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Analysis of direct expansion heat recovery ventilation devices by orthogonal optimization method

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Abstract

Heat recovery ventilation devices include rectangular plate cross-flow, hexagonal plate combined counter and cross-flow, rotary wheel sensible, sorption rotor hybrid sensible and latent heat exchanger. Currently, existing studies have produced no clear findings on which climatic conditions latent heat recovery would be optimal, and therefore sought to determine in which climatic conditions it would be suitable to use devices that perform latent heat recovery. This study analysed the performance of different heat recovery devices in different climatic conditions in a ventilation project of a sample hotel building. In the case study, while there is a useful heat recovery between 44.01 and 58.68 kW at low outdoor temperatures in devices with only sensible heat transfer, this value increases up to 158.42 kW, as the outdoor temperature rises. In the heat recovery device providing latent heat transfer, the amount of useful heat recovery varies between 51.34 and 352.16 kW at low outdoor temperatures, depending on the outdoor relative humidity, while this amount increases to 411.26 from 773.25 kW at high outdoor temperatures. Outdoor temperature and humidity levels required for latent heat recovery was also determined by orthogonal optimization method. By using the orthogonal optimization, the study found that under conditions of high temperature that exceeds 35 °C in outdoor ambient temperature, and high humidity that exceeds 60% relative humidity, usage of latent heat recovery devices caused significant differences in total heat recovery ratio. Analysis also concludes that these devices can be used under these conditions.

Keywords Covid-19 · Ventilation · Heat recovery · Energy efficiency · Orthogonal optimization method

List of symbols

$\dot{Q}$	Heat rate/kW
$\dot{V}$	Air flow rate/m^3 s^{-1}
C_p	Specific heat/kJ kg^{-1} K^{-1}
h	Enthalpy/kJ kg^{-1} dryair
h_{fg}	Latent heat of evaporation/kJ kg^{-1}
w	Humidity ratio/g H$_2$O kg^{-1} dryair
L_n	Number of analyses
F	Number of levels
M	Number of factors
T	Temperature/°C

Subscripts

build	Building
s	Sensible
l	Latent
shr	Sensible heat recovery
o	Outlet
lhr	Latent heat recovery
thr	Total net heat recovery

Greek symbols

η	Efficiency/%
ρ	Density/kg m^{-3}

Abbreviations

BLE	Effect on the building load
CF-HRV	Rectangular plate cross-flow heat exchanger heat recovery ventilation device

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C/CF-HRV	Hexagonal plate combined counter and cross-flow heat exchanger heat recovery ventilation device
SR/H-HRV	Sorption rotor hybrid sensible and latent heat exchanger heat recovery ventilation device
R-HRV	Rotary wheel sensible heat exchanger heat recovery ventilation device
OLC	Optimal level combination
RD	Relative domination
DBT	Dry-Bulb thermometer temperature
WBT	Wet-Bulb thermometer temperature

Introduction

The concept of nearly zero-energy buildings is important in the process of climate crisis and reducing carbon emissions. However, to reduce the risk of Covid-19 transmission, the pandemic has led to an increase in fresh air rates in buildings. It is at this point that heat recovery has become even more important for energy efficiency in buildings. It is necessary for air-conditioning systems to ensure that the need for fresh air is met. It is equally important to remove the air supplied to the environment after its use. The air is conditioned to the desired temperature and supplied to the environment. The conditioned air then becomes waste air through usage in the environment. It is later discharged and removed from the environment. The energy in the air discharged from the environment can be recovered at 50–80% efficiency rates with a suitable device. These devices are known as heat recovery devices. With these devices, the heat recovered is transferred to fresh air which is taken from the outside environment so that energy efficiency can be achieved [1–3].

With the Covid-19 pandemic, which originated in China, very serious changes in ventilation systems have become a topic of conversation. In addition to UV-illuminated lamps and special filter solutions, the need to increase the proportion of fresh air and to carry out revisions of existing air-conditioning ventilation systems has arisen. As a result, the importance of heat recovery devices has also increased. To avoid creating a suitable environment for viruses, air-conditioning with a high level of fresh air is needed. It is known fact that increasing the number of air changes will reduce the spread of harmful microorganisms [1, 4].

Different systems are designed in air-conditioning projects. Heat recovery ventilation (HRV) systems are very important for energy savings. However, the type of device to be used in the HRV system depends on the heat recovery rate. In today's conditions, systems with direct expansion (DX) batteries enjoy widespread use due to their high COP (coefficient of performance) values and ease of application. Because of this, the use of heat recovery devices with DX batteries is becoming widespread. For this purpose, rectangular plate cross-flow heat exchanger (CF-HRV), hexagonal plate combined counter and cross-flow heat exchanger (C/CF-HRV), rotary wheel sensible heat exchanger (R-HRV), sorption rotor hybrid sensible and latent heat exchanger (SR/H-HRV) recovery devices are often preferred in air-conditioning systems. These heat recovery ventilation device types are shown in Fig. 1. In the rectangular plate cross-flow heat exchanger (CF-HRV) heat recovery ventilation device, the air discharged from the environment flows diagonally to the air received from the outside environment (Fig. 1a). It then flows through two separate surfaces of the plate and carries out energy transfer without interfering with each other. The basic principle is the same in the hexagonal plate combined counter and cross-flow heat exchanger heat recovery ventilation device (C/CF-HRV) (Fig. 1b). The two fluids flow in opposite directions through the hexagonal plate, which increases heat transfer efficiency. In rotary wheel sensible heat exchanger heat recovery ventilation devices (R-HRV), waste energy from the fluid is stored on one surface beforehand. The stored energy is then transferred to another fluid. In all these three heat recovery devices, heat transfer is in the form of sensible heat transfer. In the sorption rotor hybrid sensible and latent heat exchanger heat recovery ventilation device (SR/H-HRV), moisture control

