JREE: Vol. 3, No. 3, (Summer 2016) 44-52

Journal of Renewable Energy and Environment

Journal Homepage: www.jree.ir

Research Article

Passive Energy Air-to-Water Heat Pipe Based Heat Exchanger and its Potential of Air Pre-cooling in Air Conditioning Systems for Iran Climate

Mohammad Ahmadzadehtalatapeh

Department of Marine & Mechanical Engineering, Chabahar Maritime University, Chabahar, Iran

P A P E R I N F O

Paper history:
Received 12 March 2016
Accepted in revised form 13 December 2016

Keywords:
Effectiveness-NTU
Heat Pipe based Heat Exchanger (HPHEX)
Air Pre-Cooling
Thermal Performance

A B S T R A C T

Air pre-cooling equipment is normally being employed in air-conditioning systems for pre-cooling the ambient outdoor air to enhance the air-conditioning systems performance. In this study, the potential of a passive air-to-water Heat Pipe based Heat Exchanger (HPHEX) for air pre-cooling purpose in air-conditioning systems for the high cooling load demanding regions of Iran was investigated. To this end, effectiveness-NTU approach was employed to determine the thermal performance of the heat exchanger. Air-to-water HPHEX with different numbers of rows namely two, four, and six was studied to determine the heat transfer characteristics of the heat exchanger. The thermal performance of the air-to-water HPHEX was investigated under different operating conditions in terms of evaporator inlet air and condenser inlet water coil face velocities and temperatures. After determining the thermal performance of the air-to-water HPHEX, the air pre-cooling capability of the air-to-water HPHEX was explored hour-by-hour for the required months of the year by using TRNSYS software. Based on the simulation results, the air-to-water HPHEX shows an acceptable thermal performance under the operating conditions. In addition, studies showed that the air-to-water HPHEX has a significant capability for air pre-cooling, which makes it applicable to be implemented in the air-conditioning systems operating in south of Iran.

1. INTRODUCTION

In order to improve the energy performance of the air-conditioning systems, pre-cooling heat exchangers such as direct evaporative cooling units, indirect evaporative cooling units, air-to-air Heat Pipe Based Heat Exchangers (HPHEXs), and energy recovery wheels are placed in the ducting systems of the air-conditioning systems. By the application of these pre-cooling units, the ambient outdoor air temperature reduces before entering the air handling unit of the system and therefore, the cooling capacity of the system reduces.

HPHEXs offer significant advantages over the conventional heat exchangers. The advantages can be summarized as: compactness, reliability, no contamination, and minimum maintenance requirements. Moreover, simplicity of design and manufacturing, small temperature drops, wide temperature application range and the ability to control and transport high heat rates at various temperature levels are the unique characteristics of the HPHEXs. A considerable point regarding the HPHEXs performance is that the HPHEX do not need any external power to operate and works as a passive energy equipment. This characteristic makes the HPHEXs very interesting for energy conservation purposes.

HPHEXs are consisted of heat pipe tubes filled with a refrigerant as the working fluid. The heat is absorbed by the refrigerant at the evaporator section and evaporates and releases its latent heat of vaporization in the condenser section. The condensed liquid returns to the evaporator with the aid of the capillary action in the horizontal configuration and gravity in thermosyphons. Fig. 1 illustrates a schematic diagram of a heat pipe structure.

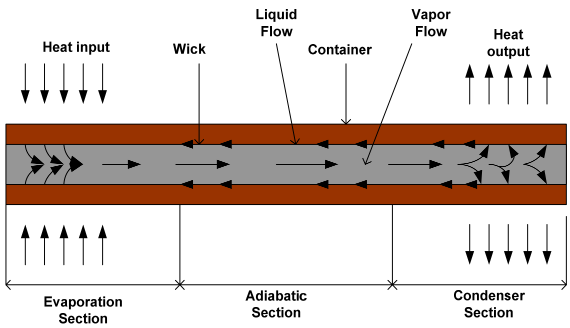


Figure 1. A schematic diagram of a heat pipe structure

*Corresponding Author's Email: m_ahmadzadeh56@yahoo.com (M. Ahmadzadehtalatapeh)

HPHEXs in the air-to-air configuration have been utilized in air-conditioning systems to recover energy between the exhaust air and supply stream [1-5]. Application of an air-to-air configuration HPHEX in a hospital ward was reported in Ref. [6]. The study showed that by the application of HPHEXs in the system, a considerable amount of energy could be saved. Moreover, the heat pipe technology in the air-to-water configuration was used in the solar thermal collectors to improve the efficiency [7-10].

For instance, Azad [7] studied the performance of a prototype solar collector interconnected with heat pipes. In this configuration, the evaporator section of the heat pipes gets the heat from the air and the condenser section repels the heat to the flowing water.

Literature survey showed that research studies on the thermal performance of the HPHEXs have been focused on the air-to-air configuration [11-14].

This might be because of the fact that the air-to-air configuration HPHEXs are normally applicable for wide range of applications such as electronic equipment and air-conditioning systems. Therefore, HPHEXs in air-to-water configuration have not been considered by the researchers and the research studies on this configuration is limited and mainly for industry purposes [15,16].

Literature survey revealed that studies on the application of air-to-water configuration for possible air pre-cooling and energy recovery in buildings air-conditioning systems are limited and actually none to the best knowledge of the author.

