

EXERGOECONOMIC ANALYSIS OF THE POTENTIAL EXPLOITATION OF CONDENSATION WATER VAPOUR WASTE HEAT IN A THERMAL POWER PLANT USING HEAT PUMPS

Summary

This paper deals with the possibilities for the reduction of thermal environmental pollution and increases in the efficiency of the condensate system of a turbine by installing an inverter heat pump system. The inverter heat pump system will use the heat energy of the turbine exhaust steam that would otherwise be rejected. The operation of a condenser cooling system in a heating plant will be presented, and the possibilities of an inverter heat pump system installation will be analysed. The envisaged waste heat recovery system will be presented and analysed. The analysis will involve an evaluation of exergy and anergy efficiency of the system to minimize the generation of entropy, thus reducing the irreversibility of the system. Some guidelines regarding the utilization of heat energy generated by the inverter heat pump system and the impact of the utilization of heat on turbine efficiency will be indicated.

Key words: *adiabatic damping, heat accumulator, inverter heat pump, steam generator, turbine condenser*

1. Introduction

A turbine condenser is designed to condense steam exiting a turbine through which the latent heat of the turbine exhaust steam is conducted to the atmosphere. The volume of the turbine exhaust steam varies according to the volume of energy produced. As the heating plant is a cogeneration facility, the turbine steam flow rate constantly changes. The planned power generation needs must be met as well as the requirements regarding district heating and industrial steam. The heat energy for district heating and industrial steam is fed from the turbine through the third and fourth turbine steam extractions [1], [2]. The above-indicated energy needs are met by controlling the turbine steam inlet rate. Many other authors have also presented a turbine condenser system that was based on energy balances [3], [4], [5], [6], [7], [8].

The above factors can cause oscillation of the turbine condenser heat flow fed within the existing heating plant system in Slovenia with the cooling water to the River and disposed of into the environment. The possibility of utilizing the turbine condenser waste heat exists if an inverter heat pump is installed. The energy generated by the inverter heat pump may be utilized by the existing heating plant users. The large inverter heat pump has been widely applied in various energy related issues [9], [10], [11], [12]. This means that an inverter heat

pump system will have to be designed so that the inverter heat pump will generate steam of the quality corresponding to the quality of the steam of the fourth turbine extraction. A heat pump evaporator unit consist of two heat exchangers (evaporator 1 and evaporator 2) which will be installed between the turbine exhaust and the turbine condenser, Figure 1.

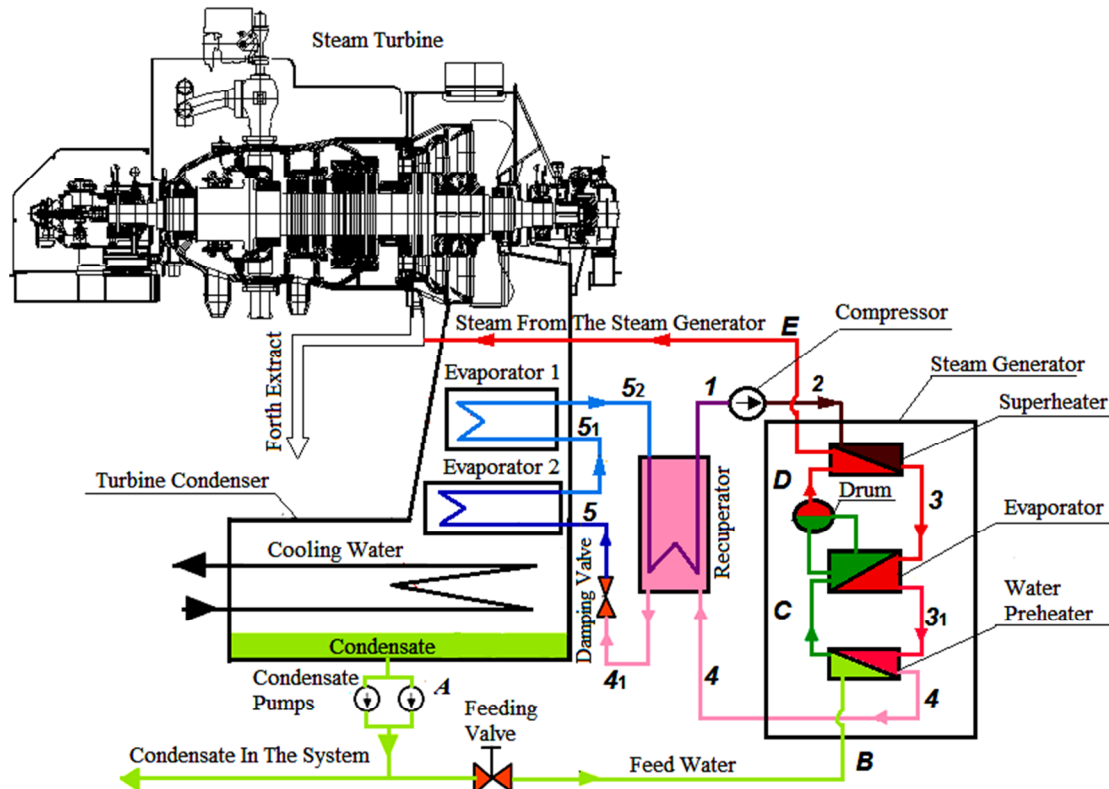


Fig. 1 The inverter heat pump-based turbine system

The inverter heat pump compressor unit may be supplied with power from the power grid or the electricity it produces. The use of an adequate source of electricity is to be based on the electricity price ratio (own price and market price) or is to be adjusted to the required operating conditions. The heat generated by the inverter heat pump is used in the steam generator unit and the recuperator unit (Figure 1). The steam generator unit produces water steam of 0.2 MPa and 140 °C, which is used for district heating and the recuperator unit, heated the heat pump refrigerant before compression by the heat pump waste heat. All the pressures in this paper are absolute.

