Desalination and Water Treatment
www.deswater.com
doi: 10.5004/dwt.2022.29065

279 (2022) 36–41
December

Two-stage evaporative cooling for improving poultry housing environment in Algerian arid zones

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Received 30 June 2022; Accepted 25 September 2022

ABSTRACT

The hot and dry climate of countries with arid and semi-arid zones is the main reason that poultry products are less available and more expensive than elsewhere. Investing in livestock in these regions requires the use of suitable cooling systems that humidifies the dry air and lowers its temperature. Thermal environment control in poultry houses is greatly recommended to ensure good productivity. In the present work, a cooling solution was proposed with very low energy consumption and that did not use harmful refrigerants, for economic, ecological, and sustainable farming. It consists of a two-stage indirect/direct evaporative cooling system that reduces the temperature and increases specific humidity to maintain animal comfort conditions inside the poultry house. Biskra City in Algeria with a hot and dry climate was employed as a case study. The evaporative cooling system used the outside air, for air circulation needs in the poultry houses.

Keywords: Evaporative cooling; Humidification; Ventilation; Solar energy; Poultry housing; Broiler production

1. Introduction

Availability, affordability and accessibility are the primary factors in food security. Availability is based on the production rate and may be improved by using additional land for agriculture and animal breeding. However, high temperatures and droughts keep occurring with greater frequency due to climate changes. Nevertheless, greenhouses can have a real impact by diminishing extreme weather conditions and thus improving productivity. Various technologies have been implemented to ensure the control of heating, cooling, humidity, and toxic gases [1].

In poultry houses, chickens' wellbeing affects the productivity. Chickens are warm-blooded animals that maintain a constant internal body temperature. However, during the feathering phase (1 day–3 weeks of age), they are sensitive to cold thermal stress. After the 5th week, birds have excellent insulation and will be sensitive to excess heat. A comfortable temperature is in the range of 22°C–27°C [2]. When the temperature rises, exceeding the animal's ability at adaptation (i.e., $T > 30°C$), a heat stroke can be experienced by the animal and is manifested by exhaustion thus causing significant mortalities [3]. Properly regulated effective cooling is arguably the most important factor to manage the atmosphere of a poultry housing building, by fighting against excess heat and humidity, for successful farming.

The relative humidity of the air is also an important factor that influences the development of pathogens and the condition of the litter. On the other hand, the humidity has no direct effect on the behavior of a chicken but can

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Presented at the First International Congress of Energy and Industrial Process Engineering (ICEIPE'22) 23–25 May 2022, Algiers, Algeria
1944-3994/1944-3986

cause problems indirectly. Thus, a dry atmosphere leads to a dusty litter, irritating the respiratory tract and disseminating microbial infections. The optimum relative humidity for raising chickens is between 60% and 75%. Beyond that, pathological risks may appear [2]. Likewise, the cooling method is also an important factor in poultry farming. It depends on the climatic conditions. In dry and hot climates such as southern Algeria, evaporative cooling has proven to be efficient [4]. Low-energy processes offer substantial savings and fall within an energy efficiency range comparable to vapor compression systems.

In the north of the country, the climate is hot and humid; evaporative cooling system effectiveness decreases and the process can no longer ensure adequate cooling. Desiccant cooling system powered by solar energy could be an interesting alternative in these conditions [5]. It is low energy consuming and does not use harmful refrigerants. Furthermore, using solar energy is a motivating option since there is a balance between the cold demand and high temperature periods. The desiccant cooling process could be in liquid or solid phase. It is an innovative technology to refresh based on water state changes, solar energy exploitation and desiccant materials use [6].

This study was aimed at evaluating the performance of a two-stage evaporative cooling system for an arid zone climate using Biskra City in Algeria as a case study. The two-stage indirect/direct evaporative cooling system is compared to direct evaporative cooling one. Both were investigated for thermal comfort based on temperature-humidity index (THI) of poultry birds. Feasibility analysis of these systems was carried out to choose the more suitable device for poultry cooling in arid zones. The operating principle of both systems was assessed with performances evaluated taking into account temperature and relative humidity for the poultry bird's comfort.

