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A ventilation system for Abu Dhabi using a Solar Chimney, an Earth Tube and a Desiccant Wheel

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Abstract

This paper proposes a low energy ventilation system for the hot, humid maritime desert climate of Abu Dhabi city. The cost of energy to the government is becoming steep. In addition, the ventilation does not always perform well, leading to problems such as respiratory diseases. The system has 3 main components: A Solar Chimney (SC) that provides a passive drive for ventilation, an Earth to Air Heat exchanger (EAHE) for ventilation air cooling (sensible load) , and a Desiccation wheel (DW) to remove unwanted air moisture (latent load). The performance of the system was analysed using WinAir for the SC, GAEA for the EAHE, and Desiccant Wheel Analyzer for the DW. A psychrometric study was undertaken to analyse the enthalpy reduction. It was found that the ventilation related enthalpy could be reduced by 38% by using the SC-EAHE system alone, and by 47% when using the full system.

Keywords: ventilation, solar chimney, earth tube, desiccant, Abu Dhabi

1. Introduction

Abu Dhabi is an Island close to the shore (almost a peninsula) of the Arabian Gulf to its North and the Ruba Al Khali desert to its South. Because of this opposing influence of the Desert and the Gulf, the climate of the city is of a maritime desert, hot and humid. The Tropic of Cancer runs at just 110 Km south of the City.

Abu Dhabi is the capital and the largest and richest of the seven Emirates making up the United Arab Emirates (UAE). The extended city consists of the island of Abu Dhabi and its suburbs. This study will focus on the climate context of the City of Abu Dhabi. However, it can be generalized to cover the entire northern coast of the UAE, including Dubai, and any other site with similar climate. The weather data collected for the purpose of this study was obtained from ADAC (2011). The station is located in the Abu Dhabi Airport which has a central location to the scope area of this paper. The sun is available all year round, and summers are especially hot, but also humid. The most intolerable periods are when the temperature is above 35°C, and the humidity is above 70% (Abu Dhabi Environment Agency, 2008). Because of that, cooling is required most of the year. During the day, the sun shines brightly and abundantly with little or insubstantial cloud cover most summer days. The available direct solar radiation daily average ranges between 600 and 800 W/m^2 all year long. The ground is always at a lower temperature than the air (ADAC, 2011).

2. Aim of the study

Passive cooling including ventilation may not function properly due to the amount of humidity in the air. The aim of this study is to propose a system integrating desiccant dehumidification with a solar chimney (SC) – earth-to-air heat exchanger (EAHE) system installed on a single residential house: a dwelling for an individual family of 2 stories, which is a common type in the city. This is a previously unexplored strategy in the city and could be applied to similar maritime desert climate regions, or humid climate regions.

3. Baseline building

The building chosen for this study is located in Al Reef compound, a modern village designed in line with the new urban framework of Abu Dhabi (Property Shop Investment, 2012). Building design is shown in Figure 1, building zones modelled in Ecotect are detailed in Table 1, and baseline building design summary is listed in Table 2.

Table 1 Baseline Building Zone Summary

Zone Name	Floor (m2)	Surface (m2)	Exposed (m2)	Window (m2)	Volume (m3)	HVAC System	Temp. Range	Operation Hours
GROUND FLOOR	89.001	301.377	123.375	19.7	266.662	Air Conditioning	23.0-25.0	00-24/00-24
FIRST FLOOR	98.574	326.898	238.06	15.36	296.116	Air Conditioning	23.0-25.0	00-24/00-24
TOTAL	**187.575**	**628.275**	**361.435**	**35.06**	**562.778**			

Table 2 Baseline building design summary

Built area	188 m^2
Cooling zones	Ground floor:89 m^2
	First floor: 99 m^2
Total annual cooling loads	20 MWh
Cooling load per m2 (annual total)	106 KWh/m^2
Cooling load per m2 (monthly maximum)	16 KWh/m^2
Ventilation gain (annual total)	3.8 MWh
Maximal ventilation flow rate	127 Ls^{-1}
Ventilation gain per m2 (annual total)	20 KWh/m^2
Ventilation gains ratio to total gains	18% of the total building gains.

