Applied Thermal Engineering 275 (2025) 126889

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Reducing CO_2 emissions by improving HVAC system efficiency of data centers through nanofluids: a case study

Francesco Micali, Marco Milanese *, Gianpiero Colangelo, Arturo de Risi

Department of Engineering for Innovation, University of Salento, 73100 Lecce, Italy

ARTICLE INFO

Keywords:
CO_2 emission reduction
Data center
HVAC plant
Nanofluid
Coefficient of Performance

ABSTRACT

Nowadays, energy conservation is a crucial issue because of its many benefits, such as reducing greenhouse gas emissions, decreasing dependence on energy imports, and reducing costs for households and businesses. Data center energy consumption accounts for a significant portion of global energy consumption and may increase dramatically in the next years with the growing popularity of compute-intensive applications such as A.I., video-on-demand services, autonomous vehicles and advanced 5G technology. A major problem for data centers is the dissipation of heat generated by computers, for which various cooling systems are used. The objective of this work is to demonstrate the increase in cooling system efficiency directly attributable to the use of an aluminum oxide-based heat-transfer nanofluid, resulting in cost and energy savings and therefore in greenhouse gas emission reduction. In this investigation, through an extended experimental campaign, the comparison in terms of COP between a baseline period (before installation of the heat transfer nanofluid) and a reporting period (after installation), maintaining the same heat load, was shown. Measurements demonstrated an average COP improvement of 9.1 %, confirming the effectiveness of nanofluid in improving chiller efficiency. This result demonstrates that the use of nanofluids in HVAC systems serving data centers can help significantly reduce CO_2 emissions while containing energy costs. In order to strengthen the conclusions of the present study, through an LCA analysis, greenhouse gas emissions related to the aluminum oxide nanofluid filled into the plant were calculated, finding 14.3 tons of CO_2, compared with an annual CO_2 emission reduction of 50.9 tons/y. Finally, considering the expected electrical output of data centers in the next years, the global average CO_2 emission factor, and the increase in chiller performance related to the use of nanofluids, the maximum achievable result in terms of global GHG emission reduction was calculated, yielding 16.5 Mt CO_2.

1. Introduction

Data centers are facilities designed to house computer systems and the necessary components for their operation, including network and storage systems. It features a dual power system, a redundant communication network, environmental control systems (such as cooling and air conditioning), and security systems. Data centers became crucial for the operations of many businesses worldwide [1]. According to a recent study of the International Energy Agency [2], electricity demand from data centers is currently around 2 % of total global electricity consumption [2], consuming approximately 460 TWh of energy per year (demand related to 2022), and this is expected to rise further, due to artificial intelligence (A.I.) and the cryptocurrency sector: total data center electricity consumption could reach more than 1,000 TWh in 2026.

In large economies such as United States, China and the European Union, data centers account for around 2–4 % of total electricity consumption at present. In many countries, the sector has already surpassed 10 % of electricity consumption, as for example in Ireland, where it now accounts for over 20 % of all electricity consumption.

Although the data center sector contributes only about 0.6 % of total carbon emissions, its broader impact is significant, accounting for more than 2 % of global emissions when considering the entire information and communications technology (ICT) ecosystem, which includes personal devices, mobile phone networks, and televisions.

In this scenario, technological improvements related to data center energy efficiency will be crucial to moderating global CO_2 emissions.

Electricity demand in data centers is mainly from two processes, with computing accounting for 40 % of electricity demand of a data center. Cooling requirements to achieve stable processing efficiency similarly makes up about another 40 %. The remaining 20 % comes from other

* Corresponding author.
E-mail address: marco.milanese@unisalento.it (M. Milanese).

https://doi.org/10.1016/j.applthermaleng.2025.126889
Received 22 January 2025; Received in revised form 9 May 2025; Accepted 17 May 2025
Available online 19 May 2025
1359-4311/

Nomenclature

OAT	outside air temperature [°C]
COP	Coefficient of performance [-]
HVAC	Heating, Ventilation, and Air Conditioning
IPMVP	International Performance Measurement and Verification Protocol
LCA	Life Cycle Assessment
OAT	Outdoor Air Temperature
OLS	Ordinary Least Squares
n	Number of samples
x, y, z	generic variables
ε	error

associated IT equipment [2]. Therefore, one of the primary challenges faced by data centers is the dissipation of heat generated by IT equipment. High temperatures can compromise the proper operation of this equipment, potentially causing significant damage to the entire infrastructure. To address this issue, data centers employ various cooling and heat extraction systems of varying complexity. A commonly used solution is based on hydronic systems, supplied by water chillers.

One possible solution for increasing the efficiency of hydronic HVAC systems is represented by nanofluids [3]. They are specially engineered heat transfer fluids designed to enhance heat transfer and improve energy efficiency in various applications, including chillers, heat pumps, and other hydronic HVAC systems. These fluids consist of nanoparticles suspended in a liquid, formulated to achieve superior heat transfer performance compared to their base fluids. Numerous studies have shown that the thermal conductivity of nanofluids can be enhanced by factors such as nanoparticle volume concentration, size, and morphology [4,9].

In early experiments, Lee et al. [5] used a transient hot-wire method to measure the thermal conductivity of nanofluids, demonstrating that even a small quantity of nanoparticles could significantly increase the thermal conductivity of the base fluid. Beck et al. [6] provided data on thermal conductivity enhancement in seven nanofluids containing alumina nanoparticles with diameters ranging from 8 to 282 nm, suspended in water or ethylene glycol. They found that the thermal conductivity enhancement decreased as the particle size dropped below approximately 50 nm, likely due to phonon scattering at the solid–liquid interface [7].

To further investigate these findings, Colangelo et al. [8] designed, built, and tested a new experimental setup to explore physical phenomena involved in thermal conductivity enhancement of nanofluids. Oresta et al. [9] demonstrated the theory on the nanofluid thermal conduction increase.

Abdollahi-Moghaddam et al. [10] studied the influences of adding nanoparticles to water flowing through a horizontal tube, measuring heat transfer coefficient and pressure drop at different Reynolds number, while different studies [11,12] have been developed to analyze the correlations between temperature, viscosity, and nanofluid concentration.

In recent years, experimental investigations have demonstrated significant improvements in the heat transfer through nanofluids under several conditions compared to conventional heat transfer fluids [13–17]. Raza et al. [13] the heat transfer mechanism considering the attributes of viscous dissipation, Joule heating, and nonlinear thermal radiations in the three-dimensional steady incompressible flow. Ahmed et al. [15] investigated the effect of heat transfer on magnetic peristaltic flow of a couple stress fluid in an inclined annular tube.

Balla et al. [18] studied suspensions of Cu and Zn nanoparticles (50 nm in size) in a water-based fluid and found that the heat transfer coefficient of nanofluid was higher than that of the base fluid. Similar results were observed by Kai et al. [19], who studied heat transfer in a mini-tube using SiO2 nanofluid. Mukherjee et al. [20] investigated energy efficiency, exergy efficiency, and entropy generation of a flat plate solar collector with Al2O3-CuO/Water hybrid nanofluid.

