

Influence of Surfactant on Supercooling Degree of Aqueous Titania Nanofluids in Energy Storage Systems

Hoda Aslani, Mohammad Moghiman, Mohammad Aslani

Abstract—Considering the demand to reduce global warming potential and importance of solidification in various applications, there is an increasing interest in energy storage systems to find the efficient phase change materials. Therefore, this paper presents an experimental study and comparison on the potential of titania nanofluids with and without surfactant for cooling energy storage systems. A designed cooling generation device based on compression refrigeration cycle is used to explore nanofluids solidification characteristics. In this work, titania nanoparticles of 0.01, 0.02 and 0.04 wt.% are dispersed in deionized water as base fluid. Measurement of phase change parameters of nanofluids illustrates that the addition of polyvinylpyrrolidone (PVP) as surfactant to titania nanofluids advances the onset nucleation time and leads to lower solidification time. Also, the experimental results show that only adding 0.02 wt.% titania nanoparticles, especially in the case of nanofluids with a surfactant, can evidently reduce the supercooling degree by nearly 70%. Hence, it is concluded that there is a great energy saving potential in the energy storage systems using titania nanofluid with PVP.

Keywords—Cooling energy storage, nanofluid, PVP, solidification, titania.

I. INTRODUCTION

COOLING energy storage systems are applicable to retrieve energy in order to bridge time gap between energy demand and supply. There are two types of cooling energy storage systems; sensible and latent heat. Latent heat storage systems possess higher capability to store and release energy in comparison with sensible heat storage. The phase change materials due to high storage density, small temperature span and low cost are used in latent heat storage systems. [1]-[4]. The ability of phase change material to store/release latent heat is an important parameter in storage applications. As the large thermal resistance within phase change materials limits the thermal response, the serious points in phase change materials are the improvement of their low thermal conductivity and prevention of the occurrence of supercooling phenomenon [5].

While supercooling is lower, the evaporator operating temperature is higher and more energy is saved. Supercooling degree is defined as the difference between the phase change

temperature and nucleation temperature [6]:

$$SD = T_{PH} - T_N \quad (1)$$

where SD is supercooling degree, T_{PH} denotes phase change temperature and T_N refers to nucleation temperature. [6].

Nowadays, due to development of nanotechnology, many researchers have investigated the solid-liquid transitions of phase change materials at the presence of various nanoparticles; because metal oxide nanoparticles are capable to enhance the thermal conductivity of base fluid. Enhancement of thermal conductivity of nanofluids as phase change materials depends on size, shape and also concentration of nanoparticle [7].

Investigating of solidification characteristics of nanofluid phase change materials, Liu et al. [2] studied the supercooling degree of water-based graphene oxide nanofluids. Their results showed that the supercooling degree can evidently reduce. Also, they claimed that graphene oxide nanofluids have potential to be used as phase change material in energy storage applications. Fan et al. [1] experimentally investigated the solidification behavior of aqueous nanofluids in the presence of carbon nanotubes and graphene nanoplatelets. They concluded that loading of nanoparticles leads to a reduction of supercooling degree and acceleration of solidification process. Kumaresan et al. [3] performed the experiments of multi wall carbon nanotubes, they found that the multi wall carbon nanotubes acted as nucleating agent and caused considerable reduction in supercooling. Chandrasekaran et al. [8] prepared CuO-H₂O nanofluids and found a significant reduction in solidification time. Teng [9], Wu et al. [10] and Altohamy et al. [11] used alumina nanoparticles in deionized water as a base fluid to investigate the phase change properties of aqueous nanofluids. Their results showed that the presence of alumina nanoparticles affects the thermal properties, reduces the supercooling degree and freezing time and advances the beginning freezing time. Mo et al. [12] studied the effects of titania nanoparticles and sample containers on crystallization supercooling degree of nanofluids. They discovered that the addition of titania nanoparticles decreases the supercooling degree of water. Also their results showed that higher roughness of plastic surface leads to lower supercooling degree in plastic test tube compared to glass one.

As can be seen, there are few investigations focusing on the solidification behavior of nanofluids. In an effort to extend

H. Alani and M. Moghiman are with the Mechanical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran (phone: +985138805091; e-mail: aslani_hoda@yahoo.co.in, moghiman@um.ac.ir).