Figure 1 Selected unit in Al Reef compound type C

4. Proposed System Concept

4.1.Proposed system's basic cycle

The principal drive of the system is the vertical air movement in the solar chimney. The ascending heated air column causes a pressure drop in the cooled space, and in the lower down EAHE. Assuming the pressure drop is large enough to compensate for infiltration, for the friction in the tubes and the desiccant apparatus resistance; it should cause air suction through the EAHE intake, starting the ventilation cycle. The EAHE will release the ventilation air heat to the surrounding earth and causing it to undergo sensible cooling. The hot, humid summer air entering the desiccant apparatus, releases part of its humidity causing the dry bulb temperature to increase while the wet bulb temperature remains the same, and moisture mass in the air to be reduced.

Table 3 SC-EAHE and DW System Operation Modes

Mode #	Temperature Condition	Humidity Condition	Solar Radiation Availability	SC OPERATION	EAHE OPERATION	DESICCANT OPERATION	DESICCANT WHEEL AUXILIARY POWER REQUIRED	ELECTRIC FAN REQUIRED
1	HOT	HUMID	DAY	YES	YES	YES	NO	NO
2	HOT	DRY	DAY	YES	YES	NO	NO	NO
3	NORMAL	HUMID	DAY	YES	NO	YES	NO	NO
4	NORMAL	DRY	DAY	YES	NO	NO	NO	NO
5	COLD	HUMID	DAY	YES	YES	YES	NO	NO
6	COLD	DRY	DAY	YES	YES	NO	NO	NO
7	HOT	HUMID	NIGHT/OVERCAST	NO	YES	YES	YES	YES
8	HOT	DRY	NIGHT/OVERCAST	NO	YES	NO	NO	YES
9	NORMAL	HUMID	NIGHT/OVERCAST	NO	NO	YES	YES	YES
10	NORMAL	DRY	NIGHT/OVERCAST	NO	NO	NO	NO	YES
11	COLD	HUMID	NIGHT/OVERCAST	NO	YES	YES	YES	YES
12	COLD	DRY	NIGHT/OVERCAST	NO	YES	NO	NO	YES

The ventilation air is then mixed in an air mixing box with the cool recycled air from the HVAC system, and is then dehumidified further. The mixture then reaches an equilibrium point of moisture content and temperature for delivery to the conditioned space. Part of the process air would then be exhausted to the SC, which continuously drives the cycle.

4.2.Proposed System's Operation Modes

The 12 operation modes in which the building is occupied shall be considered and are listed in Table 3. Since the ventilation requirement is linked to the number of occupants in residential buildings, then the ventilation system is assumed to be OFF when the building is unoccupied (CIBSE, 2006). This table lists operational settings corresponding to each case of temperature and humidity. For example, during the night the solar radiation is not available and thus there is no possibility for actively using the SC. In this case, the use of an auxiliary ventilation fan is required. Another example is for the operation of the DW. When humidity is low, there is no need to burden the system with the extra force needed to drive air through the DW, and there is no need for this apparatus to be ON. In this case, a provision of a bypass would be appropriate, and the desiccant apparatus would be set to OFF.

4.3. Proposed System concept

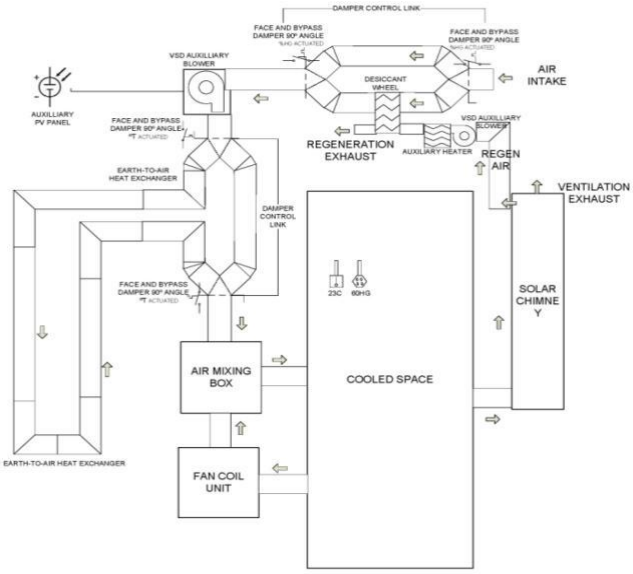

Figure 2 Full system concept

The flowchart is shown in Figure 8 (in Appendix A System Flowchart). The bypass for the EAHE and for the DW operate with the use of thermal and humidity sensors that are linked to locked-blades Face & Bypass Dampers (Greenheck, 2012) on both sides insuring that, if one path of air was open, the other will be closed. The reset mechanism for the DW is also shown. When solar radiation is available, it is used to reset the DW. Otherwise, an auxiliary heater is used. Figure 2 shows The full system concept. Also, a PV array may be connected to the auxiliary fan as shown on the top left of Figure 2 to provide a further reduction in energy consumption whenever solar energy is available.