Therefore, this study was conducted and the major aim was to investigate the performance of an air-to-water configuration HPHEX theoretically to understand its capability as air pre-cooling in cases, which water and air could be used as two heat transferring streams. The design can be considered for air pre-cooling and energy recovery purposes in air-conditioning systems.

2. RESEARCH METHODOLOGY

The major purpose of the present research is to determine the capability of an air-to-water HPHEX for air pre-cooling and energy recovery in air-condoning systems operating in high cooling demanding regions of Iran. For this purpose, the air-to-water HPHEX thermal performance is evaluated in Section 4 mathematically and the results are presented in Subsection 5.1.

The air pre-cooling potential of the studied air-to-water HPHEX for the cooling load demanding months of the year would be estimated for Bandar Abbas and Bushehr, two high cooling load demanding cities located in south of Iran. TRNSYS software is employed for the energy estimations. The energy discussion will be presented in Subsection 5.2.

3. SYSTEM DESCRIPTION

Fig. 2 shows the schematic diagram of the considered air-to-water HPHEX in this research. As illustrated in Fig. 2 the heat exchanger is consisted of individual heat pipe tubes with 11 tubes in every row and two, four, and six rows in the flow direction. The evaporator and condenser sections are separated by an adiabatic length of 180 mm. The tubes with 13.4 and 12.7 mm external and internal diameter, respectively, are placed in staggered configuration. The heat pipe tubes are externally finned in the air side (evaporator section) and bare tubes are located in the condenser section. The centre-to-centre tube spacing is 31.75 and 27.5 mm for the transverse and longitudinal states, respectively, and aluminum corrugated wavy plates with 12 fin/inch and fin thickness of 0.15mm was assumed for the pipes. Wick structure is considered to be consisted of three wire mesh layers with 100 mesh/inch and saturated with R-134a as the working fluid. The pressure level (vacuum level) for charging the working fluid could be established at a level as low as 10^{-3} mbar. Physical dimensions of the studied air-to-water HPHEX are shown in Fig. 2.

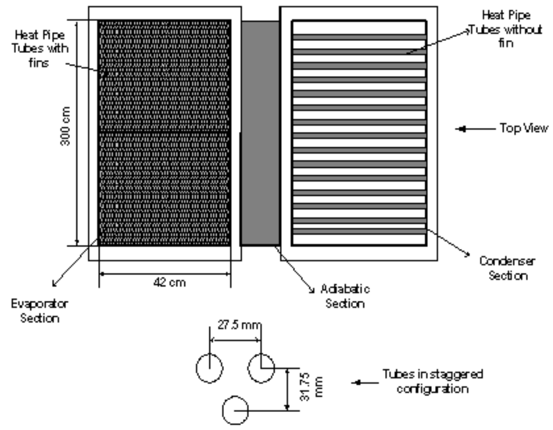


Figure 2. Schematic diagram of the air-to-water HPHEXs

4. AIR-TO-WATER HPHEX SIMULATION USING EFFECTIVENESS-NTU METHOD

The thermal performance and heat transfer characteristics of the air-to-water HPHEX were simulated using the effectiveness-NTU approach [17]. In the evaporator and condenser sections of the heat pipe tubes, the warm air and water are in cross flow with the vapor inside the heat pipe tubes. Moreover, the vapor inside the tubes is almost at the constant temperature. Therefore by definition its specific heat, c_p, and capacity rate, C_v, become equal to infinity and as a result, $C_e / C_v = C_c / C_v = 0$ yields.

Considering the above mentioned points, the effectiveness-NTU approach recommends the following equations for a HPHEX with n rows of heat pipes in the flow direction [12,13]:

$$\varepsilon_{en} = \frac{\left(\dfrac{1-\dfrac{C_e}{C_v}\varepsilon_{e1}}{1-\varepsilon_{e1}}\right)^n - 1}{\left(\dfrac{1-\dfrac{C_e}{C_v}\varepsilon_{e1}}{1-\varepsilon_{e1}}\right)^n - \dfrac{C_e}{C_v}} \quad (1)$$

For the condenser section:

$$\varepsilon_{cn} = \frac{\left(\dfrac{1-\dfrac{C_c}{C_v}\varepsilon_{c1}}{1-\varepsilon_{c1}}\right)^n - 1}{\left(\dfrac{1-\dfrac{C_e}{C_v}\varepsilon_{c1}}{1-\varepsilon_{c1}}\right)^n - \dfrac{C_c}{C_v}} \quad (2)$$

And since and , the above equations will be written in the form of [12,13]:

$$\varepsilon_{en} = 1-(1-\varepsilon_{e1})^n \quad (3)$$

and,

$$\varepsilon_{cn} = 1-(1-\varepsilon_{c1})^n \quad (4)$$

Effectiveness of a single row air-to-water HPHEX for the evaporator section is as:

$$\varepsilon_{e1} = 1-\exp(-NTU)_e \quad (5)$$

Effectiveness of a single row air-to-water HPHEX for the condenser section is given by:

$$\varepsilon_{c1} = 1-\exp(-NTU)_c \quad (6)$$

Then, the overall effectiveness (ε) of the air-to-water HPHEX is written as:

If $C_e > C_c$, $\varepsilon = (\dfrac{1}{\varepsilon_{cn}} + \dfrac{C_c/C_e}{\varepsilon_{en}})^{-1}$ (7)

and

If $C_c > C_e$, $\varepsilon = (\dfrac{1}{\varepsilon_{en}} + \dfrac{C_e/C_c}{\varepsilon_{cn}})^{-1}$ (8)

The NTU value for the evaporator and condenser sections is calculated from the following equations, respectively.

$$(NTU)_e = \frac{(UA)_e}{C_e} \quad (9)$$

$$C_e = (\dot{m}c_p)_e \quad (10)$$

$$(NTU)_c = \frac{(UA)_c}{C_c} \quad (11)$$

$$C_c = (\dot{m}c_p)_c \quad (12)$$

U as the overall heat exchanger heat transfer coefficient can be written as [18]:

$$U = \frac{1}{[R_{e.s,e} + R_{h.p} + R_{e.s,c}]A} \quad (13)$$

$R_{h.p}$ is the thermal resistance of the heat pipe structure and is consisted of wall and wick thermal resistance as the dominant thermal resistances in the heat pipe structure [19,20].

$$R_{h.p} = R_{wall} + R_{wick} \quad (14)$$

The thermal resistance for tubular heat pipe wall and wick structure is given by [18]:

$$R_{wall} = \frac{\ln(D_o/D_i)_{wall}}{2\pi L_{tube} N k_{wall}} \quad (15)$$

$$R_{wick} = \frac{\ln(D_o/D_i)_{wick}}{2\pi L_{wick} N k_{eff}} \quad (16)$$

To determine the external surface thermal resistance of the evaporator section ($R_{e.s,e}$), the mean heat transfer coefficient (α_{fin}) can be estimated using the correlation for the airflow over the finned tube banks as:

The equations describing the hydro power plant behavior are summarized in this section. All variables are in per-unit deviations.

$$Nu = \alpha_{fin} D_{hydraulic} / k_{air} \quad (17)$$

and Nusselt number is given by [21]:

$$Nu = 0.19(\frac{a}{b})^{0.2}(\frac{\zeta}{D_{tube}})^{0.18}(\frac{L_{fin}}{D_{tube}})^{-0.14}\,\mathrm{Re}^{0.65}\,\mathrm{Pr}^{0.33} \quad (18)$$

The heat transfer in the external finned surface is determined using the fin efficiency [22].

$$\eta_{fin} = \tanh(mL_{fin})/(mL_{fin}) \quad (19)$$

and,

$$m = \left(\frac{2\alpha_{fin}(1+\delta_{fin}/L_{fin})}{k_{fin}\delta_{fin}}\right) \quad (20)$$

Then, the thermal resistance between the air flow and the external surface ($R_{e.s}$) can be estimated using the following equation:

$$R_{e.s} = \frac{1}{\eta_{fin}\alpha_{fin}A_{fin}} \tag{21}$$

However, the condenser section is consisted of bare tubes in contact with the water flow. Therefore, to estimate the external surface thermal resistance of the condenser section ($R_{e.s,c}$), the mean heat transfer coefficient can be estimated using the correlation for the liquid flow over the bank of bare tubes as:

$$Nu = \alpha D_{tube} / k_{water} \tag{22}$$

and Nusselt number is given as [23]:

$$Nu = c_1 1.11 \text{ Re}^{c_2} \text{ Pr}^{0.33} \tag{23}$$

3. SIMULATION RESULTS AND DISCUSSION

In the preset study, the effect of five parameters on thermal performance of the air-to-water HPHEX was investigated, as: evaporator coil face velocity, evaporator inlet air temperature, condenser face velocity, condenser inlet water temperature, and number of the rows in the flow direction.
The considered parameters were studied in the range of:

- Evaporator coil face velocity of 1 to 2.4 m/s with the 0.2 increment.
- Evaporator inlet air temperature of 20 to 28 $^{\circ}C$ with the 2 $^{\circ}C$ increment.
- Condenser face velocity of 0.1 to 0.8 m/s.
- Condenser inlet water temperature of 16 to 24 $^{\circ}C$ with the 2 $^{\circ}C$ increment.
- Number of the rows in the flow direction as two, four, and six.

5.1. Performance Study

The influence of evaporator inlet air temperature on the effectiveness of the heat exchanger was shown in Figs. 3 and 4 for two and four rows air-to-water HPHEXs, respectively. The results were presented for different evaporator coil face velocities within the studied temperature range. According to the simulation results, evaporator inlet air temperature has no considerable effect on the thermal performance of the HPHEX and deviation between the maximum and minimum effectiveness values is less than 2% for the evaporator inlet air temperatures from 20 to 28 $^{\circ}C$.
Fig. 5 shows the effect of evaporator coil face velocity for the six rows air-to-water HPHEX as the representative of the rows examined. As illustrated in Fig. 5, the effectiveness decreases from 86 to 69% as the evaporator coil face velocity increases from 1 to 2.4 m/s. The decrease in the effectiveness may be due to the fact that by increasing the face velocity, the duration time of the heat exchange would be insufficient and consequently, heat transfer between air and tubes decreases.