M. Alani is with the Mechanical Engineering Department, Quchan University of Technology, Quchan, Iran (phone: +985147344001; e-mail: m.aslani1994@yahoo.com).

solidification data of nanofluids, the effects of PVP as surfactant on solidification behavior of aqueous titania nanofluids was experimentally investigated in this paper. Also the comprehensive comparison of supercooling degree between titania nanofluids with and without surfactant was performed.

II. EXPERIMENTAL MEASUREMENTS

A. Nanofluid Preparation

In the present investigation, two-step method for preparing nanofluids is used. In this method, nanoparticles are produced as dry powders and dispersed into the base fluid in the second processing step, through sonication in an ultrasonic processor. PVP as surfactant is added to mixture to reduce particle agglomeration and to increase stability of suspension; also sonication is used to properly disperse nanoparticles in base fluid [13].

In this experimental investigation, spherical shape titania nanoparticle with an average diameter of 20 nm was procured from US Research Nanomaterials, Inc., USA. Fig. 1 shows the SEM image of titania nanoparticles. Experimental measurements are performed for titania nanofluids with mass concentrations of 0.01, 0.02 and 0.04 wt. % with and without PVP.

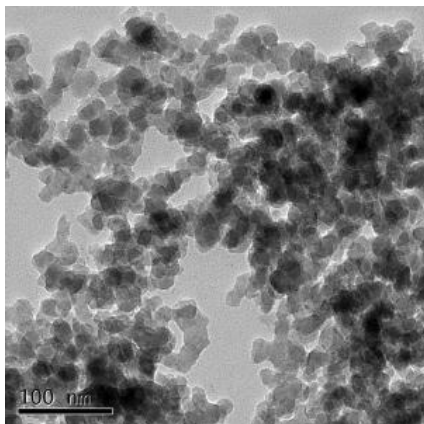


Fig. 1 SEM image of titania [14]

B. Experimental Apparatus and Procedure

Fig. 2 shows the experimental apparatus to measure the solidification behavior of titania nanofluids. This setup consists of a cooling system based on compression refrigeration cycle, thermally insulated tank, K-type thermocouple and data logger. Insulated tank of 10 Liter capacity was filled with a mixture of 25% ethylene glycol and 75% water by volume (phase change temperature of -12°C). A K-type thermocouple with an accuracy of $\pm 0.01^{\circ}\text{C}$ was implemented to control the temperature of ethylene glycol-water mixture to be at -12°C . A cylindrical polyethylene test section (80 mm in diameter and 200 mm in volume) placed at insulated tank, was used to study nanofluid solidification behavior. To continuously monitor the temperature variation of the nanofluid (every 1 min.), K-type thermocouple with an

accuracy of $\pm 0.01^{\circ}\text{C}$ was located at the center of test section. Prior to performing the experiments, measuring instruments had been calibrated and the experiments were repeated three times. The uncertainty of nanofluid temperature and mass was estimated to be 4% and 0.1%, respectively.

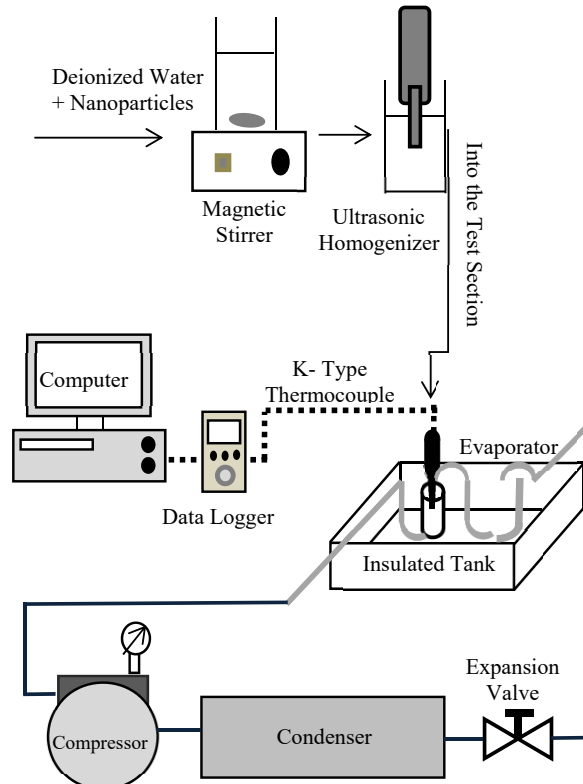


Fig. 2 Schematic diagram of the experimental setup

III. RESULTS AND DISCUSSION

The experimental comparison of solidification behavior between aqueous titania nanofluids with and without PVP as surfactant is presented at this section.

