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Improvement in Energy Performance of a HVAC System Working with Nanofluid

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Abstract **-** In the present work, a HVAC system in a residential building, operating with water firstly, followed by a nanofluid named Maxwell, has been experimentally monitored to evaluate the improvement in energy performance. Particularly, a robust measurement and verification equipment has been installed on the chillers and the pumps firstly, next a baseline data for a 30-day period has been acquired, by operating the HVAC system with water, then the same data have been measured for a 30-day nanofluid operating period, and finally the baseline data were compared to the nanofluid data. All collected data have been normalized according to the ambient temperature conditions, since this parameter plays a significant role in chiller performance and energy consumption. Furthermore, in order to ensure an objective, transparent and conservative evaluation of energy-conservation measures, the International Performance Measurement and Verification Protocol (IPMVP) was applied.
The present experimental demonstration has evaluated chiller energy consumption and pump energy consumption as well as coefficient of performance (COP) resulting in a mean decrease in chiller energy use of about 16.85%.

Keywords**:** HVAC system, Nanofluid, Energy performance, IPMVP, COP

1. Introduction

The high environmental and energy costs associated with heating, ventilation and air-conditioning (HVAC) systems are a very important issue for the civil and industrial sectors. For this reason, several scientific papers have been published in recent decades, describing various technologies and techniques that can be used to reduce HVAC energy consumption. Among these, one possible solution concerns the use of nanofluids as enhanced heat transfer fluid [1,2]. Indeed, improving thermal capacity and thermal conductivity are the keys to enhancing the heat transfer capability of conventional fluids, such as water and glycol: this translates to enhanced heat transfer and energy efficiency in closed loop hydronic systems.

Nanofluids are suspensions of nanoparticles dispersed in a base fluid in order to achieve higher heat transfer performance. In this regard, numerous studies have been done on the relationship between nanofluid thermal conductivity and nanoparticle volume concentration, size, morphology, etc. In early experiments on nanofluids, Lee *et al*. [3] demonstrated that a small amount of nanoparticles added into the base fluid can be enough to increase its thermal conductivity. Next, a lot of studies confirmed this result [2] and, in some works, experimental setups have been designed and built to investigate the physical phenomena involved in the thermal conductivity enhancement of nanofluids [4].

A very important parameter in HVAC applications that differentiates nanofluids from base fluids is the convective heat transfer coefficient [5,6]. Then, in recent years, several experimental investigations on convective heat transfer characteristics of nanofluids under turbulent and laminar regimes have been carried out, as resumed by Colangelo *et al.* in [7].

Being nanofluids enhanced heat transfer fluid, numerical and experimental studies have been carried out on their applications in several civil and industrial sectors. Lee *et al*. [8] and Al-salame *et al*. [9] studied photovoltaic thermal systems based on nanofluids. Colangelo *et al.* [10-11] and Chaji *et al.* [12] experimentally investigated traditional solar flat panels coupled with the use of nanofluids. Furthermore, the application of nanofluids on different solar thermal energy conversion systems was investigated in [13–16].

Nanofluids have also been tested to increase the performance of internal combustion engines. Zhang *et al*. [17] developed a study on diesel cylinder-head cooling system, while Micali *et al.* [18] developed an experimental campaign on a biodiesel four-strokes engine.

Further studies have been done on the application of nanofluids to electronic devices [19], geo-thermal heat exchangers [20,21], cooling system for wind turbines [22], demonstrating significant increases in heat transfer performance versus traditional fluids.

The objective of this study was to evaluate the improvement in energy performance of the chillers operating on the existing water firstly, followed by operation with a nanofluid named Maxwell.

To accomplish this, robust Measurement and Verification (M&V) equipment has been installed on the chillers and the pumps. The M&V equipment gathered baseline data for a 30-day period, after which the nanofluid has been installed, following which the M&V equipment gathered the same data for a 30-day nanofluid operating period, and the baseline data then compared to the nanofluid data. Since ambient temperature plays a significant role in chiller performance and energy consumption, weather normalization over the ambient temperature operating range was performed using data collected by the M&V equipment. This demonstration has evaluated chiller energy consumption, and coefficient of performance (COP) as well as pump energy consumption resulting in a decrease in chiller energy use and an increase in COP with little impact on pump energy consumption.

