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Laura Fedele
Istituto per le Tecnologie della Costruzione, Consiglio Nazionale delle Ricerche, Corso Stati Uniti 4, 35131 Padova, Italy,
laura.fedele@itc.cnr.it

Laura Colla
Istituto per le Tecnologie della Costruzione, Consiglio Nazionale delle Ricerche, Corso Stati Uniti 4, 35131 Padova, Italy,
laura.colla@itc.cnr.it

Mauro Scattolini
Istituto per le Tecnologie della Costruzione, Consiglio Nazionale delle Ricerche, Corso Stati Uniti 4, 35131 Padova, Italy,
mauro.scattolini@itc.cnr.it

Filippo Bellomare
Industrial Engineering Department, University of Padova, Via Venezia 1, 35131 Padova, Italy,
filippo.bellomare@studenti.unipd.it

Sergio Bobbo
Istituto per le Tecnologie della Costruzione, Consiglio Nazionale delle Ricerche, Corso Stati Uniti 4, 35131 Padova, Italy,
sergio.bobbo@itc.cnr.it

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Nanofluids Application as Nanolubricants in Heat Pumps Systems

Laura FEDELE[1,*], Laura COLLA[1], Mauro SCATTOLINI[1], Filippo BELLOMARE[2], Sergio BOBBO[1]

[1]Consiglio Nazionale delle Ricerche, Istituto per le Tecnologie della Costruzione, Padova, Italy
Ph: +39 049 829 5831; Fax +39 049 829 5728; laura.fedele@itc.cnr.it, laura.colla@itc.cnr.it,
sergio.bobbo@itc.cnr.it

[2]Dipartimento di Ingegneria Industriale, Università di Padova, Padova, Italy,
filippo.bellomare@studenti.unipd.it

[*]Corresponding Author

ABSTRACT

In the past few years, various applications have been proposed for nanofluids in the Heating, Ventilation, Air Conditioning and Refrigeration (HVAC&R) field; their use as primary and secondary fluids, also as lubricants, was kept into account to improve the systems performance. The present work was developed to test the applicability of nanofluids as lubricants in the compressors of heat pump systems, with the purpose to experimentally detect the possible positive effects of nanolubricants. Several nanolubricants, formed by Polyolester (POE) or mineral oil as base fluid, and titanium oxide (TiO_2) or single wall carbon nano-horns (SWCNH) as nanoparticles, were studied in a dedicated test rig. In contrast with the published literature, no improvement was detected using nanofluids instead of commercial oil. All results will be discussed in detail in the paper.

Keywords: nanofluid, POE, mineral oil, titanium oxide, single wall carbon nano-horns

1. INTRODUCTION

Performance improvements in Heating, Ventilation, Air Conditioning and Refrigeration (HVAC&R) applications are a stringent requirement in the industry, even if it seems that all the system features have already reached their maximum efficiency. Nanotechnologies and, in particular, nanofluids can supply interesting possibilities in this direction. In literature, several applications of nanofluids in HVAC&R have been studied, both as primary or secondary fluids. In particular, some very recent papers suggested their use as lubricants in the compressors, promising improvement in the total system efficiency, due to better thermal dissipation, lower wearing and improved lubrication properties. Ahamed *et al*. (2011) published a review on exergy analysis of vapour compression system, finding a reduction in the energy losses when nanofluids are used as nanolubricants instead of base lubricants. Even Lee et al. (2006-2007) reported a decrease in the friction coefficients for scroll compressors when lubricants added with nanoparticles are employed. More specifically, Wang et al. (2003) analysed the influence of adding titanium oxide (TiO_2) nanoparticles in mineral oil to improve the solubility of HFC. They studied a refrigeration system working with R134a and mineral oil added with TiO_2 nanoparticles; better performances than using polyolester (POE) oil and R134a were obtained and a larger return of lubricant to the compressor was observed. In Bi *et al*. (2008) the operation of a domestic refrigerator, working with R134a and a mineral oil added with TiO_2 and aluminium oxide (Al_2O_3) nanoparticles, instead of POE oil, was analysed. Results highlight about 26% increase of refrigerator performance compared to the use of R134a with POE oil, with a nanoparticles concentration around 0.1% in mass. Similar results were found by Subramani and Prakash (2011). They employed Al_2O_3 nanoparticles at 0.06% by weight in mineral oil instead of POE in the cycle compressor, with about 25% reduction of power consumption. In Sabareesh *et al*. (2012), a refrigeration system working with R12 was taken under consideration. The mineral oil, usually employed in the compressor, was substituted with the same oil added with TiO_2 nanoparticles at 0.01 wt%. An increase of coefficient of performance (COP) was found up to 17%. Kumar and Elansezhian (2012) tested a nanolubricant formed by Al_2O_3 at 0.2 vol% nanoparticles in polyalkylenglycol (PAG) oil in a refrigeration system instead of pure PAG; they found about 10% reduction of energy consumption.

