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Investigating a Combined Cooling, Heating and Power System from Energy and Exergy Point of View with RK-215 ICE Engine as a Prime Mover

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ABSTRACT

Using cogeneration systems is a great way to tackle fossil fuel consumption problems. This paper introduces a Combined Cooling Heating Power (CCHP) system to recover the waste heat of an RK215 heavy diesel engine as a prime mover. Therefore the CCHP system consists of Internal Combustion Engine (RK215), a heat storage tank, and an absorption chiller. Also, the system has been studied in four modes: CCHP, CHP, CCP, and single generation. The waste heat ratio has changed due to a y factor, and the effect of this different parameter, such as the start of fuel injection and exhaust gas heat, on the system's efficiency by considering first and second laws of thermodynamic in different operating modes has been investigated. The system's highest energy and exergy efficiency in CCHP mode is equal to 50.46 and 30.8%, respectively. According to the result, as the CCHPs cooling load to the absorption chiller increases, the performance also rises. Also, the system's carbon dioxide emissions reduction has been studied. The results showed that using different modes for waste heat recovery can reduce carbon dioxide by up to 30% approximately for different modes. Also, the fuel energy saving ratio (FESR) has been investigated, and the results showed that systems in CCHP, CHP, and CCP modes could have FESR approximately equal to 21%.

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NOMENCLATURE

Abs	Absorber	SOI	Start of injection (angle °)
BDC	Bottom Dead Centre	T	Temperature (° K)
CCP	Combined Cooling and power	TDC	Top Dead Centre
CCHP	Combine Cooling, Heating, and Power	$\dot{W}$	Work (kW)
CDE	Carbon Dioxide Emission	η	Efficiency
$CDER$	Carbon Dioxide Emission Reduction	μ	carbon dioxide emissions factor
CHP	Combined Heating and Power	**Subscripts**	
Cond	Condenser	0	Environmental Condition
COP	Coefficient of Performance	b	Boiler
E	Electrical Load (kW)	c	Chiller
Eva	Evaporator	$Conv$	Conventional System
$\dot{E}x_D$	Exergy Destruction Rates (kW)	e	Outlet
ex	Specific exergy (kJ/kg)	el	Electricity
F	Fuel	ex	Exergy
$FESR$	Fuel Energy Saving Ratio	f	Fuel
FS	Fuel Saving	g	gas
Gen	Generator	hx	Heat exchanger

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h	Specific enthalpy (kJ/kg)	i	Inlet
HST	Heat Storage Tank	mix	Mixture
ICE	Internal Combustion Engine	ph	Physical
LHV	Low Heating Value (kJ/kg)	Q	Heat
$\dot{m}$	Mass flow rate (kg/s)	th	Thermal
P	Power generation mode	w	work
$\dot{Q}$	Heat load (kW)		
s	Specific entropy (kJ/kg K)		

INTRODUCTION

Due to population growth and increasing demand for energy consumption, decentralized energy generation systems with higher efficiency and less pollution have become increasingly crucial to communities. Conventional power generation systems convert only about 30% of the total energy of the input fuel into electricity, which indicates the low efficiency of this type of system due to high fuel consumption and high pollution generation [1].

Cogeneration systems (CCHP and CHP) are more efficient and can reduce emissions and tackle the problems of fossil fuel consumption. These systems have three main parts: prime mover, refrigeration, and heating. Different options, such as internal combustion engines, gas turbines, steam turbines, Sterling engines, and fuel cells, can be used as primary actuators in this system [2]. Different components have been introduced to recover waste heat of the prime mover, heating unit, and other cycles for cooling, such as the absorption refrigeration cycle, ejector cycle, and organic Rankin [3].

In the last decades, many research has been done on waste heat recovery of internal combustion engines: Angrisani et al. [4] cogeneration system with prime mover of the internal combustion engine was tested to meet the cooling, heating, and power requirements of a lecture room. Their results showed that using the proposed system reduces fuel consumption by 7.7% and reduces carbon dioxide generation by 15.3% compared to the conventional system. Manzela et al. [5] studied a cogeneration system with a diesel engine as the primary driver and an absorption refrigeration cycle. Their results showed that when waste heat of the engine is given to the absorption refrigeration cycle, it reduces pollution generation. In an experimental study, Tiwari et al. [6] Designed a system to use truck exhaust heat in an absorption refrigeration cycle; their results showed that the system weighing 30 kg could generate cooling at a rate of 1 kW. Godefroy et al. [7] Studied a system of CCHP; the prime mover of their system was a 5.5 kW internal combustion engine. Their results showed that their system could achieve 50% energy efficiency. Huangfu et al. [8] Studied a CCHP micro-cogeneration system for domestic and light commercial applications. The prime mover of their system was an internal combustion engine that used natural gas as fuel and an absorption refrigeration cycle to meet the cooling demand. Their results showed that the electricity output condition is very important for determining the electricity efficiency. Abusoglu et al. [9] Studied a cogeneration system that used a diesel engine as the prime mover; They investigated the efficiency of the CCHP system. Their results showed that their proposed CCHP's energy efficiency is 44.2% . Also, the highest exergy efficiency of their system is 50%. Wang et al. [10] investigated a CCHP from the perspective of energy and carbon dioxide emissions. The prime mover of their proposed system was a diesel engine, and they also investigated the effect of using two types of fuel, hydrogen, and diesel, on the system's performance. Their results showed that for the CCHP system, the highest energy efficiency was related to the use of hydrogen fuel, which was equal to 82%. Also, the highest amount of carbon dioxide generation was for to the single electricity generation system, which was 80% more than the CCHP generation mode. Daghigh and Shafieian [11] proposed a CCHP system to use the heat of the exhaust gas of a diesel engine of a submarine, In their proposed system, an absorption chiller was used for cooling. Also, an organic Rankine cycle with methane working fluid was used to generate power; their results showed that the maximum power generation in the organic Rankine cycle was 53 kW, which occured when the working fluid mass rate and gas output from the engine were 0.6 and 0.27 kg/s, respectively.

