Since exergy analysis is based on the second law, it ensures that the irreversibility in the process is detected better than the energy analysis. Increased complexity of processes and power plants requires thermodynamic analysis to ensure optimum use of energy sources.[8]

For this reason, some researchers[9–13] use a new method of combining both first and second law. This method is called usability analysis. In various studies, energy has been considered together with the economy. Today, the concepts "energy costs" and "energy prices" are widely accepted as synonyms. However, the costs are not related to the facts. In general, the energy cost includes a raw material cost because energy generally does not have a value. However, exergy is the basis of the economy. It covers wages and costs precisely. Business is in association with exergy and economy. The relationship between the entropy and economy is discussed in most of the studies and the data are presented successfully. One of the important studies in this field was conducted by Roegen.[14] His book with the title of "Law of Entropy and Economic Process", published in 1971, has been a reference for many researchers and their projects. Many researchers have included the relationship between exergy and economy in their studies.

Some researchers[15–17] achieved efficiency by applying exergy analysis in heat pumps systems, while others[8,9,11] achieved efficiency by applying them in power plants. There are some exergy analysis studies in cooling and air conditioning (HVAC). A study by Hepbaşlı and Ozgener[18] indicate that energy consumption of heating, cooling, and air conditioning (HVAC) systems is approximately 20% of total energy consumption. Consequently, effective and efficient use of energy and even the waste energy has great importance. They also state that for the performance evaluation of heating, cooling and ventilation systems, the first law of thermodynamics has been used; however the required energy for these systems is usable energy in order to have effective work.

However, there is few studies presented performance analysis of the mushroom compost fermentation using a heat recovery device with an air sourced heat pump. In this study, efficiency and thermoeconomic and thermodynamic analyses were performed using the data obtained by operating the device without heat recovery and with heat recovery. This study will guide those working in this field in analyzing costs and efficiency.

Materials and Methods

The study was conducted at Kastamonu University Central Research Laboratory Mushroom Research Center and the materials to be used in the study included l × 5 Hp Heat Pump, construction of lx Compost Room (6 × 4 × 2.40 m), supply and installation of lx Humidity Control and Humidification Unit. The installed device is shown in Fig. 1.

The device design is based on the cooling cycle system. Due to the continuous operation of the system to be used and the need for heat and humidity especially in pasteurization processes, efficiency was calculated on the device and the aim was to achieve this efficiency level with revisions on the device. Gas 407 C widely used in heating and cooling processes, was used in the air conditioning system.

In the study, the inlet and outlet points of each unit were determined depending on the flow chart of the device. Thermodynamic properties (temperature, pressure and mass flow) of the determined points were read and obtained instantly on the device. With these properties, enthalpy, entropy and exergy of each point were calculated numerically with the help of energy and exergy formulas. In the study, exergy calculations were made by operating the device without heat recovery and with heat recovery. Various analyzes can be

Fig. 1 — Unit room and air conditioning device

$$W_{comp,el} = \frac{W_{comp}}{\eta_{el}\eta_{mac}} \quad \ldots (9)$$

$$\dot{ED}_{comp} = (Ex_4{'} + Ex_1) + W_{comp,el} \quad \ldots (10)$$

$$\eta_{Ex\ comp} = \frac{Ex_{4'} - Ex_1}{W_{comp,el}} \quad \ldots (11)$$

$$\dot{ED}_{cond} = (Ex_{1'} + Ex_8) - (Ex_2 + Ex_{8'}) \quad \ldots (12)$$

$$\eta_{Ex,cond} = \frac{Ex_2 + Ex_{8'}}{Ex_{1'} + Ex_8} \quad \ldots (13)$$

$$\dot{ED}_{expa} = Ex_3 - Ex_{2'} \quad \ldots (14)$$

$$\eta_{expa} = \frac{Ex_{2'}}{Ex_3} \quad \ldots (15)$$

$$\dot{ED}_{evap} = (Ex_{3'} + Ex_7) - (Ex_4 - Ex_{7'}) \quad \ldots (16)$$

$$\eta_{Ex\ evap} = \frac{Ex_4 + Ex_7}{Ex_{3'} + Ex_{7'}} \quad \ldots (17)$$

$$\dot{\eta}_{II} = \frac{\dot{ED}_{evap}}{W_{comp,el}} \quad \ldots (18)$$

Exergy Loss for the Condition with Heat Recovery

The corresponding enthalpy and entropy values were obtained by finding the pressure and temperature values obtained from the points determined in the device in the psychometric diagram of the R_{407C} gas. These obtained values were the main element of the calculation. Measurement points with heat recovery were detected on the device and shown in Fig. 3 below.

