EXPERIMENTAL EVALUATION OF THE ENERGY EFFICIENCY OF A DATA CENTER COOLING SYSTEM WITH HEAT TRANSFER NANOFLUID

Version 1

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Executive Summary

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 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. 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.

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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. Electricity demand from data centers is currently around 1-1.3% of total global electricity consumption 1, consuming approximately 240 TWh of energy per year, and this is expected to rise up to 8% of overall electricity demand. Although the data center sector contributes only about 0.3% 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.

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 2. 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 3,4.

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. 8-10 designed, built, and tested a new experimental setup to explore physical phenomena involved in thermal conductivity enhancement of nanofluids. Oresta et al. 11 demonstrated the theory on the nanofluid thermal conduction increase.

In recent years, experimental investigations have demonstrated significant improvements in the convective heat transfer coefficient of nanofluids under both laminar and turbulent conditions compared to conventional heat transfer fluids. Balla et al. 12 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. 13, who studied heat transfer in a mini-tube using SiO2 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. 14 and Alsalame et al. 15 investigated photovoltaic thermal systems using nanofluids. Colangelo et al. 16,17 experimentally examined the use of nanofluids in flat solar thermal collectors, studying technical issues related to nanoparticle sedimentation and resolving these issues by modifying the panel shape. Chaji et al. 18 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 19-22.

Studies have also focused on enhancing the performance of internal combustion engines. Zhang et al. 23 improved the heat transfer performance of a diesel-engine cylinder head using a nanofluid coolant. Micali et al. 24 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 25, geothermal heat exchangers 26,27, plate heat exchangers 28 and cooling systems for wind turbines 29 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. Kulkarni et al. 30 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 31 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 Al2O3 nanofluid and 29.4% using CuO nanofluid. Hatami et al. 32 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 33. According to Hwang et al. 34 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 35,36.

To tackle these challenges, this study focused on a nanofluid composed of a water-glycol mixture and aluminum oxide (Al2O3) nanoparticles with controlled size distribution (Dv90=617nm) 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 37 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 Al2O3-nanofluid. They found a numerical efficiency increase of about 10%.

The objective of this work was to conduct an extended experimental campaign in a data center under real operating conditions to demonstrate the increase in chiller COP through the use of a commercial nanofluid (Maxwell ®) based on water and Al2O3.

2. Compliance with Open Compute Project Tenets

2.1. Efficiency

When Maxwell ® is introduced into closed loop hydronic systems, the heat transfer capacity of the base fluid is enhanced. Utilizing the enhanced fluid properties allows for more effective heat transfer on all heat exchangers that are in the hydronic loop. While comparing water with Maxwell ® to water only systems the increase is roughly 15%, however when comparing a higher percentage glycol mixture to water-glycol with Maxwell ® ,the increase in heat transfer is upwards of 25%.

2.2. Impact

Your contribution should have a transformative impact on the industry by introducing new technology, accelerating time-to-market, or enabling technology through global supply chains. Impact is amplified when new technologies are made accessible to many customers worldwide. Examples include widely adopted specifications or more specifically, open security features that establish and verify product trust. Ensure your contribution creates meaningful positive impact within the OCP ecosystem.

2.3. Scale

Design your contribution for easy implementation and deployment at any scale, with minimal intervention. Aim to create additive solutions where minimal usage or instances can be deployed and incrementally scaled as needed to effectively address the entire problem. Provide all necessary tools and supporting documentation, such as installation guides, initialization processes, configuration information, and details on obtaining service support. Include features like simple manual and automated maintenance, remote management, upgradability, and error reporting. Management tools should be open-sourced and/or made available to adopters.

2.4. Sustainability

Your contribution must be sustainable, maximizing transparency of environmental impacts with the goal of continuous improvement. Focus on the responsible use of natural resources, fostering positive societal impacts, and minimizing environmental harm. This can be achieved through design decisions that promote circularity, efficient use of materials, power-saving features, and sustainability labeling. For software, consider optimizing code to reduce resource consumption and incorporating features that enable energy efficiency.

3. 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.