2. Test Conditions and Experimental Apparatus

The experimental campaign was carried out in a residential building, where cooling is provided by a chilled water plant consisting of (2) Carrier 60-ton, air-cooled, parallel, on grade chillers. Chilled water is circulated through the building by primary and standby chilled water pumps located in a first-floor mechanical equipment room. The chilled water plant, through a network of piping, serves (2) pipe fan coil units that provide cooling for each resident room and the common areas. These fan coil units include chilled water valves and fans that are controlled by local room thermostats. This system operates 24/7 year-round.

Fig. 1: Residential building in which the experiment was carried out

The experimental plan has been designed to ensure the following:

- evaluations are as accurate as possible;
- interactive effects are considered;
- analysis is always conservative;
- all significant and relevant factors are measured;
- data is recorded and analyzed in an open manner.

Since, objective, transparent and conservative evaluation of energy-conservation measures is a critical element in ensuring that resources are effectively saved, in the present work, the International Performance Measurement and

Verification Protocol (IPMVP) [23] was applied. According to this protocol, the comparison of before and after energy consumption should be made, using the following general M&V equation:

$$Savings = (Baseline\ Period\ Energy - Reporting\ Period\ Energy) \pm Adjustments \quad (1)$$

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

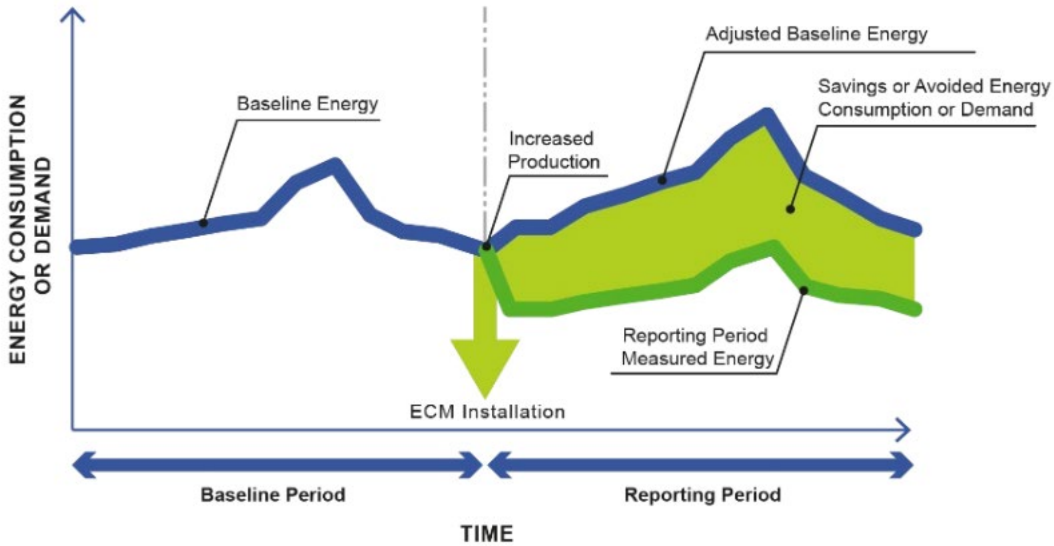

Fig. 2: International Performance Measurement and Verification Protocol

In the case under investigation, the comparison was between what the consumption would have been without implementation of nanofluid in the HVAC system of the building, and the actual consumption measured after installation of nanofluid into the system.