The cogeneration systems can provide all types of energy required by the consumer units. The consumer's demand for heating, cooling, and electricity is variable and depends on various factors, the most important of which are the weather and climate conditions. For instance, in the summer season, the demand for cooling is more than heating; Therefore, choosing a flexible system that can provide cooling, heating, and electricity as desired according to the user's needs is crucial. The research conducted on cogeneration systems in recent years focused on only one or two functional modes of the systems. While in this research, a CCHP cogeneration system was investigated in 4 generation modes, CCHP, CCP, CHP, and single electricity generation mode, so that the energy generation potential of the system was evaluated in order to take advantage of this, the diesel engine used in Iranian national railway, named RK215, is a good choice as the primary mover of the proposed system. The GT-Power software first numerically models the engine, and the output results of the modeling, such as temperature, mass rate, and dew point of exhaust gases, are used to start the CCHP system. According to the research on CCHP systems with diesel engine prime mover, an absorption chiller is the most common system for refrigeration systems. In this study, an absorption refrigeration cycle is considered a cooling unit. Also, a heat storage tank is used as a heating unit to store heat and provide heating to the user. The work output from the engine is also given to a generator to produce electricity. First, the variables that have the most significant impact on the system in terms of performance have been identified. The best operating point to achieve the maximum energy efficiency and exergy for different functional modes was determined. At the end, for the system under different functional modes, the percentage of fuel energy saving ratio and the carbon dioxide emission reduction generation at their best performance point compared to the conventional system were calculated. To sum up, the highlights of this research the following are included:

1. In order to increase efficiency, we investigated solutions for using the waste heat generated in RK215 engines in Iran.
2. To the authors' best knowledge, most studies done on cogeneration systems with ICE (as the prime mover) are based on general results. The RK215 engine is not modeled and validated in the GT software to understand the effect of engine operational parameters (such as SOI) on the entire cogeneration system.
3. Since the demand for electricity exist, heating, and cooling loads is not always constant during the entire year. In this research, the system is studied in four operational modes of single, CHP, CCP, and CCHP by defining the y factor. The y factor is between 0 and 1 and represents the portion of the cooling load from exhaust heat. Finally, after finding the best performance point of the system in different performance modes, the system's fuel saving and reduction of emissions were compared to the conventional system.

SYSTEM DESCRIPTION

The system's prime mover is the RK215 16-cylinder diesel engine developed by Man Diesel Company. The specifications of the 16RK215 engine are summarized in Table 1. A heat storage tank is provided to supply the consumer heating demand, and cooling is done by the absorption refrigeration cycle. CCHP's configuration is shown in Figure 1.

How the CCHP works is that in a specific SOI, first the heat of the engine exhaust gas, which is the result of cooling the exhaust gas up to 10 degrees above the dew point of the combustion products, which is given to the chiller generator with a coefficient of y [1]. In the generator, the waste heat of exhaust gas is given to the lithium bromide water. Due to the difference in saturation temperature between water and lithium bromide, the solution's two components are separated. Evaporated water enters the condenser, and concentrated lithium bromide is cooled from the other side of the generator after passing through a heat exchanger with 70% efficiency and enters the absorber through the pressure relief valve. The water vapor entering the condenser loses heat, leaves the condenser in the saturated liquid state, and enters the evaporator through a pressure relief valve. In the evaporator, the water receives the ambient heat and performs the refrigeration operation, and in the state of saturated steam, it leaves the evaporator and gets to the absorber. At the end, in the absorber, water is combined with lithium bromide again. The absorption refrigeration cycle operates at high and low pressures of 5.5 and 0.9 kPa, respectively [1]. Finally, the remaining part of the exhaust gas (1-y) is heated to a storage tank (HST) that provides the required heat to the consumption unit. The engine's mechanical work is given to the electricity generator to meet the consumer's electricity needs. Figure 2 shows the absorption refrigeration cycle with cycle components. The system was investigated in three general modes: triple generation, double generation, and single generation. The investigated cases are as follows:

1. Triple generation of electricity, heat, and cold (CCHP)
2. Dual generation of electricity and cold (CCP) and dual generation of heat and electricity (CHP)

Table 1. 16RK215 engine's specifications [12]

Parameter	Value
Engine Type	Heavy duty diesel
Brake Power (kW)	2844 at 1000 RPM
Maximum cylinders Pressure (bar)	154
The total volume of cylinders (lit)	159.52
Number of cylinders	16
compression ratio	13.5:1
Bore (mm)	215
Stroke (mm)	275
Connecting rod Length (mm)	502
Nozzle configuration	8×0.36 mm
Fuel per shot (mg)	1226
Injection duration	30°CA
Fuel	$C_{13.5}H_{27.6}$
SOI	-20AFTDC
Intake valve opening	303.5
Intake valve closing	-146.5
Exhaust valve opening	121.5
Exhaust valve closing	405.5

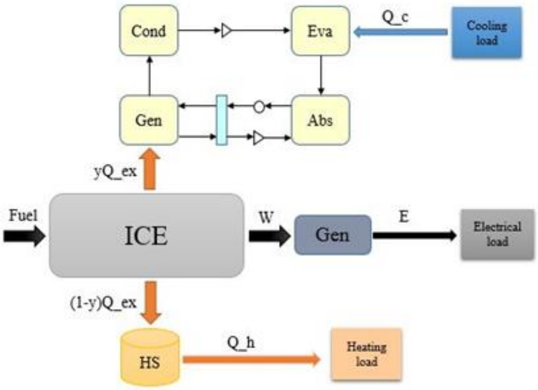

Figure 1. Configuration of triple cogeneration system based on absorption refrigeration cycle with primary diesel engine drive

