The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 2024

Volume 28, Pages 390-396

ICBASET 2024: International Conference on Basic Sciences, Engineering and Technology

Integration of Air Conditioning Systems in Intelligent Buildings to Increase Efficiency

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Abstract: Heating, ventilation, air conditioning, and cooling, collectively known as HVAC, account for more than 40% of the electricity consumed in buildings. Global climatic factors, referring to comfort and factors related to health, dictate that there is an increasing need for the application of HVAC/R systems. Therefore, it is increasingly compelling to investigate various approaches to enhance the effectiveness of air treatment systems. The automation of buildings has facilitated the integration of air treatment systems with "other existing" systems that can impact the indoor climatic conditions, such as automated windows and curtains, etc. In order to achieve this, it is essential to employ calculation techniques for air handling systems and for the heat transfer between buildings and the external environment. By integrating these systems, it becomes possible to maintain a comfortable environment while actively minimizing the electricity consumption of the heat pump. This article focuses on the integration of air conditioning systems in intelligent buildings to enhance efficiency.

Keywords: HVAC/R, Energy consumption, Automation, Integration

Introduction

Within an autonomous air treatment machine, the primary energy-consuming components are the ventilators and the heat pump. On average, the heat pump alone would consume over 65% of the electricity. More precisely, this consumption would refer to the electricity consumed by the compressor motor of the heat pump. Therefore, it is imperative to examine the potential and techniques for maximising the efficiency of heat pumps.

When the entire system is taken into consideration, it is observed that the thermal capacity and consumption would be determined by the physical dimensions of the components (compressor, condensing heat exchanger, and evaporating heat exchanger), in addition to the working conditions under which the system would be operating. When we talk about the "working conditions", we are referring to the air flux that is passing through each of the heat exchangers specifically. Specifically, the factors of interest are airflow, air temperature, and relative air humidity.

From all the parameters mentioned above, it can be said that the physical parameters of the system are unchangeable. Also, the temperature and humidity of the air flow that would pass through the heat exchanger that is exposed to the outside air are unchanging parameters. Effectively, the parameters that can be manipulated are the air flow in the external exchanger, the air flow in the internal exchanger, as well as the temperature and relative humidity of the internal air. In this paper, we will examine whether it is possible to regulate the climatic conditions within a specific range by integrating the air conditioning system with other intelligent components of the building, with the aim of optimizing the coefficient of performance (COP).

Method

Compressor Model

The most widespread model for calculating the parameters of refrigeration power, absorbed electrical power, absorbed current, and gas mass flow in a compressor, is the third-order polynomial model with two parameters, specifically the evaporation temperature and the condensation temperature, as shown below.

$$F(T_{ev}, T_{co}) = A + BT_{ev} + CT_{co} + DT_{ev}^2 + ET_{ev}T_{co} + FT_{co}^2 + GT_{ev}^3 + HT_{co}T_{ev}^2 + IT_{ev}T_{co}^2 + LT_{co}^3 \quad (1)$$

The numerical method approach presented by Daci, A., & Bundo, J. (2020) was used to determine the equilibrium point of the refrigeration circuit. The application of this method is fundamental because it helps on the determination of evaporation and condensation temperatures in a relatively short time, which is crucial on the application of control with the aim of optimizing efficiency. COP (coefficient of performance) is defined as the ratio of the thermal power of the compressor to its electrical power. Thus, it results:

$$COP = \frac{P_f(\mathrm{T_{ev}}, T_{co}) + P_{el}(T_{ev}, T_{co})}{P_{el}(T_{ev}, T_{co})} \quad (2)$$

Where the index “f” represents the term “refrigerator” (frigo) while the index “el” represents the term “electrical”. The symbol P in both cases represents power. The outcome would be:

$$\frac{\sigma_A + \sigma_B T_{ev} + \sigma_C T_{co} + \sigma_D T_{ev}^2 + \sigma_F T_{co}^2 + \sigma_G T_{ev}^3 + \sigma_L T_{co}^3 + \sigma_E T_{co} T_{ev} + \sigma_H T_{co} T_{ev}^2 + \sigma_I T_{co}^2 T_{ev}}{L_{el} T_{co}^3 + I_{el} T_{co}^2 T_{ev} + F_{el} T_{co}^2 + H_{el} T_{co} T_{ev}^2 + E_{el} T_{co} T_{ev} + C_{el} T_{co} + G_{el} T_{ev}^3 + D_{el} T_{ev}^2 + B_{el} T_{ev} + A_{el}} \quad (3)$$

