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Article

Experimental Evaluation of a Full-Scale HVAC System Working with Nanofluid

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Abstract: Nowadays, energy saving is considered a key issue worldwide, as it brings a variety of benefits: reducing greenhouse gas emissions and demand for energy imports and lowering costs on a household and economy-wide level. Researchers and building designers are looking to optimize building efficiency by means of new energy technologies. Changes can also be made in existing buildings to reduce energy consumption of air conditioning systems, even during operational conditions without modifying dramatically the system layout and impacting as lower as possible on the cost of the modification. These may include the usage of new heat transfer fluids based on nanofluids. In this work, an extended experimental campaign (from February 2020 to March 2021) has been carried out on the HVAC system of an educational building in the Campus of University of Salento, Lecce – Italy. Scope of the investigation was comparing the COP for the two HVAC systems (one with nanofluid and the other one without) operating concurrently during Winter and Summer: simultaneously measurements on the two HVAC systems show that the coefficient of performance (COP) with nanofluid increased meanly of 9.8% in winter and 8.9% in summer, with average daily peaks of about 15%. Furthermore, the comparison between the performance of the same HVAC system, working in different comparable periods with and without nanofluid, shows a mean increase of COP equal to about 13%.

Keywords: heat transfer fluid; nanofluid; heating, ventilation and air conditioning system; experimental test; coefficient of performance.

1. Introduction

Decreasing energy consumption of heating, ventilation and air conditioning (HVAC) systems is a very important issue, due to their high environmental and energy costs together with a significant actual increase of their request from the market. Several studies described various technologies and techniques that can be used to reduce HVAC energy consumption and one of them can be identified in nanofluids [1,2].

Nanofluids are engineered heat transfer fluids which can be used to improve heat transfer, thus, increasing energy efficiency in a variety of applications based on chillers, heat pumps and other hydronic HVAC systems. They are suspensions of nanoparticles dispersed in a liquid that are formulated to achieve higher heat transfer performance than their base-fluids. Numerous studies demonstrated that nanofluid thermal conductivity can be improved based on some variables, such as nanoparticle volume concentration, size, morphology, etc.

In early experiments on nanofluids, Lee *et al*. [3] measured the thermal conductivity by a transient hot-wire method, demonstrating that a small amount of nanoparticles was enough to increase the thermal conductivity of the base fluid.

Beck *et al*. [4] presented data for the thermal conductivity enhancement in seven nanofluids containing 8–282 nm diameter alumina nanoparticles in water or ethylene glycol. They found that the thermal conductivity enhancement in these nanofluids decreases as the particle size decreases below about 50 nm. This finding could be attributed to phonon scattering at the solid–liquid interface.

To confirm this result, Colangelo *et al*. [5-6] designed, built and tested a new experimental setup to investigate the physical phenomena involved in the thermal conductivity enhancement of nanofluids.

In the last years, experimental investigations on the effects of nanofluids on convective heat transfer coefficient in laminar and turbulent conditions were developed, demonstrating a significant improvement with respect to conventional heat transfer fluids [7].

Balla *et al*. [8] studied several suspensions of Cu and Zn nanoparticles with the size 50 nm in water base fluid. They found that the heat transfer coefficient of nanofluid was higher than its base fluid. Similar results were found by Kai *et al.* [9] studying nanofluid heat transfer in a mini-tube using SiO_2 nanoparticles.

Recently, several numerical and experimental studies on nanofluids and their applications have been developed, such as solar thermal systems. Lee *et al*. [10] and Alsalame *et al*. [11] studied photovoltaic thermal systems based on nanofluids. Colangelo *et al*. [12,13] experimentally investigated the use of nanofluid in flat solar thermal collectors: tests in traditional solar flat panel revealed some technical issues, due to the nanoparticles' sedimentation. Therefore, the modification of the panel shape allowed to fix this problem. Flat plate solar collectors based on nanofluid were also studied by Chaji *et al*. [14]. Furthermore, the application of nanofluid on different solar thermal energy conversion systems was investigated in [15-18].

Different studied have been carried out to increase the performance of internal combustion engines. Zhang *et al*. [19] improved the heat-transfer performance of a diesel-engine cylinder head by means of a nanofluid coolant.

Micali *et al*. [20] developed an experimental campaign aimed at assessing whether the use of nanofluids in a biodiesel four-strokes engine could be a valuable solution to reduce its temperature. Particularly, several experimental tests have been carried out on the CAT-AVL single cylinder engine to compare the temperature achieved with pure water and CuO nanofluid as engine coolant. Experimental results showed that, at 100% engine load in unsteady conditions, it was possible to achieve a temperature reduction up to 13.6% on the exhaust valve seat and up to 4.1% on the exhaust valve spindle, when nanofluid at 2.5% volume concentration was used.

Further studies related to the use of nanofluid within electronic devices [21], geothermal heat exchangers [22,23], cooling system for wind turbines [24], demonstrated a significant increase in heat transfer performance versus traditional fluids.

Considering these thermal performance improvements, the use of fluids containing suspended solid particles in HVAC systems is expected to show significant enhancements of their efficiency.

Devdatta *et al*. [25] observed that the use of nanofluids inside the heating system of the building is a suitable solution to reduce the size of the heat transfer system, and, in particular, the size of heat exchangers, heat pumps and other components as well. This will reduce energy consumption and will, thus, indirectly reduce environmental pollution.

Ahmed and Ahmed Khan [26] used nanofluid into the external cooling jacket around the condenser of an air conditioner. Particularly, they studied the benefits of two types of nanofluids, made of copper and aluminum oxide respectively, on performance of an air / water conditioner. Their experimental results showed a significant enhancement in Coefficient of Performance (COP), up to 22.1% with Al_2O_3 nanofluid and 29.4% with CuO nanofluid.

