Research Paper

Comparative study on AL₂O₃ nanoparticle addition on cool storage system performance

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HIGHLIGHTS

- An evaluation study to determine which is more beneficial to be used nanoparticle with PCM or with HTF.
- AL₂O₃ nanoparticle was added to ethylene glycol-water as a HTF with (0, 0.25, 0.5, 0.75 and 1%).
- Spherical capsule filled with pure water (PCM) was used on cool storage during charging process.
- The reduction in complete charging time was 20% for 0.75% and 1 % of nanoparticle volume fraction.
- Comparison shows that adding nanoparticle to PCM is more benefit than adding it to HTF.

ARTICLE INFO

ABSTRACT

Adding nanoparticles almost enhance the thermal transport properties in thermal storage system. Nanoparticles could be used in two manners, the first one with Phase Change Material (PCM) as a nucleation agent to help the fast formation of crystals in solidification process. The second manner with Heat Transfer Fluid (HTF) to enhance the rate of heat transfer through the heat transfer process. In the present study a comparison between adding Al₂O₃ nanoparticles to either distilled water as PCM, and to aqua ethylene glycol solution of 50% wt as a HTF on the performance of cool storage system.

A spherical capsule with 85% filling of its internal volume with PCM is used as a tested platform. A set of experiments to study the effect of adding Al₂O₃ nanoparticles to HTF at different volume fraction concentrations up to 1% for different HTF inlet temperature and volume flow rates on the solidified mass fraction, surface heat flux and complete solidification time, was performed. Comparing the present results with those for nanoparticles with PCM, it could be concluded that adding the nanoparticles to PCM alone is much beneficial to cool storage system than adding it to HTF alone.

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1. Introduction

With the rise of energy costs and increasing demand for renewable energy sources, the Thermal Energy Storage (TES) systems are becoming an interesting option and considered as a key component for any successful thermal system. Also the improved methods of storing energy will make it possible for intermittent sources provide power continuously. Therefore, the design and development of thermal energy storage systems are of vital importance.

With the nano technology development and effect of nanoparticles on the enhancement of the effective thermal conductivity which can be more beneficial and suitable for many applications such as heat exchanger and cool thermal storage systems. With this trend, there is a need to study the effect of shape,

size, type and concentration of nanoparticle which added to different base fluids (water or ethylene glycol). A nanoparticle with PCM enhances the thermal conductivity of PCM or increases nucleation agent and consequently fastest a process of solidification (charging) and melting (discharging) of PCM. A nano particle with HTF enhances the heat transfer coefficient from the energy source to energy storage part. Each one of the above techniques has an advantage and a disadvantage like sedimentation, forming collided and unexpected performance drop with long time use (especially for nano particle in PCM). In the following an experimental study to evaluate which trend has more effect on energy storage system performance.

The experiment that was performed by Kumaresan et al. [1] explored the effect of dispersing copper oxide nanoparticles as a nucleation agent for PCM on the solidification process. The experiments were conducted at different bath temperatures (–2 °C and –6 °C). The results showed that the addition of nanoparticles to PCM (NFPCM) exhibited a significant reduction about 35% of solidification time due to heat transport enhancement, which means operate

the evaporator of the chiller at high temperature, which result in energy saving.

Another experiment was performed by Kumaresan et al. [2] indicated that the presence of multi wall carbon nanotubes (MWCNT) acts as nucleation agent that caused an appreciable reduction in the cooling process. Also, they found that there is a possible energy saving potential of 6–9% in the CTES using the NFPCMs. Using (MWCNT) has a significant effect on time of charging process, which reduced by 14% and 20.1% when the surrounding HTF temperature was the –9 °C and –12 °C respectively. The experiment was performed using a volume fraction, 0.15%, 0.3%, 0.45%, and 0.6% with deionized water (DI) as a base for phase change material in the solidification process in a spherical container.

A suspended 0.1 wt. % multiwall carbon nanotubes (MWCNT) in deionized water (DI water) along with pseudomonas as a nucleation agent for cool thermal energy storage (CTES) system at different HTF surrounding temperature (–6, –9, –12 °C) had been used by Chandrasekaran et al. [3]. The results concluded that there is an enhanced heat transport properties of the NFPCM which belongs to elimination of under cooling and accelerating charging, which result in the operating chiller at higher temperatures which save energy consumed through the solidification process.

Copper particle of nanometer sized dispersed in ethylene glycol, which has a percentage increase in thermal storage about 40% when using 0.3% Cu nanoparticles with mean diameter, 10 nm, had been studied by Eastman et al. [4] through experimental work.

The effect of Al2Cu and Ag2Al nanoparticle size and volume fraction on the effective thermal conductivity of a solution of water and ethylene glycol as base nano fluid was discussed by M. Chopkar et al. [5]. The results showed a significant increase of the effective thermal conductivity up to 100% with only 1.5% by volume nanoparticles of 30–40 nm average diameters. Also the results indicated that thermal conductivity ratio, relative to that of base fluid increases non linear with the volume fraction increase and the decrease in the size/diameter ratio of nanoparticles.

Madhusree Kole et al. [6] studied the ZnO-ethylene glycol (EG) nano fluid, which was treated by sonication process (for a long time about 60 h). The results showed that a maximum thermal conductivity enhancement of ~40% (3.75 Vol% of ZnO) is obtained at 30 °C this means that high thermal conductivity enhancement of surfactant free ZnO–EG nano fluids prepared using long duration sonication processes may find potential applications as coolants.

The effect of adding TiO_2 nanoparticles in rod-shapes of Ø10 nm × 40 nm (diameter by length) and in spherical shapes of diameter Ø15 nm in deionized water were investigated experimentally by Murshed et al. [7]. The results showed that the thermal conductivity increased with an increase of particle volume fraction. The particle size and shape also have effects on this enhancement of thermal conductivity. For TiO_2 particles of Ø10 nm × 40 nm and Ø15 nm dimensions with maximum 5% volume fraction, the enhancement is observed to be nearly 33% and close to 30%, respectively over the base fluid.