The data analysis of the cogeneration at power plant in the Slovenian heating plant showed the exhaust water steam flow rate oscillations between 0 kg/s to 22 kg/s, with the average rate being 7.6 kg/s. The turbine condenser waste heat ranging from 0 MW to 50 MW is discharged into the River. In winter, when the district heating needs are higher, the waste heat volume is halved. An inverter heat pumping system is needed to remove between 1000 kW and 12000 kW of heat from the turbine condenser and to use it in the steam generator unit to generate the water steam.

2. Steam production in a steam generator unit and selection of a heat pump

Steam production takes place in the steam generator unit illustrated in Figure 1. The turbine condensate is used as feedwater, fed into the steam generator unit by means of condensate pumps via a feeding valve. The steam generator unit consists of three heat exchangers. The first heat exchanger is called the water preheater, heating the feedwater almost to the boiling point. The next heat exchanger is called the evaporator, where water is

converted to steam by means of a drum. The last heat exchanger is called the superheater, which serves to raise the temperature of the generated steam to the working temperature (140°C). Figure 2 shows the thermodynamic process of water steam in steam generator unit.

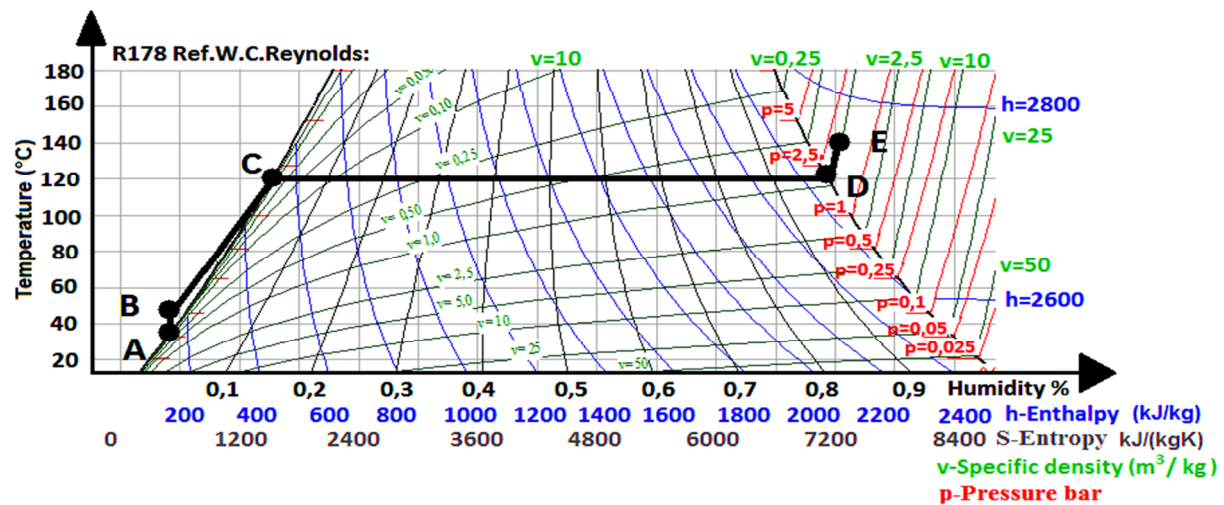


Fig. 2 Steam production (0.2 MPa and 140 °C) in T-S diagram [3]

The A-B area represents the feedwater pressure rise achieved by means of the condensate pump. This is followed by the B-C area, where water is isobarically heated up to the temperature around 120 °C. It is followed by the C-D area, where an isobaric phase change of water steam occurs. In the D-E area, the steam is to be heated up to the desired temperature of 140° C using the steam superheater. The inverter heat pump unit meeting the above requirements will be designed on the basis of the diagram of the generated steam thermodynamic process, Figure 2. When selecting the inverter heat pump refrigerant (R123), the thermodynamic conditions of the generated steam and of the turbine exhaust steam are taken into consideration. In the selection of an appropriate inverter heat pump, CoolPack software [13] was used. The inverter heat pump calculation data are shown in Figure 3.