Hatami *et al*. [27] experimentally tested three types of nanoparticles (SiO_2, TiO_2 and Carbon Nanotubes), dispersed in water inside HVAC systems. They found the best result, in terms of energy consumption reduction, with SiO_2-based nanofluid.

In order to use nanofluids as heat transfer fluid within full-scale HVAC systems, different problems have to be solved, such as nanoparticles stability in suspension [28] and increment in viscosity [29]. Regarding the first issue and according to Awais *et al*. [30], sedimentation and agglomeration of nanoparticles within nanofluids can produce fouling on heat transfer surfaces and, therefore, higher pressure drop and damages in ducts, pumps, etc. On the other hand, the use of nanoparticles, having optimal shape, size and volume fraction in base-fluid coupled with the addition of surfactants can improve the suspension stability, avoiding the above problems [31].

The electrical potential at shear slippage plane is called zeta potential (ZP), and its value aids in evaluating nanoparticles' (NPs) stability in suspension [32,33], according to Bogdan [34] and Lee [35]: indeed, particles in colloidal suspension tend to develop a surface charge by adsorption of ions from base fluid. This superficial charge is double-layer-structured, with a sliding surface located beyond the first layer. In the nanofluid formulation used in this investigation, an anionic surfactant was used in order to improve the stability. The stability of Aluminum Oxide suspension depends on the dispersant to modify the ZP and the surface repulsion between particles. In case of anionic dispersant ZP value higher than 25 mV (absolute value) is necessary to achieve enough repulsion forces.

In case of sample at rest, the settling occurs over a long time, with 50% of particle settled in 6 months.

Regarding the second issue (viscosity), it is important to remark that the variation in nanofluid viscosity is directly proportional to the particles' concentration in suspension. In the nanofluid formulation only 2% in volume of nanoparticles has been added to achieve a very limited viscosity increment. Furthermore, the test campaign was carried out in big size HVAC system, where the relevant diameter of the pipes and relevant size of the heat exchangers limited the impact of viscosity increment on the pressure drop in the system. Pantzali *et al*. [36] studied the nanofluid use in industrial applications mainly being focused on pressure drop increment related to the viscosity of the nanofluid. They concluded that in case of industrial heat exchangers and large pipes, with turbulent flow, usually developed inside, the substitution of conventional fluids by nanofluids had not relevant incidence on pressure drop in the system.

In order to overcome the above discussed problems, this work was based on a nanofluid composed by water-glycol and aluminum oxide (Al_2O_3) nanoparticles, having controlled size distribution (D_{v90}=617nm) and good stability, that deliver efficient, reliable and consistent performance over a wide temperature range, with little effects on viscosity, and, therefore, on system fluid pumping energy. Particularly, in [37] Colangelo *et al*. developed dynamic simulations in order to compare the efficiency of two full-scale HVAC systems (installed at the educational building "Corpo O" in the Campus of University of Salento, Lecce – Italy), working with traditional water-glycol mixture and with Al_2O_3-nanofluid: they found a numerical increment in efficiency of about 10%. As a follow-up to that study, the objective of this work was to carry out an extended experimental campaign on the same building, in order to quantify over a long period of time and under real operating conditions, the increase in performance of the HVAC system due to the use of nanofluid. Besides, these results will also allow to validate the numerical results previously found, verifying their congruence with the experimental measurements.

2. Test conditions and experimental apparatus

The experimental campaign has been carried out on an educational building, named "Corpo O" (Figure 1), at the Campus of University of Salento, which is in Lecce (Italy) at latitude 40° 21′ and longitude 18° 10′.

The building consists of two symmetrical wings (left and right wings), each of which has its own HVAC system. Besides, each wing is composed by three floors: ground floor, first floor and second floor, with a total area of 2400 m^2 and a total volume of 13163 m^3. The HVAC systems are used for air conditioning of offices and labs inside the building.

The experimental test campaign was focused on data acquisition during winter (heating mode) and summer (cooling mode).

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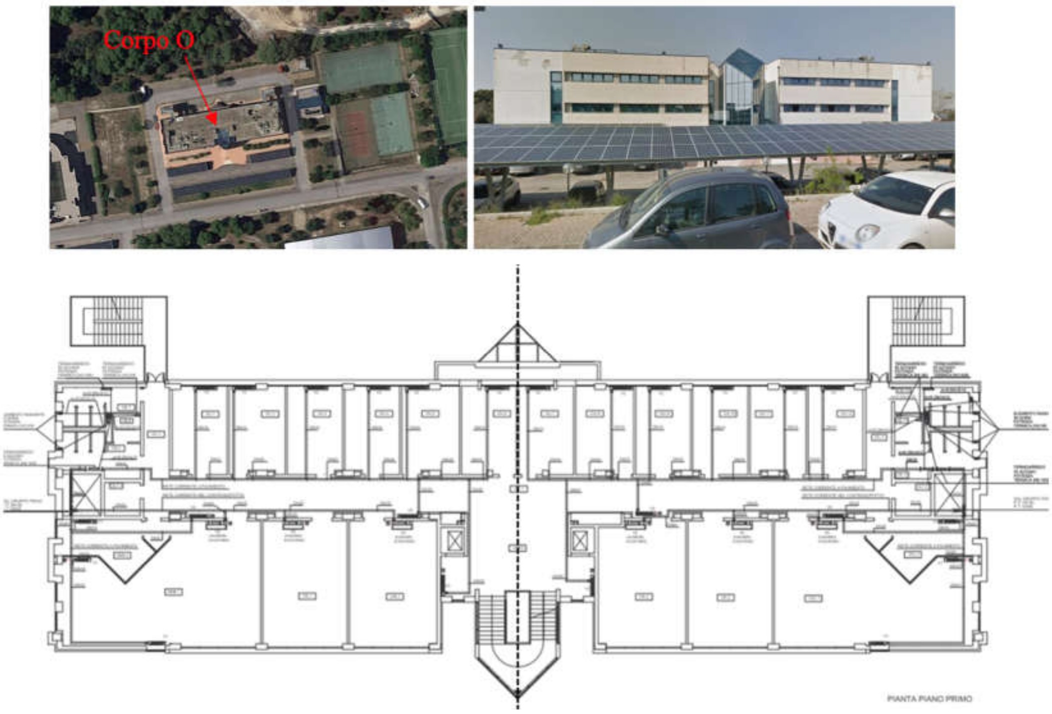

