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ORIGINAL RESEARCH ARTICLE

Experimental designs applied to a direct expansion heat pump with solar energy

Francis B. Gorozabel-Chata[1*], Tania Carbonell-Morales[2]

[1] *Department of Mechanical Engineering, Universidad Técnica de Manabí, Portoviejo, Ecuador. E-mail: fgorozabel@utm.edu.ec*

[2] *Renewable energy technology research center, Universidad Tecnológica de la Habana José Antonio Echeverría, Havana, Cuba.*

ABSTRACT

The direct expansion heat pump with solar energy is an energy conversion system used for water heating applications, air heating for air conditioning buildings, water desalination, solar drying, among others. This paper reviews the main designs and analysis of experiments in order to identify the fundamental objectives of any experiment which may be: to determine the factors that have a significant influence, to obtain a mathematical model and/or to optimize performance. To achieve this task, the basic and advanced configuration of this system is described in detail in order to characterize its thermal performance by means of energy analysis and/or exergy-based analysis. This review identifies possible lines of research in the area of design and analysis of experiments to develop this water heating technology for industrial applications.

Keywords: Heat Pump; Solar Energy; Direct Expansion; Exoergic Analysis; Design of Experiments

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1. Introduction

A solar-assisted direct expansion heat pump (BCAES-ED) is a technology that combines a conventional solar heating system with a heat pump. As the solar collector and the evaporator are integrated in the same unit, the working fluid is a refrigerant which expands in the collector/evaporator panel. Due to the gain of solar energy, it transits from liquid to steam through the collector/evaporator plate. According to Omojaro *et al.*[1], there are two types of configurations when referring to a BCAES-ED, basic and advanced. In the basic configuration model, the system works with the mechanical vapor compression cycle at one compression stage and in the advanced configuration model it uses two compression stages. Chaturvedi *et al.*[2] mark a clear dividing line between the two configurations. They concluded that at temperatures above 70 ºC, a BCAES-ED with a basic configuration loses efficiency and economic advantages over electric systems.

To characterize the thermal performance of a BCAES-ED, two types of analysis are used: energy analysis, which evaluates the coefficient of performance (COP) of the system; and exergy-based methods, which identifies the system component(s) that are underperforming and allows improvements to be implemented. Since the idea was conceived in 1955 that solar energy can evaporate a refrigerant circulating through a heat pump by using a solar collector as an evaporator, analytical, theoretical, numerical and experimental studies were not carried out until the late 1970s. Gorozabel and Carbonell[3] provide a comprehensive review of the current status and prospects of this technology.

The purpose of this study is to characterize the thermal performance of the energy conversion system through energy analysis and/or (exergy) methods, and to elaborate the common experimental design of BCAES-ED for developing, improving and evaluating this energy conversion system. To meet this objective, we intend to describe the research problem, specify the objectives of the experiment, characterize the experimental design and evaluate the experimental results that the authors have reported in each of the scientific article of this review.

BCAES-ED is a technology with great potential in the world market, but it is still limited by some economic and technical barriers, which can be overcome with state policies that allow the development of the technology as concluded by Raisul Islam *et al.*[4]. Buker and Riffat[5] indicate that the averages of the studies conducted show that heat pump technology and solar thermal energy have the potential to provide an effective alternative for different climates and configurations.

The present review identifies future research work to increase the energy and exergy efficiency of the basic configuration, and BCAES-ED as an advanced configuration of water heating technology, which shows great potential for development and is an effective alternative for different climates around the world.

2. Model of basic and advanced configuration of a BCAES-ED

A BCAES-ED is composed of four main components: the collector/evaporator panel, the compressor, the expansion valve and the heat exchanger tank known as the condenser. Amin *et al.*[6] conducted a comprehensive study on the thermal performance of a two-phase bare-type solar collector/evaporator whose results show that, instead of losing energy to the environment, it gains a significant amount of energy due to the low operating temperature of the collector; Gorozabel and Carbonell[7] concur with these results when experimentally analyzing the performance coefficient for tropical zones characterized by ambient temperatures higher than 25 °C.

Most commercially available heat pumps operate in the mechanical vapor compression cycle as shown in **Figure 1a)**, where the working fluid is a refrigerant. A numerical analysis is performed by Molinari *et al.*[8] in order to evaluate the refrigerant 407-C while Kong *et al.*[9] performs it for Refrigerant 410-A. Among the main applications of a BCAES-ED are water desalination reported by Amin *et al.*[10] and heating swimming pools presented by Starke *et al*.