2. Materials and methods

2.1. Evaporative cooling systems

Evaporative cooling systems are classified in three main categories, direct evaporative cooling (DEC), indirect evaporative cooling (IEC) or the combination of both (IEC/DEC). In direct evaporative cooling (DEC) systems, hot and dry outside air draw in through a wetted filter pad fed with water from a reservoir at its bottom. The water in the pad evaporates, absorbing heat from the air. Consequently, the air is humidified and its temperature decreases. The collected air after wet pads has a dry bulb temperature approximating the wet bulb temperature of the surrounding air. Cool, moist air is then blown across the space to be refreshed. However, the humid supply air could never be cooler than the wet bulb temperature; direct evaporative cooling is than more effective in arid zones with hot and dry climates [7]. Typical evaporation efficiencies are in the range of 75%–95% [8]. They work best in hot, dry conditions and are not very suitable for humid environments. They cannot achieve a large temperature drop and they add more moisture to the already humid air [9].

It is important to note that the efficiency of the evaporative cooler depend on several factors, as the evaporative pad thickness, the air velocity, the dry and wet bulb temperature of the outside air [Eq. (1)].

$$\varepsilon_e = \frac{t_1 - t_2}{t_1 - t'} \tag{1}$$

where ε^e = (DEC) direct evaporative cooling effectiveness, %; t_1 = dry-bulb temperature of entering air, (°C); t_2 = dry-bulb temperature of leaving air, (°C); t' = wet-bulb temperature of entering air, (°C).

The supply air temperature (t_2) can be calculated from Eq. (1) to give Eq. (2):

$$t_2 = t_1 - \varepsilon_e \left(t_1 - t'\right) \tag{2}$$

The indirect evaporative cooling (IEC) system cools air using a secondary air stream produced by a direct evaporative cooling by means of a heat exchanger. As cooling takes place without mixing of the two streams, the primary outdoor air stream temperature decreases without an increase in its humidity. This process is effective in moderate or high humidity regions. Indirect evaporative cooling effectiveness ranges from 50% to 80% [10] [Eq. (3)].

$$\varepsilon_{\text{ie}} = \frac{t_1 - t_2}{t_1 - t_s'} \tag{3}$$

where ε_{ie} = (IEC) indirect evaporative cooling effectiveness, %; t_1 = dry-bulb temperature of outdoor air, (°C); t_2 = dry-bulb temperature of exhaust air, (°C); t_s' = wet-bulb temperature of (DEC) air, (°C).

One more type of evaporative cooling is a combination of both systems (DEC) and (IEC), known as two-stage evaporative cooling. In the first stage (IEC), the primary air temperature decreases without changing moisture. After this sensible change, the air is wetted in the second stage and consequently cooled further as shown in Fig. 1c. The effectiveness of the indirect/direct evaporative system is in a range of 108% and 111% [11].

For the rest of the work we will consider the two systems DEC and the combined IEC/DEC. The IEC system will not be considered alone since it cannot be sufficient to ensure the cooling required in the arid and semi-arid regions climatic conditions.

The IEC system is used in combination with the DEC to provide a two-stage evaporative cooler.

Fig. 2 illustrates the cooling process of the two systems on the psychrometric chart.

