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Incorporating novel heat recovery units into an AHU for energy demand reduction-exergy analysis

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Abstract

The building sector is the major energy consumer, accounting for over 40% of global energy demand. Heating and cooling together with domestic hot water energy consumption are estimated to account for 60% of the required energy for buildings' maintenance and operation. Energy recovery is a suitable technique to tackle high energy consumption in the building. In this study, a new layout of heat recovery units installation (i.e., primary and secondary) is investigated. The main objective of this study is to reduce energy consumption in an air handling unit through the exergy analysis. Owing to adding heat recovery units, cooling and heating coil loads reduced by 7.8% and 43%, which in turn decreased the total required load of AHU by 17.84%. From the viewpoint of the second law and based on the results, incorporating the primary and secondary heat recovery units into the base AHU in hot and dry climate regions led to decrease in the total irreversibility up to 26.29%, while in hot and humid climate this figure is 14.25%. Consequently, the positive effect of using heat recovery units in the hot and dry climate region is superior to the hot and humid one.

Keywords Air handling unit · Exergy · Irreversibility · Energy saving

List of symbols

Ex	Exergy $\left(\mathrm{J\,kg^{-1}}\right)$
h	Enthalpy $\left(\mathrm{J\,kg^{-1}}\right)$
h_s	Supply air enthalpy
IR	Irreversibility ratio
IRV	Irreversibility (W)
$\dot{m}$	Mass flow rate $\left(\mathrm{kg\,s^{-1}}\right)$
$\dot{m}_\mathrm{s}$	Supply air mass flow rate $\left(\mathrm{kg\,s^{-1}}\right)$
$\dot{m}_\mathrm{f}$	Fresh air mass flow rate $\left(\mathrm{kg\,s^{-1}}\right)$
$\dot{m}_\mathrm{r}$	Return air mass flow rate $\left(\mathrm{kg\,s^{-1}}\right)$
$\dot{m}_\mathrm{c}$	Cold water mass flow rate $\left(\mathrm{kg\,s^{-1}}\right)$
PENR	Percent of energy recovery
PEXR	Percent of exergy recovery
Q	Power (W)
Q_S	Sensible heat transfer rate
ϑ	Specific volume $\left(\mathrm{m^3\,kg^{-1}}\right)$
RPR	Required power ratio
s	Entropy $\left(\mathrm{J\,kg^{-1}\,K^{-1}}\right)$
SER	Second efficiency ratio
T	Temperature (K)
T_ax	Air temperature at the condensation point (K)
T_o	Ambient temperature (K)
T_s	Supply air temperature (K)

Greek letters

φ	Relative humidity
ω	Humidity ratio $\left(\frac{\mathrm{kg_v}}{\mathrm{kg_a}}\right)$
ε	Effectiveness

Subscripts

ai	Air inlet
ao	Air outlet
cc	Cooling coil
ci	Chilled water inlet
co	Chilled water outlet
cond	Condensation
cw	Chilled water
h	Heating coil
hi	Hot water inlet

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ho	Hot water outlet
hw	Hot water
max	Maximum
min	Minimum
mix	Mixing box
o	Ambient
pr	Primary heat exchanger
r	Conditioned space
se	Secondary heat exchanger
t	Total

Introduction

Energy consumption in buildings has increased so much that it exceeds energy demand in the industrial sector. The rate of increase in building energy consumption is higher than in all sectors [1–4]. Using energy recovery is an effective way to reduce energy consumption in buildings [5–8]. Improvements in heat transfer to enhance the performance of various applications including heat transfer have been studied by many researchers [9–28].

AlAjmi et al. [29] considered three scenarios to convert the building with high energy consumption into a zero energy building. They proved that the best scenario causes a 27% decrease in energy demand. In a similar study, the reduction in 17% in energy demand has been observed [30]. One of the common ways to provide comfortable conditions is the use of the air handling unit (AHU). The most important part of the AHUs is the heating and cooling coils. This part uses a lot of energy to provide comfort conditions in the conditioned space [31]. Therefore, to reduce the energy consumption of the AHUs, designers should focus on the heating and cooling coils load. In winter, fresh air energy content is lower than the conditioned space energy content; hence, heating coil is used to increase the fresh air energy content. In summer, the energy content of the fresh air is higher than the energy content in the conditioned space. Therefore, cooling coil is used to reduce the energy content of the fresh air [32]. Studies affirmed that the cooling coil energy consumption is very significant [33]. Fresh air must be used to supply the required oxygen in the conditioned space. On the other hand, to meet the comfort conditions, the air in the conditioned space must be changed. As usual, a part of the return air is exhausted. Note that the energy content of the exhaust air is lower than the fresh air. It seems that the potential of the exhaust air may be used to reduce the energy content of the fresh air. Air-to-air energy recovery is one of the main energy-efficient devices that has been approved to transfer the energy [34]. In the air-to-air heat recovery, the sensible (heat) and latent energy (vapor mass) of the stream are transferred to another stream [35].

Deshko et al. [36] numerically studied the sensible and latent heat transfer of an enthalpy air-to-air with the cross-flow arrangement. At first, the condensation was studied to locate the frost formation area. The most important parameters affecting the frost formation zone are ambient temperature and the amount of relative humidity of the humid air in the conditioned space.

Many experiments have been made to investigate the effect of frost formation on the thermal performance of the air-to-air heat recovery unit [37]. It was found that the presence of a frost formation zone decreases the mass flow rate of the passing air.

