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52. Thermodynamic Assessment of Solar Chimney Based Air-Conditioning System for Agricultural and Livestock Applications

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Abstract

The present study addresses the applicability of solar-chimney based passive-air-conditioning (SCAC) system for agricultural and livestock applications. As the system is free from any kind of refrigerant, therefore enables zero ozone depletion (ODP) and global warming (GWP) potential. The SCAC utilizes well-known Maisotsenko cycle (M-Cycle) in order to achieve the sensible load of air-conditioning (AC) efficiently. Recent studies have proven the advancement of M-Cycle in the field of AC. Therefore, in the present work SCAC system's applicability together with M-Cycle conception has been thermodynamically investigated. Ideal AC zones are established on psychrometric charts for storage of various agricultural products (including: 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.), and for animals' thermal comfort (including: sheeps and lambs at growing stage, dairy cattle and cows, pig farrowing houses, pig nursery barns, beef cattle and cows, poultry breeders and laying houses etc.).

A simplified correlation has been established in order to predict the M-Cycle performance for SCAC system on the basis of experimental data available in literature. The correlation shows good agreement with the experimental data, and therefore is analyzed for four big cities of Pakistan namely (1) Karachi, (2) Lahore, (3) Multan, and (4) Peshawar. The thermodynamic analysis shows that the SCAC can efficiently achieve the sensible AC load for various agricultural and livestock applications, however, the performance index may vary according to the nature of application. Results showed that the SCAC system's applicability is limited in humid areas because of the nature of M-Cycle operation, therefore, may not be sustainable standalone AC system for various applications. However, it can be handy solution in order to minimize the AC load as well as to develop low-cost chilled ceiling for various agricultural and livestock applications. It is worth mentioning that it can be efficiently utilized in most of the dry and moderate areas.

Keywords: *air-conditioning; solar chimney; M-Cycle; agricultural products; livestock*

1. Introduction

Modern life style requires huge amount of primary energy due to extensive & precise thermal comfort in terms of heating, cooling, humidification, dehumidification and ventilation. In this regard, air-conditioning (AC) becomes basic need for offices, buildings, schools, shopping malls, and transport busses/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 specially in developing countries. Similarly in 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 prospective, authors investigate the M-Cycle based [1] renewable energy (i.e. solar-chimney) driven passive air-conditioning (SCAC) system for various agricultural and livestock applications. The concept of M-Cycle [1] driven SCAC system was first time introduced by Miyazaki et al. [2] which presents the numerical simulation model for the SCAC system. One of the key component of SCAC system is M-Cycle unit for indirect evaporative cooling. In the present work, authors tried to utilize the experimental findings of M-Cycle (available in literature) in order to investigate the SCAC system's applicability in agricultural and livestock applications. Consequently, a simplified correlation has been established in order to find out the performance by M-Cycle unit on the basis of Anisimov et al. [3] and Pandelidis et al. [4].