2.2. Poultry house cooling loads

To evaluate the cooling loads for the cooling system design, all heat release parameters of the poultry house and animals must be considered. The poultry house was 8 m wide by 10 m length and 5 m high, occupied by 1200 chickens with a part reserved as a food storage. There was two doors each of 2 m length and 3 m width. The surface of windows was 1.05 m^2 [2]. The provided light was principally artificial 23 h of light with an intensity of 3 w/m and 1 h of darkness to allow the chicks to get

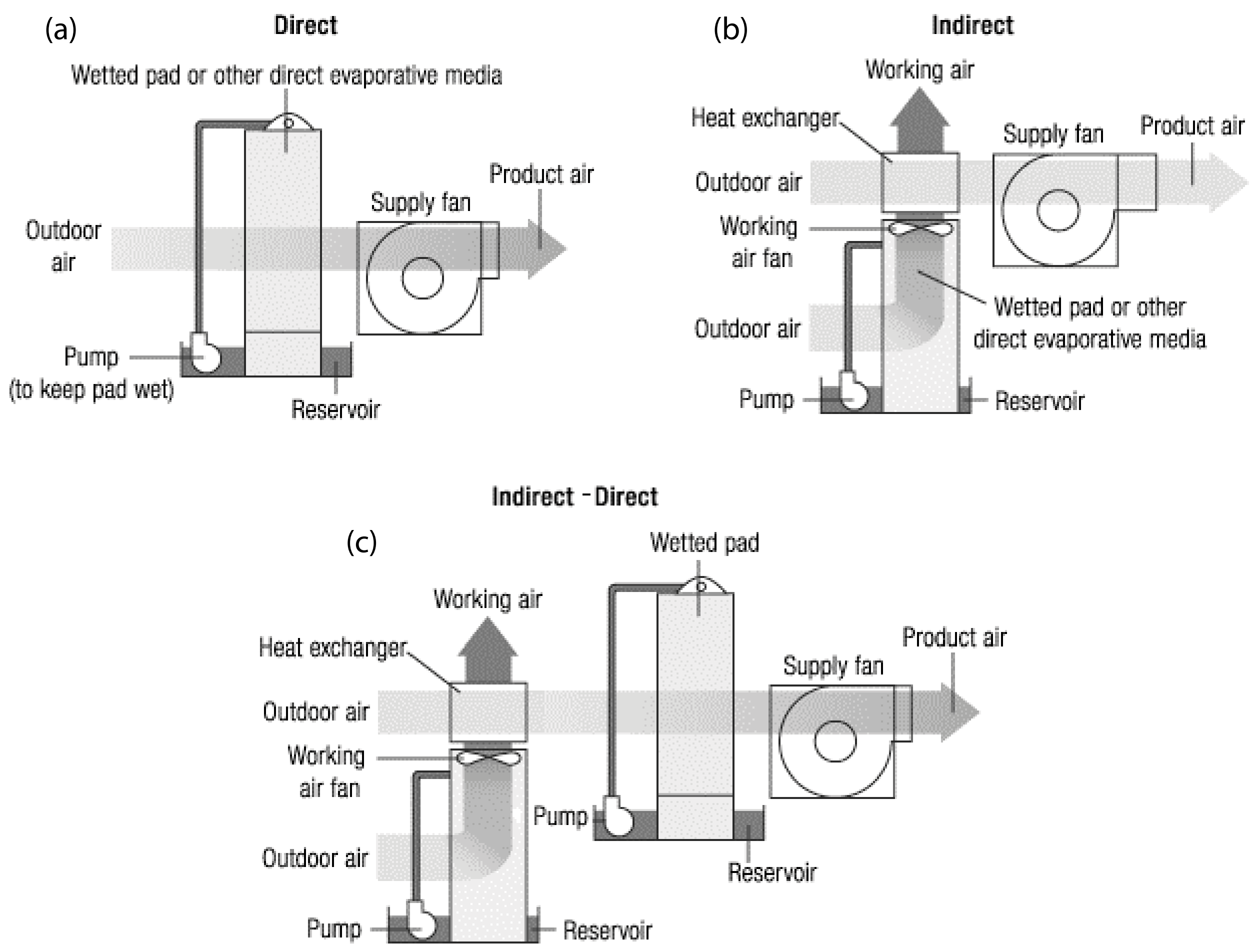

Fig. 1. Evaporative cooling systems modes: (a) DEC, (b) IEC and (c) combined IEC/DEC.