For 6 °C and 5 bar in Heat Recovery Device;

$$_3 = {}_{3\,liquid} + x\,({}_{3\,steam} - {}_{3\,liquid}) \quad \ldots (19)$$

$x = 0{,}273$ %27,3

Fig. 3 — Measurement Points for Heat Recovery Device

By using the x value we find here in formula (20) below, we calculate the s_3 value.

$$s_3 = s_{3\,liquid} + x\,(s_{3\,steam} - s_{3\,liquid} \quad \ldots (20)$$

Data for h_3, s_3, Q_E, $\dot{m}_{R407C}$ values for 6℃ and 5 bar in heat recovery device are shown in Table 5.

Cooling load was taken as 8.21 kW from the manufacturer catalog of the device. With this data, we find the evaporator mass flow rate using the formula (21).

$$Q_E = \dot{m}_{R407C}\,(h_4 - h_{3'}) \quad \ldots (21)$$

In order to find the energy values of points 1, 2, 3, 4, 5, 6, 7, 8 and 9 for the device with heat recovery, the Q values were calculated by using the formula (22) below [19] and shown in Table 6 below.

$$Q_n = \dot{m}_{R407C}\, x_n \quad \ldots (22)$$

Exergy Balance and Efficiency in Device with Heat Recovery

In exergy balance and efficiency calculation studies for operation with heat recovery, compressor power was found with the help of formula (23). The compressor energy value was calculated with formula (24). The energy balance value of the compressor was calculated using formula (25). The exergy efficiency value of the compressor was calculated by formula (26). The energy balance of the condenser was calculated with the formula (27). The exergetic efficiency of the condenser was calculated with the formula (28). The energy balance value of the expansion valve was calculated with the formula (29). The exergetic efficiency value of the expansion valve was calculated with the formula (30). Evaporator energy balance value was calculated with formula (31). The evaporator exergy efficiency value was found using the formula (32). Also, the total exergy efficiency is shown by the formula (33).[19]

$$W_{comp} = \dot{m}_{R407C}\,({}_1 - {}_{4'}) \quad \ldots (23)$$

Table 5 — Values h3, s3, QE, $\dot{m}_{R407C}$ for 6°C and 5 Bar for heat recovery device

$h_{3\,liquid}$	$h_{3\,steam}$	h3	$s_{3\,liquid}$
208.82	417.80	265.88	1.031
QE (kW)	$\dot{m}_{R407C}$	$s_{3\,steam}$	s_3
8.21	0. 052	1.798	1.24

Table 6 — Values (Q and Ex) measured and calculated from the measuring points in the device with heat recovery