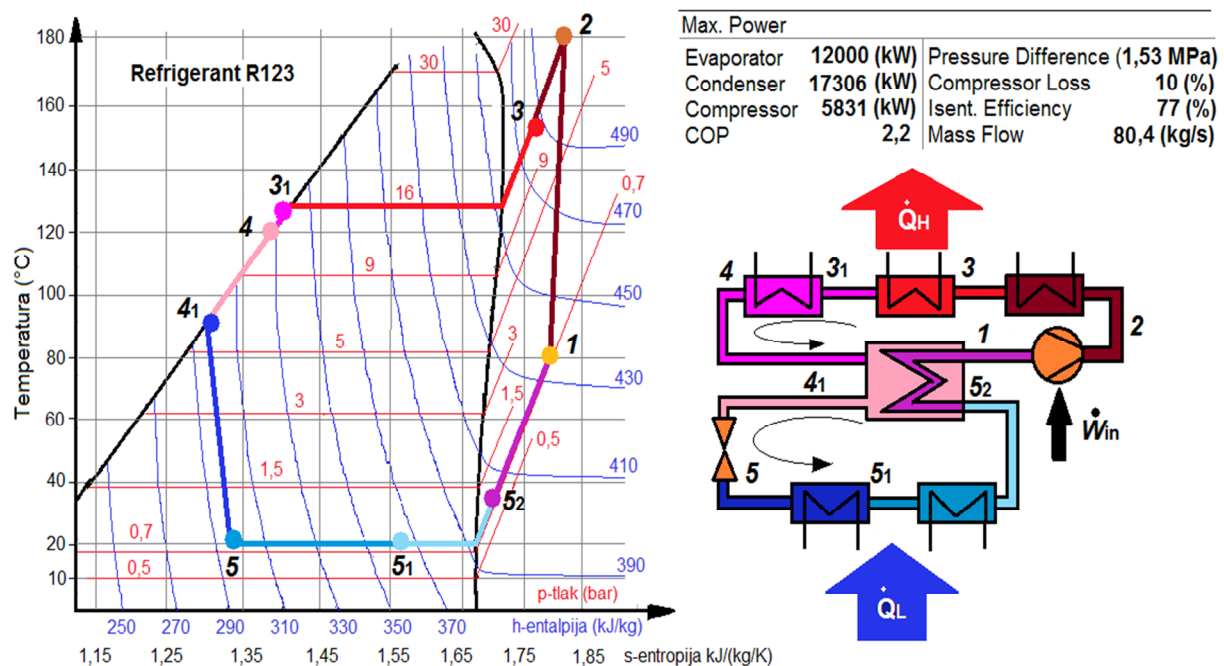


Fig. 3 The inverter heat pump calculation data and working gas thermodynamic process [3]

If 12000 kW of the turbine exhaust heat is used by means of the inverter heat pump evaporator unit (evaporator 1 and evaporator 2, Figure 1) or points 5 to 5₂ (Figure 3), a 5831 kW compressor power is required to generate 17306 kW of heat. With the above amount of the generated heat of the inverter heat pump, it is possible to produce 5.7 kg/s of water steam (0.2 MPa and 140 °C) in a steam generator unit to be used in district heating. Feedwater is heated from 40 °C to 120 °C in the water heater (B-C state, Figure 1). A phase change of water into water steam takes place in the steam generator unit (evaporator-drum, Figure 1). The evaporating substance volume greatly increases, which is compensated for by evaporator drum. The evaporator drum serves as a separation element between the water and water steam of the substance to be evaporated. The water is in the lower half of the drum volume and the water steam in the upper half. The balance between the generated water steam and the steam generator unit feeding is regulated with regard to the water level in the drum. If the water steam generation increases, the level of the water in the drum starts to decrease, which means that more feedwater has to be supplied to the steam generator unit and vice versa. A condensate-controlling valve controls the water quantity in the steam generator unit, serving as the water steam generator unit feed valve at the same time. The third heat exchanger in the steam generator unit is the water steam superheater. Dry generated water steam is heated up here to the process temperature of 140 °C. The approximate price of installing a heat pump in the turbine condenser system is 3.2 million EUR [14].

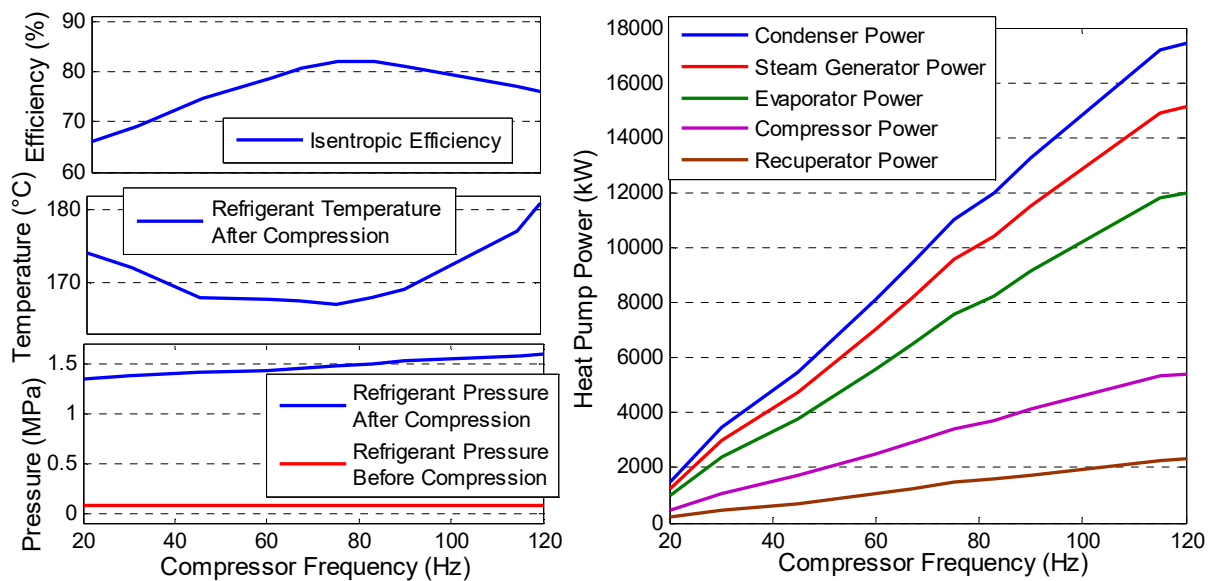


Fig. 4 The inverter heat pump characteristics

The inverter compressor adjusts the frequency of the compressor on the amount of waste heat-based turbine system. The inverter heat pump characteristic was selected from previous research [15], [16], [17], [18]. The utilized waste heat-based turbine system power and generated inverter heat pump power were calculated using the general power equations. The inverter heat pump characteristics are shown in Figure 4, it can be seen that the inverter heat pump isentropic efficiency is best at the 80 Hz inverter compressor frequency. In this case, the inverter heat pump refrigerant pressure after compression is 1.52 MPa, inverter compressor power consumption is 3620 kW and generated heat power is 11990 kW. Generated heat power is used in the steam generator unit and in the recuperator unit, (Figure 1). The steam generator unit produces the water steam and the recuperator unit heat refrigerant by the heat pump waste heat.