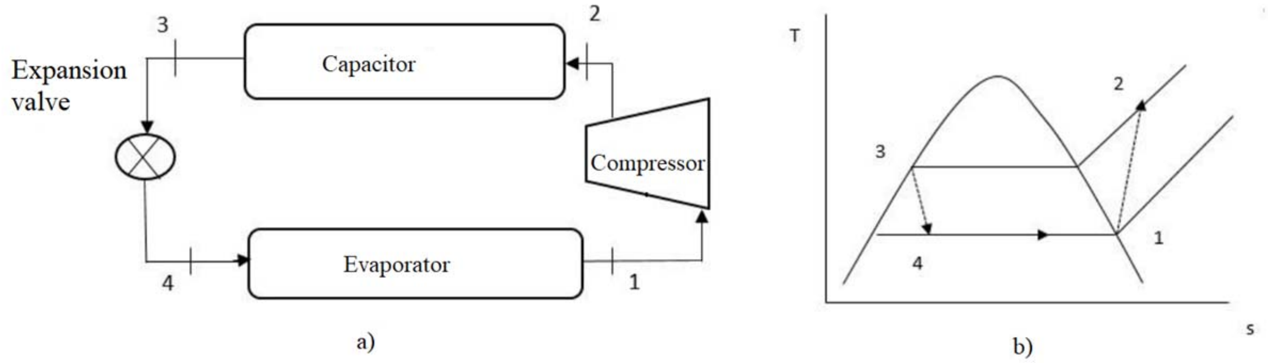

Figure 1. Mechanical vapour compression cycle.

A BCAES-ED is shown in **Figure 2**, which works with the mechanical vapor compression cycle illustrated in **Figure 1a)**, and whose thermodynamic processes are shown in **Figure 1b)**. Currently Scarpa *et al.*[12] and Tagliafico *et al.*[13] have succeeded in developing a steady state approach based on the Carnot cycle and the concept of efficiency based on the second law of thermodynamics to relate the main characteristics of the system and its interrelationships with the environment without calculating the properties of the refrigerant fluid.

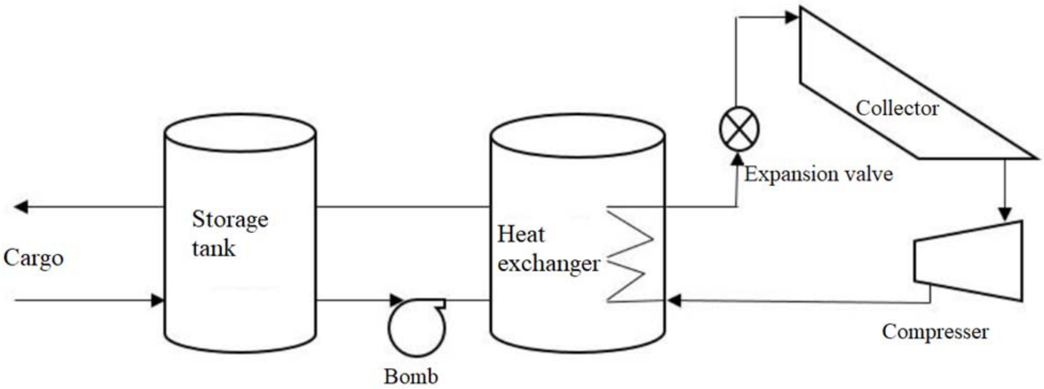

Figure 2. Solar-assisted direct expansion heat pump.

A theoretical analysis of BCAES-ED using two stages of compression to achieve corresponding temperature applications between 60 °C and 90 °C is proposed by Chaturvedi *et al.*[14]. A two-stage mechanical compression cycle is shown in **Figure 3a)** and a T-s diagram in **Figure 3b)**. The cycle shown in **Figure 3a)** assumes that there is no pressure drop in the heat transfer in the collector/evaporator panel and in the condenser. The compression process is assumed to be non-isentropic and is characterized for the two compressors by the efficiency of an adiabatic compressor. Besides, the pressure drop in the connecting pipes is depreciable.

