Experimental indirect evaporative air conditioning system - a possible implementation

Norbert Szaszák[1*], *Attila* Juhász[2]

[1]Institute of Energy Engineering and Chemical Machinery, Department of Fluid and Heat Engineering, University of Miskolc, H-3515 Miskolc, Hungary
[2]University of Miskolc, H-3515 Miskolc, Hungary

Abstract. This article presents the principle of operation of an experimental indirect evaporative cooling system which applies liquid desiccant solution as a drying agent. This mobile system is going to be built for the investigation of the effects of different working parameters (e.g. regenerating temperature of the desiccant salt-solution, air flow rates, solution flow rates, droplet size and mixing path length, etc.) on the produced cooled and dehumidified air, as well as the effects of the initial hot-air parameters (temperature and humidity) on the effectiveness (cooling and dehumidification rate) of the system. In this paper the basic mechanisms of both the direct and indirect evaporative cooling systems are presented with their advantages and disadvantages. It is shown how the solar energy by means of solar collector(s) can be utilized as an energy source of the regeneration of the diluted desiccant solution. Besides the 3D drawing and the parts of the experimental cooler and air dryer system will be presented and explained.

1 Introduction

Both in the industrial and residential buildings the appropriate conditions of the indoor air quality (humidity and temperature) are requirement to provide adequate comfort for the people. During hot seasons (especially in summer) air conditioning systems are applied to create indoor air conditions which meets the requirements of the comfort theory [1]. This consists of two basic physical processes: one is the cooling and the other is the dehumidification of the air. According to some sources for human beings, the most ideal air-condition in a room for low-power work (e.g. in an office) is the temperature of 25°C and relative humidity of 55% [2]. The relative humidity, φ is the ratio of the partial pressure of the water vapor ($p_{p,water\,vapor}$) in the air to the pressure of equilibrium water vapor $p^*_{water\,vapor}$ belongs to a certain air temperature and atmospheric pressure (p_a):

$$\varphi = \frac{p_{p,water\,vapor}}{p^*_{water\,vapor}(T_a, p_a)} \cdot 100\% \quad (1)$$

* Corresponding author: norbert.szaszak@uni-miskolc.hu

If the air is totally dry, its relative humidity φ=0%. If φ=100% the wet air is saturated: more water can not be evaporated into the air (the cooling effect of sweating which is based on the evaporation does not occur), or by cooling the saturated air condensation occurs.
As an example, the results of a NASA-case study can give us a clear correlation between the effectiveness and the accuracy of the human work versus the room temperature (see Table 1).

Table 1. NASA case study: effectiveness and the accuracy of the human work vs. the room temperature. [3]

Temperature, °C	24	27	29	32	35	38	41
Loss of work output, %	3	8	18	29	45	62	79
Error rate increase, %	-	5	40	300	700	-	-

Based on the data of Table 1 it is clear that the temperature has to be kept within limits to get maximal productivity and ideal comfort. In the point of view of the human comfort, besides the optimal temperature range (20°C $\leq T_a \leq$ 26°C), the humidity of the air must be in the range of 40% $\leq \varphi \leq$ 60% based on the literature [4]. This comfort zone can be observed on a psychometric diagram where the properties of the wet-air is presented as a function of the dry-bulb temperature and several parameters (absolute humidity ratio, relative humidity φ, specific enthalpy, specific volume), see Figure 1.

