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SOLAR ASSISTED EVAPORATIVE COOLING BASED PASSIVE AIR-CONDITIONING SYSTEM FOR AGRICULTURAL AND LIVESTOCK APPLICATIONS

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Abstract

Solar-chimney assisted evaporative cooling based passive-air-conditioning (SCAC) system has been investigated for different climatic cities of Pakistan. Driving force of system is based on solar chimney and electric fan for day and night time operations, respectively. Ideal temperature and humidity zones are formulated for agricultural products' storage and animals' thermal comfort. Recent studies have proven the advancement of Maisotsenko Cycle (M-Cycle) in air-conditioning (AC) field; therefore, SCAC system utilizes M-Cycle conception in order to achieve dew-point cooling. On the basis of M-Cycle experimental data available via literature, study provides thermodynamic investigation of SCAC system for various conditions. Two simplified correlations are developed for performance evaluation of M-Cycle unit. Both correlations showed precise agreement with experimental data with $R^2 > 0.95$. The SCAC system could achieve sensible load of AC efficiently for various applications; however, performance index varies according to climatic conditions. The SCAC system's applicability was found limited in humid areas because of nature of M-Cycle operation. Therefore, it has been concluded that system may not be sustainable as standalone AC, but it can be a convenient solution in order to reduce the AC load. Moreover, it can provide chilled ceiling for various applications with the low-cost operation. It can be efficiently utilized in most of the dry and moderate areas, whereas, the system's applicability is limited in humid and water scared regions.

Keywords: Air-conditioning, Solar chimney, M-Cycle, Agricultural products, Livestock.

Nomenclatures

A_1, B_1, C_1	Constants of correlation-I (Eq. 5), dimensionless
A_2, B_2, C_2	Constants of correlation-II (Eq. 6), dimensionless
h	Enthalpy, kJ/kgDA
H^{spc}	Air specific humidity (humidity ratio), g/kgDA
Q	Specific cooling capacity of M-Cycle unit, kW/(kg/s)
R^2	Coefficient of determination, dimensionless
RH	Relative humidity, %
T	Air temperature, ºC

Subscripts

db	Dry-bulb
dp	Dew-point
i	Inlet
o	Outlet
wb	Wet-bulb

Abbreviations

AC	Air-Conditioning
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
FAO	Food and Agriculture Organization
IEC	Indirect evaporative cooling
M-Cycle	Maisotsenko Cycle
SCAC	Solar-chimney driven passive air-conditioning

1. Introduction

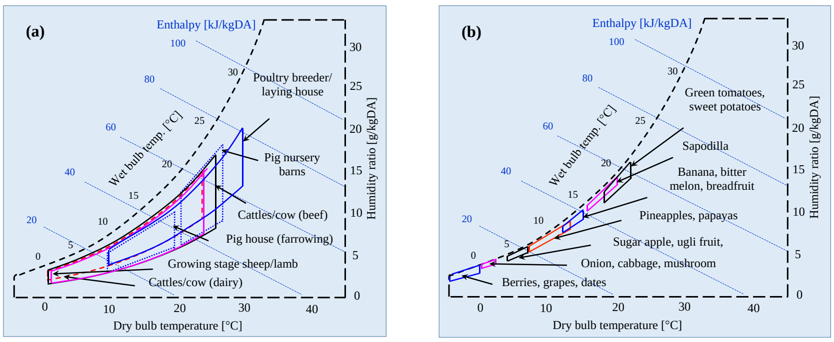
Modern lifestyle requires a huge amount of primary energy due to extensive and precise thermal comfort in terms of heating, cooling, ventilation, humidification, and dehumidification [1-3]. In this regard, air-conditioning (AC) becomes basic the need for offices, buildings, schools, shopping malls, and transport buses/trains etc. Therefore, lots of research and systems have been studied and are in practice in order to achieve humans' thermal comfort. However, animals' thermal comfort is hardly studied and implement especially in developing countries. Similarly, in the agricultural sector of developing countries, proper storage structures, as well as conditions, are rarely accomplished for the storage of post-harvest agricultural products due to the high pricing of conventional AC technologies.