3. Exergo-energy analysis, and the irreversibility of the heat pump

In accordance with the 2nd law of thermodynamics, energy may be divided into exergy and anergy. Each amount of energy consists of exergy and anergy, whereby one of both parts may be equal to zero. In any irreversible process, exergy is converted into anergy. In reversible processes, however, exergy remains constant, and anergy cannot be converted into exergy [19], [20]. Many other authors have also presented the exergy, anergy and the irreversibility of the heat pump [21], [22], [23], [24], [25], [26].

Exergy analysis is a useful method to complement, but not to replace, energy analysis. Exergy analysis yields useful results because it deals with the irreversible minimization or maximization of exergy delivery. Exergy analysis can indicate the possibilities of thermodynamic improvement of the process under consideration. Figure 5 shows a graphic presentation of the heat pump thermodynamic process. Q_H shows the heat flux of a heated reservoir, Q_L the heat flux of a cold reservoir, $Q_{H,rev}$ the reversible part heat flux of a heated reservoir and W the transformation of work [27].

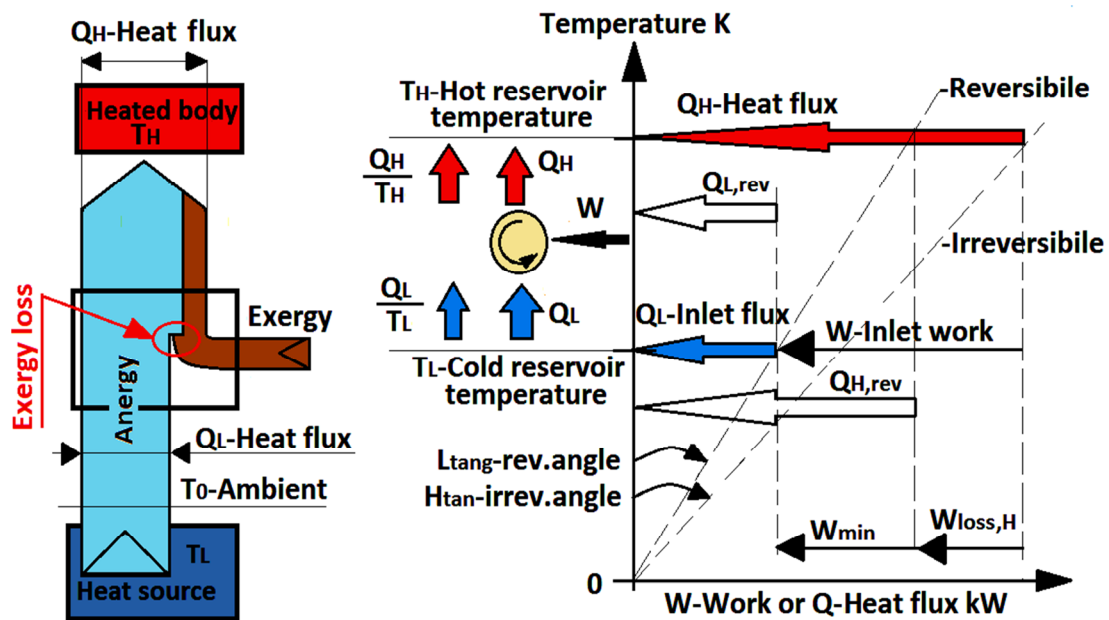


Fig. 5 Thermodynamic process between two heat reservoirs [27]

The fluxes of the heat engine thermodynamic process may be computed by means of a graphical analysis (Figure 5) [27]:

$$Q_{H,rev} - Q_{L,rev} - W_{min} = 0 \quad (1)$$

where $Q_{L,rev}$ is the reversible part heat flux of a cold reservoir and W_{min} is the minimum input work. Irreversible process fluxes S_{gen} are computed [27]:

$$S_{gen} = \frac{Q_{H,rev}}{T_H} - \frac{Q_{L,rev}}{T_L} = 0 \quad (2)$$

where T_H is the hot reservoir temperature and T_L is the cold reservoir temperature. With the hot body fluxes being $Q_L - Q_{L,rev}$, it is possible to compute the loss of work $W_{loss,H}$ [27]:

$$W_{loss,H} = W - W_{min} = T_H \left(\frac{Q_H}{T_H} - \frac{Q_L}{T_L} \right) = T_H \cdot S_{gen} \quad (3)$$

The inverter heat pump refrigerant-specific exergy loss of refrigerant transformation at the working points from the Figure 3 is calculated using the specific exergy general equation:

$$e_{loss,transf} = e_{before,transf} - e_{after,transf} = h_{before,transf} - h_{after,transf} - T_0 \cdot (S_{before,transf} - S_{after,transf}) \quad (4)$$

where $e_{loss,transf}$ is the transformation refrigerant-specific exergy loss, $e_{before,transf}$ is refrigerant-specific exergy before transformation, $e_{after,transf}$ is refrigerant-specific exergy after transformation $h_{before,transf}$ is the refrigerant-specific enthalpy before transformation, $h_{after,transf}$ is the refrigerant-specific enthalpy after transformation, T_0 is the temperature state of surrounding, $S_{before,transf}$ is the refrigerant-specific entropy before transformation and $S_{after,transf}$ is the refrigerant-specific entropy after transformation.

