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RESEARCH

Thermocapillary Convection of Evaporating Thin Nanofluid Layer in a Rectangular Cavity

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Abstract
Thermocapillary convection of nanofluid with evaporating phase change interface occurs in a variety of industrial processes such as micro/nano fabrication, ink-jet printing, thin film coatings, etc. Previous studies have mostly focused on the phenomena of thermocapillary convection in pure fluids without phase change. This paper reports the first fundamental experimental work on the thermocapillary flow of a thin nanofluid layer under the effect of evaporation. This research focuses on the behavior of a volatile thin nanofluid layer in a rectangular test cell under the effects of horizontal temperature gradient. The buoyancy effect can be neglected inside this thin liquid layer as in microgravity conditions. HEE7200 and HFE7200-Al_2O_3 nanofluid are used as working fluids to analyze the effect of nanoparticle addition. The results indicate that the linear relationship between the thickness of the liquid layer and the duration of evaporation is not changed by nanoparticles. HFE7200-Al_2O_3 nanofluid always has a higher evaporation rate than its base fluid with the temperature ranging from 2.98 °C to 13.92 °C. The critical Marangoni number for the nanofluid is lower than that of the pure fluid, which indicates that the addition of nanoparticles promotes the flow pattern transition.

Keywords Thermocapillary flow · Evaporation rate · Flow pattern transition · Nanofluid

Introduction

Thermocapillary convection is driven by local variations of surface tension when the temperature gradient is applied to the free surface. Thermocapillary convection has received considerable attention in recent years since it plays a key role in a variety of industrial processes such as crystal growth (Li et al. 2018), thin film coating (Haas and Birnie 2002), laser welding (Li et al. 2022), cooling of electronic devices (Nithyadevi et al. 2015), glass manufacturing and some chemical processing (Dhavaleswarapu et al. 2007). Initially, researchers conducted extensive research on the stability of thermocapillary convection without phase change interfaces (Hossain et al. 2005; Shevtsova et al. 2003; Pelacho and Burguete 1999; Riley and Neitzel 1998; Liu et al. 2004). One of the most important research content and goals is to control the flow pattern transition. With the deepening of scientific research, there has been growing interest in the more complicated physical phenomenon of thermocapillary convection with evaporating interface due to the important effects of evaporation on the above-mentioned applications. Especially when the gravity effect weakens and the interface effect becomes more significant, it is necessary to consider the heat and mass transfer process of evaporation at the gas-liquid interface.

Chai and Zhang (1998) and Zhang and Chao (1999) experimentally studied convection in an evaporating liquid layer heated or cooled from the substrate and found that evaporation rate and enthalpy of evaporation are important parameters for instability and convection of the evaporating liquid layer. Sáenz et al. (2013, 2014) developed a two-phase direct numerical model to investigate the effects of evaporation considering the deformation of the gas-liquid interface in an open rectangular pool with a horizontal temperature gradient. They found that evaporation has dual effects on flow instabilities. Qin and Grigoriev (2015), Qin et al. (2014) studied the coupling effects of evaporation and thermocapillary convection in a closed rectangular pool using a two-sided numerical model considering interface heat and mass transfer which are induced

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Table 1 Datasheet of high purity γ-Al_2O_3 nanoparticles

Particle size	**Purity**	**Specific surface area**	-
10-15 nm	99.9wt%	$120m^2/g$	Hydrophilicity
Specific heat capacity	**Conductivity**	**Thermal expansion coefficient**	**Density**
765 J/(kg·K)	25 W/(m·K)	0.85×10^{-5} K^{-1}	$3970Kg/m^3$

evaporation. The results show that non-condensable gas has important effects on evaporation rate and hence plays a significant role in flow patterns evolution and heat and mass transfer at the interface. Our research group has carried out a series of numerical and experimental research on thermocapillary-buoyancy convection with interfacial phase change to reveal the coupling effect. Zhu et al. (2009), Zhu and Liu (2010) carried out an experimental investigation on thermocapillary convection with an evaporating interface in a thin liquid layer with a horizontal temperature gradient. The result indicates that the coupling of the evaporation effect and thermocapillary convection decreases the slopes of temperature profiles. Qin et al. (2022) carried out an experimental study on the stability of a sidewall-heated liquid layer. The results showed the generation of hydrothermal waves is hindered while the occurrence of oscillating multicellular convection is prompted by evaporation. Based on the constant Biot numbers of numerical simulations. Liu et al. (2020) found evaporation plays an opposing role in flow stability. Xu et al. (2020) further developed the numerical model to account for the convection of gas and prove that evaporation improves the stability of thermocapillary-buoyancy convection.