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

2.1. Main equipment layout and sensor deployment

The HVAC system was equipped with 2 chillers, Carrier Model 30RB-060: air-cooled, 3 scroll compressors, R-410a, whose main characteristics are reported next:

- Power: 70.4 kW;
- EER: 9.7 (full load);
- COP: 2.9 (full load);
- GPM (each): 136.5 (nominal);
- Exp. Valve: electronic;
- Pumps: Bell & Gossett Model 1510 - power 15 hp - GPM 280 (nominal).

The two chillers are connected in parallel on the hydronic loop. In this work only the first chiller was monitored by means of two contact temperature probes and an external ultrasonic flow meter. The temperature probes were installed at the inlet-outlet of the circuit collectors while the flow meter was installed only at the outlet of the circuit, as shown in Fig. 3. Also, a third set of contact temperature probes and an external ultrasonic flow meter were installed on the common pipe entering and leaving the building.

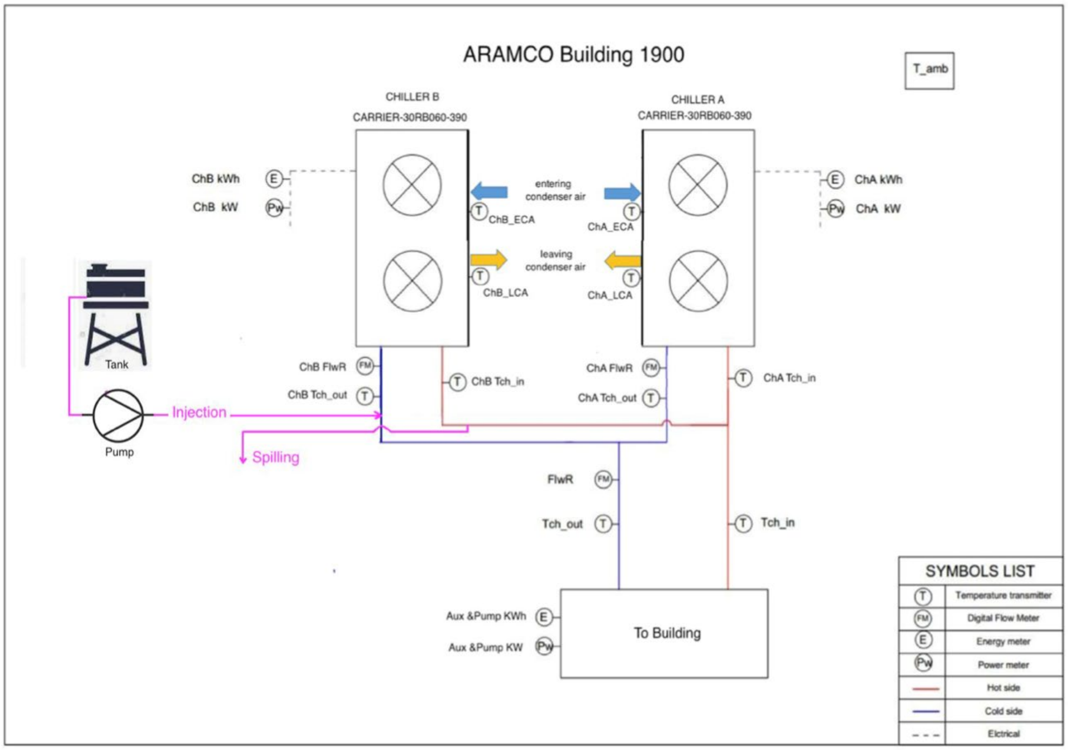

Fig. 3: Hydronic circuit and sensor deployment layout

Acquiring the inlet-outlet temperatures of the fluid and its flowrate, while knowing the specific heat of the fluid, allowed us to calculate the chiller's thermal power in the hydronic loop. We monitored electric current input by a triphasic energy meter system on the side of the two chillers.

Electric consumption was measured by an energy meter directly on the power supply. Fan motors and the chiller compressor were separately monitored. There were two pumps, one primary and one standby, so only one pump worked at a time. There were no variable frequency drives, and the operating pump ran at a constant speed and flow rate. Energy meters were installed on the pumps. Ambient temperature was monitored by a weather station.