Recently, numerous numerical and experimental studies have explored the application of nanofluids in different fields, such as in solar thermal systems. Lee et al. [21] and Alsalame et al. [22] investigated photovoltaic thermal systems using nanofluids. Chaji et al. [23] also studied flat plate solar collectors using nanofluids. Besides, further research on the application of nanofluids in various solar thermal energy conversion systems has been conducted [24,25].

Studies have also focused on enhancing the performance of internal combustion engines. Zhang et al. [26] improved the heat transfer performance of a diesel-engine cylinder head using a nanofluid coolant. Micali et al. [27] conducted an experimental campaign to assess the potential of nanofluids in reducing the temperature of a biodiesel four-stroke engine. They performed several tests on the CAT-AVL single-cylinder engine, comparing the temperatures achieved with pure water and CuO nanofluid as engine coolants. The experimental results showed that, at 100 % engine load, the nanofluid provided better cooling performance.

Further studies on the use of nanofluids in electronic devices [28], geothermal heat exchangers [29,30], plate heat exchangers [31] and cooling systems for wind turbines [32] have shown a significant increase in heat transfer performance compared to traditional fluids.

Given these thermal performance improvements, incorporating fluids with suspended solid nanoparticles in HVAC systems is expected to significantly enhance their efficiency [33]. Kulkarni et al. [34] found that using nanofluids in building heating systems can reduce the size of heat transfer systems, particularly heat exchangers, heat pumps, and other components. This reduction in size leads to lower energy consumption and, consequently, a decrease in environmental pollution. Ahmed and Ahmed Khan [35] investigated the use of nanofluids in the external cooling jacket around the condenser of an air conditioner. They studied the benefits of two types of nanofluids, made from copper and aluminum oxide, on the performance of an air/water conditioner. Their experimental results showed a significant enhancement in the Coefficient of Performance (COP), with increases up to 22.1 % using Al_2O_3 nanofluid and 29.4 % using CuO nanofluid. Hatami et al. [36] experimentally tested three types of nanoparticles (SiO2, TiO2, and Carbon Nanotubes) dispersed in water within HVAC systems. They found that SiO2-based nanofluid provided the best results in terms of reducing energy consumption.

To utilize nanofluids as heat transfer fluids in full-scale HVAC systems, several challenges must be addressed, such as nanoparticle stability in suspension and increased viscosity [37]. According to Hwang et al. [38] sedimentation and agglomeration of nanoparticles in nanofluids can cause fouling on heat transfer surfaces, leading to higher pressure drops and damage to ducts and pumps. However, using nanoparticles with optimal shape, size, and volume fraction in a base fluid, along with surfactants, can enhance suspension stability and mitigate these issues [39,40].

To tackle these challenges, this study focused on a nanofluid composed of a water-glycol mixture and aluminum oxide (Al_2O_3) nanoparticles with controlled size distribution (Dv90 = 617 nm) and good stability. This composition ensures efficient, reliable, and consistent performance over a wide temperature range with minimal impact on viscosity and system fluid pumping energy. Specifically, in [41] Colangelo et al. conducted dynamic simulations comparing the efficiency of two full-scale HVAC systems (installed at the educational building “Corpo O” at the University of Salento, Lecce, Italy), one using a traditional water-glycol mixture and the other using an Al_2O_3-nanofluid. They found a numerical efficiency increase of about 10 %.

From the above scientific scenario, it appears that in recent years, nanofluids have been extensively studied: there are numerous articles concerning both their chemical and physical properties and heat transfer performance. However, their full-scale applications represent a new topic, as it allows highlighting aspects that can be useful in future applications. Therefore, the objective of this work was to conduct an extensive experimental campaign in a data center under real operating conditions to demonstrate how increasing chiller COP, through the use of a commercial nanofluid based on water and Al_2O_3, can contribute to significant reduction in greenhouse gas emissions.

2. Test condition and experimental equipment

The heat transfer nanofluid was installed in the HVAC system which serves the cooling system of a data centers located in Italy. The refrigeration system comprises three air-cooled chillers with a cooling capacity of 616 kW each, providing a total cooling capacity of 1848 kW. Table 1 summarizes the main specifications of the cooling facility.

The aluminum oxide-based nanofluid was chosen because of several considerations: dozens of types of nanofluids are described in the scientific literature, but only a few have reached sufficient product maturity to be used in real applications. For example, CuO nanofluids offer higher thermal conductivity and better heat transfer performance, making them ideal for high-performance applications, such as electronic cooling or solar collectors. However, they exhibit higher viscosity, lower colloidal stability, higher cost, and a greater tendency to cause corrosion compared to aluminum oxide nanofluid. Other nanofluids, such as carbon-based ones, (including graphene-based and carbon-nanotubes-based nanofluids) shows an increase in thermal conductivity, specific heat and viscosity reduction. On the other hand, these nanofluids still require further studies to increase their stability and in any case have costs that are not yet acceptable at full scale. As shown in Table 2, Al_2O_3 nanofluids, while having lower thermal conductivity, are more stable, less viscous, more cost-effective, and less corrosive, making them better suited for general applications like HVAC systems and automotive heat exchangers. Therefore, in this experiment the choice of Aluminium Oxide nanofluid for enouncing thermal performance has been made based on stability, cost, and material compatibility reasons.

The concentration of aluminum oxide nanoparticles equal to 2 %vol was selected to maximize the thermal conductivity and minimize the pump energy absorption related to viscosity and density increase. Indeed, the increase in the energy consumption of the pump working with nanofluid was less than 0.1 % compared to the overall energy need of the chiller.

In order to measure the performance of the chiller, the system was equipped with the following sensors, according to the schematic of Fig. 1:

- Flow meter: Siemens Sistran 5000.
- Termocouples: k-type.
- Thermal energy meter: Sistran FUE 950.
- Transmitter: MAG 5000.

Table 3 summarizes the accuracy of measuring instruments used to detect temperatures, volumetric flow rate and electric power.

The nature of using instruments to measure physical properties introduces a level of inaccuracy, as any instrument has limitations imposed by the method of measurement. When multiple measurements are used to make calculations these inaccuracies compound and propagate an increased error in the results. Therefore, measures must be taken to mitigate and minimize the propagation of error [42].

- Error (ε) of the sum/subtraction

$$(x \pm \varepsilon_x) + (y \pm \varepsilon_y) = z \pm \varepsilon_z \rightarrow \varepsilon_z = \varepsilon_x + \varepsilon_y \quad (1)$$

- Error (ε) of the multiplication/division

$$(x \pm \varepsilon_x)(y \pm \varepsilon_y) = z \pm \varepsilon_z \rightarrow \frac{\varepsilon_z}{z} = \frac{\varepsilon_x}{x} + \frac{\varepsilon_y}{y} \quad (2)$$

- Average of error in case of multiple sampling

$$\varepsilon_{z\_averaged} = \frac{\varepsilon_z}{n}; \text{with } n \text{ number of samples} \quad (3)$$

Increasing the accuracy of the instruments is one method decreasing error rate, the other is increasing the sampling rate which reduces the error rate by averaging out the error.