From the above perspective, authors investigate the M-Cycle [4] based renewable energy (i.e., solar-chimney) driven passive air-conditioning (SCAC) system for various climatic cities of Pakistan. The study is focused on considering the system's application in agriculture and livestock industry [5, 6]. As water vapor evaporation into the air is the key scientific concept behind the M-Cycle principle, therefore, the application of M-Cycle as well as proposed SCAC system will be limited in humid areas. However in humid regions many thermally driven technologies can also be considered intelligently which could perform better economically than conventional vapor compression AC [7-10]. Similarly, the combination of evaporative cooling and thermally driven technologies can yield an optimum solution for all kinds of environmental conditions. Moreover, hybrid systems can be considered for high performance and reliability.

The concept of M-Cycle [4] driven SCAC system was first time introduced by Miyazaki et al. [11] which presents the numerical simulation model for the SCAC system. The system is designed in a way that driving force of system could be a solar chimney in daytime, whereas it could be an electric fan for night time operations. One of the key components of SCAC system is M-Cycle unit for dew-point evaporative cooling. Therefore on the basis of M-Cycle system's experimental results available via references [12, 13], linear correlations have been established by optimization technique which can simulate the performance of M-Cycle unit efficiently. It is worth mentioning that all the M-Cycle models available in the literature are complex and require detailed scientific knowledge in order to simulate of M-Cycle performance. On the other hand, the present study provides the simplified correlations, which can predict M-Cycle performance efficiently, consequently shows the novelty of the present work.

Temperature and humidity requirements

Temperature and humidity requirements for ideal AC vary according to nature of an individual application. As far as storage of post-harvest agricultural products is a concern, it may vary according to respiration, transpiration, and fermentation etc. of the agricultural product [14]. On the other hand, the AC requirements for animals are completely different as compared to conventional AC for humans' thermal comfort which is due to the variability in metabolism rate, respiration rate, nature of food and genetic factor etc. [15-19]. In the present study, ideal AC zones are developed on psychrometric charts for various agricultural and livestock applications on the recommendation given by the ASHRAE [5, 17, 20] and FAO [21, 22]. Figure 1(a) shows the ideal AC zones for animal's thermal comfort for: (i) sheep and lambs (growing stage), (ii) dairy cattle and cows, (iii) pig farrowing houses, (iv) pig nursery barns, (v) beef cattle and cows, and (vi) poultry breeders and laying houses. Figure 1(b) shows ideal storage zones for various agricultural products which include: green tomatoes, sweet potatoes, sapodilla, banana, bitter melon, breadfruit, papayas, sweet pepper, pineapples, ugli fruit, sugar apples, cabbage, onion, mushroom, dew/ blue/ black- berries, grapes, and dates etc. [15, 17, 20, 23].



(a) Animals' air-conditioning. **(b) Agricultural products' storage.**

Fig. 1. Psychrometric representation of ideal AC zones for various applications, reproduced from [20].

2. Proposed SCAC System

A typical renewable energy operated evaporative cooling based SCAC system was first time introduced by Miyazaki et al. [3, 11]. The system captures the psychrometric renewable energy from the ambient air (from roof-side) and produces cooling effect via chilled ceiling (in room side). The driving force for the system air flow comes from the thermal head of the solar chimney. The system can be designed in a way that driving force of system could be a solar chimney in daytime, whereas it could be an electric fan for night time operations. A typical schematic diagram of the SCAC system is shown in Fig. 2 [3, 11].

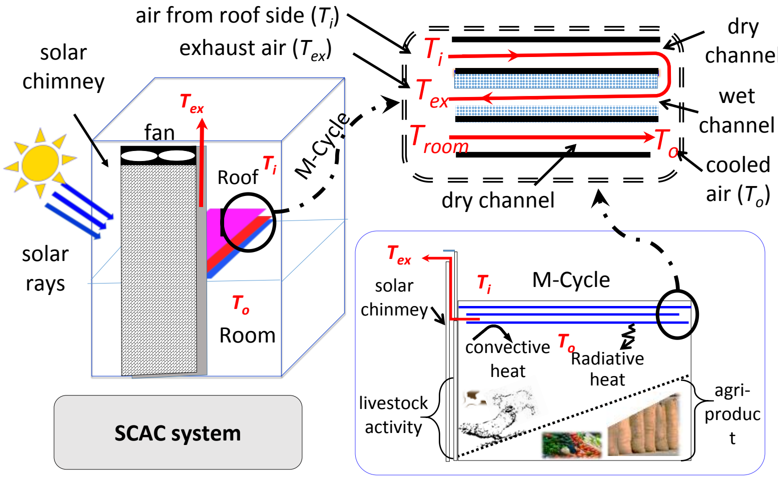


Fig. 2. Schematic diagram of SCAC system for agricultural and livestock applications, reproduced from [11].