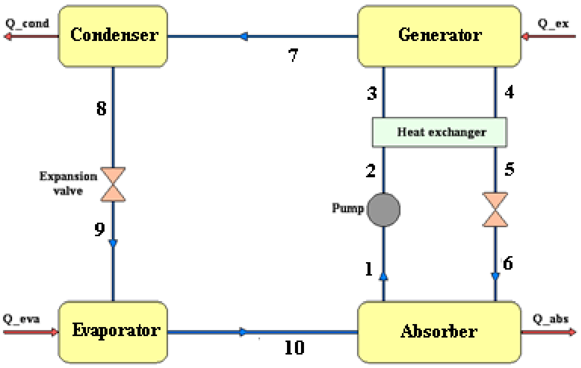

Figure 2. Different components of the lithium bromide-water refrigeration cycle

3. Individual generation of electricity (P)

The current research aims to find the system's best operating point for different functional modes, including CCHP, CCP, CHP, and single power generation. The meaning of the best operating point is finding an SOI and a y coefficient for different functional modes, where the system has the highest energy efficiency and exergy at this point compared to other points. To find the best operating point, first, CCHP's exergy and energy efficiency are calculated in all SOIs and different y. The best operating point has the highest energy efficiency and exergy. If efficiency are maximized separately in different SOIs, the distance of these points to the ideal point (d) with 100% energy efficiency and exergy is calculated according to given equation in th next section. The minor point d is selected as the best operating point. For example, suppose for a specific functional mode, the highest efficiency are achieved in SOI=B and SOI=A, respectively, according to Figure 3. In that case, the distance to the ideal point (d1 and d2) is compared with each other, and the point with the lowest d value, i.e. SOI=B, is selected for the best operating point.

MODELING

Numerical modeling of RK215 engine

GT-Power software is used for the numerical modeling of diesel engines. Engine speed and the start of injection are two input parameters to the engine, and components such as temperature, mass rate of exhaust gas from the engine, braking power, etc., are selected as modeling outputs. The assumptions considered for modeling the engine are as follows:

- The temperature and pressure of the dead state are 25°C and 101.325 kPa.
- The discretization length for input and output components is 70 mm.
- The temperature of the cylinder wall and the piston surface are considered to be 590°C and 450°C, respectively. This value is assumed to be 550°C for the piston head surface.

Validation of engine numerical model

To validate the numerical model of the diesel engine, a comparison between two pressure parameters and the heat release rate in the cylinder for the numerical model and the laboratory results were conducted [12]. The obtained data are shown in Figures 4 and 5.

According to the comparison made between the numerical and experimental model for two parameters of pressure and heat release rate inside the cylinder, It is evident that data obtained from numerical simulation are very similar to experimental data and the small difference between them can be ignored.

Thermodynamic modeling

In order to thermodynamically study the entire system and each of its components, thermodynamic modelling

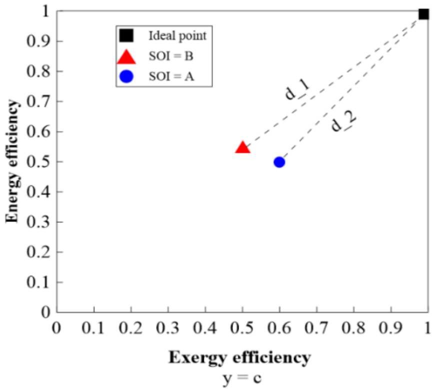

Figure 3. Comparing the efficiency of the simultaneous generation system in different SOIs with the ideal point

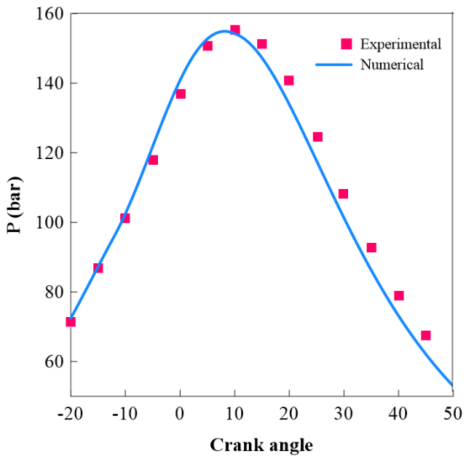

Figure 4. Validation of cylinder pressure for numerical model and experimental results

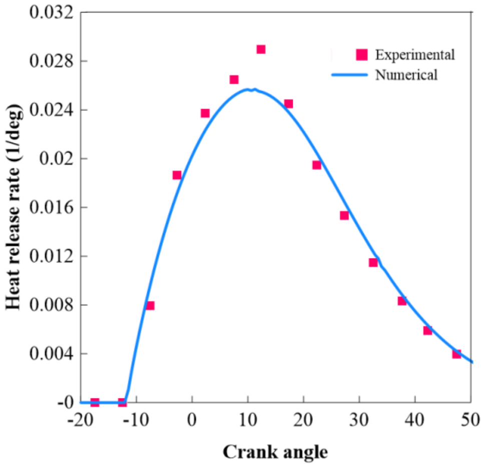

Figure 5. Validation of cylinder heat release rate parameter in the numerical model and experimental results

was performed. In order to better develop the thermodynamic model, the following assumptions are considered for the studied system:

- Steady conditions are considered for all system processes.
- Kinetic and potential energy changes system are eliminated.
- The pressure drop in heat exchangers is ignored.
- The isentropic efficiency of the pump and turbine used in the system is assumed to be 85% and 80%, respectively.
- The efficiency of the heat storage tank is considered to be 80%.
- To prevent acid corrosion in the heat exchanger, the diesel engine's exhaust gas temperature after recovery is considered to be 57°C, i.e., 10 degrees higher than the dew point temperature of the combustion products.

Law of conservation of mass and energy

In the steady state for a certain control volume, the energy and mass equations are stated as follows [3]:

$$\sum \dot{m}_e - \sum \dot{m}_i = 0 \tag{1}$$

$$\dot{Q} + \sum \dot{m}_i\, h_i = \dot{W} + \sum \dot{m}_e\, h_e \tag{2}$$

where h is the specific enthalpy, fuel energy is calculated using equation (3) [13, 14].

$$\dot{Q}_{fuel} = \dot{m}_{fuel} LHV \tag{3}$$

in equation (3), the LHV is fuel's low heating value. system's efficiency from the energy viewpoint of the system is calculated according to equation (4) [13].

$$\eta_{\mathrm{th}} = \frac{\text{total energy output}}{\text{total energy input}} \tag{4}$$

$$\dot{Q}_{exhaust} = \dot{m}_{gas}\left(h_{gas.in} - h_{gas.out}\right) \tag{5}$$

in equation (5), $\dot{Q}_{exhaust}$ represents the heat from the engine exhaust gas and h_{gas} is the enthalpy of the engine exhaust gas. $\dot{Q}_{exhaust}$ is given to the absorption chiller generator according to equation (6) with the coefficient y and the remaining fraction is given to the storage tank according to equation (7).