Refs. [38, 39] carried out studies on the cities of the southern European region to estimate the potential of installing an air-to-air heat exchanger using the psychometric chart. These studies indicated that the use of psychometric charts can determine whether air-to-air converter installation is beneficial.

Refs. [40] developed a methodology to compare the usefulness of installing the enthalpy recovery unit with the sensible recovery unit. It was found that if the ambient relative humidity was high, the installation of the enthalpy recovery unit would be preferable to the installation of the sensible one.

Exergy analysis is used as a valuable technique in optimizing various systems [4, 41–44]. The maximum useful work obtainable from a thermodynamic system can be called exergy [45]. The first law deals with the amount of energy in thermodynamics, while the second law deals with the quality of energy [45].

Survey studies show that the exergy analysis has been applied on the building envelope [46, 47], cooling system [48], heat pumps [49, 50], energy storage systems [51] and HVAC [52] to improve the thermal performance.

Razmara et al. [53] developed the exergy analysis based on model predictive control (MPC) technique to enhance thermal performance. It was found that applying exergy analysis and MPC techniques can decrease the irreversibility up to 22% which in turn reduced the energy demand up to 36%. The effects of different strategies from the perspective of the first and second laws of thermodynamics on the performance of a ground source heat pump for the building were examined by Hu et al. [54]. Among the five strategies proposed by the authors, it was found that in the best technique, the irreversibility and energy consumed by the system are reduced. Due to the decrease in these parameters, the second and first laws of thermodynamics increase, respectively. The exergy analysis of a large and complex building was examined by Sayadi et al. [55]. First, the authors found that the second law efficiency of the building is very low (approximately 4%). Exergy analysis showed that most exergy losses occurred in energy conversion systems (54% of total losses). In a study by Caliskan et al. [56], a new desiccant air cooling consisting of an evaporative cooler, a sensible heat wheel and a desiccant wheel was proposed. The desiccant wheel has the highest share of exergy losses 0 (42.78%) among the other components of the desiccant air cooling. They showed that desiccant wheel has the highest share of exergy destruction (42.78%).

In [57], it was found that the second law efficiency of the variable air volume system operating in a large office building is very low (2–3%). Energy and exergy analysis of an air conditioning system involving various thermodynamic processes such as cooling with dehumidification, heating and cooling of the space, evaporative cooling, heating and humidification were performed by Ghosh and Dincer [58]. They proved that the heating and cooling of the space have the largest irreversibility quarto (31.2%). Calculations on the first and second laws of thermodynamics showed the first and second law efficiencies are 18.6% and 33.31%, respectively. Ghazikhani et al. [41] compared the constant enthalpy humidification with the constant temperature humidification base on the exergy analysis. The results showed that constant temperature humidification needs more energy so that its energy consumption is about 12% higher than the enthalpy one. Exergy analysis proved that the amount of irreversibility in the constant enthalpy humidification has a lower value rather than the constant temperature humidification. Less energy consumption and less irreversibility prove that constant enthalpy humidification is superior to constant temperature humidification. Focusing on previous studies indicates that no study has been made on the heat recovery potential of the exhaust air. This study aims to reduce cooling and heating coil power consumption through the exergy analysis to improve the second law efficiency.

Energy recovery units (primary and secondary air-to-air heat exchanger) recover the energy and exergy of the exhaust air. The warmness from the return air is recovered to the cooling coil outlet cold air to decrease the heating coil load through the secondary heat exchanger, while in the primary heat exchanger, the coldness from the exhaust air is transferred to the fresh air to reduce the cooling coil load.

System description

AHU can be used to meet the ventilation requirements in the conditioned space. As mentioned, AHUs are composed of heating and cooling coils. In the summer, heating and cooling coils are used to provide the desired temperature and relative humidity in the conditioned space. The return air as shown in Fig. 1 (point G) is divided into two streams. Part of the air enters the mixing chamber at point M. The remaining part enters the primary heat exchanger. The air temperature at point N is lower than the temperature at point A, and therefore, the fresh air is pre-cooled. Due to the cooling of the air in the primary heat exchanger, the power required by the cooling coil is reduced. The outlet air temperature of the cooling coil is very low. In the secondary heat exchanger, the heat potential of point H is used to preheat point D. Therefore, the heating coil load is expected to decrease as well.

Exergy analysis

The exergy of a system is the maximum useful work via a reversible process acquired with respect to the environment. The exergy analysis deals with the quality of energy. The exergy analysis is treated with the degradation of the opportunities to do work and is a suitable method to analyze the HVAC process.

Applying the exergy balance method, the irreversibility through the primary air-to-air heat exchanger is written as:

$$\mathrm{Ex}_{\mathrm{pr}}^{\mathrm{des}} = \dot{m}_{\mathrm{A}}\,\mathrm{Ex}_{\mathrm{A}} + \dot{m}_{\mathrm{N}}\,\mathrm{Ex}_{\mathrm{N}} - \dot{m}_{\mathrm{B}}\,\mathrm{Ex}_{\mathrm{B}} - \dot{m}_{\mathrm{H}}\,\mathrm{Ex}_{\mathrm{H}} \tag{1}$$

The exergy destruction rate through the mixing box is obtained by the following exergy rate balance:

$$\mathrm{Ex}_{\mathrm{m}}^{\mathrm{des}} = \dot{m}_{\mathrm{B}}\,\mathrm{Ex}_{\mathrm{B}} + \dot{m}_{\mathrm{G}}\,\mathrm{Ex}_{\mathrm{G}} - \dot{m}_{\mathrm{C}}\,\mathrm{Ex}_{\mathrm{C}} \tag{2}$$

