Report on the Airzone solution for individual temperature control per zone and its comparison with a conventional system

Airzone Zoning Model. Case Study

1. Introduction

Nowadays, in the residential sector, a widely used Heating, Ventilation and Air Conditioning (HVAC) system is the ducted direct expansion (DX) inverter system based on the on/off control of a single zone [1]. This system, whose indoor unit has a constant volume fan, can be configured to serve multiple zones based on an on/off control. However, in many buildings, there is a variety of zones with different users, desired temperatures and varying thermal loads. It means, this kind of system ensures the comfort level in the zone where the thermostat is placed but, regarding the rest of the zones, if the load profile is not similar to the control zone (use, orientation, thermal loads, etc.), their temperatures can fall outside the comfort range. In the U.S., 90% of single-family detached homes utilizes this type of AC equipment [2], which cannot guarantee thermal comfort in each room of the building.

Recently, the last report of the Intergovernmental Panel on Climate Change (IPCC) [3] ensures that the use of air conditioning systems in buildings will increase with the constant rise in temperature leading to high energy consumption rates.

According to the last data of the US Energy Information Administration [4], the average annual electricity consumption for a U.S. residential utility customer was 10,715 kWh, an average of about 893 kWh per month. Louisiana had the highest annual electricity consumption at 14,407 kWh per residential customer, and Hawaii had the lowest at 6,446 kWh per residential customer. Therefore, adoption of energy efficient air conditioning is pertinent to balance the provision of comfortable indoor conditions and energy consumption.

The aim of this study is to demonstrate how the implementation of smart control systems in HVAC applications contributes effectively to the energy efficiency of a building. The Corporación Empresarial Altra, through Airzone North America Corp. division, aims to evaluate the advantages of a system of this type, from the point of view of occupant comfort, thermal demand and annual electrical consumption, with respect to a non-zoned conventional inverter system.

2. Airzone solution for individual temperature control per zone

As an alternative to the ducted DX inverter system based on the on/off control of a single zone, the Airzone zoned system is based on independently controlling the temperature of each of the zones. To do this a thermostat is installed in each room, allowing the thermal demand for each of the zones to be determined, and the selection of an independent setpoint temperature depending on the preferences of the user. In this way, when the set-point temperature established for the zone is reached, a control signal is sent to the zone's motorized damper which interrupts the airflow supply to that room. Figure 1 shows a diagram of a zoned system.

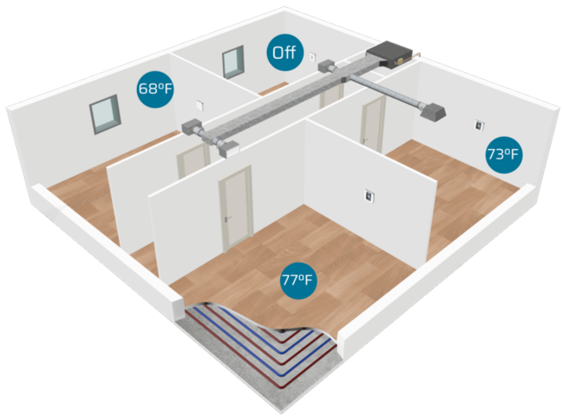

Figure 1. Scheme of a zoned system

The control system is a distributed system capable of controlling up to 10 zones through heating/cooling air and/or radiant heating stages through zone modules connected to the main control board. The advantage of the distributed connection architecture is the versatility of the system. The same system can include zone modules for ducted AC units (the system of the case of study), individual AC units, as well as radiant heating-only zone modules for radiant heating stage control with the help of their corresponding control module (Figure 2).