Referring to the system schematics, it can be seen that ambient air from roof side is passed from the wet and dry channels of M-Cycle and exhausted into the ambient air. However, water evaporated into the wet channel of M-Cycle unit produced cooling effect due to the heat of water vaporization. Therefore cooling is induced in the conditioned room due to convective and radiative heat transfer from M-Cycle dry channel [11]. This is a kind of indirect evaporative cooling, however, in this case, air has the potential to be cooled to the ambient air dew-point temperature by means of the innovative conception of M-Cycle [24]. M-Cycle attains energy from the air by utilizing psychrometric renewable energy available from the latent heat of ambient air water evaporation [4]. It can be seen that M-Cycle unit has three channels of which two are dry but intermediate channel possesses water for evaporation. Firstly, air from roof side enters in the dry channel and then moved to wet channel where it is cooled due to water vapor evaporation similar to indirect evaporative cooling (IEC). On the other hand, heat is transfer from the room air (lower dry channel in Fig. 2) via radiative and convective heat transfer while keeping the humidity ratio constant. The details of M-Cycle can be found from [4, 24]. It is worthy to mention that the conventional IEC system limits the cooling effect up to the ambient air wet bulb temperature, whereas it is the dew-point temperature in the case of M-Cycle.

3. Research Methods

The SCAC system has been proposed for various agricultural and livestock applications. As the efficiency of SCAC system is based on performance by the M-Cycle unit, therefore, experimental data of M-Cycle unit is explored from the literature carefully. It has been realized that studies by Anisimov et al. (2014) and Pandelidis et al. (2015) can provide the real insights of M-Cycle performance [12, 13]. In the studies [12, 13] a model was developed based on the real M-Cycle experimental data for the estimation of M-Cycle performance for various ambient air conditions. Although the model is precise however requires detailed scientific knowledge of M-Cycle in order to simulate the M-Cycle performance. On the other hand, simplified linear correlations have been developed in the present study in order to simulate the M-Cycle performance for various ambient air conditions. In this regard, experimental data of M-Cycle unit at different ambient air conditions were taken from references [12, 13]. Optimizations technique has been used in MATLAB for the statistical error minimization and confidence interval more than 95%. Consequently, the coefficient of determination (R^2) values were yielded more than 0.95 in each case. It is important to mention that the optimization results are valid for the following ambient air conditions: $T_i \approx$ 20°C to 45°C and $H_i^{spc} \approx$ 10 g/kgDA to 25 g/kgDA. The validity range of optimization covers the typical ambient air conditions for summer season, which can also be realised by psychrometric chart as well as by the ASHRAE guidelines [16-19]. In addition, the optimization codes were based on the following fundamental conceptions presented by equations (1)-(4):

$$T_o = f\left(T_i \, , H_{spc}\right) \tag{1}$$

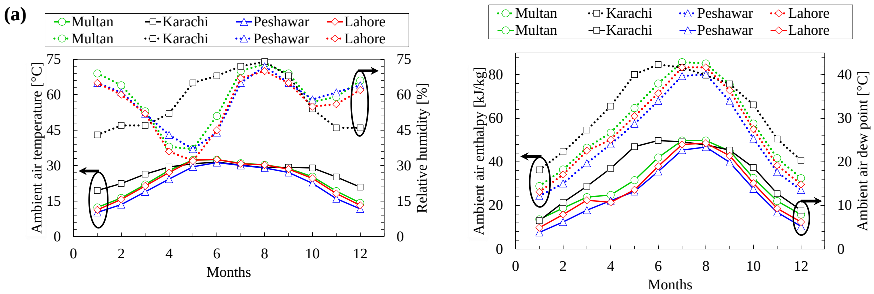
$$H_o^{spc} = H_i^{spc} = H_{spc} \tag{2}$$

$$RH_o \, , h_o \, , T_{dp} \, , T_{wb} = f\left(T_o \, , H_o^{spc}\right) \tag{3}$$