The exergy destruction rate through the cooling coil is acquired by the following equation:

$$\mathrm{Ex}_{\mathrm{cc}}^{\mathrm{des}} = \dot{m}_{\mathrm{c}}\,\mathrm{Ex}_{\mathrm{c}} + \dot{m}_{\mathrm{cw}}\,\mathrm{Ex}_{\mathrm{ci}} - \dot{m}_{\mathrm{cw}}\,\mathrm{Ex}_{\mathrm{co}} - \dot{m}_{\mathrm{D}}\,\mathrm{Ex}_{\mathrm{D}} - \dot{m}_{\mathrm{cond}}\,\mathrm{Ex}_{\mathrm{cond}} \tag{3}$$

where $\dot{m}_{\mathrm{cond}}$ and $\mathrm{Ex}_{\mathrm{cond}}$ denote the mass flow rate and exergy of the condensation vapor. Similar to the primary heat recovery unit, the following equation determines the exergy destruction through the secondary heat recovery unit:

$$\mathrm{Ex}_{\mathrm{se}}^{\mathrm{des}} = \dot{m}_{\mathrm{D}}\,\mathrm{Ex}_{\mathrm{D}} + \dot{m}_{\mathrm{H}}\,\mathrm{Ex}_{\mathrm{H}} - \dot{m}_{\mathrm{E}}\,\mathrm{Ex}_{\mathrm{E}} - \dot{m}_{\mathrm{I}}\,\mathrm{Ex}_{\mathrm{I}} \tag{4}$$

Also, the exergy loss for the heating coil is:

$$\mathrm{Ex}_{\mathrm{hc}}^{\mathrm{des}} = \dot{m}_{\mathrm{E}}\,\mathrm{Ex}_{\mathrm{E}} - \dot{m}_{\mathrm{F}}\,\mathrm{Ex}_{\mathrm{F}} + \dot{m}_{\mathrm{hw}}\,\mathrm{Ex}_{\mathrm{hi}} - \dot{m}_{\mathrm{hw}}\,\mathrm{Ex}_{\mathrm{ho}} \tag{5}$$

where $\dot{m}_{\mathrm{hw}}$ is the hot water mass flow rate. Finally, the irreversibility through the conditioned space is calculated from the following equations:

$$\mathrm{Ex}_{\mathrm{r}}^{\mathrm{des}} = \dot{m}_{\mathrm{F}}\,\mathrm{Ex}_{\mathrm{F}} - \dot{m}_{\mathrm{G}}\,\mathrm{Ex}_{\mathrm{G}} \tag{6}$$

Note that the exergy content of the humid air, condensation, hot and cold water streams are calculated with the following equations [59]:

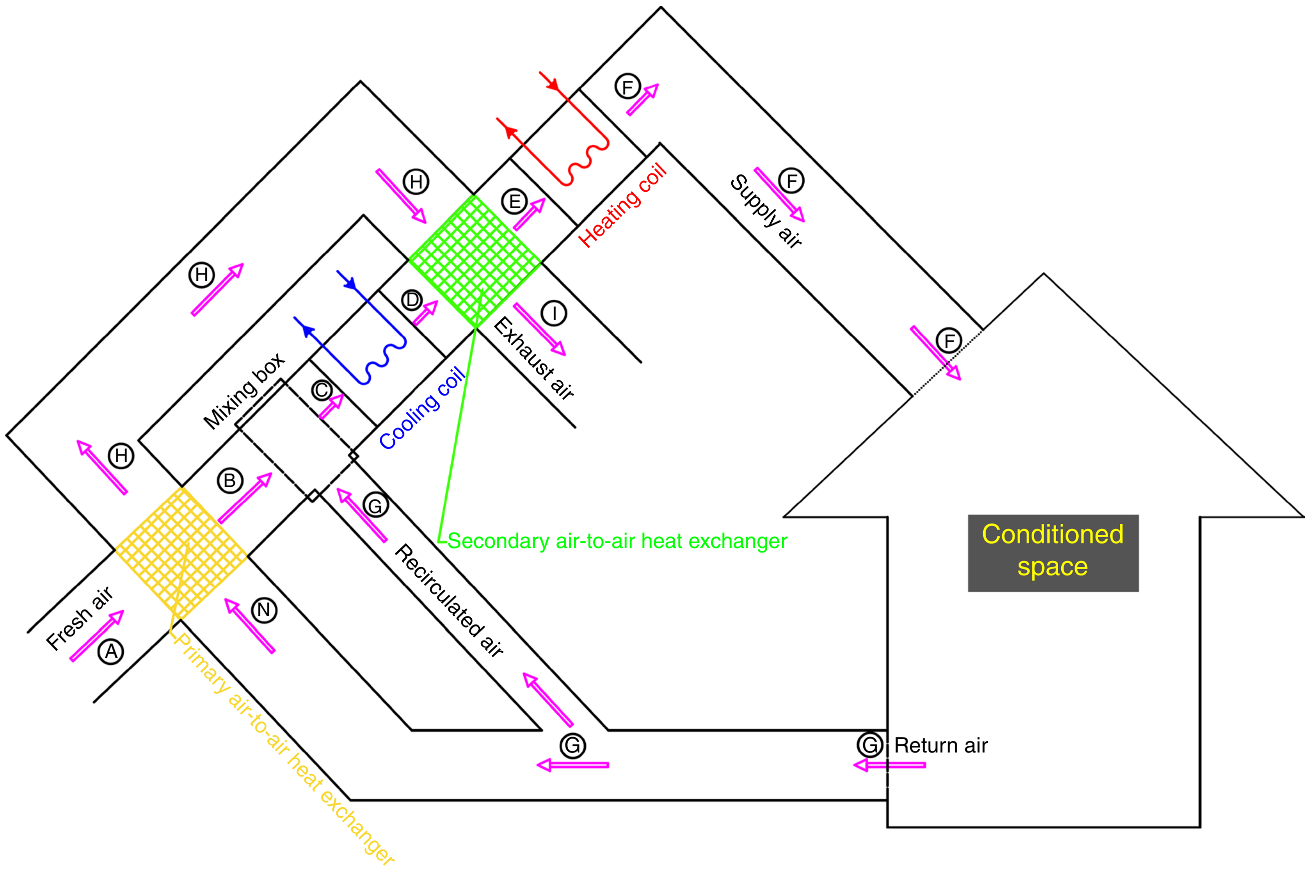

Fig. 1 Modified AHU equipped with primary and secondary heat exchangers

$$
\begin{aligned}
\mathrm{Ex}_{\text{humid air}} = {} & \left(c_{\mathrm{p,a}} + \omega c_{\mathrm{p,v}}\right)\left(T - T_0 - T_{\mathrm{o}} \ln\left[\frac{T}{T_{\mathrm{o}}}\right]\right) \\
& + (1 + 1.608\omega) R_{\mathrm{a}} T_{\mathrm{o}} \ln \frac{P}{P_{\mathrm{o}}} \\
& + R_{\mathrm{a}} T_{\mathrm{o}} \left[(1 + 1.608\omega) \ln \frac{1 + 1.608\omega}{1 + 1.608\omega_{\mathrm{o}}} + 1.608\omega \ln \frac{\omega}{\omega_{\mathrm{o}}}\right]
\end{aligned} \tag{7}
$$

$$
\mathrm{Ex}_{\mathrm{cond}} = h_{\mathrm{f}} - h_{\mathrm{f0}} - T_0\left(s_{\mathrm{f}} - s_{\mathrm{f0}}\right) - R_{\mathrm{v}} T_0 \ln\left(\varphi_0\right) + v_{\mathrm{f}}\left(P - P_{\mathrm{sat}}\right) \tag{8}
$$

$$
\mathrm{Ex}_{\text{hot and cold water}} = h_{\mathrm{f}} - h_{\mathrm{f0}} - T_0\left(s_{\mathrm{f}} - s_{\mathrm{f0}}\right) \tag{9}
$$

In this paper, a novel criterion is introduced to determine the AHU first law efficiency. This criterion affirms how much cooling and heating powers must be consumed to satisfy the ventilation requirement in the conditioned space:

$$
\eta_{\mathrm{I}} = \frac{\text{desired output}}{\text{required input}} = \frac{Q_{\mathrm{s}} + Q_{\mathrm{l}}}{Q_{\mathrm{cc}} + Q_{\mathrm{h}}} \tag{10}
$$

Also, the second law efficiency is calculated from Eq. (11) to show the system deviation from the ideal state:

$$
\eta_{\mathrm{II}} = 1 - \frac{\text{destroyed exergy}}{\text{input exergy}}. \tag{11}
$$

Results

To evaluate the usefulness of incorporating heat recovery units into the base AHU, the efficiency of the first and second laws must be calculated through the energy and exergy analysis. Assuming a cinema hall with a volume of $40 \times 20 \times 8\,\mathrm{m}^3$ at temperature 24 °C, relative humidity 50% and capacity of 800 people, latent and sensible heat gains for each person are considered to be 40 and 100 W, respectively [60]. It is assumed that the relative humidity and temperature of the ambient are 40% and 35 °C, respectively. Because the ambient temperature is higher than the conditioned space, it is assumed that the sensible heat of 14 kW is transferred from the outside to the inside. To meet the ventilation requirement, the number of air changes per hour is selected to be 7 and the required fresh air per person of $7\frac{\mathrm{L}}{\mathrm{s}}$ is selected from the HVAC standards [60]. The heating process and cooling process of the air are carried out by heating and cooling coils. The cooling coil is fed from the chilled water (6 °C) and for the heating coil the hot water of the boiler (60 °C) is used. The power of the heating and cooling coils is obtained using thermodynamic calculations. For base AHU, the required power of cooling and heating coils is 450.34 kW and 177.74 kW, respectively. Therefore, using Eq. (10), the first law of thermodynamic efficiency is 0.2. Applying exergy balance equations on the AHU, irreversibility in each section is acquired. Calculations show that the irreversibility for heating and cooling coils is 12.94 kW and 22.85 kW, respectively. Also, exergy loss for mixing box and conditioned space is 1.213 kW and 2.021 kW, respectively. Therefore, the sum of the total irreversibility is equal to 39.024 kW. According to Eq. (11), the second law efficiency is calculated to be 58.52%.

In the modified AHU (Fig. 1), part of the energy and exergy of the return air is recovered using primary and secondary heat recovery units. Both energy recovery units are the sensible type with an efficiency of 0.6.

For modified AHU, the required power of cooling and heating coils is 414.85 kW and 101.18 kW, respectively. Therefore, using Eq. (10), the first law of thermodynamic efficiency is 0.2442.

As shown in Fig. 2, comparison between the approved AHU and the base AHU shows that incorporating primary and secondary heat recovery units into the base AHU changes the cooling coil load from 450.34 to 414.85 kW (7.8% decrease) and consuming power of the heating coil from 177.74 to 101.18 kW (43% reduction).