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

Existing equipment	Technical specifications
Air-cooled water-cooling Chillers	Chiller with cooling power of 616kW
Total volume of heat transfer fluid	31.48 m^3
Aluminum Oxide nanoparticle concentration	2% [v/v]
Annual electricity demand	1600 MWh

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

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

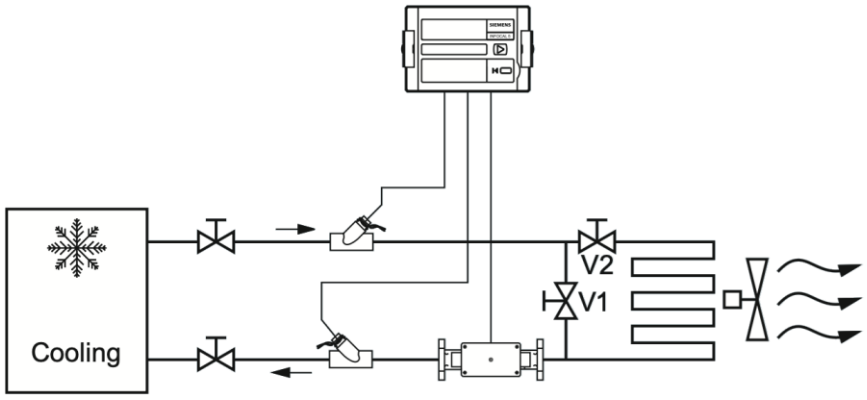

Figure 1. Schematic of chiller performance measurement system.

Table 2 summarizes the accuracy of measuring instruments used to detect temperatures, volumetric flow rate and electric power.

Table 2. 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

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.

- Error (ε) of the sum/subtraction

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

- Error (ε) of the multiplication/division

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

- Average of error in case of multiple sampling

$$\varepsilon_{z_averaged} = \frac{\varepsilon_z}{n}; \text{with n number of samples} \qquad (3)$$

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%.

4. 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 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.

Figure 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.

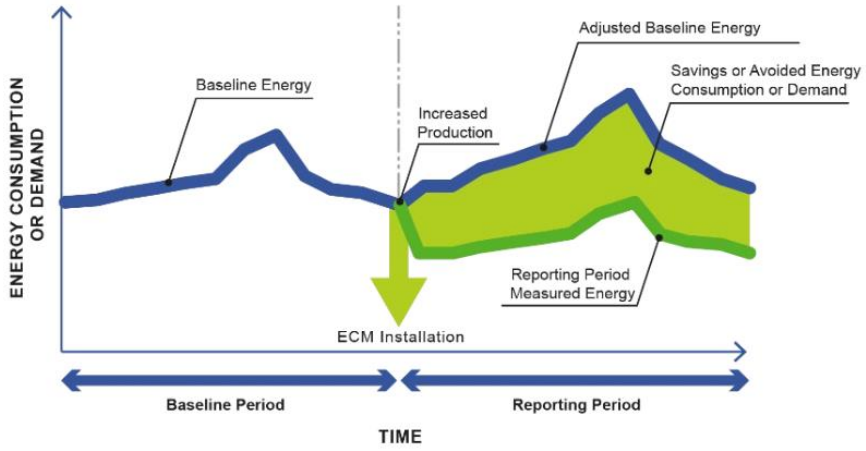

Figure 2. Schematic of the International Performance Measurement and Verification Protocol 38.

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 57681 measurement points were acquired during the baseline period and 103360 points during the reporting period.