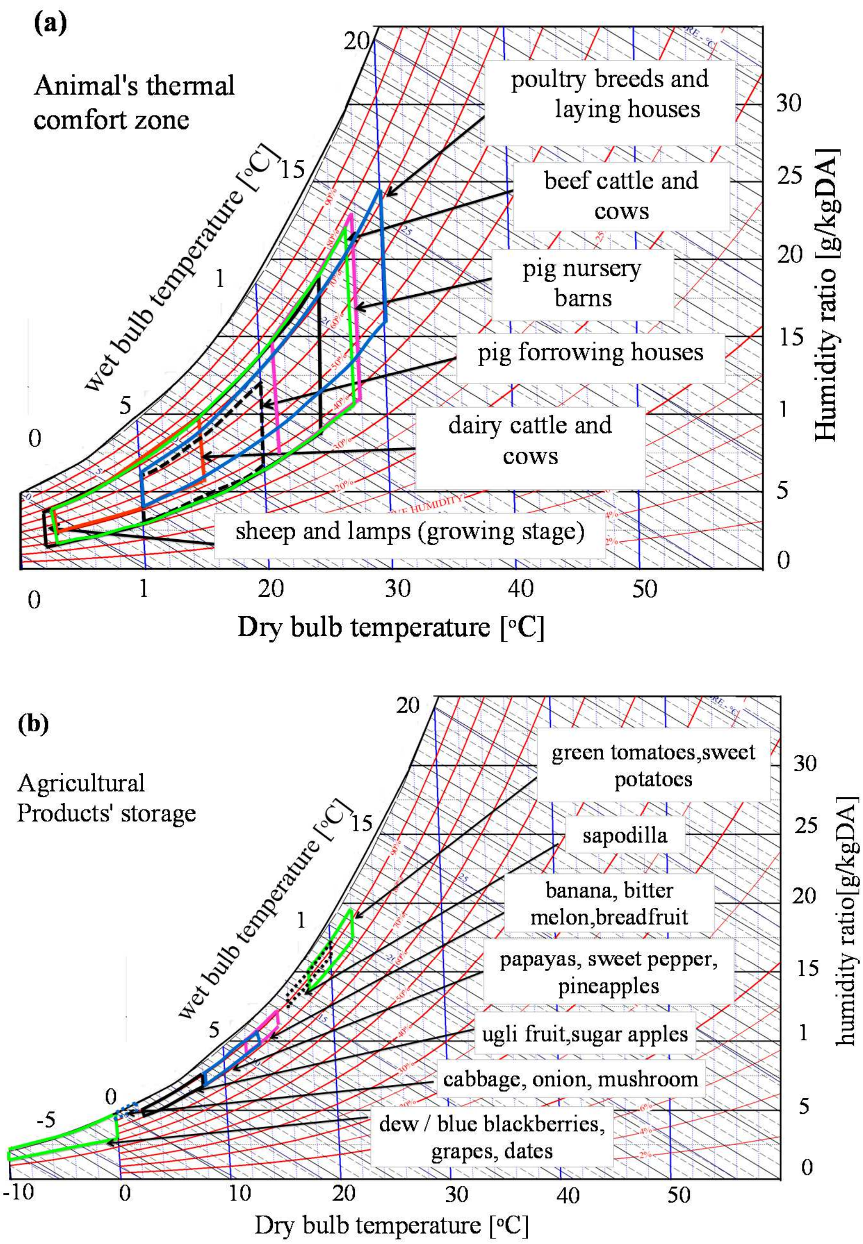

Fig. 1. Psychrometric representation of ideal AC zones for: (a) animals' air-conditioning; and (b) agricultural products' storage

1.1. Development of ideal AC zones

Temperature and humidity requirements for ideal air conditioning vary according to nature of an individual application. As far as storage of post-harvest agricultural products is concern, it may vary according to respiration, transpiration, and fermentation etc. of the agricultural product [5]. 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. In the present study ideal AC zones are developed on psychrometric charts for various agricultural and livestock applications on the recommendation given by ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) [6] and FAO (Food and Agriculture Organization) [7]. Fig. 1(a) shows the ideal AC zones for animal's thermal comfort for: (i) sheeps 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. Fig. 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.

2. Solar chimney based air-conditioning (SCAC) system

A typical renewable energy operated M-Cycle based SCAC system was first time introduced by Miyazaki et al. [2] in 2011. 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 thermal head of the solar-chimney. A typical schematic diagram of the SCAC system is shown in Fig. 2. 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 effect has be induced in the room side by means of convective and radiative heat transfer from the additional dry channel of M-Cycle unit. This is a kind of indirect evaporative cooling, however, the in this case air has the potential to be cooled to the ambient air dew-point temperature by means of innovative conception of M-Cycle. M-Cycle attains energy from air by utilizing psychrometric renewable energy available from the latent heat of ambient air water evaporation [1]. It can be seen that M-Cycle unit has three channels in which two are dry but intermediate channel possesses water for evaporation. Firstly, air from roof side enters in dry channel and then moved to wet channel where it is cooled due to water vapor evaporation similar to 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 the authors' previous work [1]. It is worthy to mention that the conventional IEC system limits the cooling effect up to the ambient air wet bulb temperature.

