Design and Manufacture of a High Efficiency Plate Heat Exchanger

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Paper History:

Received: 5th May. 2020

Revised: 23rd June 2020

Accepted: 25th Sep. 2020

Abstract

Heat recovery (HR) is often mentioned as a device that operates between two heat sources in different temperatures. In this device, the heat is transferred from one side to another in order to have a heat balance. Therefore, the device is working on preheating/precooling supplying air to the space by waste heat. The main aims of this work are to design and manufacture of a plate heat exchanger (PHE) with a high efficiency and low cost, calculate the cost of the PHE unit and compare it with the other HEs model from different companies. The PHE was manufactured at the University of Technology from aluminum plates in a simple and inexpensive way. The performance of the HE was evaluated in different external conditions and different air flow rates. The maximum effectiveness value of the HE is 50.76% at a condition of hot air side (DBT= 41°C, RH=21%, W=10.2 g/kg, and air flow rate = 0.476 m^3/s) and a condition of cold air side (DBT= 22.2°C, RH=92.02 %, W=15.6 g/kg, and air flow rate = 0.476 m^3/s).

Keywords: Plate Heat Exchanger, Heat Recovery, Preheating, Precooling

تصميم وتصنيع مبادل حراري عالي الكفاءة

براء بشير محمد ، عمار سعدون عبد الزهرة ، احمدعبد محمدصالح

الخلاصة:

غالبًا ما يُشار إلى استرداد الحرارة على أنه جهاز يعمل بين مصدرين للهواء عند درجة حرارة مختلفة ينقل الطاقة من جانب إلى آخر. وبعبارة أخرى ، فإنه يقوم على تسخين الهواء الداخل إلى الداخل من خلال الحرارة العادمة المعاد تدويرها. الأهداف الرئيسية لهذا العمل هي تصميم وتصنيع مبادل حراري لوحي (استرداد الحرارة) بكفاءة عالية وتكلفة منخفضة ، وحساب تكلفة وحدة استرداد الحرارة ومقارنتها بنماذج مبادلات حرارية أخرى من شركات مختلفة. تم تصنيع المبادل الحراري لوحي في الجامعة التكنولوجية من صفائح الألمنيوم بطريقة بسيطة وغير مكلفة. تم تقييم أداء المبادل الحراري في ظروف خارجية مختلفة ومعدلات تدفق هواء مختلفة. قيمة الفعالية القصوى للمبادل الحراري هي 50.76٪ في حالة ظروف الهواء الساخن (DBT =41 درجة مئوية ، RH =21 % ، المحتوى الرطوبي = 10.2 جم / كجم ، معدل تدفق الهواء = 0.476 مترمكعب/ ثانية) وحالة ظروف الهواء البارد (DBT = 22.2 درجة مئوية ، RH = 92.02% ، المحتوى الرطوبي = 15.6 جم / كجم ، معدل تدفق الهواء = 0.476 متر مكعب / ثانية).

English symbols

Symbol	Description	Unit
$A_{surface}$	Surface area of HE	m²
A_{Flow_hot}	Area of hot flow rate section	m²
A_{Flow_cold}	Area of cold flow rate section	m²
V_{air}	Velocity of air	m/s
$\dot{V}_{air}$	Air flow rate	m^3/s
L_c	Characteristic length	m
k_{air}	Thermal conductivity of air	W/m. K
H	Height of HR	mm
W	Width of HR	mm
L	Depth of HR	mm

X	Center to center distance of plates	mm
NO_{Pass}	Number of pass of HR	mm
NO_{hot}	Number of pass of hot air	mm
NO_{cold}	Number of pass of cold air	mm
D_{hyd_hot}	Hydraulic diameter of hot section	mm
D_{hyd_cold}	Hydraulic diameter of cold section	mm
V_{hot}	Hot air velocity	m/s
V_{cold}	Cold air velocity	m/s
Re_{cold}	Cold air Reynolds number	-

NJES is an **open access Journal** with **ISSN 2521-9154** and **eISSN 2521-9162**