Taking into account both the instrument accuracy and the error propagation models, the mean accuracy of the chiller COP was found to be 0.1 %.

3. Measurement and verification methodology

The measurement and verification methodology is based on the widely adopted standards set forth in the International Performance Measurement and Verification Protocol (IPMVP). The IPMVP is now used by utilities and government agencies for their demand-side management incentive programs and for studies of building, manufacturing, and industrial companies to evaluate and improve their facilities' performances. The IPMVP is owned and maintained by Efficiency Valuation Organization (EVO®), a non-profit organization whose mission is to ensure that the savings and impact of energy efficiency and sustainability projects are accurately measured and verified.

The estimation of the baseline energy forecast model by ordinary least squares (OLS) linear regression involves the following steps:

- Data collection and preparation: outdoor air temperature (OAT) and coefficient of performance (COP) data were initially recorded at one-minute intervals and then aggregated into 10-minute intervals. This averaging process helps to minimize noise and reduce variability in the dataset.
- Data segmentation and grouping: the averaged COP values are grouped according to OAT intervals. In this case, 1 °C intervals were used, ranging from 25–26 °C up to 49–50 °C, covering the full spectrum of climatic conditions during the analysis period. The choice of interval width should be guided by the data distribution.
- Calculation of average COP for each OAT interval: for each OAT band, the average COP is computed. Each interval is represented by its midpoint, which serves as a representative temperature value.

Table 1
Specifications of the main equipment and layout of the cooling facility.

experimental setup	Technical specifications
Air-cooled water-cooling chillers	HiRef TVA0621
Nominal Cooling Power	616 [kW]
Circulating Pumps	KSB ETABLOC-SIC GN11
Total volume of heat transfer fluid	31.48 [m^3]
Inlet nanofluid temperature	10 [°C]
Outlet nanofluid temperature	13 [°C]
Average flow rate	$20*10^{-3}$ [m^3/s]
Aluminum Oxide nanoparticle concentration	2 %vol
Annual electricity demand	1600 MWh

Table 2
Comparison between different nanofluid cooling solutions.

Property	CuO nanofluid	Al_2O_3 nanofluid	Carbon-based nanofluid
Thermal conductivity	Higher	Moderate	Higher
Stability	Lower	Higher	Higher
Viscosity	Higher	Lower	Lower
Heat transfer efficiency	Better	Good	Better
Cost	Higher	Lower	Higher
Corrosion tendency	Higher	Lower	Lower

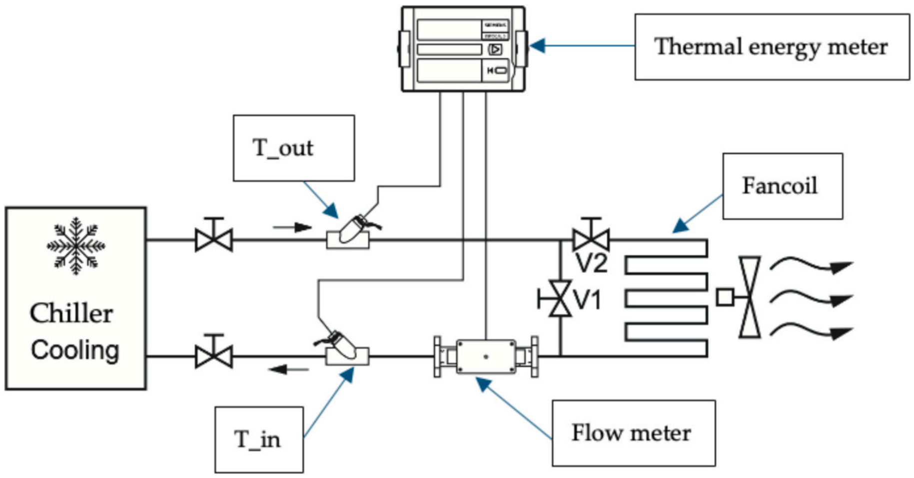

Fig. 1. Schematic of chiller performance measurement system.

Table 3
Accuracy of measuring instruments.

Parameter	Accuracy of the measuring instruments
Temperature (°C)	0.8 %
Flow rate (L/s)	1.0 %
Electric power (kW)	0.5 %
Number of samples for one measurement	60

- Linear regression modeling: a linear regression is performed using the OAT midpoints as the independent variable and the corresponding average COP values as the dependent variable. This establishes a baseline model describing the relationship between operational efficiency (COP) and climatic conditions (OAT).

The aim of the experimental campaign was to measure COP during the baseline period (interval of time in which HVAC system performance is measured under normal operating conditions, i.e., without making changes to the system) and reporting period (interval of time in which the performance of the HVAC system is measured under changed operating conditions by adding the nanofluid to the system) at a specific climatic condition and operating system settings.

Fig. 2 represents a schematic of the International Performance Measurement and Verification Protocol.

In the case under investigation, the comparison was made between the energy consumption measured after the installation of the nanofluid in the HVAC system and the consumption that would have occurred without the use of the nanofluid.

According to the IPMVP, to define a reliable adjustment rule, the baseline period was sampled to determine the interdependence between the variables. Particularly, a linear adjustment rule has been determined under the general assumption that the electrical consumption in the HVAC system was dependent on the two independent variables, Outside Air Temperature (OAT) and thermal energy demand of the building.

The baseline and reporting periods were of 40 and 90 days respectively divided into two periods: September – October (baseline) and November – December – April– May (reporting period). The chiller performance in terms of COP was calculated for the baseline period with water as heat transfer fluid and then for the reporting period with the adding of nanofluid.

A total of 57,681 measurement points were acquired during the baseline period and 103,360 points during the reporting period.

The chiller's performance is strictly related to condenser temperature conditions (outside air temperature, OAT) but can also be dependent on chiller loads which can be influenced by non-climatic factors such as occupancy intensity, shifts in operating schedules, alterations in cooling demand and system settings among other operational parameters. Therefore, in this work, the comparison between baseline and reporting periods was done taking quite constant the chiller load (20–25

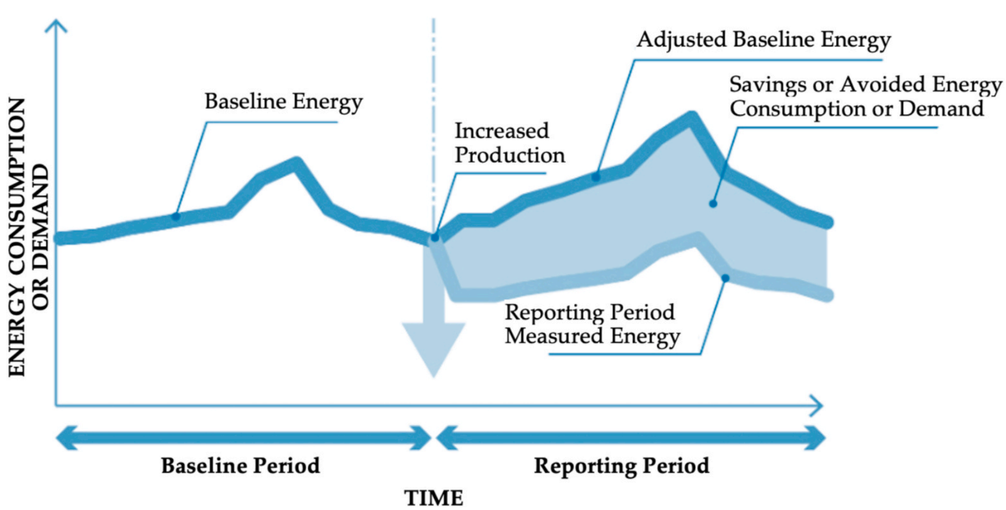

Fig. 2. Schematic of the International Performance Measurement and Verification Protocol [43].