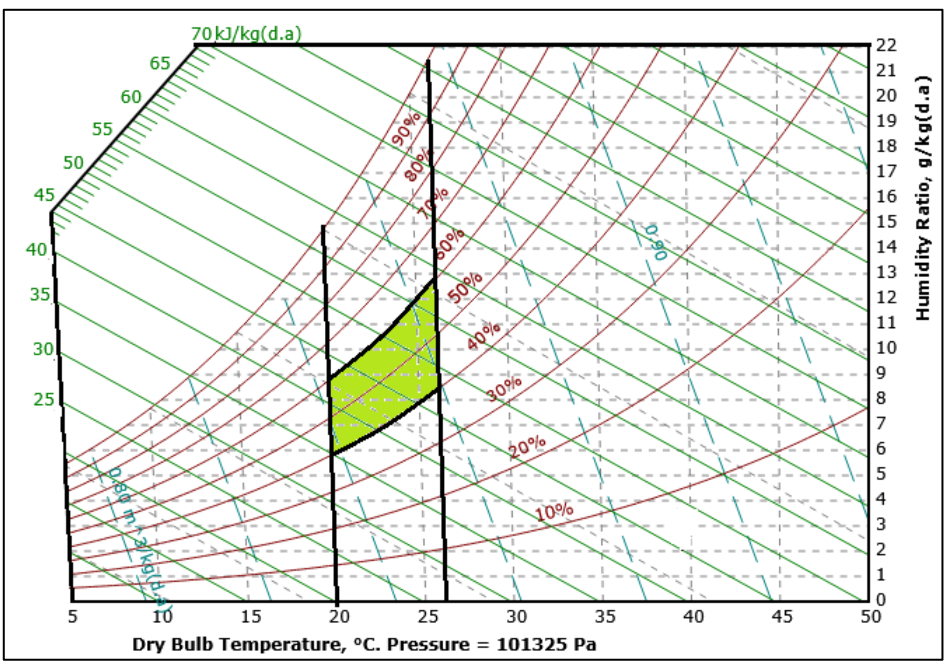

Fig. 1. The interval of the comfort zone (green) on a psychrometric chart (edited figure, original [5]).

Based on the diagram it can be seen that the human comfort zone is only a narrow region of the possible conditions: therefore – especially during hot seasons in continental and Mediterranean or the tropic climate – not only the cooling but also the dehumidification of the indoor air is necessary.
For this reason, the widespread split-air conditioning systems are applied which working principle is based on the compression of the vapor of the working medium (refrigerant). All

these kinds of A/C units require a huge amount of electrical power, primarily for the compressors driven by electric motors (a smaller portion of power is required for the control unit and the fan of the evaporator in the conditioned room and the fan of the condenser unit outside). The most residential use units have an average coefficient of performance (COP) in the range of 3÷4 W/W which means, each 1W of electrical power carries 3 or 4W of heat from the conditioned space to outside environment. This may seem a good value, however the production of the electricity and the total energy chain has relatively low efficiency which compensates the optimistic COP value of such an A/C device.

An alternative of the compressor A/C unit is the evaporative air cooling (in some cases air conditioning) system. Both direct and indirect evaporative devices are available. The direct term means that the temperature of the cooled air is decreased by the energy demand of the evaporation of water in the treated air itself, which goes together increased relative humidity. This kind of direct evaporative coolers hence are called swamp coolers (the air of the swamps is very humid). A mathematic model for the direct evaporative cooling was presented by Camargo et al [6], and later the theory was proven by their experimental results [7]. Following them, a numerical model was developed and validated by experimental results by Kovacevic and Sourbron [8]. Mathematical calculations and experiments were performed in topic of evaporative cooling in a greenhouse by Franco et al. [9]. The review of the environmental effects and the potential in energy saving of the evaporative cooling was presented by Xuan et al. [10,11]. Evaporative cooling based on absorbent material was reviewed by Rafique et al. [12], while the effectiveness of modern materials was compared to materials used in traditional systems. In case of the indirect evaporative system the air which is humidified and therefore cooled is physically separated but is thermodynamically coupled with the indoor air which is hence cooled but not humidified. An indirect evaporative system with Maisotsenko-cycle was investigated on hot, Mediterranean climate in Greece by Rogdakis et al. [13]. It was found that based on the experimental data this kind of cooler is capable to satisfy the cooling demand at a high efficiency.

Based on the previous information it can be seen that both the direct and indirect evaporative cooler solutions can be applied, the appropriate type is strongly depended on the demand regarding the humidity of the cooled air. Where the high humidity is not an issue or preferred (e.g. mushroom-farms), direct cooling should be chosen, otherwise indirect system is preferred.