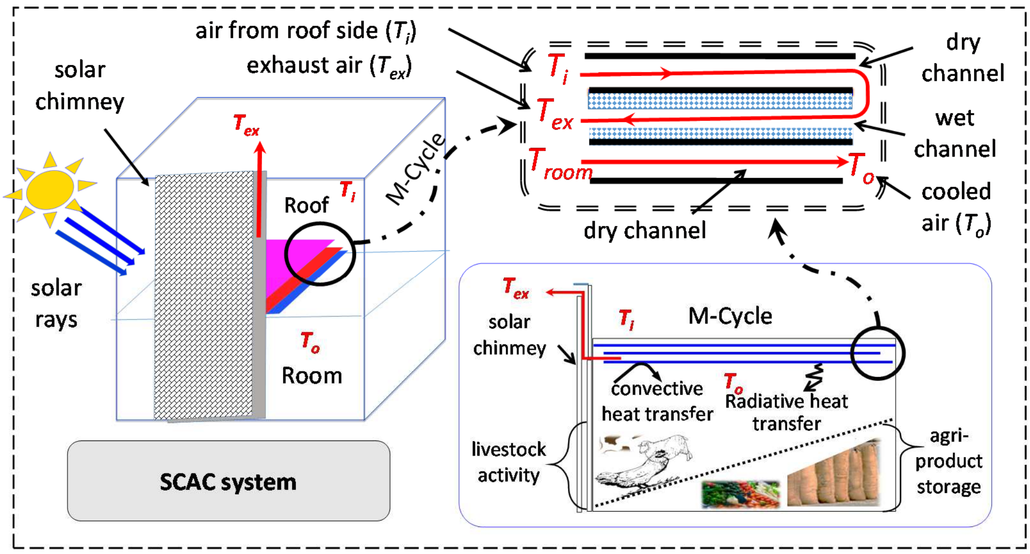

Fig. 2. Schematic diagram of SCAC system for agricultural and livestock applications, reproduced from [2].

3. Research methodology and development of simplified correlation

In the present study 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. Upon review of available literature on M-Cycle [1], it has been realized that the studies published by Anisimov et al. [3] and Pandelidis et al. [4] can give the real insights of M-Cycle performance. In the studies [3-4] authors also developed a precise model for the estimation of M-Cycle performance based on experimental data of M-Cycle for various ambient air conditions. However, the model is relatively complicated, therefore, in the present study a simplified correlation has been established in order to find out the M-Cycle performance for various ambient air conditions. In this regard, experimental result points of M-Cycle unit at different ambient air conditions were taken from the studies [3-4], and optimizations has been made for: $T_i \approx$ 20°C to 45°C and $H_i^{spc} \approx$ 10 g/kgDA to 25 g/kgDA, using the following fundamental conceptions:

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

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

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

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

Where T_o and T_i represent the outlet and inlet air temperature [ºC], respectively, in the product channel (lower dry channel in Fig. 2) of M-Cycle. H_o^{spc} and H_i^{spc} represent the specific humidity (humidity ratio) of corresponding outlet and inlet air [g/kgDA]. Q represent the cooling capacity of M-Cycle unit [kJ/kg/s] whereas subscript *i* & *o* represent inlet and outlet to the product channel of M-Cycle. Rest of the parameters are explained in nomenclature in detail. Optimization has been made for the statistical error minimization and consequently the R^2 values were kept more than 0.95 in each formulation.

Using the above mentioned correlation, the performance of M-Cycle as well as SCAC system has been investigated for four big cities of Pakistan namely: (1) Karachi, (2) Lahore, (3) Multan, and (4) Peshawar. As the scope of the M-Cycle is limited in humid areas, therefore, different ambient air conditions were selected. Similarly, the scope may be limited depending upon the nature of application as well as air flow rates. It is worthy to mention that, the metrological data of the cities was obtained from the Meteonorm 7 (licensed version) from Swiss Meteotest Company. 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.