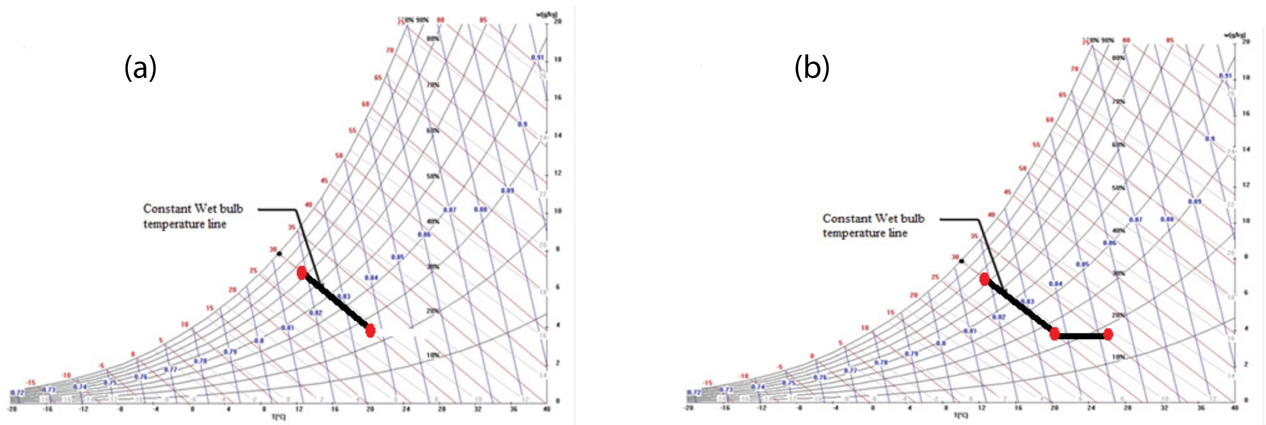

Fig. 2. Psychrometric chart representation for evaporative cooling process: (a) one-stage (DEC) and (b) two-stage (IEC/DEC).

use to the darkness in case of a blackout [2]. Air movements influenced the thermal comfort of animals. An air speed of 0.20 to 0.30 m/s characterized calm air [12]; the air movements was homogeneous over the entire living area of the animals. When breeding temperatures was at the critical lower limit, air velocity should be between 0.1 and 0.2 m/s. On the other hand, in the case where the upper critical temperature was exceeded (at the end of breeding, in the hot season), an increase in these speeds (0.3–0.7 m/s or even more) helped to maintain the thermal balance of animals by allowing them to increase their heat loss by forced convection [12].

Heat produced by the birds and their temperature-humidity index were required. Sensible and latent heat produced per animal had to be calculated. Fig. 3 represents an illustration of evaporative cooling system into a poultry house. Heat loads produced by a poultry bird are illustrated; they depended, basically on bird's weight. The birds grew muscles by consuming food and producing energy and thus more heat [13]. The heat produced by poultry was governed by Eq. (4) [14].

$$\text{HP} = 60.64 + 0.04\text{LW} \quad (4)$$

where HP is the heat produced by animal (W/kg); LW is the animal weight (kg).

Heat production per animal was calculated using the Pedersen model [Eqs. (5) and (6)] [15,16].

$$Q_t = 9.84 m_a^3 \left(4.10^{-5}\left(20 - T_{\text{db}}\right)^3 + 1\right) \quad (5)$$

$$Q_t = 0.83 Q_t \left(0.8 - 1.85e^{-7}\left(T_{\text{db}} + 10\right)^4\right) \quad (6)$$

where Q_t: total heat production (J/s), Q_s: sensible heat production (J/s), m_a: animal mass (kg), T_{db}: dry-bulb temperature (°C).