$$\sigma_x = X_{el} + X_f \quad (4)$$

On the other hand, EER (energy efficiency ratio) will be defined as the ratio of the cooling power developed by the compressor to the electrical power it receives from the power network:

$$EER = \frac{P_f(\mathrm{T_{ev}}, T_{co})}{P_{el}(T_{ev}, T_{co})} \quad (5)$$

$$\frac{L_f T_{co}^3 + I_f T_{co}^2 T_{ev} + F_f T_{co}^2 + H_f T_{co} T_{ev} + E_f T_{co} T_{ev} + C_f T_{co} + G_f T_{ev}^3 + D_f T_{ev}^2 + B_f T_{ev} + A_f}{L_{el} T_{co}^3 + I_{el} T_{co}^2 T_{ev} + F_{el} T_{co}^2 + H_{el} T_{co} T_{ev} + E_{el} T_{co} T_{ev} + C_{el} T_{co} + G_{el} T_{ev}^3 + D_{el} T_{ev}^2 + B_{el} T_{ev} + A_{el}} \quad (6)$$

Analysis

Let's try to see the differential expression of COP in order to get a better understanding of the shape of the tendency of these curves so that we can determine whether or not the hypothesis that was explained earlier is correct, or more specifically, whether or not there is such a place for the application.

The first derivative of the refrigerating power in relation to the evaporation temperature is as follows:

$$\frac{\partial Pf(T_{ev},T_{co})}{\partial T_{ev}} = I_f T_{co}^2 + 2H_f T_{co} T_{ev} + E_f T_{co} + 3G_f T_{ev}^2 + 2D_f T_{ev} + B_f \tag{7}$$

Meanwhile, the first derivative of the refrigeration power in relation to the condensation temperature would be:

$$\frac{\partial P_f(T_{ev},T_{co})}{\partial T_{co}} = 3L_f T_{co}^2 + 2I_f T_{co} T_{ev} + 2F_f T_{co} + H_f T_{ev}^2 + E_f T_{ev} + C_f \tag{8}$$

Let us proceed and examine the partial derivatives of the coefficient of performance in relation to the temperature of evaporation and condensation.

$$\frac{\partial COP(t_{ev},t_{co})}{\partial t_{ev}} = \frac{B_{el}+B_f+2D_{el}T_{ev}+2D_fT_{ev}+E_{el}T_{co}+E_fT_{co}+\sigma_1+3\,G_fT_{ev}^2+I_{el}T_{co}^2+I_fT_{co}^2+2H_{el}T_{co}T_{ev}+2H_fT_{co}T_{ev}}{\sigma_2} -$$
$$\left[(I_{el}T_{co}^2 + 2H_{el}T_{co}T_{ev} + E_{el}T_{co} + \sigma_1 + 2D_{el}T_{ev} + B_{el})\big(A_{el} + A_f + B_{el}T_{ev} + B_fT_{ev} + C_{el}T_{co} +\right.$$
$$C_fT_{co} + D_{el}T_{ev}^2 + D_fT_{ev}^2 + F_{el}T_{co}^2 + F_fT_{co}^2 + G_{el}T_{ev}^3 + G_fT_{ev}^3 + L_{el}T_{co}^3 + L_fT_{co}^3 + E_{el}T_{co}T_{ev} +$$
$$\left.E_fT_{co}T_{ev} + \sigma_4 + H_fT_{co}T_{ev}^2 + \sigma_3 + I_fT_{co}^2T_{ev}\big)\right]\frac{1}{\sigma_2^2} \tag{9}$$

$$\sigma_1 = 3G_{el}T_{ev}^2$$

$$\sigma_2 = L_{el}T_{co}^3 + \sigma_3 + F_{el}T_{co}^2 + \sigma_4 + E_{el}T_{co}T_{ev} + C_{el}T_{co} + G_{el}T_{ev}^3 + B_{el}T_{ev} + A_{el}$$