$$\dot{Q}_{generator} = \mathrm{y}\dot{Q}_{exhaust} \tag{6}$$

$$\dot{Q}_{heat\_storage} = \eta_{Hs}(1 - \mathrm{y})\dot{Q}_{exhaust} \tag{7}$$

in equation (7), η_{Hs} is the HST efficiency. The energy balance relationships for the absorption refrigeration cycle are expressed as follows [15]:

$$\dot{Q}_{generator} = \dot{m}_4 h_4 + \dot{m}_7 h_7 - \dot{m}_3 h_3 \tag{8}$$

$$\dot{Q}_{absorber} = \dot{m}_6 h_6 + \dot{m}_{10} h_{10} - \dot{m}_1 h_1 \tag{9}$$

$$\dot{W}_{pump} = \dot{m}_2 h_2 - \dot{m}_1 h_1 \tag{10}$$

$$\dot{m}_2 h_2 - \dot{m}_3 h_3 = \eta_{Hx}(\dot{m}_4 h_4 - \dot{m}_5 h_5) \tag{11}$$

$$\dot{Q}_{condenser} = \dot{m}_7 h_7 - \dot{m}_8 h_8 \tag{12}$$

$$\dot{Q}_{evaporator} = \dot{m}_{10} h_{10} - \dot{m}_9 h_9 \tag{13}$$

$$\dot{m}_8 h_8 = \dot{m}_9 h_9 \tag{14}$$

$$\dot{m}_5 h_5 = \dot{m}_6 h_6 \tag{15}$$

in equation (11), η_{Hx} is the efficiency of the heat exchanger in the absorption refrigeration cycle.

Exergy Analysis

Exergy equations for a control volume is stated as follows [1]:

$$\dot{E}x_Q + \sum \dot{m}_i ex_i = \dot{E}x_w + \sum \dot{m}_e ex_e + \dot{E}x_D \quad (16)$$

$$\dot{E}x = \dot{m}ex \quad (17)$$

where ex and $\dot{E}x_D$ are specific exergy and exergy destruction rate, respectively. In equations (18) and (19), $\dot{E}x_Q$ and $\dot{E}x_w$ are the exergy related to the heat transferred and the work done between the control volume and the environment [1].

$$\dot{E}x_Q = \dot{Q}(1 - \frac{T_0}{T}) \quad (18)$$

$$\dot{E}x_w = \dot{W} \quad (19)$$

In equation (18), T_0 represents the ambient temperature. Specific physical exergy in a certain state is defined as follows [16]:

$$ex_{ph} = (h - h_0) - T_0(s - s_0) \quad (20)$$

Index 0 shows the value of a variable in environmental conditions. Also, the amount of chemical exergy for an ideal gas mixture is expressed by equation (21) [16].

$$ex_{ch.mix} = \left[\sum_{i=1}^{n} X_i ex_{ch_i} + RT_0 \sum_{i=1}^{n} X_i \mathrm{Ln}\,(X_i)\right] \quad (21)$$

where ex_{ch_i} and X_i are the chemical exergy per mole and the mole fraction of the i-th component of the gas mixture, respectively. Equation (22) calculates the exergy of chemical fuels with the formula C_aH_b per mass unit [17]. The absorption equations are shown in Table 2.

Table 2. Absorption refrigeration cycle components Exergy equations.

Component	Exergy balance equation
Absorber	$\dot{m}_1 ex_1 = \dot{m}_{10} ex_{10} + \dot{m}_1 ex_1 + \dot{E}x_{Q.absorber} + \dot{E}x_{D.absorber}$
Generator	$\dot{m}_3 ex_3 + \dot{E}x_{Q.generator} = \dot{m}_7 ex_7 + \dot{m}_4 ex_4 + \dot{E}x_{D.generator}$
Condenser	$\dot{m}_7 ex_7 = \dot{m}_8 ex_8 + \dot{E}x_{Q.condenser} + \dot{E}x_{D.condenser}$
Evaporator	$\dot{E}x_{Q.evaaporator} + \dot{m}_9 ex_9 = \dot{m}_{10} ex_{10} + \dot{E}x_{D.evaporator}$
Heat exchanger	$\dot{m}_5 ex_5 + \dot{m}_3 ex_3 = \dot{m}_4 ex_4 + \dot{m}_2 ex_2$
Pump	$\dot{m}_2 ex_2 + \dot{W}_{pump} = \dot{m}_1 ex_1 + \dot{E}x_{D.pump}$

$$\frac{ex}{LHV} \cong 1.04224 + 0.011925\frac{b}{a} - \frac{0.042}{a} \quad (22)$$

The relationship related to exergy efficiency to check the performance of the cogeneration system is as follows [13]:

$$\eta_{\mathrm{ex}} = \frac{\text{total exergy output}}{\text{total exergy input}} \quad (23)$$

Fuel saving

equations (24) and (25) can be used to calculate the fuel energy saving ratio [18].

$$F_{CCHP} = m_{fuel}LHV \quad (24)$$

$$F_{conv} = \frac{E_{conv}}{\eta_{el}} + \frac{Q_b}{\eta_b} + \frac{Q_c}{\eta_{el}COP_{conv}} \quad (25)$$

Where η_{el} is the efficiency of the conventional system, Q_b is the heat produced in the boiler, and COP is the electrical chiller performance coefficient. Consumption reduction's amount and its percentage are calculated according to relations (26) and (27), respectively, where FS represents the amount of fuel saved and $FESR$ shows the percentage of fuel consumption savings [18].

$$FS = F_{conv} - F_{CCHP} \quad (26)$$

$$FESR = \left(\frac{F_{conv} - F_{CCHP}}{F_{conv}}\right)100 \quad (27)$$

Carbon dioxide emissions

To review the system from an environmental perspective, amount of pollution produced by cogeneration system and the conventional system are calculated, which means the generation pollution is the amount of carbon dioxide gas emission. Finally, the cogeneration system's emission reduction percentage is calculated [19].

$$CDE_{CCHP} = \mu_g F_{CCHP} \quad (28)$$

$$CDE_{conv} = \mu_{el}E_{conv} + \mu_g\left(\frac{Q_b}{\eta_b}\right) + \mu_{el}(\frac{Q_c}{COP_{conv}}) \quad (29)$$

where CDE is the system emissions and μ_{el} and μ_g are the factors related to carbon dioxide emissions for electricity and gas networks, respectively.

$$CDER = \left(\frac{CDE_{conv} - CDE_{CCHP}}{CDE_{conv}}\right)100 \quad (30)$$

In equation (30), $CDER$ represents the emission reduction percentage [19]. The coefficients are represented in Table 3.