Re_{hot}	Hot air Reynolds number	-
Nu_{hot}	Hot air Nusselt number of	-
Nu_{cold}	Cold air Nusselt number	-
h_{hot}	Hot side heat transfer coefficient	W/m² .K
h_{cold}	Cold side heat transfer coefficient	W/m² .K
U_{tot}	Total U-value	-
R_{tot}	Total resistance	-
C_{hot}	Capacitance rate of hot side	kJ/kg. °C
C_{cold}	Capacitance rate of cold side	kJ/kg. °C
CR	Capacitance ratio	-
ϵ	Effectiveness of HE	-
Q	Sensible heat transfers	kW
T_{in_hot}	Hot air inlet temperature of	°C
T_{in_cold}	Cold air inlet temperature	°C
T_{out_hot}	Hot air outlet temperature	°C
T_{out_cold}	Cold air outlet temperature	°C
K_{plate}	Conductivity of Aluminum	W/m. K

1. Introduction

One of the most important topics in the world today is the energy conservation. The researchers have tested many ways to reduce the energy consumption. The studies showed that the heating and ventilation air conditioning (HVAC) systems are one of the main parts that should be improved due to the high energy consumption of this devises.

In the developed countries, the HVAC systems consume around a third of the total energy consumption of the whole world [1].

The improvement of HVAC systems could decrease the energy consumption by 30-60% [2]. One method to reduce the energy consumption is using HR unit. The disadvantage of HR is the increasing of the initial cost of the system. The principle of HR unit is to extract the heat from the return air in order to cool or heat the supplied air. There are two types of HR mechanisms (PHE and a rotating wheel). PHEs are the most common HR units. A cross air flows is used for supply and return air. In this devise, the supply and return air are not mixed. Therefore, only sensible heat is transferred. A material with a high thermal conductivity is preferred for producing flat plates, e.g., aluminum, etc.

Regarding the effectiveness of heat recovery, the increase in the temperature difference between the inlet of system and the return from space improves the effectiveness. Also, the flow rate has a great impact

From the above, it can be concluded that the heat recovery is useful in improving the heating and cooling systems and thus reducing the electrical energy consumption. Also, it is useful in countries having very hot climates and thus it can be used and applied in the airspace of Iraq.

Many papers have been published about cross-flow PHE to cooling air. Therefore, an extensive survey, comparison and evaluation of published papers are required.

M. K. Drost 1993 [3] evaluated the performances of air to air HE (AAHX) system in a large scale of residential buildings. Data collected were used in this study. The aims of the study were the analysis and performance study of AAHX. It was found that the thermal efficiency of the device was 52% with seven hours per day working time.

A. Vali et al. 2009 [4] presented the results of two types of HX. The combination between counter and cross flow was tested. The authors used finite difference method to solve the equations. The results depicted that the effectiveness of HE was between the effectiveness of systems with either two cross-flow exchangers or two counter-flow exchangers.

K. Anastasiia 2012 [2] calculated the annual efficiency in addition to the temperature ratios of the HR unit. The results were compared with the manufacturer's data. The influence of using the HR unit on the energy saving was estimated with the goal of comparing the cost of the system with and without HR unit. The type of HR unit in the study was a rotating wheel. The results revealed that the annual efficiency of HR unit was (77.3%). The author was not able to compare the results with manufacturer's data due to the mismatch between the conditions of both tested. European standards do not give specific details about the annual efficiency and the temperature efficiency of the HR unit. Therefore, it was hard to compare with the standard.

G. E. Vlad et al. 2014 [5] analyzed a HR unit, which was a part of the HVAC system. Mechanical ventilation HR system of an experimental house was built inside the campus of Politehnica University of Bucharest. This work presented an algorithm used to determine the thermal efficiency of the air to air PHE. The most important component of the mechanical ventilation heat recovery unit (MVHR) and the analysis of the experimental data were presented as well. The comparison made between the theoretical and measured efficiency indicated that the values of the efficiency calculated by number of transfer unite (NTU) method are close to the temperature efficiency. The study showed that both the theoretical and measured efficiency depend on the flow rates. Both decreased when the air flow is increased.

S. Riffat et al. 2019 [6] introduced four types of HR systems. The effect of using HR system on the energy saving was investigated. It was concluded that these devices are a promising approach to decrease the energy consumption in the buildings and support the comfort requirements. However, the economic analysis evinced that there is no high economic benefit of these systems. The HR system could combine successfully with the solar energy systems due to its easy manufacturing and maintenance along with the ability of reducing the contamination.

F. Babota 2014 [7] concluded that the extra energy for the HR unit is equal to the energy saved by the device. The economic viability is the basic of using HR systems in the buildings. In case of the cost of energy saving is greater than the operation cost of the device, the HR device will be viable.