Figure 1. Building "Corpo O" at Campus Ecotekne of University of Salento in Lecce (Italy)

2.1. Description of the thermal system

Two symmetrical HVAC systems (named HVAC-1 and HVAC-2 in the following) are installed on the roof of the building and each system is used for thermal conditioning of half of the building. Besides, both systems are equipped with heat pumps (model CLIVET WSAN-XEE 302 38), having the following technical specifications (**Error! Reference source not found.**).

Finally, each HVAC unit supplies three pipelines, through which the heat transfer fluid is pumped:

- Fan coils and radiators lines;
- ATU line.

Table 1. Characteristics of the heat pump CLIVET WSAN-XEE 302 38.

Characteristics	Value
Compressor	
Type	2 Scroll
Refrigerant charge	8.28 l
Internal heat exchanger	
Water flow	3.4 l/s
Maximum water flow	5.4 l/s
Pressure drop	41.9 kPa
Useful pump discharge	131 kPa
External heat exchanger	
Fans	6
Standard air flow	6971 l/s
Installed power unit	0.18 kW
Expansion vessel	
Capacity	5 l
Maximum pressure on the water	550 kPa
Storage tank	
Inertial tank	130 l

2.2. Nanofluid characteristics

In order to evaluate the increase in performance, due to the use of a nanofluid as heat transfer fluid, in this study an aluminum oxide-based nanofluid has been loaded inside the HVAC-1 system. This nanofluid has been chosen taking into account its high stability and its low viscosity, which are comparable to the base fluid ones. **Error! Reference source not found.** summarizes the main specifications of the nanofluid.

Table 2. Specifications of the nanofluid.

Composition (% by weight):	
Propylene Glycol	37
Performance additives	2
Water	61
Color	White
Odor	Odorless
pH	10
Specific Weight [kg/m³] at 25°C	1.079
Operating Range [°C]	-22 to 65
Freeze Point [°C]	-22
Burst Point [°C]	-51
Boiling Point [°C]	105
Thermal Conductivity [W/m K] at 20°C	0.471
Specific Heat [kJ/kg K] at 20°C	3.51
Viscosity [mPa s] at 20°C	4.74

The nanofluid was made of Aluminum Oxide nanoparticles at 2% in volume concentration and size distribution with Dv_{90} =617 nm, with a density of 1079 g/l. Density is strictly related to the particles concentration, therefore samples density has been measured over the test campaign to monitor sedimentation phenomena inside the system. According to regulation and restrictions, the use of Propylene Glycol in the composition of the nanofluid for the test campaign comes from the necessity to avoid toxic grade of glycol, as Ethylene Glycol is.

The remaining 2% in weight are dispersants, anti-corrosion inhibitor and Aluminum Oxide nanoparticles.

2.3. Test instrumentation and data acquisition system

The Coefficient Of Performance (COP) of each HVAC Unit was calculated as the ratio between thermal (E_{th}) and electrical (E_{el}) energy:

$$COP = E_{th}/E_{el} \quad (1)$$

Therefore, the energy monitoring system required the installation of several instrumentations, such as electricity meters, temperature sensors and mass flow rate meters:

- electricity meters were used to measure current, tension and electrical power, absorbed by the HVAC systems. Data were collected for all pumps and heat pumps by means of the energy meter IME – NEMO D4 - three phase (**Error! Reference source not found.**). It measures active energy and energy/power, with accuracy ±1% for active energy, conforming to IEC62053-23, and ±2% for reactive energy, conforming to IEC 61557-12;
- thermal energy was evaluated by measuring the heat transfer fluid mass flow rate and its temperature at the heat pump inlet and outlet. In particular the energy meter Caleffi – Conteca Easy is an ultrasonic direct heat meter with 2 temperature probes, with accuracy ≤ 0.05°C and one flowmeter with accuracy ±2% according to EN 1434 (Figure 2);

- environmental measurements (indoor and outdoor air temperature and RH) were carried out in order to analyze the heat pump performance under different meteorological conditions;
- all data were recorded using a dedicated PLC to acquire and to store the data, sampled every 60 seconds by sensors, through the communication bus. Using the integrated web interface, it was possible to monitor consumption and other data and review data history (Figure 3).

Figure 2. Acquisition system for the electrical energy measurements IME – NEMO D4.

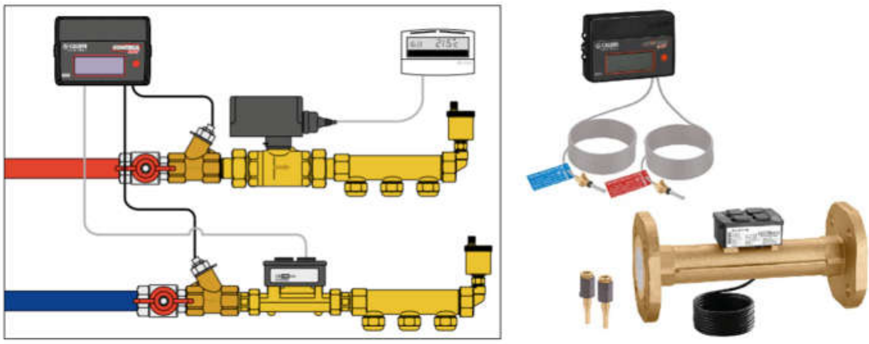

Figure 2. Drawing of the acquisition system for thermal energy Caleffi – Conteca Easy- Ultra.