Li and Peterson [8] also studied the effect of CuO and Al2O3, nanoparticles with area weighted diameter ratio of 29 and 36 nm, respectively dispersed in distilled water at 2%, 4%, 6%, and 10% volume fractions. The resulted suspensions were evaluated at temperatures ranging from 27.5 to 34.7 °C, they indicate that there is an increase in the effective thermal conductivity about 1.52 times with 6% volume fraction of CuO nanoparticles and 1.3 times with 10% volume fraction for Al2O3 nanoparticles compared with pure distilled water at a temperature of 34 °C.

The enhancement in thermal conductivity of the fluid (aqua mono ethylene glycol solution) due to the CuO nanoparticles, types of base fluids, sonication time and settlement time was discussed by Roohit Khedkar et al. [9]. The result indicated that the thermal conductivity increases with the increase of concentration and the sonication

process time also they found that lower base fluid viscosities are supposed to contribute greater enhancement.

The enhancement of the effective thermal conductivity by adding of Al_2O_3 and CuO in both water and ethylene glycol was experimentally investigated by Eastman et al. [10]. About 20% enhancement was found when 4% volume fraction of CuO was used in the ethylene glycol system. The increase in conductivity ratio of nano fluid systems that uses ethylene glycol as base fluid is always higher than those nano fluids that use water as a base fluid. For nano fluids using the same base liquid the increasing in conductivity ratio when using CuO as nano particle is always higher than that when using Al2O3 as a nano particle.

A cylindrical phase change storage tank linked to a solar powered heat pump system is investigated experimentally and theoretically [11]. A simulation model defining the transient behavior of the phase change unit was used. In the tank, the phase change material (PCM) is inside cylindrical tubes and the heat transfer fluid (HTF) flows parallel to it. The heat transfer problem of the model (treated as two dimensional) was solved numerically by enthalpy-based finite difference method and validated against experimental data.

In this work, the performance of a solar assisted cylindrical energy storage tank is investigated.

Theoretically a model describing the transient behavior of a phase change energy storage unit is used. The model of the tank holds the numerical description of a short term (by day) beat-storage tank ref. [12]. In the tank, the PCM is packed in cylinders, and the heat transfer fluid (HTF) flows parallel to it. The basis of the model is the enthalpy method. Results show that the PCM, cylinder radius, the mass flow rate, and the inlet temperature of the HTF must be chosen carefully in order to optimize the performance of the tank.

The results concluded that there is a significant effect of concentration and shape on the enhancing of thermal conductivity but most of them stated that there no effect or a slight effect of particle size. There are two techniques in using nano particle with thermal storage. First one is used it with PCM and second one is adding it to HTF.

It is clear from the above overview that nanoparticles could be utilized to enhance the heat transfer coefficient through enhancement of thermal conductivity of the used fluid or as nucleation enhancement agent for phase change materials. A serious question should be mentioned here. Which one – utilizing nanoparticles with PCM as (NFPCM) or utilizing it to enhance heat transfer coefficient for heat transfer fluids (HTF) – has the major real impact on cool system performance? Through the next study a set of experiments is performed to investigate the effect storage of HTF temperature, volume flow rate and effect of nanoparticles additive (with a different volume concentration of aluminum oxide (Al_2O_3) on complete charging time of the system, solidified mass fraction, and surface heat flux. This will help in deciding which one of previous mention techniques has more reliability to be used.

2. Experimental setup

The schematic diagram of the experimental test rig is shown in Fig. 1. The experiment consists of two loops, one for refrigerant and the other for ethylene glycol solution (water + ethylene glycol) which is considered as a heat transfer fluid, which is responsible about adding or removing heat from the PCM that is contained in the spherical capsule as a test section. The heat transfer fluid is a mixture of water and ethylene glycol with a concentration of 50% by weight to freezing point –25 °C.

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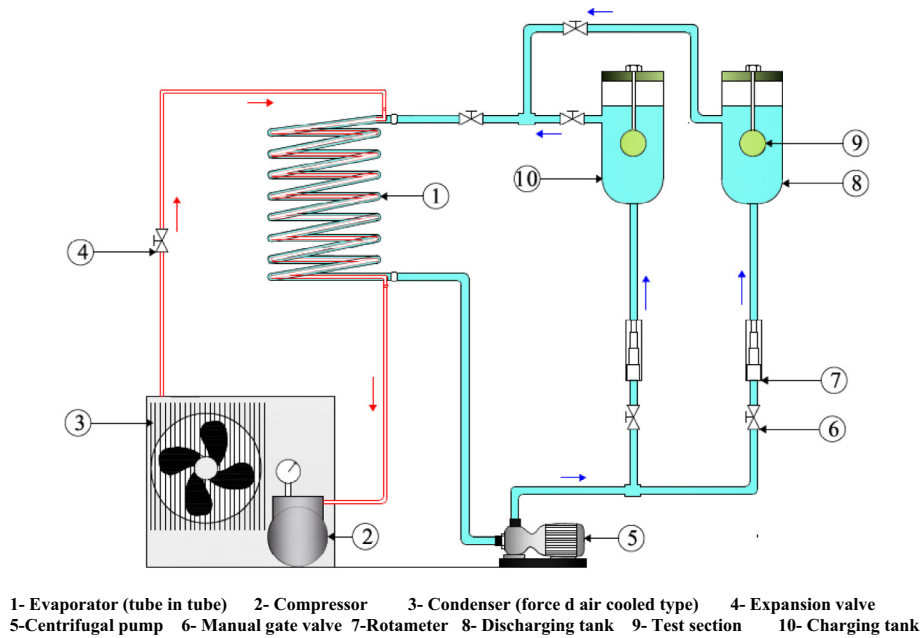
1- Evaporator (tube in tube)   2- Compressor   3- Condenser (force d air cooled type)   4- Expansion valve
5-Centrifugal pump   6- Manual gate valve 7-Rotameter 8- Discharging tank 9- Test section   10- Charging tank

Fig. 1. The schematic diagram of the experimental test rig.

spherical capsule as a test section. The heat transfer fluid is a mixture of water and ethylene glycol with a concentration of 50% by weight to freezing point –25 °C.

Two cylindrical tanks with end cap having dimensions of 200×900 mm, were used as charging and discharging processes. They are insulated by a 50 mm thickness thermal insulation to reduce the heat gain with the surrounding. Each one of them is filled with 0.027 m³ of the HTF. They are provided with inlet and outlet pipes including manual gate valves for the HTF circulation, with notes that the bottom was formed as a conical shape to ensure the overcoming of the sedimentary processes.

