoelectric generator (TEG) to generate power from condenser heat dissipation be considered. The power generated by TEG is given to the pump so that the combined cycle provided is completely independent of receiving energy from outside. It seems that the use of TEG in this cycle will lead to an increase in the first and second law efficiencies of thermodynamics and greater efficiency.

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