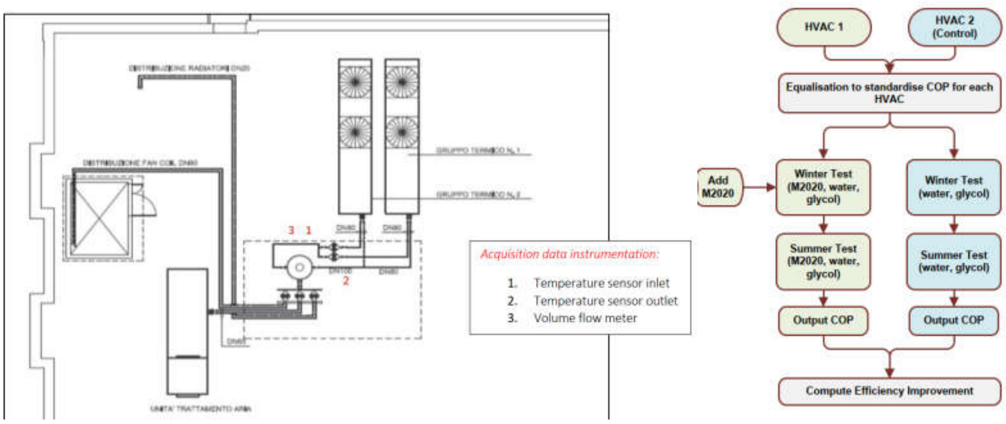

Figure 3. HVAC system with data sensors positions and flowchart of test methodology.

2.4. Nanofluid loading procedure

The volume of heat transfer fluid within each HVAC thermal line was 1460 liters. As the final step in preparing the building for experimental testing, the concentration of propylene glycol within the HVAC system (left and right wings of the building) was measured: it was the same in both systems and equal to 30%vol.

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Therefore, the nanofluid was loaded within the HVAC-1 system (left wing) only, up to reach a nanoparticles concentration of 2%vol, leaving the right wing of the building (HVAC-2) loaded with the conventional water-propylene glycol heat transfer fluid: this approach allowed to compare the performance of 2 identical systems, working with different heat transfer fluids at the same time.

3. Experimental results

This paper summarizes and compares the heat pumps performance, recorded in 3 experimental tests, carried out from February 2020 to March 2021, according to the following scheduling:

- first test (heating mode): February, 10, 2020 – March, 9, 2020;
- second test (cooling mode): September, 7, 2020 – September, 25, 2020;
- third test (heating mode): November, 27, 2020 – March, 9, 2021.

Being this study referred to a real building, the parameters which can affect the performance of the HVAC systems cannot be fully controlled. For this reason, in order to minimize their effects, in this study the performance has been evaluated over a long period of time, balancing as much as possible, oscillations related to stochastic variables.

3.1. February-March 2020 results

In the first week of monitoring (from February, 10, 2020 to February, 14, 2020), the HVAC-1 and HVAC-2 systems were loaded with the same heat transfer fluid (water-glycol 30%vol). During this period, a short database was acquired, to be used as a reference data for the experiment. Then, on February 17th, nanofluid was loaded in the HVAC-1 and the next 7 working days were used to balance both the heat pumps by performing preliminary tests. After such balance, energy consumption comparison between both the machines restarted on February 26th and continued until March 9th.

Figure 4 shows the hourly COP comparison between HVAC-1 and HVAC-2, while Figure 5 shows the average daily COP comparison and the daily COP ratio between HVAC-1 and HVAC-2.

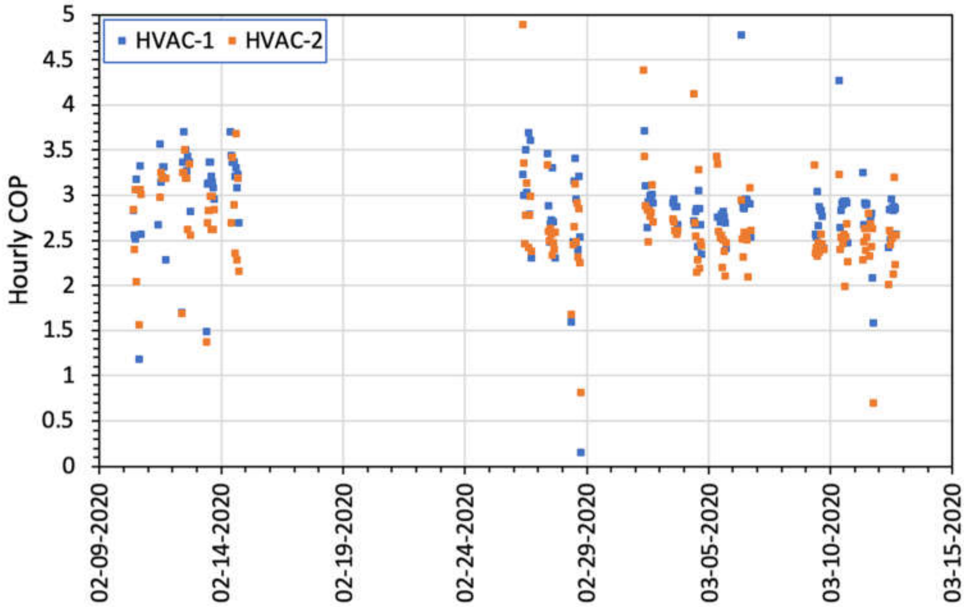

Figure 4. Hourly COP comparison between HVAC-1 and HVAC-2 (February 10, 2020 – March 9th, 2020).