2 Direct evaporative cooling

The direct evaporative cooling is based on the vaporization of the water which is an endothermic process. It is well known that the boiling of the water requires a huge amount of heat while the temperature of the boiling water is constant. In this process the heat added to the water helps in the phase-change of the liquid to vapor, and it is called latent heat of vaporization or heat of transformation. This latent heat, l_v (energy per unit mass of water) is depended on the temperature of the boiling (saturation temperature, T_{sat}), which is a function of its pressure (during the boiling process it is called saturation pressure, p_{sat}). Table 2 shows some values of the latent heat as a function of the saturation temperature and pressure.

Table 2. Latent heat of vaporization of the water [14].

T_{sat} [°C]	20	40	60	80	100	120
p_{sat} [bar]	0.0234	0.0738	0.1994	0.4739	1.014	1.985
l_v [kJ/kg]	2454.1	2406.7	2358.5	2308.8	2257.0	2202.6

It can be seen that the specific latent heat is greater in the direction of lower temperatures, but it is more important that it has a huge value in the whole ambient temperature range while the cooling of the air can be necessary: at the temperature of 40 °C more than 2.4 MJ of heat is needed to evaporate 1 kg of water. Thus, in case of direct evaporative cooler the evaporation of water in the air removes a huge amount of heat energy which cause the decrease of the temperature of the moist air. The enthalpy of the moist air is the energy content relative to a datum of the dry air portion which is the function of its temperature and the energy content of the water vapor in the air at the temperature of the air and at the partial pressure of the vapor (thus the relative humidity, φ). If water (which temperature equals to the temperature of the air) is evaporated in the air, the total specific energy of the wet air (namely the enthalpy) remains constant while a part of its energy is used to evaporate the water. This can happen only if the temperature of the air decreases during the humidification process and it is called isenthalpic process. The process of the direct evaporative cooling can be observed in Fig. 2 where the initial conditions (**1**): T_1=35°C and φ_1=20% after the cooling (**2**): T_2≈20°C and φ_2=90%.

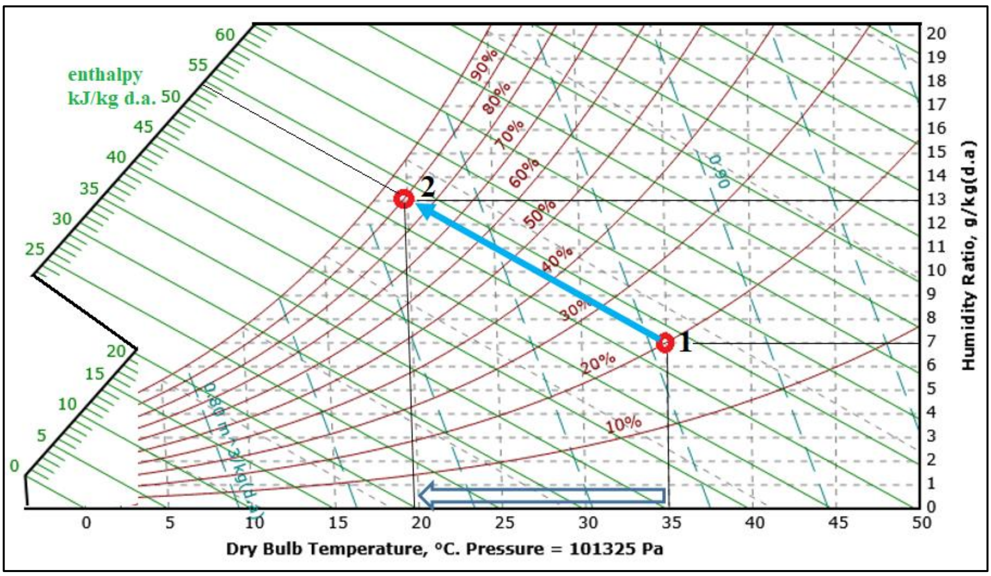

Fig. 2. Adiabatic, direct evaporative cooling on a psychrometric chart (edited figure, original [5]).

