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Numerical study on the fluctuation characteristics of nanofluid thermocapillary convection in an annular pool under microgravity

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Abstract: To understand nanofluid thermocapillary convection instability in an annular liquid pool deeply, the effects of nanoparticles volume fraction, the liquid layer thickness, and the gravity level on the flow pattern evolution and the temperature fluctuation characteristics are numerically investigated. The results indicate that as the volume fraction of nanoparticles increased from 1.0% to 2.5%, the amplitude of temperature fluctuations at the free surface progressively enhanced. At high volume fractions, phase delays emerged in the temperature oscillations, with a maximum lag of 1.2 seconds relative to $\phi=1.0\%$. Frequency domain analysis revealed a decrease in the dominant frequency of temperature fluctuations from 0.379 Hz to 0.359 Hz, accompanied by an increase in the proportion of high-frequency energy. Distinct fluctuation striations emerge when the liquid layer thickness is less than 5 mm. These fluctuations diminish beyond 7.5 mm and disappear entirely at 10 mm. Under microgravity conditions, the fluctuation intensity slightly increases while the dominant frequency remains unchanged, though energy disperses towards the higher-frequency range.

Keywords: Thermocapillary convection; Nanofluid; Annular pool; Interface fluctuations; Numerical simulation

1. Introduction

1 With the fast development of microscale nanotechnology, human spaceflight technology and
2 smart manufacturing, thermocapillary effect is widely used in scientific fields such as microscale
3 flow control, space material synthesis and space energy management(Borshchak Kachalov et al.
4 2024; Kudo and Igarashi 2024; Xu et al. 2024; Zhuang et al. 2025). Thermocapillary convection is
5 a flow phenomenon driven by surface tension gradients(Huang et al. 2017; Meng et al. 2024). In
6 the space environment, gravity is significantly weakened and buoyancy effect is suppressed, while
7 the thermocapillary convection mechanism driven by surface tension gradient dominates the fluid
8 flow(Gligor et al. 2024; Shitomi et al. 2019). Nevertheless, sometimes unpredictable oscillations
9 still occur during space experiments due to the instability of thermocapillary convection. Therefore,
10 it is necessary to supplement and develop the relevant kinetic theories to achieve a deeper
11 understanding of the thermocapillary convection mechanism.

12 In recent experimental researches of thermocapillary, Yu et al.(Yu et al. 2015) used infrared
13 thermography technology to observe the process of fluid flow transformation in a circular pool with
14 outer wall heating and inner wall cooling. It was found that the number of ripples in the
15 hydrothermal wave decreased with the increase of aspect ratio and thermal Reynolds number. Duan
16 et al.(Duan et al. 2018) detected temperature oscillations in the liquid layer through a single point
17 temperature measurement system and studied the transition pathways of oscillations using the Step-
18 heating mode. They identified three main transition paths for temperature oscillations and surface
19 oscillations: quasi periodic bifurcation, period doubling bifurcation accompanied by quasi periodic
20 bifurcation, and tangential bifurcation accompanied by quasi periodic bifurcation. Kang et al.(Kang
21 et al. 2019b; Kang et al. 2019a) conducted liquid experiments on China's SJ-10 satellite to
22 investigate the critical conditions for the initiation of oscillations by thermocapillary convection and

1 the characteristics of the oscillation frequency, and revealed the instability mechanism of
2 thermocapillary convection. Qin et al.(Shu et al. 2022; Shu et al. 2021) performed thermocapillary
3 experiments by using medium Prandtl number liquid and recorded the temperature fluctuation
4 patterns at free surface by texture shadowing, and found that spoke structures appeared in the surface
5 of the liquid pool of 6 to 8 mm when the flow was destabilized. Wang et al.(Wang et al. 2024)
6 designed an annular flow load with a central heating column and explored the liquid surface state,
7 temperature oscillations, and infrared temperature field evolution of the annular flow for a range of
8 volume ratios from 0.45 ~ 1.06 based on this device. They found that hydrothermal waves of
9 different wave numbers were observed at free surface when the volume ratio was varied.