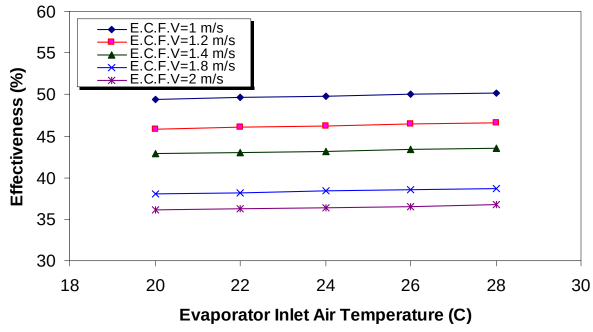


Figure 3. Effectiveness vs. evaporator inlet air temperature for typical two rows

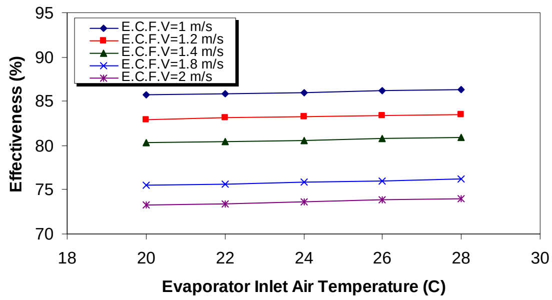


Figure 4. Effectiveness vs. evaporator inlet air temperature for typical four rows

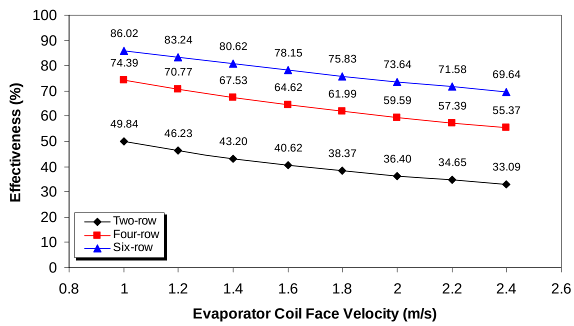


Figure 5. Effectiveness vs. evaporator coil face velocity for typical six rows

The effect of condenser inlet water temperature on the thermal performance of the air-to-water HPHEX was shown in Fig. 6 Based on the results, condenser inlet water temperature has no significant effect on the thermal performance of the HPHEX. Condenser inlet water temperature was examined in the range of 16 to 24 $^{\circ}C$. Normal water from the water distribution system of the building could be used as the entering water to the condenser section of the HPHEX. The condenser section leaving water could also be added to the building hot water distribution system or any other applicable usage to increase the buildings energy efficiency.
The effect of condenser coil face velocity on the thermal performance of the air-to-water HPHEX was also

investigated. To this end, coil face velocity in range of 0.2 to 0.8 m/s was considered. Fig. 7 shows the results for the case of 24 $^{\circ}C$ and 2 m/s evaporator inlet air temperature and evaporator coil face velocity, respectively. Based on the simulation results, the thermal performance of the HPHEX varies between 72 to 75% by increasing the condenser coil face velocity from 0.2 to 0.8 m/s. Therefore, the influence of the condenser face velocity on the thermal performance of the HPHEX is not considerable.

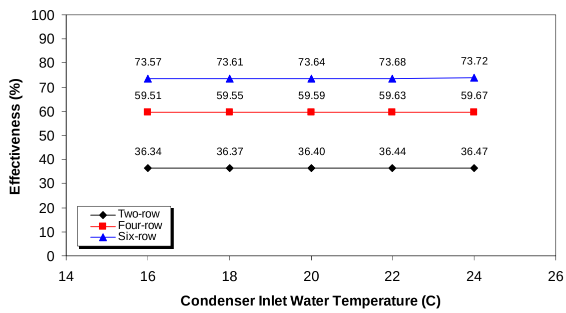


Figure 6. Effectiveness vs. condenser inlet water temperature

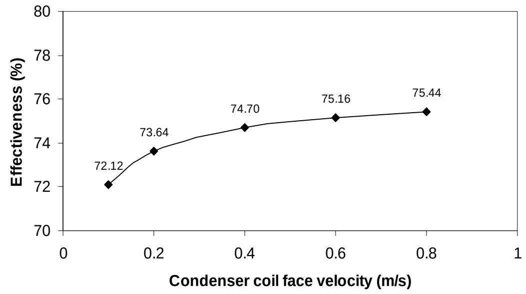


Figure 7. Effectiveness vs. condenser coil face velocity for typical six rows

Air-to-water HPHEX with three different numbers of the rows namely, two, four, and six rows was studied to determine the effect of the rows on the thermal performance of the HPHEX. The rows were considered in the flow direction, as illustrated in Fig. 2 The effect of number of the rows was examined in different operating conditions; however, the results for the case of evaporator inlet air temperature of 24 $^{\circ}C$, condenser inlet temperature of 20 $^{\circ}C$, evaporator coil face velocity of 2 m/s, and condenser coil face velocity of 0.2 m/s was illustrated in Fig. 8 as the representative.