In the compressor, refrigerant-specific exergy losses, two types of losses are taken into consideration. The first refrigerant-specific exergy loss refers to specific exergy losses due to electromechanical losses that depend on the compressor design [28]. The second refrigerant-specific exergy loss occurs at polytropic compression of the refrigerant from States 1 to 2 in Figure 3. The refrigerant-specific exergy loss refers to specific exergy losses due to electromechanical losses, which is calculated [28]:

$$e_{loss:EM} = \frac{e_{comp.in}}{100} \cdot (1 - \eta_{comp}) \quad (5)$$

where $e_{loss:EM}$ is refrigerant-specific exergy loss resulting from electromechanical losses, $e_{comp.in}$ is the compressor-specific exergy input into the inverter heat pump and η_{comp} is the compressor efficiency. The compressor-specific exergy input into the inverter heat pump is calculated [28]:

$$e_{comp.in} = \frac{P_{el}}{\dot{m}_{refr}} \quad (6)$$

where P_{el} is the inverter compressor electric power consumption and \dot{m}_{refr} is the inverter heat pump refrigerant mass flow. The refrigerant-specific exergy loss occurs at a polytropic compression that is calculated as [28]:

$$e_{loss.pol} = e_{loss1-2} - e_{loss:EM} \quad (7)$$

where $e_{loss.pol}$ is the refrigerant-specific exergy loss occurs at polytropic compression and $e_{loss1-2}$ is refrigerant compression specific exergy loss. The heat flow through a heat exchanger wall takes place between temperature differentials, i.e. $T_1 > T_2$. The exergy loss in heat transfer does not solely depend on the difference between temperatures T_1 and T_2 but also on the product of the temperatures [27]:

$$E_{loss,t} = T_0 \cdot Q \cdot \left(\frac{T_1 - T_2}{T_1 \cdot T_2} \right) \quad (8)$$

where $E_{loss,t}$ is the exergy loss in heat transfer, Q is the heat flux across from the heat exchanger wall, T_1 is the wall hot side temperature and T_2 is the wall cold side temperature. The thermodynamic perfection of a system is assessed by calculating the inverter heat pump unit percentage specific exergy loss ratio:

$$\varepsilon_{e,unit} = \frac{e_{loss,unit}}{e_{comp,in}} * 100 \quad (9)$$

where $\varepsilon_{e,unit}$ is the inverter heat pump unit percentage specific exergy loss ratio, and $e_{lost,unit}$ is the specific exergy loss of inverter heat pump unit.

4. Modelling irreversibility of the inverter heat pump

An analysis of the inverter heat pump system was made using the Matlab-Simulink software tool [29]. The tool consists of the main model, illustrated in Figure 6, five submodels, and an m-file. The m-file is used for storing the data required for heat pump analysis (enthalpy, entropy, temperature, specific exergy in points from Figure 3, etc.). The sub-models presented by means of Equations 1 to 9 compute exergy losses for each inverter heat pump unit (compressor, condenser, evaporator, recuperator and damping valve). The sub-model turbine condenser computes thermal power for each inverter heat pump unit, inverter heat pump refrigerant mass flow, generated steam mass flow in the steam generator unit, turbine condenser discharged specific exergy to the environment with or without using inverter heat pump and turbine condenser generated entropy, with or without using an inverter heat pump. Heat pump modelling of various energy systems has been recently studied by numerous researchers [30], [31], [32], [33], [34], [35].

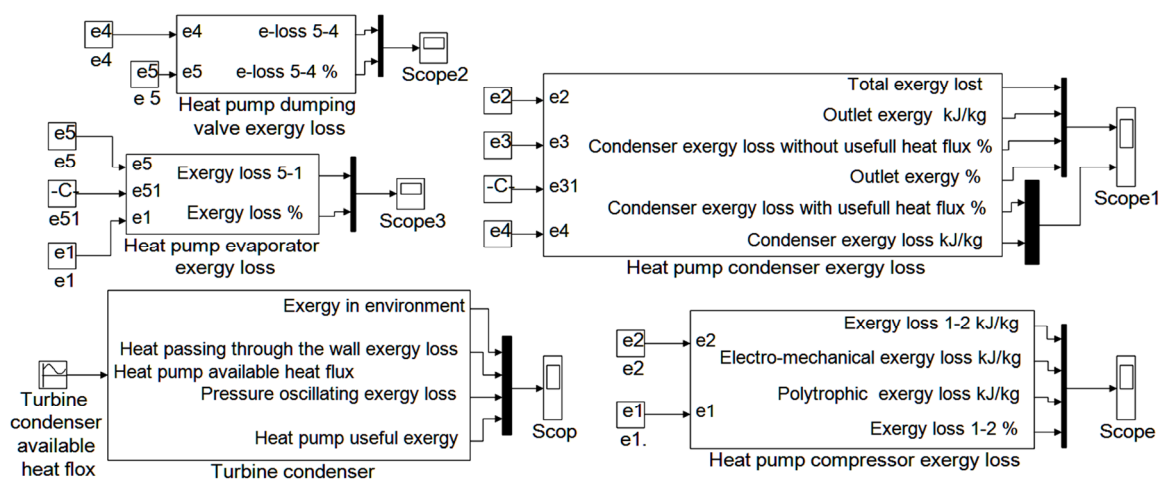


Fig. 6 The main simulation model of the irreversibility of the inverter heat pump

5. Simulation model results

The turbine condenser available heat flux presents the input dates into the submodule. The turbine condenser available heat flux input to the system was simulated in a range from 1000 kW to 12000 kW. The sub-model turbine condenser computes the powers for each inverter heat pump unit. The above results are shown in Figure 7.

