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Application of the counter- and cross-flow indirect evaporative cooler for heat recovery under different climate conditions

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Abstract. This paper investigates the potential of applying an indirect evaporative cooler for heat recovery in air-conditioning system under various climate conditions. The counter- and cross-flow configurations of the indirect evaporative exchanger are addressed in this study in terms of their performance and applicability for different climate zones. Presented analyses are carried out with original ε-NTU model considering condensation from the product airflow and validated against experimental data. It was stated that both configurations of the indirect evaporative exchanger have a high application potential to be employed as a heat recovery device under most climatic parameters. Additionally for each climate zone considered in this paper, the air-conditioning system that consists of either the indirect evaporative exchanger and vapor-compression cooler or indirect evaporative exchanger and direct evaporative cooler is proposed.

1 Introduction

Worldwide energy demand has increased in recent years, and it is expected to further grow in coming years [1]. The significant part of global energy consumption relates to the building sector, where it is largely used for air-conditioning (AC) and cooling purposes. Nowadays, most of conventional cooling devices are driven by electric energy, which production is based on fossil fuels. One of the promising cooling technology, that is driven mainly by the process of water evaporation instead of electricity, is the indirect evaporative cooling (IEC) [2, 3].

The IEC heat and mass exchanger consists of two adjacent channels, namely the product and working air channels, arranged in repetitive series. The plates in the working air channels are covered with water that evaporates into the working airflow and as a result of water evaporation, temperature of the plate that separates the working and product air channels decreases. The product airflow flowing through the product air channels contacts with the plate of decreased temperature and so it is therefore cooled without adding any moisture.IEC exchangers can be arranged in many ways, among others in a counter-flow or a cross-flow configuration. In the counter-flow configuration, working and product airflows

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move parallel in opposite directions while in the cross-flow configuration, the working airflow moves perpendicularly to the product airflow (Fig. 1).

Recent development of the IEC technology allows to apply both the counter- and cross-flow IEC exchangers as a heat recovery devices. To meet comfort requirements of the conditioned space, the IEC cooler used for heat recovery should be followed by a vapor-compression cooler (VCC) or by a direct evaporative cooler (DEC), depending on the climate conditions. The schematic design of the AC system that is addressed in this study, is presented in the Figure 1. Before the product airflow is delivered to a conditioned space, it passes through the IEC unit and then, if necessary, is additionally cooled and dehumidified in the VCC unit or cooled and humidified in the DEC unit. The exhaust airflow from the conditioned space is thereafter employed as the working airflow in the IEC exchanger. In such case, due to the low temperature of the working airflow, the process of water vapor condensation from product airflow is likely to occur and so is has to be taken into account. IEC exchanger performance was addressed in several studies that proved high potential of the IEC technology to operate under various parameters [4–7]. This paper aims to investigate the performance of the counter- and cross-flow configuration of the IEC exchanger under specific climate conditions. Based on the airflow parameters at the outlet of the IEC exchanger, it is also proposed whether the IEC unit in the AC system should be followed by the VCC or DEC unit.

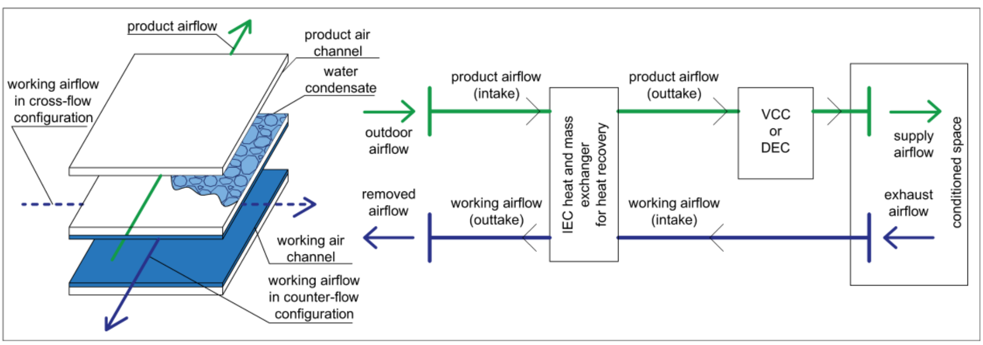

Fig. 1. Scheme of the AC system consisted of the IEC heat and mass exchanger for heat recovery.