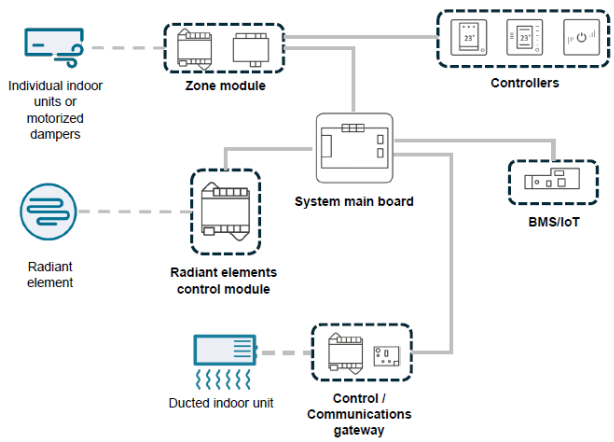

Figure 2. General architecture of the control system

In addition to thermal zoning, it is particularly important to highlight the role of the communication gateway. Achieving a high comfort level at the same time as reducing power consumption requires seamless communication between the zoning system and the AC unit. The communication gateway is the device that enables this two-way communication between the control board and the AC unit. Airzone has agreements in place with the main manufacturers to share the communication protocols used by their AC units. This makes possible to have information about their operational parameters, so actions can be performed such as:

- Operation mode.

The performance of the AC unit (cooling, heating). The user can define the minimum temperature for cooling mode and the maximum temperature for heating mode.

- Fan speed selection of the indoor unit.

Q-Adapt is the algorithm that automatically selects the fan speed of the units with individual zone control depending on the number of zones calling for demand. The algorithm adapts the control system to the solutions and the air flow demand of each zone. This adaptation is carried out by assigning a weight (percentage) to each zone, which is mainly suitable for complex ducted applications with numerous zones.

By using this algorithm and having a dynamic control of the fan-speed, we do not need to add a bypass damper, or dump zones, like most zoning systems do.

- Dynamic control of the set-point temperature of the Inverter indoor unit.

To obtain the highest energy efficiency of Inverter indoor units, it is essential to manage them to run at a partial load regime (peak efficiency) as long as possible. By modifying the set-point temperature in relation to the return air temperature, it is possible to vary the Partial Load Ratio (PLR) of the compressor and, therefore, its efficiency. Figure 3 shows a diagram of a zoned ducted system in a building, with the control board and communication gateway.

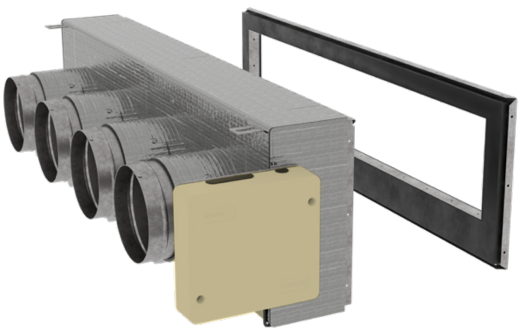

Figure 3. Diagram of a zoned system

3. Integration and IoT

Airzone control solution works with updated and certified integration drivers and IoT features that helps with the efficiency, energy savings, connectivity and comfort of the occupants such as Home Automation, Alexa & Google Home, and remote Wi-Fi control. Also, with the local API, any 3rd party integration is allowed into the system.

These features are incorporated through the Webserver included in the Airzone system. This allows the HVAC unit to be connected to the latest IoT technology, which has a high pace of change.

4. Implementation of the models in TRNSYS

The present study has been modeled using the TRNSYS software [5], a benchmark program for research into thermo-energy applications. Mathematical models of all HVAC systems defined in the previous section have been running using this calculation platform. These models have been obtained through experimental tests of a direct expansion unit in a double climatic chamber. The idea is to determine the behavior of the AC unit within the range of working conditions to which it will be subjected in a real application. This ensures we achieve good coupling between building and system (Figure 4).