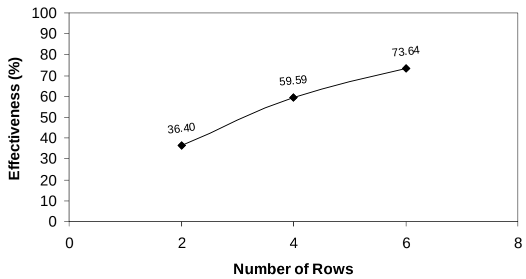


Figure 8. Effectiveness vs. number of the rows

As illustrated in Fig. 8 effectiveness of the HPHEX has increased from 36 to 73% as the numbers of rows increased form two to six. Based on the simulation data, the thermal performance of the HPHEX has increased about 102% by increasing number of the rows from two to six. As a result, it can be concluded that the number of rows has a considerable effect on the thermal performance of the HPHEX. On the other hand, increasing number of the rows would increase the pressure drop in the flow direction.

5.2. Energy Performance: Air Pre-cooling Capability

The capability of the studied air-to-water HPHEX for air pre-cooling (i.e. removing the energy of ambient outdoor air before entering into the air handling unit) was presented in this section. Fig. 9 illustrates the schematic diagram of the pre-cooling process in an air-conditioning system.

For this purpose, TRNSYS software as a Transient System Simulation Software was employed in the present study to estimate the yearly air pre-cooling potential of the studied air-to-water HPHEX [24]. TRNSYS software uses the Typical Meteorological Year (TMY) weather files to simulate the hour-by-hour air pre-cooling potential.

Fig. 10 illustrates the latest available mean monthly ambient temperature for different regions of Iran [24]. As shown in Fig. 10 south of Iran has the highest ambient temperature, which means higher cooling load demanding region of the country. Therefore, Bandar Abbas and Bushehr as the cities located in the south and southwest of Iran were considered for the yearly estimations in this study. For convenience, the mean monthly ambient temperature for different regions of Iran was tabulated in Table 1.

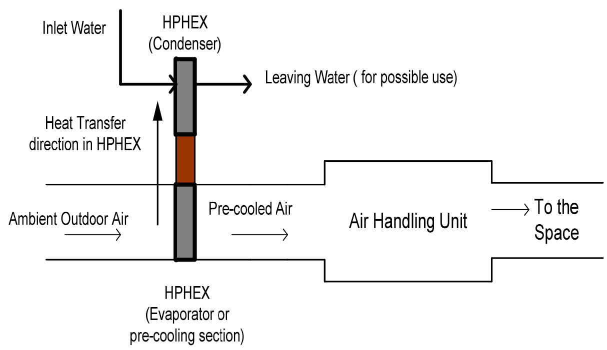


Figure 9. Schematic diagram of the pre-cooling process in an air-conditioning system (top view)

As illustrated in Fig. 8 the thermal performance of the air-to-water HPHEXs under the explained operating conditions was estimated at about 36, 59, and 73%, respectively. The air pre-cooling potential of the HPHEXs could be achieved by the flow passing through the evaporator section and would be obtained by cooling effect of the evaporator section. During the heat transfer, the temperature of the air passing through the evaporator section would be decreased by the cooling effect of the condenser section.

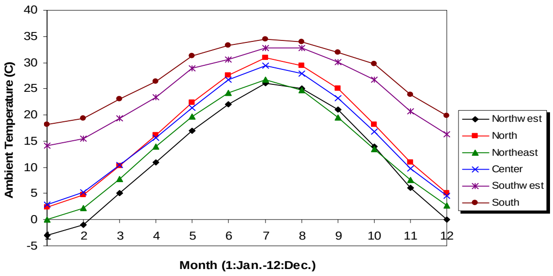


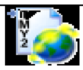
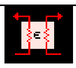
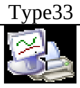
Figure 10. Mean monthly ambient temperature for different regions of Iran, [24]

In order to estimate the yearly air pre-cooling potential of the studied air-to-water HPHEX, the heat exchanger needs to be defined as a component and added to the software library. To this end, mathematical performance of the HPHEX, which was derived in Section 4, was written in FORTRAN source code and added as a new component to the software studio (Type 250). Fig. 11 shows the TRNSYS component to estimate the hourly air pre-cooling potential of the air-to-water HPHEX. Functions of the components are explained in Table 2.

TABLE 1. Mean monthly temperature ($^{\circ}C$) for different regions of Iran [24]

	Northwest (Tabriz)	**North (Tehran)**	**Northeast (Mashhad)**	**Center (Esfahan)**	**Southwest (Bushehr)**	**South (Bandar Abbas)**
January	-3	2.4	0.1	2.9	14.1	18.1
February	-1	4.8	2.2	5.3	15.5	19.3
March	5	10.2	7.7	10.5	19.4	23.1
April	11	16.2	13.9	15.6	23.4	26.4
May	17	22.3	19.7	21.3	28.9	31.2
June	22	27.5	24.3	26.7	30.6	33.3
July	26	30.9	26.7	29.4	32.8	34.4
August	25	29.5	24.7	27.9	32.7	34
September	21	25	19.5	23.2	30.1	32
October	14	18.2	13.4	16.9	26.7	29.7
November	6	11	7.6	9.7	20.7	23.9
December	0	5	2.7	4.5	16.3	19.8

TABLE 2. The processes and functions in Fig. 11, [24]

Code or label	**Description of the components**	**Function**
 Type109-TMY2	Region weather data	This component reads TRNSYS TMY2 format weather file to determine the outdoor condition.
 250	Air-to-water HPHEX	This component takes the inlet water and air properties and calculates the leaving water and air properties.
 Equa	Equation	This component is used for calculation purposes.
 Type33	Psychrometric Calculator	This component takes any two properties of moist air to calculate all other properties of moist air.
 Type65c	Printer	This component prints and saves the simulated data into a specified file.