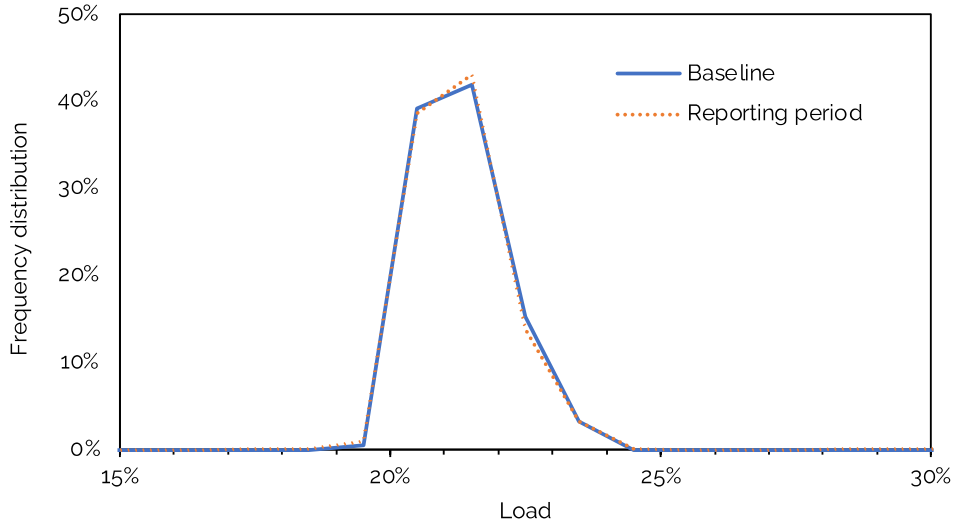

Figure 3. Frequency distribution of the chiller load.

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% of the maximum load value), as shown in Figure 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 properties of the heat transfer nanofluid sample were measured to determine the fluid density and specific heat. The results are summarized in Table 3.

Table 3. Properties of the heat transfer fluid at test conditions.

Fluid	Density (kg/m3)	Cp (J/kg K)
Water @ 10 °C	1002	4130
Nanofluid Maxwell ® 2%vol @ 10 °C	1061	4090

5. Discussion of Results

The baseline and reporting periods were chosen to cover a wide range of climatic conditions, achieving a consistent analysis of the chiller performance. Furthermore, 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, was 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 +/- 2σ.

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, Figure 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.

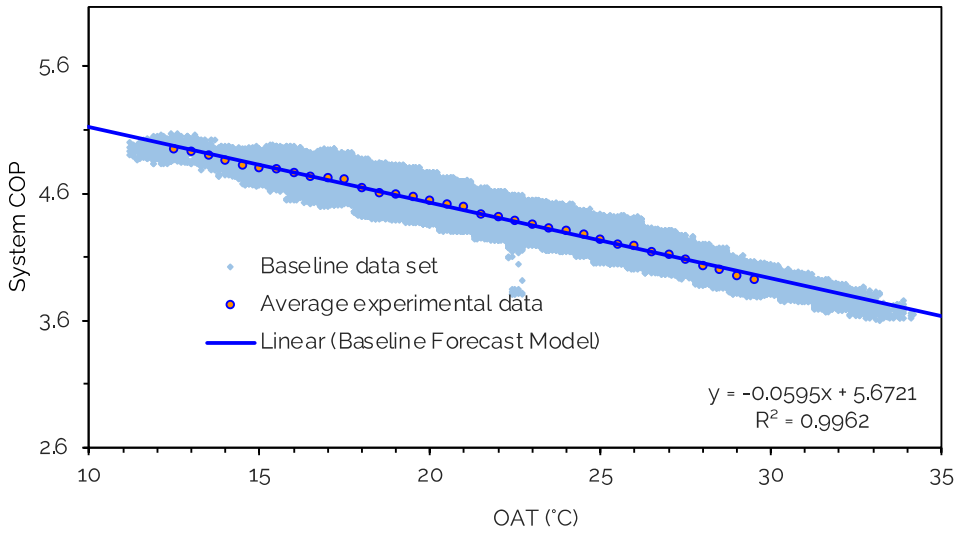

Figure 4. Baseline period – COP as a function of OAT. Light blue points represent all baseline data set; blue circles are the average COP values calculated every 0.5 °C; blue line is the linear regression of the average COP values.

As expected, chiller performance improved at lower external operating temperatures. Besides, Figure 4 demonstrates, a good correlation between COP values and OAT, being the coefficient of determination (R^2) equal to 0.9962.

A similar analysis has been carried out during the reporting period: Figure 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.