Similar calculations also affirm that by installing primary and secondary heat exchangers, the total power required is reduced from 628 to 516 kW (17.84% reduction). In other words, it is recycled up to (628–516 = 112 kW) of energy by installing primary and secondary heat recovery units. According to Eq. (10), the efficiency of the first law depends on the amount of required power. So that any reduction in required power increases the efficiency. Due to the adding two heat recovery units, the first efficiency is improved from 0.2 to 0.2442 (22.1% enhancement).

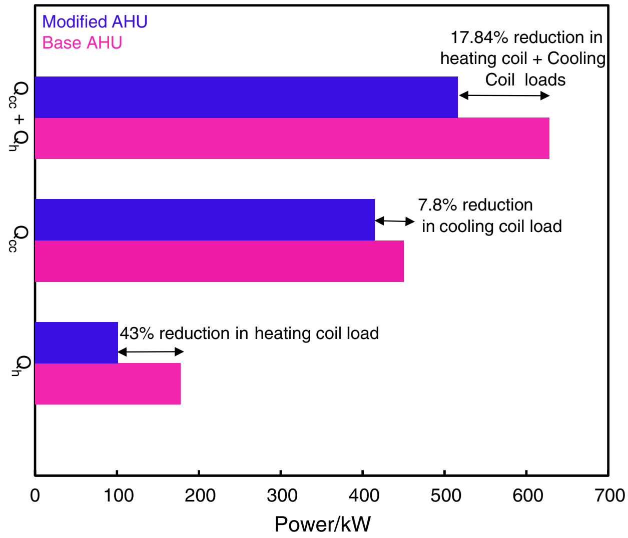

Fig. 2 Comparison between the modified AHU and base AHU

From the viewpoint of the second law, using primary and secondary heat exchangers have an impact on the amount of irreversibility content. Results of the exergy analysis affirm that the irreversibilities are 12.48 and 10.55 kW through the heating and cooling coils, 4.265 kW in the heat exchangers, 2.074 kW in the conditioned space and 0.609 kW in the mixing box. Therefore, the total irreversibility and the second law efficiency are 29.98 kW and 68.12%, respectively. To better understand the effect of using primary and secondary heat exchangers, the results of the exergy balance are compared in Fig. 3. According to this figure, it is found that the irreversibility decrease from 39.024 to 29.98 kW (23.15% reduction) which in turn increases the second law efficiency by 15.85%. Finally, adding primary and secondary heat exchangers leads to the recovery of exergy of 9.04 kW (Fig. 4).

The effects of ambient conditions on the total irreversibility are shown in Fig. 5. As shown in Fig. 5, the irreversibility of the modified AHU is maximum at the hot and humid climate. For hot and humid ambient at temperature of 313.15 K and humidity ratio of 90%, the total irreversibility of the modified AHU is reached up to 45.661 kW.

For base AHU at the same ambient, the total irreversibility is 53.88 kW. Therefore, in hot and humid climate regions, using primary and secondary heat exchangers causes a 15.25% decrease in total irreversibility. However, for hot and dry ambient, (313.15, 0.1) this figure is 24.77%. Consequently, the positive effect of using heat exchangers in the hot and dry climate region is better than the hot and humid one.

In Fig. 6, the amount of exergy recovered under different ambient conditions is shown. At constant relative humidity, as the temperature increases, the amount of recovered exergy increases. At constant temperature, with as the relative humidity decreases, the amount of recovered exergy increases.

Effect of ambient temperature

As mentioned, the installation of primary and secondary heat recovery units reduced power consumption which in turn improved the first law efficiency. Simultaneously, reduced exergy losses which in turn enhanced the second law efficiency. Now the question must be answered: Can ambient conditions affect the usefulness of heat recovery units installation?