To estimate the air pre-cooling potential, the evaporator passing mass flow rate and effectiveness of the air-to-water HPHEXs are needed to be considered. In addition, the amount of pre-cooling potential depends on the mass flow rate and the maximum temperature difference in the HPHEX (i.e. temperature difference between the evaporator inlet and condenser inlet temperatures). Therefore, three different coil face velocities namely, 1, 1.5, and 2 m/s and two different condenser inlet water temperatures of 20 and 24$^{\circ}C$ were considered for energy estimations. The evaporator inlet temperature is the ambient air temperature in the study. As shown in Fig. 8 the six rows air-to-water HPHEX has the highest amount of effectiveness for the situations studied. Therefore, for the energy analysis section the six rows air-to-water HPHEX was considered and discussed. However, the pre-cooling capability of the two and four rows HPHEX for Bandar Abbas and Bushehr was also tabulated in Table 3. for comparison purpose. The one row air-to-water HPHEX air pre-cooling potential was also estimated to make a clear illustration on the effect of number of the rows on the HPHEX performance in terms of air pre-cooling (Table 3).

As already mentioned, the air pre-cooling potential of the HPHEX was studied for the south-Iran located cities of Bandar Abbas and Bushehr. Based on the tabulated ambient data for the mentioned cities, the months, in which cooling load is required for the spaces i.e. April till October for Bandar Abbas and May till October for Bushehr, were considered for the simulations and yearly air pre-cooling estimations.

Fig. 12 illustrates the temperature reduction of the supply air (ambient air) by the evaporator section of the six rows HPHEX at 20 $^{\circ}C$ condenser inlet temperature and 1.5 m/s coil face velocity for Bandar Abbas as the representative of the situations studied. Since the temperature reduction is one of the main parameters to evaluate the air pre-cooling potential of the air-to-water HPHEX, Fig. 12 is presented.

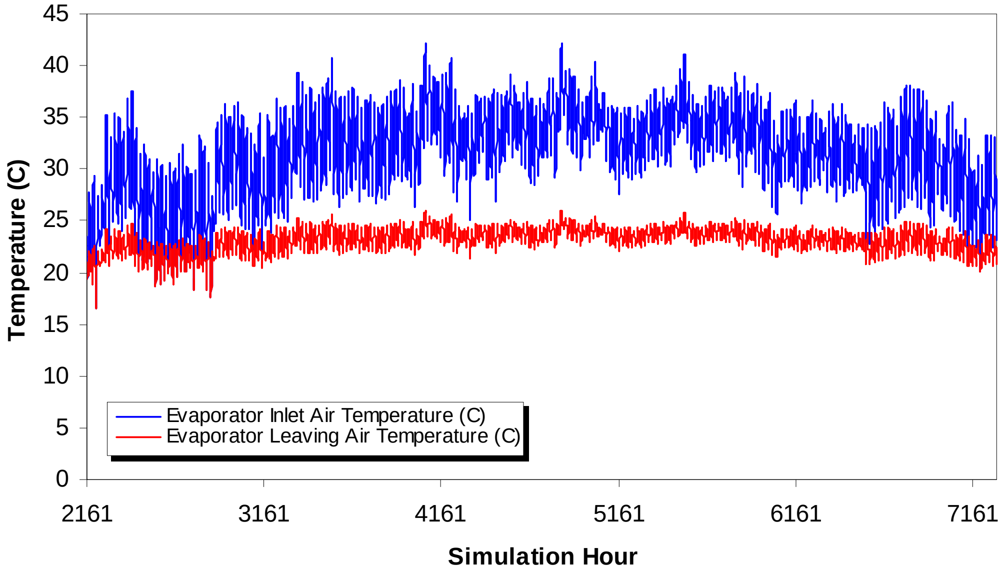


Figure 12. Hourly temperature reduction by the evaporator section of the six rows air-to-water HPHEX at 20 $^{\circ}C$ condenser inlet temperature and 1.5 m/s coil face velocity for Bandar Abbas.

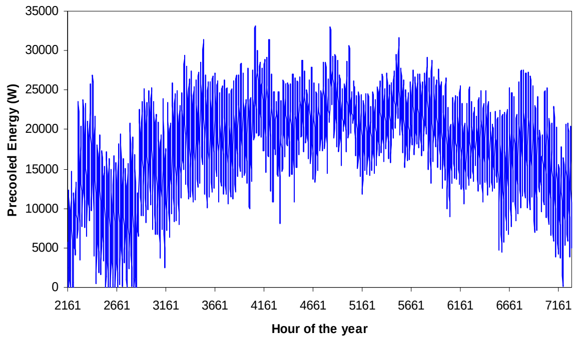


Figure 13. Hourly air pre-cooling by the six rows air-to-water HPHEX at 20 $^{\circ}C$ condenser. inlet temperature and 1.5 m/s coil face velocity for Bandar Abbas

Figs. 13 and 14 illustrate the hourly air pre-cooling energy by the six rows air-to-water HPHEX for Bandar Abbas at 20 and 24 $^{\circ}C$ condenser inlet temperatures, and 1.5 and 1 m/s coil face velocities, respectively as the representatives of the situations studied.