$$Q = f\left(T_i \, , H_{spc}\right) \tag{4}$$

where T_o and T_i represent the outlet and inlet air temperature [ºC], respectively, in the product channel of M-Cycle (lower dry channel in Fig. 2). H_o^{spc} and H_i^{spc} represent the specific humidity or humidity ratio [g/kgDA] of corresponding outlet and inlet air. Q represent the specific cooling capacity of M-Cycle unit [kW/(kg/s)] whereas subscript i & o represent inlet and outlet to the product channel of M-Cycle. The details of the parameters are given in nomenclature. It is worth mentioning that the absolute cooling capacity [kJ/s] is the multiplication of process air flow rate [kg/s] and enthalpy difference of ambient and supply air [kJ/kg]. However, the specific cooling capacity [kW/(kg/s)] is the cooling capacity respected to the 1 kg/s of the process air flow rate [25].

Using the established correlations, performance of the M-Cycle unit as well as SCAC system has been investigated for four different climatic cities of Pakistan: (i) Karachi (24.8615° N, 67.0099° E), (ii) Lahore (31.5546° N, 74.3572° E), (iii) Multan (30.1984° N, 71.4687° E), and (iv) Peshawar (34.0150° N, 71.5805° E). It is worthy to mention that, the metrological data of the cities was obtained from the licensed version of Meteonorm 7 i.e. Swiss Meteotest Company based metrological data bank. Consequently, Fig. 3(a) shows the outdoor air profile (monthly basis) of ambient air temperature and relative humidity whereas Fig. 3(b) represents the outdoor air profile (monthly basis) for ambient air enthalpy and ambient air dew point. Keeping in view the geographic conditions of studies cities in Pakistan's map, one could imagine the results shown in Fig. 3. The climatic conditions are obvious due to the following key points: Karachi is typically humid and windy because it is located on the shores of the Arabian Sea. Lahore is located at the north-eastern end of Punjab and Ravi River flows on the northern side of Lahore. Multan is located in the southern part of Punjab and features an arid climate with very hot summers and cold winters. Peshawar is located on the northern side of Pakistan and features semi-arid climate with hot summers and mild winters.



(a) Ambient air temperature and relative humidity.

(b) Ambient air enthalpy and ambient air dew point.

Fig. 3. Outdoor air profile on monthly basis for four big cities of Pakistan.

4. Results and Discussion

In the present study, solar assisted evaporative cooling based passive air-conditioning (SCAC) system has been proposed for the storage of agricultural products and for animals' thermal comfort. Schematic diagram of SCAC system is shown in Fig. 2 whereas the agricultural and livestock AC applications are represented by psychrometric charts in Fig. 1. It is obvious that the output performance of SCAC system is based on the net performance of integrated M-Cycle unit and the net effect of solar chimney. The system is designed in a way that driving force of system could be a solar chimney in daytime, whereas it could be an electric fan for night time operations.

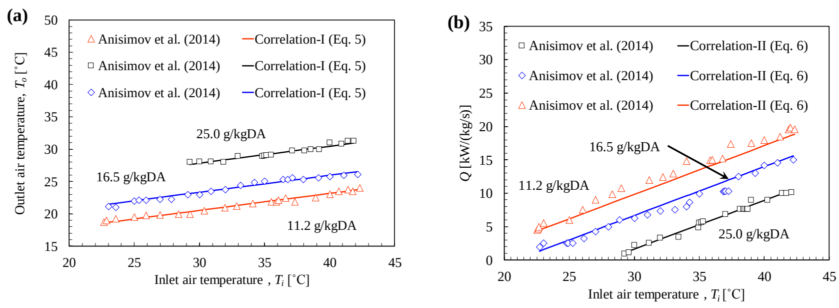
The M-Cycle [4] is well known in AC field due to its potential of dew-point evaporative cooling. The M-Cycle conception was integrated in SCAC system first time by Miyazaki et al. [11] in which the authors developed a simulation model in order to predict the system performance. On the other hand, experimental results of M-Cycle are available in the literature by the studies of Anisimov et al. (2014) and Pandelidis et al. (2015) [12, 13]. Although the studies available via references [12, 13] provide a precise M-Cycle model but requires detailed scientific knowledge of M-Cycle to in order to simulate the system performance. Therefore, simplified linear correlations are established in this study for the approximation of thermodynamic properties of M-Cycle product air as explained in heading 3. The developed correlations are named as: correlation-I (i.e. Eq. 5) for the approximation of M-Cycle product air outlet temperature (T_o), and correlation-II (i.e. Eq. 6) for the approximation of specific cooling capacity