Points	Equipment	Gas	T (° C)	P(bar)	m (kg/s)	h (kj/kg)	s (kj/kgK)	Q (Kw)	Ex (Kw)
1	Compressor Outlet	R_{407C}	87	27	0.052	465.62	1.814	24.2122	4.590214
1'	Condenser Inlet	R_{407C}	86	27	0.052	464.39	1.811	24.1483	4.572766
2	Condenser Outlet	R_{407C}	41	27	0.052	265.88	1.22	13.8258	3.412991
2'	Expansion Valve Inlet	R_{407C}	41	27	0.052	265.88	1.22	13.8258	3.412991
3	Expansion Valve Outlet	R_{407C}	6	5	0.052	265.88	1.24	13.8258	3.102915
3'	Evaporator Inlet	R_{407C}	6	5	0.052	265.88	1.24	13.8258	3.102915
4	Evaporator Outlet	R_{407C}	13	5	0.052	423.79	1.82	22.0371	2.322031
4'	Compressor Inlet	R_{407C}	13	5	0.052	423.79	1.82	22.0371	2.322031
7	Indoor Temperature	Air	46	1	2.82	319.29	1.765	900.398	0.917684
7'	Indoor Unit lowing Temperature	Air	68	1	2.82	341.43	1.83	962.833	8.701589
8	Outdoor Temperature	Air	18	1	1.86	291.16	1.67	541.558	0.967
8'	Outdoor Unit Blowing Temperature	Air	9	1	1.86	282.13	1.642	524.762	−0.30156
5	Fresh Air Intake with Heat Recovery	Air	18	1	0.36	291.16	1.67	104.818	0.187081
5'	Fresh Air Outlet with Heat Recovery	Air	36	1	0.36	209.97	1.344	75.5892	5.949565
6	Indoor suction with Heat Recovery	Air	46	1	0.36	219.97	1.391	79.1892	4.504867
6'	Outdoor Suction with Heat Recovery	Air	26	1	0.36	299.19	1.699	107.708	−0.0348
9	pulverized water	Water	15	5	0.0083	61.92	0.22	0.51394	0.007617

$$W_{comp,el} = \frac{W_{comp}}{\eta_{el}\,\eta_{mac}} \quad \dots (24)$$

$$\dot{ED}_{comp} = (Ex_{4'} + Ex_1) + W_{comp,el} \quad \dots (25)$$

$$\eta_{Ex\ comp} = \frac{Ex_{4'}+Ex_1}{W_{comp,el}} \quad \dots (26)$$

$$\dot{ED}_{cond} = (Ex_{1'} + Ex_8) - (Ex_2 + Ex_{8'}) \quad \dots (27)$$

$$\eta_{Ex\ cond} = \frac{Ex_2+Ex_8}{Ex_{1'}+Ex_{8'}} \quad \dots (28)$$

$$\dot{ED}_{expa} = Ex_3 - Ex_{2'} \quad \dots (29)$$

$$\eta_{Expa} = \frac{Ex_{2'}}{Ex_3} \quad \dots (30)$$

$$\dot{ED}_{evap} = (Ex_{3'} + Ex_7 + Ex_{5'}) - (Ex_4 + Ex_{7'} + Ex_6) \quad \dots (31)$$

$$\eta_{Ex\ evap} = \frac{Ex_4+Ex_7+Ex_6}{Ex_{3'}+Ex_{7'}+Ex_{5'}} \quad \dots (32)$$

$$\eta_{II,eat\ recovery} = \frac{\dot{ED}_{evap}}{W_{comp,el}} \quad \dots (33)$$

Q and E_X values were calculated by using the existing formulas above to find the energy values of points 1, 2, 3, 4, 5, 6, 7, 8 and 9 and are shown in Table 6.

The measurement point number 9 is the final product output of the device (pulverized water) and it is sent to the mushroom compost room environment.

Thermoeconomic Analysis

The financial efficiency of the device can be found by different calculations for conditions with heat recovery and without recovery. The data cost and operating cost of the device are required before using those calculations. The following formula (34) was used for the cost of the device.

$C_T = C_{inv} + C_{op}$ (Total cost = Capital cost + Operating cost) … (34)

If we estimate that the device is operated for 4380 hours and the total payment for the device is 5525$ (5249$ (device fee) and an additional 276$ (heat recovery device fee)), thermoeconomic calculations can be made with the following formulas for the device without heat recovery.