A linear combination of dry-bulb and wet-bulb temperature gives the temperature humidity index (THI) [Eq. (7)]. It evaluates the environment thermal conditions effect on comfort regulating status of poultry birds [17].

$$\text{THI} = 0.85 T_{\text{db}} + 0.15 T_{\text{wb}} \quad (7)$$

where THI: temperature humidity index (°C), T_{wb}: supply air wet-bulb temperature (°C).

The wet-bulb temperature is given by Eq. (8) [18,19].

$$T_{\text{wb}} = T_{\text{db}} \tan^{-1}\left[0.151977 + \left(\text{RH} + 8.313659\right)^{1/2}\right] + \tan^{-1}\left(T_{\text{db}} + \text{RH}\right) - \tan^{-1}\left(\text{RH} - 1.676331\right) + 0.00391838\text{RH}^{3/2} \tan^{-1}\left(0.023101\text{RH}\right) - 4.68603 \quad (8)$$

where RH: relative humidity of air (%).

3. Results and discussions

In July, the hottest month of the year, the weather in Biskra is extremely hot. The average temperature is 34.5°C, with a minimum of 28°C and a maximum of 40.9°C. On the hottest days of the month, the temperature usually reaches around 46°C.The air is dry with an average humidity of 26%. The average wind speed is 14 km/h.

Hourly simulation of the two evaporative cooler types (two-stages IEC/DEC and one-stage DEC) under TRNSYS software environment and three consecutive months simulation: June, July and August are given. Actual meteorological data of an arid zone (City of Biskra) were used in the simulation outlet temperature and relative humidity has been carried out. Evaporative pad manufacturer's technical data have been implemented in the model to evaluate the performances of each device. An effectiveness of 0.85% was applied in the model [20].

The viability of using evaporative cooling process in poultry house is confirmed by using the feasibility index (FI) method, it is defined by Eq. (9):

$$\text{FI} = T_{\text{wb}} - \Delta T \quad (9)$$

When the difference between dry bulb and wet bulb temperature increases, the feasibility index decreases. The evaporative cooling will be more efficient as FI is smaller. This number specifies the evaporative cooling potential to refresh ensures comfort. Under or equal to 10, it indicates the needed comfort cooling. Between 11 and 16 concerns moderate cooling. FI over than 16 indicates that the use evaporative cooling systems is not recommended. At least 12°C of wet bulb temperature depression is needed [4]. Fig. 4 shows the difference between the ambient temperature and the wet bulb temperature. It indicates that the feasibility index was less than 15 which classified the case study site of Biskra as being suitable for evaporative cooling technology.

The difference between the outlet temperatures of the two systems during the hottest day in July is given

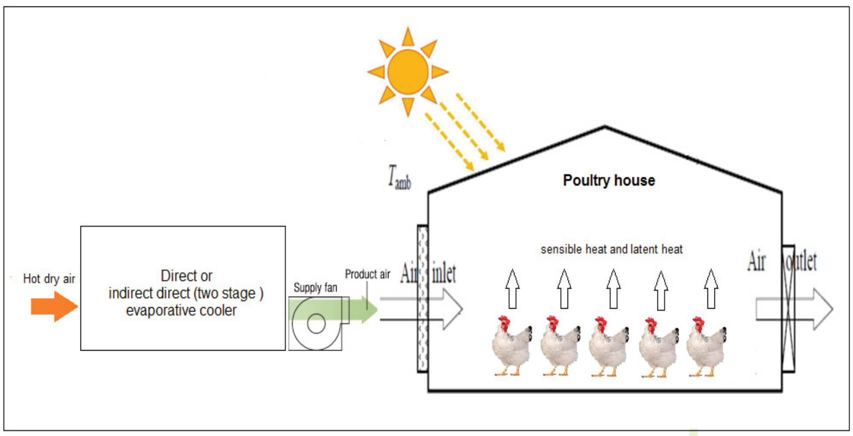

Fig. 3. Scheme of evaporative cooling systems in a poultry house.

in Fig. 5. For ambient temperature of 40°C a temperature of 21°C can be reached for the two-stages (IEC/DEC) and 25°C for the one-stage (DEC). An average cooling of 15°C of decreased temperature was obtained for direct evaporative cooling (DEC) and 19°C for two-stages evaporative cooling (IEC/DEC). The two-stage evaporative cooler was more efficient and provided better conditions.