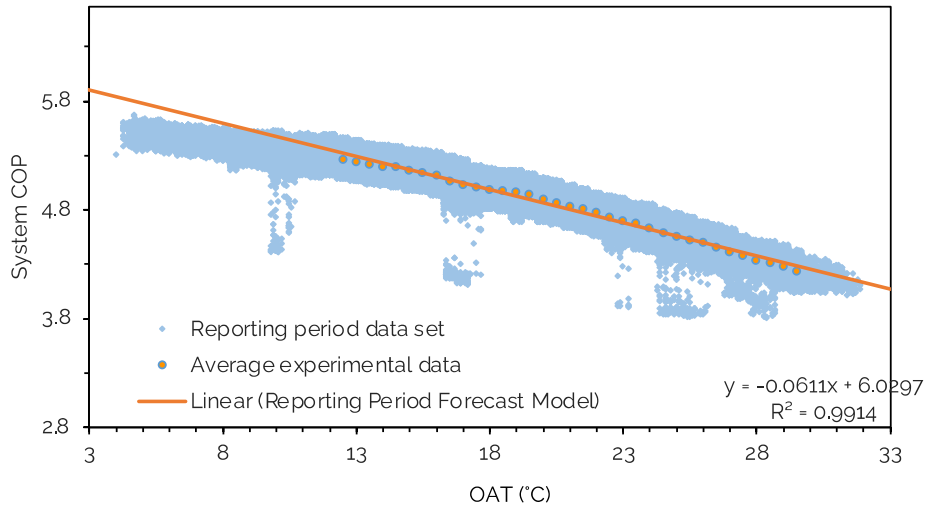

Figure 5. Reporting period – COP as a function of OAT. Light blue points represent all reporting period data set; orange circles are the average COP values calculated every 0.5 °C; orange line is the linear regression of the average COP values.

The COP frequency distribution, for the baseline and reporting periods is presented in Figure 6.

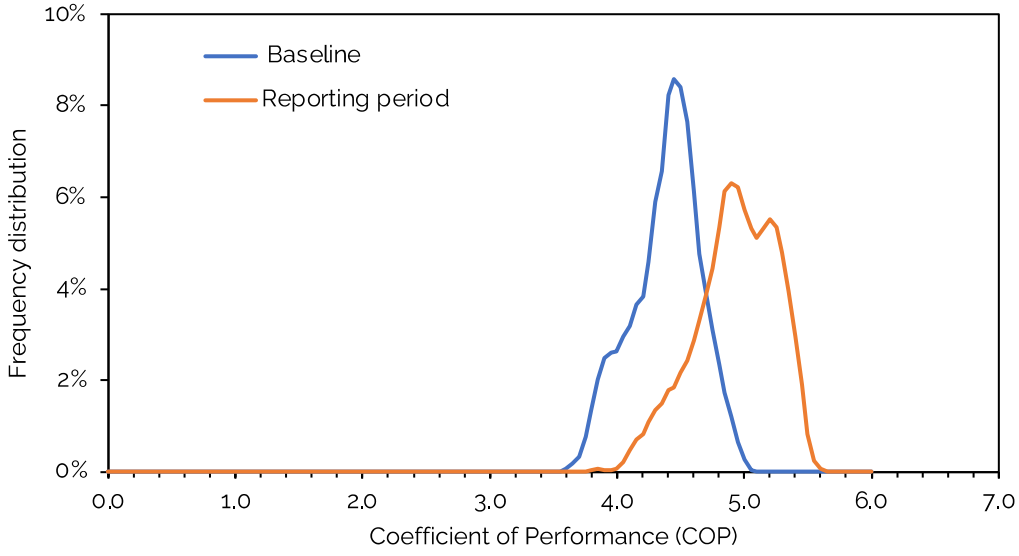

Figure 6. COP frequency distribution: baseline versus reporting period.

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 Figure 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.