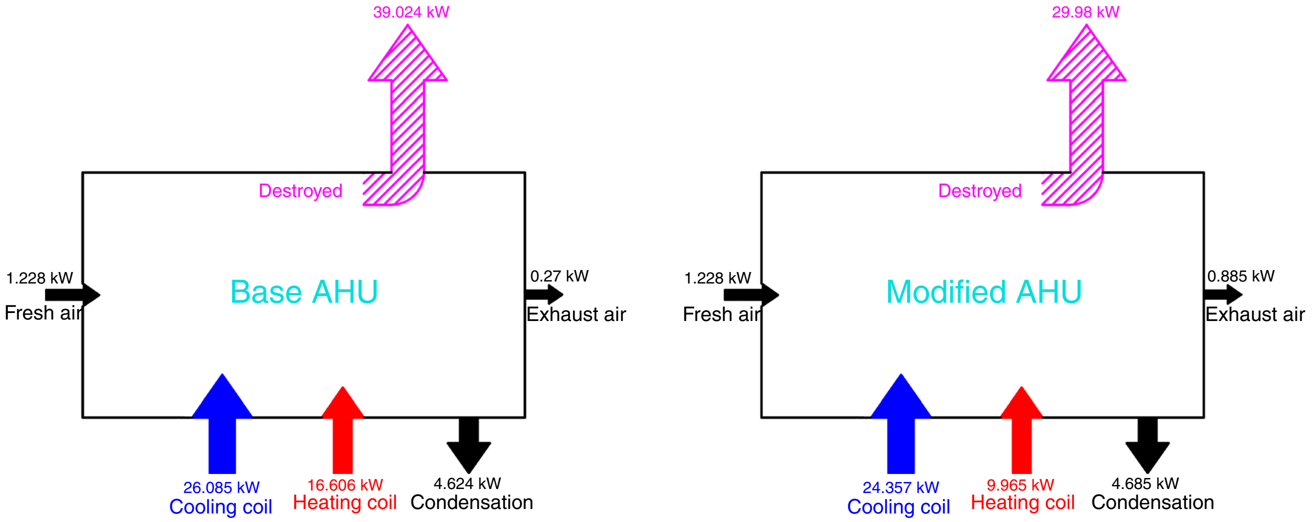

Fig. 3 Exergy balance comparison between the base and modified AHU

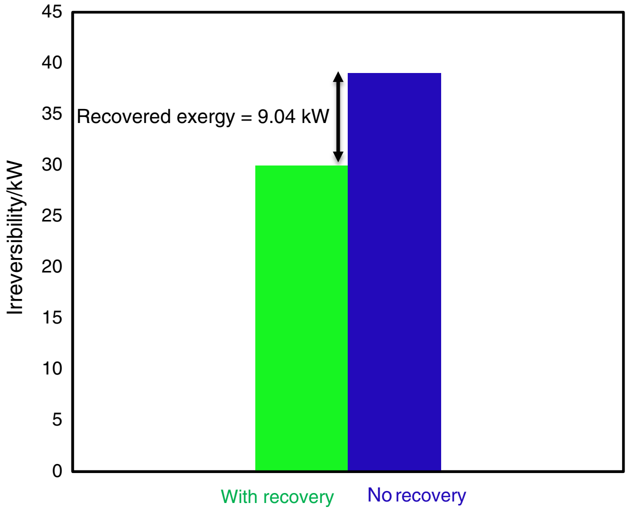

Fig. 4 Amount of exergy recovery due to adding two heat recovery unit

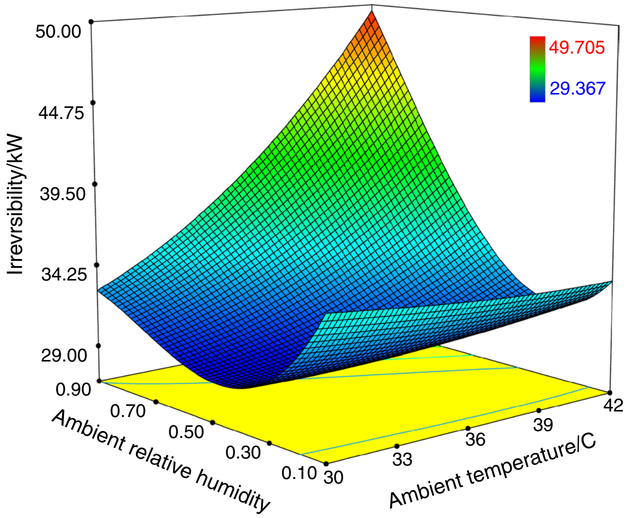

Fig. 5 Effects of ambient conditions on the total irreversibility

The following equations can be used to evaluate the usefulness of heat recovery units installation:

$$\mathrm{SER} = \frac{\eta_{\mathrm{II,modified}}}{\eta_{\mathrm{II,base}}} - 1 \tag{12}$$

$$\mathrm{IR} = 1 - \frac{\mathrm{IRV}_{\mathrm{modified}}}{\mathrm{IRV}_{\mathrm{base}}} \quad \text{(irreversibility ratio)} \tag{13}$$

$$\mathrm{RPR} = 1 - \frac{\text{required power}_{\mathrm{modified}}}{\text{required power}_{\mathrm{base}}} \quad \text{(required power ratio)} \tag{14}$$

Second efficiency ratio (SER) states: how the second law efficiency enhances owing to the heat recovery units installation. For example, the value of SER = 0.3 shows that installing heat recovery units improves the efficiency of the second law by 30%.

Exergy calculations show that in the temperature range of 303.15–315.15 K, if the relative humidity varies from 0.1 to 0.9, then SER, IR and RPR change within the ranges of 12.69–22.79%, 14.25–26.29% and 10.57–26.38%, respectively.

The variations of the second efficiency ratio in terms of temperature and relative humidity are shown in Fig. 7. This figure indicates that at constant temperature, if the relative humidity increases, SER decreases. The reduction in SER means that the effect of heat recovery installation