The cool thermal storage process is carried out using a spherical capsule (test section) charged with water as PCM material. The capsule is made of low-density polyethylene (LDPE) material with an outer diameter of 84 mm and thickness of 2 mm, and filled with 85% of its inner volume with a PCM to avoid damage of thermal expansion during the solidification process. Nine calibrated Copper-Constantan (T-type) thermocouples were employed to measure the temperature distribution with ±0.5 °C distributed on the horizontal and vertical axes of the spherical capsule at specified locations as shown in Fig. 2. The thermocouples are located at the intersection points of concentric circles with the vertical and half of the horizontal axes of spherical capsule. The center of concentric circles is located at the center of the spherical capsule where thermocouple no. 3 was placed. Thermocouple nos. 2, 7, 4 located at the intersection points of a circle with diameter 20 mm. Thermocouple nos. 8, 5 are located at the intersection points of a circle with diameter 40 mm except thermocouple no. 1 is little dropped to be assured that it is fully immersed in PCM. The circle with diameter 60 mm the third intersection point is located over the maximum level of PCM material so only two thermocouple nos. (6, 9) are located in this circle. For horizontal axis of capsule the symmetric configuration makes it possible to use one side of the intersection with circles.

To achieve the requirements of HTF outlet temperature for the charging and discharging process, a simple vapor-compression cycle (refrigeration unit) operate with R-404A was installed. It includes a hermetic compressor of 3 HP; air cooled condenser (forced type), filter, dryer, thermostatic expansion valve, and one ton refrigeration

evaporator (tube-in-tube type). A 1 HP centrifugal pump is used to circulate the HTF through the piping system to carry out the charging and discharging process of the experiments. The piping system and the manual gate valves are arranged to enable the pump to circulate the HTF through charging and discharging loops.

A data acquisition card (National Instruments, NI USB-6210, 32-inputs, resolution of 16-bit and scanning rate of 250 kS/s) and a laptop are used to record temperatures through aforementioned thermocouples. The HTF volume flow rate is monitored by using a calibrated Rotameter. A digital temperature controller (ELIWELL IC 901, 0.5% accuracy, and 1 °C set-point differential) is used to control
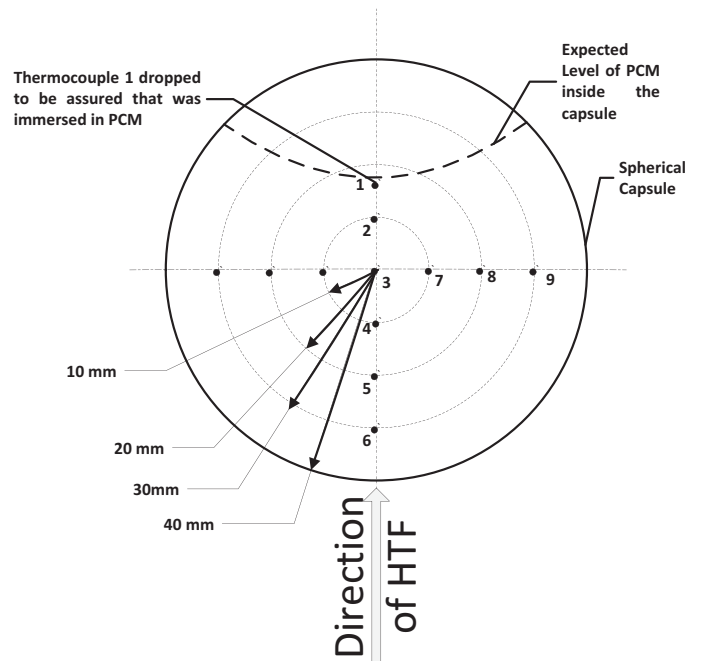

Fig. 2. Thermocouples distribution inside PCM Capsule.

Table 1
Experiment parameters.

HTF	Temperature (during charge process): –6, –8, –10, and –12°C
	Volume flow rates: 8.0, 10.0, and 12.0 LPM.
	(EG + water) + Nano (Al$_2$O$_3$) volume fractions (0.0%, 0.25%, 0.5%, 0.75% and 1%)

Table 2
Uncertainty of the measured quantities.

Parameter	Relative uncertainty
Encapsulated volume, (V$_o$)	±0.332%
Solidified mass fraction (m_s)	±1.12%
Surface heat flux(q$_{ins}$)	±1.9%
Latent heat(L.H)	±1.5%

Table 3
Properties of γ – Al$_2$O$_3$ nanoparticles.

Thermal conductivity (W/m.°C)	Density (kg/m^3)	Specific heat (J/kg.°C)
36	3600	773

The solidified mass fraction is calculated from

$$= m_s/(\rho_w * V_{PCM}) ---- \tag{4}$$

The PCM volume

$$V_{PCM} = 0.85 V_{capsule}(m^3) \tag{5}$$

Surface heat flux

$$q_{ins} = m_s * L.H/\Delta t\, (W/m^2) \tag{6}$$

2.2. Nano fluid preparation

The particles used in the nano fluid experiments are gamma-alumina (γ – Al$_2$O$_3$) nano powders, 50 nm average particle size with surface area > 200 m^2/g). The thermo physical properties of γ – Al$_2$O$_3$ nanoparticles are revealed in Table 3.

The γ – Al$_2$O$_3$/water nano fluid was prepared in this study with four different nanoparticles volume concentrations of 0.25, 0.5, 0.75 and 1.0%. The dispersion of particles in water was done in two step the first step is putting the mixture in ultra-sonication for 90 min in an EG bath temperature of 30 °C. The second steps to achieve good mixing for the nano fluid the mixture was pumped in the tube coil for six hours before beginning the experiments.

3. Result and discussion

The transient variation of the PCM capsule central temperature for different inlet HTNF temperature of (–6 and –12 °C) is represented at Figs. 3 and 4. A sharp temperature decrease reaching the phase change temperature of PCM (about 0 °C) within about 25 min is an indication that the conduction is the dominant mode of heat transfer at start of the process. This followed by a constant temperature zone (the longest period of the solidification process) indicating that the convection is the dominant heat transfer mode. Finally a sensible heat extraction below freezing which is characterized by sharp decrease in temperature started until the temperature of PCM has reached to the temperature of HTF. Also, it is indicated that the effect of nanoparticles volume fraction is significant in the latent heat extraction zone, but it is insignificant in the two other sensible heat zones.