10 Due to limitations in the means of measurement, it is difficult to obtain more data in
11 thermocapillary convection experiments. While numerical simulation provides a more convenient
12 and powerful tool for the in-depth investigation of the thermocapillary convection mechanism. Liu
13 et al.(Liu et al. 2019; Liu et al. 2018) conducted numerical analysis on the linear stability of
14 thermocapillary flow. They used Legendre SEM to obtain the steady-state ground state of
15 thermocapillary convection, and then found through energy analysis that liquids with Prandtl
16 numbers less than 0.02 are due to pure water dynamic inertial instability. Li et al.(Li et al. 2022)
17 studied the flow stability of medium Prandtl number liquids driven by thermodynamic force,
18 buoyancy force, and Coriolis force in a rotating annular liquid pool. They found that there are three
19 ways of flow instability when the Taylor number is between 0 and 60. Wang et al.(Wang et al. 2022)
20 calculated the thermocapillary of an annular layer with a non-flat free surface and investigated the
21 evolution of hydrothermal waves. It was found that in the critical state, liquid level oscillation begins
22 in the form of standing waves; Under micro supercritical conditions, standing waves transform into

traveling wave oscillations. Guo et al.(Guo 2023) used direct numerical simulation to investigate the thermocapillary convection in liquid pools with different volume ratios, and combined dynamic mode decomposition method to analyze the inherent structure of the flow field. It showed that a liquid layer with a smaller volume ratio would suppress new fundamental modes, and the liquid layer would also be maintained in a periodic state. Kurian et al.(Jory and Satheesh 2024) designed three cylindrical configurations of annular liquid pools and investigated the effects of Prandtl number and layer depth on the fundamental characteristics of thermocapillary convective fluid dynamics. They found that liquid pools with an external cylinder configurations can affect overall convection, and higher Pr fluids are more effective in providing more significant peak surface velocities. Qin et al.(Shu et al. 2024) explored the mechanism of thermocapillary flow formation and evolution at different depths in an annular liquid pool, it shows that the phase lag between temperature and velocity fluctuations after flow destabilization would form different base flow configurations. Jiménez Blanco et al.(Jiménez Blanco et al. 2025) numerically explored the free surface motion characteristics of thermocapillarity under steady-state thermal forcing in a semi-filled elliptical vessel, and they found that elliptical shapes can change the direction of the effective temperature gradient and thus enable control of the free surface shape.

At present, most of the studies on thermocapillary convection stability or transition mechanisms are based on pure fluids, such as silicone oil(Le et al. 2021; Zhou et al. 2022a). In experiments or simulations, the selection of these liquid media provides a rich complement to the theory of thermocapillary convection. However, with the updating and development of technology, nanofluid are gradually being used in more and more fields, due to their higher heat transfer performance compared to pure fluids(Siow et al. 2025; Taneja et al. 2025). Hakobayan et

al.(Hakobyan and Hakobyan 2017) investigated the thermocapillary mechanism of convection in nanofluid due to the absorption of spatially periodic laser radiation, and determined the velocity and temperature distribution within the volume of the medium. Jiang et al.(Jiang and Zhou 2019) reported the flow, heat transfer, and entropy generation characteristics of nanofluid buoyancy thermocapillary convection around bubbles in a cavity for the first time. Zhou et al.(Zhou 2023; Zhou et al. 2022b) numerically simulated the thermocapillary convection of nanofluid in a rectangular square cavity, and they found that the nanofluid have a lower critical temperature difference in the thermocapillary convection process compared to the pure fluid. Hassen et al.(Hassen et al. 2022) simulated thermocapillary convection and buoyancy-driven convection of a mixed nanofluid in a square cavity equipped with obstacles, and they analyzed the evolution of the flow profile, temperature profile, and Nussel number of the nanofluid. Chen et al.(Chen et al. 2025) explored the effect of the shape of nanoparticles on thermocapillary instability, and it found that nanofluid with plate particles can significantly enhance interfacial oscillations. Overall, there is not much research on the thermocapillary convection mechanism of nanofluid at present, so it is necessary to conduct relevant studies to further explore the theory of thermocapillary convection of nanofluid. In this paper, a model of an annular pool with heated inner wall and cooled outer wall is constructed. The volume fraction, thickness of the nanofluid and gravity factor are fully considered. The evolution and fluctuation characteristics at free surface of nanofluid thermocapillary convection are discussed in detail.