(Q). Both corrections are valid for the ambient air conditions of: $T_i \approx 20°C$ to 45°C and $H_i^{spc} \approx 10$ g/kgDA to 25 g/kgDA.

$$T_o = A_1 + B_1(T_i) + C_1(H_{spc}) \quad (5)$$

$$Q = A_2 + B_2(T_i) + C_2(H_{spc}) \quad (6)$$

where T_o and T_i represent the outlet and inlet air temperature [ºC], respectively, in the product channel of M-Cycle (see Fig. 2). The parameters A, B, and C are the constants of correlations. The optimized values of the constants are given in Table 1. A comparison has been made between the developed correlations (Eqs. 5 and 6) with the experimental data available from references [12, 13]. Figure 4(a) and (b) shows comparison outcomes for outlet air temperature (T_o) and specific cooling capacity (Q), respectively. It can be seen that the simplified correlations can represent the experimental data reasonably for all cases with R^2 values more than 0.95. It is obvious that SCAC system's functionality is based M-Cycle unit whose performance indices are based on ambient air conditions [4]. Therefore, the performance of M-Cycle unit is investigated for four cities of Pakistan i.e. Karachi, Lahore, Multan, and Peshawar, which enable different nature of atmospheric conditions of temperature and humidity. In this regard, thermodynamic properties of M-Cycle product air are estimated by correlation-I and II, Eqs. (5) and (6), for summer and winter seasons.



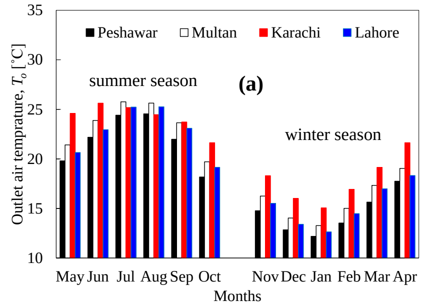
(a) Outlet air temperature. **(b) Specific cooling capacity.**

Fig. 4. Validation of correlation-I and II (Eqs. 5 and 6) with the M-Cycle experimental results by Anisimov et al. [12] and Pandelidis et al. [13].

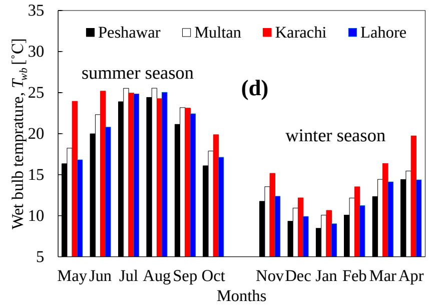
Table 1. Optimized values for the constants of correlation-I and II, i.e., Eqs. (5) and (6).

Parameters	Values
A_1 [-]	6.70
A_2 [-]	-5.48
B_1 [-]	0.2630
B_2 [-]	0.7317
C_1 [-]	0.5298
C_2 [-]	-0.5946

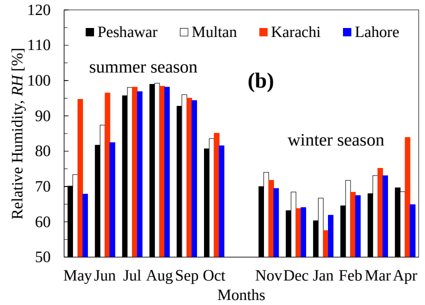
Figures 5(a)-(f) show the resulted profile for outlet air: (a) dry-bulb temperature profile; (b) relative humidity profile; (c) dew point temperature profile; (d) wet-bulb temperature profile; (e) enthalpy profile; and (f) specific cooling capacity of M-Cycle unit, respectively. It can be seen that the Karachi possesses the worst scenario in all the profiles due to excessive ambient air humidity (as depicted in Fig. 3) which is the outcome of sea water evaporation. As the M-Cycle performance is based on the net amount of water vapor evaporation, and the humid air is unable to support this phenomenon, therefore, resulting in a low cooling effect. Similarly, in monsoon season no city has many different results due to the higher humidity. Therefore, it can be concluded that the SCAC system will be totally based on the ambient air conditions and will not really base on the nature of AC application shown in Fig. 1. However, if the AC application is based on medium or low humidity, then the return air from the conditioned space can be passed through the M-Cycle wet-channel of the SCAC system for a higher coefficient of performance. On the other hand thermally driven AC conceptions, e.g., desiccant AC, adsorption cooling etc. [1, 7, 8] are always beneficial for humidity control.