$$\sigma_3 = I_{el}T_{co}^2T_{ev}$$

$$\sigma_4 = H_{el}T_{co}T_{ev}^3$$

$$\frac{\partial COP(T_{ev},t_{co})}{\partial t_{co}} = \left[C_{el} + C_f + E_{el}T_{ev} + E_fT_{ev} + 2F_{el}T_{co} + 2F_fT_{co} + H_{el}T_{ev}^2 + H_fT_{ev}^2 + \sigma_1 + 3L_fT_{co}^2 +\right.$$
$$\left.2I_{el}T_{co}T_{ev} + 2I_fT_{co}T_{ev}\right]\frac{1}{\sigma_2} - \left[(\sigma_1 + 2I_{el}T_{co}T_{ev} + 2F_{el}T_{co} + H_{el}T_{ev}^2 + E_{el}T_{ev} + C_{el})\big(A_{el} + A_f +\right.$$
$$B_{el}T_{ev} + B_fT_{ev} + C_{el}T_{co} + C_fT_{co} + D_{el}T_{ev}^2 + D_fT_{ev}^2 + F_{el}T_{co}^2 + F_fT_{co}^2 + G_{el}T_{ev}^3 + G_fT_{ev}^3 +$$
$$\left.L_{el}T_{co}^3 + L_fT_{co}^3 + E_{el}T_{co}T_{ev} + E_fT_{co}T_{ev} + \sigma_4 + H_fT_{co}T_{ev}^2 + \sigma_3 + I_fT_{co}^2T_{ev}\right]\frac{1}{\sigma_2} \tag{10}$$

$$\sigma_1 = 3L_{el}T_{co}^2$$

$$\sigma_2 = L_{el}T_{co}^3 + \sigma_3 + F_{el}T_{co}^2 + \sigma_4 + E_{el}T_{co}T_{ev} + C_{el}T_{co} + G_{el}T_{ev}^3 + D_{el}T_{ev}^2 + B_{el}T_{ev} + A_{el}$$

$$\sigma_3 = I_{el}T_{co}^2T_{ev}$$

$$\sigma_4 = H_{el}T_{co}T_{ev}^2$$

In this way we can estimate in which direction we would move on the surface of the COP with the change of the temperature of evaporation and condensation, trying to go towards the maximum.

Here, we will examine a compressor of type **GMCC KSK66D43UEZA_30 Hz** produced by Toshiba with the following parameters of third order polynomials considering as input evaporation and condensation temperature:

Table 1. Polynomial model for refrigerant power of compressor GMCC KSK66D43UEZA_30 Hz

Parameter	**Value**
A_f	3655.27
B_f	132.62
C_f	-4.78
D_f	1.86
E_f	-0.24
F_f	-0.58
G_f	0.01
H_f	-0.0067
I_f	-0.0104464
L_f	0.003776

Table 2. Polynomial model for electrical power of compressor GMCC KSK66D43UEZA_30 Hz

Parameter	**Value**
A_{el}	336.1
B_{el}	-17.62
C_{el}	-2.36
D_{el}	-0.51
E_{el}	0.45
F_{el}	0.46
G_{el}	-0.004
H_{el}	0.0052
I_{el}	0.000228
L_{el}	-0.00363

The graphic representation of the relationship between the coefficient of performance (COP) and the temperature of evaporation and condensation is the following, based on the data from the model for the compressor described above.