Fluids used in the above literature are usually pure fluids, such as water, mineral oils, alcohol, FC-72, etc. Nanofluid is a new type of uniform and stable suspension, which contains solid particles with particle sizes less than 100 nm. With the development of nanofluid technology, evaporation and thermocapillary convection of nanofluid are applied in processes of micro/nano fabrication, ink-jet printing, thin film coatings as well as many chemical processes. Steady-state numerical investigations on thermocapillary-buoyancy convection were carried out by previous researchers (Aminfar et al. 2012; Saleh and Hashim 2015; Kolsi et al. 2017), these computation results indicate that the nanoparticles can influence the flow pattern and heat transfer of thermocapillary-buoyancy convection. Zhou et al. (2022a, b) first reported the oscillation characteristics and evolution process of large and moderate Prandtl number nanofluid thermocapillary convection. Abdullah et al. (2018) analyzed the linear stability of its nanofluid Marangoni convection in a thin liquid layer under a vertical temperature gradient. However, the effect of evaporation was not accounted for in the above-mentioned numerical studies.

Within the knowledge of the authors, there is still no relevant research simultaneously considering the thermocapillary convection and surface evaporation effect for the nanofluid liquid layer. This paper presents the first original experimental work that is devoted to understanding the effects of nanoparticle addition on the evaporation rate and instability of the thermocapillary flow of a thin liquid layer with evaporation at the interface.

Experimental Setup and Procedure

Nanofluids Preparation

The technical parameters of the Al_2O_3 nanoparticles (produced by Nanjing Pioneer Nanomaterials Co., Ltd) are listed in Table 1. A two-step method for preparing HFE7200-Al_2O_3 nanofluid is used in the present study. Al_2O_3 nanoparticles are first produced as dry powders. Then in the second processing step, the nanoparticles are dispersed into the HFE7200 base fluid through sonication for 1 h. OP-10($C_{32}H_{58}O_{10}$) is used to help stabilize. The volume concentration of nanofluid used in this experiment is 0.05%. Before each experiment, magnetic stirring is used to deal with the nanofluid for 10 min to ensure uniformity. No visible settlement aggregation phenomenon takes place before each experiment.

Surface tension σ of HFE7200 at different temperatures is measured using a KRUSS K12 surface tension analyzer. The results are shown in Table 2.

Experimental Setup and Observation Methods

The experimental system is shown in Fig. 1. The core part is a rectangular liquid pool with a length of 80 mm and a width of 40 mm. The two long sidewalls are made of copper and each is mounted with a thermocouple in the middle. The temperature of the hot sidewall is controlled by the electrical heating component using the PID method, which has an accuracy of 0.05 °C. The cold sidewall is machined with liquid flow channels. Through the cooling water circulation, the cold wall is kept at the desired constant temperature with an accuracy of 0.02 °C. The substrate and two short walls of the rectangular pool are made of K9 glass and are adiabatic. The top of the liquid pool is exposed to the surrounding air environment.