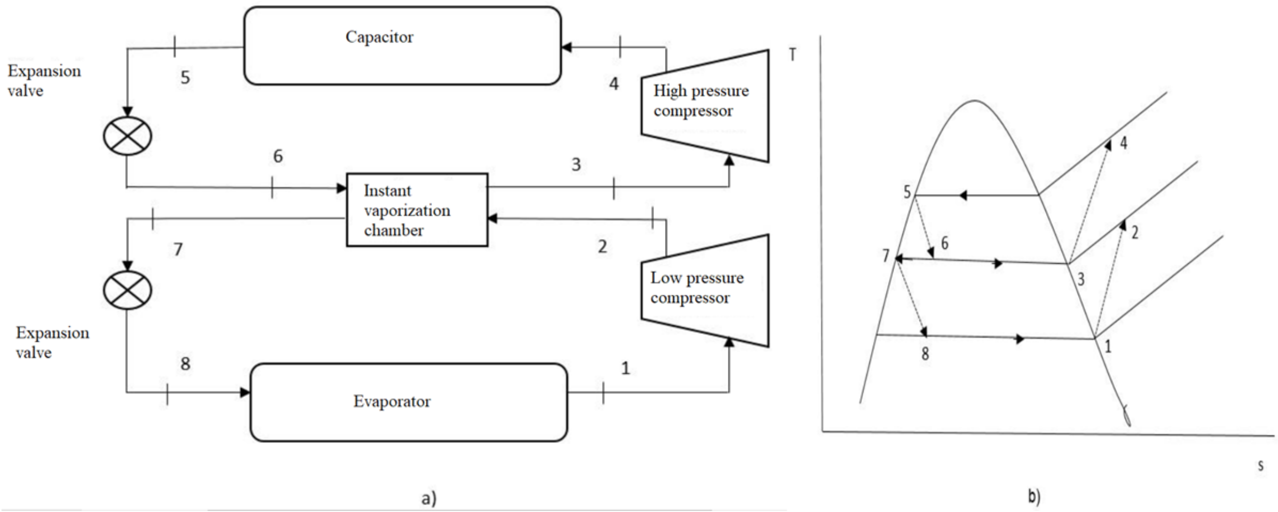

Figure 3. Solar-assisted two-stage direct expansion heat pump.

In general, the COP for an advanced BCAES-ED configuration is a function of several parameters, such as the refrigerant fluid, the efficiency of the system components, the source and heatsink temperature. Chaturvedi *et al.*[14] find a significant improvement of the system operating coefficient when using the two compression stages to reach high condensing temperatures. However, at the same temperature levels the two-stage system requires a larger collector area than single-stage systems.

BCAES-ED technology is currently of great interest to researchers who see great development potential in both basic and advanced configurations, as demonstrated by the analytical, numerical and experimental studies reported in the last five years with the aim of improving its thermal performance and introducing new applications such as water desalination, pool heating and solar drying.

3. Energy analysis and exergy-based analysis methods of a BCAES-ED

The thermal efficiency of a heat pump is characterized by the defined COP performance coefficient:

$$COP \ = \frac{Q_H}{W_c}$$

(1)

W_c is the compressor input power and Q_H is the heat flow delivered. In general, the COP of a heat pump depends on several parameters, including refrigerant, efficiency of system structural components, temperature of heat source and radiator.

In a two-stage heat pump, a modified version of equation 1 is used to calculate the COP to take into account the effect of the double stage in the advanced system configuration.

$$COP \ = \frac{Q_H}{\Sigma W}$$

(2)

ΣW is the total work input and is calculated as follows:

$$\Sigma W = W_{12} + W_{34}$$

(3)

Exergy refers to the maximum available theoretical work obtained when the energy conversion system interacts with the environment while reaching thermodynamic equilibrium with the environment. To perform an analysis of efficiency and losses, it is necessary to express in general form the energy balance equation shown below.

$$\Sigma \dot{E}_{in} = \Sigma \dot{E}_{out}$$

(4)

For Tsatsaronis and Morosuk[15], exergy analysis determined the location, magnitude and causes of thermodynamic inefficiencies, which takes the form of exergy destruction or exergy losses. Exergy destruction is due to the irreversibilities existing within the system, and exergy losses are related to the exergy lost in the environment. To identify and quantify the losses when performing an exergy analysis of the system, process or component, it is necessary to calculate the destroyed exergy, supplied exergy and exergy efficiency.