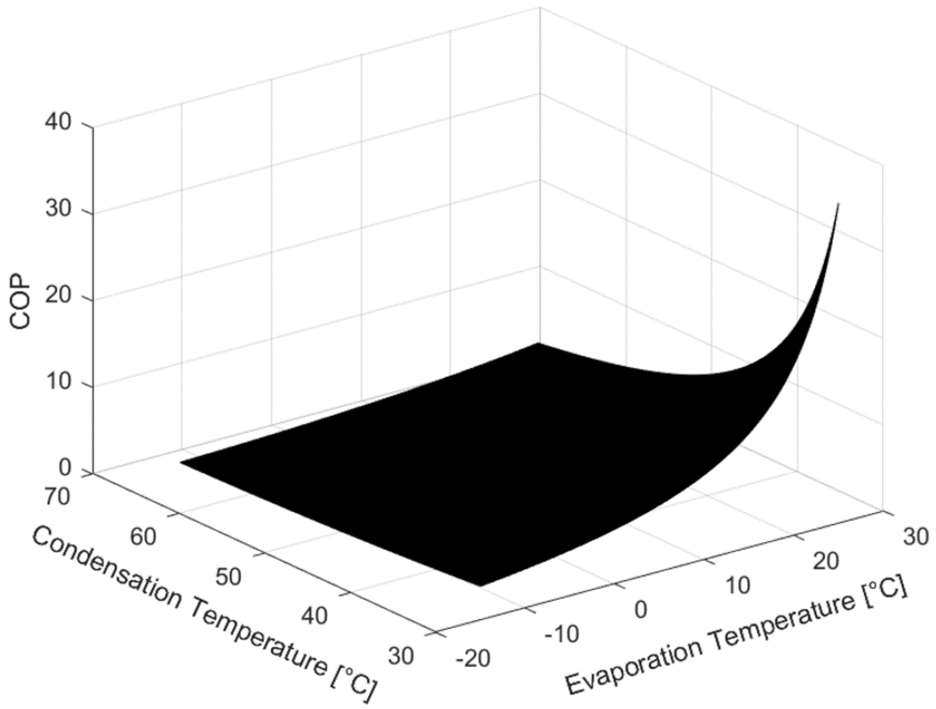

Figure 1. COP vs evaporation temperature and condensation temperature

Results and Discussion

A number of factors, which can be classified as either manipulable or not, will determine the coefficient of performance (COP) of a system. The fixed parameters would be associated with the physical aspects of the components, such as heat exchangers, the architecture of the refrigeration circuit (parallel evaporative exchanger, parallel condensing exchanger, water exchanger, air exchanger, etc.), and the compressor. On the other hand, the variable parameters would take into consideration air flow, temperature, and air humidity.

In the following we will consider an autonomous air handling machine which is simulated in the summer season. The temperature of the internal environment will vary between 20°C and 26°C, while the temperature of the external environment will be between 30°C and 37°C. Knowing the geometry of each of the heat exchangers and the above model of the compressor, we will simulate the system under the conditions indicated above by applying as a calculation method presented by Daci & Bundo (2020). Following is a plot that illustrates the data that was generated by the simulation, which generated a total of 56 samples. From the graph above, the trend shown by EER can be seen in relation to the temperature of evaporation and condensation. It is important to note that the EER is increased when the temperature of evaporation is increased, and the EER is increased when the temperature of condensation is decreased. This element also corresponds to what we see in the theoretical presentation of COP in Figure 1.