Table 2 Variation of surface tension of HFE7200 with temperature

T(K)	293.25	303.28	313.24	323.25	333.25
σ(mN/s)	13.75	12.90	11.92	11.10	10.28

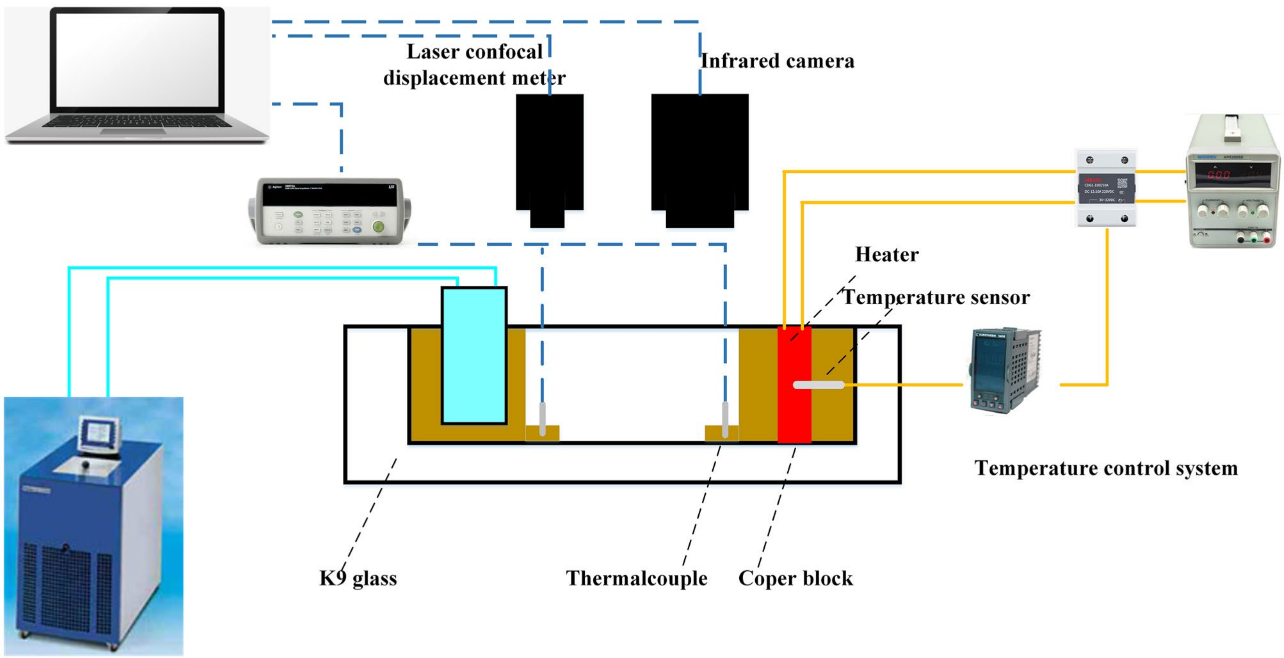

Fig. 1 Schematic drawing of the experimental apparatus

The temperature distribution of the liquid-vapor interface is observed using an infrared camera. The observation area measures 50 mm in width and 40 mm in height. A laser confocal displacement meter is used to test the thickness of the liquid layer. The stable temperature gradient is first established and then HFE7200-Al_2O_3 nanofluid liquid layers are injected into the pool from topside. The whole evaporation process is observed from initial injection to dry-out state.

Results and Discussion

Evaporation Rates of Pure HFE7200

Experiments of pure HFE7200 evaporation are carried out at different horizontal temperature differences. The normalized liquid layer thickness is defined as the ratio of the instantaneous liquid layer thickness in the center of the cavity to the initial liquid layer thickness at the same place, i.e., 2.1 mm in the present study. For this thickness, the gravity effect is not significant inside the liquid layer. The variation of normalized liquid layer thickness H versus the experiment duration t at different ΔT conditions is shown in Fig. 2. It can be seen from Fig. 2 that the liquid layer thickness is a linear function of evaporation time. The trend is consistent with our previous studies on evaporation of 0.65cSt oil liquid layer (Qin et al. 2022).

The derivative of liquid layer thickness over time is used to describe the evaporation rate as,

$$E = \partial H / \partial t \tag{1}$$

The experimental results show that the average evaporation rate increased from 0.7478 to 0.9762 μm/s. This increase occurred as the horizontal temperature difference rose from 3.04 to 12.66 ℃, as presented in Table 3. During the thin liquid layer evaporation process, the following factors will promote the evaporation process. Firstly, when the temperature difference is higher, heat transfer is accelerated and hence enhances the average evaporating rate. Secondly, the rapid evaporation zone will lead to the movement of internal fluids towards this area. Therefore, more heat is transported to this area to increase evaporation. It should be noted that the buoyancy convection in the air phase will change the concentration distribution and the vapor mass transfer, which also plays an important role in the average evaporating rate.

Effect of Al_2O_3 Nanoparticles Addition on the Evaporation rate

Table 4 shows the average evaporation rate of the thin nanofluid liquid layer at the conditions of different temperature differences. The evaporation rate increases with the increasing temperature. Figure 3 compares the evaporation rates of pure HFE7200 and HFE7200-Al_2O_3 nanofluid for different horizontal temperature difference. It can be seen that HFE7200-Al_2O_3 nanofluid has a higher evaporation