Figure 5a,b shows the effect of adding nanoparticles having a volume fraction of 0.25, 0.5, 0.75 and 1% by volume to HTNF on complete charging time at a different volume flow rate and inlet temperature –6 °C and –12 °C for HTNF. It has been noticed that the complete charging time decreases with a nanoparticles concentration increase in all volume flow rates (12, 10 and 8 LPM) by about 18%, 17% and 19% when temperature for HTNF was –6 °C. This enhancement reaches to be about 18.5, 21.5 and 18% when temperature of HTNF was –12 °C. It is interesting to note that these reduction percentages occur at 0.75 % volume fraction with a little enhancement for 1% compared with volume fraction (0.25% and 0.5%). These reduction ratios in complete charging time are due to the enhancement of thermal properties and capacity of HTNF and these were referred by ref. [4–6] specially the enhancement of the effective thermal conductivity which yield in accelerating the freezing process. Finally the more increasing nanoparticles volume fraction means more enhancements in complete charging time of both temperatures of HTNF (–6 °C, –12 °C). The difference in percentage of
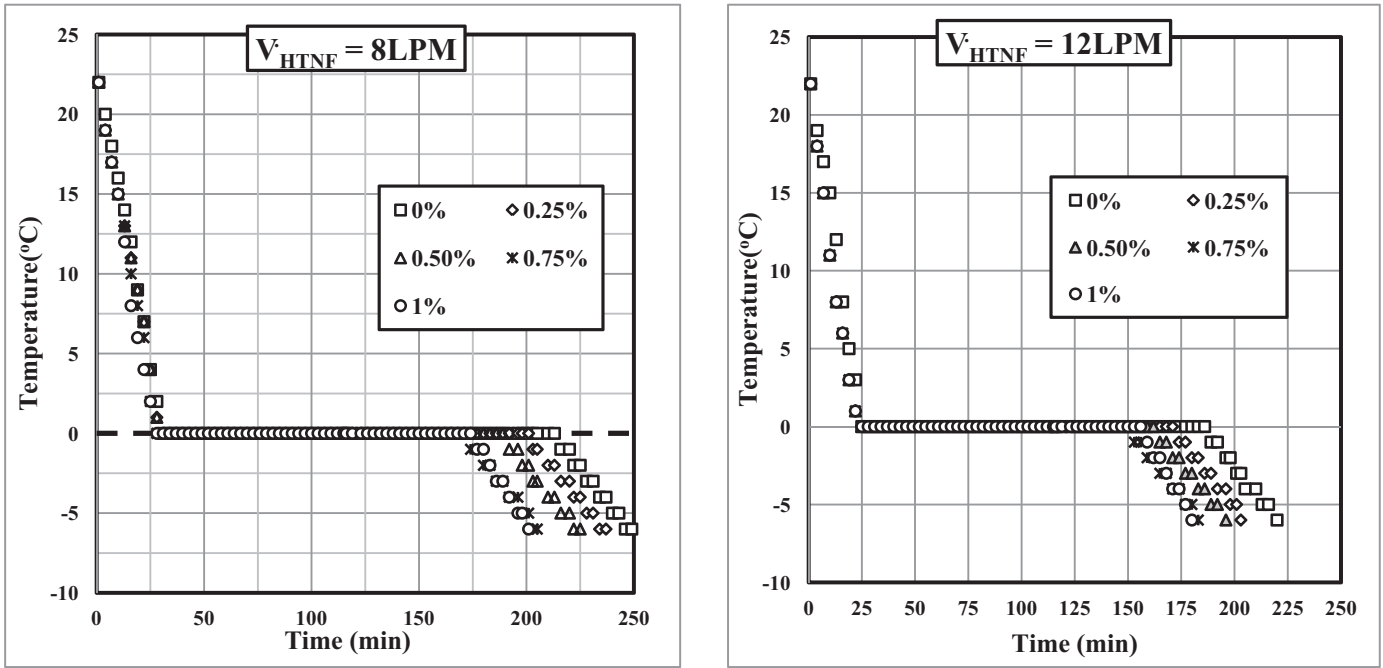
the required temperature inside the charging or discharging tank during the charging and discharging experiments. A series of charging experiments are performed under different operating condition. The parameters in the present study are listed in Table 1. Also Table 2 represents the experimental error analysis for the studied parameters).

At charging process, the manual gate valves incorporated with the piping system are positioned for the charging mode, and the refrigeration unit operates to cool the circulating HTF. The digital temperature controller set at one of the four test temperatures as listed in Table 1. The PCM temperature is maintained at 22 °C at an initial temperature for all charging experiments. Once the adjusted HTF temperature is reached, the volume flow rate of the HTF is set at one of the four volume flow rates listed in Table 1. Then the capsule is immersed and suspended by long screw bolt fixed at the center of the top end cap and two nuts which adjust the position of the capsule at the center of the tank, the measurements of the PCM temperatures inside the test capsule and the HTF temperatures around it were scanned and recorded every one second by the data acquisition system. The experiment is terminated when the temperature of the PCM inside the capsule starts to be equal to that of the HTF. This indicates that the water is completely frozen and the ice is being sensibly sub-cooled. The refrigeration unit and the pump are switched off, and the frozen test capsule is kept inside the charging tank to maintain its temperature until finishing the preparation of the discharging experiment (which will takes a few minutes).

The thermocouples were set in these specified places in the sphere capsule to indicate the temperature changes through the solidification process. This will make it useable to specify the solidification volume of PCM inside the capsule through the test and get r$_h$ and r$_v$ then get r$_{avgh,v}$ and finally get the solidified volume at any time through the experiment [5].