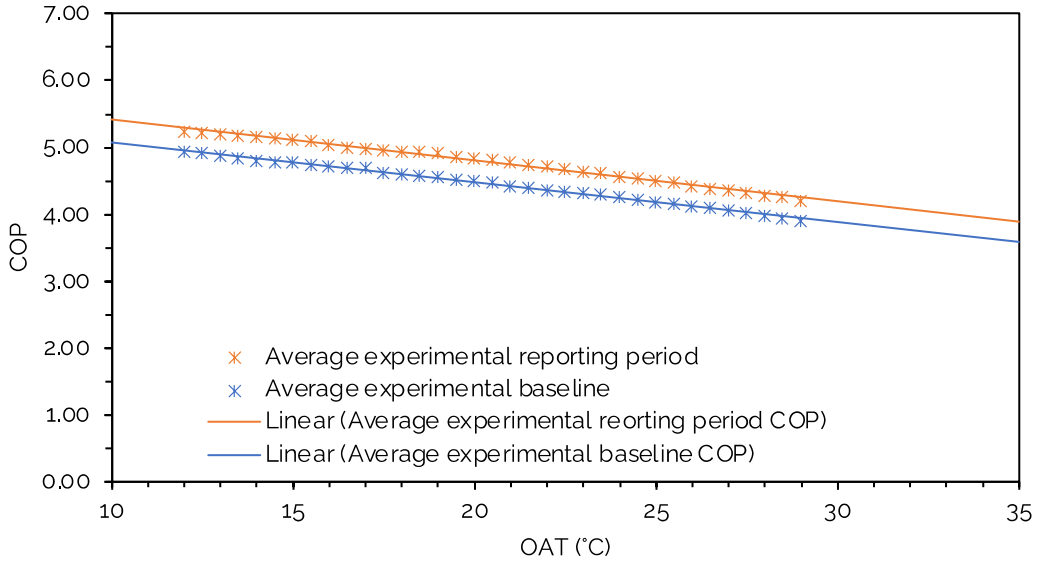

Figure 7. Baseline and reporting period: energy forecast model comparison

As can be seen from Figure 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 4 summarizes the results in terms of COP improvement.

Table 4. 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%

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 Figure 8.

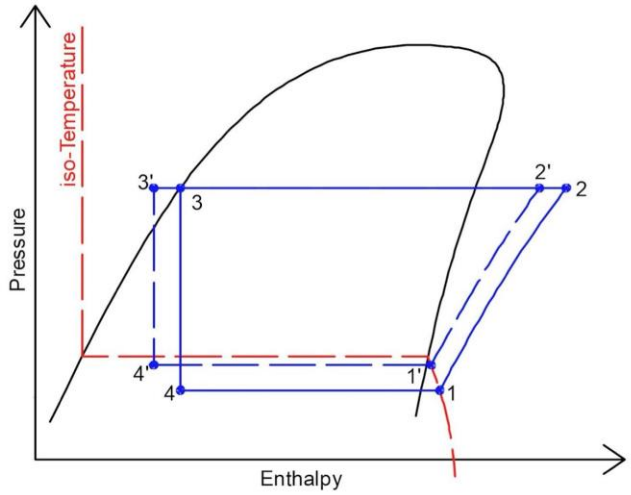

Figure 8. Schematic of typical pressure-enthalpy chart of a chiller.

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 Figure 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 compressor damage, and on the right, by the isothermal passing through point 1 (reported in Figure 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 Figure 8 by points 1'-2'-3'-4'.

Table 5. Economical analysis.

Annual electricity consumption	1600	MWh/y
Unit cost of electricity	250	Euro/MWh
Annual cost of electricity	400000	Euro/y
Percentage reduction of electricity consumption	9.1%	
Annual reduction of electricity consumption	144	MWh/y
Annual savings for electricity	36000	Euro/y

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 4.

Finally, 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 250 Euro/MWh. Table 5 summarizes the results of the economic analysis, indicating significant yearly savings of 36,000 Euro.

Table 1. Example of caption formatting for tables

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6. Conclusion

The objective of this work was to conduct an extended experimental campaign in a data center under real operating conditions to demonstrate the increase in COP of the chiller due to the use of a Al2O3 water-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.

Date: February 4th, 2025

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.

Finally, 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%.

7. Glossary

Term: definition.

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Appendix A. [Title]