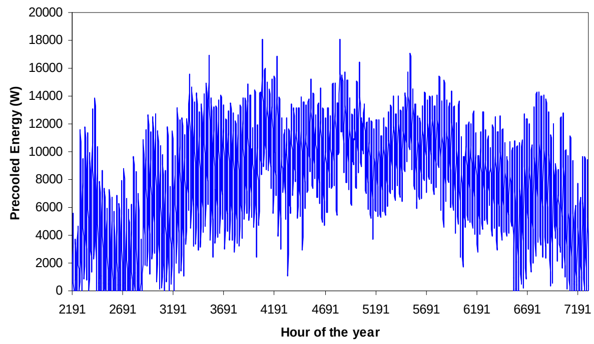


Figure 14. Hourly air pre-cooling by the six rows air-to-water HPHEX at 24 $^{\circ}C$ condenser. inlet temperature and 1 m/s coil face velocity for Bandar Abbas

The yearly estimations indicated that the six rows air-to-water HPHEX is capable of removing 41, 61.5, and 82 MW of energy from the outdoor air at 1, 1.5, and 2 m/s coil face velocities and 24 $^\circ C$ condenser inlet temperature, respectively for Bandar Abbas climate condition. In addition, the air pre-cooling potential could be further improved to 61.8, 92.7, and 123.6 MW if the condenser inlet temperature could be reduced to 20 $^\circ C$. This may be because of the fact that reducing the condenser inlet temperature means increasing the maximum temperature difference in the HPHEX, which will increases the temperature reduction in the evaporator section. The yearly simulations, predicted the pre-cooling potential of 30.8, 46.2, and 61.6 MW at 1, 1.5, and 2 m/s coil face velocities and 24 $^\circ C$ condenser inlet temperature, respectively for Bushehr climate condition (see Table 3). Therefore, based on the estimations, the considered air-to- water HPHEX energy performance is superior in Bandar Abbas compared to Bushehr.

Considering the above discussions, the air-to-water HPHEXs are recommended to be incorporated in the air-conditioning systems in high cooling load demanding regions of Iran to improve the energy performance of the air-conditioning systems. speed, and turbine blade angular position, respectively [1]. These partial derivatives depend on machine loading and can be obtained from the characteristic curves of the hydro turbine at the operating point [2].

TABLE 3. Pre-cooling energy by the air-to-water HPHEX (MW)

	Bandar Abbas (Evaporator inlet air temperature as the ambient air temperature varies between 26.4 $^\circ C$ - 34.4 $^\circ C$)			Bushehr (Evaporator inlet air temperature as the ambient air temperature varies between 26.7 $^\circ C$ - 32.8 $^\circ C$)		
	Coil Face Velocity (m/s)			Coil Face Velocity (m/s)		
Condenser Inlet Temperature ($^\circ C$)	1	1.5	2	1	1.5	2
	Six-row					
20	61.8	92.7	123.6	47.5	71.3	95.0
24	41.0	61.5	82.0	30.8	46.2	61.6
	Four-row					
20	50.4	75.7	100.9	46.4	69.6	92.8
24	33.5	50.2	66.9	31.5	47.3	63.0
	Two-row					
20	30.8	46.2	61.6	28.3	42.5	56.7
24	20.4	30.7	40.9	19.2	28.9	38.5
	One-row					
20	18.1	27.2	36.2	16.7	25	33.3
24	12	18	24	11.3	17	22.6

6. CONCLUSIONS

In the present research, capability of the air-to-water HPHEX for air pre-cooling in air-conditioning systems was investigated. For this purpose, air-to-water HPHEX with two, four, and six rows were theoretically investigated. Effectiveness-NTU approach was used for this purpose. The HPHEXs were simulated at different operating conditions and the effects of evaporator coil face velocity, evaporator inlet air temperature, condenser coil face velocity, condenser inlet water temperature, and number of the rows in the flow direction on the thermal performance of the HPHEXs were discussed. Based on the findings, evaporator inlet air temperature, condenser inlet temperature, and condenser coil face velocity have not significant effects on the thermal performance of the air-to-water HPHEXs. However, the influence of the evaporator coil face velocity is considerable. The effect of number of rows on the thermal performance of the HPHEX was also investigated. It was shown that the number of rows has a significant effect on the thermal performance of the HPHEX. It was found that as the number of the rows increases from two to six, the effectiveness of the HPHEX is increased from 36% to 73%. Based on the simulation data, by increasing number of the rows from two to six, the thermal performance of the HPHEX is increased by about 102%.

The capability of the air-to-water HPHEXs for air pre-cooling in south of Iran, which is the highest cooling load demanding region of the country, was also investigated. The estimations were conducted for the months, in which the cooling load for the spaces is required. According to the predictions, the studied six rows air-to-water HPHEX is capable of removing 41, 61.5, and 82 MW of energy from the outdoor air at 1, 1.5, and 2 m/s coil face velocities and 24 $^{\circ}C$ condenser inlet temperature, respectively for Bandar Abbas, Iran climate condition. Moreover, it was found that the air pre-cooling potential could be further improved to 61.8, 92.7, and 123.6 MW by decreasing the condenser inlet temperature to 20 $^{\circ}C$. Furthermore, the yearly simulation predicted the air pre-cooling potential of 30.8, 46.2, and 61.6 MW at 1, 1.5, and 2 m/s coil face velocities and 24 $^{\circ}C$ condenser inlet temperature, respectively for Bushehr, Iran climate condition.