Moreover, fullerene (C_{60}) was studied by Xing *et al*. (2014) as additive of mineral oil in a domestic refrigerator working with isobutane (R600a). They found about 5-6% COP improvement with a nanoparticles concentration of 3 $g \cdot L^{-1}$. Considering the extraordinary importance of any possible improvement in the HVAC&R applications performance, the employment of nanofluids should be seriously evaluated. In this paper, the use of nanofluids as nanolubricants in compressors for heat pump systems has been tested in order to detect any possible positive effect. Different nano-oils, based on POE and mineral oil added with TiO_2 or Single-Wall Carbon Nanohorns (SWCNH) nanoparticles, have been studied in a properly built test rig.POE oil with TiO_2 nanoparticles at 0.1 wt%, 0.05 wt% and 0.5 wt%, POE oil with SWCNH nanoparticles at 0.1 wt% and mineral oil with TiO_2 nanoparticles at 0.1 wt% were tested.

2. EXPERIMENTAL SECTION

2.1 Nanofluids preparation

The optimization of the two-step preparation method of nanofluids has been deeply explained in Colla *et al*. (2013). A commercial polyolester (POE) oil and a mineral oil were used as base fluids; TiO_2 nanoparticles, purchased from Degussa (TiO_2, P25), with a spherical shape and a declared 21 nm diameter, and SWCNH nanoparticles, supplied by Carbonium Srl, with an estimated equivalent diameter of 100 nm, were chosen as particles. No dispersant was added. Nanoparticles were dispersed in the lubricant by means of ultrasound irradiation, supplied by a Sonics & Materials VCX130 sonicator, operating at 20 kHz frequency and 130 W maximum power, equipped with a 6 mm diameter Ti-6Al-4V alloy tip. Nanoparticles mass fraction, sonication time, sonication power and sample temperature reached during sonication were optimised in order to obtain the most stable suspension. The best conditions were 180 minutes sonication time at the 50% of the maximum power of sonication (65 W) and the reached preparation temperature of about 69°C.

2.2 Nanofluids characterization

As described in Colla *et al*. (2013), all the considered nanofluids, *i.e*. POE oil with TiO_2 nanoparticles at 0.1 wt%, 0.05 wt% and 0.5 wt%, POE oil with SWCNH nanoparticles at 0.1 wt% and mineral oil with TiO_2 nanoparticles at 0.1 wt%, were characterized in order to check their stability, dynamic viscosity and thermal conductivity.

All nanofluids showed a good stability, proved by DLS measurements. Thermal conductivity and dynamic viscosity were respectively measured by means of a Hot Disk thermal conductivity-meter and a rotational cone-plate rheometer. Generally, from these experimental results, pure oil and nano-oils seem very similar in terms of thermal conductivity and dynamic viscosity.