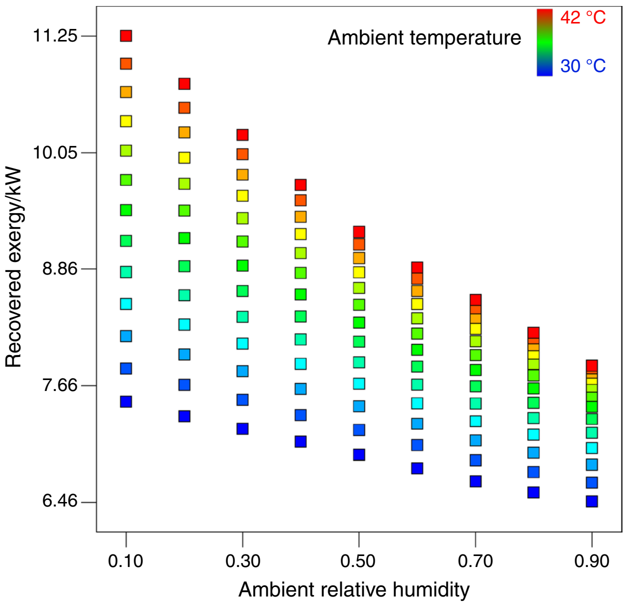

Fig. 6 Effects of ambient conditions on the total irreversibility

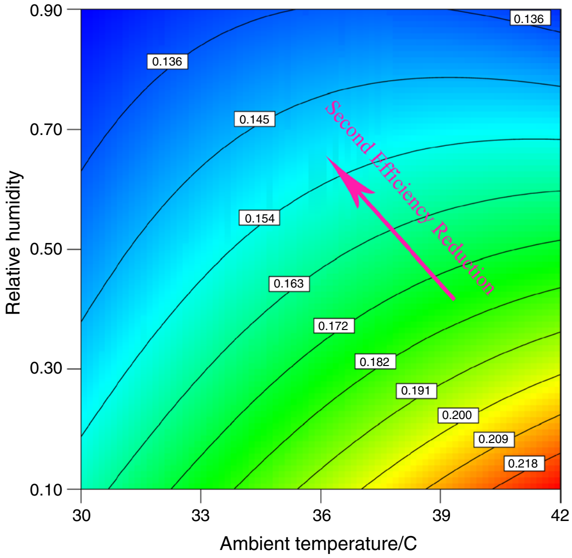

Fig. 7 Variation of second efficiency ratio with respect to the ambient temperature and relative humidity

on the second law efficiency is decreased. But the opposite is true for relative humidity. At constant relative humidity, if the ambient temperature increases, then SER increase. An increase in SER proves that incorporating the heat recovery units into the base AHU is more advantageous. Therefore, it can be concluded that at the locations with high temperature and low relative humidity incorporating primary and secondary heat recovery units has the most effect on the second law analysis.

In Fig. 8, the irreversibility ratio (IR) is plotted in terms of temperature and relative humidity. As stated, the exergy losses are reduced by installing primary and second heat exchangers. In other words, the reduction in exergy losses may indicate that the system behavior is closer to its ideal state by installing primary and secondary heat exchangers. The location identified by pink color has the maximum irreversibility ratio (hence the minimum irreversibility). In this area, if the primary and secondary heat exchangers are added to the base AHU, we will have the greatest improvement in the system behavior from the viewpoint of the second law.

In Fig. 9, the energy and exergy recovery are shown. As seen, the more energy recovery, the more exergy recovery. In Fig. 9a, the variations of the energy and exergy recovery are demonstrated with respect to the ambient temperature while in Fig. 9b, the relative humidity is the independent variable. In both figures, it is found that in hot and dry ambient the energy and exergy recovery has the highest value.

Now, it should be answered the following question:

How many percents of energy or exergy is recovered by installing primary and secondary heat exchangers?

At first, parameters $\mathrm{PENR} = \frac{\text{energy recovery}}{\text{base AHU required power}}$ and $\mathrm{PEXR} = \frac{\text{exergy recovery}}{\text{base AHU consumed exergy}}$ are defined. The variations of the PENR and PEXR with respect to the ambient temperature and relative humidity are shown in Fig. 10. As shown in Fig. 10, the maximum percent of the energy recovery is reached up to 26.38%. This figure is 26.54% for the exergy recovery. In other words, the same percentage of the energy