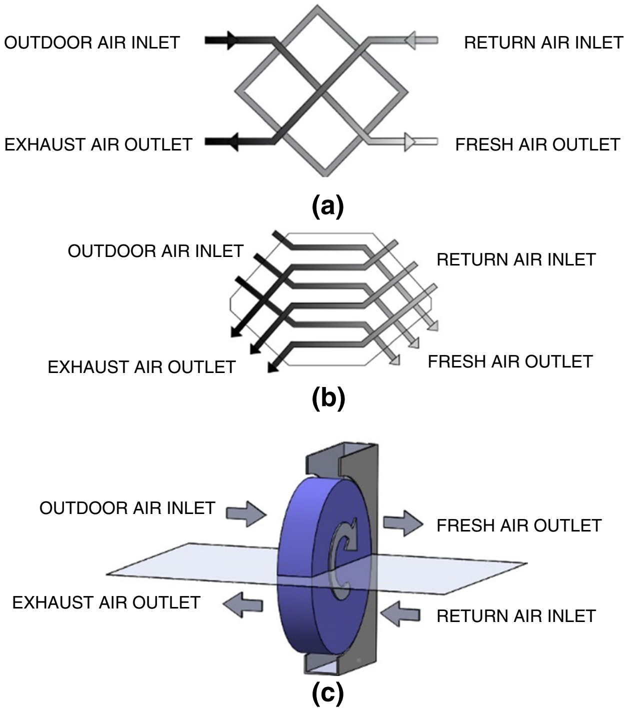


Fig. 1 Types of HRV devices **a** Rectangular plate cross-flow heat exchanger, **b** Hexagonal plate combined counter and cross-flow heat exchanger, **c** Rotary wheel heat exchanger

can also be achieved with chemicals that will be applied to the surface where the heat will be stored, so that latent heat recovery is also possible (Fig. 1c) [2, 3].

Unarguably, studies on the subject have gained momentum with the increase in fresh air quantities in air-conditioning of buildings during the pandemic conditions. Zheng et al. examined the effects of air-conditioning on energy consumption in Covid-19 conditions. Similarly, issues such as transmission characteristics of Covid-19 in indoor environments, the search for innovations expected for ventilation systems in the future have been discussed. Handling and smoother operation of ventilation systems reduces the risk of transmission. Measures such as increasing the outdoor air ratio of ventilation systems during the epidemic period cause the energy used in air conditioning to increase by 128%. Therefore, it is recommended to keep human health at the forefront of the design of ventilation systems and to design systems aimed at reducing increased energy costs [1]. Herath et al. calculated the energy potential of a rotary heat wheel heat recovery device for different situations. They have also made calculations for different outdoor temperatures. Their first calculation found the relative humidity of fresh air as 80%, the effectiveness of the HRV wheel as 0.55, return air condition as 25 °C for temperature, and 50% for relative humidity. In the second case, the outdoor air temperature was 30 °C, the effectiveness of the HRV wheel was also 0.55, the return air conditions were considered as 25 °C for temperature and 50% for relative humidity. The study concluded that the amount of heat recovery increases as relative humidity of outdoor air increases [5]. Min et al. examined two different HRV systems in a hot and humid area located in Hong Kong and in eight different cities in southern China. The first system was an evaporative cooler system with an HRV system, used as a new system, while the second system was an air-conditioning system integrated with an HRV exchanger. Analyses were performed with a simulation. With the platform installed in different cities, it was determined that it is more convenient to use a system with evaporative HRV according to the cooling mode operation data of the two systems during summer. It was also found that the air outlet temperature in the system with evaporative HRV was 4 °C lower than in the system integrated with the HRV exchanger [6]. Pourhoseinian et al. numerically analysed the sensible and latent heat factor, energy recovery rate and pressure drop of the ducted type air-to-air HRV device using CFD analysis. They carried out their work with different system characteristics and operating conditions. Their results concluded that the application of air with an opposite flow showed 7–14% more efficiency than with a cross-flow model. They also found that multichannel heat exchangers performed better than single-channel heat exchangers at low flow rates among. They emphasized that there are applications where a high amount of heat can be recovered when the air has higher humidity levels [7]. Gendebien et al. conducted a study on the improvement and experimental verification of a surface-to-air HRV model. Their studies focused on the sensible and latent heat transfer rates of the HRV device in dry and wet (humid) conditions. First, they conducted experiments in dry weather conditions and applied a sample correlation study identified in the literature review. They repeated the experiments in humid conditions for the second time. Their results emphasized that humidity is very important on latent heat transfer in the HRV system. They added that suitable conditions should be selected for freezing HRV device exchangers [8]. Ribé examined the ERV (sensible and latent heat recovery device) and HRV (sensible heat recovery device) devices in his research and calculated the results for the Spanish climate. The study was presented with a seasonal and annual analysis of ERV and HRV devices and ventilation systems in 48 different locations. From the analysis of the data obtained, it was concluded that it is more suitable to use ERV devices in places with high humidity during summer in the city of Barcelona [9]. Ghalandari et al. reviewed different applications of intelligent methods in performance modelling of heat exchangers. Also, the main outputs of the studies examined were presented [10]. Koç et al. designed a new organic liquid filled regenerative heat exchanger used in heat recovery ventilation system. The heat recovered by the regenerative heat exchanger was analysed depending on the varying air velocities [11].