B. Ghida 2019 [8] presented a new methodology to reduce the energy consumption of the buildings without decreasing the thermal comfort in the space. The study showed that the humans spent most of the time inside the buildings. Therefore, using warm fresh air in winter or cold fresh air in summer has become a priority. The HR ventilation system can improve the efficient buildings along with increased the filtration and elimination of micro pollutants. The HR system could improve the indoor air quality, which leads to generate more comfort and reduce the health problems.

The object of this work is to manufacture of a Plate Heat Exchanger with local and low expansive material and investigate the main performance parameters to reach the ultimate efficiency (Heat Exchanger locally HE with highly efficient with cost close to international companies).

2. Design Model of HR

The design and layout of the PHE made from aluminum sheets are shown in the figures (1) and (2).

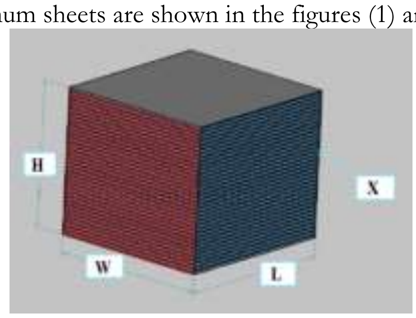


Figure (1): PHE design

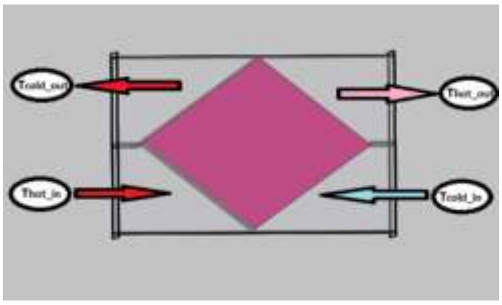


Figure (2): PHE layout

Below is the procedure of designs parameter.

A. The heat transfer area of PHE:

$A_{surface}$ =2*W*L *NO_{Plate} … (1)

NO_{Plate}= NO_{Pass} -1 … (2)

A_{Flow_hot} =L*X* NO_{hot} … (3)

$NO_{hot}=\frac{NO_{Pass}}{2}$ … (4)

A_{Flow_cold} =W*X* NO_{cold} … (5)

Where: NO_{cold}=NO_{hot}

B. The hydraulic diameter:

D_{hyd_hot} $=2*\frac{(L*H)}{(L+H)}$ … (6)

D_{hyd_cold} $=2*\frac{(W*H)}{(W+H)}$ … (7)

C. The Reynolds number:

$Re_{hot} = \frac{V_{hot}* D_{hyd\_hot} *\rho_{air}}{\mu_{air}}$ … (8)

Where:

ρ_{air} = Air density (kg/m³)

μ_{air} = Air viscosity ($\mathbf{kg/m.s}$)

D_{hyd_hot} = From equation (6)

$V_{hot} = \frac{\dot{V}_{hot}}{A_{Flow\_hot}}$ … (9)

$\dot{V}_{hot}$: $\mathbf{0.476\ m^3/s}$ (depends on the load)

$Re_{cold} = \frac{V_{cold}* D_{hyd\_cold} *\rho_{air}}{\mu_{air}}$ … (10)

$V_{cold} = \frac{\dot{V}_{cold}}{A_{Flow\_cold}}$ … (11)

$\dot{V}_{cold}$: The return air from the zone

D. The Nusselt number:

Nu_{hot} =0.023* ${p_r}_{air}^{\ 0.3}$ * $Re_{air}^{\ 0.8}$ … (12) **[9]**

${p_r}_{air}$= Prandtl number of air

Nu_{cold} =0.023* ${p_r}_{air}^{\ 0.4}$ * $Re_{air}^{\ 0.8}$ … (13) **[9]**

E. The coefficient of heat transfer:

Heat transfer coefficient of hot side:

$h_{hot} = \frac{Nu_{hot} * K_{air}}{D_{hyd\_hot}}$ … (14)

K_{air} = Thermal conductivity of air

Heat transfer coefficient of cold side:

$h_{cold} = \frac{Nu_{cold} * K_{air}}{D_{hyd\_cold}}$ … (15)

F. The U-value:

$U_{tot} = \frac{1}{R_{tot}}$ … (16)

Where:

$R_{tot} = \frac{1}{h_{hot}} + \frac{t}{K_{plate}} + \frac{1}{h_{cold}}$ … (17)

K_{plate}=Conductivity of Aluminum

t = thickness of plates.