The nanofluid was introduced to the system from a tank with a dedicated pump connected to a standard chemical injection and spilling point, as shown in Fig. 3.

2.2. Test instrumentation and data acquisition system

The HVAC system was equipped with:

- Thermocouple sensors, model CWT-L1T-TC by Netico. The sensors were pressed against the fluid pipes and isolated, so as to be protected from external influence. The thermocouples are type-K (0-1000 Celsius) waterproof.
- Air temperature sensor and weather station, model CWT-LiTH-AM (-40~80 Celsius / 0- 100 RH) by Netico. The sensors were positioned against the direct air flow.
- Ultra-sonic flow meters sensors by Mial Instruments, Model MUF1000, were installed on Chiller #1 and on the Common Pipe. Flow range was from 0.03 ft/s to 40 ft/s (0.01 m/s to 12 m/s) with an accuracy of 1% of the measured value, for pipe size 1"" to 48".
- Energy/power meters, model NPTM 100/110A by Netico which combined the monitoring of electrical energy consumption, power quality analysis and management of electrical energy use in a single instrument with 0.5 precision class.

- Real time data acquisition and monitoring system: The data monitoring system was based on six Power meters and three BTU meters interconnected to a GPRS modem, and 5 self-connecting remote sensors for measuring the entering and leaving air temperature.
  Fig. 4 shows a schematic of the real-time data acquisition system.