Examination of existing studies found no clear evidence regarding which climatic conditions latent heat recovery would be optimal. This has led to the need to investigate the type of climatic conditions suitable for latent heat recovery. Consequently, this study sought to determine which climatic conditions would be suitable to use devices that perform latent heat recovery. This study therefore analysed the performance of different heat recovery devices in a ventilation project of a sample hotel building for different climatic conditions. Outdoor temperature and humidity levels required for latent heat recovery were also determined through orthogonal optimization method. Regardless of outdoor ambient relative humidity and temperature, devices suitable for the transition of latent heat will create a difference in total heat recovery compared to other types of heat recovery devices. However, it should also be noted that this choice will cause an initial investment cost. Therefore, it is extremely important to determine the outdoor temperature and relative humidity values where significant differences will occur in the total heat recovery after latent heat recovery.

Material and method

This study examined the architecture of a hotel with about 150 rooms as a material. Five-year hourly dry thermometer and relative humidity data of four provinces (Ankara, Antalya, Istanbul and Sanliurfa) with different climatic conditions in Turkey were used as input data. The thermal load calculations required for the design of the project and the analyses to be performed in the study were performed with HAP (Hourly Analysis Program), a simulation program that can perform hourly analysis in building air conditioning [12]. The data obtained from meteorology were dry-bulb thermometer and relative humidity data, and the wet-bulb thermometer temperature and specific humidity values were determined using the ESS (Engineering Equation Solver Program) program [13]. Subsequently, psychrometric analyses and evaluations of heat recovery devices in the climatic conditions of Ankara, Antalya, Istanbul and Sanliurfa provinces were carried out.

In the study, a hotel architecture consisting of three blocks and five floors, with a usage area of about 13,000 m^2 having different usage purposes, was discussed. Considering that the hotel is in cities with four different climate types in Turkey, thermal load calculations were repeated. After analysing the architecture of the hotel, the attic floors, the indoor areas in m^2, it was decided where to use the HRV air handling unit or ceiling type devices. The use of a ceiling-type HRV device in each room on the upper floors was not considered suitable given the terms of application, initial investment cost and architectural situation. An HRV air handling unit was preferred in the attics of three separate blocks that architecturally have dormitories. Architectural shafts were created at the suitable points in each attic, and the ventilation ducts were extended to the lower floors through these shafts. The fourth air handling unit used in the hotel is in the multi-purpose hall. In places such as the hotel lobby, gym, staff areas and cafeteria, a ceiling-type HRV device was used. The list of HRV devices used in the study and fresh air flow rates is given in Table 1.

The climate classification of the provinces where heat recovery devices will be examined is determined according to the Trewartha Climate Classification (universal temperature scale). The humidity classification of the cities is also determined according to the Thornthwaite Climate Classification [14]. The climate types determined according to each of the two classifications are presented in Table 2.

In order to compare the performances of four different types of HRV devices, it is necessary to calculate and determine the DX battery capacities because the deceleration loads due to heat gained by the HRV device will be provided by these DX batteries mentioned. The device battery capacity (cooling load) is calculated by deducting the useful

Table 2 Climatic classes of the studied cities

Cities	Climatic class	Design temperature	
		DBT/°C	WBT/°C
Ankara	D, Hot and low humid	36.5	21.1
Antalya	B1, Very hot and humid	39.1	27.4
İstanbul	C2, Hot and semi-humid	33.9	24.3
Şanlıurfa	D, Very hot and low humid	43.1	24.9

D: Semi-Arid-Low Humid, B1: Humid, C2: Semi-Humid

Table 1 Types of HRV devices used indoors and required amounts of fresh air

Device number	Floor	Zone	Fresh air flow/m^3 h^{-1}	Device type
1	Basement floor	Multipurpose hall	6500	Heat recovery air handling unit
2	Roof floor	A block bedrooms	4700	Heat recovery air handling unit
3	Roof floor	B block bedrooms	4700	Heat recovery air handling unit
4	Roof floor	C block bedrooms	8600	Heat recovery air handling unit
5	Basement floor	Fitness centre	1000	Ceiling type HRV-1
6	Basement floor	Pool bar	2000	Ceiling type HRV-2
7	Basement floor	Material receiving	1500	Ceiling type HRV-3
8	Basement floor	Laundry room	1000	Ceiling type HRV-4
9	Basement floor	Staff lockers-1	1500	Ceiling type HRV-5
10	Basement floor	Staff lockers-2	1000	Ceiling type HRV-6
11	Basement floor	Office and warehouse	500	Ceiling type HRV-7
12	Basement floor	Foyer	2000	Ceiling type HRV-8
13	Basement floor	Meeting room and office	1000	Ceiling type HRV-9
14	Ground floor	Lobby-1	1000	Ceiling type HRV-10
15	Ground floor	Lobby-2	2000	Ceiling type HRV-11
16	Ground floor	Lobby-3	2000	Ceiling type HRV-12
17	Ground floor	Restaurant	2000	Ceiling type HRV-13
	Total fresh air flow/m^3 h^{-1}		43,000	

recovered heat load in the HRV device from the total sensible and latent heat load of fresh air to be supplied to the environment. The sensible cooling load, latent heat cooling load and total cooling load carried indoors through fresh air are expressed in Eqs. (1), (2) and (3), respectively.

$$\dot{Q}_{\mathrm{s}} = \dot{V}\rho\left(h_2 - h_1\right) \tag{1}$$

where $\dot{Q}_{\mathrm{s}}$ is sensible cooling of fresh air, $\dot{V}$ is air flow rate, ρ is density of air, h_2 is inlet enthalpy of fresh air, and h_1 is the indoor exhaust air enthalpy.

$$\dot{Q}_{\mathrm{l}} = \dot{V}\rho\left(w_2 - w_1\right)h_{\mathrm{fg}} \tag{2}$$

where $\dot{Q}_{\mathrm{l}}$ is latent heat-cooling load of fresh air, w_2 is specific humidity of fresh air, w_1 is specific humidity of expelled indoor exhaust air (under indoor comfort conditions), and h_{fg} is evaporation latent heat.