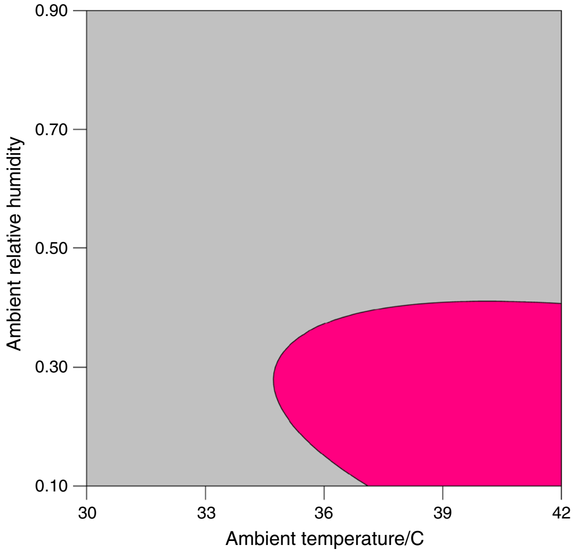

Fig. 8 Locations with the least irreversibility ratio

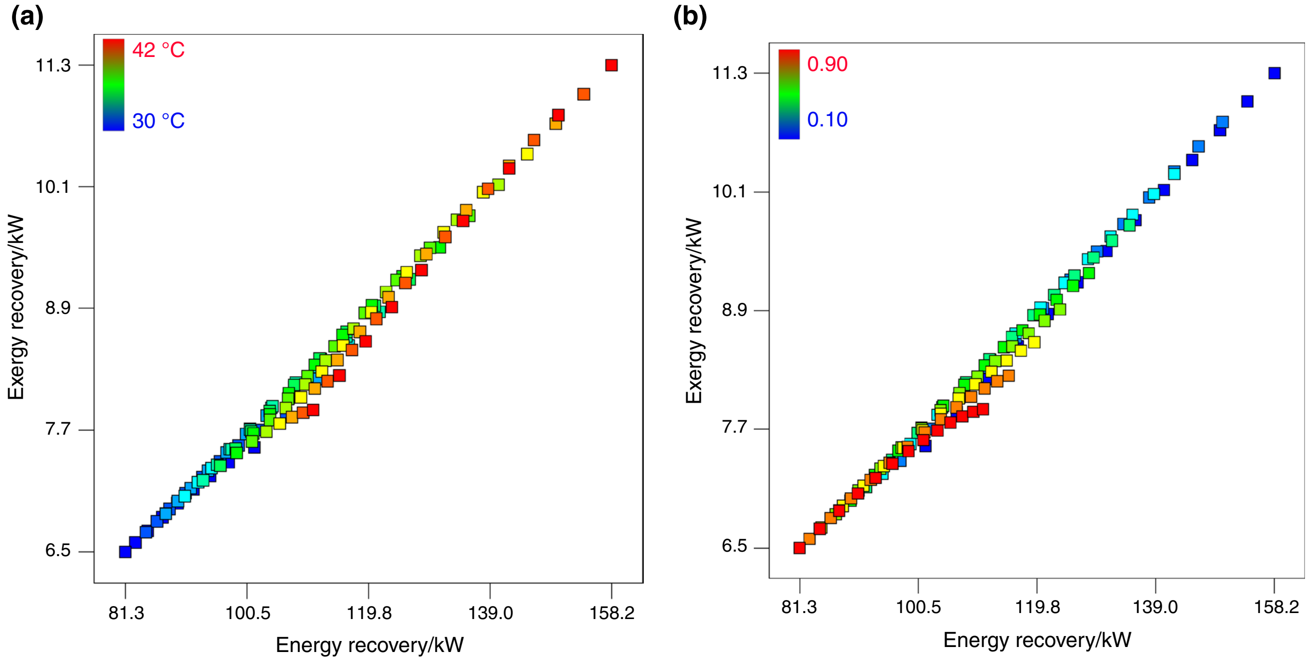

Fig. 9 Energy and exergy recovery with respect to the ambient conditions

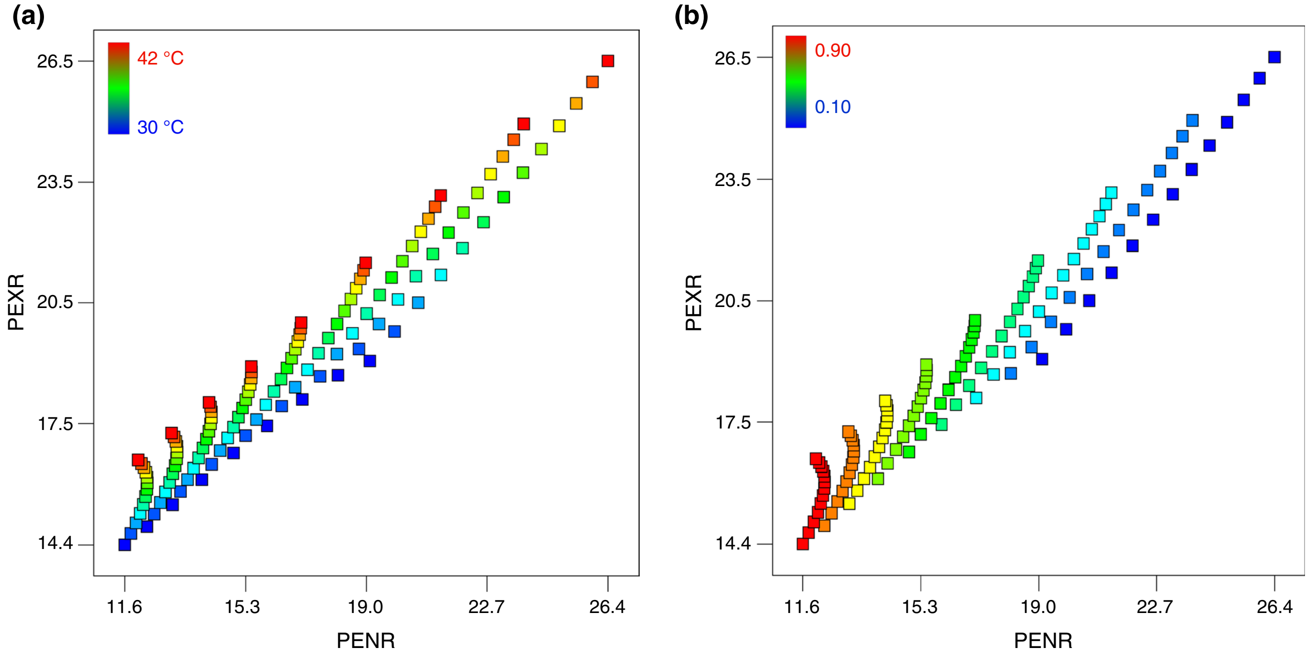

Fig. 10 Percent of exergy and recovery with respect to the ambient conditions

and exergy is recovered owing to installing primary and secondary heat exchangers.

Conclusions

In this study, the effects of incorporating primary and secondary heat recovery units from the perspective of the second law were investigated. To examine the usefulness of installation of the heat recovery units, the irreversibility of the modified AHU was compared with the base one. Calculations on exergy balance equations showed that the total irreversibility was 29.98 kW, which was decreased by as much as 23.17% compared to the base AHU irreversibility (39.024 kW). Due to the less irreversibility, the second law efficiency increased from 0.584 to 0.677 (15.85% enhancement).

The usefulness of installing heat recovery units depends on the ambient conditions. It was concluded that at the locations with high temperature and low relative humidity incorporating primary and secondary heat recovery units has the most effect on the second law analysis. In hot and humid climate regions, using primary and secondary heat exchangers causes a 14.25% decrease in total irreversibility. However, for hot and dry ambient, this figure is 26.29%. Consequently, the positive effect of using heat exchangers in the hot and dry climate region is better than the hot and humid one.

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