Table 3. Coefficients related to the calculation of fuel consumption reduction percentage and emission reduction percentage [20]

Parameter	Value
η_{el}	0.3
η_b	0.8
COP_{conv}	3
μ_g (g kWh $^{-1}$)	220
μ_{el} (g kWh $^{-1}$)	836

Best operating point

The best operating point corresponds to the point that has the shortest distance to the ideal point. The ideal point has 100% efficiency. The distance d is calculated through equation (31).

$$d = \sqrt{(1-\eta_{\text{th}})^2 + (1-\eta_{\text{ex}})^2} \tag{31}$$

RESULTS AND DISCUSSION

16RK215 diesel engine

Figure 6 shows the motor output power in different SOIs. The results show that the start of fuel injection at very low crank angles and very high crank angles is inappropriate. In fact, if the start of fuel injection is done very early, such as SOI=-36, -32, the piston starts to move towards the bottom dead point (BDC) before it reaches the top dead point (TDC) and cannot fill the entire volume. It sweeps slowly from BDC to TDC, decreasing engine efficiency at low SOIs. On the other hand, increasing the crank angle means the start of combustion near TDC, which causes phenomena such as knocking, which leads to an increase in the impact on the engine and ultimately reduces the engine power. For this reason, the engine always has an optimal SOI, which is The modeling done for the RK215 engine is equal to -24 degrees. A negative number indicates the angles before the top dead point, for example, the number -24 means 24 degrees.

Performance study

Using the numerical simulation results of the RK215 diesel engine, the heat obtained from the engine's exhaust gas at different fuel injection times has been considered as input energy to the absorption refrigeration cycle and the heat storage tank. To study the cogeneration system's efficiency under variable input energy, the coefficient y is considered between 0.2 and 0.8, representing the contribution of the cooling cycle from the exhaust gas's heat.

According to Figure 7, with the increase of the y coefficient, the system's energy efficiency always

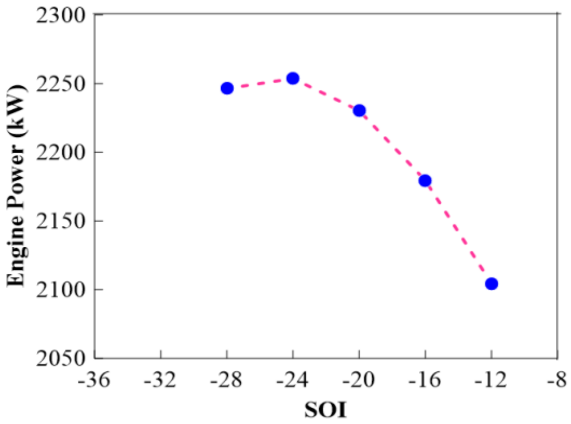

Figure 6. Engine braking power at different SOIs

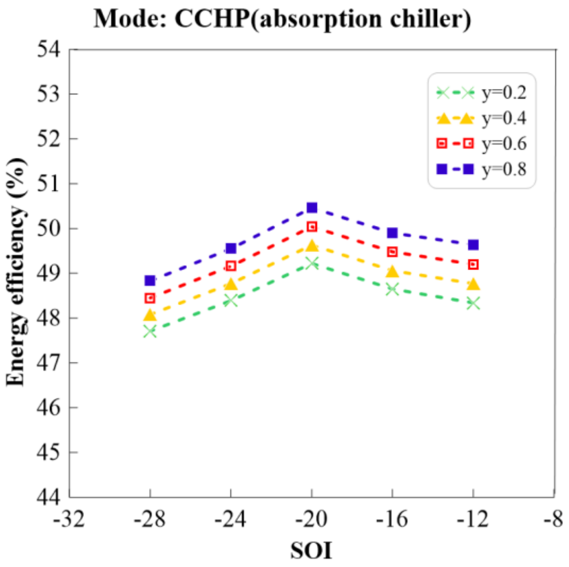

Figure 7. Energy efficiency of the CCHP system

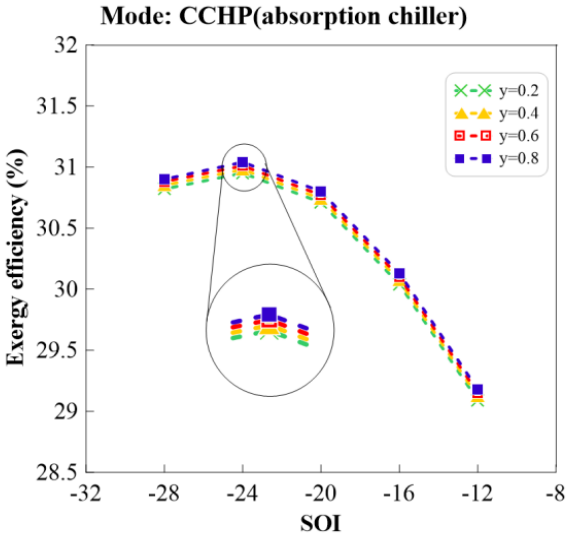

Figure 8. CCHP's exergy efficiency

increases in all SOIs, because an increase in the y coefficient means an increase in and decrease of the heat supplied to the absorption chiller and HST, respectively. The refrigeration cycle's efficiency is higher than HST's, so an increase in the y coefficient always increases CCHP's efficiency. Figure 8 shows the CCHP's exergy performance in terms of SOI and different y coefficients, according to which the changes in the y coefficients do not cause a noticeable change in the exergy efficiency, and only the SOI change causes an increase or decrease in the exergy efficiency.

the exergy effect of the mechanical work output from the CCHP system is larger than the exergy effect of the heat and cold produced by the system, so with changes in the y coefficient, which ultimately leads to a change in the amount of heat and cold the system becomes productive, there are no noticeable changes in exergy efficiency, on the other hand, since at SOI=-24, the system has the highest mechanical power, at this point, the highest exergy efficiency is obtained for all y coefficients.