5. Sub-Systems Models

For the purpose of this study, 4 models were constructed using different software to validate the use of each component of the system described in the following sections using Ecotect,WinAir4, GAEA, and Desiccant Wheel Performance Estimator, by ASHRAE Technical Committee 8.12 (2011).

5.1. Solar Chimney Tilt Optimization

To obtain the best tilt of the solar chimney, an Ecotect model was constructed containing square surfaces of $1m^2$ each at various tilts from the horizontal. The squares were placed facing south. It was found that the tilt from the vertical receiving the highest solar radiation was 70^0. The tilt of 35^0 was a balance position between buoyancy and solar exposure.

5.2. SC and EAHE WinAir4 Model

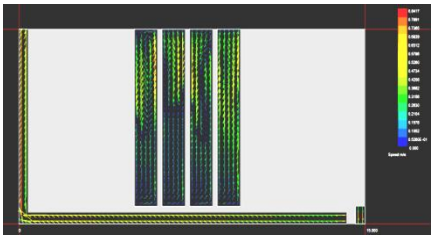

Figure 3 Air velocity vector inside SC

Although WinAir4 could be used as a plugin to Ecotect, it was used in this study as a stand-alone package. A workaround was used: all the models were constructed upright, and to emulate the chimney tilt, the gravitational vector was rotated. This is acceptable since the two main geometrical properties that have a substantial effect on the SC-EAHE system performance are the cooling surface area of the EAHE and the absorbing surface area of the SC (Maerefat and Haghighi, 2010). Speeds inside the model chimney reached 0.68 ms-1 and inside the model EAHE $0.84ms^{-1}$. Based on the building design assumptions, the maximum air change

required is 0.81 ACH. This is equal to 215m^3/hr. It is shown that, for a range of radiation from 400 to 800 W, the SC arrangement of 4 chimneys 1 m wide and 0.4 m deep with a tilt of 35° from vertical would provide enough energy to power the entire ventilation need for this building. In addition, the ventilation rate for the available radiation range considered is between 280.8 and 356.4 m^3/hr, which is higher than the requirement. This suggests that, with the use of proper pressure sensing, the extra rate energy could be used to help in reducing the energy

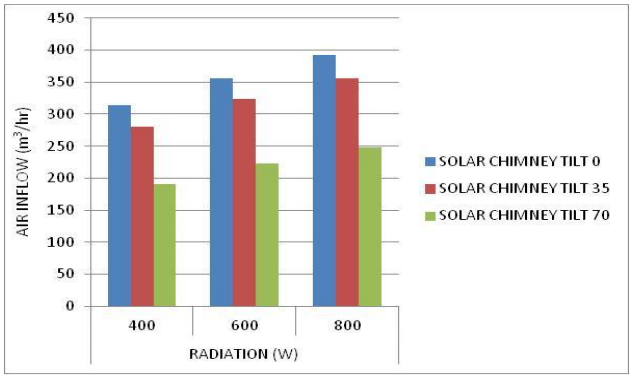

Figure 4 Solar Chimney Model Results Ventilation Inflow Related to Available Radiation and SC Tilt

required to push air through the desiccant wheel. Another noteworthy result is that the air temperature inside the model SC reached 121 °C which is enough for desiccant regeneration.