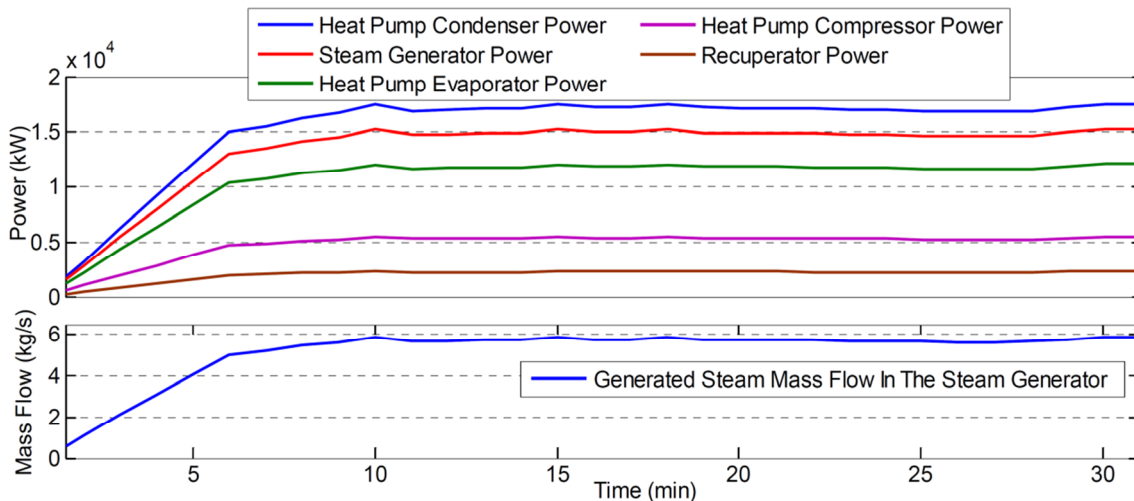


Fig. 7 Results of the inverter heat pump unit's power

Figure 7 show that inverter heat pump compressor unit consumes between 452 kW and 5831 kW of electric power. The inverter heat pump evaporator unit (evaporators 1 and 2) consume thermal power from the turbine condenser between 1000 kW and 12000 kW. In this case, the inverter heat pump condenser unit generated thermal power between 1390 kW and 17306 kW. The inverter heat pump generated thermal power is used for water steam production in the steam generator unit and for refrigerant heated in the recuperator unit, Figure 1. The water steam production mass flow fluctuated between 0.3 kg/s and 5.7 kg/s, which are used for district heating. The recuperator unit consume thermal power between 220 kW and 2200 kW.