In Table 4, the CCHP's highest exergy and energy performance obtained in SOI=-20 and SOI=-24 are compared to the ideal point. d parameter is lower for SOI=-20 than SOI=-24, which means it is closer to the ideal point, so it can be chosen as the best operating point for the CCHP.

For the system in single power generation mode, according to Figure 9, the highest efficiency is achieved at SOI=-24, where the efficiency values are 31.88 and 29.97%, respectively. In the case of single generation, the goal is only to produce electricity, so in this case, it can be said that system performance are directly related to the output power from the engine. The highest engine power is achieved in SOI=-24, so at this point, the highest performance is achieved for producing only electricity mode. According to Figure 10, by increasing the refrigeration cycle's high pressure, CCHP's efficiency decreased slightly. However, the absorption chiller's cop decreased a little more noticeably, in general, because the discussion of cooling in the definition of the efficiency of the whole cycle is only a part of the fraction. Changing the chiller's performance even from a numerical order of hundredths does not affect the efficiency of the whole cycle.

By increasing the y coefficient, the heat that is provided to the absorption refrigeration cycle from the hot source (exhaust gas) increases and less heat is provided to the heat storage tank. Therefore, with an increase in y coefficient, the cooling capacity of the cogeneration system increases (Table 5) and its heating capacity decreases. Also, according to Figures 7 and 8, increasing the y coefficient in all SOIs increases the energy efficiency and exergy because the absorption chiller efficiency is always higher than the heat storage tank efficiency; therefore, the cooling capacity of the triple generation system rises and its ability to heat decreases, exergy and energy performance of it will also improve. The cogeneration system in dual power and cold generation (CCP) mode has the best performance, because, in this state y=1, all the exhaust heat is given to the absorption refrigeration cycle. In fact, the y

Table 4. The distance of the points with the highest CCHP's efficiency to the ideal point

d	Exergy efficiency (%)	Energy efficiency (%)	y	SOI
0.8510	30.8	50.46	0.8	-20
0.8544	31.04	49.55	0.8	-24

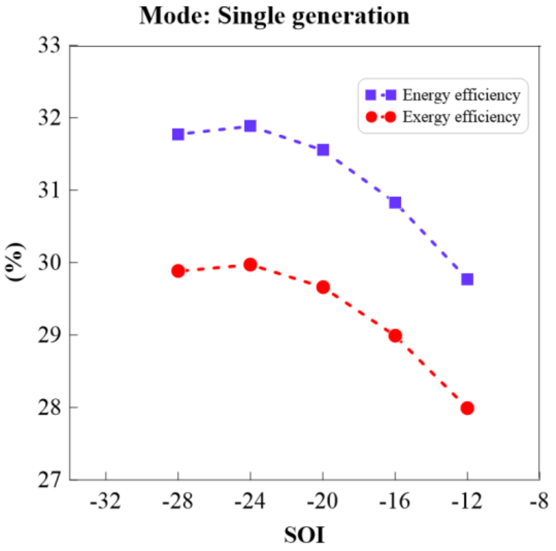

Figure 9. system's Energy efficiency and exergy in the mode of producing only electricity

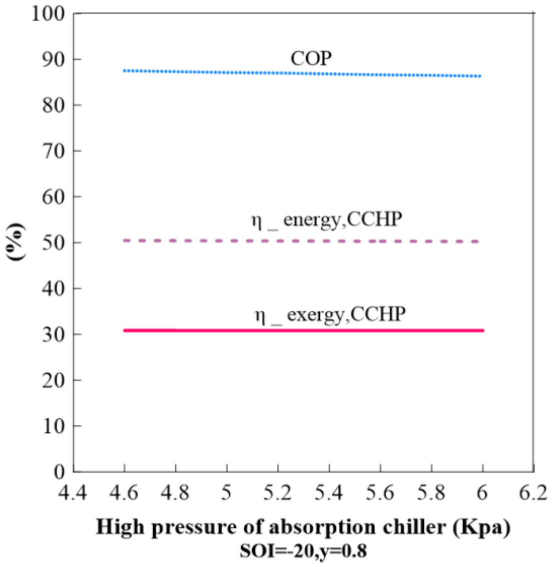

Figure 10. Effect of high pressure of absorption refrigeration cycle on exergy and energy efficiency of CCHP system at best operating point

coefficient helps to find the best way to use heat of exhaust gas to achieve the best performance.

For CHP mode (combined heating and power), when the system's heating capacity increases, CHP's performance also improves. At y=0, all the exhaust heat is given to the HST, so the CHP system has the best performance at this point.

In Figure 11, maximum cogeneration's energy efficiency in different modes is shown. single power generation mode has the lowest energy efficiency because the system in this mode has no cooling and heating potential and only produces electricity, which causes a decrease in the system's energy efficiency compared to other functional modes.

Also, according to Figure 11, it is clear that exhaust gas heat recovery and its use in an absorption refrigeration cycle and storage tank in CCHP, CCP and CHP modes lead to an increase in engine efficiency in single power generation mode by 58.2%, 59.5% and 55%, respectively. This increase in efficiency means that starting a cogeneration system with a diesel engine under different modes than the conventional system produces more useful work for the same input energy, or in other words, to achieve the same amount of work The specific benefit of the cogeneration system is that it requires less input energy than the conventional system, which causes the cogeneration's fuel consumption to be lower than the traditional system.

According to Figure 12, the percentage of fuel consumption savings for the simultaneous generation system in different functional modes is approximately equal to 21%.