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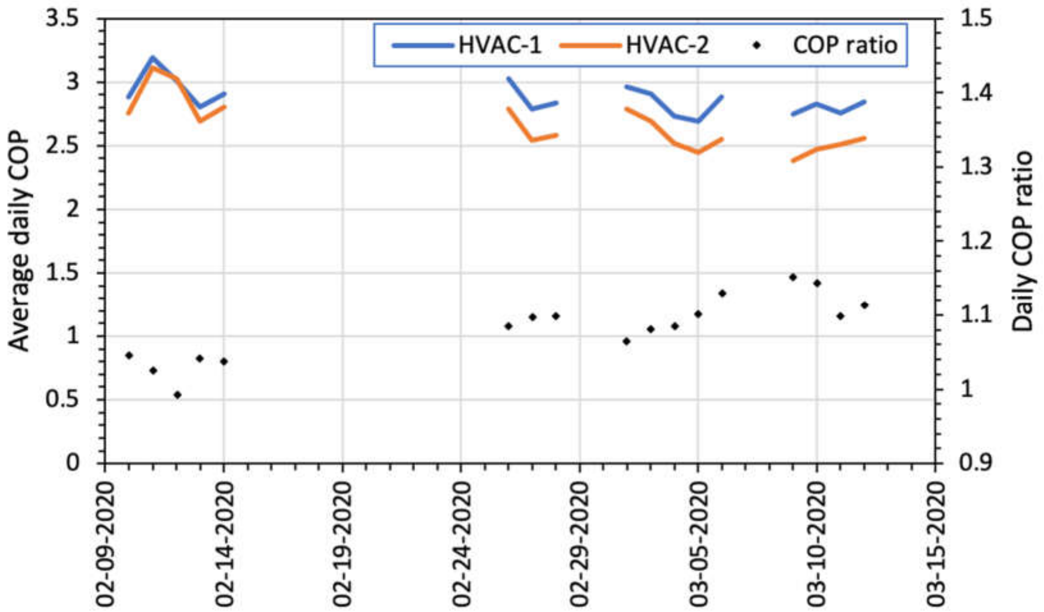

Figure 5. Average daily COP comparison and daily COP ratio between HVAC-1 and HVAC-2 (February, 10th, 2020 – March 9th, 2020).

In the first 3 days of monitoring (from February 26 to February 28), after nanofluid loading, the mean increase of performance was 9.36%. But, the best performances have been achieved in the last two weeks of experimental data acquisition, when the average increase in performance was 10.8%. On March 12, 2020, the HVAC systems have been shut off.

During such acquisition period, density of nanofluid was weekly measured by sampling from the system in operation. Since it was 1079g/l over the test period, constant concentration of 2% of nanoparticles was ensured inside the system fluid.

3.2. September 2020 results

Figure 6 and Figure 7 show the experimental results in terms of mean hourly COP and average daily COP obtained in September 2020. In this period, the HVAC machines worked as chiller in cooling mode.

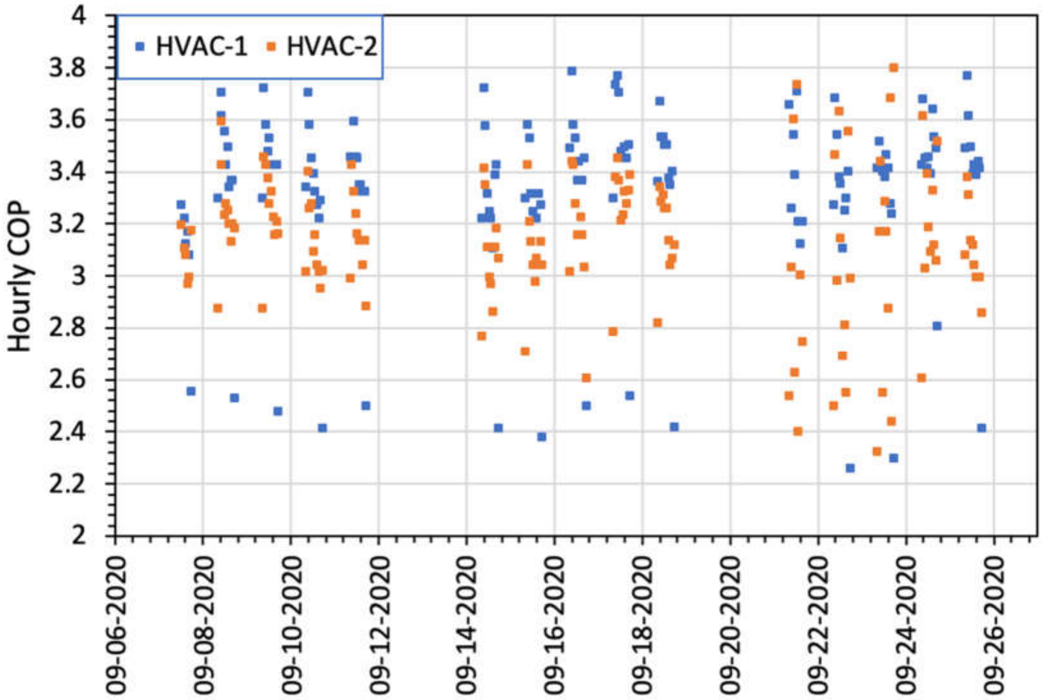

Figure 6. Hourly COP comparison between HVAC-1 and HVAC-2 (September, 7th, 2020 – September, 25th, 2020).