% of the maximum load value), as shown in Fig. 3.

The average chiller COP was calculated measuring the following data over the entire baseline and reporting periods with a frequency of one minute:

- Volume flow rate of system fluid passing through the chiller
- Chiller inlet – outlet temperatures
- Outside air temperature
- Electrical consumption of the chiller

The main properties of a heat transfer nanofluid sample were measured as summarized in Table 4.

Furthermore, it is pointed out that, the Al_2O_3 nanofluid is classified as not hazardous based on the calculation methods defined in Regulation (EC) 1272/2008 (CLP).

Table 4
Properties of the nanofluid at test conditions.

Fluid @ 10 °C	Density (kg/m3)	Cp (J/kg K)	Thermal Cond. [W/m K]	Viscosity [mPa*s]	Sedimentation rate [μm/min]
Water	1002	4130	0.580	1.31	–
Al_2O_3 Nanofluid 2 %vol	1061	4090	0.637	1.32	0.237

4. Discussion of results

Comparison of the baseline and reporting periods was done in a manner that maximized the constancy of key operational factors, such as climatic conditions, operating conditions, chiller load profiles, operating hours, system settings. Recording the baseline period immediately prior to the installation and testing period may often be the preferred approach, as more operational variables can be held constant between these periods, thus limiting the necessary adjustments to climatic factors. Furthermore, the baseline and reporting periods were chosen to cover a wide range of climatic conditions, achieving a consistent analysis of the chiller performance. Finally, quite constant chiller load conditions were assured to avoid any influence on the COP analysis.

The raw data, recorded during the baseline and reporting period, were used for COP calculation and analysis. Preliminarily, all recorded data were pre-processed to remove outliers, keeping only the values within the range mean COP $+/- 2\sigma$.

Subsequently, the data were normalized by estimating a linear relationship between COP and OAT, using OLS regression methods based on 40 days for system's baseline data and 90 days for reporting period data.

Regarding the baseline period, Fig. 4 shows the results in terms of COP as a function of OAT: the light blue points represent all baseline data set, the blue circles are the average COP values calculated every 0.5 °C, while the blue line is the linear regression of the average COP values.

As expected, chiller performance improved at lower external operating temperatures. Besides, Fig. 4 demonstrates, a good correlation between COP values and OAT, being the coefficient of determination (R^2) equal to 0.9962. The mathematical result is represented by a linear regression of the measured baseline data (COP as a function of OAT). From a mathematical point of view, this model can be extended over OAT values not sampled during the baseline acquisition period.

A similar analysis has been carried out during the reporting period: Fig. 5 shows the results in terms of COP as a function of OAT. Also in this case a good correlation between COP values and OAT has been observed, being the coefficient of determination (R^2) equal to 0.9914.

By analyzing the frequency distribution of COP, it is possible to visualize the change in chiller performance as a result of nanofluid installation. For this reason, the COP frequency distributions, for the baseline and reporting periods are presented in Fig. 6.

As expected, the performance recorded during the reporting period was higher than during the baseline period. However, in accordance with the IPMVP protocol, the comparison should be made at the same outside air temperature, as shown in Fig. 7.

Note that the high coefficient of determination, $R^2 = 0.9963$ for the baseline energy forecast model and $R^2 = 0.9776$ for the reporting period model, demonstrates the "closeness of fit" of this model.

As can be seen from Fig. 7, considering only the OAT range (12–29 °C) where the baseline and reporting period overlap, the two energy forecast models are substantially parallel: this demonstrates the validity of the forecast models developed. According to these models Table 5 summarizes the results in terms of COP improvement.

The increase in chiller performance can be explained taking into account that by adding the nanofluid into the HVAC system, the chiller's working cycle changes, as schematically illustrated in the typical pressure-enthalpy chart of Fig. 8.

For the chiller under investigation working with the standard heat transfer fluid (water), the cycle follows path 1–2-3–4 in the diagram with the temperature of point 1 fixed by the electronic expansion valve, which adjusts the final pressure acting on the refrigerant expansion as represented in Fig. 8 by the segment 3–4.

Position of point 1 is limited on the left by the saturation vapor curve to prevent the formation of a liquid phase that could result in

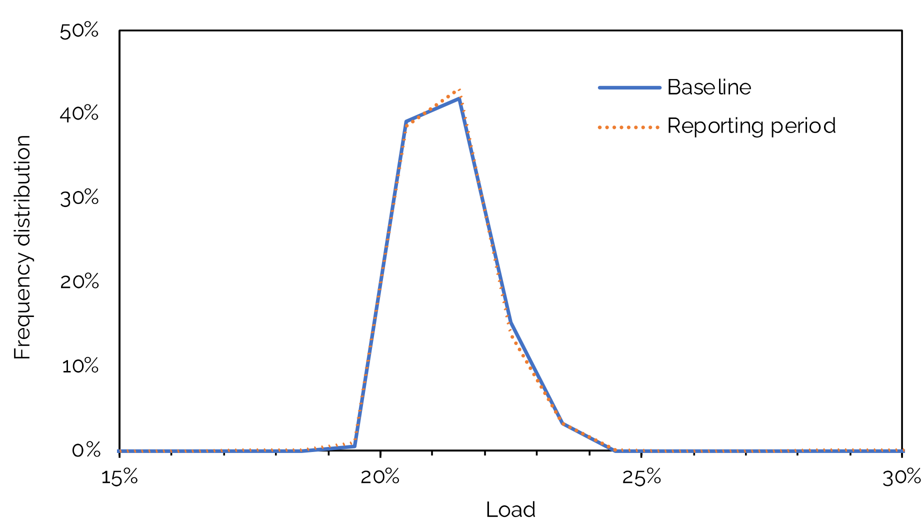

Fig. 3. Frequency distribution of the chiller load.