Fig. 6 shows that the maximum temperature difference between the one-stage (DEC) and the two-stage systems was 5.4°C and it occurred in the month of July which had the lowest relative humidity. It means that the less the relative humidity, the greater the temperature difference.

It can be concluded that in the case study's hot and dry climate, the evaporative cooling technology was suitable for poultry house cooling. Comparing the two processes, the two-stage (IEC/DEC) was more effective than the one-stage and the former could achieve lower temperatures with the same outlet relative humidity.

Results confirmed that the difference between evaporative cooler outlet and outdoor air relative humidity in the case study's climate was acceptable for animal comfort. Figs. 7 and 8 show the relative humidity evolution where the values came closer. This was since in the second stage or indirect evaporative cooler there was a sensible transformation so that the relative humidity changed in the direct evaporative cooler. The specific humidity remained almost the same and relative humidity changed a little. It appeared that the inlet air was refreshed by decreasing its temperature and increasing its humidity for both types (DEC) and two-stage (IEC/DEC). The two devices were well suited for comfort cooling in poultry houses in arid areas. An average moisture improvement of 63% was obtained that matched with the recommended indoor conditions of poultry environment for bird's wellbeing and better productivity.

On the other hand, the two-stage evaporative cooler (IEC/DEC) was distinguished by a temperature reduction comparable to the one-stage evaporative cooler (DEC). The two-stage evaporative cooler was thus the recommended solution for poultry house refreshing in arid zones hot and dry climate.

4. Conclusion

The two-stage evaporative cooling system (IEC/DEC) is the satisfactory solution for poultry house cooling. The humidity and temperature ratio difference of the supply and ambient air were the principal parameters involved under arid zones conditions. A temperature of 21°C can

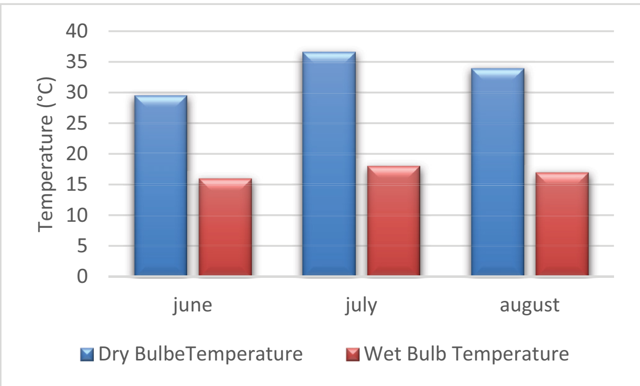

Fig. 4. Difference between the ambient temperature and the wet bulb temperature.

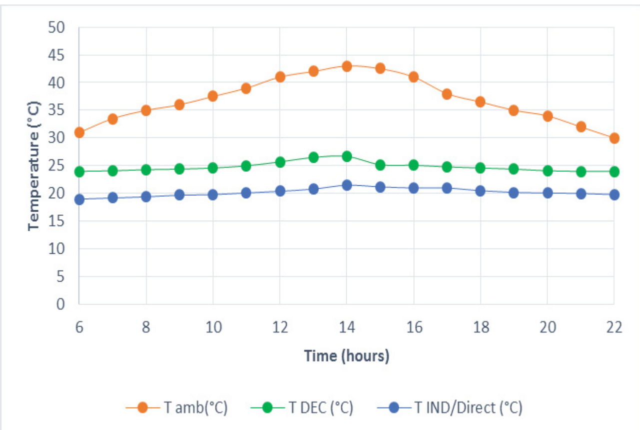

Fig. 5. Outlet temperatures of the two systems (DEC) and (IEC/DEC) during the hottest day in July.