The destroyed exergy is calculated with the following equation:

$$\Sigma \dot{E}x_{in} = \Sigma \dot{E}x_{out} + \Sigma \dot{E}x_{destruida}$$

(5)

The supplied exergy is expressed by means of the following equation:

$$\dot{E}x_{suministrada} = \dot{m}[(h - ho) - To(s - so)]$$

(6)

Where $\dot{m}$ is the mass flow of the refrigerant, h is the specific enthalpy, s is the specific entropy, T is the temperature, while the subscript o means the dead center state of the refrigerant. The exergetic efficiency will be the ratio between the exergy recovered and the exergy supplied.

$$\eta_{ex} = \frac{\dot{E}x_{recuperada}}{\dot{E}x_{suministrada}}$$

(7)

According to Lazzaretto and Tsatsaronis[16], exergy-economic analysis is a unique combination of exergy and cost driven single component level analysis, which provides the designer or researcher of an energy conversion system with crucial information for the design of a cost-effective system. Exergy-economics is an exergy-based approach to cost reduction that uses the “exergy cost” principle. This principle states that exergy is the only rational basis for assigning monetary values to energy transport and thermodynamic inefficiencies within the system. The exergy cost principle is the basis for calculating the costs associated with each material and each energy flow in an energy conversion system. A complete exergy-economic analysis consists first of an exergy analysis, then an economic analysis and finally an exergy-economic evaluation.

According to Meyer *et al.*[17], an exergy-environmental analysis rests on the premise that exergy is the only rational basis for assigning not only a monetary value, but also an environmental impact value to energy transport and inefficiencies within each component, which is known as exergy-environmental cost. Exergy environment analysis includes exergy analysis, life cycle assessment of each relevant component in the system and all relevant flows entering the system, and finally calculation of the environmental impact related to each exergy flow and the destruction of exergy in each component in the system.

According to Tsatsaronis[18], it is known as Advanced Analysis when the avoidable/inevitable part and the endogenous/exogenous part of the exergy destruction of each important component in the system, investment cost and constructive components related to environmental impact, as well as the cost of exergy destruction and the environmental impact associated with exergy destruction are divided; in this analysis the interactions between different components are estimated to improve the quality of the conclusions obtained from an exergy, exergy-economic or exergy-environmental assessment. The main applications reported by researchers include the research of Gungor *et al.*[19,20], who studied the exergy destruction in the avoidable and unavoidable part, and conducted advanced exergy economic analysis of gas engine driven heat pumps.

Exergy and exergy-based analyses are important tools in evaluating, developing, and optimizing energy conversion systems such as a BCAES-ED in its basic and advanced configuration. Advanced exergy-based analyses have the potential to improve the quality of exergy, exergy-economic, and exergy-environmental assessment conclusions applied to a BCAES-ED.

4. Analysis and design of experiments on a BCAES-ED

An experimental design aims to obtain the maximum information of the process, in the fastest, most economical, simplest and most accurate way. The objectives of an experimental design, according to Montgomery[21], is to first identify the most influential factors in a performance, and then to relate the independent variables or factors with the dependent variable or performance, and the third objective is to determine the region of the most important factors that lead to the best possible performance. **Table 1** shows various experimental studies on energy and exergy-based analysis applied to a basic and advanced configuration of a BCAES-ED, and compares them with the objectives of the experimental design.

Table 1. Energy and exergy-based analysis applied to a basic and advanced configuration of a BCAES-ED

NO.	Objectives of the experimental design	References (Ref.)	
		basic configuration	Advanced configuration
1	Determine the factors that significantly influence the thermal performance of a BCAES-ED.	[22, 23, 24, 26, 27, 29, 30, 31, 35, 36, 37, 38]	
2	Obtain a mathematical model of a BCAES-ED.	[25, 28, 32, 33, 34]	
3	Optimize the thermal performance of a BCAES-ED.	[39, 40, 41, 42, 43, 44, 45]	