2 Methods

In this study, ε–NTU mathematical model is used to describe heat and mass transfer in the counter- and the cross-flow IEC exchanger. Heat and mass balance is calculated under steady-state operation with ordinary differential equations for the counter-flow configuration and partial differential equations for the cross-flow configuration, solved with numerical methods. In order to determine whether the condensation has to be taken into consideration or not, the control algorithm is applied that compares the product airflow dew-point temperature and the temperature of the plate surface at each step of solving differential equations. The condensation process is taken into consideration when product channel plate surface temperature is lower than product airflow dew-point temperature.

Based on energy and mass balance equations that describe the airflow passing through the control volume of the investigated exchanger, the overall energy balance equations under non-condensation state are developed. The overall energy balance for the counter-flow configuration of the IEC exchanger is described with Eq. (1) and with Eq. (2) for the cross-flow configuration.

$$\left(\frac{dt_1}{d\overline{X}}\right)-\left(\frac{W_2}{W_1}\right)\left[\left(\frac{dt_2}{d\overline{X}}\right)+\frac{\left(i_{g2}-i_{w2}\right)}{c_{p2}}\left(\frac{dx_2}{d\overline{X}}\right)\right]=0 \tag{1}$$

$$\left(\frac{\partial t_1}{\partial\overline{X}}\right)+\left(\frac{W_2}{W_1}\right)\left[\left(\frac{\partial t_2}{\partial\overline{Y}}\right)+\frac{\left(i_{g2}-i_{w2}\right)}{c_{p2}}\left(\frac{\partial x_2}{\partial\overline{Y}}\right)\right]=0 \tag{2}$$

where: t – temperature, °C; $\overline{X}$ – relative coordinate along product airflow direction, -; $\overline{Y}$ – relative coordinate perpendicular to product airflow direction, -; W – heat capacity rate of the fluid, W/K; i – specific enthalpy, J/(kgK); x – humidity ratio of moist air, kg/kg; c_p– specific heat capacity of moist air, J/(kgK). Subscripts: 1 – related to product channel; 2 – related to working channel; g – related to water vapor; w – related to water film.

The overall energy balance under condensation state for the counter-flow configuration of the IEC exchanger is described with Eq. (3) and with Eq. (4) for the cross-flow configuration.

$$\left[\left(\frac{dt_1}{d\overline{X}}\right)+\frac{\left(i_{g1}-i_{w1}\right)}{c_{p1}}\left(\frac{dx_1}{d\overline{X}}\right)\right]-\left(\frac{W_2}{W_1}\right)\left[\left(\frac{dt_2}{d\overline{X}}\right)+\frac{\left(i_{g2}-i_{w2}\right)}{c_{p2}}\left(\frac{dx_2}{d\overline{X}}\right)\right]=0 \tag{3}$$

$$\left[\left(\frac{\partial t_1}{\partial\overline{X}}\right)+\frac{\left(i_{g1}-i_{w1}\right)}{c_{p1}}\left(\frac{\partial x_1}{\partial\overline{X}}\right)\right]+\left(\frac{W_2}{W_1}\right)\left[\left(\frac{dt_2}{d\overline{Y}}\right)+\frac{\left(i_{g2}-i_{w2}\right)}{c_{p2}}\left(\frac{\partial x_2}{\partial\overline{Y}}\right)\right]=0 \tag{4}$$

The mathematical model accuracy for the counter-flow IEC exchanger, under condensation state, was verified by authors with experimental data obtained at the dedicated test station [8]. It was concluded that the model can predict outlet product airflow temperature with average accuracy (mean absolute percentage error) equal to 2.5% and outlet product airflow relative humidity with average accuracy equal to 0.9%. The model accuracy under non-condensation state for the counter-flow configuration, was verified with the existing experimental study carried out by Riangvilaikul et al. [9]. It was found that the model can predict outlet product airflow temperature with average accuracy equal to 1.8%. The maximum discrepancy does not exceed 5%. It is assumed that accuracy of the mathematical model predictions for the cross-flow IEC exchanger, are similar for those of the counter-flow unit. The similarity results from the analogy in the mathematical model equations used for describing heat and mass transfer in both exchangers.