Thermoeconomic Analysis of the Device without Heat Recovery

C = Total purchasing cost of device (5249 $)
I = Annual interest (%15)
N = Operating time (10 years)

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad \ldots (35)$$

$$C_{inv} = \frac{\text{CRF x Total device cost}}{\text{Cooling load (Qc)x Estimated operating time(4380)}} \quad \ldots (36)$$

$$C_{inv} = \frac{CRF \times C}{Q_c \times 4380}$$

$$C_{op} = \frac{C_{el} \times P_{inp}}{Q_c} = \frac{C_{el}}{COP} \quad \ldots (37)$$

$$C_T = C_{inv} + C_{op} \quad \ldots (38)$$

Thermoeconomic Analysis of the Device with Heat Recovery

C= Total purchase cost of device (5525 $)
i = Annual interest (%15)
n= Operating time (10 years)

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad \ldots (39)$$

$$C_{inv} = \frac{CRF \text{ x } C}{Q_c \times 2280} \quad \ldots (40)$$

$$P_{inp} = \frac{\text{amps used by the device x volt}}{1000} \quad \ldots (41)$$

$$C_{op} = \frac{C_{el} \times P_{inp}}{Q_c} = \frac{C_{el}}{COP} \quad \ldots (42)$$

$$C_T = C_{inv} + C_{op} \quad \ldots (43)$$

Calculation of Coefficient of Performance (COP) Value

COP value, the efficiency of the heat pump according to the 1st law of thermodynamics, is calculated by the ratio of the evaporator load to the compressor load. For cases with heat recovery and without heat recovery, we can express the calculation of compressor power with formula (44) and formula (46) below. COP values calculated for cases without heat recovery and with heat recovery are shown in formula (45) and formula (47), respectively.

$$W_{comp} = \dot{m}_{R407C}\,(h_1 - h_{4'}) \quad \ldots (44)$$

$$COP_{witout\ eat\ recovery} = \frac{\dot{Q}_{Evap}}{W_{Comp}} \quad \ldots (45)$$

$$W_{comp} = \dot{m}_{R407C}\,(h_1 - h_{4'}) \quad \ldots (46)$$

$$COP_{wit\ eat\ recovery} = \frac{\dot{Q}_{Evap}}{W_{Comp}} \quad \ldots (47)$$

Results and Discussion

According to these calculations, when heat recovery device is added to the system, the work done by the compressor, loss of exergy, exergy balance and efficiency decreases. While the exergy balance of the condenser, expansion valve and evaporator decreases, their efficiency increases. Overall, the efficiency of the device increases. The total exergy balance and efficiencies obtained as a result of the calculations are shown in Table 7.

The overall efficiency of the device is increasing. The work done by the compressor has decreased from 2.55 to 2.17. The exergy breakdown of the compressor decreased from −0.66 to −0.83 and the exergy balance decreased from 10.73 to 9.66. The exergy balance of the expansion valve, and evaporator increased from approximately −0.34 to −0.31, −6.80 to −5.56 respectively. The exergy balance of the condenser decreased from −0.37 to −0.86. The exergy efficiency of the condenser and evaporator increased from approximately 0.48 to 0.89, 0.31 to 0.44, respectively. The comparison of exergy values based on measurement point for both cases (with and without using the heat recycled device) is shown in Fig. 4.

As can be seen from Fig. 4, it is seen that the 5' point is effective in increasing the exergy value of the system. The exergy value continued to increase

Table 7 — The total exergy balance and efficiencies obtained because of the calculations (Using the non-heat recovery and heat recovery device, respectively)

W_{comp}	2.557	2.1752
$W_{comp.el}$	3.228	2.7464
ED_{comp}	10.7304	9.658645
$\eta_{Ex\ comp}$	−0.662589	−0.825875
ED_{cond}	−0.366118	−0.858215
η_{Excond}	0.48139	0.8986
ED_{Expa}	−0.338102	−0.310076
η_{Expa}	1.00	1.09
ED_{evap}	−6.800084	−5.558323
$\eta_{Ex\ evap}$	0.31436	0.43621
η_{II}	2.106593	2.123857

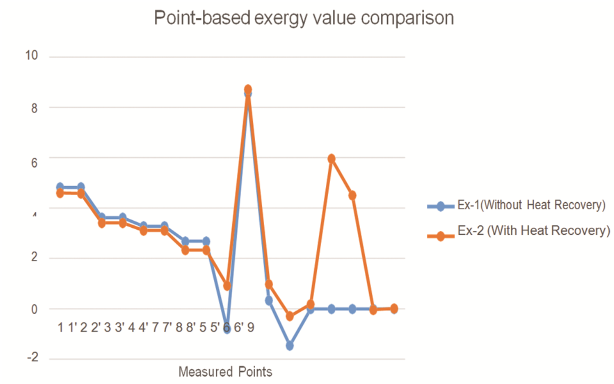

Fig. 4 — Exergy Values Comparison on the Measured Points

with the introduction of heat from the recovery system on the measured 6th point.