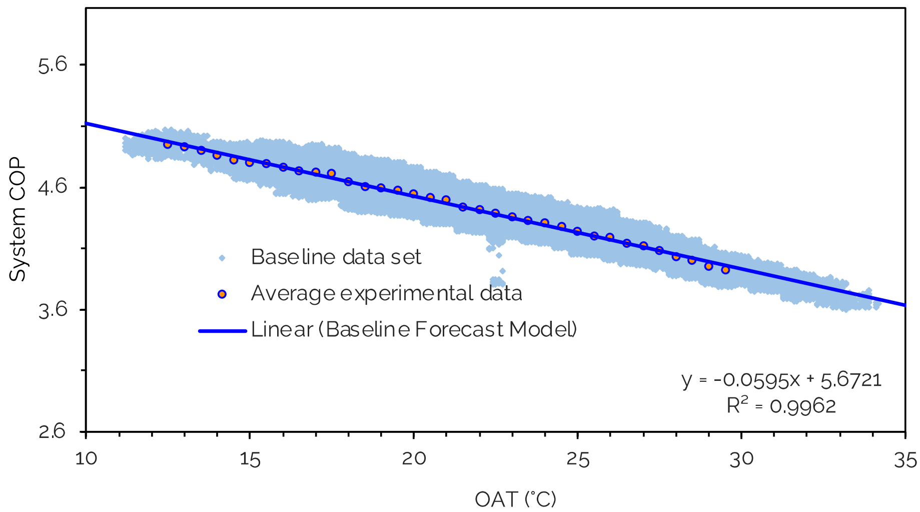

Fig. 4. Baseline period – COP as a function of OAT. Light blue points represent all baseline data set; blue circles are the average COP values calculated every 0.5 °C; blue line is the linear regression of the average COP values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

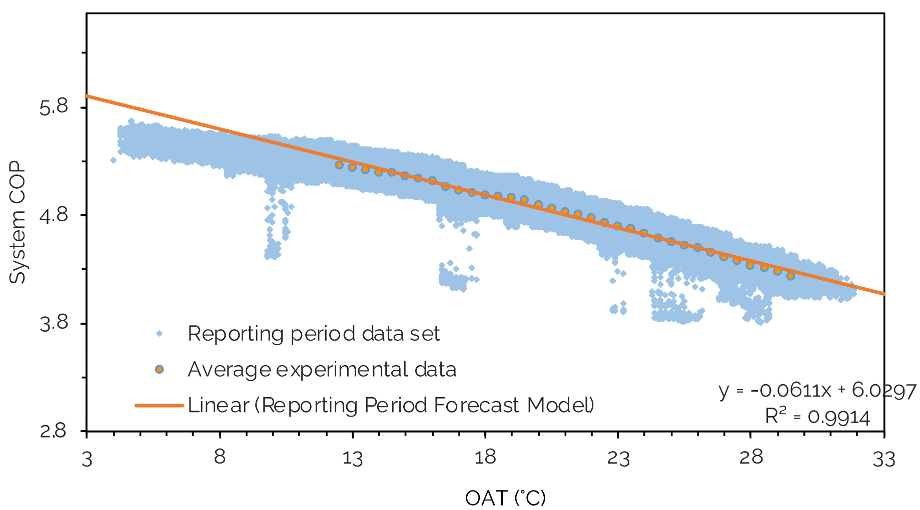

Fig. 5. Reporting period – COP as a function of OAT. Light blue points represent all reporting period data set; orange circles are the average COP values calculated every 0.5 °C; orange line is the linear regression of the average COP values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

compressor damage, and on the right, by the isothermal passing through point 1 (reported in Fig. 8 as dashed red line).

The increased heat transfer due to nanofluid results in an increased pressure in the evaporator, modifying the working cycle as indicated in Fig. 8 by points 1′-2′-3′-4′.

Therefore, the compressor needs to provide less "lift" (effort) by having to increase the vapor pressure from points 1' to 2', instead of from points 1 to 2, as in the case of standard fluids.

The chiller thus uses less electrical energy to produce the same thermal energy, increasing its efficiency, as experimentally demonstrated and reported in Table 5.

Based on the annual energy demand of 1,600 MWh, the economical savings due to higher COP performance of the chiller has been quantified, assuming the unit cost of electricity equal to 243.5 Euro/MWh. Table 6 summarizes the results of the economic analysis, indicating significant yearly savings of 35,456 Euro.

With regard to plant maintenance related to the use of nanofluid, it is pointed out that:

- nanoparticles do not suffer alteration over time;
- nanoparticles can accelerate the wear of the pumps, but this phenomenon can be greatly mitigated by using SiC seals on the pumps.

To calculate CO_2 emissions for a chiller consuming 1600 MWh of electricity, the emission factor of the electricity source must be used. The typical European grid CO_2 emission factor can be assumed to be 350 kg CO_2/MWh. Therefore, the annual CO_2 savings related to the percentage reduction in electricity consumption can be calculated as:

$$1600MWH \times 0.091 \times 350kg\,CO_2/MWh = 50.9\,tons\,of\,CO_2 \tag{4}$$

In order to complete the study on greenhouse gas emissions, an LCA analysis (Life Cycle Assessment is a methodology used to analyze the overall environmental impact of a product, process, or service throughout all stages of its life cycle, which includes: extraction of raw materials, production and manufacturing, distribution, use and maintenance, end of life) was carried out to quantify CO_2 emissions per liter of aluminum oxide nanofluid at 2 %vol. The results are summarized in Table 7. In the case under investigation, the CO_2 emissions per liter of

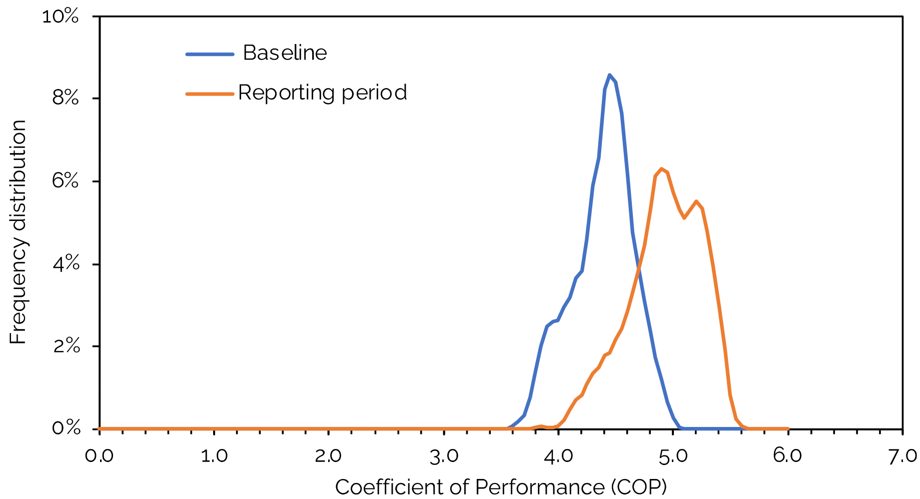

Fig. 6. COP frequency distribution: baseline versus reporting period.

