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Increasing Energy Efficiency of Central Cooling Systems with Engineered Nanofluids

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Abstract: Buildings consume about 40% of the world's energy consumption and of that, 65% is dedicated to cooling (or heating) systems. Central building cooling uses water as the main heat transfer medium. The nanoparticle fluid suspension exhibits thermal properties superior to water. The goal was to achieve the highest possible thermal properties with just the right amount of nanoparticles in a uniform and stable dispersion and suspension in water. This engineered nanofluid contains a uniform and stable suspension of graphene nanoparticles (GNP) in water. Using covalent functionalization, centrifugation and high-speed dispersion, the GNP remains in a stable suspension indefinitely. The nanofluid is applied to the closed loop of the chilled water system, where the heat transfer enhancement occurs at the fluid tubes within the evaporator and the tubing in the chilled water coils within the Air Handling Units (AHUs). The Proof of Concept (POC) completed in 2019 using laboratory-derived nanofluid resulted in energy savings that averaged at 32% compared with the baseline fluid (water). In 2022, a Scaled-Up mini plant produced GNP nanofluids in a commercial process environment, showing an average energy savings of 21%. These results were further verified and validated on small chilled water plants outside of the Scaled-Up plant with 25% and 29% average savings.

1. Introduction

High-performance cooling is one of the most vital needs of many industries. All past efforts to improve cooling technology were made by improving systems and equipment but with very little focus on heat transfer fluids. Liquids are used in cooling systems to help dissipate heat or maintain an even temperature. A nanofluid coolant would significantly enhance this process to benefit a range of industries, such as refrigeration systems, data centre cooling and battery cooling. As illustrated in Figure 1, graphene is an allotrope of carbon consisting of a single layer of atoms arranged in a two-dimensional honeycomb lattice.

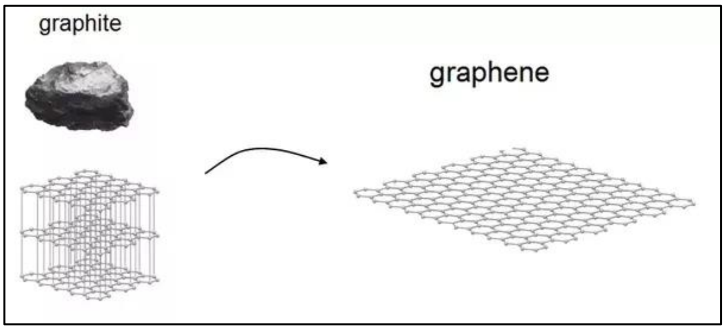


Figure 1: Graphene vs Graphite (From Graphene: The Material That Is Changing The World by Charlotte Brown 2021[1])

Each atom in a graphene sheet is connected to its three nearest neighbors by a σ or sigma bond, and contributes one electron to a conduction band (the $2p_z$ orbital) that extends over the whole sheet and makes graphene a semimetal with unusual electronic properties. Graphene conducts both heat and electricity very efficiently along its plane. It also strongly absorbs light of all visible wavelengths and that is why it appears black, but a single graphene sheet is nearly transparent because it is extremely thin. The material is also about one hundred times stronger than would be the strongest steel of the same thickness.

Although graphene has various excellent properties, the one that is of main interest in this paper is its thermal properties. Thermal transport in graphene is still an active area of research, which has attracted attention because of the potential for thermal management applications.

1.1 Graphene Nanofluid

The basic concept of dispersing solids in fluids to enhance thermal conductivity is not new; solid particles were added in the past because they conduct heat much better than liquids. The major problem with the use of microparticles is the rapid settling of these particles in fluids. Other problems include abrasion and clogging. These problems are highly undesirable for many practical cooling applications. Nanofluids overcome these problems by stably suspending nanometer-sized particles in base fluids. Nanoparticles stay suspended much longer and possess a much higher surface area. The surface/volume ratio of nanoparticles is one thousand times larger than that of microparticles. The high surface area of nanoparticles enhances the thermal conductivity of nanofluids since heat transfer occurs on the surface of the particle.

These unique properties of nanoparticles are exploited to develop nanofluids for heat transfer systems possessing extreme stability and ultrahigh thermal conductivity. Other benefits of nanofluid include decreased demand for pumping power, reduced inventory of heat transfer fluid (through initial design) and significant energy savings. Stable suspension of minuscule quantities of nanoparticles makes the base fluid cool faster and thermal management systems smaller and lighter.

This is a technical paper built on applied research on graphene nanofluids by which the production method is the subject of a patent filed by this author [2]. The patent filed was for the laboratory method production of the nanofluid and this paper focuses on the application and the validation of the performance of the nanofluid in commercial chilled water plants. The laboratory-produced nanofluid [2] gave an average of 32% savings compared with the baseline using water but this was tested on a laboratory-scale chilled water system.