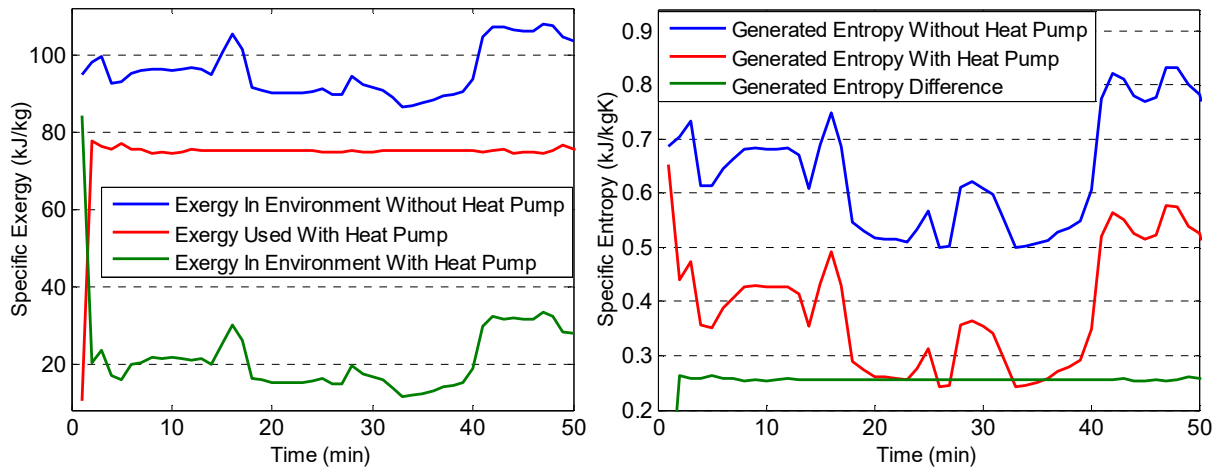


Fig. 8 Results of the turbine condenser-specific exergy and generated entropy

Simulating the model results of the turbine condenser-specific exergy and generated entropy with or without using inverter heat pump is illustrated in Figure 8. That shows the turbine condenser mean value discharged specific exergy into the environment without using inverter heat pump is 95.61 kJ/kg, the turbine condenser mean value discharged specific exergy into the environment with using inverter heat pump is 21.69 kJ/kg and the mean value specific exergy which is used with the inverter heat pump is 73.92. The turbine condenser mean value generated specific entropy without using inverter heat pump is 0.6395 kJ/(kgK), the turbine condenser mean value generated specific entropy with using inverter heat pump is 0.2623 kJ/(kgK). The turbine condenser mean value-generated specific entropy with the use of the inverter heat pump is reduced by 0.3872 kJ/(kgK). The turbine condenser operates more efficiently, and the inverter heat pump generates the heat, which is used for water steam production in the steam generator unit. The oscillation behaviour of specific exergy and entropy in Figure 8 is attributed to the fluctuations in the turbine exhaust steam quality. The better quality turbine exhaust steam contains more specific exergy and vice versa. The reason for exhaust steam quality fluctuation lies in varying speed of the turbine condenser exhaust steam condensation process. The exhaust steam condensation process speed is dependent on the amount of cooling water and air in the turbine condenser. An increased volume of air around the cooling tubes reduces the heat transfer and increases the turbine condenser entropy generation.

Figure 9 and Table 1 shows the results of the condenser unit, evaporator unit, recuperator unit, compressor unit and dumping heat pump units sub-models exergy losses. The left upper diagram in Figure 9 shows the mean value of the heat pump condenser unit-specific exergy loss ratio. The mean value of the condenser unit-specific exergy loss ratio is 9.2 %. The ratio presents the ratio between the input specific exergy by inverter compressor unit into the inverter heat pump and specific exergy loss inverter heat pump single unit. The right upper diagram in Figure 9 shows the inverter heat pump compressor unit-specific exergy

loss ratio. The mean value of the compressor unit-specific exergy loss rate is 9.4 %. The left lower diagram shows the heat pump recuperator unit-specific exergy loss ratio. The mean value of the recuperator unit-specific exergy loss ratio is 14.6 %. The right lower diagram in Figure 9 shows the heat pump damping valve unit-specific exergy loss ratio. The mean value of the dumping specific exergy loss ratio is 12.7. The mean value of the heat pump evaporator unit-specific exergy loss ratio is 1.9 %.

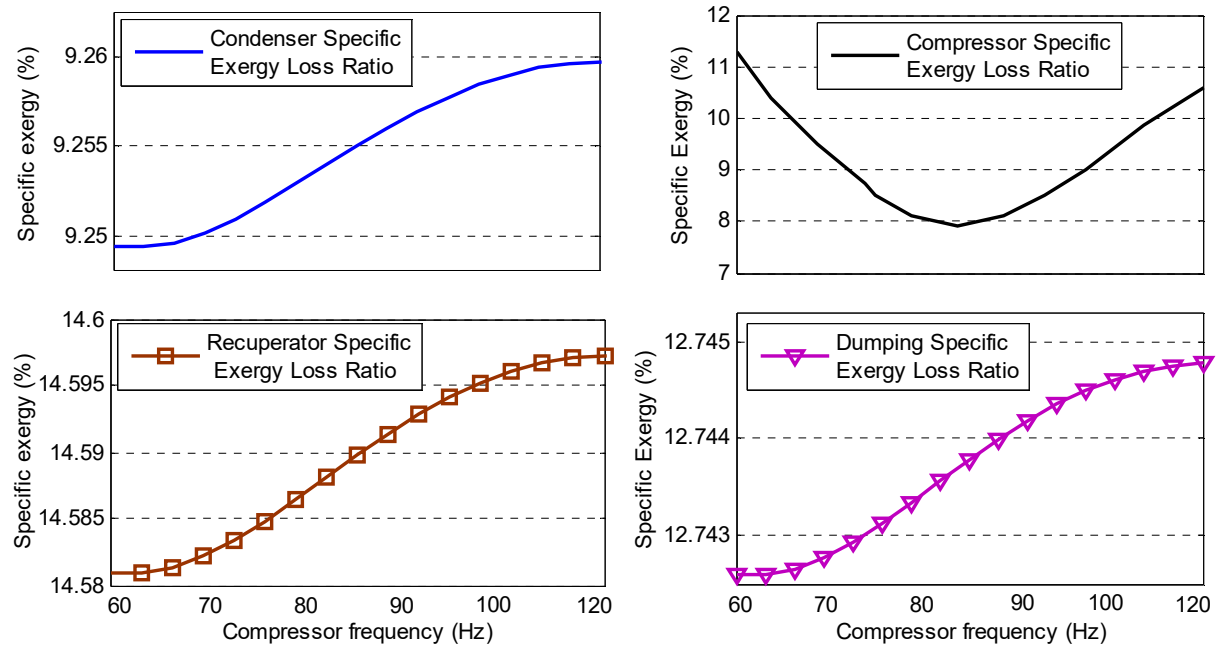


Fig. 9 The heat pump-specific exergy loss ratio and compressor-specific exergy loss

Table 1 The heat pump thermodynamic states of the refrigerant at heat working points from Figure 1 or Figure 3 and percentages specific exergy ratios

Point	Temperature (K)	Pressure (MPa)	Enthalpy (kJ/kg)	Entropy kJ/(kgK)	Exergy (kJ/kg)	Heat pump unit	Specific exergy (%)
0	293	0.1	218.5	1.065	0		
1	353	0.062	434.8	1.801	0.652	Compressor loss	9.4
2	458	1.83	498.5	1.789	67.868		
3	438	1.77	481.1	1.750	61.895	Condenser loss	9.2
3 ₁	398	1.67	334.1	1.398	18.531		
4	392	1.64	327.4	1.381	16.312		
4 ₁	368	1.6	299.1	1.308	9.401	Recuperator loss	14,6
5	293	0.079	299.0	1.339	0.218	Damping loss	12.7
5 ₁	293	0.071	358.3	1.542	0.625	Evaporator loss	1,9
5 ₂	309	0.069	405.6	1.696	2.217		
Total loss							47.8
Usefully							52.2