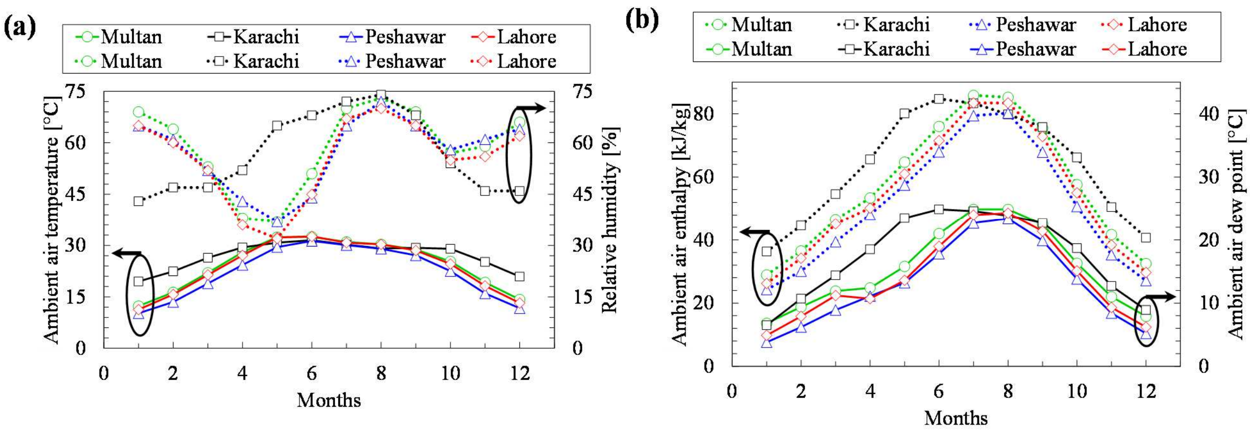

Fig. 3. Outdoor air profile on monthly basis for four big cities of Pakistan: (a) ambient air temperature and relative humidity; and (b) ambient air enthalpy and ambient air dew point.

4. Results and discussion

In the present study M-Cycle based solar-chimney driven passive air-conditioning (SCAC) system has been proposed for the storage of various agricultural products and for animals' thermal comfort. Schematic diagram of SCAC system is shown in Fig. 2 whereas the various agricultural and livestock AC applications are represented on psychrometric charts on Fig. 1. It is obvious that the output consistency of SCAC system is based on the net performance of integrated M-Cycle unit and the net effect of solar-chimney. The M-Cycle [1] is well known in AC field due to its potential of dew-point evaporative cooling. The M-Cycle conception was first time integrated in SCAC system by Miyazaki et al. [2] and the authors developed a simulation model for the system. However, in the present study, experimental results of M-Cycle available in the literature by Anisimov et al. [3] and Pandelidis et al. [4] are utilized for the formulation of simplified correlation for the approximation of thermodynamic properties of M-Cycle product air. Although model of Anisimov & Pandelidis et al. [3-4] is precise but relatively complicated, therefore, a simplified correlation is established using the fundamental conceptions (Eqs. 1-4) as explained in methodology (heading 3). The developed simplified correlation is represented by Eq. 5 and Eq. 6 for product air temperature (T_o) and for cooling capacity (Q), respectively. The validity range of simplified correction is: $T_i \approx$ 20°C to 45°C and $H_i^{spc} \approx$ 10 g/kgDA to 25 g/kgDA.