2. Work Done and Results

2.1 Nanofluid Production - Lab Scale Proof of Concept Stage (2018 - 2019)

A version of the Two-Step Method was used to produce the nanofluid at our facility and our formulation is patent pending. These nanoparticles in themselves are hydrophobic and are repelled by the molecules of water [2]. The nanoparticles were functionalized using a method called covalent functionalization.

Functionalization makes the GNPs hydrophilic. The final nanofluid is prepared by dispersing the functionalized GNP in water. Once this is complete, agglomeration issues become almost non-existent. To further complete the process to decrease the aggregation and enhance the dispersion capability, the f-GNP is dispersed in an ultrasonic bath and an ultrasonicator.

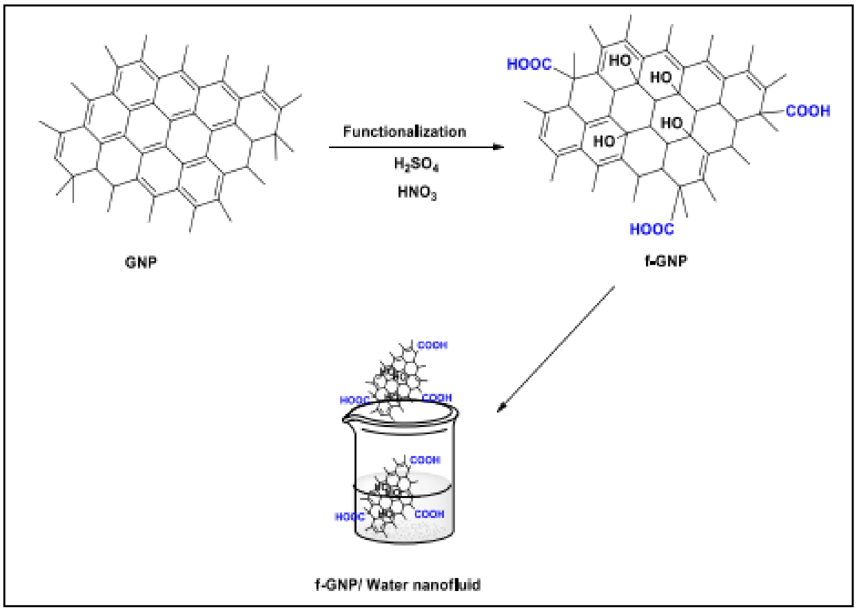


Figure 2: Method of Nanofluid Production

2.2 The POC Test Rig POC (2018-2019)

The GNP nanofluid was tested in a small 1.5 RT (Refrigeration Tons) cooling system. The test rig was connected to a room adjacent to it where the room dry bulb temperature (T) and relative humidity (RH%) and the ambient T and RH% were regularly measured. This was to ensure that both tests i.e., with water or the baseline fluid and with the nanofluid were measured under the same internal and external conditions.

Lower compressor runtimes were observed with the nanofluid. This meant the nanofluid had a better thermal performance compared to water. The ‘valleys’ in the Figures below represent the time when the compressor cuts off.