2.1. Data reduction

The output of data acquisition system for each experiment for different concentration of nanoparticle used with the following equations

$$V_s = \rho\left(\frac{\rho_w}{\rho_i}\right)(2/3)\pi\left(r_{in}^3 - r_{avgh,v}^3\right) + \pi h\left(r_{in}^2 - r_{avgh,v}^2\right)(m^3) \tag{1}$$

$$r_{avgh,v} = \frac{r_h + r_v}{2}(m) \tag{2}$$

The solidified mass is calculated as

$$m_s = \rho_i * V_s(kg) \tag{3}$$

Fig. 3. Transient temperature variation of PCM at center of capsule for different concentration of nano particle in HTNF at $T_{HTNF} = -6\,°C$ for different volume flow rate.

enhancement for nanoparticles volume fraction, 0.75% and 1%, is very small. This happened due to the concentration of nanoparticles volume fraction reach to saturation point of it's effect.

The complete charging time of NFPCM at HTNF temperature –6 °C and –12 °C at different HTNF volume flow rates (8, 10 and 12 LPM) is illustrated in Figs. 6 and 7 at the following three cases.

- The first case, pure water as a PCM, and an aqua ethylene glycol solution with nanoparticles 0% volume fraction, as a HTF. This case will be referred as (PCM (0%)).

- The second case uses pure water as a PCM, and an aqua ethylene glycol solution with Al_2O_3 nanoparticles with 1% volume fraction as a HTNF. This case will be referred as (HTNF 1%).

- The third case uses pure water with a 2% Al_2O_3 nanoparticles volume fraction as a NFPCM and an aqua ethylene glycol solution, with 0% nanoparticles volume fraction as a HTF. This case will be referred as (NFPCM (2%)).

As seen from figures and comparison it shows that using nanoparticles in NFPCM has a high effect on reduction the com-
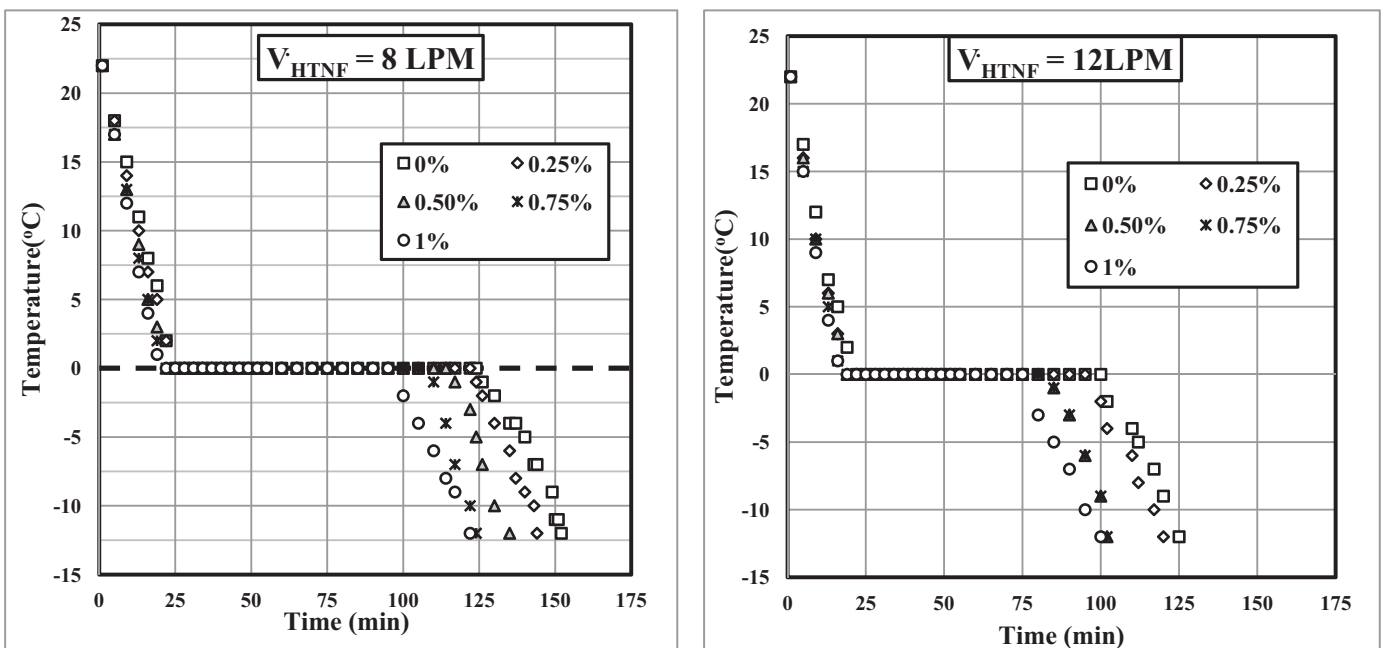

Fig. 4. Transient temperature variation of PCM at center of capsule for different concentration of nano particle in HTNF at $T_{HTNF} = -12\,°C$ for different volume flow rate.