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

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

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 parameter A, B, and C are the constants of simplified correlation, and their optimized values given in Table 1. A comparison has been made between the developed simplified correlation (Eq. 5-6) with the experimental data [3-4]. Fig. 4(a) and (b) shows comparison outcomes for outlet air temperature (T_o) and cooling capacity (Q), respectively. It can be seen that the simplified correlation can represent the experimental data reasonably for both of the 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 humidity [1]. Therefore, the performance of M-Cycle unit is investigated for four big cities of Pakistan (namely: 1. Karachi, 2. Lahore, 3. Multan, and 4. Peshawar) which enable different nature of atmospheric conditions of temperature and humidity. In this regard, thermodynamic properties of M-Cycle product air are estimated from simplified correlation (Eqs. 1-6) for four big cities of Pakistan for summer and winter seasons. Fig. 5(a)-(f) shows the resulted profile for: (a) outlet air temperature (dry-bulb) profile; (b) relative humidity profile; (c) dew point temperature profile; (d) wet-bulb temperature profile; (e) enthalpy profile; and (f) 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. It is because the M-Cycle performance is based on net amount of water vapor evaporation, and the humid air is unable to support the phenomena which results in low cooling effect. Similarly, in moon-soon season all the cities don't have much different results due to the higher humidity.

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 higher solar radiations. Moreover, system can be utilized in the hours of a particular day when there are drier conditions as well as sunny hours (or in optimised situations). Same as, SCAC systems' applicability will be limited for the agricultural and livestock applications which has to carry out in humid climates. Therefore, the SCAC conception may not be feasible as a standalone AC device in various climates,

Table 1. Optimized values/parameters of simplified correlation presented via Eqs. 1-6.