3 Results and discussion

In this section simulations results are presented and discussed. The geometric parameters of the counter- and cross-flow configuration of the IEC exchanger investigated in this study are given in the Figure 2 and Table 1. Numerical simulations based on the mathematical model presented in previous section, are carried out for inlet product airflow parameters characteristic for different climatic locations listed in Table 2. Inlet product airflow parameters (temperature and humidity ratio) are defined based on the climatic design conditions given by ASHRAE [10]. Each location in Table 2 represents one of the climate zone in the Köppen-Geiger climate classification system (following climate zones: Dwd – monsoon-influenced extremely cold subarctic climate, Dsd – extremely cold, subarctic climate, ET – tundra climate and EF – ice cap climate are not taken into consideration in this study due to the low population density ratio and therefore scarce data available) [11]. Inlet working airflow parameters are: temperature t_{2i}=25°C and relative humidity RH_{2i}=50%.

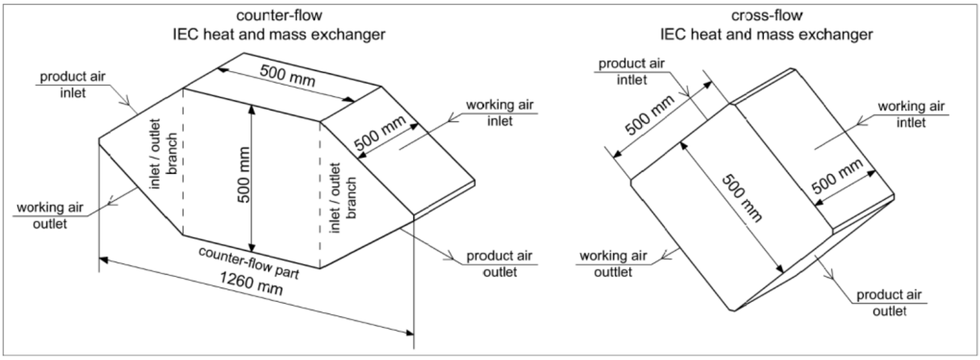

Fig. 2. General dimensions of the IEC heat and mass exchanger in different configuration.

Table 1. Characteristic parameters of the IEC heat and mass exchanger in different configuration.

Parameters	Counter-flow	Cross-flow
Wall thickness, mm	0.3	0.3
Channel length/width/height, m	0.5/0.5/0.0034	0.5/0.5/0.0034
Number of product air channels	68	68
Working to product air ratio/NTU$_1$†	1/6	1/6
Airflow rate, m^3/h	500	500
Total sheet surface, m^2	52	34
Heat exchange sheet surface, m^2	34	34

3.1 IEC exchanger applicability under different climate conditions

In this study, different performance indicators were used to evaluate performance of the IEC heat and mass exchanger under various climatic conditions. For the counter- and cross-flow configuration of the exchanger, average temperature drop is calculated with Eq. (5). In case of water vapor condensation from the product airflow, the average humidity ratio drop is described with Eq. (6). Average total cooling capacity, given by Eq. (7), is the sum of average sensible cooling capacity and average latent cooling capacity related with condensation process. The average values $\bar{t}_{1o}$, $\bar{x}_{1o}$, $\bar{i}_{1o}$ relate to the outlet section of the exchanger. Calculated performance indicators are listed in Table 3.

$$\Delta\bar{t}_1 = t_{1i} - \bar{t}_{1o},\ \text{°C} \tag{5}$$

$$\Delta\bar{x}_1 = x_{1i} - \bar{x}_{1o},\ \text{g/kg} \tag{6}$$

$$\bar{Q}_1^T = V_1 \cdot \rho_1 \cdot \left(i_{1i} - \bar{i}_{1o}\right) = \bar{Q}_1^S + \bar{Q}_1^L,\ \text{kW} \tag{7}$$

where: Q – cooling capacity, kW; V – airflow rate, m^3/s; ρ – density, kg/m^3. Subscripts: i – inlet parameters; o – outlet parameters; T – related to total heat transfer; S – related to sensible heat transfer; L – related to latent heat transfer.

† NTU – number of transfer units, - (NTU = αF / (Gc_p)); α – convective heat transfer coefficient, W/(m2 K); F – surface area, m^2; G – mass flow rate, kg/s.

Table 2. Climatic parameters for cooling design conditions [11] for different climate zones [10] (*DB*– dry-bulb; M-i - Monsoon-influenced).