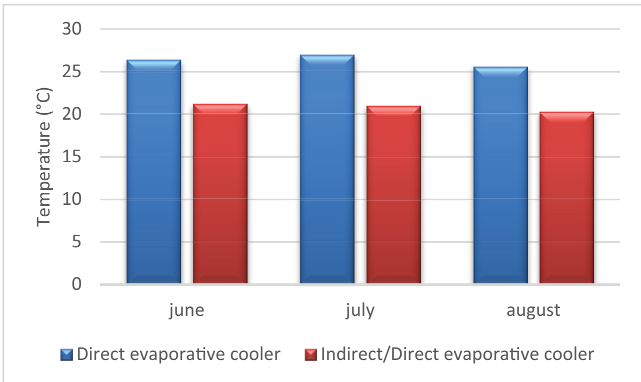

Fig. 6. Maximum monthly average temperature difference between the two-stage (IEC/DEC) and the one-stage (DEC) systems.

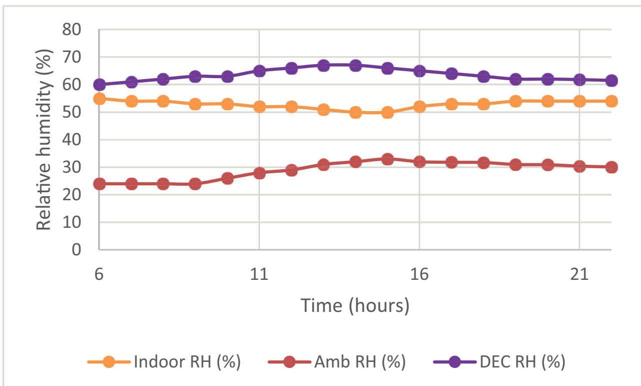

Fig. 7. Relative humidity (RH) evolution in DEC system.

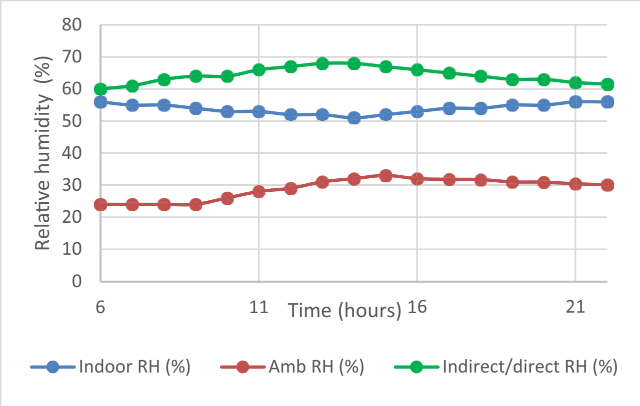

Fig. 8. Relative humidity (RH) evolution in IEC/DEC system.

be reached, an average moisture improvement of 63% was obtained and a gap of 19°C decreased temperature can be achieved with 40°C of ambient temperature. Those results match and are consistent with the requirements for raising chickens which are 22°C to 27°C of temperature and a relative humidity between 60% to 75%. The equipment is well adapted for the hot and dry arid southern regions of the case study region.

Consequently, the use of two-stage evaporative cooling system could stimulate poultry farming in these regions and allow for investing in livestock. The two-stage evaporative cooling system has furthermore no influence whatsoever on the environment since it does not use harmful refrigerants. Its energy consumption is much lower compared to conventional air conditioning equipment and therefore applications in poultry buildings are highly recommended for the affordability of broilers' meat. In isolated areas, the use of solar photovoltaic energy allows farm operators to break free from conventional pollutant energy sources. This is a very attractive, economic, and environmentally friendly choice for sustainable livestock and agriculture.

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