The arrow of the process is parallel to the neighbour constant enthalpy lines and points in the direction of the increasing relative humidity (and so the increasing absolute humidity, see vertical axis on the right). Based on the vertical axis of the diagram, in order to decrease the temperature of the hot air (**1**) to the condition (**2**), the evaporation of totally 13-7=6 g water/kg dry air is required. Moreover, it can be seen that the minimum temperature which can be achieved by evaporative cooling is theoretically given: the temperature which belongs to the φ=100%, which is called dew point. This limits the maximum achievable temperature drop and is depended on the initial properties of the air.

In order to evaporation occurs the water has to be in contact with the flowing air. One way is the atomization into the air stream by spraying the water at high velocity. The atomized water droplets are small therefore their sedimentation rate is negligible, so they have enough time to be evaporated before getting out from the air stream. On the other hand, the smaller the droplet size, the greater the specific area is which is one of the most important conditions of the evaporation. Such devices are the vapor gates with high pressure water sprayers or the swamp coolers which in the most cases use axial fan equipped with water sprayer.

Another solution to achieve great contact surface between air and water is the application of a porous evaporator media which is wetted by the water and has low flow resistance so the air can pass it while it evaporates the water by contacting the surface of the liquid film. The evaporator media can be made of wood shavings, cellulose or synthetic threads. Nowadays new, high-performance materials are used as the cellulose-honeycomb, coconut hair, melamine-paper, ceramics, or steel wool. Bishoyi et al. [15] proved experimentally that the honeycomb-structure is the most effective solution as an evaporative medium.
All of the previously presented direct coolers have the same disadvantage: the cooling goes together with the humidification, which may cause discomfort and in case of coolers with evaporative medias bacteria and fungi can settle causing odour and infections. To overcome these issues, so called indirect evaporative coolers can be chosen.

3 Indirect evaporative cooling

The difference between the direct and indirect systems is that the evaporation of the water does not increase the absolute humidity of the conditioned air, instead a secondary air stream is used to evaporate the water thus cool down. This cooled and humid air is then applied to cool down the air to be treated by using heat exchanger. Such a solution is the Maisotsenko cycle [16], which is capable to cool the air to the dew point temperature of the incoming secondary air. This cycle applies a special crossflow heat exchanger and evaporator unit in which a portion of the incoming air is used to cool down another part of the air while evaporating the water.
If the air with a certain vapor content is cooled e.g. in a surface heat exchanger, its absolute humidity ratio is constant until its dew point, where the relative humidity reaches the value of 100%. This cooling method can be seen in Fig. 3 where the hot air (state **1**) is cooled to condition (**2**).