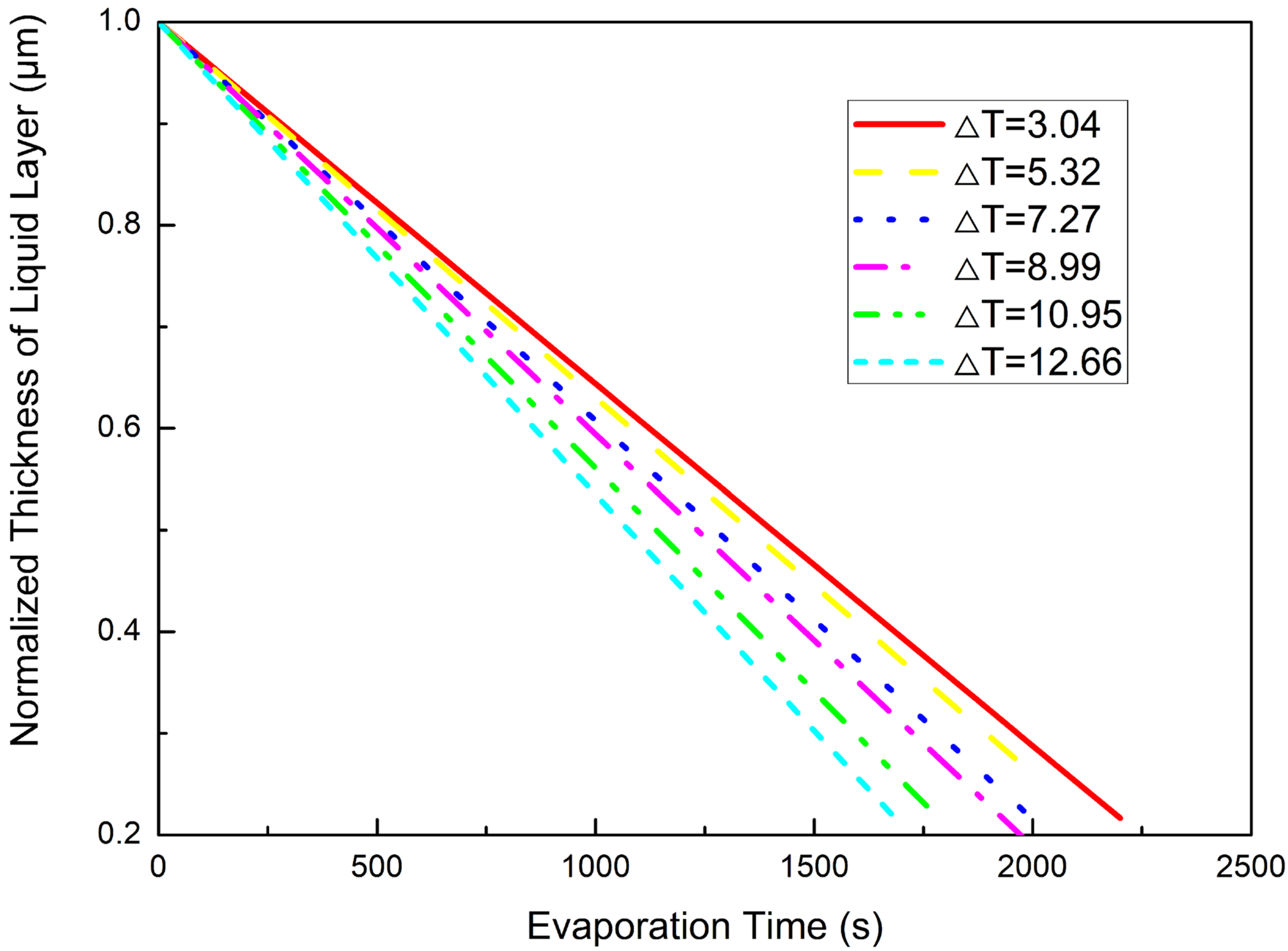

Fig. 2 Variation of normalized liquid layer thickness with evaporation time at a range of horizontal temperature difference

rate than its base fluid for all horizontal temperature differences shown in the figure. The average evaporation rate for HFE7200-Al_2O_3 nanofluid is about 1.2 times higher than that of pure HFE7200. This occurs because adding nanoparticles into the thin liquid enhances the conductivity of the liquid layer, which has direct implications for the evaporation process. In a review of previous research, there were some divergent results about the effect of nanoparticle addition on evaporation rate. The enhanced or reduced evaporation rate of nanofluid depends on their volume fraction and the type of nanofluid. The detailed mechanism needs further study. In many industrial applications, such as cooling systems, printing, and coating processes, it is necessary to increase the evaporation rate. However, the nanoparticle type and the volume fraction should be properly selected to make use of nanofluid to enhance the evaporation rate.

The Flow Pattern of pure HFE7200

Thermocapillary convection occurs when a horizontal temperature difference is established. The temperature gradient at the gas-liquid interface generates a surface tension gradient. Under the effects of surface tension, the fluid at the interface will move from the hot wall to the cold wall and recirculate at the bottom. Buoyancy convection also has a significant impact on flow. However, for the sufficiently thin liquid layer in the present study, the influence of

Table 3 The average evaporation rate of HFE7200 at 6 sets of horizontal temperature difference

ΔT °C	3.04	5.32	7.27	8.99	10.95	12.66
E(μm/s)	0.7478	0.7976	0.8235	0.8518	0.9219	0.9762

Table 4 The average evaporation rate of 0.05% HFE7200-Al_2O_3 nanofluid at 6 sets of horizontal temperature difference

ΔT °C	2.98	5.37	7.56	8.72	10.84	13.92
E(μm/s)	0.8749	0.97	1.019	1.0051	1.1063	1.1909

buoyancy on the flow is relatively weak. Meanwhile, latent heat absorption induced by evaporation also influences the interfacial temperature and temperature gradients, which has impacts on the thermocapillary convection.