Since using a cogeneration system compared to the conventional system reduces fuel consumption, it also produces less pollution. Figure 13 shows the reduction in

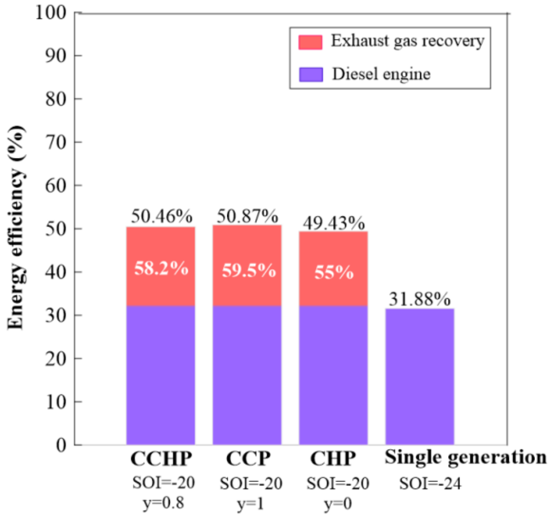

Figure 11. The highest energy efficiency of the system in different operating modes at the best operating point

Table 5. Cooling, heating and electricity generation load of the system in different functional modes at the best operating point

Electricity (kW)	Heating load (kW)	Cooling load (kW)	y	SOI	Functional mode
2230.36	252.8	1084.121	0.8	-20	CCHP
2230.36	0	1366.49	1	-20	CCP
2230.36	1264.34	0	0	-20	CHP
2253.64	0	0	-	-24	Single generation

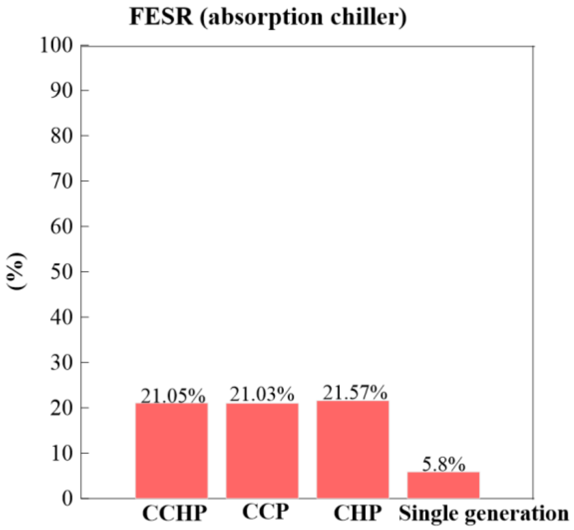

Figure 12. The percentage reduction in fuel consumption of the cogeneration system in different functional modes compared to the conventional system

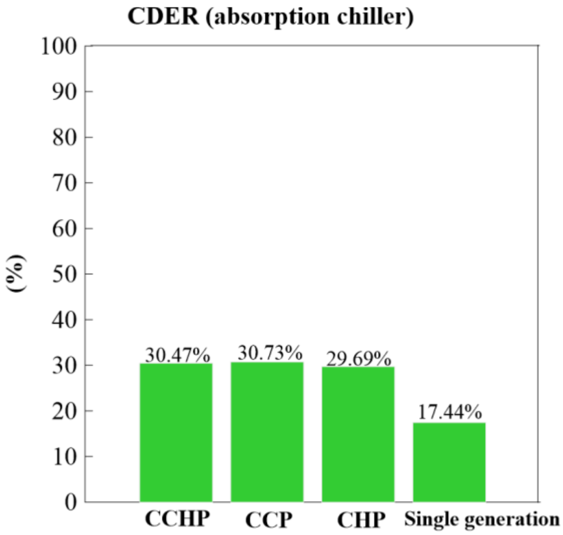

Figure 13. The percentage reduction of cogeneration system emissions in different modes compared to the conventional system

emissions of the cogeneration system under different operating conditions compared to the conventional system.

CONCLUSIONS

The results of this research are as follows:

- The highest engine power is obtained at SOI=-24, which is equal to 2253.64 kW.
- The more heat is available to the absorption refrigeration cycle, the cooling potential of the CCHP system increases, which improves the performance of CCHP
- CCHP system at SOI=-20 and y=0.8 has the best efficiency performance compared to other places. The system's efficiency at this point is equal to 50.46% and 30.8%, respectively.
- High-pressure changes of the absorption refrigeration cycle do not cause a noticeable change in CCHP's exergy and energy performance.
- CCP mode has the highest energy efficiency, which is equal to 50.87%
- single power generation mode has the lowest efficiency, with values of 31.88% and 29.97%, respectively.
- The cogeneration system in double and triple generation modes has approximately 21% less fuel consumption than the conventional system.
- The pollution of the cogeneration generation system in double and triple modes is almost 30% less than the conventional system.