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

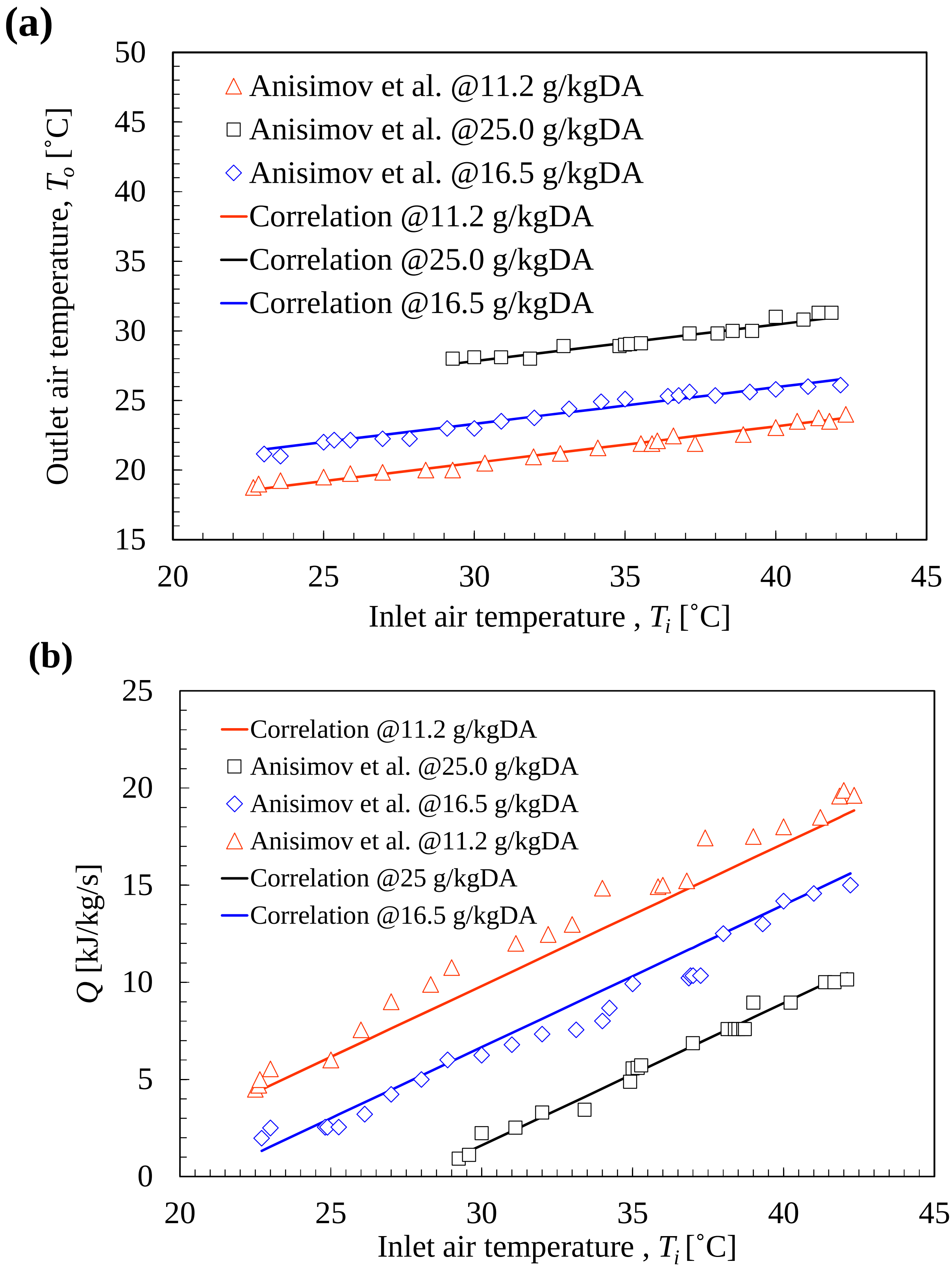

Fig. 4. Validation of developed simplified correlation (Eqs. 1-6) with the experimental data of Anisimov et al. [3] and Pandelidis et al. [4] for: (a) outlet air temperature; and (b) cooling capacity. The correlation is valid for the range of $T_i \approx$ 20°C to 45°C and $H_i^{spc} \approx$ 10 g/kgDA to 25 g/kgDA.