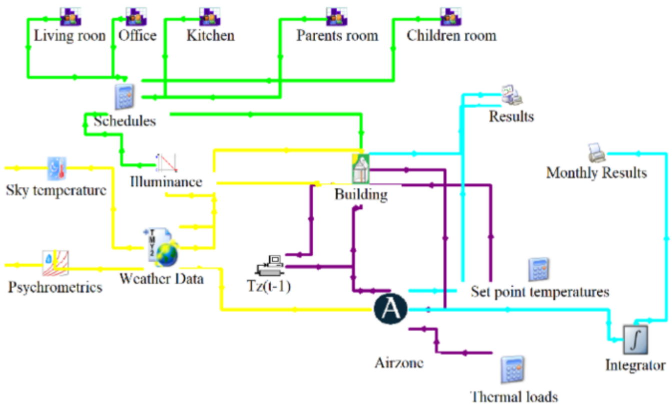

Figure 4. Setting up the zoned system in TRNSYS

In the modeling of a direct expansion inverter unit, when characterizing the behavior of the AC unit, it must be considered that the operating mode, the AC unit's performance and the power consumption required will vary depending on the operating conditions. To this end, an AC unit of this type was used in the research and the different characteristic performance curves with their corresponding coefficients were obtained.

An inverter unit can regulate its working regime in order to adjust the production of thermal energy to the demand. The partial load factor (PLR) is defined as the ratio between the sensitive load demanded and the maximum load that the AC unit can provide under the same working conditions:

$$PLR = \frac{Q_{demand}}{Q_{sens,max}}$$

Figure 5 shows the three working regimes of an inverter unit with the evolution of the AC unit's performance according to the partial load factor.

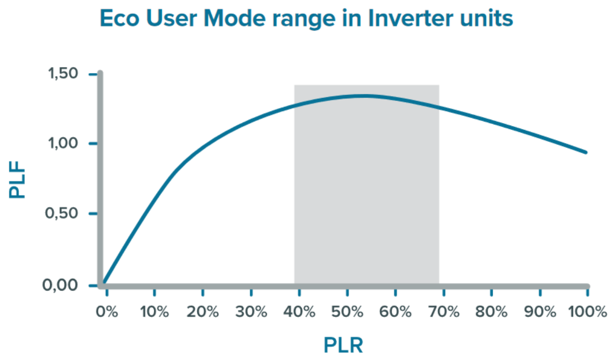

Figure 5. Working regimes of an inverter unit

The working regimes are as follows:

- For PLR values lower than 0.3, as the refrigerant mass flow cannot be made arbitrarily small, there is a minimum speed at which the AC unit ceases to function as an inverter system, to become on/off.
- With PLR values between 0.3 and 1, the AC unit works at partial load and high EER values are obtained.
- With PLR values greater than 1, the AC unit works at full capacity and there is a significant decrease in performance.

5. Results: case study

The aim of this study is to compare the advantages of an inverter system with individual temperature control per zone with the different control configurations offered by Airzone North America Corp, with a non-zoned inverter system. The criteria used for comparison are the annual electricity consumption and the comfort level provided by each of them. Thus, this section will be divided into two parts: on the one hand, the comfort levels provided are established, and on the other hand, the associated annual electricity consumption is examined.

Case study

The home under study has five heated/cooled zones (Living room and Kitchen, the Study, and the three Bedrooms), with a surface area of 1988 sq ft. (Figure 6).

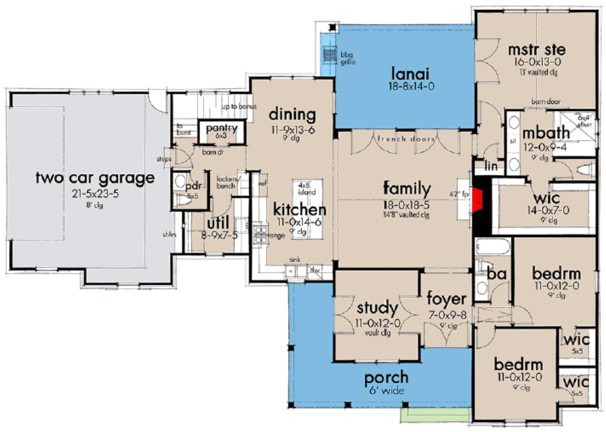

Figure 6. Floor plan of the single-family home [6]

The simulation is conducted in different climate conditions: 1A Miami, 3B Los Angeles, CA; 4A New York, NY; 5A Chicago, IL, from the climatic data of EnergyPlus [7].