Symbol	Climate zone	City, country	t_{DB}, °C	*x*, g/kg
Af	Tropical rainforest	Singapore	33.5	18.9
Am	Tropical monsoon	Miami, Florida, USA	32.7	17.4
As	Tropical savanna, dry	Lihue, Hawaii, USA	29.1	15.9
Aw	Tropical savanna, wet	Caracas, Venezuela	33.1	21.8
BWk	Hot semi-arid	Damascus, Syria	38.1	5.0
BWh	Cold semi-arid	Cairo, Egypt	36.9	9.8
BSk	Hot deserts	Denver, Colorado, USA	32.9	4.1
BSh	Cold desert	Nicosia, Cyprus	37.7	7.0
Cfa	Humid subtropical	Buenos Aires, Argentina	30.0	11.6
Cfb	Temperate oceanic	London, United Kingdom	25.6	10.0
Cfc	Subpolar oceanic	Auckland, New Zealand	24.3	11.9
Csa	Hot-summer Mediterranean	Izmir, Turkey	35.8	8.9
Csb	Warm-summer Mediterranean	Cape Town, South Africa	29.8	9.8
Csc	Cool-summer Mediterranean	Bolmaceda, Chile	22.9	5.8
Cwa	M-i, humid subtropical	New Delhi, India	40.8	10.7
Cwb	Subtropical highland	Mexico City, Mexico	28.1	2.6
Cwc	Cold subtropical highland	La Paz, Bolivia	17.0	0.7
Dfa	Hot-summer humid continental	Bucharest, Romania	32.7	10.3
Dfb	Warm-summer humid continental	Oslo, Norway	24.8	8.5
Dfc	Subarctic	Fairbanks, Alaska	25.6	7.0
Dfd	Extremely cold subarctic	Yakutsk, Russia	28.4	9.0
Dsa	Hot, dry-summer continental	Bishkek, Kirgizstan	33.7	7.6
Dsb	Warm, dry-summer continental	Sivas, Turkey	30.7	6.9
Dsc	Dry-summer subarctic	Homer, Alaska, USA	17.3	7.7
Dwa	M-i, warm-summer humid continental	Beijing, China	33.5	12.5
Dwb	M-i, subarctic	Irkutsk, Russia	26.9	8.7
Dwc	M-i, extremely cold subarctic	Mohe County, China	28.3	9.5

Based on the conducted simulation it is stated that in two cases (Cwc, Dsc), the IEC heat and mass exchanger is not recommended as a heat recovery unit for cooling purposes due to the low temperature of the outdoor airflow. The IEC exchanger may be rather considered as a cooling unit that operates on the outdoor air instead on the exhaust airflow. In other cases, IEC exchanger can operate as a heat recovery device even if outdoor air temperature is lower than temperature of the working airflow (Cfc, Csc, Dfb). Under these climatic conditions, $\bar{Q}_1^T$ of the IEC exchanger is the lowest ($\bar{Q}_1^T$ for Cfc zone is equal to 1.1kW for the counter- and cross-flow configuration), nevertheless it is possible to decrease the temperature of the outdoor airflow on average by 6.1°C (Table 3). Among all considered cases, the highest $\Delta\bar{t}_1$ is achieved for Cwa climate zone (22.7°C for the counter- and 22.2°C for the cross-flow configuration). The lowest $\Delta\bar{t}_1$ is achieved for Csc climate zone (5.1°C for the counter- and 4.9°C for the cross-flow configuration).

The water vapor condensation from the product airflow occurs in four tropical climate zones (Af, Am, As, Aw). In these cases, the $\Delta\bar{x}_1$ is equal to 4.1g/kg for the counter-flow configuration and 3.5g/kg for the cross-flow configuration. The highest $\Delta\bar{x}_1$ is achieved for Aw climate zone (6.7g/kg for the counter- and 6.0g/kg for the cross-flow configuration). For the Aw climate zone, also $\bar{Q}_1^T$ of the of the IEC exchanger is the highest (5.1kW for the counter- and 4.6kW for the cross-flow configuration). It is due the fact that with intense condensation process in product air channels, additional latent heat is released, and in this case it accounts for up to 56% of total cooling capacity.

Table 3. Performance indicators of the counter- and cross-flow configuration of the IEC heat and mass exchanger for different climatic conditions (VCC - vapor compression cooling unit; DEC - direct evaporative cooling unit).