$$\dot{Q}_{\mathrm{total}} = \dot{Q}_{\mathrm{s}} + \dot{Q}_{\mathrm{l}} \tag{3}$$

$\dot{\mathrm{Q}}_{\mathrm{total}}$ signifies the total cooling load that must be drawn from the fresh air. The useful heat energy recovered in HRV devices depends on the device efficiency rate, outdoor temperature and indoor air temperature. By Eq. (4), the HRV device output temperature of the air can be calculated depending on the device efficiency. The amount of net sensible heat recovery with the HRV device, device air output specific humidity and the amount of net latent heat load recovered can be determined by Eqs. (5), (6) and (7), respectively.

$$T_{\mathrm{o}} = T_2 + \eta_{\mathrm{s}}\left(T_1 - T_2\right) \tag{4}$$

where T_{o} signifies HRV device output air temperature, and η_{s} signifies device sensible heat transfer efficiency.

$$\dot{Q}_{\mathrm{shr}} = \dot{V}\rho\left(h_2 - h_0\right) \tag{5}$$

where $\dot{Q}_{\mathrm{shr}}$ signifies HRV device net sensible heat recovery, and h_{o} signifies HRV device output air enthalpy.

$$w_{\mathrm{o}} = w_2 + \eta_{\mathrm{l}}\left(w_1 - w_2\right) \tag{6}$$

where w_{o} signifies device air output specific humidity and η_{l} signifies device latent heat transfer efficiency.

$$\dot{Q}_{\mathrm{lhr}} = \dot{V}\rho\left(w_2 - w_{\mathrm{o}}\right)h_{\mathrm{fg}} \tag{7}$$

where $\dot{Q}_{\mathrm{lhr}}$ signifies HRV device net latent heat recovery.

The total useful amount of heat recovery performed by the heat recovery device can be calculated as:

$$\dot{Q}_{\mathrm{thr}} = \dot{Q}_{\mathrm{shr}} + \dot{Q}_{\mathrm{lhr}} \tag{8}$$

where $\dot{\mathrm{Q}}_{\mathrm{thr}}$ signifies HRV device total net heat recovery.

$$\dot{Q}_{\mathrm{net}} = \dot{Q}_{\mathrm{total}} - \dot{Q}_{\mathrm{thr}} \tag{9}$$

$\dot{Q}_{\mathrm{net}}$ signifies net cooling load that the DX battery must meet. In air-conditioning and ventilation projects, in addition to sensible and latent heat load from the fresh air pumped indoors, heat loads from many factors such as walls and windows of the area, non-conditioned air leaks, people indoors, devices, etc. occur. The combination of indoors cooling load and the total fresh air load gives the total cooling need for the area to be climatized to comfortable conditions. In this study, the fresh air-cooling load was met with HRV devices, and the rest was met with DX batteries. The cooling load of the entire hotel was also calculated through the HAP program. The alternatively analysed effect of HRV devices on the calculated total cooling load of the building was also studied. It was then calculated and evaluated as a ratio of DX battery cooling load to the total cooling load of the building under consideration. The more heat recovery is achieved by the HRV device, the more cooling load that will be loaded on the DX battery will be reduced. In other words, the lower the effect of the device on the building load, the more useful heat recovery HRV device under consideration is provided. $\dot{Q}_{\mathrm{build}}$ signifying total building cooling load, the effect on the building load (BLE) was determined as follows:

$$\mathrm{BLE} = \frac{\dot{Q}_{\mathrm{net}}}{\dot{Q}_{\mathrm{build}}} \tag{10}$$

This study examined HRV devices with four different heat exchanger types. The material structures and efficiency of these devices are presented in Table 3. The assumptions made for the analysis are as follows:

1. Analyses were carried out under steady-state conditions.
2. It is assumed that the indoor air temperature and indoor air relative humidity remain constant at 24 °C and 50%, respectively.
3. The heat transferred to the air due to the fans in the heat recovery devices is neglected.
4. It is assumed that the heat exchanger efficiencies of the heat recovery ventilation devices are constant as presented in Table 3.
5. It is assumed that the properties of the air during its passage through the heat exchanger remain constant at the average temperature and relative humidity values.

This study analysed the amounts of useful heat recovery of HRV devices according to outdoor temperature and relative humidity through orthogonal optimization method. Analysis of the result determined the type of device suitable for use at which temperature and relative humidity values. Orthogonal design is an important branch of statistical

Table 3 Types and efficiencies of analysed HRV devices [2, 3]

Heat exchanger type of HRV device	Material used	Sensible heat recovery efficiency/%	Latent heat recovery efficiency/%
Rectangular plate cross-flow/CF-HRV	Aluminium	50	–
Hexagonal plate combined counter and cross-flow/C/CF-HRV	Aluminium	70	–
Rotary wheel sensible/ R-HRV	Aluminium	80	–
Sorption rotor hybrid sensible and latent/SR/H-HRV	Aluminium	80	50

Table 4 Factors and their levels

Factors	Notation	Levels		
		1	2	3
Temperature/°C	*A*	Low	Medium	High
Relative humidity/%	*B*	Low	Medium	High

Table 5 $L_9/3^2$ orthogonal design table

Analysis number	Factors		Optimization parameters
	A	*B*	
1	1	1	K_1
2	1	2	K_2
3	1	3	K_3
4	2	1	k_1
5	2	2	k_2
6	2	3	k_3
7	3	1	Range
8	3	2	RD/%
9	3	3	Order
			OLC

OLC: Optimal level combination, Order: Ranking of the most influential and least influential data, RD: Relative domination

mathematics based on probability theory. This scientific test and design method obtain results by performing analyses with the help of analysis of data numbers and tests of these data. Orthogonal design is a multifactorial study. For this reason, the data to be analysed will be evaluated with the help of determined factors and levels. In Eq. (11), the formula for orthogonal optimization is expressed [15].

$$L_n = (f^m) \tag{11}$$

where L_n signifies number of analyses, *f*, signifies the number of levels, *m*, signifies number of factors.