The enclosures are representative of the different regulations prevailing in each climatic zone according to the Building Energy Codes Program developed by the Office of Energy Efficiency & Renewable Energy of the USA Energy Department [8]. Table 1 shows the values considered for the overall heat transfer coefficient of the different enclosures of the dwelling.

City	Wall	Roof	Floor	Window
Miami	0.53	0.41	1.7	1.4
Los Angeles	0.36	0.32	1.7	1.4
New York	0.28	0.26	1.7	1.4
Chicago	0.28	0.24	1.7	1.4

Table 1. Threshold U-values (W/m^{2}K)

A typical occupancy profile in residential buildings is applied to determine the operation of the HVAC system (Figure 7). The family consists of four people with the typical profile of use of a home, with a level of metabolic activity of sitting very light work (120 W) in the living room and office, sitting at rest (100 W) in the bedrooms and standing light work (185 W) in the kitchen. The internal gains corresponding to lighting and equipment are 5 W/m^2 and 10 W/m^2, respectively. A rate of 0.6 renewals/hour is set for outdoor ventilation airflow in all rooms except the kitchen, which is set at 2.9 renewals/hour.

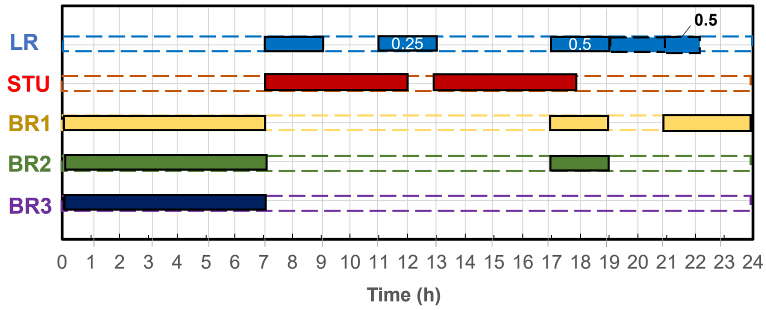

Figure 7. Typical residential occupational profile

Calculation of loads. Sizing of the AC units.

The sizing of the AC units is done considering that the user comfort range will be set between 71.6 ºF (T_{lower}) y 75.2 ºF (T_{upper}).

In a non-zoned system, the distribution network has no element that allows the system to deal separately with the needs of each zone. Therefore, to guarantee the possibility of meeting peak load in all zones, the performance rating of the AC unit must be equal to or greater than the sum of peak sensible loads of the zones, even if they are not simultaneous.

On the other hand, in a zoned system, the distribution network has motorized dampers that allows you to adjust the thermal contribution of the system to the demand of each zone separately. This means that the AC unit is sized by taking into account the maximum simultaneous sensible load of the zones. In other words, for every time step, the loads of all zones are added together, and the AC unit is sized based on the annual maximum for cooling and heating.

Table 2 shows the peak and simultaneous loads for the three cities, from the data of a typical manufacturer [9].

System		Non-Zoned	Zoned
City	**Loads (btu/h)**	**Peak**	**Simultaneous**
Miami	Q_{COOL}	32111.8	23253.2
	Q_{HEAT}	14290.0	9627.5
	DX MODEL	LV361HHV4	LV241HHV4
Los Angeles	Q_{COOL}	27966.7	17751.1
	Q_{HEAT}	18449.4	13181.6
	DX MODEL	LV361HHV4	LV181HHV4
New York	Q_{COOL}	28554.3	18914.1
	Q_{HEAT}	36528.0	29323.1
	DX MODEL	LV361HHV4	LV361HHV4
Chicago	Q_{COOL}	26553.8	18181.6
	Q_{HEAT}	39865.7	32119.5
	DX MODEL	LV420HHV4	LV361HV4

Table 2. Summary of thermal loads

It should be noted that the influence of the zoned control system allows to select an inverter unit model with a lower capacity resulting in a reduction in initial cost and lower energy consumption.