5.3. EAHE GAEA Model

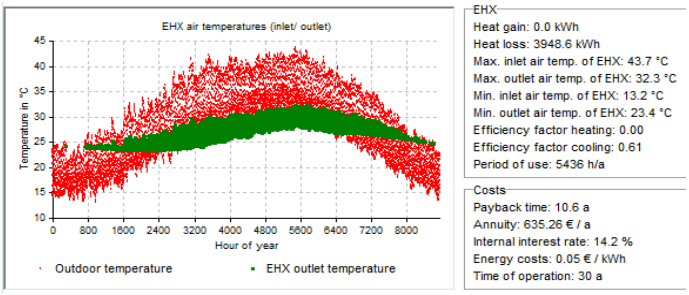

Figure 5 GAEA sample run annual temperature reduction at: 225mm pipe dia, 75m pipe length, 2m pipe depth

GAEA provides a calculation tool to match earth heat exchangers and buildings (Benkert et al., 2003). It is used in this study as a stand-alone tool to evaluate and size the EAHE parameters required for the baseline building and at the climate conditions of Abu Dhabi. A compilation of data analysis between June and October (summer season) showed that the highest heat flow for this period of 10MWh for a 40mm pipe with a length of 75m at a depth of 2m, and 8.5MWh for a 225mm pipe at the same length and depth; also with these 2 values significantly higher than the others.

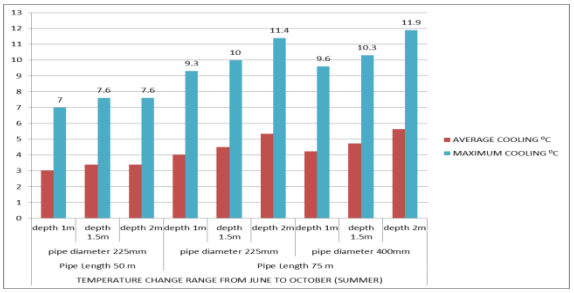

Figure 6 GAEA compiled results for temperature change between June and October

The efficiency factor of cooling given by GAEA was 0.61. That would give an actual cooling capacity of 8.45 to 9.15MWh for the whole year, and 5.2 to 6.1MWh for the Summer Season. Going back to the baseline building cooling loads, the EAHE cooling is capable of reducing the cooling loads by a factor of up to 42% to 46%.

5.4. Desiccant wheel model

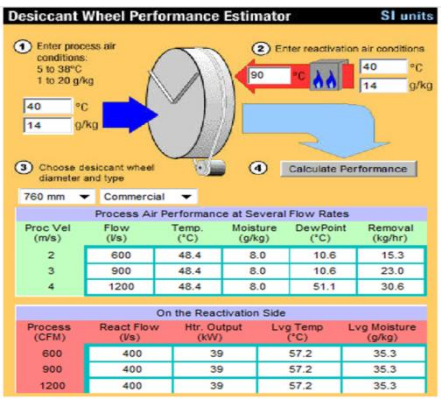

Figure 7 Desiccant Wheel Estimator

ASHRAE Technical Committee 8.12 (2011) published an estimator that was used here to estimate the desiccant wheel performance. The results of the run show that for a process air moisture content of 8 g.kg-1, the removal was between 15.3 kg.hr-1 and 30.6 kg.hr-1 for a flow rate range of 600 Ls^{-1} to 1200 Ls^{-1}. These values are sufficient for the ventilation dehumidification. Process air temperature output was 48.4 °C, with an increase of 8.4 °C. The Gaea model EAHE was shown to cool down the ventilation air by more than this value, ensuring ventilation air does not increase heat gain beyond the baseline model value. On the reactivation side, a moisture removal of 35.3 g.kg^{-1} resulted from a reactivation air flow of

400 Ls^{-1}, at a reactivation air temperature of 90 °C, which is lower than the temperature reached inside the solar chimney.

6. Psychrometric study of results

3 phase change paths are shown on the psychrometric chart in Figure 9 (in Appendix B Psychrometric diagram). The first case (case A-E) is the baseline case and corresponds to the highest enthalpy of 53 $Kj.Kg^{-1}$. The second case (case A-B-E) corresponds to the SC/EAHE without dehumidification. The active systems' enthalpy in this case is 33 $Kj.Kg^{-1}$ and is lower than that of the traditional cooling system with a saving of 38%. The third case depicted in blue (case A-C-D-E) corresponds to the full system including the SC/EAHE and desiccant dehumidification. The considered enthalpy in this case is 28 $Kj.Kg^{-1}$ and corresponds to the highest energy saving of 47%.

7. Conclusion

The city of Abu Dhabi has a maritime desert climate. It is very hot and humid all year long, and especially in the summer. A large part of the city is comprised of individual residential single-family dwellings that are mostly cooled using traditional DX HVAC systems. Ventilation is often performed using simple air extract fans, bringing in the raw hot humid and dusty outside air. It was found that, on the baseline building, ventilation corresponds to 18% of the total heat gain.