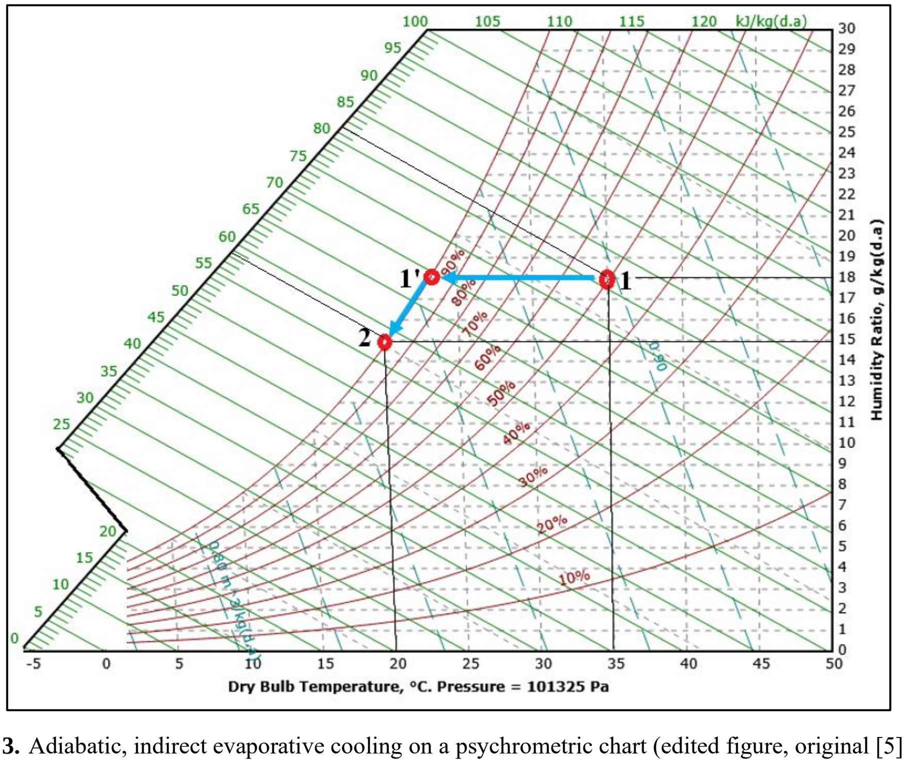

Fig. 3. Adiabatic, indirect evaporative cooling on a psychrometric chart (edited figure, original [5]).

During the indirect cooling of the initial state of the air is T_1=35°C and φ_1=50%. While cooling its temperature decreases along with its enthalpy, while its absolute humidity keeps constant until state **1'** while its relative humidity becomes 100%, which is called the dew point. From this point if more heat is subtracted by the heat exchanger the temperature and the enthalpy of the air decreases while its relative humidity keeps constant (**1'**–**2**). This means a decrease in the absolute humidity thus the difference of the absolute humidity (18-15=3 g/kg d.a., see diagram) condensates on the surface of the heat exchanger. This process happens in case of the indoor part of the conventional compressor driven A/C units. The reason why the relative humidity of the air in the room is not high is that the air in state **2** is mixing with the air in the conditioned room while its temperature increases and its relative humidity decreases. This process finally decreases both the temperature and the humidity since both energy subtraction and condensation occurs.

In the previous case condensation occurred so the processed air had less humidity. But this is not the case if the initial humidity is lower or the temperature drop is not enough to reach the dew point, which can happen when indirect evaporative cooling is used with smaller temperature drop. In this case there is no change in the absolute humidity, only the temperature decreases. This means a cooled air with higher relative humidity which is may not suitable for the people. To solve this problem, it is necessary to dry the air in a separated process or, as it is going to be presented a complex process can be applied where both cooling and dehumidification occurs. This process will be applied in our experimental evaporative air conditioning system.

4 Experimental indirect evaporative cooler and dehumidifier unit

As it was shown, due to the small temperature drop of the evaporative cooling condensation may not occur in case of indirect cooling which results cooled but humid air. To solve this problem a hygroscopic material, so called desiccant has to be applied. The desiccant may be a solid substrate with high specific surface area, e.g. several metal-salts or silica gel which adsorbs a huge amount of water on its surface, or liquid desiccant, e.g. salt-water solution. The cooled air has to be in contact with the desiccant material in order to give some of its humidity to the desiccant and hence it becomes dryer. This process is exothermic, so it increases the temperature of the desiccant and the air too, so it has to be taken into account.

Our experimental device was inspired by Robert Heron by his indirect-evaporative cooler video on the "Tech Ingredients" YouTube-channel [17]. This device applies solution of calcium-chloride ($CaCl_2$) and water which is pumped into a sprinkler in a desiccant and cooling-tower where both cooling and drying happens. During the process of drying the initially concentrated desiccant solution becomes more and more diluted so it has to be regenerated. This can be done by heating up and then mixing with ambient air which becomes more humid while the desiccant becomes more concentrated.

The 3D model of the experimental system can be observed in Figure 4.