2.3 Experimental test rig

In order to test the synthesized nanolubricants, the experimental circuit shown in Figure 1 was built; the typical operating conditions of a heat pump system were carried out. The most important parts of the circuit were the rotary compressor, the concentric tube condenser, the thermostatic expansion valve and the concentric tube evaporator. Two see-through tubes made of polycarbonate for visual inspection were installed in order to visually observe the refrigerant and the dispersed nanoparticles flow. The two tubes were installed downstream of the condenser and downstream of the evaporator. All the necessary parameters to control the entire functioning of the system were acquired, as refrigerant flow rate, temperatures and pressures. In Figure 2, all the acquisition points are indicated. Water was involved as secondary fluid in both the heat exchangers; inlet temperature was controlled by means of two different thermostatic baths and flow rate was set through two pumps. Refrigerant and water temperatures were measured by means of thermoresistances Pt100; the total uncertainty includes the measurement uncertainty, the error in the acquisition of the digital multimeter and the data interpolation. An overall uncertainty of 0.07 ˚C was estimated for all the employed Pt100 sensors. Refrigerant pressures were acquired by means of piezoresistive transmitters; three different models with different precision were used: sensors supplied by Wika have a total percentage error equal to 0.75%, sensors supplied by Bell&Howel equal to 0.05% and sensors supplied by CEC Instrument equal to 0.036%. The total percentage error takes into account the non-linearity, non-repeatability, stability over time and the acquisition system accuracy. The water flow rates through the two heat exchangers were measured by means of two magnetic flow meters, with an uncertainty of 0.35%, as declared in the calibration certificate. A Coriolis mass flow meter, supplied by Emerson, was used for refrigerant flow rate measurement; as indicated by the calibration certificate, the overall uncertainty is 0.00000176 kg/s. Moreover, the ambient temperature and the temperature at the base and the head of the compressor were acquired by means of T type thermocouples provided by Tersid with a declared error of ±0.3˚C. The experimental data were acquired, elaborated and visualized in real time through a LabVIEW 12.0 dedicated software, in order to allow the immediate control of the system; refrigerant and water properties were calculated by means of Refprop 9.0 (Lemmon *et al*., 2010).

2.4 Experimental procedure

As first step, the rotary compressor (BEARS 39E073B), provided completely devoid of oil and internally cleaned, was filled with 180 cm^3 of POE oil and connected to the circuit, previously put under vacuum. Then, the system was connected to the refrigerant cylinder (1,1,1,2-tetrafluoroethane, R134a) to permit the charge of about 500 g. At the end of each test, the system was evacuated and cleaned. Then the compressor was substituted with a new one, filled with the nanolubricant; all the system was put under vacuum and then charged with the refrigerant again.

Figure 1. Experimental test rig.

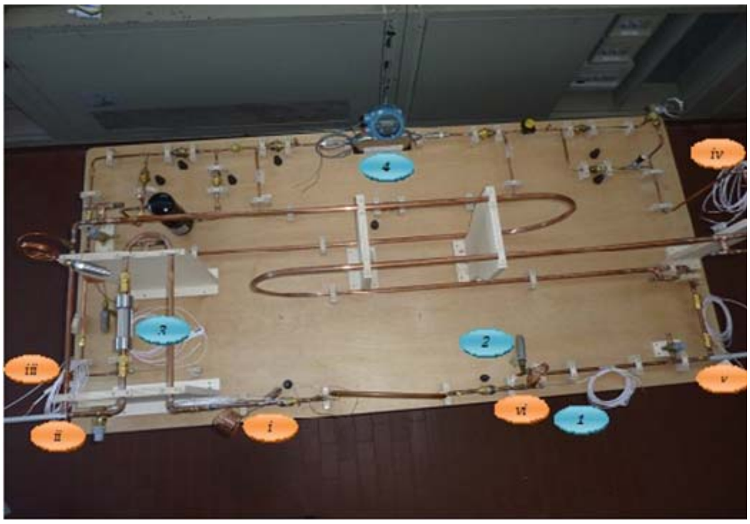

Figure 2. Employed sensors, as Pt100 Ω thermoresistances (1), pressure transducers (2), Coriolis mass flow meter (4). Polycarbonate tube for visual inspection is also shown in the figure (3). Different positions (i – vi) for the acquisition of temperature and pressure.

2.4.1 Experimental conditions

All the performed tests can be divided into three groups; different heat pump working conditions were in fact analysed. The boundary conditions had to be kept constant for the entire length of each test; the temperature and the flow rate of the water from the external thermostatic baths surrounding the heat exchangers were set in order to fix the evaporation and condensation temperatures. Depending on water conditions at the inlet of the evaporator and the condenser, the following three types of tests were performed:

- Test *A* represents the typical operating conditions of a heat pump system, *i.e.* condensation temperature equal to 60°C and evaporation temperature fixed at 20°C. The water conditions were 105 L/h for water flow rate and 40°C at the inlet of the evaporator and 115 L/h for water flow rate and 34.5°C at the condenser side.
- Test *B*. The condensation temperature was around 52.5°C and the evaporation around 19°C; all the other parameters were kept equal to Test *A*, except the water temperature surrounding the condenser fixed at 30°C.
- Test *C*. The condensing temperature was lowered to 50°C and the evaporation temperature at 10°C, just setting the water temperature at 32°C inlet to the condenser and 15°C inlet to the evaporator.