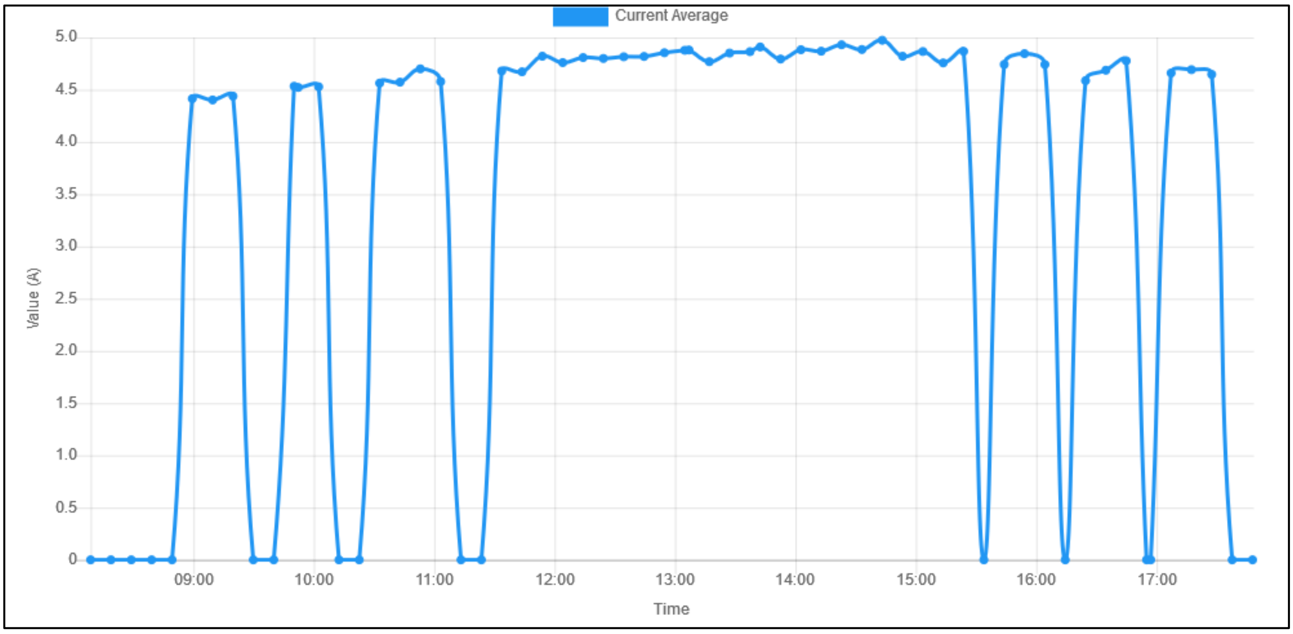


Figure 4: Current (Amp) draw of the unit (23rd of September 2019) with water

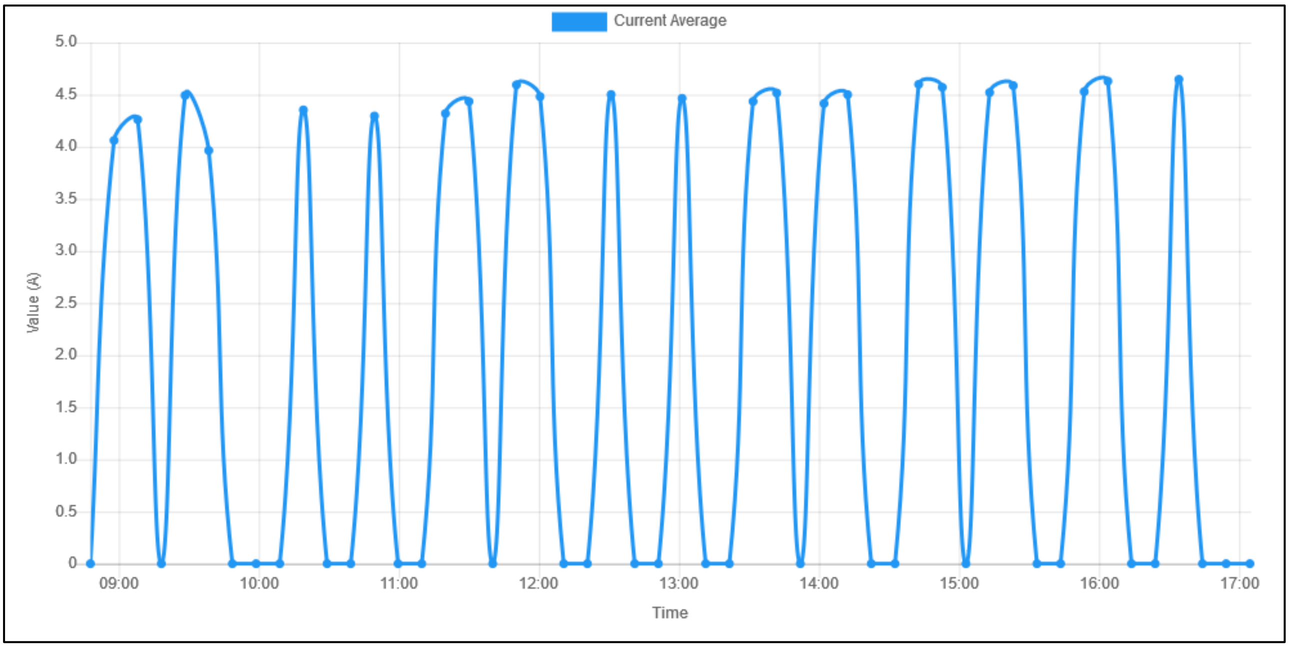


Figure 5: Current (Amp) draw of the unit (4th of October 2019) with GNP nanofluids

The area under the curve (A-s) has a direct relationship to the energy consumed. This was calculated by integrating the curve function between limits (in this case the time signatures). The savings ranged between 18% to 46.1% (average of 32 %). Although this was an excellent result in the world of energy efficiency, the real task ahead was replicating this success in a small industrial-scale manufacturing system, and this was carried out at the Scale-Up stage.

2.3 The Scale-Up Production (2021-2022)

In 2021, the Scale Up lab was designed and installed to produce the nanofluid on a small industrial scale and then test it on a chilled water system to try to replicate the POC results.