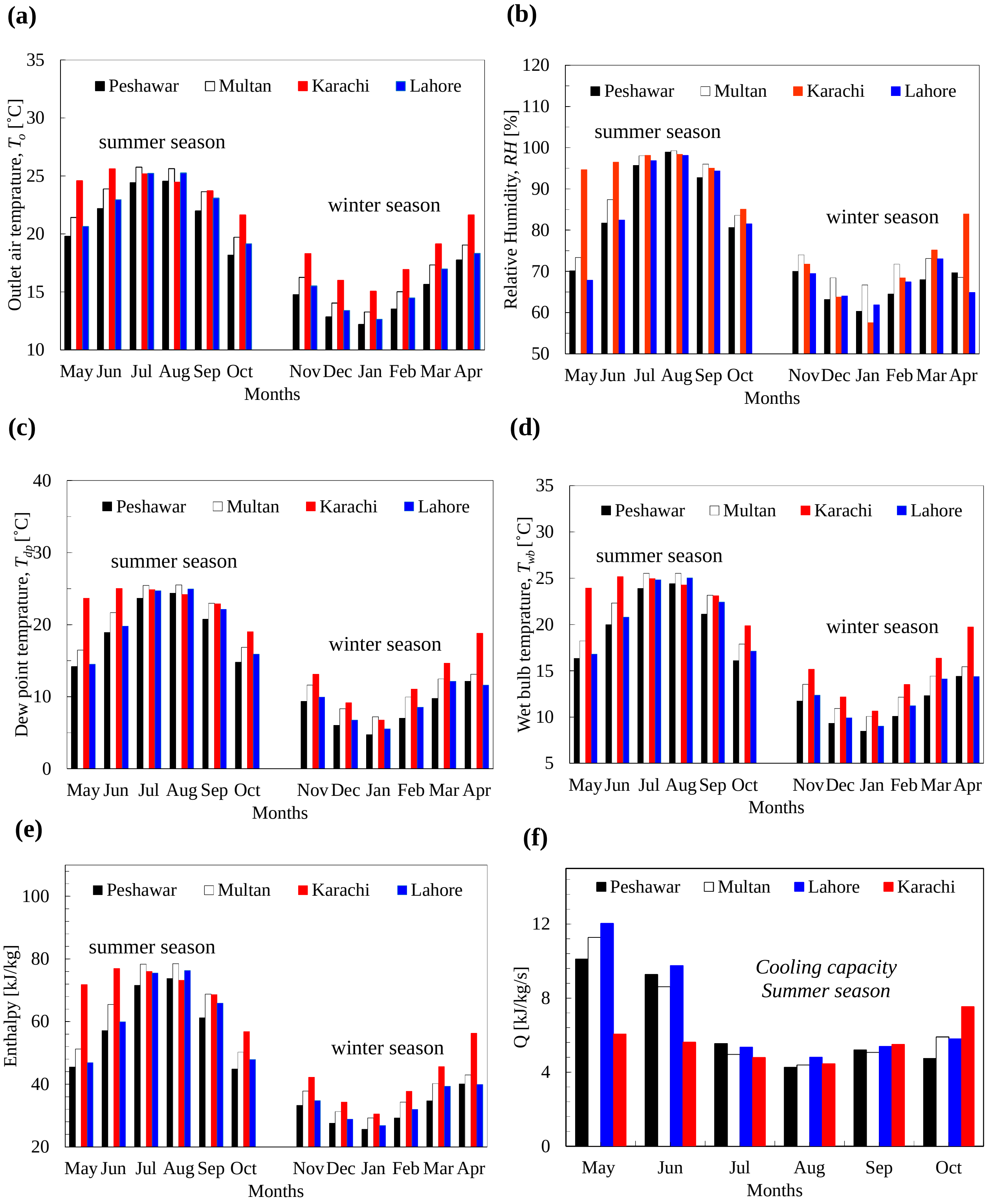

Fig. 5. Thermodynamic properties of M-Cycle product air estimated from simplified correlation (Eqs. 1-6) for four big cities of Pakistan for summer and winter seasons: (a) outlet air temperature (dry-bulb) profile; (b) relative humidity profile; (c) dew point temperature profile; (d) wet-bulb temperature profile; (e) enthalpy profile; and (f) cooling capacity of M-Cycle unit.

however, it will be a handy and low-cost solution for the reduction of AC loads in various applications. Moreover, a 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. 2.

5. Conclusions

The present study addressed renewable energy (i.e. solar-chimney) operated passive air-conditioning (SCAC) system for the storage of various 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 cooling effect by means of water vapor evaporative similar to indirect evaporative cooling using the concept of chilled ceiling. However, M-Cycle 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 has been investigated, and a simplified correlation has been established which can predict the M-Cycle performance accurately. The simplified correlation has been verified against the published data of M-Cycle experiments and a reasonable agreement has been found (with R^2 values more than 0.95 for all cases).

The correlation is further utilized for the analysis of SCAC system for four big cities of Pakistan namely: (1) Karachi, (2) Lahore, (3) Multan, and (4) Peshawar. Results showed that the system's applicability is limited in humid areas and worst situation (among the studied) are resulted for the climate of Karachi. Similarly, it has been found that the system may not be valid for the highly humid period and/or climates e.g. moon soon season of Pakistan and climate of Malaysia etc. Therefore, it is recommended that the system may not be a sustainable as standalone system for optimum AC, however, it can be a handy solution in order to reduce the AC load as well as in order to develop the chilled ceiling for various application in agriculture and livestock.

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Nomenclature

A, B, C	constants of correlation [-]
AC	air conditioning
GWP	global warming potential
H	humidity [g/kgDA]

h	enthalpy [kJ/kg]
IEC	indirect evaporative cooling
M-Cycle	Maisotsenko Cycle
ODP	ozone depletion potential
Q	specific cooling capacity [kJ/kg/s]
RH	relative humidity [%]
SCAC	solar chimney based air conditioning
T	outlet air temperature [ºC]
η	M-Cycle effectiveness [-]

Sub/super-scripts

amb	ambient
dp	dew point
ex	exhaust
i	inlet
o	outlet
spc	specific
wb	wet bulb