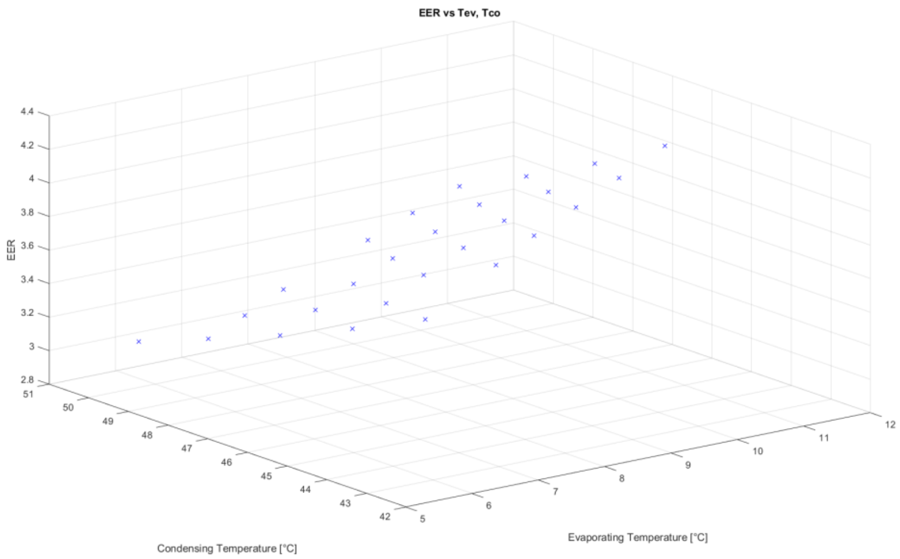

Figure 2 EER vs evaporation and condensation temperatures

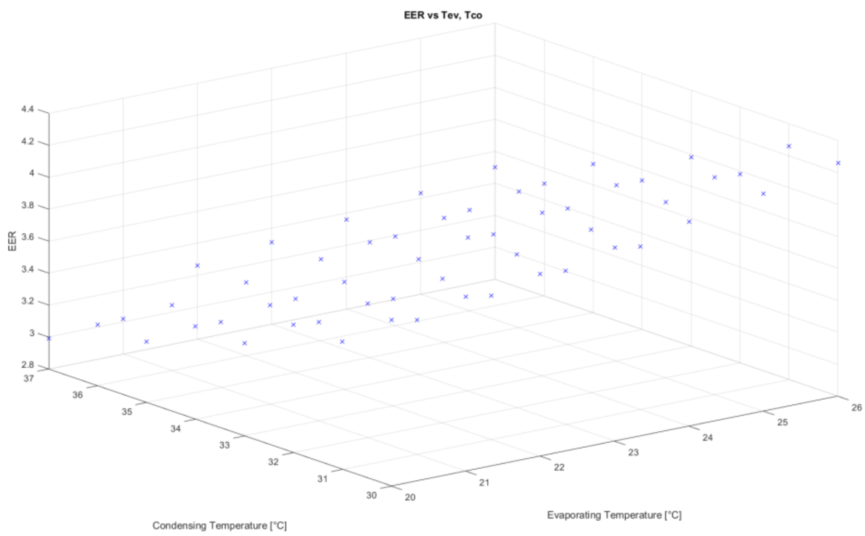

Figure 3 EER vs indoor and outdoor temperatures

In this figure, a similarity can be seen with the dependence that EER presents on the temperature of evaporation and condensation. By analogy, we can say that increasing the temperature of the internal environment, i.e. increasing the temperature of the air that exchanges heat with the evaporating element, the EER will also increase. On the other hand, reducing the value of the temperature of the external environment, that is, of the air that exchanges heat with the condensing element, the EER will increase.

The above analysis and the three graphs presented show the potential of improving the efficiency of HVAC systems through control and integration with other existing systems where their action can affect the change of climatic conditions in the indoor environment. On the other hand, the development of technology and the possibility of achieving the weather forecast within a day with satisfactory accuracy presents a new opportunity to realize the improvement of efficiency through utilisation of advanced control techniques such as model predictive control (MPC).

Conclusion

In the HVAC/R industry, the calculation and simulation of the heat pump is an argument that, with the progression of technology, the rise in demands in terms of quantity and complexity, and most recently, the energy crisis that the modern world is experiencing, is becoming increasingly interesting.The presentation of new software methods for the calculation within a relatively fast time and with an acceptable accuracy of the heat pump, has presented new possibilities for the optimization of these systems. After looking at the information presented above, we are able to comprehend the connection that exists between the EER and the temperatures of evaporation, condensation, indoor air, and outdoor air.. If we can define a comfort zone in relation to the temperature of the surrounding environment, and the heating/cooling system can be "helped" by integrating other elements so that the indoor air enters this comfort zone which would result in a significant improvement in both efficiency and system performance, then the system would be significantly improved.

In order to realise this integration, the physical elements that are necessary are those that have the potential to influence the climatic conditions of the air inside the building through the processes of radiation and convection of air. In this context, we may make reference to controlled doors, controlled windows, controlled shutters or curtains, or other components of a similar nature. In the graph that was just presented, the conditions that result in the lowest possible value of EER are those in which the internal temperature is 20°C, the external temperature is 37°C, the evaporation temperature is 6.15°C and the condensation temperature is 50.66°C. The maximum value of the condensation temperature would be 4.26 where the internal temperature is 26°C, the external temperature is 31°C, the evaporation temperature is 10.65°C and the condensation temperature is 44.93°C.

Recommendations

In order to make the implementation of such a integrated system a reality, it is recommended that a product be developed that automates and optimises buildings. It is necessary to provide the relevant parameters of the building in this product in order to be able to calculate the thermal balance of the building in relation to the external environment as a single system. On the other hand, this intelligent system would have to take into consideration the possibility that there are elements that can be controlled that have an effect on the climate conditions of the building. The geometry of each of the air handling components and the architecture of the system are two additional important aspects that need to be determined in addition to these data.

The optimisation of the system in terms of efficiency can be carried out by remaining within a comfort zone. This is made possible by having knowledge of the meteorological forecast for the next twenty-four hours as well as the effect that the controllable elements would have if the heat pump calculation method presented by Daci and Bundo (2020) was applied.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

* This article was presented as a poster presentation at the International Conference on Basic Sciences, Engineering and Technology (www.icbaset.net) held in Alanya/Turkey on May 02-05, 2024.

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To cite this article:

Bundo, J., Sharko, G., Spahiu, A., Panxhi, D., & Dhamo, D. (2024). Integration of air conditioning systems in intelligent buildings to increase efficiency. *The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM), 28,* 390-396.