The analysis carried out in this study is a three-level orthogonal factorial design for two factors. It is expressed by $L_9(3^2)$. The factors and their levels determined for orthogonal optimization performed in this study are shown in Table 4. According to factors and the determined levels of analysis values given in the table, the total useful heat recovery rate of HRV devices used in the project for four different cities will be analysed in nine steps.

The orthogonal design table created is given in Table 5. The analysis was repeated in nine steps according to the given principle. Different temperature and humidity values were analysed at each step. Thus, the useful heat recovery amounts of the devices were determined as low, medium and high according to the analysis values examined. K_1, K_2 and K_3 values given in the table refer to the sum of the values of low, medium and high temperature and humidity, respectively. k_1, k_2 and k_3 are the average values of K_i values. For example, the value of K_1 for the *A* factor is the sum of the amount of useful heat recovery at low temperature points. For *A* having 1 as its number of levels k_1 value is the average of K_1 values. The offset is the difference between the two maximum values. The impact rates were determined by proportioning the determined offset values. *A* factor that is higher in rate of impact has a greater effect on the amount of useful heat recovery.

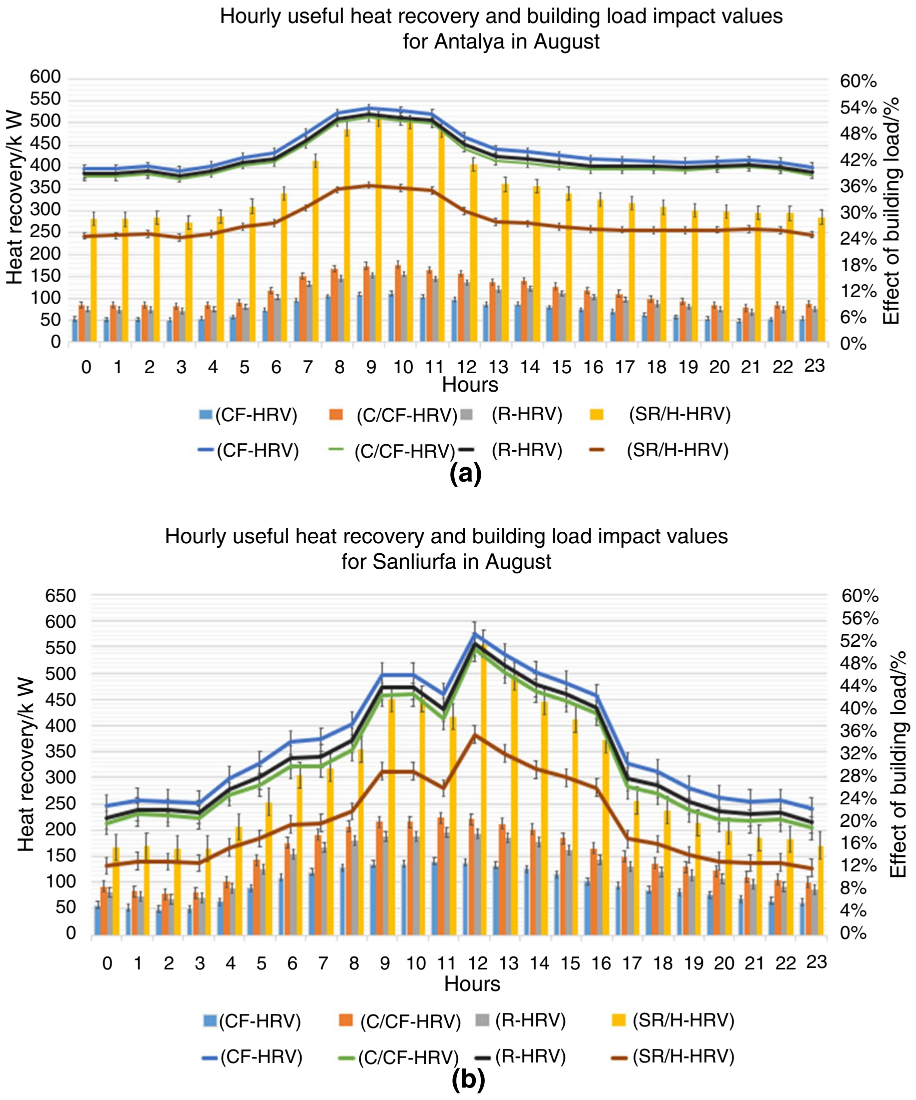
For example, if the impact rate is calculated as $A > B$, temperature > RH can be established. As a result, the effect of outdoor air temperature and relative humidity on the amount of useful heat recovery will be analysed, and the effect of temperature and humidity on HRV devices will be examined. In addition, the result of which temperature and humidity value affects which HRV device will be examined [16].

Results and discussion

In the study, critical months (months with most cooling needs) for provinces of Antalya, Sanliurfa, Istanbul and Ankara which have very hot-humid, very hot-low humidity, hot-semi humid and hot-low humidity climates, respectively, were determined. Recovered heat amounts recovered by HRV devices for every hour increment in these months and the effect of these on total building load were also determined and examined. It was determined as critical months that August for Antalya, Şanlıurfa, and Istanbul, and July for Ankara. Analysis was performed with the design data presented in Table 2.