Table 2. Factors that most influence the performance of a BCAE-ED

Performance	Factors investigated	References (Ref.)	
		basic configuration	Advanced configuration
COP	Refrigerant evaporating temperature	[22, 23, 24, 30, 31, 36]	
	Collector efficiency	[23, 26–28, 35, 36]	
	Solar radiation	[23, 24, 26, 29–31, 35, 38]	
	Ambient temperature	[23, 26, 29–31, 38]	
	Temperature increase	[23]	
	Local time	[23]	
	Time in days	[26]	
	Time in minutes	[27, 29, 35]	
	Variable frequency compressor	[24]	
	Water temperature at the condenser inlet and outlet	[24, 27, 30, 31, 35, 36, 37, 38]	
	Refrigerant condensing temperature	[30, 31]	
	Heat gained in the condenser	[24, 36]	
	Condenser pressure drop	[30, 31]	
	Pressure drop in the solar collector	[30, 31]	
	Compressor pressure drop	[31]	
	Type of solar collector	[35, 36, 37]	
	Compressor power consumption	[35, 36]	
	Water heating technology	[38]	

Table 2 shows the investigated factors that have the greatest impact on the performance of a BCAE-ED, where the COP is the most investigated performance, while the refrigerant evaporation temperature, solar radiation, water temperature at the inlet and outlet of the condenser, and ambient

temperature are among the most investigated factors.

In order to determine the factors that significantly influence the thermal performance of a BCAES-ED, we can summarize the following conclusions: Kush[22] recommend avoiding evaporation temperatures higher than 25 ºC–30 ºC due to a marginal improvement of the COP as these impose a penalty on the collector efficiency. Chaturvedi and Shen[23] demonstrate the importance of correctly matching the solar collector area and compressor pumping mass. Chaturvedi *et al.*[24] find significant improvements in system performance by lowering the compressor speed when the ambient temperature increases. According to the studies conducted by Hawlader *et al.*[26], Kuang *et al.*[27] and Zhu *et al.*[35], the COP of the system is significantly affected by the following factors: compressor speed, solar radiation, collector area and stored volume. Li *et al.*[29] find that the system achieves significant thermal efficiencies in favourable climatic conditions and COP values between 3.11 and 3.23 in conditions of zero solar radiation. Sun *et al.*[38] conclude that in an annual performance analysis the average COP of a BCAES-ED is much higher than the conventional system. The configurations and types of collectors affect the COP of the system according to Zhu *et al.*[35], Garg *et al.*[36], and Sun *et al.*[37].

Table 3. Mathematical models reported in a BCAES-ED

Mathematical model	Range of application	Ref.
$W_c = 4{,}3(T_{w,1} - 273.15) + 151$ $COP = a_i + b_i(T_{w,p} - T_e)\ (i = 1a4)$ $T_{w,1} =$ Water temperature at inlet $T_{w,p} =$ Average water temperature $T_e =$ Refrigerant evaporating temp	$a_1 = 8.0;\ b_1 = -0.17$; for $0 < (T_{wp} - T_e) \leq 20K$ $a_2 = 6.6;\ b_2 = -0.10$; for $0 < (T_{wp} - T_e) \leq 30K$ $a_3 = 5.7;\ b_3 = -0.07$; for $0 < (T_{wp} - T_e) \leq 50K$ $a_4 = 3.7;\ b_4 = -0.03$; for $0 < (T_{wp} - T_e) \leq 60K$	[25]
$\eta_{col} = 0.684 - 13.4\frac{(T_e - T_a)}{I} R^2 = 0.86$ $\eta_{comp} = 0.32\, ln(f.m_{ref}) + 0.885$ $\eta_{col} =$ Collector efficiency $\eta_{comp} =$ Compressor efficiency $f =$ Frequency $m_{ref} =$ refrigerant mass	$700 < I < 1000\frac{W}{m^2}; 10 < pc < 13.5$ bar $15 < T_a < 30°C; 14 < T_c < 26°C$ Valid within the range 25 to 55 HZ	[28]
$\eta_v = 0.9953 - 0.037PRR^2 = 0.86$	Valid for $3 < PR < 7$	[32]
$COP = -0.0501(T_w - T_a) + 3.980$ $R^2 = 0.9718$	Valid for $7.8°C < T_a < 21.9°C$	
$W_c = 5.2032(T_W - T_a) + 310.62$ $R^2 = 0.993$	Valid for $T_a = 21.9°C$	
$W_c = 4.9538(T_W - T_a) + 275.56$ $R^2 = 0.978$	Valid for $T_a = 16.9°C$	
$W_c = 4{,}2037(T_W - T_a) + 256.80$ $R^2 = 0.987$	Valid for $T_a = 11.3°C$	
$W_c = 4.0703(T_W - T_a) + 234.87$ $R^2 = 0.982$	Valid for $T_a = 7.8°C$	
$Tcd = 20°C + 20°C + (0{,}8T_e + 7°C)$ *Tcd* = Temperature of condensation	Dg = 0.8 Dg = Creep term	[33,34]
$COP \frac{\frac{1}{4}UAT_a[\tau_c^{-1} - \tau^{-1}] - Q_i}{\dot{W}k}\ _{max}$	U = Heat transfer coefficient $T_a =$ Ambient temperature $\tau_c =$ temperature ratio between the refrigerant temperature in the evaporator and the condenser $\tau =$ temperature ratio between ambient temperature and air temperature *Qi* = Internal heat transfer *Wk* = Electrical power	[40]