3. RESULTS AND DISCUSSION

3.1 Experimental results

Firstly, tests with pure POE oil were carried on, according to the three operative conditions described above.
180 cm^3 of POE oil were loaded into the compressor and the experimental obtained data were used as reference point for tests with nanofluids. The acquired data were used to calculate several parameters to evaluate the system performance, as:

- Superheating (SH);
- Subcooling (SC);
- Heat transferred through the condenser in both refrigerant (Q_{cond}) and water side (Q_{w_cond});
- Heat transferred through the evaporator in both refrigerant (Q_{evap}) and water side (Q_{w_evap})
- Heating (COP_H) and Cooling (COP_C) coefficient of performance;
- Compressor isentropic efficiency (η_{is});
- Compressor volumetric efficiency (η_{vol}).

Obtained results are summarized in Table 1, Table 2 and Table 3, according to selected test conditions. First of all, the POE oil with TiO_2 nanoparticles at a mass concentration of 0.1% was tested. Then, the nanolubricants with TiO_2 nanoparticles at 0.05% and 0.5% in mass and with SWCNH at 0.1 wt% were considered. Therefore, mineral oil was also kept into account as base fluid. As widely known, R134a is not miscible with mineral oil (MO). As proposed in Wang *et al.* (2003), MO was studied, initially without nanoparticles and then with TiO_2 nanoparticles at a mass concentration of 0.1%. For each nanolubricant and experimental condition, tests were repeated at least three times and were found to be repeatable in all cases, within the limits of the experimental errors.
As standard procedure, after tests with each nanofluid, the system was carefully cleaned and the compressor was sectioned to visually observe any possible deposition of nanoparticles inside it. The presence of nanoparticles was evident on the surface of the rotor, as shown in Figure 3. Moreover, the nanolubricant was extracted and analysed by means of DLS technique. It was observed that for each nanofluid, the nanoparticles dimensions remained constant before and after the tests.

3.2 Results discussion

Analysing the experimental results and the derived parameters, it seems that nanoparticles do not have any influence on system performances, in contrast with the literature reported above. In Tables 1, 2 and 3, the deviations between system parameters working with POE pure oil and with nanolubricants are also reported. They were calculated form Equation 1

$$deviation\% = \frac{data_{calculated} - data_{reference}}{data_{reference}} \cdot 100 \tag{1}$$

where “data” stands for the property indicated in the table. From these results, an appreciable performance increase was not found, if compared with the reference test carried out with pure POE oil; improvements were not obtained even when MO is used, pure or as base fluid mixed with TiO_2 nanoparticles.

Table 1. Experimental obtained results. Test *A*

TEST *A*	SH [°C]	SC [°C]	Q_{cond} [kW]	Q_{w_cond} [kW]	Q_{evap} [kW]	Q_{w_evap} [kW]	COP_H [-]	COP_C [-]	η_{is} [-]	η_{vol} [-]
POE										
Average values	6.10	3.62	1.37	1.33	1.12	1.17	3.95	3.23	0.74	0.86
Uncertainty %			0.12	0.91	0.10	1.07	1.31	1.52		
POE with TiO_2 0.1% wt										
Average values	5.22	3.66	1.38	1.34	1.12	1.17	3.97	3.23	0.73	0.86
Deviation %	-14.42	1.23	0.46	0.63	0.17	-0.29	0.50	0.20	-1.00	-0.25
POE with TiO_2 0.05% wt										
Average values	6.10	4.28	1.37	1.33	1.11	1.16	3.89	3.17	0.71	0.85
Deviation %	-0.04	18.29	-0.32	-0.34	-0.61	-0.80	-1.45	-1.72	-3.32	-1.33
POE with TiO_2 0.5% wt										
Average values	4.77	3.97	1.38	1.35	1.12	1.16	3.98	3.23	0.71	0.85
Deviation %	-21.78	9.70	1.00	1.41	0.22	-1.13	0.98	0.20	-3.76	-0.55
Mineral Oil										
Average values	5.87	3.79	1.29	1.26	1.04	1.07	3.74	3.00	0.70	0.85
Deviation %	-3.76	4.66	-5.89	-5.61	-7.63	-8.88	-5.33	-7.08	-5.11	-0.61
Mineral Oil withTiO_2 0.1%wt										
Average values	6.12	5.05	1.30	1.27	1.05	1.08	3.66	2.94	0.69	0.86
Deviation %	0.36	39.58	-4.89	-4.57	-6.69	-7.46	-7.16	-8.91	-5.80	0.38
POE with SWCNH 0.1%wt										
Average values	5.87	5.33	1.36	1.32	1.10	1.14	3.89	3.15	0.72	0.86
Deviation %	-3.78	47.27	-2.34	-2.21	-2.76	-2.74	-2.88	-3.29	-1.54	-0.03