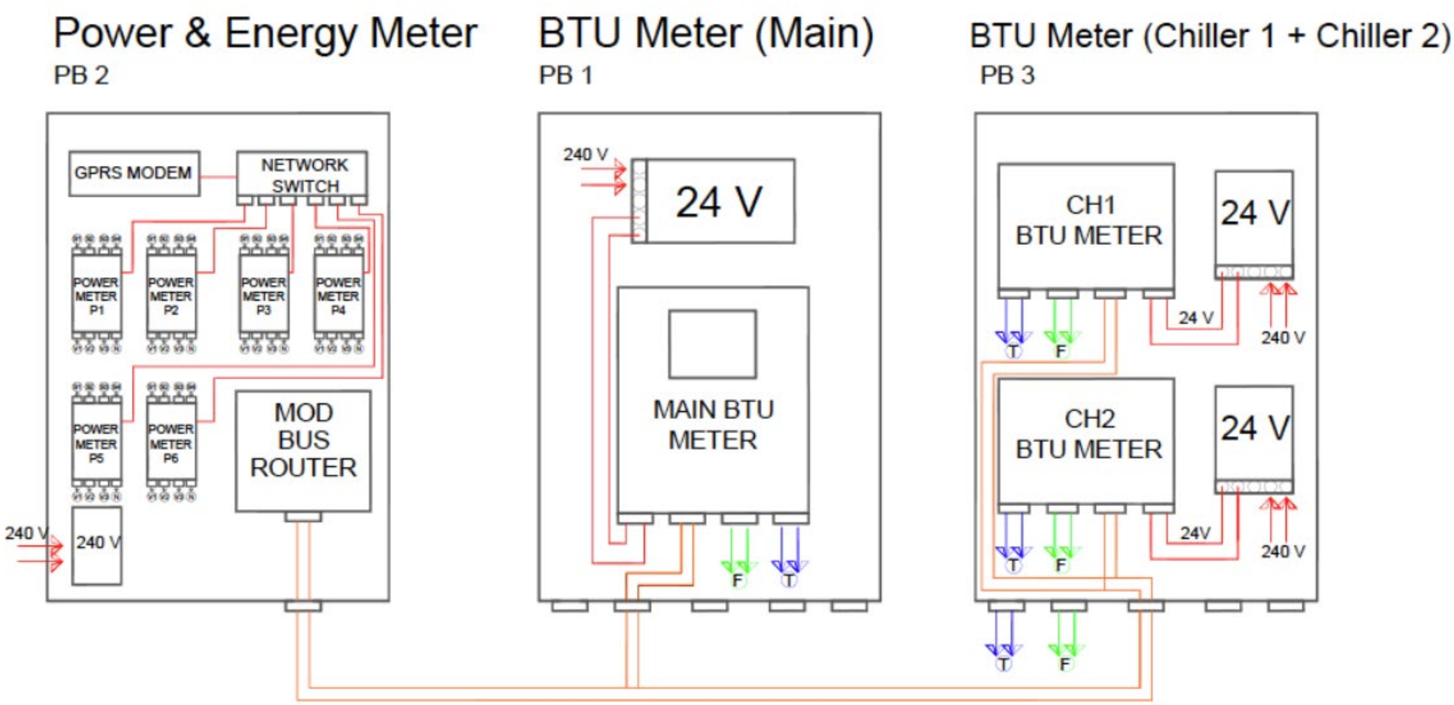

Fig. 4: Real-time Data Acquisition System

2.3. Nanofluid Maxwell™

As said before, the objective of this work was to evaluate the improvement in energy performance of the chillers operating with a nanofluid named Maxwell, whose main characteristics are summarized in Table 1.

Table 1: Maxwell characteristics.

Composition (% by weight): - Performance additives - Water	 9% 91%
Colour	White
Odour	Odourless
pH	10
Density @ 20 °C	1058 kg/m^3
Operating range	0 °C
Burst point	0 °C
Boiling point	100 °C
Flash point	na
Thermal conductivity @ 20 °C	0.648 W/m K
Specific heat @ 20 °C	4.08 kJ/kg K
Viscosity @ 20 °C	1.05 mPa s

Maxwell is an engineered suspension of sub-micron-sized aluminium oxide particles in a base fluid. Maxwell is a 'drop-in' additive for use in new or existing commercial and industrial heating and cooling systems.

In a typical building's closed loop cooling system, shown in Figure 2 below, Chillers circulate chilled water in a loop (blue) to Air Handling Units ('AHUs'). After cooling the local environment through the AHUs, the fluid returns to Chiller and the cycle repeats itself. Chillers use energy to produce this chilled water through a refrigeration cycle. The nanofluid increases the transfer of heat in the refrigeration cycle, meaning the chiller cools the fluid faster and more efficiently, thereby reducing the energy used by the Chiller. This translates into lower energy costs to operate the Chiller.

These expected results can be explained taking into account the qualitative pressure-enthalpy chart for a vapour-compression cycle working between a cooling and heating source, as shown in Fig. 5. In the evaporation cycle (points 1 to 2) heat transfers from the cooling source (e.g. chilled water return) to the refrigerant.

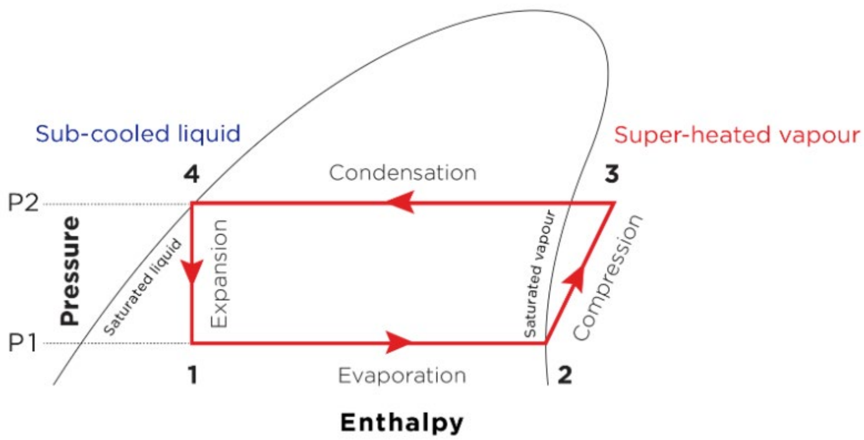

Fig. 5: Qualitative pressure-enthalpy chart for a vapour-compression cycle working between a cooling and heating source

Refrigerant compression occurs between points 2 and 3. The difference in the enthalpy between those points represents the work performed by the compressor. The phase between 3 and 4 shows condensation: heat rejection from the refrigerant in the condenser at constant pressure. Refrigerant expansion occurs between points 4 and 1.