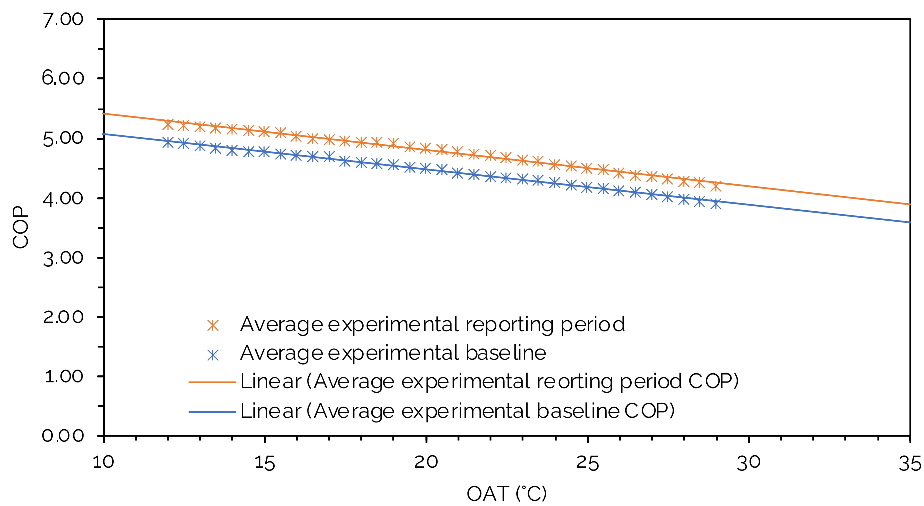

Fig. 7. Baseline and reporting period: energy forecast model comparison.

Table 5
COP improvement analysis.

Energy forecast model	Average COP @ 12 °C – 29 °C of OAT
Baseline period	4.4
Reporting period	4.8
COP improvement %	9.1 %

product are equal to 0.4544 kg/liter.

Since the total volume of aluminum oxide nanofluid filled into the plant was 31.48 m^3, the total amount of CO_2 emissions associated with it was 14.3 tons.

Therefore, already in the first year of the use of this nanofluid, the CO_2 emissions are largely compensated by the savings (50.9 tons/year), that can be achieved due to the increased performance of plant.

This result can be very important when applied to the global data center development scenario in the coming years. In fact, mainly due to the development of AI, all reports on the evolution of digital services predict a substantial increase in the number and size of data centers (average data centers are quite small in power terms, with demand in the order of 5–10 MW, but large hyperscale data centers, which are increasingly common, have power demands of 100 MW or more), resulting in an increase in electricity demand, which will only partially be mitigated by efficiency improvements in both hardware and software.

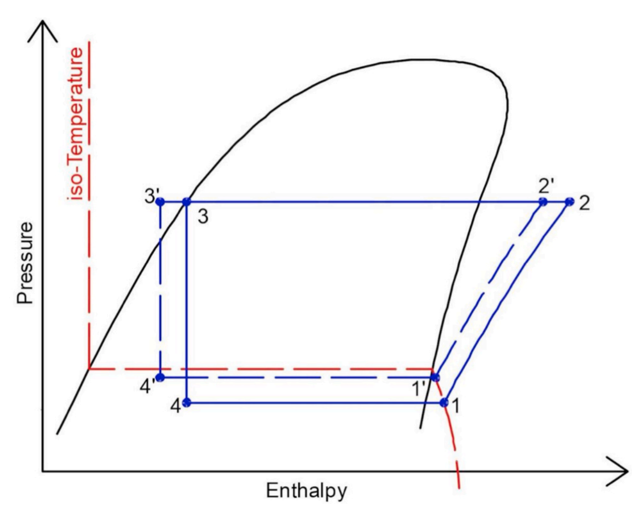

Fig. 8. Schematic of typical pressure-enthalpy chart of a chiller.

In 2022, data centers alone were responsible for about 1–1.3 % of the

Table 6
Economic analysis.

Parameter	Value	U.M.
Annual electricity consumption	1600	MWh/y
Unit cost of electricity	243.52[(*)]	Euro/MWh
Annual cost of electricity	389,632	Euro/y
Percentage reduction of electricity consumption	9.1 %	
Annual reduction of electricity consumption	144	MWh/y
Annual savings for electricity	35,456	Euro/y

(*) Average electricity overall price (year 2022/24 – Euro Area, EUROSTAT).

Table 7
LCA analysis results [(*)].

Raw materials and production process	kg CO_2 eq
Production of aluminum trihydrate (Brazil + DE)	0.027060
Transportation to European Plant (sea + truck)	0.017389
Electricity	0.003822
Heat (gas)	0.081921
Sulphuric acid	0.000939
Water	0.000240
Dispersant	0.000363
Sodium hydroxide	0.005741
Packaging and transportation	0.053417
Water	0.000009
Propylene glycol	0.158433
Surfactants	0.003143
Sodium hydroxide	0.000481
Electricity, IT	0.101390
Anti-corrosion	0.000125
CO_2 emissions per liter of aluminum oxide nanofluid at 2 % [v/v]	**0.454471**

(*) Source: HT Materials Science Limited.

world electricity consumption, and forecasts indicate that this percentage could rise to 3 % by 2026 [44]. In addition, by 2030, data center energy requirements are projected to be between 770 TWh (conservatively estimated) and 1,560 TWh, with an intermediate estimate of 1,135 TWh (Fig. 3). The upper limit of this forecast would be equivalent to 5 % of global electricity consumption by 2030 [45]. In a study, McKinsey [46] points out that the United States is the fastest growing data center market, with demand expected to grow from 25 GW in 2024 to more than 80 GW in 2030.

Data center electricity consumption is due to 2 main factors: computing power (which account for about 40 % of energy consumption) and cooling systems (which consume 38–40 % of energy consumption) [47]. These components will remain the most energy-intensive even in AI data centers. Therefore, assuming that electricity consumption by data centers grows to 1,000 TWh [48] in the next years (due to increasing deployment of information technology, A.I. use, etc.), that is, equal to about 3.3 % of global electricity demand, the GHG emissions associated with them are expected to reach 16.5 Mt CO_2, as summarized in Table 8.

Table 8
Estimated reduction in global CO_2 emissions related to the use of nanofluids in data centers.

Parameter	Value	U.M.
Global electricity production[(*)]	29,925	TWh
Global CO_2 emissions from electricity generation[(*)]	13,575	Mt CO_2
Expected electricity consumption from data centers	1,000	TWh
Expected electricity consumption from data centers for cooling	400	TWh
Reduction in electricity consumption by using nanofluids in data centers	9.1 %	
Global CO_2 emissions related to data centers	453	Mt CO_2
Reduction in global CO_2 emissions achievable by means of nanofluids in data centers	16.5	Mt CO_2

(*) Source: IEA (2024).

According to these results, the use of nanofluids in HVAC systems serving data centers can contribute to significant reductions in CO_2 emissions while containing related energy costs.

5. Conclusions

One of the main issues related to data centers is the dissipation of the heat generated by the IT structures within them. In fact, in high temperature situations, the proper functioning of IT equipment is compromised, resulting in significant damage to the entire infrastructure. To meet this challenge, each data center incorporates a more or less complex cooling and heat extraction system.