G. The capacitance rate:

Hot side:

C_{hot} = $\dot{m}_{hot}$* ${C_p}_{hot}$ … (18)

${C_p}_{hot}$= Specific Heat of hot air

$\dot{m}_{hot} = \dot{V}_{hot}*\rho_{hot}$ … (19)

Cold side:

C_{cold} = $\dot{m}_{cold}$* ${C_p}_{cold}$ … (20)

${C_p}_{cold}$= Specific Heat of cold air

$\dot{m}_{cold} = \dot{V}_{cold}*\rho_{cold}$ … (21)

Where, the, C_{min}=Minimum (C_{hot}, C_{cold}) and C_{max}=Maximum (C_{hot},C_{cold}).

CR=$\frac{C_{min}}{C_{max}}$ … (22)

H. The NTU and epsilon:

NTU= $\frac{U_{tot} * A_{surface}}{C_{min}}$ … (23)

$\mathcal{E} = \frac{1-\exp(-NTU*(1-CR))}{1-CR*\exp(-NTU*(1-CR))}$ … (24) **[10]**

I. The heat energy:

Q= Ɛ * C_{min}*(T_{in_hot} -T_{in_cold}) … (25)

J. The outlet temperature:

T_{out_hot}= T_{in_hot}-$\frac{Q}{C_{hot}}$ … (26)

T_{out_cold}= T_{in_cold} + $\frac{Q}{C_{cold}}$ … (27)

The dimensions and parameters of PHE are given in the table (1).

Table (1): The dimensions and parameters of HR

H	440 mm	Height of HR.
W	550 mm	Width of HR
L	600 mm	Depth of HR.
X	4 mm	Center to center distance of plates

Performance Parameters

Calculate the effectiveness

$$\varepsilon = \frac{T_{hot\_in} - T_{hot\_out}}{T_{hot\_in} - T_{cold\_in}} \quad \ldots (28)$$

Where:

T_{hot_in} = Inlet hot air temperature

T_{hot_out} = Outlet hot air temperature

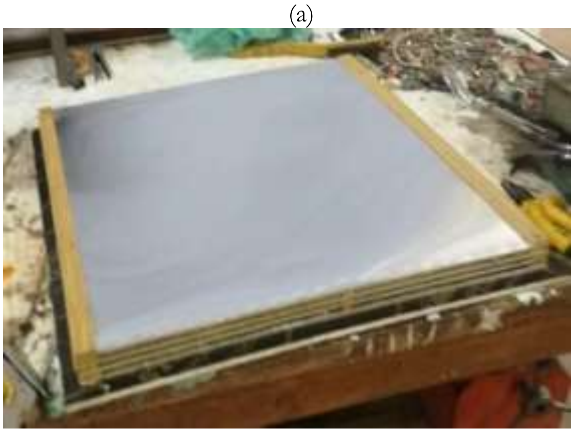
T_{cold_in} = Inlet cold air temperature

T_{out_cold} = Outlet cold air temperature

3. Experimental setup

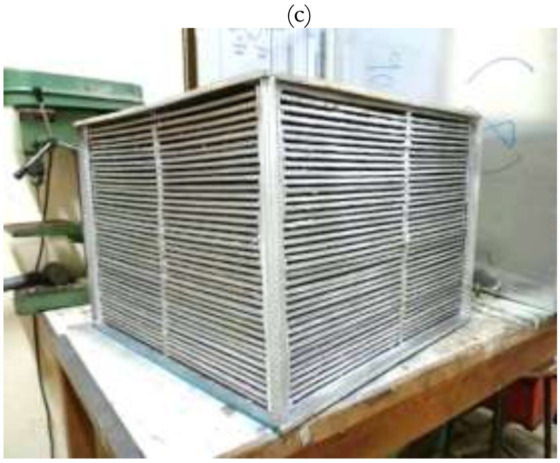
PHE is consisting of a group of aluminum sheets. The sensible heat is transferred between the cold air (return air from the zone) and the hot air (supplying air to cooling unit). The distance between a plate and another is (4 mm). The dimension of plates is (60 cm*60 cm), the thickness of every plate is (0.4 mm), and the number of plats is 79. These plates are placed with each other by using strips of wood. Strips of wood have been placed on the plate aspects. The width of the wood strip is 2.5 cm, and the height is 4 mm. Figure 3 (a, b, c, d, and e) shows the steps of manufacturing the HE.