By reducing the approach temperature of the heat exchange phases corresponding to transformations 1-2 and 3-4, the use of nanofluid in the system fluid causes a reduced pressure differential P2-P1. This requires less work from the compressor, resulting in lower energy use and less equipment wear and tear.

The nanofluid installation was facilitated by the concurrent injection of Maxwell and the release of an equivalent amount of system fluid from the hydraulic circuit, so as to maintain constant system pressure.

The nanofluid was injected into the system on October 6th 2021, as follows:

1. Insertion of Maxwell 15%.
2. System density was measured and found to be 1,005 kg/m^3 from an initial 1,000 kg/m^3 (water), equivalent to 6.5 grams of Maxwell per system litre.
3. Final verification of pH > 10.5 and Maxwell at 2%.

3. Discussion of results

The baseline and reporting periods lasted 30 days each (720 hours), as summarized in Table 2. During these periods, only normal operating activities in the HVAC system were observed, allowing the acquisition of a "clean set" of all relevant system data for the purpose of IPMVP methodology.

Table 2: Sampling and reporting periods.

		Days	Hours
Baseline period	From 2021-09-06 to 2021-10-05	30	720
Maxwell reporting period	From 2021-10-13 to 2021-11-11	30	720

All flow and temperature data were sampled locally 6 times per minute (every 10 seconds), averaged and logged to a cloud monitoring site. A further average was computed on the monitoring site over a 10-minute period, i.e. 60 samples averaged into a single value, computed every 10 minutes. This allowed to keep to an accuracy of: 1/10 of deg. Celsius; and ±1% error on flow.

The data were then further analyzed, filtered and validated according to the following rules:

- Case "return temperature, T_{out} < supply temperature, T_{in}": value eliminated, physically not possible.
- Case "volumetric flow rate, $\dot{q}$ > 0": valid value only if, concurrently verified on all the 3 sampled flow rates (Chiller #1, #2 and Common Pipe).
- Thermal power consumption calculated as $\dot{q}\rho C_p(T_{out} - T_{in})$

where:

ρ = density (1 kg/litre - baseline water or 1.06 kg/litre Maxwell;

C_p = 4,180 J/kg/°C (baseline water) or 4100 J/kg/°C (Maxwell).

Following the above, a total of 4294 (from a total of 4320 - 10 min. avg. samples) points for the baseline period and 4182 (from a total of 4320 - 10 min. avg. samples) points from the Maxwell period have been analyzed.

The sample distribution per COP (during either the Baseline or Maxwell periods), shows a "Gaussian-like" behavior, confirming a sound sampling methodology (see Figure 18 below).