The efficiency increase in the device has reduced the electricity consumption and increased the capacity, thus enabling the system to operate more efficiently. Especially the electricity savings in compressor power made the device more economical in terms of cost.

The electrical energy purchasing, and total costs of the system were calculated. Cooling powers, purchasing costs and energy costs were also calculated with the help of the consumed electrical power. During the calculation, the operating period was taken as 10 years and the annual interest was taken as 10%. While the cost of the device without heat recovery was around 5249 $, the cost of the device with heat recovery was around 5525 $. Taking these data into consideration, the total cost of application (sum of capital and operating costs) without using a heat recovery device is 0.0685 $/h, while the total cost of application with the addition of a heat recovery device is 0.0678 $/h. This translates into a per hour cost reduction of approximately 1%. As a result of the calculations and the results obtained, it was determined that the addition of a heat recovery device increased the COP value at the time of operation. While the COP value in the device without heat recovery was approximately 2.69, this value increased to 3.77 in the device with the heat recovery addition. This provided a great efficiency increase for the device, while reducing electricity consumption and increasing capacity.

The standard environmental conditions taken as reference also directly affect the calculations. Exergy values decrease as the difference between the thermodynamic properties of the standard environment and the thermodynamic properties of the fluids used in the system decreases. As this difference increases, exergy values also increase. In order to reduce exergy losses, the system should be designed using fluids with properties close to the reference environmental conditions.

Based on the thermoeconomic analysis performed during application, it is evident that by using this system, a sufficient amount of savings has been achieved. Considering that the initial investment costs of the system are also low, the system is favourable in today's conditions. Energy and exergy analyses were performed with various analysis methods, and the results showed that the device is suitable in today's conditions. These values will change positively with the development of the system and the system will become even more suitable. The methods applied in this study increase device efficiency, while saving energy and having positive effects on the environment.

Conclusions

In this study, performance analysis of the in-room heating system was performed during mushroom compost fermentation using a heat recovery device with an air sourced heat pump. While trying to prevent energy losses, the system was also examined and interpreted in terms of exergic economics. In order to make this interpretation in a healthy manner, calculations were made using various data. The following conclusions were reached due to the outcomes of the paper:

- ✓ When heat recovery device is added to the system, the work done by the compressor, loss of exergy, exergy balance and efficiency decreases.
- ✓ While the exergy balance of the condenser decreases, its efficiency increases.
- ✓ While the exergy balance of the expansion valve increase, its efficiency decreases.
- ✓ The efficiency increase in the device has reduced the electricity consumption and increased the capacity, thus enabling the system to operate more efficiently.
- ✓ Operational costs have been reduced by using the heat recovery device. There was a cost reduction of approximately 1% per hour.
- ✓ There has been an increase of approximately 40% in COP values with the use of heat recovery device.

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Nomenclature

Symbols	Meaning	Symbols	Meaning
W	Work	h	Enthalpy
$\dot{E}D$	Exergy balance	s	Entropy
n_{Ex}	Exergy efficiency	Q	Head Load
n_{ll}	Total efficiency	T	Temperature
C_{inv}	Cost of capital	P	Pressure
C_{op}	Operating cost	cm	Centimeter
C_T	Total cost	gr	Gram
C	System installation cost	kg	Kilogram
℃	Degree celsius	Ex	Exergy
m	Mass	R407C	Refrigerant gas
$\dot{m}$	Mass flow rate	CRF	Capital repayment factor
S	Second	i	Annual interest
n	Molar fraction	n	System uptime
kw	Kilowatts		

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