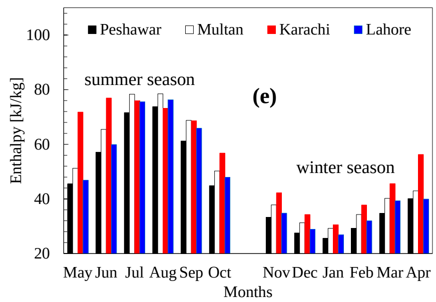
(a) Outlet air temperature (dry-bulb) profile.



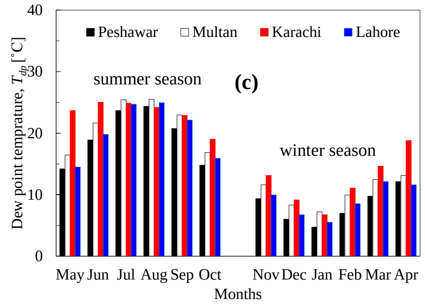
(d) Wet-bulb temperature profile.



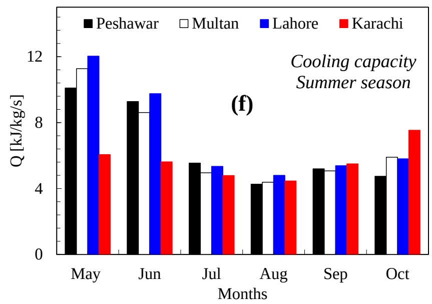
(b) Relative humidity profile.



(e) Enthalpy profile.



(c) Dew-point temperature profile.



(f) Specific cooling capacity.

Fig. 5. Thermodynamic properties of M-Cycle product air for four big cities of Pakistan for summer and winter seasons.

From the above mentioned results, it can be concluded that the SCAC system should only be adopted where the ambient air humidity is relatively lower with preferably higher solar radiations. Moreover, the system can be utilized when there are drier ambient air conditions as well as sunny hours (or in optimized situations). Same as SCAC systems' applicability will be limited for the agricultural and livestock applications which have to carry out in humid climates. Therefore, the SCAC conception may not be feasible as a standalone AC device in various climates, however, it will be a handy and low-cost solution for the reduction of AC loads in various applications. Moreover, hybrid systems can also be developed for sustainable operation. Also, innovative ceiling structures can be developed using this conception for many applications shown in Fig. 1.

5. Conclusions

The present study addresses renewable energy (i.e., solar-chimney) operated passive air-conditioning (SCAC) system for the storage of agricultural products and for animals' thermal comfort. In this regard, ideal air-conditioning zones are established on psychrometric charts for the storage of various agricultural products and for animals' thermal comfort. The SCAC system can produce a cooling effect by means of water vapor evaporative similar to indirect evaporative cooling using the concept of the chilled ceiling. In addition, M-Cycle dew-point evaporative cooling technique is integrated intelligently in SCAC system by which air can be cooled to the dew point of the ambient air. In this regard, experimental data of M-Cycle unit available in the literature have been investigated. Consequently, two simplified linear correlation has been established which can predict the M-Cycle performance accurately. Moreover, the correlations have been validated against the real data of M-Cycle experiments available in the literature, and reasonable agreement was found (with R^2 values more than 0.95 for all cases). The analysis of SCAC system is made for four different climatic cities of Pakistan. Results showed that the system's applicability is limited in humid areas and worst situation (among the studied) result for the climate of Karachi city. Similarly, it has been found that the system may not be valid for the highly humid period and/or climates e.g. monsoon season of Pakistan. Therefore, it is concluded that the SCAC system isn't sustainable for standalone AC, however, it can be handy in order to reduce the cooling load and to develop the chilled ceiling for agricultural and livestock applications.

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