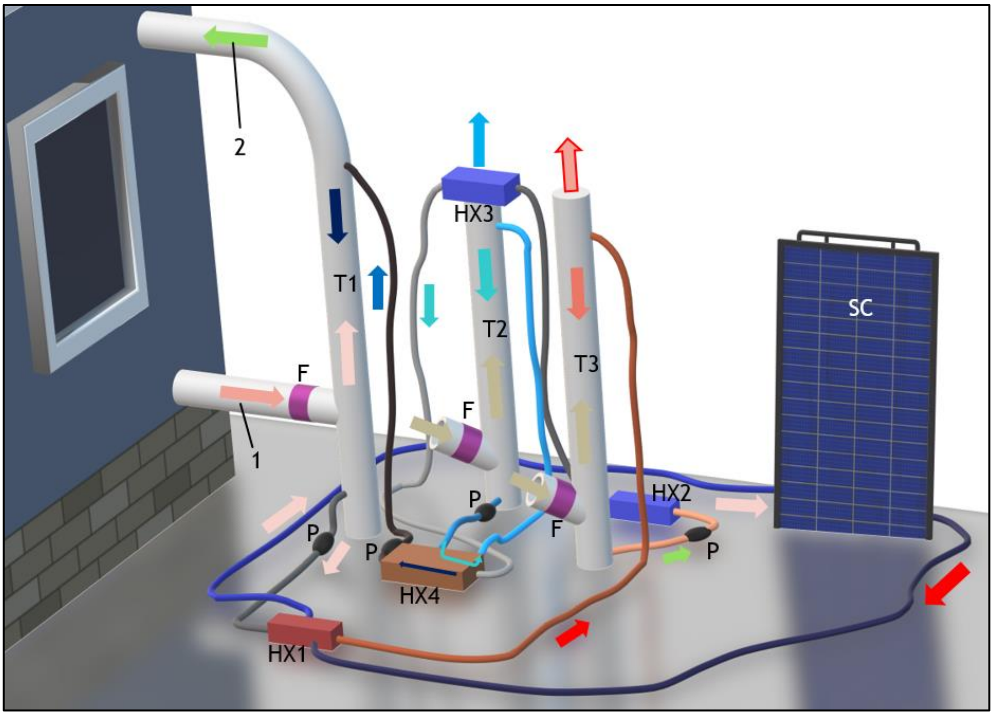

Fig. 4. 3D drawing of the experimental indirect evaporating A/C system. Notations: 1: room air to be treated, 2: conditioned air, F: fan, HX: heat exchanger, T: tower, P: pump, SC: solar collector.

The operation of this system is the following. The warm and humid room-air (1) is circulated by an axial fan (F) through the cooler and dehumidifier tower (T1) and is re-circulated to the air-conditioned space through pipe 2. In tower T1 a sprinkler is used to produce desiccant droplets of cooled and concentrated $CaCl_2$ solution that falls downward, in counterflow direction. Here the desiccant absorbs moisture from the air while it cools the air down, too. As a result, the desiccant solution warms up and become diluted, so it must be regenerated. Following this diluted solution is circulated by a pump (P) and it passes through the liquid-liquid heat exchanger (HX1) in which it is heated up by the hot heat transfer fluid coming from the solar collector (SC). The heat which is required to heat up the diluted desiccant solution can be produced by using several kind of energy sources, like electrical energy, natural gas or, in our case it utilizes the energy captured in solar collector. In terms of the whole A/C system this energy input is the dominant to maintain the system itself which makes it clear that this energy must be provided by a cheap and or a sustainable source. Since thermal energy is needed, one of the most obvious solution is the solar energy utilizing solar collectors.

The hot and diluted solution is then introduced into the regenerator tower (T3) where a sprinkler makes droplets which free fall downwards, against the flowing outside air which is blown through the tower by an axial fan (F). As a result, the hot diluted solution gives a part of its heat and water content to the flowing air, so a warm and concentrated solution leaves the tower at its bottom. A pump (P) pumps the warm solution through an air-liquid heat exchanger (HX2) where it gives off some of its heat thus it cools down a little bit higher temperature than that of the ambient air. Following this solution is pumped through another air-liquid heat exchanger (HX3) where it is cooled down below the temperature of the ambient air. To do so, evaporative cooling is applied in the tower 2 (T2).

In T2 tower distilled water is circulated in counterflow direction to the ambient air. A sprinkler is used at the top of the tower to make water droplets which fall downwards in the upwards flowing air. As a result, the droplets partially evaporate (need to be refilled) and hence cool down while the flowing air is cooled as well (see Fig. 2 for the process of the direct evaporative cooling). This cooled and moist air is therefore capable to cool down the desiccant solution below the temperature of the ambient air. Since in tower 2 the water is recirculated in a closed system by a pump (P), its temperature – with good approximation – decreases to the dew point of the ambient air. This cooled water is then used to further cooling of the diluted solution coming from HX3 by using a counterflow coaxial liquid-liquid heat exchanger (HX4). Finally, the concentrated solution has almost the same temperature as the dew point temperature of the ambient air, and it is pumped back to the tower 1 (T1) to cool and dry the indoor air so the cycle starts again.
For better understanding of the cycle, the heat transfer and the temperature-changes of the medias involved in the process can be observed on a temperature as a function of transferred heat (*Q*-*T*) diagram in Figure 5. Note that nor the temperatures nor the transferred heats are to scale.