Table 3 reviews the mathematical models developed to improve the thermal performance of a BCAES-ED. Among the main objectives proposed by researchers, we have Ito *et al.*[25] who determined the effect of copper thickness and the distance between tubes in the absorber plate of a BCAES-ED. Soldo *et al.*[28] developed a mathematical model that allows the optimization of the sys-

tem components and operating parameters. Fernández-Seara *et al.*[32] determined the effect of not having solar radiation on the thermal performance of a BCAES-ED. Moreno Rodríguez *et al.*[33,34] developed and validated a model that determines the operating parameters of a BCAES-ED and Cervantes. Torres[40] determined an expression to describe the optimal COP considering internal and external irreversibility in the thermodynamic optimization of a BCAES-ED.

Among the main conclusions of obtaining a mathematical model to improve the performance of a BCAES-ED, we have Ito *et al.*[25] who indicated that the thickness of the 1 mm copper plate used in the experiment can be reduced to 0.5 mm with very little reduction of the COP, also the distance between the copper tubes in the 100 mm plate can be changed to 190 mm obtaining a COP reduction of 4%. Soldo *et al.*[28] concluded that, to prevent high COP deterioration due to inconsistencies between climatic conditions and solar radiation, each component of the system should be optimized according to the solar collector area, compressor capacity, evaporating and condensing temperatures. Fernandez Seara *et al.*[32] obtained a COP of 3.23 when evaluated under zero solar radiation condition. Moreno Rodriguez *et al.*[33,34] found a COP of 1.7 and 2.9 for a water tank temperature of 51 °C. Cervantes and Torres Reyes[40] found that the model obtained closely represents the real performance of the system.

Table 4 shows a summary of the exergy-based analysis applied to a basic and advanced configuration of a BCAES-ED. The various objectives of the reviewed investigations are to determine the exergy efficiency[39,41-43], the exergy destruction of each component[39] and the total exergy destruction[39] in order to identify the main sources of irreversibility in a BCAES-ED and in some cases compare the use of two refrigerants[45] or determine an expression[40] to describe the optimal COP considering the internal and external irreversibility in the thermodynamic optimization of a BCAES-ED.

Table 4. Exergy analysis applied to a basic and advanced configuration of a BCAES-ED

NO.	Objectives of the experimental design	Configuration	Type of exergetic analysis			
			Conventional	Economic exergy	Environmental exergy	Advanced
3	Optimize the thermal performance of a BCAES-ED.	Basic Advanced	[39, 40, 41, 42, 43, 44, 45]			

In order to optimize the thermal performance by using exergy-based analysis of a BCAES-ED, we can summarize the following conclusions: Torres Reyes *et al.*[39] found that the operation of a BCAES-ED shows low exergy efficiency; the major exergy destruction occurs in the solar collector/evaporator panel. Cervantes and Torres Reyes[41] also agree that the main source of irreversibility is in the solar collector/evaporator panel, highlighting that the incoming solar radiation is not fully utilized. Li *et al.*[42] on the contrary found that the highest exergy loss occurs in the compressor, followed by the solar collector/evaporator, condenser and expansion valve in turn. Kara *et al.*[43] conclude that the exergy efficiency of the individual components of a BCAES-ED are in the range of 10.74% to 88.87%. Torres Reyes and Cervantes[40] obtained a model that closely represents the real performance of the system. Mohanraj *et al.*[44] confirmed with their results that it is acceptable to use artificial neural networks to predict the exergy destruction and exergy efficiency of a BCAES-ED. Mohanraj *et al.*[45] found that the average exergy efficiency of a BCAES-ED running on RM30 was slightly lower compared to R-22. However, RM30 is an ozone-friendly alternative when R22 leaves the market.