Climate zone	Counter-flow	Cross-flow	Counter-flow	Cross-flow	Counter-flow	Cross-flow	AC system
	$\Delta\bar{t}_1$, °C		$\Delta\bar{x}_1$, g/kg		$\bar{Q}_1^S / \bar{Q}_1^L / \bar{Q}_1^T$, kW		
Af	13.9	13.3	4.3	3.7	2.3/1.9/4.2	2.2/1.6/3.8	IEC + VCC
Am	13.4	12.9	3.2	2.6	2.2/1.4/3.6	2.2/1.2/3.4	IEC + VCC
As	10.3	9.9	2.1	1.7	1.7/0.9/2.6	1.6/0.8/2.4	IEC + VCC
Aw	12.9	12.2	6.7	6.0	2.2/2.9/5.1	2.0/2.6/4.6	IEC + VCC
BWk	20.1	19.6	0.0	0.0	3.4/0.0/3.4	3.3/0.0/3.3	IEC + DEC
BWh	18.8	18.4	0.0	0.0	3.2/0.0/3.2	3.1/0.0/3.1	IEC + VCC or IEC + DEC
BSk	14.9	14.6	0.0	0.0	2.5/0.0/2.5	2.4/0.0/2.4	IEC + DEC
BSh	19.7	19.2	0.0	0.0	3.3/0.0/3.3	3.2/0.0/3.2	IEC + DEC
Cfa	12.1	11.8	0.0	0.0	2.0/0.0/2.0	2.0/0.0/2.0	IEC + VCC
Cfb	7.7	7.5	0.0	0.0	1.3/0.0/1.3	1.3/0.0/1.3	IEC + VCC or IEC + DEC
Cfc	6.5	6.3	0.0	0.0	1.1/0.0/1.1	1.1/0.0/1.1	IEC + VCC
Csa	17.8	17.4	0.0	0.0	3.0/0.0/3.0	2.8/0.0/2.8	IEC + VCC or IEC + DEC
Csb	11.9	11.6	0.0	0.0	2.0/0.0/2.0	1.9/0.0/1.9	IEC + VCC or IEC + DEC
Csc	5.1	4.9	0.0	0.0	0.8/0.0/0.8	0.8/0.0/0.8	IEC + DEC
Cwa	22.7	22.2	0.0	0.0	3.8/0.0/3.8	3.7/0.0/3.7	IEC + VCC or IEC + DEC
Cwb	10.2	9.9	0.0	0.0	1.7/0.0/1.7	1.7/0.0/1.7	IEC + DEC
Cwc	-0.7	-0.7	0.0	0.0	n/a	n/a	NOT APPLICABLE
Dfa	14.7	14.4	0.0	0.0	2.5/0.0/2.5	2.4/0.0/2.4	IEC + VCC or IEC + DEC
Dfb	6.9	6.8	0.0	0.0	1.2/0.0/1.2	1.1/0.0/1.1	IEC + VCC or IEC + DEC
Dfc	7.7	7.5	0.0	0.0	1.3/0.0/1.3	1.3/0.0/1.3	IEC + DEC
Dfd	10.5	10.2	0.0	0.0	1.8/0.0/1.8	1.7/0.0/1.7	IEC + VCC or IEC + DEC
Dsa	15.7	15.3	0.0	0.0	2.6/0.0/2.6	2.6/0.0/2.6	IEC + VCC or IEC + DEC
Dsb	12.8	12.4	0.0	0.0	2.1/0.0/2.1	2.1/0.0/2.1	IEC + DEC
Dsc	-0.4	-0.4	0.0	0.0	n/a	n/a	NOT APPLICABLE
Dwa	15.5	15.1	0.0	0.0	2.6/0.0/2.6	2.5/0.0/2.5	IEC + VCC
Dwb	9.0	8.8	0.0	0.0	1.5/0.0/1.5	1.5/0.0/1.5	IEC + VCC or IEC + DEC
Dwc	10.4	10.1	0.0	0.0	1.7/0.0/1.7	1.7/0.0/1.7	IEC + VCC or IEC + DEC

It could be stated that the counter-flow configuration of the IEC exchanger allows to achieve better performance indicators than the cross-flow configuration under various climate conditions. However, the counter-flow unit requires additional inlet and outlet branches that are not involved in heat exchange (Fig. 2). It results in higher material costs to produce the IEC exchanger without increasing it performance. The required sheet surface of the counter-flow exchanger is 1.5 times higher than in the cross-flow configuration (Table 1) and therefore it can be assumed that investment cost will be 1.5 higher too. In no case addressed in this study, total cooling capacity of the counter-flow IEC exchanger does not exceeds the total cooling capacity of the cross-flow configuration high enough to compensate the high investment cost of the exchanger.