(a)

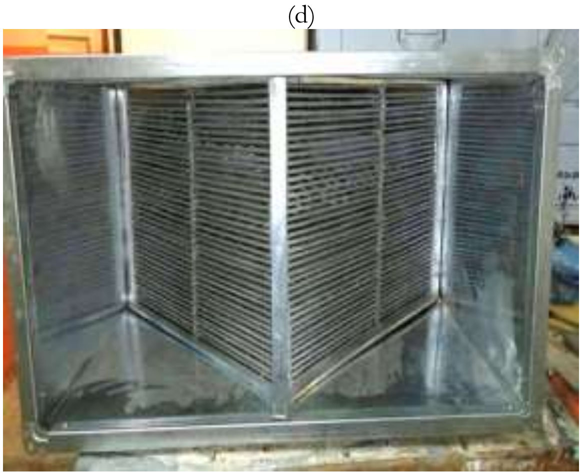


(b)

(c)



(d)



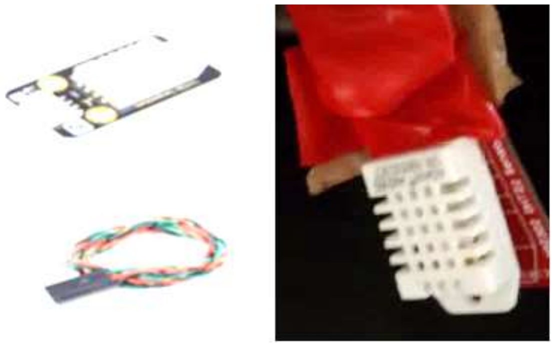
(e)

Figure (3): Steps of manufacturing PHE.

4. Experimental Instruments

Temperature and Humidity measurement:

The temperature and humidity meter DHT22 (4 sensors) have many advantages, like small in size, low energy consumption, high accuracy and transferability of up to 20 meters with specifications consisting of four pins to enable easy installation very convenient and small size (22*28*5 mm), see Figure (4).



(a) (b)

Figure (4): DHT22 Temperature and humidity

Air Velocity measurement:

The air velocity was measured by using the hot wire Anemometer, as evinced in Figure (5). This anemometer is the best choice without compromising precision or accuracy. It works excellent for conducting the commissioning work and troubleshooting of HVAC systems. Its features and benefits are clear; large, easy to read the display, precise air velocity measurement, calibration certificate included velocity range (0.2 to 20 m/s), accuracy 1 & 2 [±5% of reading or (±0.025 m/s)] and resolution (0.01 m/s), the Probe length is 101.6 cm.

Figure (5): Air velocity hot wire Anemometer (model yk-2005AH).

The characteristics of the measurement systems are shown in Table (2).

Table (2): Characteristics of the measurement system.

Sensor – model	function	range	resolution	accuracy
DHT22	Temperature	-40 ~ 80 ºC	0.1 ºC	<±0.5 ºC
DHT22	Humidity	0-100% RH	0.1% RH	±2% RH
YK-2005AH	Air velocity	0.2 to 20 m/s	0.01 m/s	±0.025 m/s
YK-2005AH	Temperature	-18 to 93 ºC	0.1ºC	±0.3 ºC

4. Results and Discussions

A. The best air flow rate to remove sensible heat from air flow:

Figure (4) depicts the relationship between the temperature changes during the HE with the time at different inlet hot and cold temperatures. Figure (5) reveals the relationship between the sensible heat transfer during the HE with the time at various flow rates (0.48 m^3/s, 0.61 m^3/s and 0.73 m^3/s). It turns out that the low flow rate is best to decrease the air temperature. Increasing flow rate leads to reduce the temperature changes during the HE, due to increase the velocity of air. Furthermore, increasing the flow rate leads to an increase in the sensible heat transfers. But the lower flow rate was chosen due to looking for the lowest possible temperature in this study. In addition, the theoretical designed was at a flow rate of 0.48 m^3/s when designing the HE.

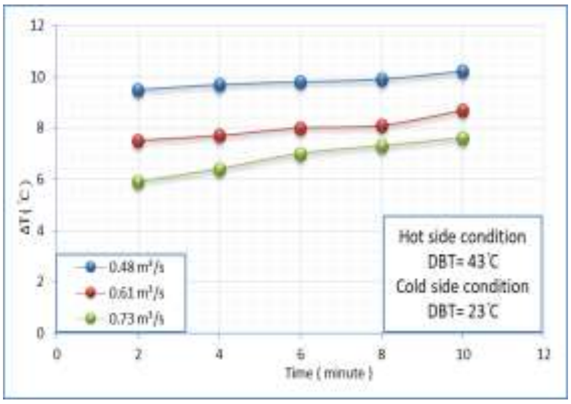


Figure (4): Relationship between temperature changes during the HE with the time at various flow rates.