Figure 2 shows the HRV device performances for each city's critical month examined on an hourly basis. In the graph, the effect of devices on the building load is expressed and presented by the ratio of useful heat recovery amount to the total building load. Since the device that performs the most heat recovery gives the least cooling load to the building load, the impact rate becomes also low. In Fig. 2a, 09.00 in August for Antalya was determined as the hour when the HRV devices in the whole building do the most heat recovery. It seems that the device that has the least impact on the building load at 09.00, when the most heat recovery is performed, is the SR/H-HRV device. In general, it can be concluded that the SR/H-HRV device allows for a high amount of heat recovery during all the hours included in the graph. In similar analyses conducted for Sanliurfa, Istanbul and Ankara, respectively, it was found that the amount of heat recovery was at its highest at 12.00 for Sanliurfa and Istanbul and 14.00 for Ankara, as shown in Fig. 2b, c and d. It is observed that the device that does the most heat recovery is again the SR/H-HRV device. When analysing other hours for all cities, it was again clearly determined that the SR/H-HRV device has a greater amount of useful heat recovery. This analysis also showed that the SR/H-HRV device has the least impact on the building load. In general, considering the useful heat recovery amounts, it is possible to sort devices low-to-high as rectangular plate cross-flow, rotary wheel sensible heat exchanger, hexagonal plate combined counter and cross, sorption rotor hybrid sensible and latent heat exchanger recovery devices.

As can be seen from the analyses, regardless of the relative humidity and temperature of the outdoor environment, SR/H-HRV, the heat recovery device suitable for latent heat transfer, creates a difference in the amount of heat recovery compared to other types. However, it should also be noted

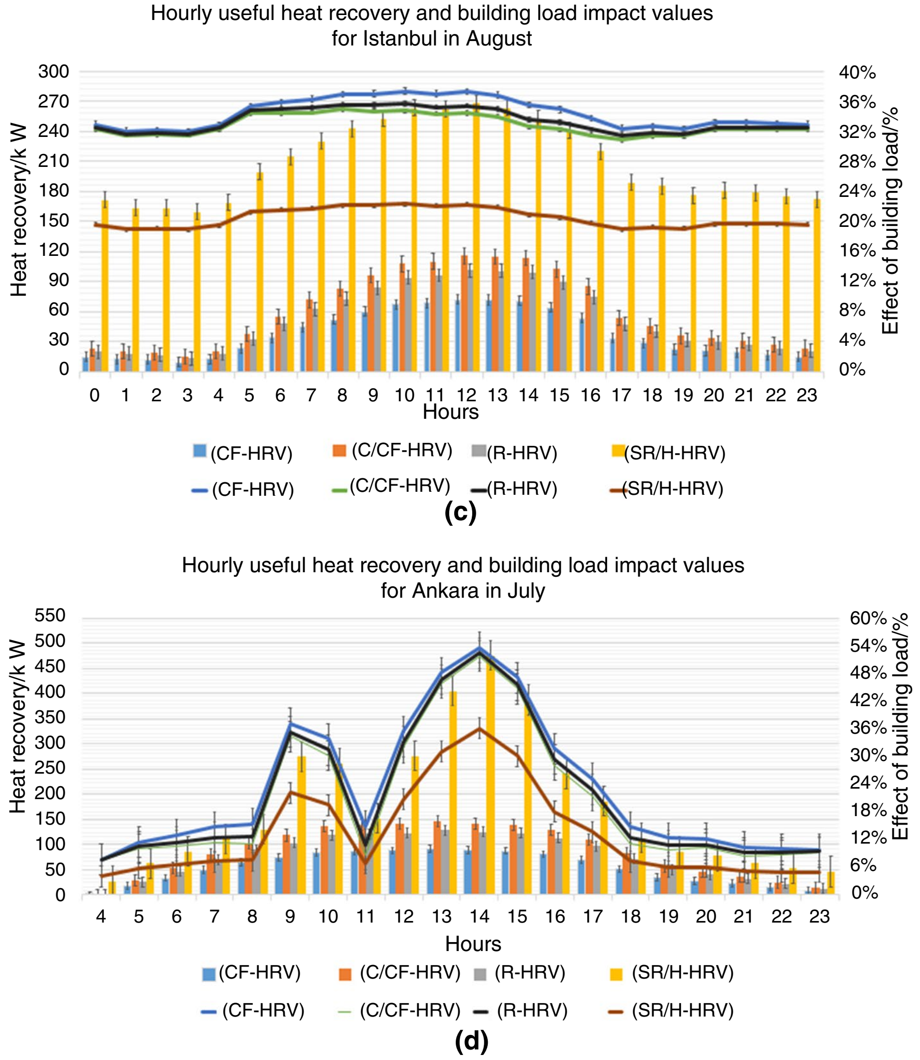


Hourly useful heat recovery and building load impact values for Antalya in August

Hourly useful heat recovery and building load impact values for Sanliurfa in August

Fig. 2 Effect of HRV devices on heat recovery and building load **a** Antalya, **b** Sanliurfa, **c** Istanbul, **d** Ankara

Fig. 2 (continued)



that this choice will cause an initial investment cost. Therefore, it is extremely important to determine the outdoor temperature and relative humidity values to understand where significant differences will occur in the total heat recovery after latent heat recovery. For this reason, the outdoor temperature and humidity levels required for latent heat recovery have been determined by orthogonal optimization method.

This optimization study was carried out using the orthogonal fractional factorial design method. The optimum values of the outdoor environment were determined according to the optimum temperature and relative humidity value, which gives the maximum useful recovered heat. Orthogonal optimization design is made for three levels and two factors. Factors A and B define the outdoor temperature and relative humidity. Factors A and B were determined to be matching the offset values specified in the factors. The temperature and relative humidity levels 1, 2 and 3, are low, medium and high values, respectively. The factors, levels and analysis values used in optimization are shown in Table 6.