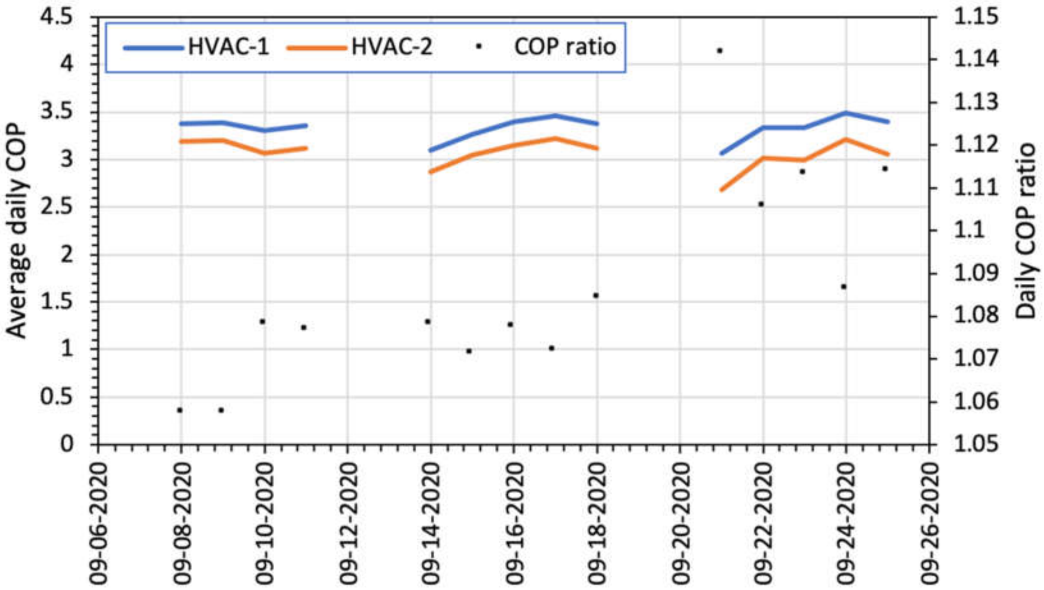

Figure 7. Average daily COP comparison and daily COP ratio between HVAC-1 and HVAC-2 (September, 7th, 2020 – September, 25th, 2020).

As it can be seen, increments in terms of COP were recorded during the entire period of experimentation, with lower values in the first week (average weekly increment equal to 6.7%), middle values in the second week (average weekly increment equal to 7.7%) and maximum values in the last week (average weekly increment equal to 11.2%), with a mean value of 8.9% over the entire period.

Nanoparticles concentration was measured before the data acquisition, in September. In fact, before the test period, the system was stopped from April to September. In that period nanoparticles sedimentation occurred in the system. Density measured before the test campaign was 1065g/l, therefore concentration was 1.7% in volume. Total re-

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dispersion of the nanoparticles was achieved after 29 hours of pumps in operation and density was again 1079 g/l, therefore concentration was again 2% (**Error! Reference source not found.**).

	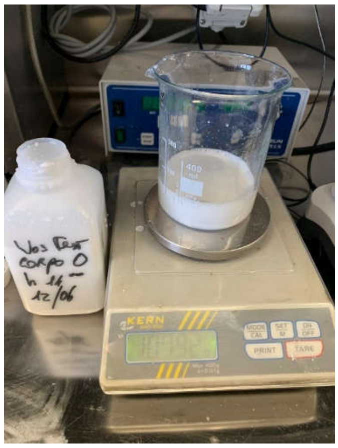
Density = 1065g/l before pumps switched on. Concentration [1.7%]	Density = 1079 g/l after 29h of running pumps. Concentration [2.0%]

Figure 9. Nanofluid dispersion during weight measurements in lab.

3.3. February-March 2021 results

In order to confirm the results acquired during winter 2020, the previous heat transfer fluid (water-glycol 30%vol) was reloaded within the HVAC-1 system and a long data set was acquired, in order to compare the performance of the two systems over a wide time period (from November 27th, 2020 to February 5th, 2021). Therefore, on February 8th, the nanofluid was reloaded again within the HVAC-1 system and the performance was monitored until March 9th, 2021. Figure 8 shows the hourly COP comparison between HVAC-1 and HVAC-2, from January 1st, 2021 to March 9th, 2021.

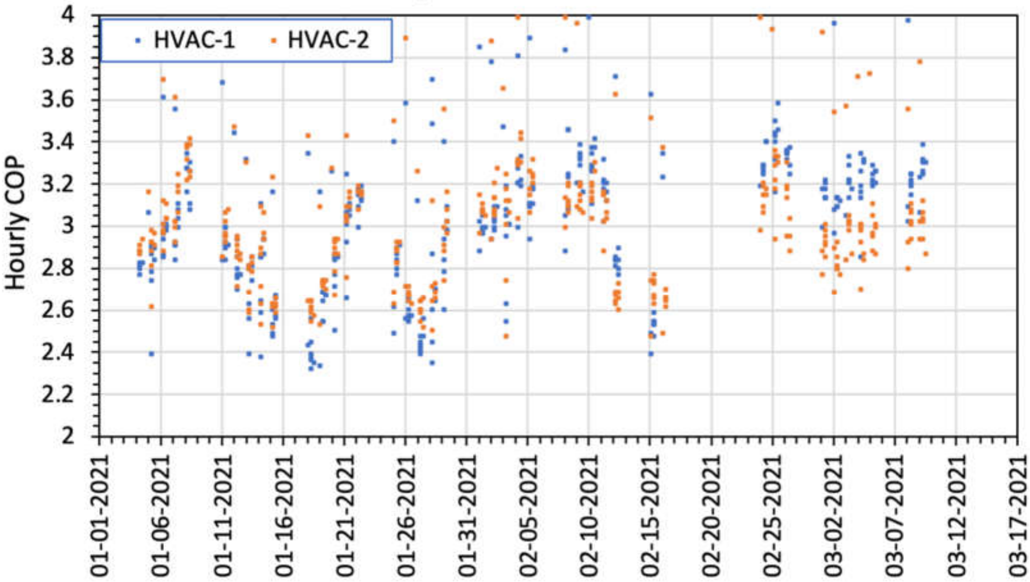

Figure 8. Hourly COP comparison between HVAC-1 and HVAC-2 (January, 1st, 2021 – March, 9th, 2021).