The experimental studies presented in **Table 1** to **Table 4**, and obtained from references[22-45] are in agreement with recent analytical and numerical studies presented by several authors. We can mention Yousefi *et al.*[46] who analyse and thermodynamically optimize a BCAES-ED with application to water heating; Kumar *et al.*[47] and Paradeshi *et al.*[48] performed parametric studies of this technology confirming the use of artificial neural networks integrated with genetic algorithms to predict the thermal performance of a BCAES-ED, as well as to characterize its performance in a hot and humid environment; Malali *et al.*[49] succeeded in developing an analytical tool by combining two models to determine the thermal performance of a BCAES-ED.

Experimental designs and analysis applied to a BCAES-ED have made it possible to identify the factors that significantly influence the thermal performance of a BCAES-ED, as well as to obtain mathematical models to predict the behaviour of the technology and optimize its operation. Energy analysis and conventional exergy analysis are most commonly used by researchers.

5. Experimental uncertainty

The uncertainty of experimental designs related to a BCAES-ED are summarized in **Table 5**, and have been estimated according to Holman[50]. Pressure, temperature, solar radiation, power consumption, coolant mass flow and air velocity are measured with the instruments listed in the sensor column. The uncertainty presented in the calculation of a parameter as a function of several independent variables is given with the following equation:

$$W_r = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_3} w_3\right)^2\right]^{1/2} \quad (8)$$

Where R is a given function; W_r is the total uncertainty; x_1, x_2, …, x_n are the independent variables; w_1, w_2, w_3 are the uncertainty in the independent variables.

In experiments performed on a BCAES-ED, data are obtained with single samples whose uncertainties cannot be discovered by repetition, as opposed to data with multiple samples whose results are reliable thanks to the application of statistical methods. Among the types of errors that can cause uncertainty, there are errors caused by the measurement instruments, fixed or systematic errors, and errors caused by random errors. The errors of the investigated parameters reported uncertainties in the range of 4.1 to 8.1%.

Table 5. Experimental uncertainty in BCAES-ED

Sensor	Accuracy	Parameter	Uncertainty	Reference
Temperature sensor	± 0.5 °C	PC (W)	5.2%	[30,31,44,45]
Thermometers	± 0.5 °C	Qcd (W)	4.2%	
Pressure sensor	± 1%	COP	6.2%	
Pressure gauges	± 2%	Td (°C)	3.9%	
Fluxometers	± 1%	SEPR	7.8%	
Wattmeter	± 0.5%	$\dot{E}x_{destruida}; \eta_{ex} compresor$	7.6%	
Digital energy meter	± 0.5%	$\dot{E}x_{destruida}; \eta_{ex} condensador$	7.3%	
Pyranometer	± 5 W/m^2	$\dot{E}x_{destruida}; \eta_{ex} válvula$	6.4%	
Anemometer	± 0.01 m/s	$\dot{E}x_{destruida}; \eta_{ex} colector$	8.1%	
Thermal Resistance	± 0.1 K	Qev	± 4.9%	[33,34]
Flowmeter	± 0.5%-3%	Qcd	± 4.9%	
Pressure sensor	± 0.25%	COP	± 4.1%	
Wattmeter	± 0.2%			
Anemometer	± 0.5%			
Pyranometer	± 0.2%			
System for the acquisition of Data	± 0.05%			

6. Conclusions

From the literature reviewed on analysis and design of experiments on a BCAES-ED, it is shown that the basic configuration model has been extensively studied with respect to energy analysis, managing to characterize the factors that significantly influence the thermal performance, as well as to obtain mathematical models and optimize the efficiency of this energy system. Compared with the exergy-based analysis, the basic configuration model shows results in conventional exergy analysis. By exploring exergy-economic and exergy-environmental analysis of this technology, as well as advanced analysis, improved conclusions have been obtained in the development, evaluation and improvement of this energy conversion system. With regard to the advanced configuration models, the literature reviewed does not report experimental designs of energy analysis and exergy-based analysis to demonstrate the benefits of this technology reported in theoretical analysis.

Conflict of interest

The authors declared that they have no conflict of interest.

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