Results. Thermal comfort

Evaluation of thermal comfort

The comfort results focus exclusively on the zone temperature comparison depending on whether the system is zoned or not.

The control of the zone temperature in a non-zoned system depends on the demand of the living room, which is the master zone where the AC unit's thermostat is located and is regulated according to the set-point temperature established for this zone, while the thermal behavior of the remaining zones depends on the specific conditions (internal loads, solar gain, etc.) at that moment in time. Unlike the zoned system where the fan speed is selected using the Q-Adapt algorithm, in a non-zoned system the fan speed varies depending on the temperature difference between the master zone set-point temperature and the temperature of that zone. The graph in Figure 8 shows an example of a three-speed fan.

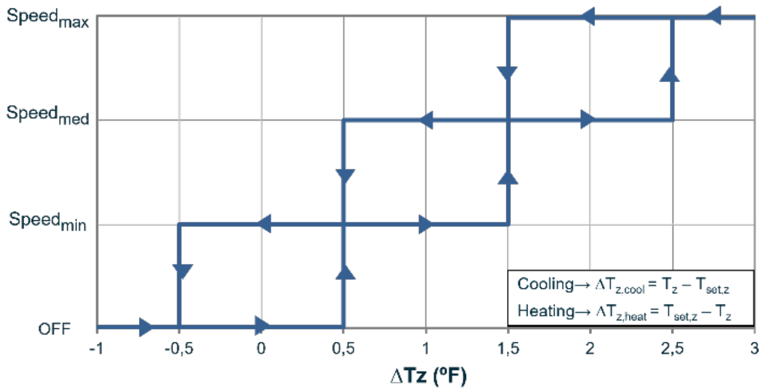

Figure 8. Selecting the fan speed for a non-zoned system

Unlike a non-zoned system, with an individual temperature control per zone system, it is the user who decides the desired set-point temperature in each of the zones, and whether the operating mode is set to heating or cooling. Regarding the set-point temperature, the system establishes a comfort range of ± 1°F, in such a way that a zone is in comfort when its temperature is within this defined range. This behavior is established to prevent the actuators from constantly changing their position in the event of slight temperature variations. Figure 9 shows the typical temperature behavior of the zone with individual temperature control per zone in heating and cooling mode.

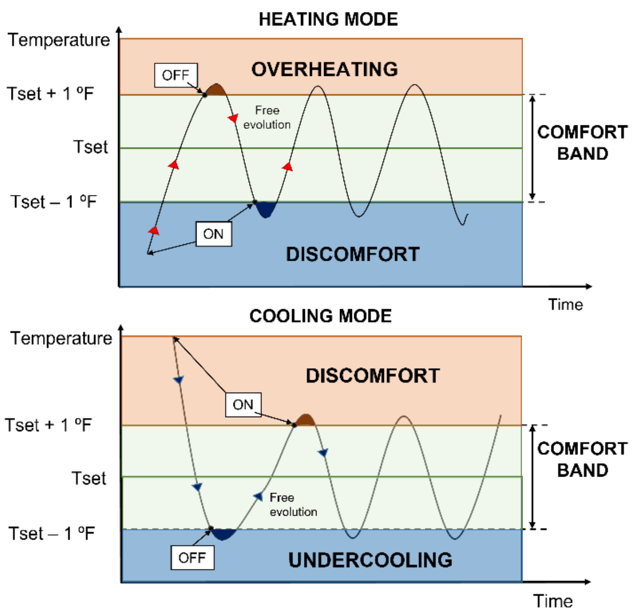

Figure 9. Evaluation of the thermal comfort in a zoned system

Comfort Parameters: PMV y PPD

From this analysis, a more detailed comfort analysis is evaluated in each zone. As comfort indicators, the Predicted Percentage of Dissatisfied (PPD) and the Predicted Mean Vote (PMV) are used according to the ISO 7730 standard [10]. The design criteria for a standing or relaxed person (1 met) wearing typical winter (1 clo) and summer indoor clothing (0.8 clo) are considered with air velocity set to 0.1 m/s. According to this standard, the comfort categories are presented as follows:

- Category A: PPD < 6% and PMV between -0.2 and 0.2.
- Category B: PPD < 10% and PMV between -0.5 and 0.5.
- Category C: PPD < 15% and PMV between -0.7 and 0.7.

Nowadays, comfort requirements in buildings are very demanding, and categories A or B are expected, especially in efficient and sustainable buildings that obtain BREEAM or LEED certifications [11]. Therefore, thermal discomfort will be considered from values with PPD greater than 15%.

Figure 10 shows a summary of thermal comfort results using the percentage of hours that the zones LR and one of the Bedrooms obtains PPD and PMV values according to the comfort categories.

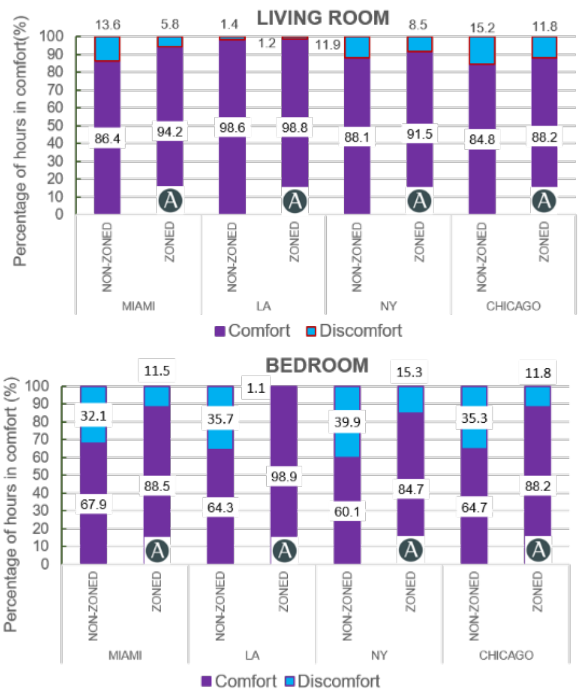

Figure 10. Thermal comfort analysis

In a first general analysis, the results of Figure 10 show how the percentage of hours of thermal comfort in the LR are remarkably high for both systems, from 86-98%. The thermostat in the Non-Zoned system is in the LR, so the unit is capable of maintaining the temperature of the zone in the comfort dead-band. Concerning to the BR, it should be noted that the results show high percentages of hours in thermal discomfort in the Non-Zoned system compared to the Zoned. The main reason is because, in the Non-Zoned system, the air supplied to the bedroom and the rest of the zones is conditioned according to the thermal demand of the living room, so undercooling in cooling mode and overheating in heating mode is produced. It is noteworthy the thermal discomfort varies from 32 to 40% depending on the climate conditions. In contrast, the Zoned system ensures a high percentage in thermal comfort higher than 86% in all the zones.

Results. Energy Consumption

After evaluating the building's thermal comfort, the next step is to compare the power consumption of an individual temperature control per zone and non-zoned HVAC system. Thanks to the Airzone North America Corp system's strategies designed to control and manage the HVAC application, energy savings are achieved and therefore also a reduction in carbon emissions. Figure 11 shows the results obtained for the comparison of these systems for the different cities under study.