Energy consumption due to air conditioning accounts for about one-third of the total energy absorbed by the data center. The environmental impact deriving from their use has therefore raised the need to develop increasingly efficient air conditioning solutions, both from a functional and economic point of view.

The solution proposed in this work was to inject an aluminum oxide nanofluid into the HVAC system of a real data center in order to increase its performance, returning both economic and energy savings.

Therefore, an extended experimental campaign, under real operating conditions, has been carried out to demonstrate the increase in chiller COP, due to the use of Al_2O_3-based nanofluid.

Monitoring of key chiller performance parameters in different period (baseline and reference period) was carried out through the IPMVP protocol to obtain a proper COP-based efficiency comparison and to ensure that any observed variation in chiller performance was due to the heat transfer nanofluid and was independent from other external factors.

The baseline and reporting periods were chosen to cover a wide range of climatic conditions, achieving a consistent analysis of the chiller performance.

The results demonstrate a good correlation between COP values and OAT, being the coefficient of determination (R^2) equal to 0.9962 in the baseline and 0.9914 in the reporting period. Besides, considering the OAT range of 12–29 °C, where the baseline and reporting period overlapped, the two energy forecast models were substantially parallel, with a COP improvement of 9.1 %.

Finally, considering the expected electrical output of data centers in the next years, the global average CO_2 emission factor, and the increase in chiller performance related to the use of nanofluids, the maximum achievable result in terms of global GHG emission reduction was calculated, yielding 16.5 Mt CO_2.

These results demonstrate that use of nanofluids in HVAC systems serving data centers can help significantly reduce CO_2 emissions while containing energy costs.

Future investigation will be focused on carbon-based nanomaterials including graphene particles, combined with critical surfactants, to enable them to maintain high dispersity in a base liquid without settling out.

In the coming years, the impact of AI applications in the energy sector and related GHG emissions will need to be fully evaluated. Promising technologies for reducing environmental impacts may include clean energy, power system management to encourage increased renewable energy, but nanofluids applied to large data centers may also play an important role.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors report that equipment, drugs, or supplies were provided by HT Materials Science Ltd. The authors Francesco Micali, Marco Milanese and Arturo de Risi acted as scientific consultants for HT materials Science Ltd. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could

have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank HT Materials Science Limited for the data made available for the preparation of the paper.

Data availability

Data will be made available on request.