As it can be seen, the hourly COP values related to the HVAC-2 (orange dots), until February 5 are mainly higher than the HVAC-1 values. Instead, after loading the nanofluid (Feb 8), the trend reverses, with blue dots over orange ones.

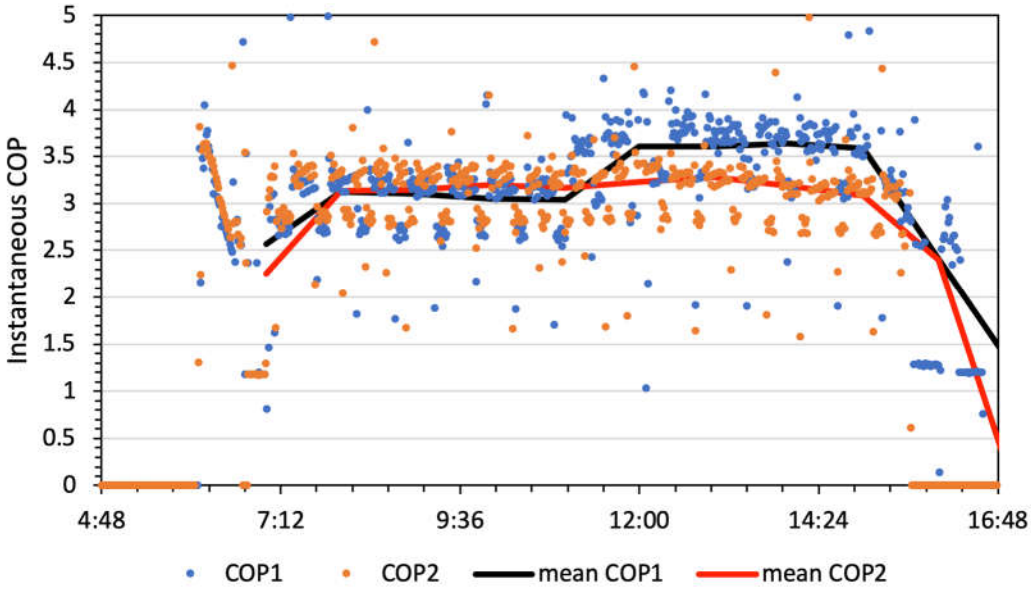

Figure 9. Instantaneous COP comparison between HVAC-1 and HVAC-2. Data acquired on February, 8th, 2021.

This effect is particularly visible in Figure 9, where a comparison of the instantaneous COP is shown, following the loading of the nanofluid around noon. A significant increase in HVAC-1 performance is evident, due to the heat transfer fluid change.

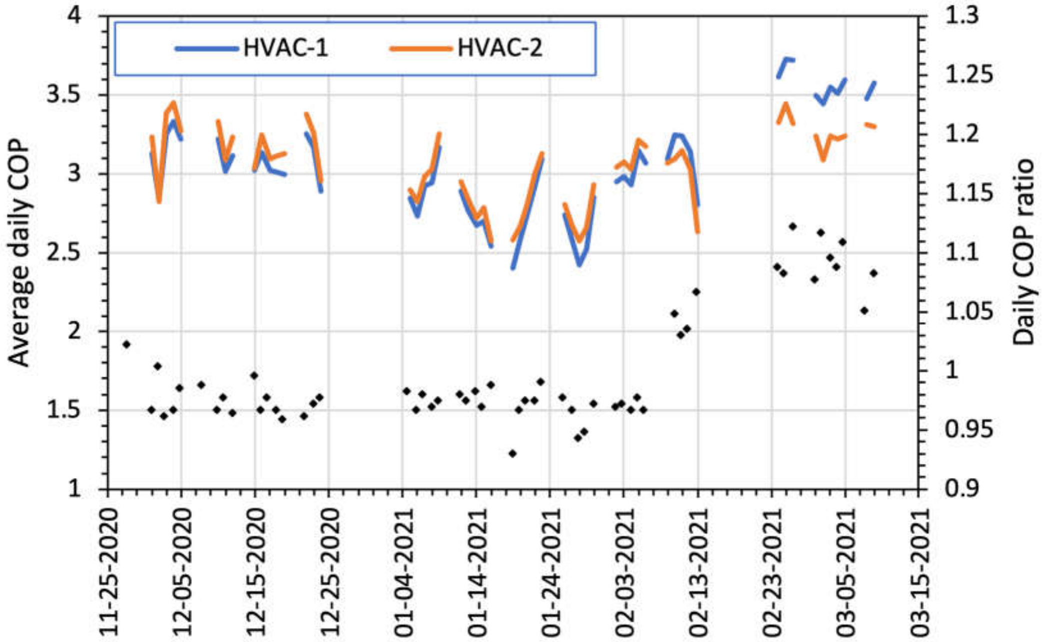

Figure 10. Average daily COP comparison and daily COP ratio between HVAC-1 and HVAC-2 (November, 27, 2020 – March, 9, 2021).