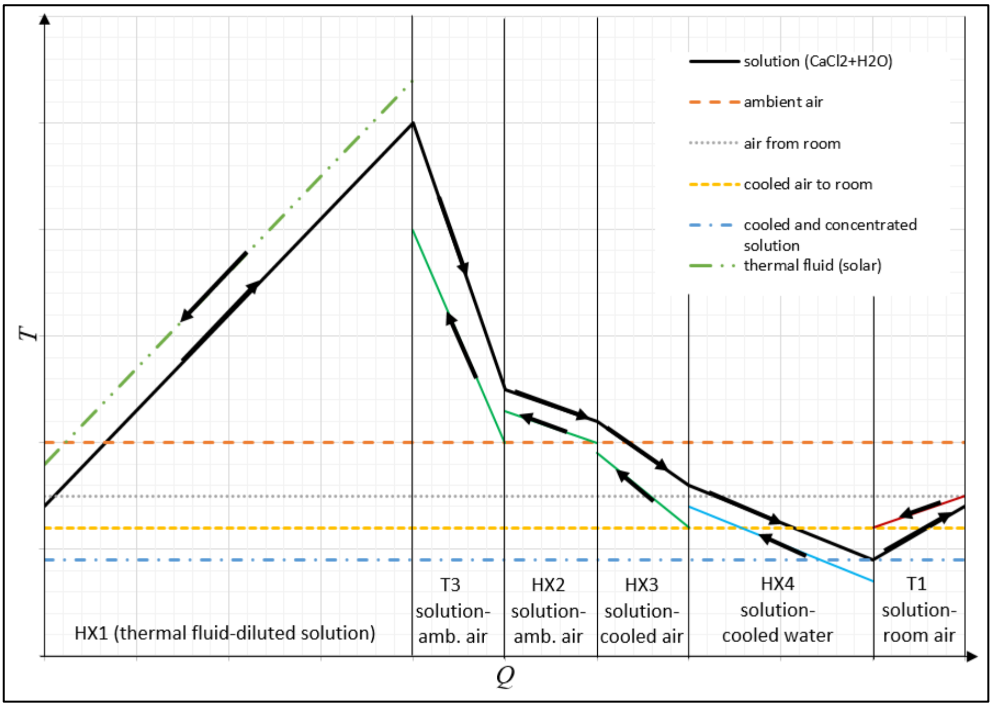

Fig. 5. The *T*-*Q* diagram of the heat transfers occur in the medias of the cycle. Ascending arrows denote heating while descending arrows denote cooling of the media.

The previously introduced system is going to built in the year 2022. As a first step the heat required for regeneration will be provided by electric power – instead of solar power – which can be controlled well. The system will be equipped with several thermocouples and humidity-sensors as well as mass flow meters and electric power meters to measure the power consumption of the fans and the pumps. The laboratory of the department has air conditioning chamber with 41 m^3 of airspace which in one case will be used as the room to be air conditioned so the experimental system will be placed outside of the chamber. During experiments target the investigation of the effects of the outer air properties the system will be placed in the chamber and only the air inlet (1) and outlet (2) will be connected to the outer air (the air of the laboratory). The purpose of the experimental system and its investigation is to characterize its working parameters and to optimize the parts of the system.

5 Conclusion

In this paper the fundamental processes applied in evaporative coolers were presented with a possible implementation of an experimental indirect evaporative air cooling and dehumidification system which applies hydrophilic salt solution as a desiccant and cooling agent. It was presented how the direct evaporative systems increase the humidity of the cooled air which has to be avoided ins several applications. Besides the disadvantage of the indirect evaporative cooling was presented as well, namely the increase of the relative humidity while the absolute humidity remains constant. This is due to the relatively low achievable temperature drop by the evaporative cooling which is not sufficient to develop condensation which would decrease the water content of the treated air.