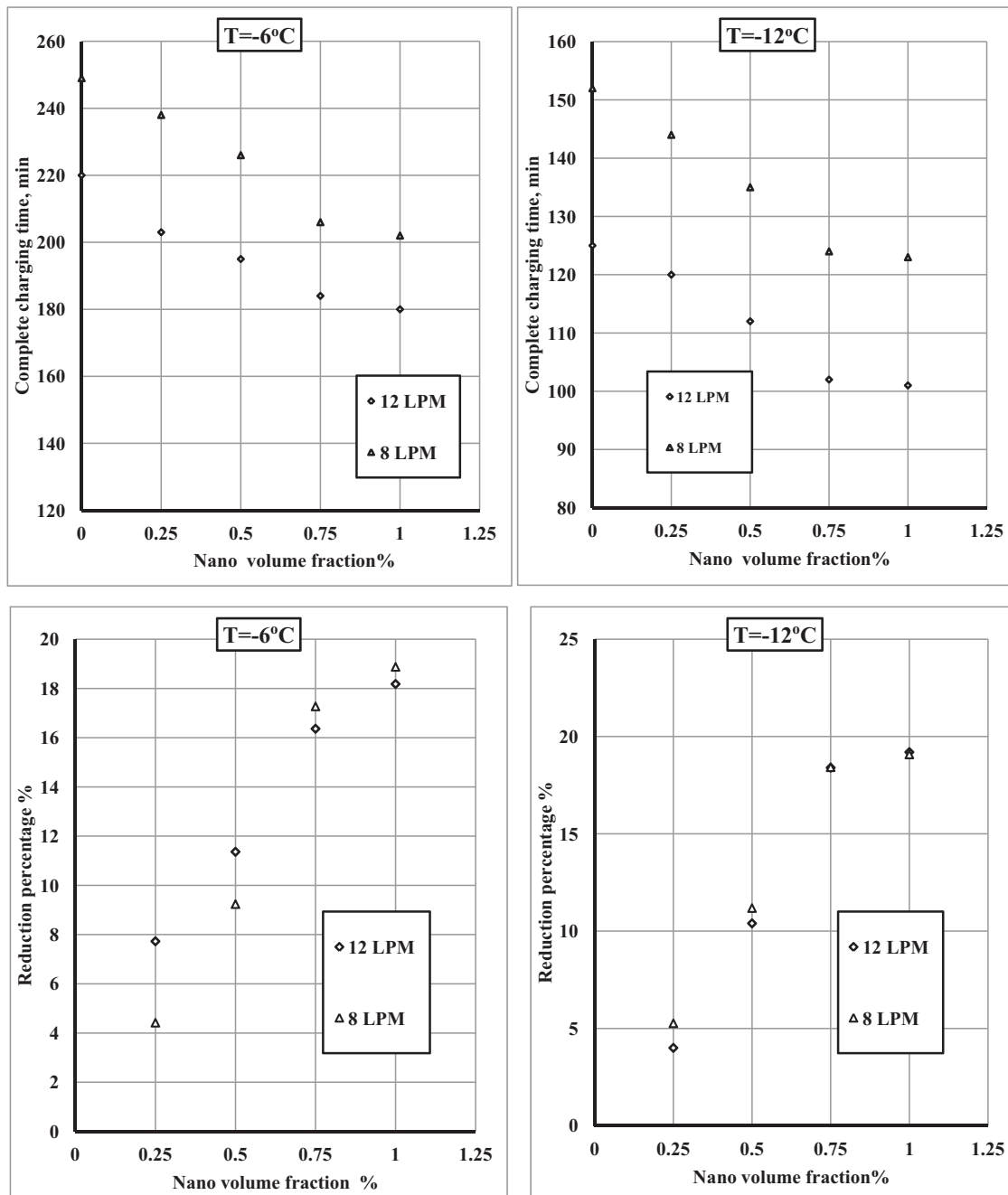**Fig. 5.** (a) Effect of nanoparticles concentration on the complete charging time for the different volume flow rate at (T $_{HTNF}$ = −6 °C) (T $_{HTNF}$ = −12 °C). (b) Effect of nanoparticles concentration on the reduction percentage in complete charging time for a different volume flow rate at (T $_{HTNF}$ = −6 °C) (T $_{HTNF}$ = −12 °C).

plete charging time than the case of no use nanoparticles in the cool storage systems. Adding nanoparticles on either PCM or HTF has a great effect on reducing complete charging time for the system. For the use of NFPCM (2%) has the same reduction percentage in complete charging time as HTNF (1%) this was at T$_{HTNF}$ = −6 °C, but at T$_{HTNF}$ = −12 °C the use of NFPCM (2%) has more effect in reducing complete charging time more than using HTNF (1%).

The solidified mass fraction given by Eq. (4) and capsule surface heat flux given by Eq. (6) variation with time is shown in Figs. 8 and 9 for the same previous three cases when HTNF inlet temperature −6 °C and −12 °C and for different volume flow rates of 8, 10, 12 LPM. It is clear from these figures that the increase in the nanoparticle volume fraction increases the solidified mass fraction of the all cases above through the charging process and the high mass solidified

fraction occurs at the lowest HTNF temperature. The surface heat flux expresses the variation of the rate of thermal energy stored. Using nanoparticles in phase change material (NPCM (2%)) gives better stored energy rate than other cases, as shown. So that using nanoparticles is recommended for cool storage system by adding it to the phase change material. The same conclusions and results could be deduced from the solidified mass fractions, which were presented in the same figures, where the NPCM (2%) has a faster rate than HTNF (1%).

4. Conclusion

From the above discussion and experimental results on the so-lidification behavior of pure water as PCM and HTNF (0.75%–1%
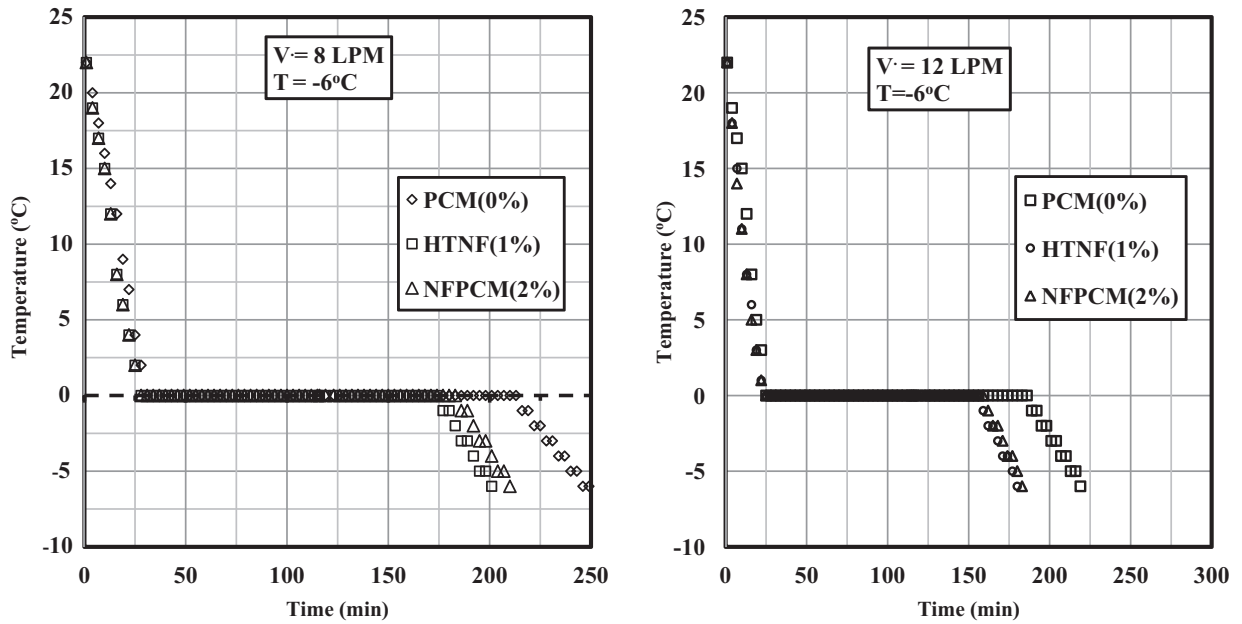
Fig. 6. Transient temperature variation of PCM at center of capsule (T_{HTNF} = –6 °C) for both pure HTF, HTNF with (1% by volume) and NFPCM with (2% Volume) nanoparticles [13].