The optimum levels of factors were determined according to the maximum amount of useful heat energy gained. Of the HRV devices examined in Table 7, CF-HRV, C/CF-HRV and R-HRV devices are sensible heat transitive devices. The SR/H-HRV device, on the other hand, is an HRV device with sensible and latent heat transfer. It is observed that in Table 8, the impact rate of moisture on CF-HRV, C/CF-HRV and R-HRV devices is zero. For this reason, it was noted that for factor B, $k_1 = k_2 = k_3$.

Table 6 Factors, levels and analysis values

Level	Factors		Analysis values	
	A Temperature/°C	*B* RH/%	*A*	*B*
1/Low	25–30	20–45	29.0	30.0
2/Medium	30–35	45–60	33.0	50.0
3/High	35–40	60–95	37.5	85.0

When the useful heat recovery rates of HRV devices are evaluated for factor *A*, it is seen that there is a ranking in the form of $k_1 < k_2 < k_3$. While K_1,K_2, K_3 signify some of the useful amounts of heat recovery at low, medium and high points of HRV devices,k_1, k_2, k_3 values refer to averages of K_1, K_2, K_3 values divided by three. The offset value was calculated by the difference between maximum and minimum values of k_1, k_2, k_3 values. The optimal points of the CF-HRV, C/CF-HRV and R-HRV devices are point *A*3, and it was found that they have the highest rate of heat recovery at high temperatures of 35–40 °C. Similarly, for factors *A* and *B* in the SR/H-HRV device, it is seen that $k_1 < k_2 < k_3$. It can be determined that the optimum points for the SR/H-HRV device are *A*3 and *B*3. The factors affecting the useful heat recovery amount of the SR/H-HRV device were determined as $B > A$. Determining the impact rate of factors as $B > A$ means that humidity is more effective than temperature. This can also be interpreted to mean that the use of a SR/H-HRV device will be far from advantageous in climates with low humidity.

In summary, the study found that SR/H-HRV-type devices of 35–40 °C high level temperature and 60–95% high relative humidity values are optimal levels. Generally, the study concluded that the most efficient HRV devices in terms of useful heat recovery rates are sorption rotor hybrid sensible and latent heat exchanger, hexagonal plate combined and cross-flow heat exchanger, rotary wheel sensible heat exchanger and rectangular plate cross-flow heat exchanger heat recovery ventilation devices, respectively. As a result of the optimization, it is observed that the use of SR/H-HRV devices that can provide heat recovery from latent heat is important and advantageous in climates with high temperatures exceeding 35 °C and high relative humidity values exceeding % 60. When Table 8 is examined again, it is seen that the device with the highest offset value among CF-HRV, C/CF-HRV, and R-HRV devices is C/CF-HRV. Thus, it can be said that it would be suitable to turn to the use of C/CF-HRV devices in high temperature and dry climates.

Table 7 Orthogonal optimization design parameters

Analysis number	Factors		$\dot{Q}_{\text{useful}}$/CF-HRV	$\dot{Q}_{\text{useful}}$/C/CF-HRV	$\dot{Q}_{\text{useful}}$/R-HRV	$\dot{Q}_{\text{useful}}$/SR/H-HRV
	A	*B*				
1	1	1	44.01	58.68	51.34	51.34
2	1	2	44.01	58.68	51.34	134.91
3	1	3	44.01	58.68	51.34	352.16
4	2	1	79.21	105.62	92.41	100.79
5	2	2	79.21	105.62	92.41	254.74
6	2	3	79.21	105.62	92.41	531.72
7	3	1	118.82	158.42	138.62	211.84
8	3	2	118.82	158.42	138.62	411.26
9	3	3	118.82	158.42	138.62	773.25
	Average		80.68	107.57	94.12	313.56

$\dot{Q}_{\text{useful}}$: Useful heat recovery/kW

Table 8 Resulting optimization parameters

Factors	Optimization for CF-HRV		Optimization for C/CF-HRV		Optimization for R-HRV		Optimization for SR/H-HRV	
	A	*B*	*A*	*B*	*A*	*B*	*A*	*B*
K_1	132.02	242.03	176.03	322.71	154.02	282.37	538.41	363.97
K_2	237.63	242.03	316.85	322.71	277.24	282.37	887.26	800.92
K_3	356.45	242.03	475.27	322.71	415.86	282.37	1396.35	1657.13
k_1	44.01	80.68	58.68	107.57	51.34	94.12	179.47	121.32
k_2	79.21	80.68	105.62	107.57	92.41	94.12	295.75	266.97
k_3	118.82	80.68	158.42	107.57	138.62	94.12	465.45	552.38
Range	74.81	0	99.75	0	87.28	0	285.98	431.05
RD/%	100	0	100	0	100	0	39.88	60.12
Order	*A* > B		$A > B$		$A > B$		$B > A$	
OLC	*A*3		*A*3		*A*3		*A*3,*B*3	