The solidification time of titania nanofluids with and without surfactant is shown in Fig. 3. The experimental results show that an increase in concentration of nanoparticles reduces the solidification time of both titania nanofluids with and without surfactant. It is due to the fact that titania nanoparticles in base fluid have tendency to enhance thermal conductivity of nanofluids [15] and higher thermal conductivity at a constant cooling rate accelerates nucleation and solidification time. Therefore, nanoparticles reduce the phase transition time by improving thermophysical properties of base fluid. The results of Fig. 3 demonstrate that the effect of nanoparticle concentration on solidification time of nanofluids without surfactant is more evident than that of with surfactant. Also, the increase in nanoparticle concentration illustrates a nonlinear reduction behavior at solidification time of nanofluid without PVP and a near linear reduction in the case of with PVP. It is observed that the solidification time difference between nanofluids with and without PVP becomes

negligible along with enhanced concentration.

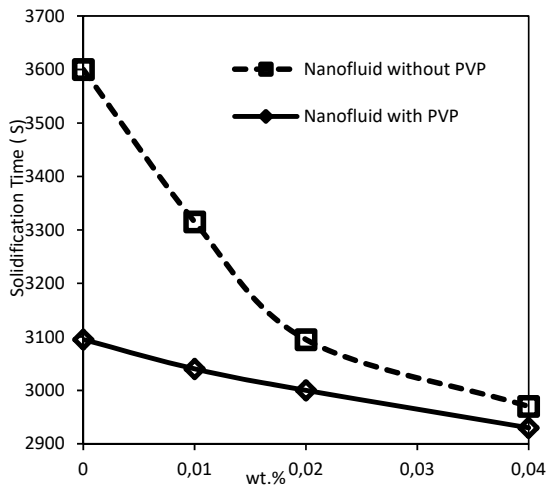


Fig. 3 Solidification time of titania nanofluid (with and without PVP) at various nanoparticle concentrations

The effect of PVP presence on the onset nucleation time of titania nanofluids at various nanoparticle concentrations is observed in Fig. 4. The results show the obvious difference between deionized water and deionized water + PVP. It is noticed that adding nanoparticles to base fluid leads to advance in onset nucleation time. Loading of 0.01 wt. % nanoparticles presents a considerable reduction in the onset nucleation time especially in the case of nanofluid without surfactant. This occurs because the presence of even low concentration of nanoparticles makes preferential sites for nucleation and impurity is an important parameter in nucleation progress. Also, from the results of Fig. 4, it is revealed that at nanoparticle concentrations higher than 0.01%, the effect of surfactant presence on onset nucleation time becomes negligible; because loading more concentrations of nanoparticles leads to hinder growth of nuclei.

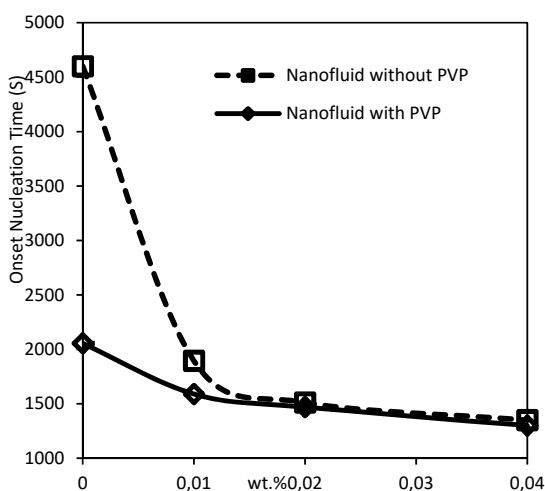


Fig. 4 Comparison of onset nucleation time between titania nanofluids with and without PVP

Fig. 5 compares the supercooling degree between titania nanofluids with and without PVP at different nanoparticle concentrations. The results of two types of nanofluids demonstrate that an increase in nanoparticles concentration reduces the supercooling degree due to the modified thermophysical properties of nanofluids and nucleating agent of nanoparticles. Also, both nanofluids are found to follow the same trend. As can be seen, the results confirm that the presence of surfactant leads to lower supercooling degree at different nanoparticle concentrations.