nanoparticles concentration) with different inlet temperature and different volume flow rate it can be concluded that the complete freezing (solidification) time was reduced by approximately 18%, 17% and 19% when HTNF volume flow rate was 12, 10 and 8 LPM respectively, and HTNF inlet temperature was –6 °C while these reduction percentage was 18.5%, 21.5% and 18% for the same HTNF volume flow but HTNF inlet temperature was –12 °C.

With the increase of the nanoparticles volume fraction in HTNF the solidification process becomes faster due to the enhancement of thermal conductivity of HTNF which accelerate and increase the rate of forced convection heat transfer coefficient between HTNF

and PCM. Also, with the increase of the nanoparticle volume fraction in HTNF, the capsule surface heat flux increases, which can be applied in cool storage energy system that needs a short duration and higher heat flux.

From comparing present results with results from ref. [13] it could be concluded that adding nanoparticles to PCM has much benefit for the cool thermal storage system than using it with HTF. Also as a result of this comparison, it could be concluded that using nanoparticles on NFPCM and HTNF have high contribution in charging time reduction and performance of cool storage system and the combination of two techniques has a good effect on reduction process of charging time.
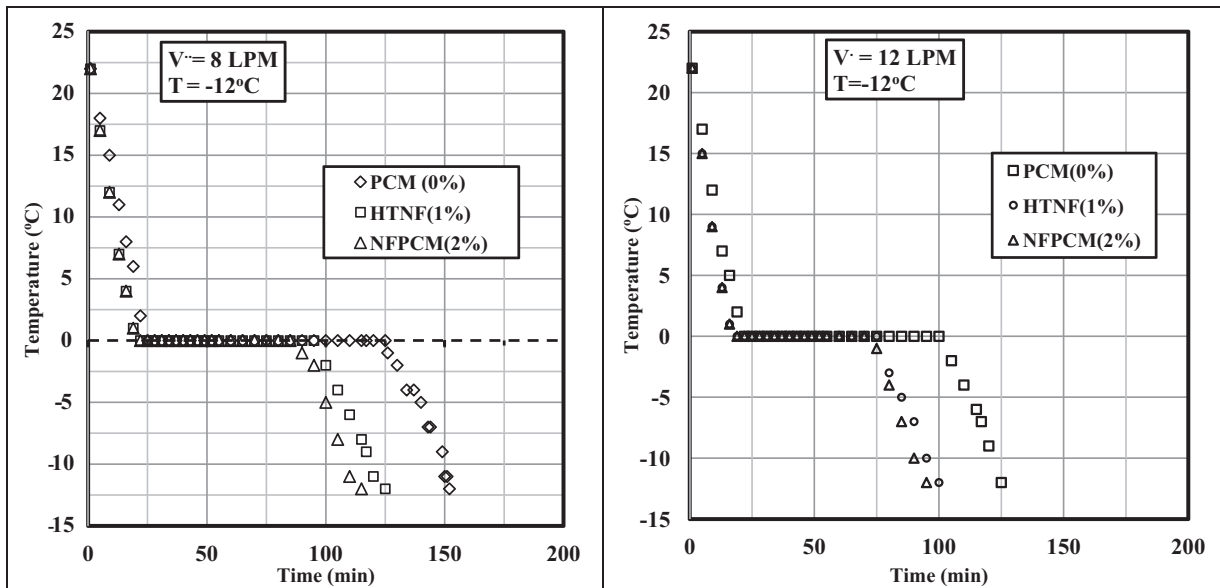

Fig. 7. Transient temperature variation of the PCM at the center of the capsule (T_{HTNF} = –12 °C) for both pure HTNF and HTNF with Nano fluid, PCM with (2% Volume) Nano particles [13].
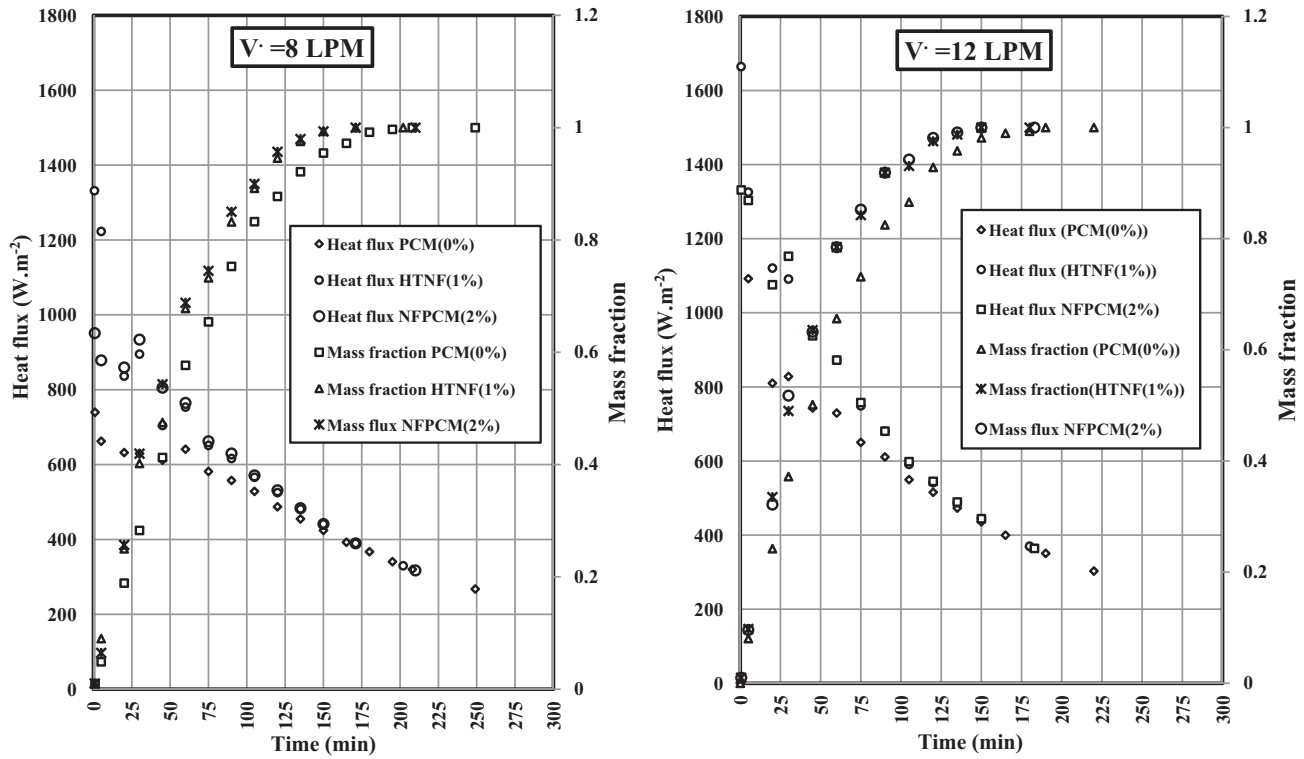
Fig. 8. Mass solidification fraction and surface heat flux during charging process for different HTNF volume flow rate and ($T_{HTNF} = -6$ °C).