OLC: Optimal level combination, RD: Relative domination

Conclusions

Currently, the amount of fresh air used in HVAC systems has increased with the Covid-19 pandemic. Therefore, heat recovery applications have become even more important. The analyses showed that generally sorption rotor hybrid sensible and latent heat exchanger recovery device provides the highest energy saving. While respectively, hexagonal plate combined counter and cross-flow heat exchanger, rotary wheel sensible heat exchanger and rectangular plate cross-flow heat exchanger heat recovery ventilation devices rank below. However, it has been clearly seen that regardless of the outdoor temperature and relative humidity values, more energy savings can be made by using latent heat recovery HRV devices. Consequently, the ratio of cooling loads that will occur due to fresh air in the total cooling load of the building will decrease. Therefore, it is extremely important to determine the outdoor temperature and relative humidity values to understand where significant differences will occur in total heat recovery after latent heat recovery. In CF-HRV, C/CF-HRV and R-HRV devices with only sensible heat transfer, useful heat recovery is provided between 44.01 and 58.68 kW in case of low outdoor temperature, depending on the device, while this value increases 79.21—105.62 kW at medium outdoor temperature values depending on the device. In high outdoor temperatures, the useful heat recovery is 118.82—158.42 kW depending on the device, and these values are completely independent of the outdoor relative humidity since there is no latent heat transfer in the devices. In the SR/H-HRV device, which has latent heat transfer as well as sensible heat transfer, while the amount of useful heat recovery varies between 51.24 and 352.16 kW depending on the outdoor relative humidity at low outdoor temperatures, this amount increases to 100.79—531.72 kW again depends on the outdoor relative humidity at medium outdoor temperature values. In this device with latent heat transfer, at high outdoor temperatures, while the useful heat recovery is 211.84 kW at low outdoor humidity, it increases to 773.25 kW at high outdoor relative humidity. Although these results show that the SR/H-HRV device is advantageous in high outdoor temperature and relative humidity and the use of C/CF-HRV device is appropriate in other conditions, especially in high outdoor temperature and low/medium outdoor relative humidity, the data have been also examined by the orthogonal optimization method. As a result of the optimization, the study found that the use of SR/H-HRV devices that can provide heat recovery from latent heat in climates with high temperatures exceeding 35 °C and high relative humidity values exceeding 60%, regardless of climate types, is important and advantageous. When the devices capable of sensible heat recovery were evaluated, it was observed that the highest energy efficiency could be achieved with C/CF-HRV. This study thus concluded that the use of C/CF-HRV devices in high temperature and dry climates is suitable. To provide a future perspective on the subject, it may be recommended to repeat similar analyses for heat recovery devices in which materials such as copper with high thermal conductivity other than aluminium are used. In addition, conducting an experimental study on the subject and the analysis of the results to be obtained from this experimental study will be extremely important in terms of contributing to the literature.

Author contribution AC involved in investigation, methodology and writing—reviewing and editing. HY involved in data collecting, data analysis and conceptualization. IA involved in investigation, methodology, revising and writing—reviewing and editing.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

1. Zheng W, Hu J, Wang Z, Li J, Fu Z, Li H, Yan J. COVID-19 impact on operation and energy consumption of heating, ventilation and air-conditioning (HVAC) systems. Adv Appl Energy. 2021;3:100040. https://doi.org/10.1016/j.adapen.2021.100040.
2. HSK. Heat recovery (in Turkish). 2010. https://www.iskav.org.tr/bilgi-bankasi/isi-geri-kazanim-hsk-1.pdf. Accessed 20 March 2022.
3. Venco. High efficiency heat recovery units. 2018. https://venco.com.tr/VHR-CF-isi-geri-kazanim-cihazlari-2020. Accessed 20 March 2022.
4. Onat A, Kabil E. Virüslerin özellikleri ve pandemi süreçlerinde (COVID-19) iklimlendirme sistem parametrelerinin değerlendirilmesi (in Turkish). Termodinamik. 2020;340:58–68.
5. Herath H, Wickramasinghe M, Polgolla A, Jayasena A, Ranasinghe R, Wijewardane M. Applicability of rotary thermal wheels to hot and humid climates. In: The 6th international conference on power and energy systems engineering. Okinawa, Japan; 2020. pp. 539–544.
6. Min Y, Chen Y, Shi W, Yang H. Applicability of indirect evaporative cooler for energy recovery in hot and humid areas: comparison with heat recovery wheel. Appl Energy. 2021;287:116607. https://doi.org/10.1016/j.apenergy.2021.116607.
7. Pourhoseinian M, Asasian-Kolur N, Sharifian S. CFD investigation of heat and moisture recovery from air with membrane heat exchanger. Appl Therm Eng. 2021;191:116911. https://doi.org/10.1016/j.applthermaleng.2021.116911.
8. Gendebien S, Bertagnolio S, Lemort V. Investigation on a ventilation heat recovery exchanger: modeling and experimental validation in dry and partially wet conditions. Energy Build. 2013;62:176–89. https://doi.org/10.1016/j.enbuild.2013.02.025.
9. Ribé O, Ruiz R, Quera M, Cadafalch J. Analysis of the sensible and total ventilation energy recovery potential indifferent climate conditions, application to the spanish case. Appl Therm Eng.

2018;149:854–61. https://doi.org/10.1016/j.applthermaleng.2018.12.076.

10. Ghalandari M, Shahrestani MI, Maleki A, Shadloo MS, El Haj AM. Applications of intelligent methods in various types of heat exchangers: a review. J Therm Anal Calorim. 2021;145:1837–48. https://doi.org/10.1007/s10973-020-10425-3.
11. Koç A, Yağlı H, Bilgic HH, Koc Y, Özdemir A. Performance analysis of a novel organic fluid filled regenerative heat exchanger used heat recovery ventilation (OHeX-HRV) system. Sustain Energy Technol Assess. 2020;41:100787. https://doi.org/10.1016/j.seta.2020.100787.
12. Carrier C. Hourly analysis program (HAP). International edition version 5.11. 2018.
13. Klein SA. Engineering equation solver (EES). Academic commercial V10.40. F-Chart software. 2008. www.fChart.com.
14. Turkish State Meteorological Service. Climate classifications (in Turkish). 2021. https://mgm.gov.tr/iklim/iklim-siniflandirmalari.aspx. Accessed 01 January 2021.
15. Wu H. Application of orthogonal experimental design for the automatic software testing. In: Proceedings of the 2nd international conference on computer science and electronics engineering. Hangzhou, China; 2013. pp. 2298–2303.
16. Atmaca İ, Şenol A, Çağlar A. Performance testing and optimization of a split-type air conditioner with evaporatively-cooled. Eng Sci Technol. 2022;32:101064. https://doi.org/10.1016/j.jestch.2021.09.010.