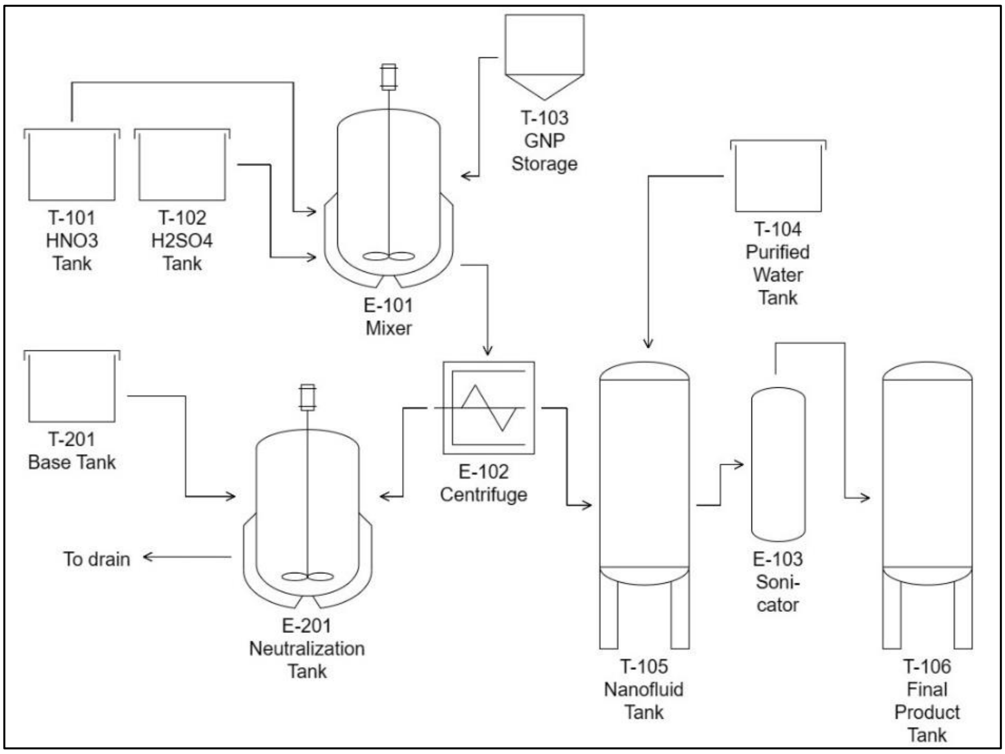
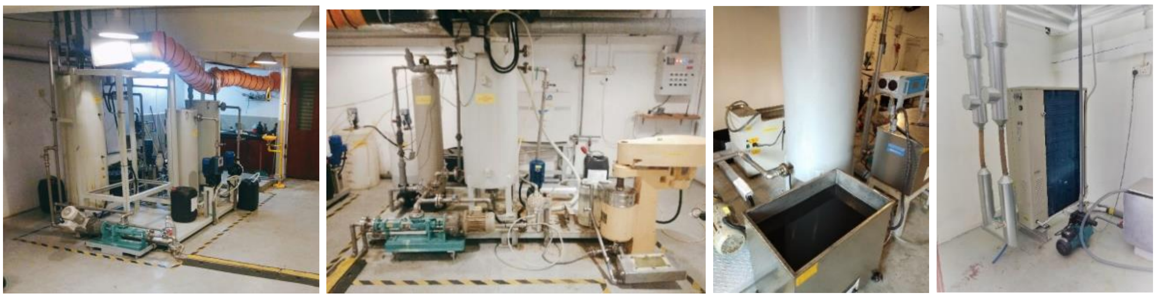


Figure 6: Process flow diagram of production of the nanofluid

Once homogenous mixing is complete, the f-GNP was then sent to centrifuge to produce the f-GNP retentate. Once the desired dispersion was achieved, the nanofluid was stored in a product tank, from which it was pumped into the Scale-Up test rig (Figure 8) for performance testing.



(a) (b) (c) (d)