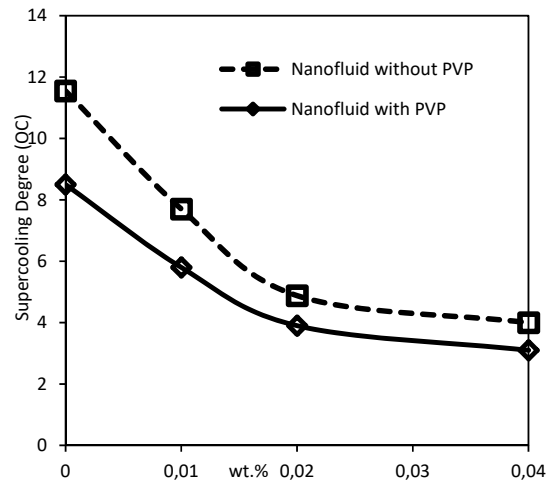


Fig. 5 Supercooling degree of titania nanofluids with and without PVP at different nanoparticle concentrations

Due to importance of supercooling degree in efficiency of energy storage systems, the results of supercooling degree reduction at different nanoparticle concentrations are presented in Fig. 6. It can be seen that the curves of reduction in supercooling degree for both nanofluids sharply increases at lower concentrations of nanoparticles (< 0.02%) and slightly increases at higher concentrations of nanoparticles. The results proved that titania nanoparticle concentration of 0.02 wt.% is optimum due to the value of supercooling degree reduction. Fig. 6 shows that for 0.02 wt.% concentration of titania nanoparticle, reduction in supercooling degree is only about 58% in the case of nanofluid without surfactant whereas the reduction in supercooling degree in nanofluid with surfactant is 70%.

TABLE I
COMPARISON OF SOLIDIFICATION PARAMETERS OF TITANIA NANOFUIDS (0.01 WT.%) WITH AND WITHOUT SURFACTANT

	With surfactant	Without surfactant	Difference (%)
Solidification time (S)	3050	3330	8
Onset nucleation time (S)	1600	1800	11
Supercooling degree (°C)	6	8	25

Table I provides a quick glance comparison of basic solidification parameters of titania nanofluids with and without PVP in nanoparticle concentration of 0.01 wt.%. The

presented data revealed that the supercooling degree in comparison with other investigated parameters (given in Table I) is highly dependent on surfactant.

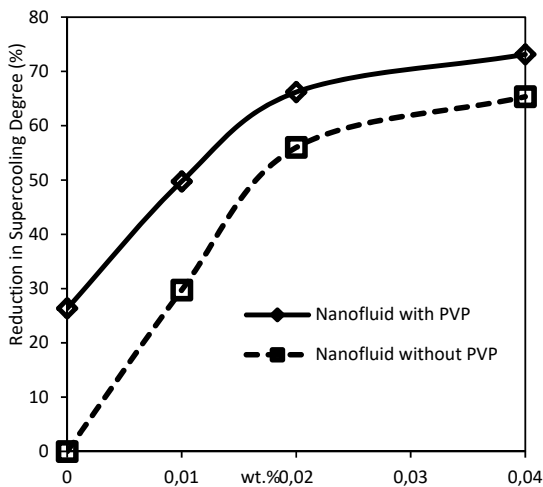


Fig. 6 Reduction in supercooling degree of titania nanofluids with and without PVP

IV. CONCLUSION

Experiments were performed to investigate the solidification behavior of titania nanofluids with PVP in comparison with that of without PVP. The major findings of this study are as follows:

- The presence of surfactant leads to reduction in solidification time of titania nanofluids.
- Adding only 0.01 wt.% titania nanoparticle to base fluid sharply decreases the onset nucleation time.
- As surfactant is added to nanofluid, the supercooling degree decreases.
- An increase in nanoparticle concentration reduces the supercooling degree of titania nanofluids.
- Titania nanoparticle concentration of 0.02 wt.% is optimum concentration due to the value of supercooling degree reduction.