Both leaded to the indirect evaporative system which is capable to decrease the absolute humidity while cooling the treated moist and wet air. The power consumption of the presented system is mainly due to the heating of the desiccant solution for regeneration. This heat input can be provided by utilizing solar energy (e.g. solar collector). In this case only the power demand of the fans, pumps and control should be provided by electric power, which makes such a system both economical and sustainable.

References

1. D. Bishoyi, K. Sudhakar, *Experimental performance of a direct evaporative cooler in composite climate of India*, Energy and Buildings, **153**, pp. 190-200 (2017)
2. ANSI/ASHRAE standard 55–2010: *Thermal Environmental Conditions for Human Occupancy*, American Society for Heating, Refrigerating and Air Conditioning Engineers Inc, Tullie Circle, NE, Atlanta (1791)
3. T. Bottomley, E. Roth, *Compendium of human responses to the aerospace environment. 6. Thermal environment.* NASA CR-1205(1). NASA Contractor report, United States, NASA (1968)
4. M. N. Shaharon, J. Jalaludin, *Thermal comfort assessment-A study toward workers' satisfaction in a low energy office building.* American Journal of Applied Sciences, **9**,7, 1037. (2012).
5. Online Interactive Psychrometric Chart. http://www.flycarpet.net/en/psyonline; access: 05.02.2022.
6. J.R. Camargo, C.D. Ebinuma, S. Cardoso, *A mathematical model for direct evaporative cooling air conditioning system,* Engenharia Térmica **4**, pp. 30–34. (2003)
7. J.R. Camargo, C.D. Ebinuma, J.L. Silveira, *Experimental performance of a direct evaporative cooler operating during summer in a Brazilian city*, Int. J. Refriger. **28**, pp. 1124–1132. (2005)
8. I. Kovacevic, M. Sourbron, *The numerical model for direct evaporative cooler,* Appl. Therm. Eng. **113**, pp. 8–19. (2017)
9. A. Franco, D.L. Valera, A. Pena, *Energy efficiency in greenhouse evaporative cooling techniques: cooling boxes versus cellulose pads,* Energies **7**, pp. 1427–1447. (2014)

10. Y.M. Xuan, F. Xiao, X.F. Niu, X. Huang, S.W. Wang, *Research and application of evaporative cooling in China: a review (I)−research*, Renew. Sustain. Energy Rev. **16**, pp. 3535–3546. (2012)
11. Y.M. Xuan, F. Xiao, X.F. Niu, X. Huang, S.W. Wang, *Research and application of evaporative cooling in China: a review (II) −system and equipment*, Renew. Sustain. Energy Rev. **16**, pp. 3523–3534. (2012)
12. M. M. Rafique, P. Gandhidasan, S. Rehman, L. M. Al-Hadhrami, *A review on desiccant based evaporative cooling systems*, Renew. Sustain. Energy Rev. **45** pp. 145–159 (2015)
13. E. D. Rogdakis, I. P. Koronaki, D. N. Tertipis, *Experimental and computational evaluation of a Maisotsenko evaporative cooler at Greek climate*, Energy Build. **70** pp. 497–506. (2014)
14. J. M. Moran, H. N. Shapiro, D. D. Boettner, M. B. Bailey, *Fundamentals of Engineering Thermodynamics*. John Wiley & Sons Inc. (8^{th} issue), (2014)
15. D. Bishoyi, K. Sudhakar, *Experimental performance of a direct evaporative cooler in composite climate of India*, Energy and Buildings **153** pp. 190-200. (2017)
16. H. Caliskan, A. Hepbasli, I. Dincer, V. Maisotsenko, *Thermodynamic performance assessment of a novel air cooling cycle: Maisotsenko cycle*, I. J. Refrigeration, **34**, 4 pp. 980-990, (2011)
17. R. Heron: Tech Ingredients channel (https://www.youtube.com/c/TechIngredients); access: 07.13.2022.