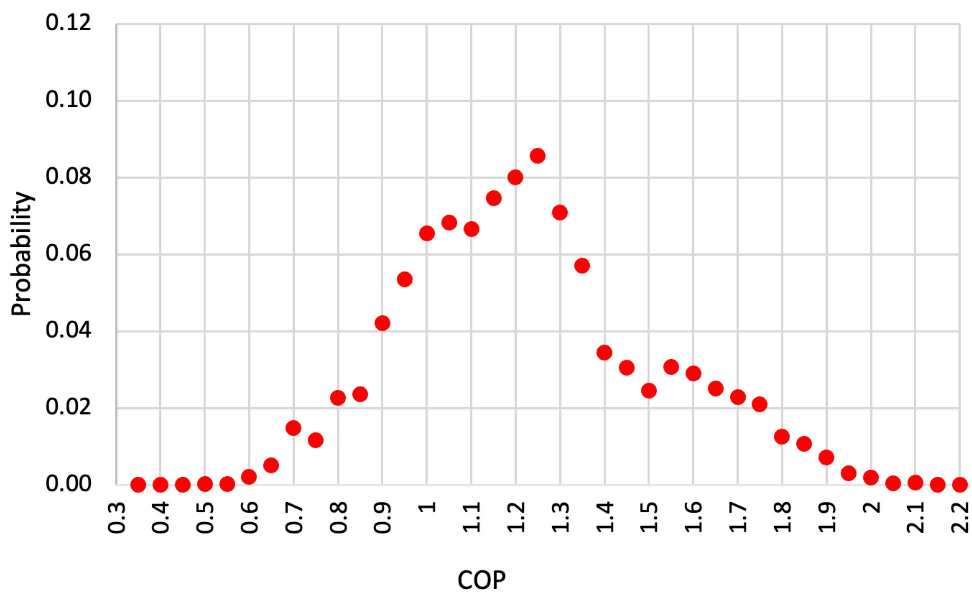

Fig. 6: Samples by COP intervals

As per IPMVP methodology, real data for system COP (as a ratio of kWth/kWe) acquired during the baseline period has been classified for each Outside Air Temperature (OAT) interval, in order to determine the linear relationship rule between COP and OAT. Fig. 7 shows the results.

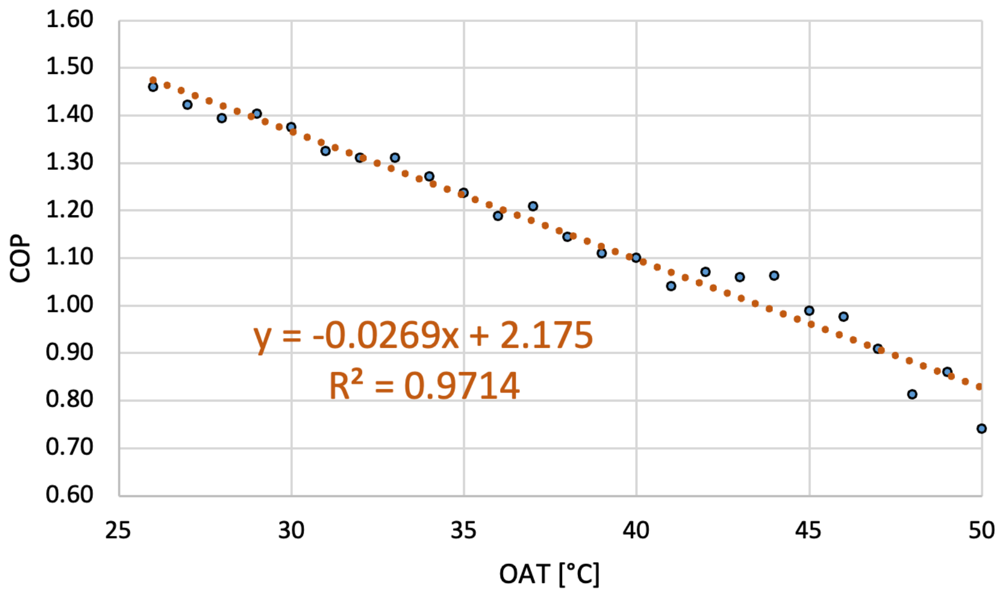

Fig. 7: Linear relationship rule between COP and OAT (with water as base fluid)

Data sample aggregation and the linear interpolation above leads to the following linear experimental rule (R^2>0.97) of:

$$\mathrm{COP} = -0.0269 * \mathrm{OAT} + 2.175 \tag{2}$$

This adjustment rule is used in the IPMVP Energy Saving Computation to estimate the electrical consumption that would have taken place if water as opposed to Maxwell, at the same independent operating conditions (OAT & kWth), was running during the Maxwell reporting period.

Fig. 8 shows the average COP calculated for each week during the baseline period and the COP value simulated according to Eq. 2.