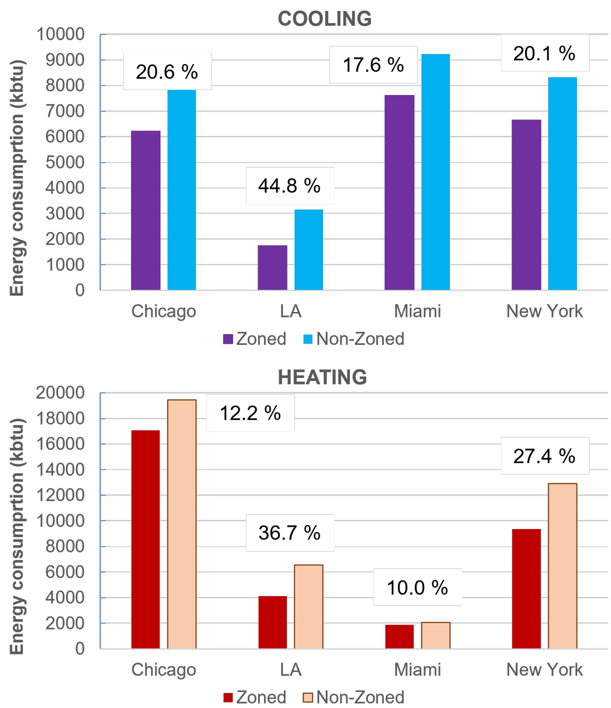

Figure 11. Comparison of energy consumption in cooling and heating modes and the percentage of energy savings

In all cases the HVAC consumption is lower in an individual temperature control per zone system than in a non-zoned system. The values obtained are within the maximum consumption limits established by the different regulations in force. The reasons have been explained in detail in this report: Reducing the thermal capacity of the HVAC system and regulating the fan speed and adapting the set-point temperature of the AC unit.

With respect to energy savings, the percentage is more important in the cases where the energy consumption is higher. As can be seen, in cooling mode there are important savings in Miami and New York, from 17-20%, and, in heating mode, from 12.2% to 27.4% in Chicago and New York, respectively.

Results. Environmental impact

The influence of the Airzone North America Corp control system could be also environmentally measured by means of the comparison of the CO_2 emissions emitted by the conventional Non-Zoned system and the Zoned system. The calculation of the CO_2 emissions is based on the use of the conversion coefficient factors obtained from the Emissions & Generation Resource Integrated Database (eGrip) [12], as can be seen in Table 3.

CO_2 conversion factor (lb/MWh)	Miami	LA	New York	Chicago
	837.48	480.49	891.0	657.32

Table 3. State annual CO_2 equivalent total output emission rate (lb/MWh)

Figure 12 shows the comparison of the total CO_2 emissions in pounds emitted by both systems.

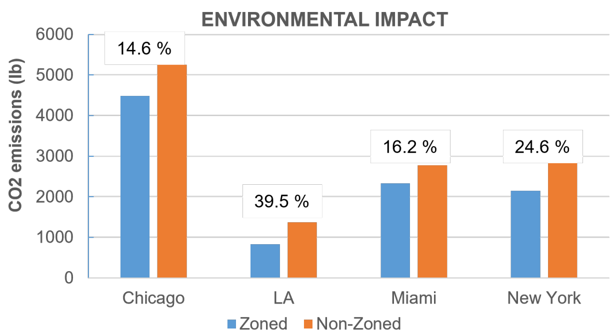

Figure 12. Comparison of the total CO_2 emissions

The environmental impact is also important, and the amount of CO_2 emissions savings is proportional to the energy consumption savings.

6. Conclusions

The aim of this study is to analyze in detail the behavior of Airzone HVAC control system based on thermal zoning and compare it with a non-zoned system. The document is structured in different sections in which the zoning system and the control algorithms are described, and it explains the modeling of the AC unit with the behavior curves at partial load obtained experimentally, and the implementation of the model of the direct expansion unit with the Airzone control system in the TRNSYS software, which will be the simulation environment of the study.

The final conclusions of the study describe the main advantages obtained in the different comparisons made between an individual temperature control per zone and a non-zoned system in terms of thermal comfort, energy consumption and thermal energy. The conclusions are defined below.