Table 2. Experimental obtained results. Test *B*

TEST *B*	SH [°C]	SC [°C]	Q_{cond} [kW]	Q_{w_cond} [kW]	Q_{evap} [kW]	Q_{w_evap} [kW]	COP_H [-]	COP_C [-]	η_{is} [-]	η_{vol} [-]
POE										
Average values	4.53	4.70	1.45	1.42	1.22	1.26	4.84	4.07	0.73	0.89
Uncertainty %			0.11	0.84	0.10	0.99	1.46	1.64		
POE with TiO_2 0.1% wt										
Average values	3.80	4.68	1.46	1.43	1.22	1.26	4.85	4.06	0.71	0.89
Deviation %	-16.05	-0.43	0.52	0.65	0.08	-0.33	0.16	-0.27	-2.56	-0.33
POE with TiO_2 0.05% wt										
Average values	4.62	5.46	1.45	1.42	1.22	1.26	4.77	3.99	0.71	0.88
Deviation %	2.03	16.21	-0.29	-0.23	-0.59	-0.48	-1.63	-1.93	-3.06	-1.01
POE with TiO_2 0.5% wt										
Average values	5.01	5.20	1.46	1.43	1.23	1.25	4.83	4.07	0.71	0.89
Deviation %	10.78	10.66	0.23	0.46	0.51	-0.66	-0.31	-0.03	-2.69	-0.61
Mineral Oil										
Average values	6.07	5.80	1.35	1.33	1.12	1.13	4.43	3.66	0.67	0.88
Deviation %	34.19	23.56	-6.95	-6.45	-8.62	-10.20	-8.52	-10.16	-7.78	-1.60
Mineral Oil withTiO_2 0.1%wt										
Average values	6.22	7.12	1.39	1.36	1.15	1.17	4.35	3.60	0.67	0.88
Deviation %	37.54	51.60	-4.66	-3.93	-6.13	-7.29	-10.13	-11.52	-8.10	-0.90
POE with SWCNH 0.1%wt										
Average values	5.08	6.16	1.42	1.39	1.20	1.23	4.70	3.96	0.73	0.89
Deviation %	33.82	31.69	-2.99	-2.62	-2.38	-2.29	-3.05	-2.44	2.26	-0.12

Table 3. Experimental obtained results. Test *C*

TEST *C*	SH	SC	Q_{cond}	Q_{w_cond}	Q_{evap}	Q_{w_evap}	COP_H	COP_C	η_{is}	η_{vol}
	[°C]	[°C]	[kW]	[kW]	[kW]	[kW]	[-]	[-]	[-]	[-]
POE										
Average values	3.61	6.26	1.13	1.10	0.92	0.93	3.98	3.24	0.70	0.88
Uncertainty %			0.11	1.04	0.09	1.26	1.65	1.85		
POE with TiO_2 0.1% wt										
Average values	3.55	6.91	1.13	1.11	0.92	0.92	3.98	3.23	0.69	0.87
Deviation %	-1.57	10.45	0.16	0.43	-0.23	-0.61	0.14	-0.25	-2.31	-0.71
POE with TiO_2 0.05% wt										
Average values	4.19	7.77	1.12	1.09	0.92	0.92	3.92	3.19	0.70	0.87
Deviation %	16.29	24.13	-0.70	-0.79	-0.68	-0.40	-1.41	-1.40	-0.81	-0.98
POE with TiO_2 0.5% wt										
Average values	3.85	8.45	1.13	1.11	0.92	0.92	3.96	3.21	0.69	0.87
Deviation %	6.66	35.11	0.07	0.22	-0.28	-0.75	-0.42	-0.77	-1.18	-0.71
Mineral Oil										
Average values	5.32	7.15	1.04	1.01	0.82	0.81	3.64	2.87	0.66	0.86
Deviation %	47.60	14.29	-8.56	-8.30	-11.22	-11.99	-8.58	-11.24	-5.63	-1.73
Mineral Oil withTiO_2 0.1%wt										
Average values	5.47	8.81	1.03	1.01	0.82	0.82	3.52	2.78	0.66	0.87
Deviation %	51.75	40.83	-8.82	-8.44	-11.42	-11.45	-11.62	-14.13	-5.62	-0.93
POE with SWCNH 0.1%wt										
Average values	5.51	9.16	1.09	1.07	0.89	0.90	3.85	3.14	0.72	0.88
Deviation %	52.83	46.42	-3.34	-3.15	-2.98	-2.38	-3.32	-2.95	3.16	-0.30