The different flow patterns during the evaporation of the HFE7200 liquid layer are recorded by the infrared camera. As shown in Fig. 4, there are three flow patterns throughout the evaporation process. In the first stage, a net-like flow pattern is observed, which is generated by oscillating multicellular convection (OMC) across the cold to the hot side. Then a V-shaped wave appears at the following second stage. This flow pattern is induced by the propagating of a pair of hydrothermal waves (HTW) from the cold wall to the hot wall in opposite directions. With the continuous evaporation of the liquid layer, the fluctuation of temperature distribution, i.e. the hydrothermal wave, gradually disappears from the hot side. The flow pattern evolves into steady flow (SF).

Effect of Al_2O_3 Nanoparticle Addition on Flow Pattern Transition

The strength of thermocapillary convection is measured using the Marangoni number. This number is defined as:

$$Ma_L = \frac{\sigma_T H^2 \Delta T}{\mu \kappa L} \tag{2}$$

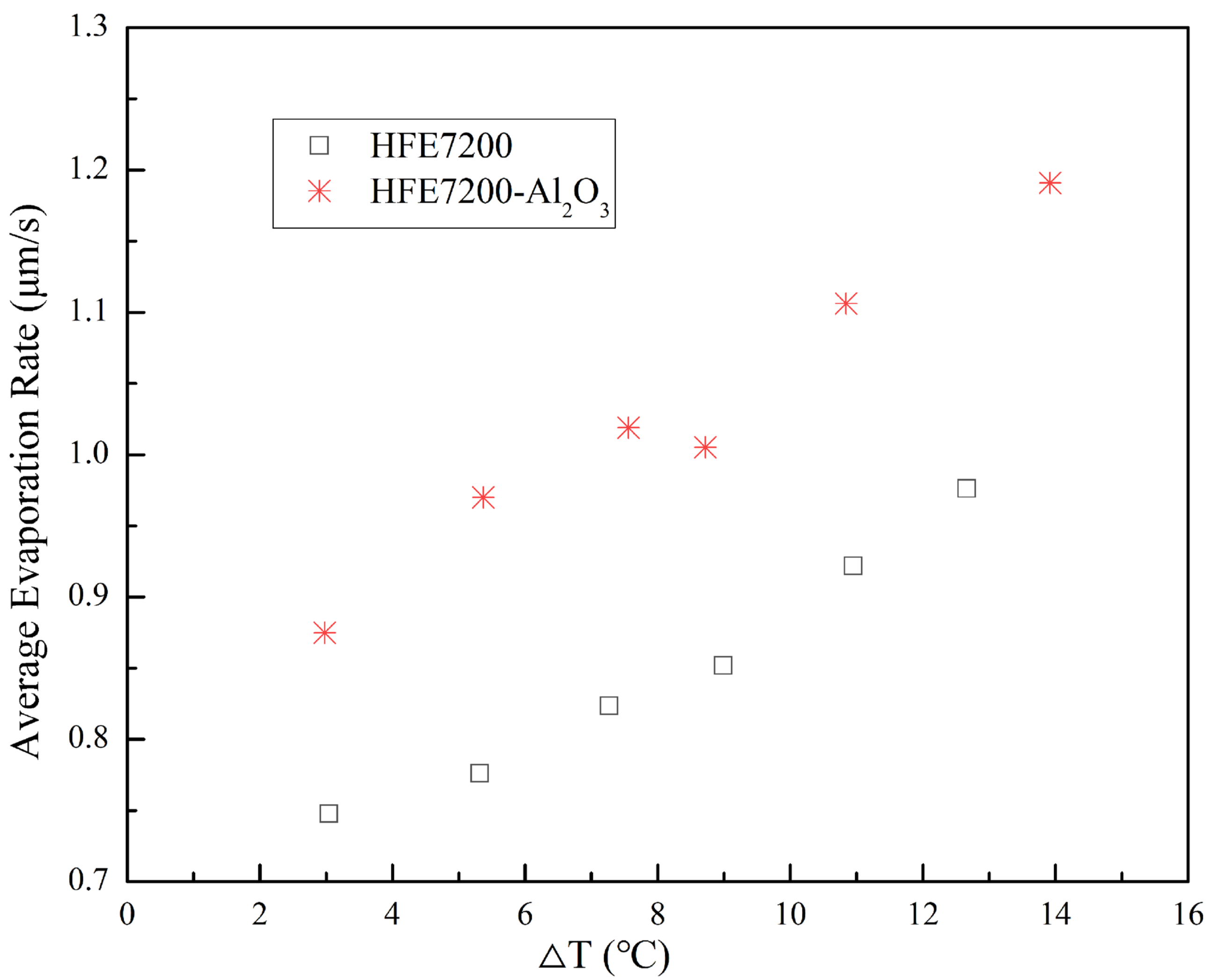

Fig. 3 The average evaporation rate of HFE7200 and 0.05% HFE7200-Al_2O_3 at a range of temperature difference