1| The specification of an inverter system with integrated zoning as opposed to a non-zoned inverter system, implies a reduction of the thermal energy to be combated, and therefore the possibility of adapting the AC unit's capacity more accurately to the thermal demand. In cities with cold climates with low thermal transmittance values, reductions in thermal demand are obtained, although, unlike in other climates, they are not significant enough to reduce the capacity of the AC unit.

2| The zoned system monitors the temperature in each of the building's zones and allows the user to set their comfort preferences in each zone. It has been demonstrated that, when compared to a nonzoned system, the percentage of hours in which the zones are in thermal comfort is much higher in a zoned system. In contrast, the non-zoned system causes overheating and overcooling in the rooms where there is no thermostat. Consequently, the zoned system guarantees a comfort category of at least level B in each zone and in every city.

3| The control algorithm of the zoned system regulates the fan speed and air supply set-point temperature adapting the performance of the equipment to the thermal needs of each zone. As a result, energy consumption is reduced in all the cases when compared to the non-zoned system. As can be seen, in cooling mode there are important savings in Miami and New York, from 17% to 20%, and, in heating mode, from 12.2% to 27.4% in Chicago and New York, respectively.

4| Energy savings give rise to CO_2 emissions savings. The environmental impact of the Airzone control system is important with a total of 2,450 lbs of CO_2 not added to the atmosphere.

The present study is an adaptation for the USA residential sector of the paper titled: “Impact of Zoning Heating and Air Conditioning Control System in Users Comfort and Energy Efficiency in Residential Buildings” [13] published in the scientific journal Energy Conversion and

Management, indexed in the Journal Citation Report as the first quartile with an impact factor of 11.53.

References

[1] K.S. Cetin, M. H. Fathollahzadeh, N. Kunwar, H. Do, P.C. Tabares-Velasco. Development and validation of an HVAC on/off controller in EnergyPlus for energy simulation of residential and small commercial buildings. Energy and Buildings, Vol 183, 2019, pp 467-483.

[2] United States Energy Information Administration. RECS, Residential Energy Consumption Survey. U.S. Department of Energy, Washington, DC, USA (2009).

[3] Bai Quan, Cabeza Luisa F., Bertoldi Paolo, Kihila Jacob, Lucena André, Mata Érika, Mirasgedis Sebastian, Novikova Aleksandra, Saheb Yamina, Keenan Jesse, Serrano Diná Maria Isabel, 2022: Buildings. In: AR6 Climate Change 2022: Mitigation of Climate Change. Available at: https://report.ipcc.ch/ar6wg3/

[4] US Energy Information Administration. Available at: https://www.eia.gov/tools/faqs/faq.php?id=97&t=3

[5] TRNSYS http://sel.me.wisc.edu/trnsys/. (Access 02.01.18).

[6] Archiectectural Designs. Selling quality house plans for generations. Available at: https://www.architecturaldesigns.com/house-plans/3-bedroom-new-american-farmhouse-plan-with-l-shaped-front-porch-16916wg

[7] EnergyPlus (2022). Available at: https://energyplus.net/weather

[8] Building Energy Codes Program. Office of Energy Efficiency & Renewable Energy (energy.gov). Available at: https://www.energycodes.gov/prototype-building-models#Residential

[9] LG Think. Vertical AHU (with LGred). Available at: https://lghvac.com/residential-light-commercial/lgred-heat/

[10] EN ISO-7730:2006. Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria.

[11] BRE, BREEAM offices 2008 assessor manual, BREEAM. Watford: BRE Global Ltd.; 2010.

[12] Emissions & Generation Resource Integrated Database (eGrip). Available at: https://www.epa.gov/egrid/download-data

[13] F. Fernández Hernández, J.M. Peña Suárez, J.A. Bandera Cantalejo, M.C. González Muriano. Impact of Zoning Heating and Air Conditioning Control System in Users Comfort and Energy Efficiency in Residential Buildings. Energy Conversion and Management (2022) 267, 115954.