Nomenclature

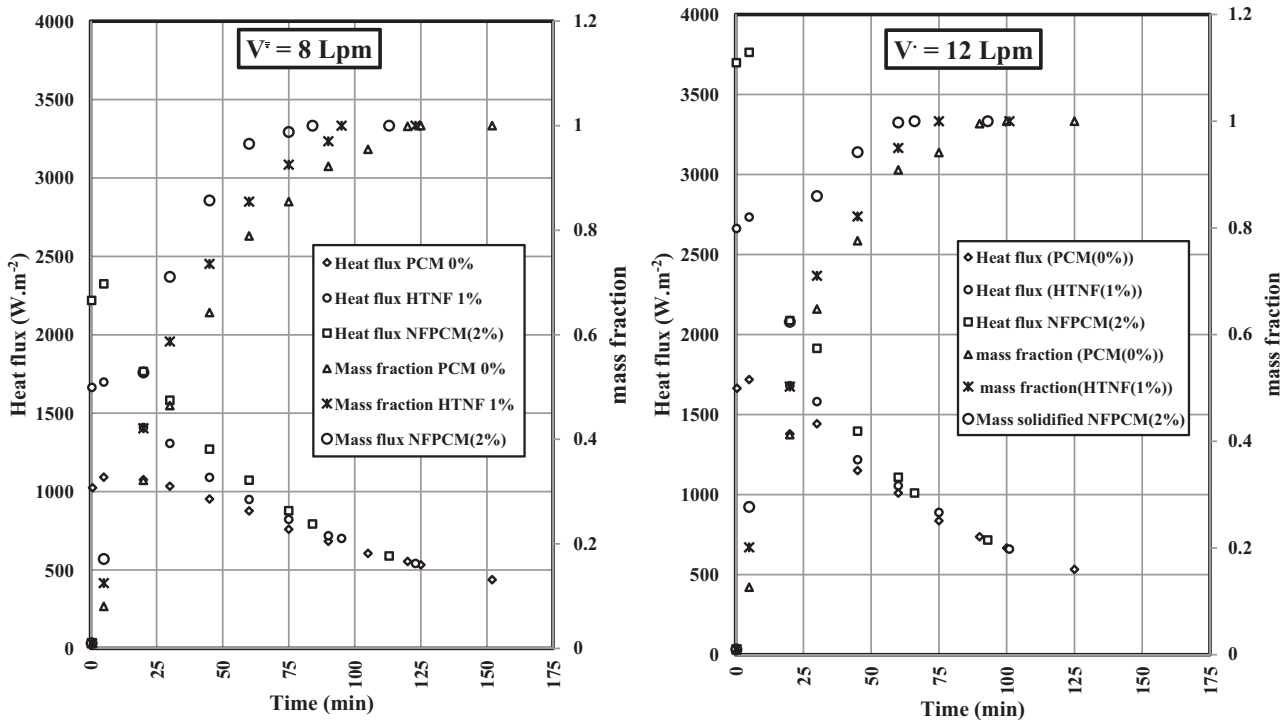|	
L.H.	Latent heat of fusion of water, KJ/kg.K
m_o	The mass of PCM encapsulated inside the spherical capsule, kg
m_s	Solidified mass, kg
m_s/m_o	Solidified mass fraction, _
q_{ins}	Instantaneously surface heat flux
$r_{avg_{h,v}}$	Average radius of solid–liquid interface in test capsule, m

Fig. 9. Mass solidification fraction and surface heat flux during charging process for different HTNF volume flow rate and ($T_{HTNF} = -12$ °C).

r_h	Horizontal radius of solid–liquid interface in test capsule, m
r_{in}	Inside radius of test capsule, m
r_v	Vertical radius of solid–liquid interface in test capsule, m
h	Vertical distance, measured from the center of the spherical capsule to the free surface of the encapsulated PCM, m
t	Time, min
Δt	Time interval, s
V_s	Solidified volume, m^3
V_{PCM}	Spherical shell volume, m^3
$V_{capsule}$	The internal volume of the capsule m^3
$V^{\cdot}$	Actual HTF volume flow rate, LPM

Greek symbols

ρ_w	Water density, kg/m^3
ρ_i	Ice density, kg/m^3
ρ	Volume correction factor

Abbreviations

PCM	Phase change material
HTF	Heat transfer fluid
HTNF	Heat transfer nano fluid
NFPCM	Nano fluid phase change material
CTES	Cool thermal energy storage
MWCNT	Multi wall carbon nanotubes
DI	De-ionized
LDPE	Low density polyethylene
AL_2O_3	Aluminum oxide
LPM	Liter per minute
Cu O	Copper oxide
ZnO	Zinc oxide
TiO_2	Titanium oxide
Al_2Cu	Aluminum, copper
Ag_2Al	Silver alumina
EG	Ethylene glycol
wt	weight

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