Finally, Figure 10 shows the average daily COP comparison and the daily COP ratio between HVAC-1 and HVAC-2 from November, 27th, 2020 to March, 9th, 2021. Clearly, it can be observed that, during the entire experimental period, in which the two plants operated with the same fluid (from November 27 to February 5), the performance of HVAC-1 was worse than HVAC-2, with an average COP1/COP2 ratio of 0.970. While, after the nanofluid loading, from February 9th to March 9, 2021, the COP1/COP2 ratio was 1.078, with a peak of 1.121 and an average increase of 10.5%.

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All the results shown in the above graphs demonstrate that the increased performance of the HVAC-2 system is not due to favorable environmental conditions, but only to the positive action of the nanofluid. The above discussed experimental results essentially agree with the numerical results found by Colangelo *et al*. [37].

In order to better understand the results described above, the performances of the HVAC-1 working with base fluid and nanofluid have been investigated in depth and compared. Particularly, the data related to the period January-March 2021 have been collected as a function of outside air temperature and fluid temperature at the inlet of HVAC-1. These parameters have been chosen since directly affect the heat pump COP. Figure 11 shows the results.

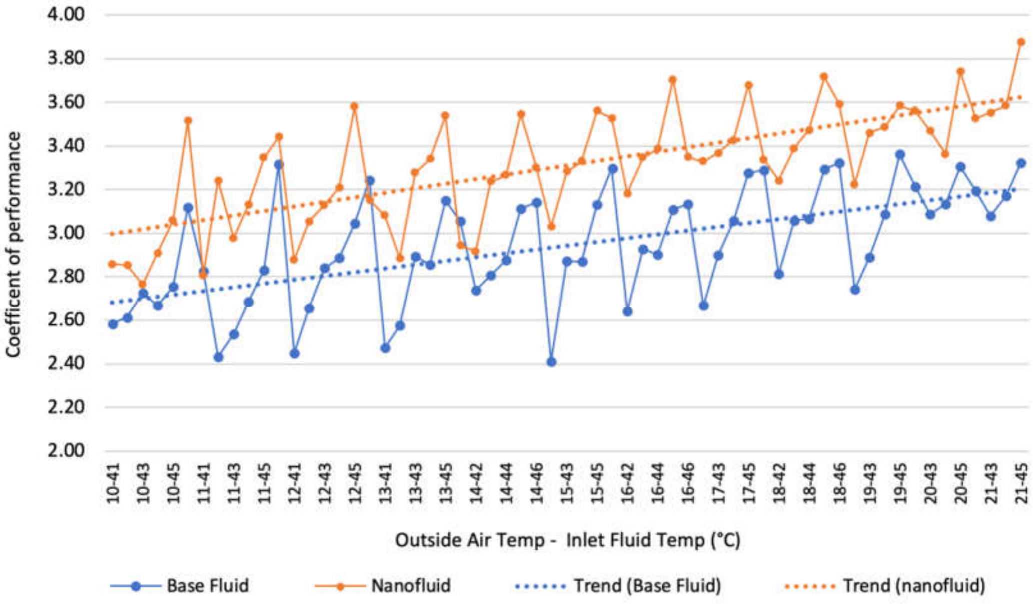

Figure 11. Average COP of HVAC-1 working with base fluid and nanofluid (January, 2021 – March, 2021).

As it can be seen, the COP was strongly influenced by the operating conditions of the heat pump. Nevertheless, the performance growth between base fluid (data until February 5) and nanofluid (data related to the following days) seems quite constant during the whole period of experimentation and equal to 13% on average.

3.4. Practical significance/usefulness

The results of this work suggest that the use of nanofluids within hydronic HVAC systems, can have a big impact under environmental, energetic and economic aspect. In fact, taking into account the annual energy consumption of the building "Corpo O" [37] it was possible to calculate annual energy savings equal to 50.2 MWh. Besides, according to the Italian CO_2 emission factor [39], it was possible to preliminarily evaluate an annual avoided CO_2 emission equal to 21.8 ton related to the use of nanofluid.

Finally, it is important to remark that the replacement of the traditional heat transfer fluid with a high performance nanofluid, does not required important modification to the HVAC plant, resulting in an easy and effective retrofitting of old systems.

4. Conclusions

In this work, the performances of two full-scale HVAC systems, installed at the educational building "Corpo O" in the Campus of University of Salento, Lecce – Italy, working with conventional water-glycol mixture and with Al_2O_3-nanofluid, have been investigated. In particular, the nanofluid was composed by water-glycol and 2%vol aluminum oxide (Al_2O_3) nanoparticles, having controlled size distribution between 100 nm and 600 nm and controlled stable suspension during the operation in the system. Long term stability of the nanofluid caused reliable and consistent thermal performance over a wide temperature range with limited effects on viscosity.

The results obtained in 3 experimental campaigns allowed both to quantify the performance increase due to the use of nanofluid instead of convention water and glycol mixture:

1) under real operating conditions, the increase in energy efficiency due to the nanofluid of HVAC-1 with respect to HVAC-2, working simultaneously, has been meanly equal to 9.8% in winter and 8.9% in summer, with average daily peaks of about 15%.
2) the comparison between the performance of the same HVAC system, working in different comparable period with and without nanofluid, shows a mean increase of COP equal to about 13%
3) density of nanofluid has been monitored over the period of the test. Constant density was measured, therefore a stable suspension of the nanofluid was found inside distribution system of HVAC-1.

Although the relationship between HVAC system performance and use of nanofluids needs to be better investigated, the results of this work suggest that nanofluids can significantly improve the performance of air conditioning systems.

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Conflicts of Interest: The authors declare no conflict of interest.

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