Figure 7: (a) Functionalization (b) Centrifugation (c) Dispersion (d) Test Rig

2.4 The Scale-Up Test Rig

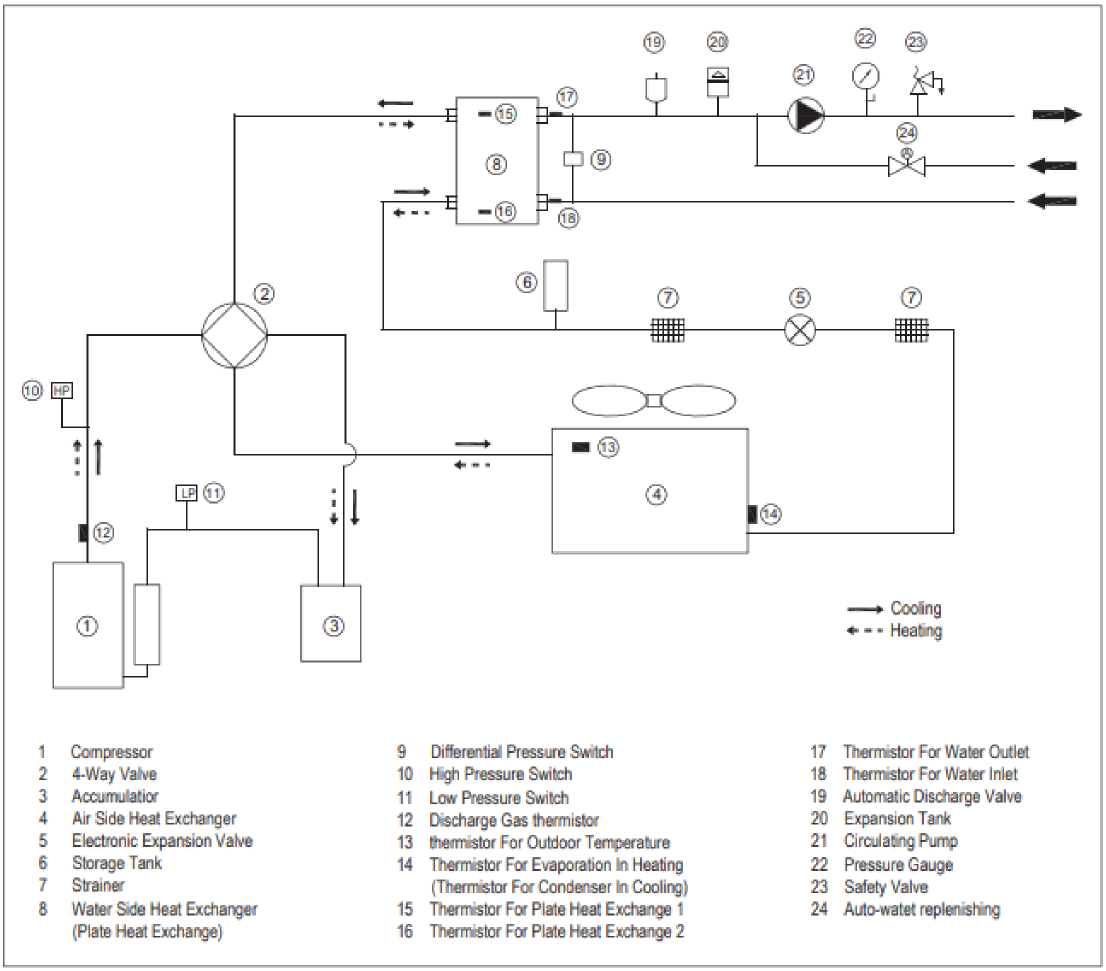


Figure 8: Cooling Test Rig Schematic

To compare both the energy consumed and the heat load, a duration of **330 minutes** were taken for all runs, and this was typically between 9 am and 5.30 pm every day after removing sensor anomalies.

Average Water Run (Nov 21 – Dec 21)	Average Nanofluids Run (Feb 22 – Mar 22)	Savings
1.16	1.14	2%
1.47	1.21	18%
1.67	1.26	24%
1.78	1.23	31%
1.46	1.21	17%
1.87	1.32	30%
1.68	1.23	27%
1.59	1.34	16%
1.58	1.17	26%
1.63	1.23	25%
1.76	1.29	27%
1.35	1.20	11%
Average savings		21%

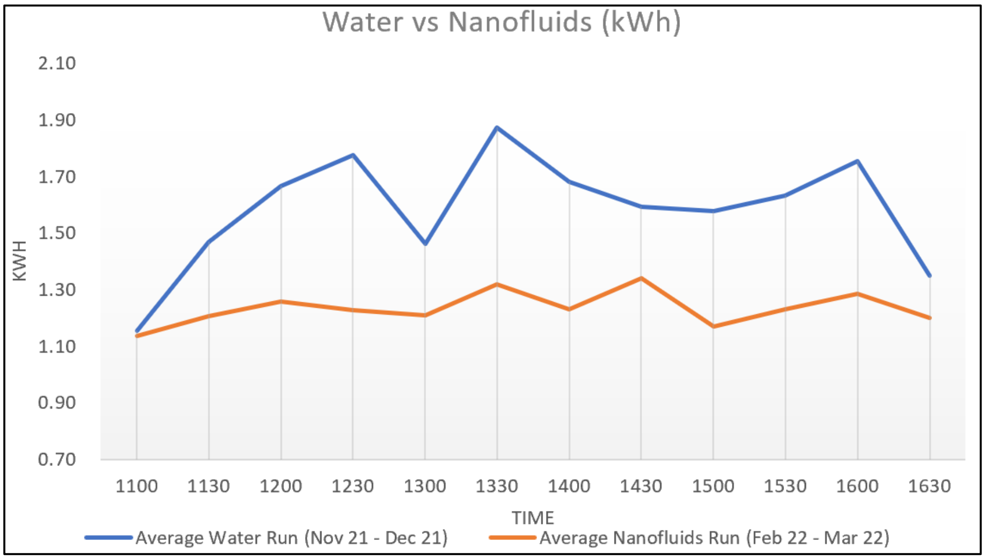


Figure 9: Scale-Up Lab Test Results

The conclusion is that there is an **average energy (kWh) reduction of 21%**.

2.5 Other Outside Lab Results

2.5.1 MFI (Malaysia France Institute) – part of UniKL (Universiti Kuala Lumpur)

An energy performance validation exercise was conducted at Universiti Kuala Lumpur - Malaysia France Institute (UniKL MFI), Bangi. This was conducted from the end of July 2022 to early September 2022. At the HVAC laboratory, the water in the chilled water system was replaced by the nanofluid to observe and measure energy performance improvement.