ACKNOWLWDGMENTS

The author would like to acknowledge the financial assistance from the Chabahar Maritime University, Iran for the author to conduct the research.

REFERENCES

1. Abtahi, H., Jayanth, M. and Khattar, M.K., "Theoretical analysis of the performance characteristics of dehumidification heat pipe heat exchangers in air-conditioning systems", In ASME Proceedings of the 1988 National Heat Transfer Conference, Vol. 18, No. 4, (1998), 311-316.
2. Mathur, G.D., "Enhancing performance of an air conditioning system with a two-phase heat recovery loop retrofit", ***In*** Proceeding of the 31st Intersociety Energy Conversion Engineering Conference, Vol. 3, (1996), 2027-2032.
3. Mathur, G.D., "Predicting yearly energy savings using BIN weather data with heat pipe heat exchangers", ***In Proceeding of the Intersociety Energy Conversion Engineering Conference***, Vol. 2, (1997), 391-1396.
4. Mostafa, A.A. and Mousa, M.M., "Heat pipe heat exchanger for heat recovery in air conditioning", ***Applied Thermal Engineering***, Vol. 27, (2007), 795-801.
5. Yau, Y.H., "The use of a double heat pipe heat exchanger system for reducing energy consumption of treating ventilation air in an operating theatre-A full year energy consumption model simulation", ***Energy and Buildings***, Vol. 40, (2008), 917-925.
6. Ahmadzadehtalatapeh, M. and Yau, Y.H., "The application of heat pipe heat exchangers to improve the air quality and reduce the energy consumption of the air conditioning system in a hospital ward - A full year model simulation", ***Energy and Buildings***, Vol. 43, (2011), 2344-2355.
7. Azad, E., "Theoretical and experimental investigation of heat pipe solar collector", ***Experimental Thermal and Fluid Science***, Vol. 32, (2008), 1666-72.
8. Azad, E., "Interconnected heat pipe solar collector", ***International Journal of Energy,*** Vol. 22, No. 3, (2009), 233-242.
9. Chun, W., Kang, Y.H., Kwak, H.Y. and Lee, Y.S., "An experimental study of the utilization of heat pipes for solar water heaters", ***Applied Thermal Engineering***, Vol. 19, (1999), 807-817.
10. Hull, J.R., "Analysis of heat transfer factors for a heat pipe absorber array connected to a common manifold", ***Journal of Solar Energy***, Vol. 108, (1986), 11-16.
11. Yau, Y.H. and Tucker, A.S., "The performance study of a wet six-row heat pipe heat exchanger operation in tropical buildings", ***International journal of Energy Research***, Vol. 27, (2003), 187-202.
12. Noie, S.H., "Investigation of thermal performance of an air-to-air thermosyphon heat exchanger using ε -NTU method", ***Applied Thermal Engineering***, Vol. 26, (2006), 559-567.
13. Azad. E. and Geoola, F., "A design procedure for gravity assisted heat pipe heat exchanger", ***Heat Recovery Systems***, Vol. 4, No. 2, (1984), 101-111.
14. Yau, Y.H. and Ahmadzadehtalatapeh, M., "Experimental investigation of the thermal performance of an air-to-air horizontal heat pipe heat exchanger", ***International Journal of Mechanical and Material Engineering***, Vol. 5, No. 1, (2010), 29-35.
15. Azad, E., Bahar, F. and Moztarzadeh, F., "Design of water-to-air gravity-assisted heat pipe heat exchanger", ***Journal of Heat Recovery Systems***, Vol. 5, (1985), 589-99.
16. Azad, E., Moztarzadeh, F., "Design of air-to-water co-axial heat pipe heat exchanger", ***Journal of Heat Recovery Systems***, Vol. 5, No. 3, (1985), 217-224.
17. Kays, W.M. and London, A.L., "Compact Heat Exchangers Design", McGraw-Hill, New York, USA, (1984).
18. Shah, R.K. and Sekulic, D.P., "Fundamentals of Heat Exchanger Design", John Wiley & Sons, New Jersey, USA, (2003).
19. Dunn, P.D. and Reay, D.A., "Heat Pipes", Pergamon Press, Oxford, (1978).
20. Peterson, G.P., "An Introduction to Heat Pipes: Modeling, Testing, and Applications", John Wiley & Sons, New York, USA, (1994).
21. Hewitt, G.F. "Heat Exchanger Design Handbook", Begell House, (1998).
22. Rohsenow, W.M., Hartnett, J.P. and Cho, Y.I., "Handbook of Heat Transfer", third edition, McGraw-Hill, (1998).
23. Holman, J.P., "Heat Transfer", McGraw Hill, (1997).
24. Solar Energy Laboratory, U.o.W.-M. TRNSYS 16, "a Transient System Simulation program", http://www.wisc.edu.