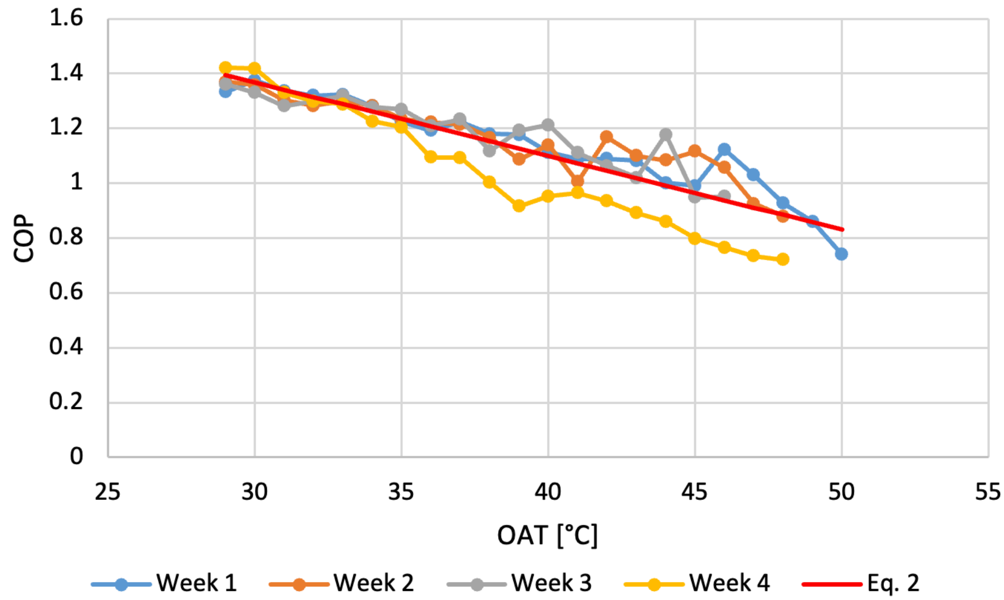

Fig. 8: Weekly average COP (experimental values) and simulated COP (red line) according to Eq. 2

Particularly, it is possible to observe that the first 3 weeks are perfectly overlapped, while the curve related to the 4th week is overlapped up to 38°C; therefore, no significant variations can be observed in the COP for the same OAT over different weeks.

The actual sampled energy consumption values per hour for Maxwell have been compared with the adjusted energy consumption values for water (determined by applying the linear predictive formula above) for the Maxwell Reporting Period. Table 3 shows the electrical energy consumption comparison over the Maxwell period.

Table 3: Total system energy balance over the Maxwell period

	Maxwell	**Water**	**Savings**
CHILLER (kWh)	**12711.7**	**15287.6**	**2576.0**
PUMP (kWh)	**3171.4**	**3003.5**	**-167.8**
CHILLER (kW)	18.24	21.93	3.70
PUMP (kW)	4.55	4.31	-0.24

Therefore, the energy efficiency value, calculated according to the IPMVP methodology, is equal to 16.85%. Moreover, by also accounting for the slight increase in pump energy demand due to the increased viscosity of Maxwell, the global energy efficiency ratio is equal to 13.17%. These results are in agreement with an extended experimental campaign carried out on an educational building, at the Campus of University of Salento, Lecce, Italy [23].

4. Conclusions

In this work, a pilot demonstration related to the use of a nanofluid named Maxwell in a HVAC system of a residential building, has been conducted. The objective of this demonstration was to evaluate the improvement in energy performance of the chillers operating on the existing water firstly, followed by operation with Maxwell.

The International Performance Measurement and Verification Protocol was applied to ensure an objective, and conservative evaluation of energy-conservation measures. The total energy savings was about equal to 16.85%. Further additional benefits from the implementation of the Maxwell include:

- It is a drop-in additive, that delivers immediate results and does not require any special retrofitting of existing systems.
- It has a useful life of 10+ years with minimal annual maintenance.
- It results in improved equipment performance and increased system capacity because the systems it is installed in, will run much more efficiently.

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