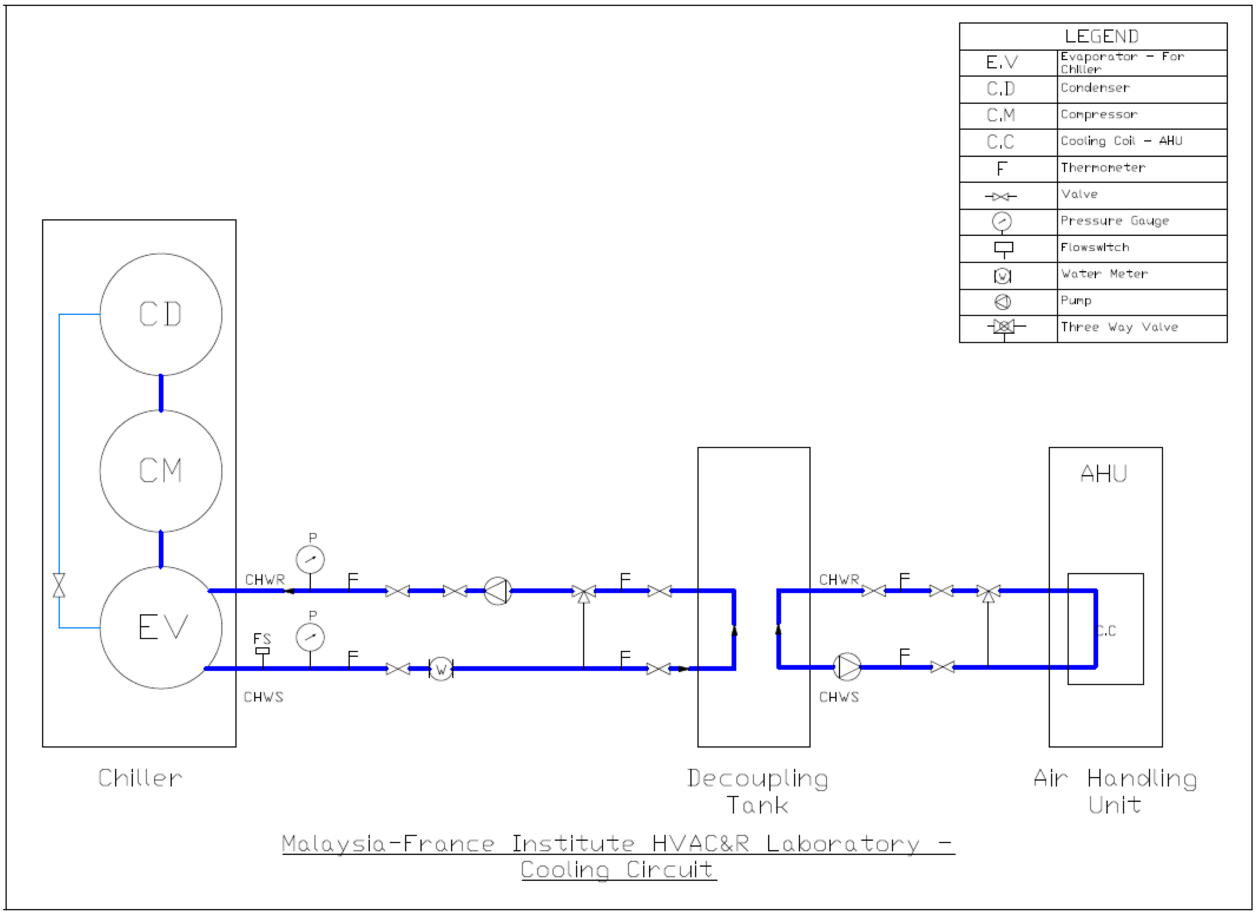


Figure 10: MFI Chiller Plant Set-Up

A duration of **446 minutes** was taken for all runs (between 9 am and 5.30 pm every day).

The following tables are summaries:

Water				
Date	**kW**	**RT**	**kW/RT**	**kWh**
24 08 2022	12.89	11.34	1.10	95.50
26 08 2022	10.63	10.02	0.96	80.51
Average	11.76	10.68	1.03	88.01
Nanofluid				
Date	**kW**	**RT**	**kW/RT**	**kWh**
30 08 2022	11.20	11.51	0.86	82.47
10 9 2022	10.92	13.28	0.76	80.89
20 9 2022	12.99	14.98	0.81	96.35
Average	11.69	13.25	0.83	86.88

If based on this result only, energy savings is only 1.3% (86.88 kW vs 88.01 kW). The compressor in this chiller could not modulate except to switch between compressors and that switching capability was unavailable during the testing period.

Water			
kW	**RT**	**kW/RT**	**kWh**
11.76	10.68	1.03	88.01
Nanofluid			
kW	**RT**	**kW/RT**	**kWh**
11.69	13.25	0.83	86,88
Comparison			
kWh	**RT**	**kW/RT**	**kWh**
-1%	**24%**	**-22%**	**-1.3%**

But since that heat load was not constant, the energy consumption needs to be normalized against the variance in the heat load.