References

[1] E. Masanet, A. Shehabi, N. Lei, Sarah Smith and Jonathan Koomey, Recalibrating global data center energy-use estimates, Science 367 (6481) (2020) 984–986.
[2] Electricity 2024, Analysis and forecast to 2026, International Energy Agency.
[3] R. Saidur, K.Y. Leong, H.A. Mohammed, A review on applications and challenges of nanofluids, Renew. Sustain. Energy Rev. 15 (2011) 1646–1668.
[4] M. Lomascolo, G. Colangelo, M. Milanese, A. de Risi, Review of heat transfer in nanofluids: conductive, convective and radiative experimental results, Renew. Sustain. Energy Rev. 43 (2015) 1182–1198.
[5] S. Lee, S.U.S. Choi, S. Li, J.A. Eastman, Measuring thermal conductivity of fluids containing oxide nanoparticles, J. Heat Transfer (1999) 280–289.
[6] M.P. Beck, Y. Yuan, P. Warrier, A.S. Teja, The effect of particle size on the thermal conductivity of alumina nanofluids, J. Nanopart. Res. 11 (2009) 1129–1136.
[7] F. Iacobazzi, G. Colangelo, M. Milanese, A. De Risi, Thermal conductivity difference between nanofluids and micro-fluids: experimental data and theoretical analysis using mass difference scattering, Therm. Sci. 23 (2019) 3797–3807.
[8] G. Colangelo, M. Milanese, F. Iacobazzi, A. De Risi, Experimental setup for low temperature thermal conductivity analysis of micro and nano suspensions, AIP Conf. Proc. 2191 (2019) 020050.
[9] P. Oresta, F. Micali, A. De Risi, Undulatory theory of phonons on the nanofluid thermal conduction, Int. J. Therm. Sci. 183 (2023) 107853.
[10] M. Abdollahi-Moghaddam, K. Motahari, A. Rezaei, Performance characteristics of low concentrations of CuO/water nanofluids flowing through horizontal tube for energy efficiency purposes; an experimental study and ANN modeling, J. Mol. Liq. 271 (2018) 342–352, https://doi.org/10.1016/j.molliq.2018.08.149.
[11] M.A. Moghaddam, K. Motahari, Experimental investigation, sensitivity analysis and modeling of rheological behavior of MWCNT-CuO (30–70)/SAE40 hybrid nano-lubricant, Appl. Therm. Eng. 123 (2017) 1419–1433, https://doi.org/10.1016/j.applthermaleng.2017.05.200.
[12] K. Motahari, M.A. Moghaddam, M. Moradian, Experimental investigation and development of new correlation for influences of temperature and concentration on dynamic viscosity of MWCNT-SiO2 (20-80)/20W50 hybrid nano-lubricant, Chin. J. Chem. Eng. 26 (1) (2018) 152–158, https://doi.org/10.1016/j.cjche.2017.06.011.
[13] R. Raza, R. Naz, S. Murtaza, S.I. Abdelsalam, Novel nanostructural features of heat and mass transfer of radiative Carreau nanoliquid above an extendable rotating disk, Int. J. Mod Phys B 38 (30) (2024) 2450407, https://doi.org/10.1142/S0217979224504071.
[14] P. Praveen Kumar, S. Balakrishnan, A. Magesh, P. Tamizharasi, S.I. Abdelsalam, Numerical treatment of entropy generation and Bejan number into an electroosmotically-driven flow of Sutterby nanofluid in an asymmetric microchannel, Numer. Heat Transf. B Fundam. 1–20 (2024), https://doi.org/10.1080/10407790.2024.2329773.
[15] M.M. Ahmed, I.M. Eldesoky, A.G. Nasr, R.M. Abumandour, S.I. Abdelsalam, The profound effect of heat transfer on magnetic peristaltic flow of a couple stress fluid in an inclined annular tube, Mod. Phys. Lett. B 38 (25) (2024) 2450233, https://doi.org/10.1142/S0217984924502336.
[16] E.G. Ghania, S.I. Abdelsalam, A.M. Megahed, A.E. Hosni, A.Z. Zaher, Computational workflow to monitor the electroosmosis of nanofluidic flow in the vicinity of a bounding surface, Numer. Heat Transf. B Fundam. 1–15 (2024), https://doi.org/10.1080/10407790.2024.2364767.
[17] S.I. Abdelsalam, N. Alsedais, A.M. Aly, Revolutionizing bioconvection: artificial intelligence-powered nano-encapsulation with oxytactic microorganisms, Eng. Appl. Artif. Intell. 137 (Part A) (2024) 109128, https://doi.org/10.1016/j.engappai.2024.109128.
[18] H. Balla, S. Abdullah, W.M.W. Faizal, R. Zulkifli, K. Sopian, Enhancement of heat transfer coefficient multi-metallic nanofluid with ANSIS modeling for thermophysical properties, Therm. Sci. 9 (5) (2015) 1613–1620.
[19] L.C. Kai, M.Z. Abdullah, M.Z. Ismail, H. Mamat, Enhancement of nanofluid heat transfer in a mini-tube using SiO_2 nanoparticles, Adv. Mater. Process. Technol. (2019) 607–616.
[20] S. Mukherjee, D. Shah, P. Chaudhuri, P.C. Mishra, Exergy, economic, and environmental impact of a flat plate solar collector with Al_2O_3-CuO/Water hybrid nanofluid: experimental study, Appl. Therm. Eng. 266 (2025) 125640, https://doi.org/10.1016/j.applthermaleng.2025.125640.
[21] J.H. Lee, S.G. Hwang, G.H. Lee, Efficiency improvement of a photovoltaic thermal (PVT) system using nanofluids, Energies 12 (16) (2019) 3063, https://doi.org/10.3390/en12163063.
[22] H.A.M. Alsalame, J. Hee Lee, L.G. Hyun, Performance evaluation of a photovoltaic thermal (PVT) system using nanofluids, Energies 14 (2) (2021) 301, https://doi.org/10.3390/en14020301.
[23] H. Chaji, Y. Ajabshirchi, E. Esmaeilzadeh, S.Z. Heris, M. Hedayatizadeh, M. Kahani, Experimental study on thermal efficiency of flat plate solar collector using TiO_2/water nanofluid, Appl. Sci. 7 (10) (2013) 60–70.
[24] M. Marefati, W. Huang, Energy, exergy, environmental and economic comparison of various solar thermal systems using water and thermic oil B base fluids, and CuO and Al_2O_3 nanofluids, Energy Rep. 6 (2020) 2919–2947.
[25] A. Sattar, M. Faroop, M. Amjad, M. Saeed, S. Nawaz, M.A. Mujataba, S. Anwar, Q. Ali, M. Imran, A. Pettinau, Performance evaluation of a direct absorption collector for solar thermal energy conversion, Energies 13 (18) (2020) 4956, https://doi.org/10.3390/en13184956.
[26] Z.D. Zhang, W. Zheng, Z.G. Su, Study on diesel cylinder-head cooling using nanofluid coolant with jet impingement, Therm. Sci. 19 (6) (2015) 2025–2037.
[27] F. Micali, M. Milanese, G. Colangelo, A. de Risi, Experimental investigation on 4-strokes biodiesel engine cooling system based on nanofluid, Renew. Energy 125 (2018) 319–326.
[28] G. Colangelo, E. Favale, M. Milanese, A. de Risi, D. Laforgia, Cooling of electronic devices: nanofluids contribution, Appl. Therm. Eng. 127 (2017) 421–435.
[29] R. Du, D. Jiang, Y. Wang, Numerical investigation of the effect of nanoparticle diameter and sphericity on the thermal performance of geothermal heat exchanger using nanofluid as heat transfer fluid, Energies 13 (7) (2020) 1653, https://doi.org/10.3390/en13071653.
[30] X. Hui Sun, H. Yan, M. Massoudi, Z.H. Chen, W.T. Wu, Numerical simulation of nanofluid suspension in a geothermal heat exchanger, Energies 11 (4) (2018) 1919, https://doi.org/10.3390/en11040919.
[31] M.N. Pantzali, A.A. Mouza, S.V. Paras, Investigating the efficacy of nanofluids as coolants in plate heat exchangers (PHE), Chem. Eng. Sci. 64 (2009) 3290–3300.
[32] A. De Risi, M. Milanese, G. Colangelo, D. Laforgia, High efficiency nanofluid cooling system for wind turbines, Therm. Sci. 18 (2) (2014) 543–554.
[33] M. Milanese, M. Potenza, C. Grisoni, A. de Risi. Improvement in Energy Performance of a HVAC System Working with Nanofluid. Proceedings of International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'23), 2023, 123.
[34] D.P. Kulkarni, D.K. Das, R.S. Vajjha, Application of nanofluids in heating building and reducing pollution, Appl. Energy 86 (2009) 2566–2573.
[35] F. Ahmed, W.A. Khan, Efficiency enhancement of an air-conditioner utilizing nanofluid: an experimental study, Energy Rep. 7 (2021) 575–583.
[36] M. Hatami, G. Domairry, S.N. Mirzababaei, Experimental investigation of preparing and using the H_2O based nanofluids in the heating process of HVAC system model, Int. J. Hydrogen Energy 42 (2017) 7820–7825.
[37] A. Ghadimi, R. Saidur, H.S.C. Metsetaar, A review of nanofluid stability properties and characterization in stationary conditions, Int. J. Heat Mass Transf. 54 (17-18) (2011) 4051–4068.
[38] Y. Hwang, J.K. Lee, C.H. Lee, Y.M. Jung, S.I. Cheong, C.G. Lee, B.C. Ku, S.P. Jang, Stability and thermal conductivity characteristics of nanofluids, Thermochim. Acta 455 (2007) 70–74.
[39] N. Bogdan, F. Vetrone, G.A. Ozin, J.A. Capobianco, Synthesis of ligand-free colloidally stable water dispersible brightly luminescent lanthanide-doped upconverting nanoparticles, Nano Lett. 11 (2) (2011) 835–840, https://doi.org/10.1021/nl1041929.
[40] J. Lee, M. Kim, C.K. Hong, S.E. Shim, Measurement of the dispersion stability of pristine and surface-modified multiwalled carbon nanotubes in various nonpolar and polar solvents, Meas. Sci. Technol. 18 (12) (2007) 3707, https://doi.org/10.1088/0957-0233/18/12/005.
[41] G. Colangelo, B. Raho, M. Milanese, A. de Risi, Numerical evaluation of a HVAC system based on a high-performance heat transfer fluid, Energies 14 (11) (2021) 3298.
[42] J.R. Taylor, An Introduction to Error Analysis, 2nd ed., University Science Books, 1997.
[43] M. Milanese M., Potenza M., Grisoni C., de Risi A. Improvement in Energy Performance of a HVAC System Working with Nanofluid. Proceedings of International Conference on Fluid Flow, Heat and Mass Transfer (FFHMT'23), 2023, 123.
[44] International Energy Agency (IEA), Electricity Mid-Year Update: July 2024, International Energy Agency, Paris, 2024.
[45] A. Ermakov. (2024) Electricity demand growth for data centres and AI and implications for natural gas-fired power generation: Expert commentary. GECF Secretariat.
[46] McKinsey & Company (2024). How data centers and the energy sector can sate AI's hunger for power.
[47] R. Poudineh. Global electricity demand: what's driving growth and why it matters?, The Oxford Institute for Energy Studies, 2025.
[48] IEA (2024), Electricity 2024, IEA, Paris https://www.iea.org/reports/electricity-2024, Licence: CC BY 4.0.