6. Capital investment recovery

The capital investment cost of the inverter heat pump system was estimated by adding together the individual prices of all the system components and by making a detailed project analysis [14]. The cost of the inverter heat pump installation into the turbine condenser system is estimated at around 3.9 million EUR. The inverter heat pump capital investment recovery is based on payback periods. The payback periods depend on the inverter heat pump

operating time and the amount of the utilized waste heat. For calculation purposes, it is required that the inverter heat pump operates 24 hours a day, 7 days a week and 150 days per year. The capital investment recovery calculations are based on the coal consumption in the boiler if the quantity of heat released into the heat pump from the turbine condenser were produced in the boiler.

The following values are taken into account in the calculations: inverter heat pump COP 2.2, boiler efficiency 89 %, coal price EUR 85/t, coal calorific value 18 000 000 kJ/ton and CO₂ credit price EUR 6/t of CO₂. The capital investment recovery results are shown in Figure 10.

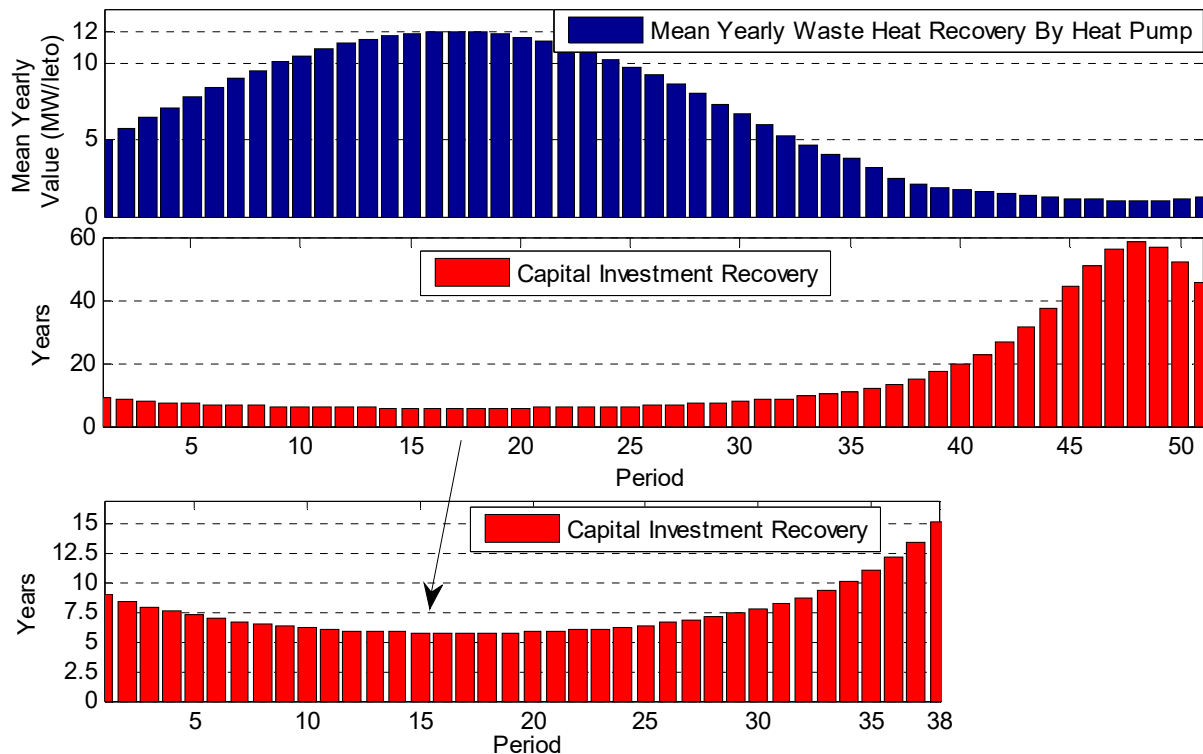


Fig. 10 The heat pump capital investment recovery

The above diagram in Figure 10 shows the average annual value of the utilization of heat from the turbine condenser. The middle diagram in Figure 10 shows the capital investment recovery and the lower diagram shows an exploded view of the middle diagram. The capital investment recovery results show that if the inverter heat pump releases 12000 kW of the mean annual waste heat from the turbine condenser the investment payback period is 5.3 years. If the inverter heat pump releases only 1000 kW of the mean annual waste heat from the turbine condenser the investment payback period is 57 years. The real inverter heat pump capacity is around 7000 kW of mean annual waste heat from the turbine condenser and the investment payback period is 7.5 years.

7. Conclusion

This paper deals with the possibilities of using the latent heat from steam turbine exhaust by means of an inverter heat pump, otherwise being released into the environment. As a result, the thermal pollution of the environment is reduced and the heat usefully employed, thus resolving the issues of the turbo generator operation in the months of without any demand for heating in the city. The inverter heat pump can generate 17306 kW thermal power and inverter compressor consume 5831 kW electric power. In this case, the steam generator

unit produces 5.7 kg/s water steam which is used for the district heating of the city. By using the inverter heat pump, the turbine condenser discharged specific exergy into the environment is reduced, and the turbine condensers operate more reversibly.

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