Note that the average RT (Refrigeration Tons or the heat load) has increased by 24% during the nanofluid run but the kW/RT or system efficiency has improved by 22%. Using this 24% difference in the RT to normalize the energy consumption, the real energy savings can be obtained as follows:

Normalized			
KWh Nanofluid	82.47	80.89	96.35
KWh Nanofluid (N)	62.59	61.39	73.12
% Saving	-28.9%	-30.2%	-16.9%
Average	**-25.3%**		

This exercise proved that the nanofluid increased the plant efficiency by **25.3%**

2.5.2 Astana Palace in Kuching

The subsequent energy performance validation exercise was conducted at Astana Palace (Governor's Residence) at Kuching, Sarawak The validation exercise was conducted over a period of 6 weeks from 29th November 2022 to 17th December 2022.

The measurements were taken between 10.50 am to 5.20 pm and on some days the durations were longer than others because this was an operational building with events running on some of those days (event days: 2 chillers running; normal days: 1 chiller running) To have an unbiased comparison, the period between 12.30 pm and 3.40 pm was selected where energy, load and temperature data was available, a duration of **190 minutes** every day for the 9 days.

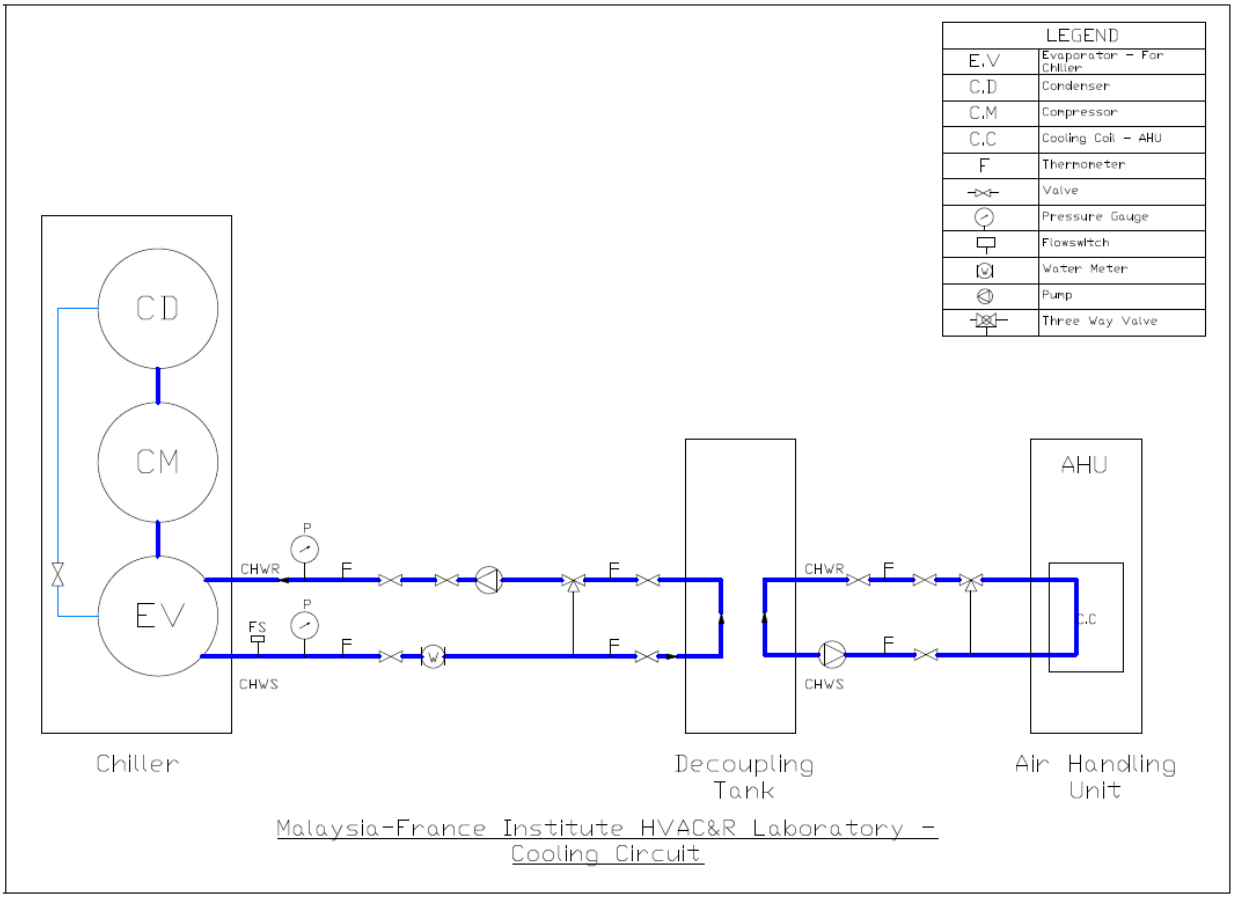


Figure 11: Astana Chiller Plant Set-Up

The following table is a summary of the results:

WATER						
		Average kW	**Average RT**	**Average kW/RT**	**Average Outdoor Deg C**	**Nos of Chiller in Operation**
Water	30th Nov 2022	85.98	58.03	1.60	35.03	1
Water	1st Dec 2022	86.20	64.49	1.37	35.03	1
Water	2nd Dec 2022	76.39	31.22	2.76	33.70	2
	Average	***82.86***	***51.25***	***1.91***	***34.59***	

NANOFLUID						
		Average kW	Average RT	Average kW/RT	Average Outdoor Deg C	Nos of Chiller in Operation
Nanofluid	7th Dec 2022	81.66	68.21	1.23	32.53	1
Nanofluid	8th Dec 2022	98.60	60.46	1.70	28.45	2
Nanofluid	12th Dec 2022	103.94	80.42	1.29	30.23	2
Nanofluid	13th Dec 2022	92.42	70.99	1.31	29.95	2
Nanofluid	15th Dec 2022	75.80	82.86	0.91	33.65	1
Nanofluid	19th Dec 2022	83.71	85.84	0.98	32.93	1
	Average	***89.35***	***74.80***	***1.24***	***31.29***	

Normalizing for the 3.3 C average temperature drop, the efficiency improvement was **29.0%**.

3. Discussion

All the tests and measurements were done and taken at the chilled water plant side while maintaining the indoor (occupied) space conditions and normalizing for any outdoor weather conditions. The focus is on the chilled water plant as this is the component in the air-conditioning system that consumes the most energy. The GNP Nanofluid increases the energy efficiency of the chilled water system. The only unknown now is how long will the GNP stay suspended in the closed loop. With stationary samples in a closed container, there does not seem to be any sedimentation or agglomeration observed and logically since a chilled water system is consistently agitated, there is no reason to see this happening in an actual functioning system. However, the nanofluid samples in the installed systems will be removed and tested from time-to-time

Why does the nanofluid show these savings and what value do the nanoparticles add to the base fluid that increases the system efficiency by such a significant %? The answers lie within research done by many scientists in this field, and it is mainly due to the higher convective heat transfer performance [3] at the heat exchangers of these systems. The reason for the increased heat transfer performance is that the nanoparticles cause disturbances in the boundary layer. The Brownian motion of the nanoparticles causes turbulences delaying the process of the boundary layer formation thereby increasing the scope for heat transfer [4]. The nanofluids show a shear thinning (non-Newtonian) rheological behaviour and this decreases the viscosity at the boundary layer leading to superior flow properties and enhanced heat transfer. The nanoparticles also increase the thermal conductivity of the nanofluid, and this gets better at higher concentrations [5] but somehow the heat transfer performance hits a plateau after a certain concentration and with this, we can infer that an extremely high concentration of nanoparticles reverses the advantages of the Brownian motion and shear thinning advantages at the boundary layer.

4. Application

In the above tests, the system's energy performance was measured while the base fluid (water) was circulating. After that, the system is stopped, base fluid drained and the system is replaced with the nanofluid, and the energy performance is tested. While this is possible with small plants with small fluid volumes, in a real operating environment, plant shutdown is almost impossible. Furthermore, large commercial plants have a few hundred thousand to more than a million litres of water (and even more for large district energy plants) and that is a major logistics issue. We have devised a system that converts the water in an operating system to a nanofluid of the required performance without disrupting the operations of the plant. This system has been successfully tested and will be used in the application to commercial plants worldwide. This will be the material of a future technical paper.

5. Conclusion

This nanofluid applied to the built environment can provide substantial energy efficiency improvements over conventional cooling. This is because the nanofluid is a heat transfer fluid that exhibits thermal properties superior to water.

References

[1] Brown, Charlotte, 2021. Graphene: The Material That Is Changing The World

[2] Nanomalaysia Berhad and Blue Snow Consulting and Engineering Sdn Bhd. 2020. Patent filing: 22965MY00031/PM/AQI/smi

[3] Yarmand, H., Zulkifli, N.W.B.M., Gharehkhani, S., Shirazi, S.F.S., Alrashed, A.A., Ali, M.A.B., Dahari, M. and Kazi, S.N., 2017. Convective heat transfer enhancement with graphene nanoplatelet/platinum hybrid nanofluid. International Communications in Heat and Mass Transfer, 88, pp.120-125.

[4] Barai et al., 2019, Bahnvase et al.,Radkar et al.,2019. Intensified convective heat transfer using ZnO nanofluids in a heat exchanger with helical coiled geometry at constant wall temperature. Mater. Sci. Energy Technology. 2,161-170

[5] Hojjat, M., et al., 2011. "Thermal conductivity of non-Newtonian nanofluids: experimental data and modeling using neural network." International Journal of Heat and Mass Transfer 54.5-6 (2011): 1017-1023.