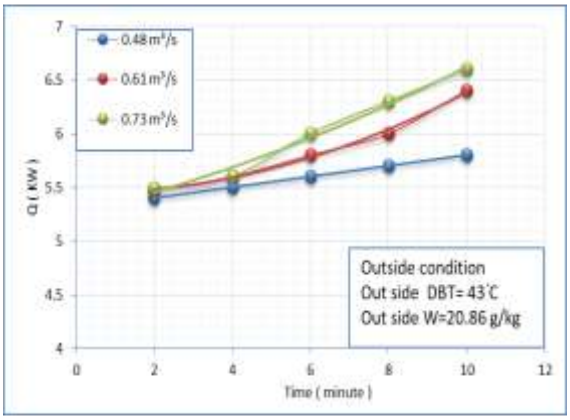


Figure (5): Relationship between the sensible heat transfers during the HE with the time at various flow rates.

B. The effectiveness of HE:

The effectiveness of the HE depends significantly on the hot and cold side temperature. Where, at low temperature, the effectiveness is high. In case of the high temperature of cold side, the effectiveness is low. Figure (6) illustrates the effectiveness of HE with various temperatures of the hot and cold side.

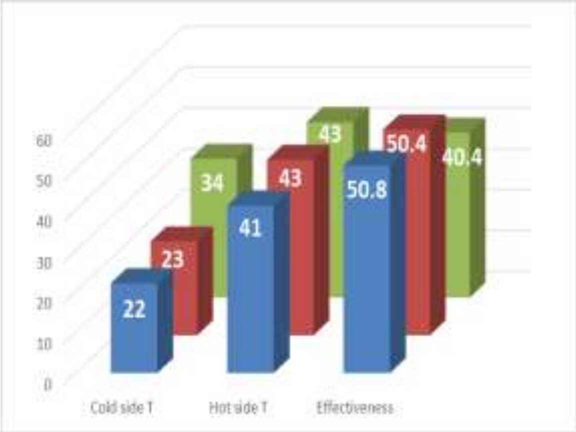


Figure (6): The effectiveness of HE with various hot and cold temperatures.

In comparison with previous research, it was seen that the HE effectiveness is very good [1, 5, 6]

C. Comparison between the Experimental and Analytical Effectiveness:

Table (3) shows some of the experimental and analytical results that are used as examples for comparison.

Table (3): Comparison between the experimental and numerical effectiveness of heat exchanger.

Cold side	Hot side	Air flow rate	Theoretical effectivenes s value	Experimental effectiveness value
22 °C	41 °C	0.48 m^3/s	44 %	50.8 %
23 °C	43 °C	0.48 m^3/s	43 %	50.4 %
34 °C	43 °C	0.48 m^3/s	43 %	40.4 %

D. Manufacturing cost and comparing it to buying:

Material cost

- Aluminum sheets = 125 $
- Wood Strips and other accessories = 33$

The total material cost is 158 $.

The cost of most companies' data of HE is shown in Table (4)

Table (4): The cost of most companies' data of HE

The company	Product code	Dimensions (mm)	Cost	material
yushun	YS-BC300013-121	(L*W*H)	200-300	aluminum
YUDA	B10514	400*400*600	1080-1800	aluminum
RECUTECH	REP+17-200-H-X-30	customized	107$	aluminum
Lifebreath	RNC5-ES	397*200*172	1025$	Aluminum
Fantech	AEV 1000	660*508*406	355$	steel
Panasonic	FV-10VE1	564*401*345	899$	aluminum
HOLTOP	XHBQ-D6.5DMTHA	995*307*723	717$	aluminum
Agcen	XF150-M52	customized	325$	aluminum

It can be concluded from the information above that the locally manufactured HE can be highly efficient and at a cost close to international companies.

5. Conclusion:

In this paper, the HR unit with a dimension of (600*550*440 mm) was manufactured and tested at the University of Technology - Iraq. The experimental results manifested that the maximum effectiveness and the temperature difference of the HE were 50.8% and 11°C, respectively. Thus, the authors have concluded that it is possible to manufacture locally HE at a cost comparable to that of international companies. Furthermore, it is clear that the effectiveness of this HE is better than the models in previous researches.

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