REFERENCES

1. Chahartaghi, M. and Kharkeshi, B. A., 2018. Performance analysis of a combined cooling, heating and power system with PEM fuel cell as a prime mover, *Applied Thermal Engineering,* 128, pp. 805-817. Doi: 10.1016/j.applthermaleng.2017.09.072
2. Chahartaghi, M. and Alizadeh-Kharkeshi, B., 2016. Performance analysis of a combined cooling, heating and power system driven by PEM fuel cell at different conditions, *Modares Mechanical Engineering,* 16(3), pp. 383-394. Doi: 10.1016/j.applthermaleng.2017.09.072
3. Nouri, M., Namar, M. M. and Jahanian, O., 2019. Analysis of a developed Brayton cycled CHP system using ORC and CAES based on first and second law of thermodynamics, *Journal of Thermal Analysis and Calorimetry,* 135(3), pp. 1743-1752. Doi:10.1007/s10973-018-7316-6
4. Angrisani, G., Roselli, C., Sasso, M. and Tariello, F., 2014. Dynamic performance assessment of a micro-trigeneration system with a desiccant-based air handling unit in Southern Italy climatic conditions, *Energy conversion and management,* 80, pp. 188-201. Doi: 10.1016/j.enconman.2014.01.028
5. Manzela, A. A., Hanriot, S. M., Cabezas-Gómez, L. and Sodré, J. R., 2010. Using engine exhaust gas as energy source for an absorption refrigeration system, *Applied Energy,* 87(4), pp. 1141-1148. Doi: 10.1016/j.apenergy.2009.07.018
6. Tiwari, H. and Parishwad, G., 2012. Adsorption refrigeration system for cabin cooling of trucks, *International Journal of Emerging Technology and Advanced Engineering,* 2(10), pp. 337-342.
7. Godefroy, J., Boukhanouf, R. and Riffat, S., 2007. Design, testing and mathematical modelling of a small-scale CHP and cooling system (small CHP-ejector trigeneration), *Applied Thermal Engineering,* 27(1), pp. 68-77. Doi: 10.1016/j.applthermaleng.2006.04.029
8. Huangfu, Y., Wu, J., Wang, R., Kong, X. and Wei, B., 2007. Evaluation and analysis of novel micro-scale combined cooling, heating and power (MCCHP) system, *Energy Conversion and Management,* 48(5), pp. 1703-1709. Doi: 10.1016/j.enconman.2006.11.008
9. Abusoglu, A. and Kanoglu, M., 2008. First and second law analysis of diesel engine powered cogeneration systems, *Energy Conversion and Management,* 49(8), pp. 2026-2031. Doi: 10.1016/j.enconman.2008.02.012
10. Wang, Y., Huang, Y., Chiremba, E., Roskilly, A. P., Hewitt, N., Ding, Y., Wu, D., Yu, H., Chen, X. and Li, Y., 2011. An investigation of a household size trigeneration running with hydrogen, *Applied Energy,* 88(6), pp. 2176-2182. Doi: 10.1016/j.apenergy.2011.01.004
11. Daghigh, R. and Shafieian, A., 2016. An investigation of heat recovery of submarine diesel engines for combined cooling, heating and power systems, *Energy Conversion and Management,* 108, pp. 50-59. Doi: 10.1016/j.enconman.2015.11.004
12. Rad, G. J., Gorjiinst, M., Keshavarz, M., Safari, H. and Jazayeri, S., 2010. An investigation on injection characteristics of direct-injected heavy duty diesel engine by means of multi-zone spray modeling, *Oil & Gas Science and Technology–Revue d'IFP Energies Nouvelles,* 65(6), pp. 893-901. Doi: 10.2516/ogst/2009048
13. Abbasi, M., Chahartaghi, M. and Hashemian, S. M., 2018. Energy, exergy, and economic evaluations of a CCHP system by using the internal combustion engines and gas turbine as prime movers, *Energy Conversion and Management,* 173, pp. 359-374. Doi: 10.1016/j.enconman.2018.07.095
14. Alizadeh Kharkeshi, B., Shafaghat, R., Mohebi, M., Talesh Amiri, S. and Mehrabiyan, M., 2021. Numerical simulation of a heavy-duty diesel engine to evaluate the effect of fuel injection duration on engine performance and emission, *International Journal of Engineering, Transactions B: Applications,* 34(11), pp. 2442-2451. Doi:10.5829/ije.2021.34.11b.08
15. Salek, F., Moghaddam, A. N. and Naserian, M. M., 2017. Thermodynamic analysis of diesel engine coupled with ORC and absorption refrigeration cycle, *Energy Conversion and Management,* 140, pp. 240-246. Doi: 10.1016/j.enconman.2017.03.009
16. Bejan, A., Tsatsaronis, G. and Moran, M. J., 1995. Thermal design and optimization. John Wiley & Sons. ISBN: 978-0-471-58467-4
17. Balli, O., Aras, H. and Hepbasli, A., 2010. Thermodynamic and thermoeconomic analyses of a trigeneration (TRIGEN) system with a gas–diesel engine: Part I–Methodology, *Energy Conversion and Management,* 51(11), pp. 2252-2259. Doi: 10.1016/j.enconman.2010.03.021
18. Balakheli, M. M., Chahartaghi, M., Sheykhi, M., Hashemian, S. M. and Rafiee, N., 2020. Analysis of different arrangements of combined cooling, heating and power systems with internal combustion engine from energy, economic and environmental viewpoints, *Energy Conversion and Management,* 203, pp. 112253. Doi: 10.1016/j.enconman.2019.112253
19. Chicco, G. and Mancarella, P., 2008. Assessment of the greenhouse gas emissions from cogeneration and trigeneration systems. Part I: Models and indicators, *Energy,* 33(3), pp. 410-417. Doi: 10.1016/j.energy.2007.10.006
20. Sheykhi, M., Chahartaghi, M., Balakheli, M. M., Kharkeshi, B. A. and Miri, S. M., 2019. Energy, exergy, environmental, and economic modeling of combined cooling, heating and power system with Stirling engine and absorption chiller, *Energy Conversion and Management,* 180, pp. 183-195. Doi: 10.1016/j.enconman.2018.10.102

Persian Abstract

چکیده

استفاده از سیستم‌های تولید همزمان برق، گرما و سرما (CCHP) راه‌حلی مناسب برای مشکلات مصرف سوخت فسیلی است. این مقاله یک سیستم تولید همزمان CCHP را برای بازیابی گرمای تلف شده موتور دیزل سنگین RK215 به عنوان محرک اولیه معرفی می‌کند. سیستم از یک موتور احتراق داخلی (RK215)، تانک ذخیره حرارت و چیلر جذبی تشکیل شده است. همچنین سیستم در چهار حالت عملکردی CCHP، CCP، CHP و تولید تکی برق مورد بررسی قرار گرفته است. نسبت گرمای اتلافی موتور با فاکتور y تغییر کرده و اثر تغییر پارامتر y و شروع پاشش سوخت (SOI) بر روی راندمان انرژی و اگزرژی سیستم در حالت‌های عملکردی مختلف بررسی شده است. بیشترین بازده انرژی و اگزرژی سیستم در حالت CCHP به ترتیب برابر با ۵۰/۴۶ درصد و ۳۰/۸ درصد است. نتایج نشان می‌دهد هرچقدر حرارت بیشتری در اختیار چیلر جذبی قرار گیرد و یا به عبارتی دیگر پتانسیل سرمایش سیستم تولید همزمان افزایش یابد، راندمان انرژی و اگزرژی سیستم نیز افزایش می‌یابد. از سوی دیگر، کاهش انتشار گاز دی‌اکسید کربن سیستم نیز مورد مطالعه قرار گرفته است. نتایج نشان داد که استفاده از حالت‌های عملکردی مختلف برای بازیابی گرمای اتلافی می‌تواند دی‌اکسید کربن را تقریباً تا ۳۰ درصد برای حالت‌های عملکردی مختلف کاهش دهد. همچنین نسبت صرفه‌جویی در مصرف سوخت (FESR) بررسی شده است و نتایج نشان‌می دهد که مقدار FESR برای سیستم در حالت‌های CCHP، CHP و CCP تقریباً ۲۱ درصد است.