A system was proposed to reduce this gain by making use of the abundant solar radiation, of the ground cooler temperature, and the adiabatic dehumidification using desiccants. 3 main components constitute the system: a Solar Chimney (SC), an Earth-to-Air Heat Exchanger (EAHE), and a desiccant wheel (DW). The system also includes technologies such as energy and humidity sensor-operated dampers to route the air inflow according to the initial conditions of temperature and humidity; an air mixing box to mix the outside and re-circulating air streams; and a variable speed drive(VSD) fan to compensate for the Solar Chimney deficiencies. It was also shown that the air stream was heated to a temperature of up to 121°C, which is more than enough to regenerate the desiccant of choice (silica gel). The psychrometric evaluation of the whole system showed that the enthalpy reduction from the baseline building values using the EAHE/SC system alone is 38%; while it was 47% by using both the SC/EAHE and the DW systems.

On the whole, it was found that using the proposed system would provide significant energy savings for single dwellings ventilation while maintaining a high standard of indoor air quality.

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Appendix A System Flowchart

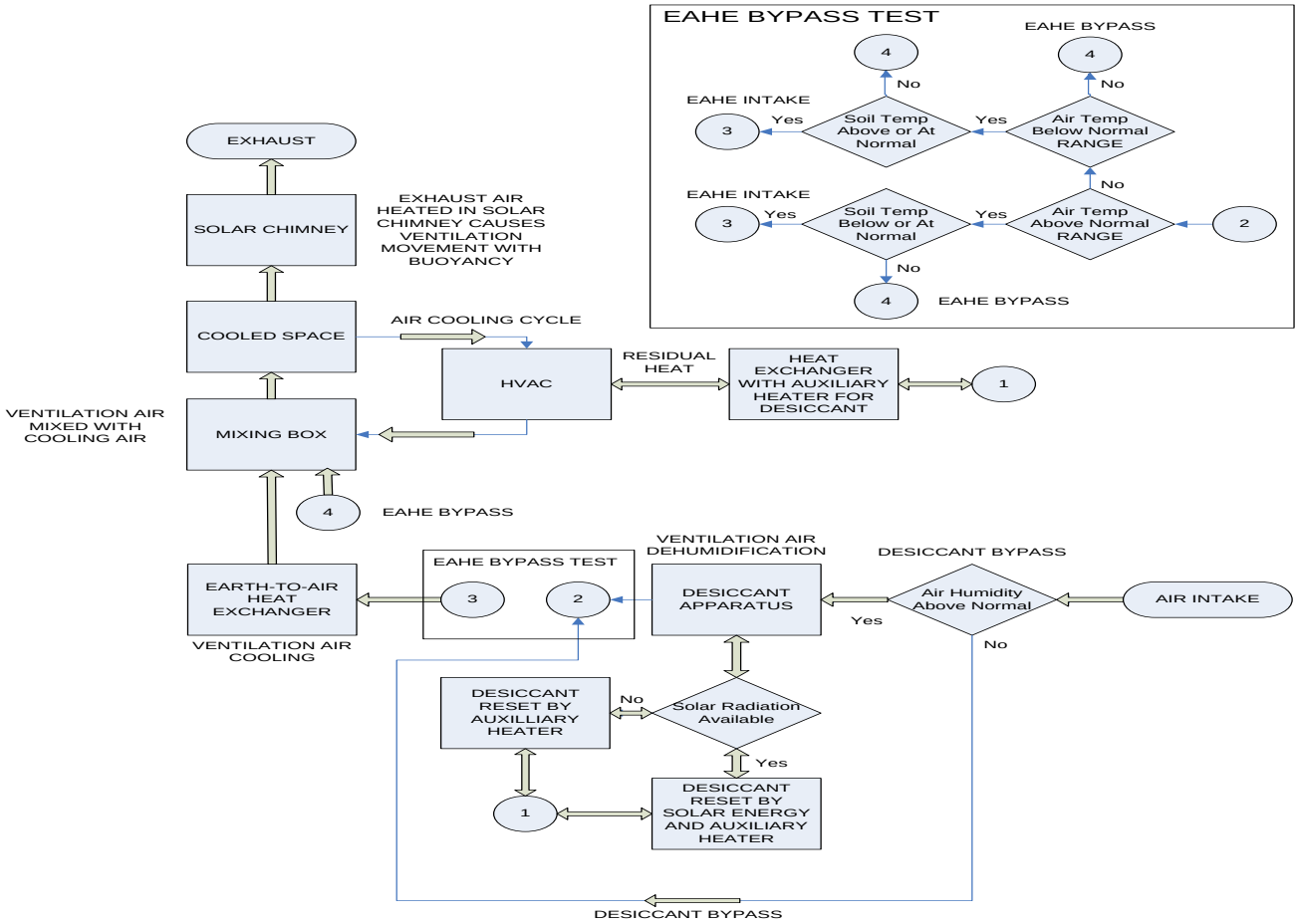

Figure 8 Proposed System's Modes Flowchart

Appendix B Psychrometric diagram

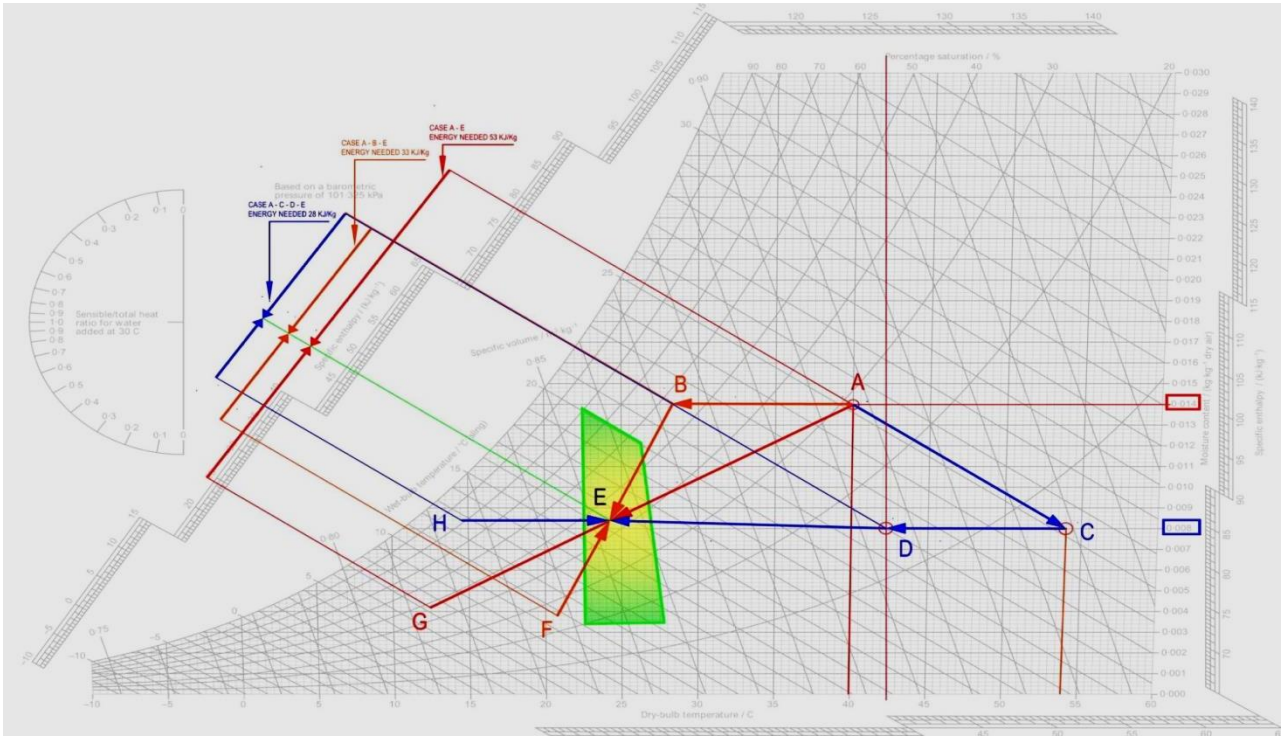

Figure 9 Comparative psychrometric study of baseline HVAC system ventilation (A-E), ventilation in system with SC/EAHE (A-B-E), and with SC/EAHE/DW (A-C-D-E). F-E, G-E, and H-E paths represent the corresponding HVAC process air psychrometry for each situation.