Figure 3. Dissected rotary compressor after experiments.

For each experimental condition, results are very similar. For a better comprehension of obtained results, calculated COP is shown in Figure 4 for POE and MO pure oils and each tested nanolubricant according to Test *A*.

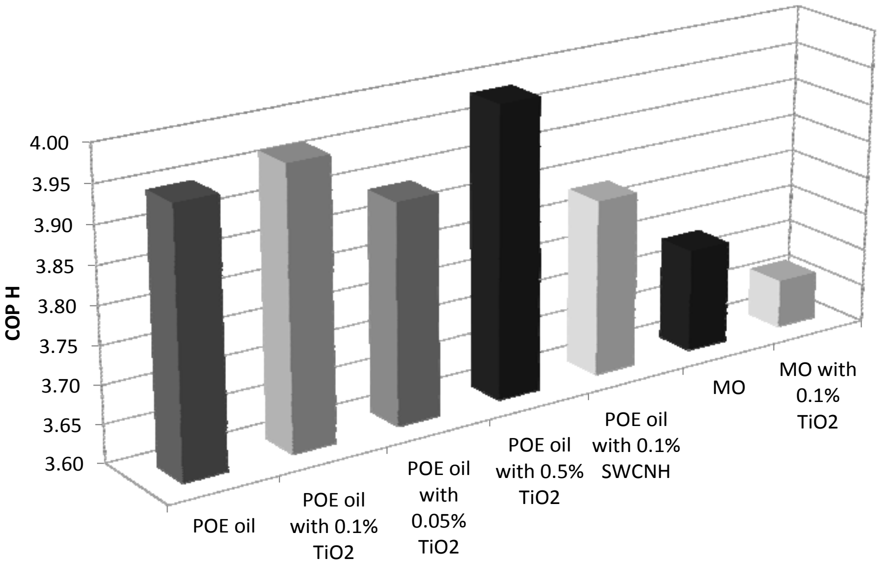

Figure 4. Comparison between COP obtained with different nanolubricant for the Test *A*.

Obtained results are in contrast with available scientific literature. Moreover, as it should be noted, using mineral oil COP decreases. Additionally, problems related to the type of used nanoparticles were excluded, since the system performance was studied using both TiO_2 and SWCNH nanoparticles, without any performance improvement.

4. CONCLUSIONS

In contrast with available literature, all the performed tests with nanolubricants did not show improvements in terms of compressor efficiency or heat transferred through the heat exchangers; consequently, system performances are comparable with the reference test carried out with pure POE oil. Tests repeatability was in all cases verified, within the experimental errors limits. Moreover, two different kinds of nanoparticles, TiO_2 and SWCNH, and two different base oils, POE and MO, were tested in order to rule out the possible influence of these parameters. Obtained results can lead thinking that the type of used compressor was not suitable for its use with nanolubricants; in fact, tests reported in available literature are usually carried out with reciprocating compressors instead of rotary models. Therefore, in future, it would be interesting to repeat the same tests, in the same working conditions, using a reciprocating compressor; a possible nanoparticles positive effect on the system performance could be obtained when a different type of compressor is involved.

NOMENCLATURE

COP	Coefficient of Performance	(-)
DLS	Dynamic Light Scattering	
HVACR	Heating Ventilation Air-Conditioning and Refrigeration	
MO	Mineral Oil	
Q	Capacity	(kW)
PAG	PolyAlkyleneGlycol	
POE	PolyOlEster	
SC	Subcooling	(˚C)
SH	Superheating	(˚C)
SWCNH	Single Wall Carbon Nano Horns	
η	Efficiency	(-)

Subscript

c	cooling
cond	condenser
evap	evaporator
h	heating
is	isentropic
vol	volumetric
w	water

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