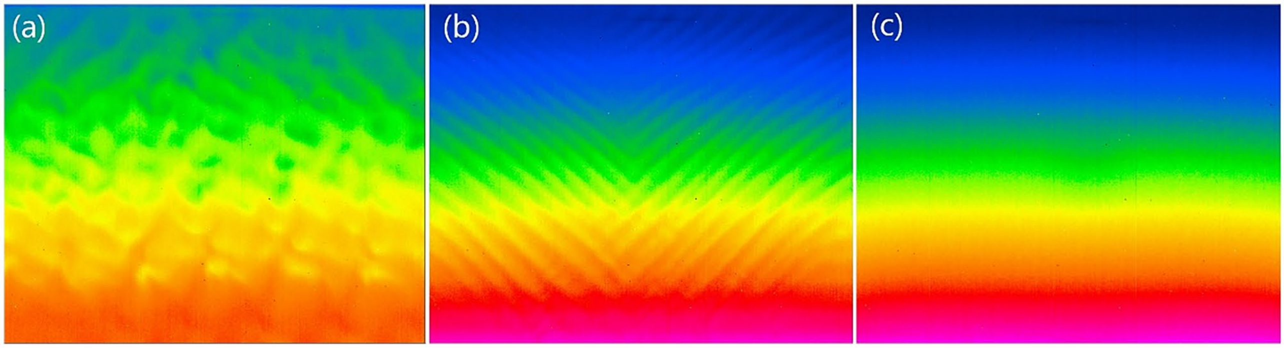

Fig. 4 Flow patterns evolution of HFE7200 liquid layer during evaporation process: **a** OMC; **b** HTW; **c** SF(**ΔT** = 6.0 °**C**)

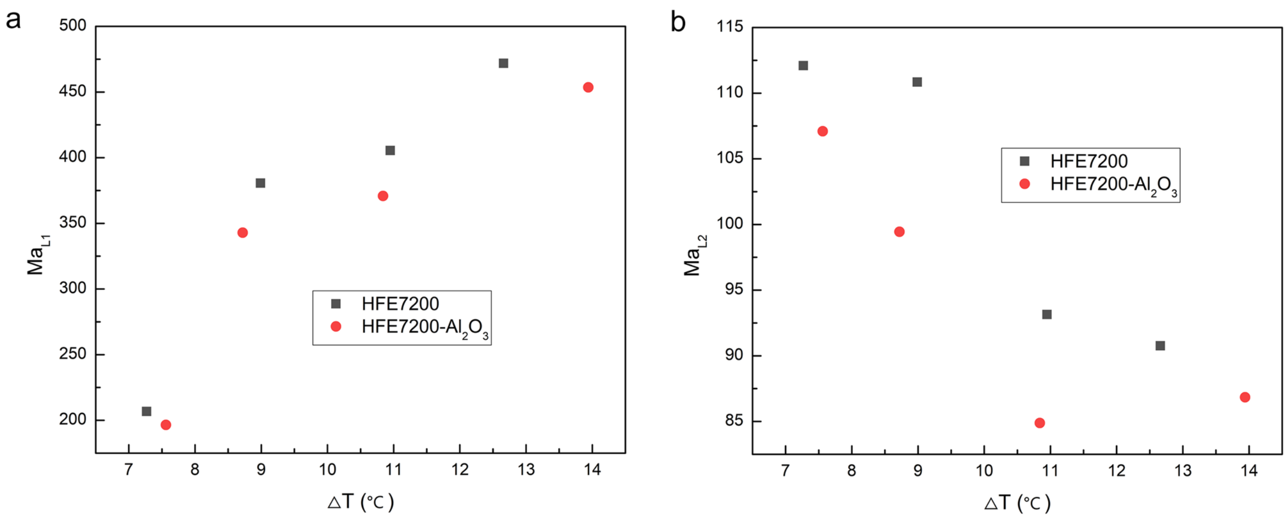

Fig. 5 The critical Marangoni number for HEF7200 and 0.5% HFE7200-Al_2O_3 under corresponding temperature differences: **a** Ma_{L1}; **b** Ma_{L2}

where σ_T is the surface tension of HFE7200, H is the instantaneous height of the liquid layer, μ is the dynamic viscosity coefficient, κ is the thermal diffusion coefficient, and L is the ratio of the width of the liquid cell from the hot side to cold side to the height of the liquid layer H. For a constant ΔT, the flow pattern changes with the decreasing Marangoni number during the evaporation process. Two critical Marangoni numbers are adopted in this paper to characterize the flow pattern transition from OMC to HTW and HTW to SF, i.e. Ma_{L1} and Ma_{L2} correspondingly.