ACKNOWLEDGMENT

The authors gratefully acknowledge the financial support from the Ferdowsi University of Mashhad and Iranian Nanotechnology Initiative Council.

REFERENCES

- [1] L. W. Fan, X. L. Yao, X. Wang, Y. Y. Wu, X. L. Liu, X. Xu, and Z. T. Yu, "Non-isothermal crystallization of aqueous nanofluids with high aspect-ratio carbon nano-additives for cold thermal energy storage," *Applied Energy* vol. 138, pp. 193–201, 2015.
- [2] Y. Liu, X. Li, P. Hu, and G. A. Hu, "Study on the supercooling degree and nucleation behavior of water-based graphene oxide nanofluids PCM," *International Journal of Refrigeration*, vol. 50, pp. 80–86, 2015.
- [3] V. Kumaresan, P. Chandrasekaran, M. Nanda, A. K. Maini, and R. Velraj, "Role of PCM based nanofluids for energy efficient cool thermal storage system," *International Journal of Refrigeration*, vol. 36, no. 6, pp. 1641–1647, 2013.
- [4] H. Zohoor and Z. M. Moosavi, "Increase in solar thermal energy storage by using a hybrid energy storage system," *WASET International Journal of Physical and Mathematical Sciences*, vol. 2, no. 7, pp. 403–408, 2008.
- [5] Y. Zeng, L. W. Fan, Y. Q. Xiao, Z. T. Yu, and K. F. Cen, "An experimental investigation of melting of nanoparticle-enhanced phase change materials (NePCMs) in a bottom-heated vertical cylindrical cavity," *International Journal of Heat and Mass Transfer*, vol. 66, pp. 111–117, 2013.
- [6] H. Aslani and M. Moghiman, "Experimental study on the effect of zirconia nanoparticles on solidification heat transfer characteristics: A comparison with titania nanoparticles," *International Journal of Refrigeration*, vol. 89, pp. 40–50, 2018.
- [7] S. Harikrishnan, M. Deenadhayalan, and S. Kalaiselvam, "Experimental investigation of solidification and melting characteristics of composite PCMs for building heating application," *Energy Conversion and Management*, vol. 86, pp. 864–872, 2014.
- [8] P. Chandrasekaran, M. Cheralathan, V. Kumaresan, and R. Velraj, "Enhanced heat transfer characteristics of water based copper oxide nanofluid PCM (phase change material) in a spherical capsule during solidification for energy efficient cool thermal storage system," *Energy*, vol. 72, pp. 636–642, 2014.
- [9] T. P. Teng, "Thermal conductivity and phase change properties of aqueous alumina nanofluid," *Energy Conversion and Management*, vol. 67, pp. 369–375, 2013.
- [10] Sh. Wu, D. Zhu, X. Li, H. Li, and J. Lei, "Thermal energy storage behavior of $\text{Al}_2\text{O}_3\text{-H}_2\text{O}$ nanofluids," *Thermochim Acta*, vol. 483, no. 1, pp. 73–77, 2009.
- [11] A. A. Altohamy, M.F. Abd Rabbo, R. Y. Sakr, and A. A. Attia, "Effect of water based Al_2O_3 nanoparticle PCM on cool storage performance," *Applied Thermal Engineering*, vol. 84, pp. 331–338, 2015.
- [12] S. Mo, Y. Chen, Z. h. Cheng, L. Jia, X. Luo, X. Shao, X. Yuan, and G. Lin, "Effects of nanoparticles and sample containers on crystallization supercooling degree of nanofluids," *Thermochim Acta*, vol. 605 pp. 1–7, 2015.
- [13] M. Moghiman and B. H. Aslani, "Influence of nanoparticles on reducing and enhancing evaporation mass transfer and its efficiency," *International Journal of Heat and Mass Transfer*, vol. 61, pp. 114–118, 2013.
- [14] US Research Nanomaterials, Inc., USA, <https://www.us-nano.com/inc/sdetail/484>; 2018 (accessed 13 March 2018).
- [15] W. H. Azmi, K.V. Sharma, R. Mamat, G. Najafi, and M. S. Mohamad, "The enhancement of effective thermal conductivity and effective dynamic viscosity of nanofluids – A review," *Renewable and Sustainable Energy Reviews*, vol. 53, pp. 1046–1058, 2016.