3.2 AC system applicability under different climate conditions

In this section, the AC system is proposed for each climate zone considered in this study. First system consists of the IEC heat and mass exchanger used for heat recovery, followed by the VCC unit for additional cooling and dehumidification. The exemplary processes in the product and working air channels of the IEC exchanger and in the VCC unit are presented on the psychrometric chart in Figure 3(a). In the second system, the IEC exchanger is followed by the DEC unit, where additional adiabatic process of cooling and humidifying is realized (Fig. 3(b)). The appropriate AC system is selected based on its ability to provide supply airflow parameters that allow to meet comfort parameters in the conditioned space (analysis performed for design conditions).

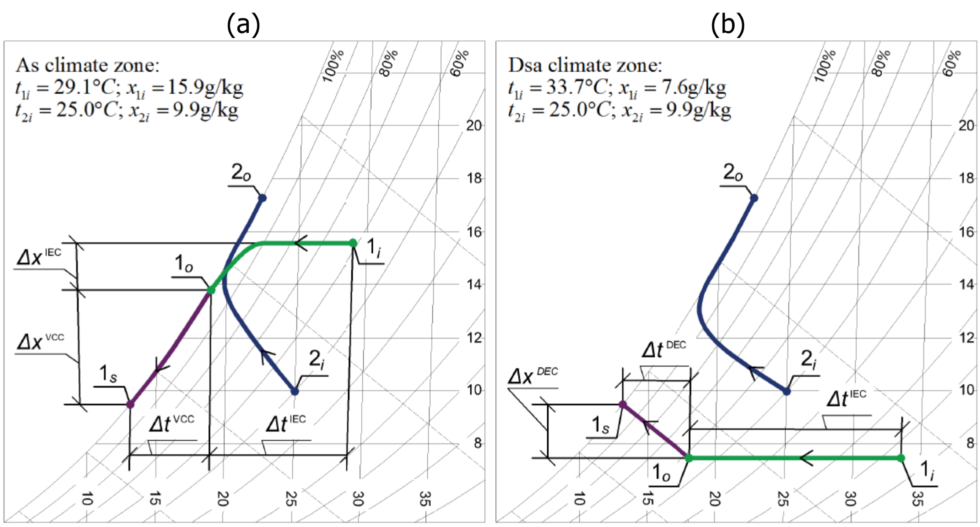

Fig. 3. Psychrometric chart for the AC system with the counter-flow IEC heat recovery unit followed by: (a) vapor-compression cooling unit; (b) direct evaporative cooling unit (1 – product channel; 2 – working channel; *i* – inlet parameters; *o* – outlet parameters; *s* – related to supply airflow).

In this study, comfort parameters in the conditioned space in summer period cover the range of temperature between 23 and 26°C and relative humidity within the range of 40 to 60%. Based on this assumption, it was stated that if the airflow that leaves IEC exchanger has the humidity ratio higher than 11.0g/kg (all tropical and some of the temperate climates), the VCC unit is required. When the humidity ratio is lower than 7.5g/kg (arid and some of the temperate climates) then the AC system should be equipped with DEC unit that follows the IEC exchanger.

With the DEC unit applied in the AC system, achieving needed parameters of the supply airflow may require partial reduction of the cooling capacity of the IEC exchanger to meet the requirements of the adiabatic process in the DEC unit. It was also concluded that when the airflow at the outlet of the IEC exchanger has the humidity ratio within the range of 7.5 and 11.0g/kg (most of the continental and some of the temperate climates) it is possible to apply either the system with the VCC unit or with the DEC unit. In these cases the cooling capacity of the exchanger does not have to be adjust to the requirement of the DEC unit.

4 Summary and conclusions

In this paper, performance studies of the counter- and cross-flow IEC heat and mass exchanger applied as a heat recovery device in the AC system are presented. Studies are carried out for inlet product airflow parameters characteristic for different climate conditions. Numerical simulations are performed with validated analytical ε–NTU model.

It was concluded that the IEC exchanger in both, the counter- and cross-flow configuration has a high potential to be employed as a heat recovery device under wide range of climate parameters. While the counter-flow configuration of the IEC exchanger is characterized by higher performance, its cost significantly exceeds the price of the cross-flow configuration. It is also stated that depending on the climate zone, the AC system consisted of IEC exchanger and VCC unit is suitable for tropical, temperate and some of the continental climates while the AC system consisted of IEC exchanger and DEC unit is suitable for arid and continental climate zones.

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