The distribution of flow patterns is examined under various temperature gradients for both HFE7200 and HFE7200-Al_2O_3 nanofluid. Four sets of horizontal temperature differences are investigated, and the results are shown in Fig. 5. As the temperature difference increases, the Ma_{L1} increases while Ma_{L2} decreases for both HEF7200 fluid and HFE-Al_2O_3 nanofluid. This means the flow pattern has more tendency to convert to and maintain the HTW states at lower temperature difference conditions. When compared to pure HFE7200, the critical Marangoni numbers for the nanofluid liquid layer are lower under similar horizontal temperature differences. This indicates that the addition of nanoparticles promotes the flow pattern transition. This is because the evaporation process of nanofluids is more intense than that of the base fluids. The results of previous studies for pure liquid also show that evaporation phase change hinders the generation of hydrothermal waves and thus conversely facilitates the transition of flow patterns (Qin et al. 2022).

Conclusions

In this work, evaporation and thermocapillary convection of thin liquid layers are experimentally investigated. HEE7200 and HFE7200-Al_2O_3 nanofluids are used as working fluid to analyze the effect of nanoparticle addition. Evaporation characteristics of HEF7200 fluid and HFE7200-Al_2O_3 nanofluid are first analyzed under six different horizontal temperature difference conditions. The experimental results indicate that the liquid layer thickness has a linear relationship with the evaporation duration. The addition of nanoparticle doesn't change this trend but increases the average evaporation rate. The average evaporation rate for HFE7200-Al_2O_3 nanofluid is about 1.2 times higher than that of pure HFE7200. The flow patterns of thermocapillary convection are then investigated. As the evaporation progresses, there occur three kinds of flow patterns, i.e. oscillating multicellular convection, hydrothermal wave, and steady flow. Compared with pure HFE7200, the critical Marangoni numbers for the nanofluid liquid layer are relatively lower under similar horizontal temperature differences. This indicates that the addition of nanoparticles facilitates the flow pattern transition from OMC to HTW and further from HTW to SF. The effects of nanoparticles type, shape, concentration, and size on the evaporation and thermocapillary convection of thin nanofluid layer should be further discussed.

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Data Availability All data included in this study are available upon request by contact with the corresponding author.

Declarations

Ethical Approval This research work doesn't involve the content of both human and/ or animal studies.

Competing Interests The authors declare no competing interests.

References

Abdullah, A.A., Althobaiti, S.A., Lindsay, K.A.: Marangoni convection in water–alumina nanofluids: Dependence on the nanoparticle size. Eur. J. Mech. B-Fluid **67**, 259–268 (2018)

Aminfar, H., Mohammadpourfard, M., Mohseni, F.: Numerical investigation of thermocapillary and buoyancy driven convection of nanofluids in a floating zone. Int. J. Mech. Sci. **65**, 147–156 (2012)

Chai, A.T., Zhang, N.: Experimental study of Marangoni-Bénard convection in a liquid layer induced by evaporation. Exp. Heat. Transfer **11**, 187–205 (1998)

Dhavaleswarapu, H.K., Chamarthy, P., Garimella, S.V., Jayathi, Y.M.: Experimental investigation of steady buoyant-thermocapillary convection near an evaporating meniscus. Phys. Fluids **19**, 082103 (2007)

Haas, D.E., Birnie, D.P.: Evaluation of thermocapillary driving forces in the development of striations during the spin coating process. J. Mater. Sci. **37**, 2109–2116 (2002)

Hossain, M.A., Hafiz, M.Z., Rees, D.A.S.: Buoyancy and thermocapillary driven convection flow of an electrically conducting fluid in an enclosure with heat generation. Int. J. Therm. Sci. **44**, 676–684 (2005)

Li, Z.Y., Yu, G., He, X.L., Tian, C.X., Li, S.X., Li, H.M.: Probing thermocapillary convection and multisolute dilution in laser welding of dissimilar miscible metals. Int. J. Therm. Sci. **172**, 107242 (2022)

Li, Y.R., Zhang, L., Zhang, L., Yu, Y.Y.: Experimental study on prandtl number dependence of thermocapillary-buoyancy convection in Czochralski configuration with different depths. Int. J. Therm. Sci. **130**, 168–182 (2018)

Kolsi, L., Lajnef, E., Aich, W., Alghamdi, A., Aichouni, M. A., Borjini, M. N., & Aissia, H. B. Numerical investigation of combined buoyancy-thermocapillary convection and entropy generation in 3D cavity filled with Al_2O_3 nanofluid. Alex. Eng. J. **56**, 71–79 (2017)

Liu, W.J., Chen, P.G., Ouazzani, J., Liu, Q.S.: Thermocapillary flow transition in an evaporating liquid layer in a heated cylindrical cell. Int. J. Heat Mass Transf. **153**, 119587 (2020)

Liu, Q.S., Zhou, B.H., Henri, N.T., Hu, W.R.: Instability of two-layer Rayleigh–Benard convection with interfacial thermocapillary effect. Chin. Phys. Lett. **21**, 686 (2004)

Nithyadevi, N., Begum, A.S., Shankar, C.U.: Buoyancy and thermocapillary driven flows in an open cavity with bottom heating and symmetrical cooling from sides. Int. J. Heat Technol. **33**, 63–70 (2015)

Pelacho, M.A., Burguete, J.: Temperature oscillations of hydrothermal waves in thermocapillary-buoyancy convection. Phys. Rev. E **59**, 835 (1999)

Qin, T.R., Grigoriev, R.O.: The effect of noncondensables on buoyancy–thermocapillary convection of volatile fluids in confined geometries. Int. J. Heat Mass Transf. **90**, 678–688 (2015)

Qin, J., Liu, Q.S., Tao, Y.Q., Qiao, L.L., Zhu, Z.Q.: Thermocapillary-buoyancy convection driven by a horizontal temperature gradient in a thin liquid layer: the effect of evaporation. Microgravity Sci. Tec. **34**, 1–9 (2022)

Qin, T.R., Tuković, Z., Grigoriev, R.O.: Buoyancy-thermocapillary convection of volatile fluids under atmospheric conditions. Int. J. Heat Mass Transf. **75**, 284–301 (2014)

Riley, R.J., Neitzel, G.P.: Instability of thermocapillary–buoyancy convection in shallow layers. Part 1. Characterization of steady and oscillatory instabilities. J. Fluid Mech. **359**, 143–164 (1998)

Sáenz, P.J., Valluri, P., Sefiane, K., Karapetsas, G., Matar, O.K.: Linear and nonlinear stability of hydrothermal waves in planar liquid layers driven by thermocapillarity. Phys. Fluids **25**, 094101 (2013)

Sáenz, P.J., Valluri, P., Sefiane, K., Karapetsas, G., Matar, O.K.: On phase change in Marangoni-driven flows and its effects on the hydrothermal-wave instabilities. Phys. Fluids **26**, 024114 (2014)

Saleh, H., Hashim, I.: Buoyant Marangoni convection of nanofluids in square cavity. Appl. Math. Mech. **36**, 1169–1184 (2015)

Shevtsova, V.M., Nepomnyashchy, A.A., Legros, J.C.: Thermocapillary-buoyancy convection in a shallow cavity heated from the side. Phys. Rev. E **67**, 066308 (2003)

Xu, G.F., Liu, Q.S., Qin, J., Zhu, Z.Q.: Numerical study of thermocapillary-buoyancy convection of volatile liquid layer in an enclosed cavity. Microgravity Sci. Technol. **32**, 305–319 (2020)

Zhang, N., Chao, D.F.: Mechanisms of convection instability in thin liquid layers induced by evaporation. Int. Commun. Heat Mass Transf. **26**, 1069–1080 (1999)

Zhou, X.M., Chi, F.X., Jiang, Y.N., Chen, Y.Q.S.: Numerical investigation of thermocapillary convection instability for large prandtl number nanofluid in rectangular cavity. Int. Commun. Heat Mass Transf. **133**, 105956 (2022a)

Zhou, X.M., Chi, F.X., Jiang, Y.N., Chen, Y.Q.S.: Moderate prandtl number nanofluid thermocapillary convection instability in rectangular cavity. Microgravity Sci. Technol. **34**, 1–10 (2022b)

Zhu, Z.Q., Liu, Q.S.: Coupling of thermocapillary convection and evaporation effect in a liquid layer when the evaporating interface is open to air. Chin. Sci. Bull. **55**, 233–238 (2010)

Zhu, Z.Q., Liu, Q.S., Xie, J.C.: Experimental study on the combined evaporation effect and thermocapillary convection in a thin liquid layer. Microgravity Sci. Tec. **21**, 241–246 (2009)