2. Physical and mathematical model

2.1 Physical model

The annular pool is a typical model for studying the instability of thermocapillary convection,

so an annular pool model with inner wall heating and outer wall cooling was constructed in this study, as shown in Figure 1. The inner wall radius of the annular pool is $r=5$ mm, and the radius of the outer wall is $R=30$ mm. d is the thickness of the nanofluid in the annular pool. Here four sizes of $d=2.5$ mm, 5 mm, 7.5 mm and 10 mm will be studied and discussed. The free surface of the nanofluid is the main region to be explored in the study. Four measurement points are uniformly distributed along the free surface at radial locations to obtain temperature data.

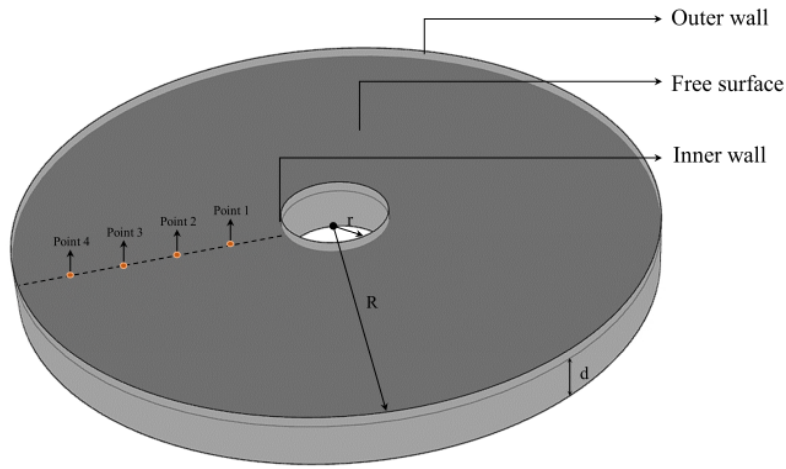


Fig. 1. Geometric model of annular pool

2.2 Mathematical models

The continuity equation, momentum equation, and energy equation are as follows(Zhou et al.

2022a):

$$\frac{\partial \rho_{nf}}{\partial \tau} + \nabla \cdot (\rho_{nf} \vec{v}) = 0 \quad (1)$$

$$\frac{\partial}{\partial \tau} (\rho_{nf} \vec{v}) + \nabla \cdot (\rho_{nf} \vec{v} \vec{v}) = -\nabla p + \rho_{nf} g \quad (2)$$

$$\frac{\partial}{\partial \tau} \left(\rho_{nf} \left(e + \frac{v^2}{2} \right) \right) + \nabla \cdot \left(\rho_{nf} \vec{v} \left(h + \frac{v^2}{2} \right) \right) = \nabla \cdot (\lambda_{nf} \nabla T) \quad (3)$$

where ρ_{nf} is the density of the nanofluid, kg/m^3 ; τ is the time of continuous heating of the inwall, s;

v is the velocity magnitude of the nanofluid, m/s ; $\vec{v}$ is the vector velocity of the nanofluid, m/s ; p

1 is the pressure of the nanofluid, Pa; e is the internal energy per unit mass of the nanofluid, J/kg; h
 2 is static enthalpy per unit mass of the nanofluid, J/kg; λ_{nf} is thermal conductivity of nanofluid,
 3 W/(m·K); T is the temperature of the nanofluid, K.

4 Inside higher concentrations of nanofluid, there is a lack of sufficient repulsive forces among
 5 nanoparticles to overcome the interaction forces among particles, which can lead to the phenomenon
 6 of particle agglomeration. However, in thermocapillary convection research, the focus has been
 7 mainly on the fluctuation patterns generated on the surface of the nanofluid. These fluctuation
 8 patterns are closely related to the fluid surface tension gradient. In this work, although particle
 9 agglomeration may exist within the highly concentrated nanofluid ($\phi > 5\%$), in order to simplify the
 10 problem when studying surface fluctuations on a macroscopic scale and to focus on understanding
 11 the surface dynamics and macroscopic flow patterns, the nanofluid is treated as a homogeneous
 12 fluid, and this simplification allows the researcher to, instead, ignore the direct effects of the internal
 13 particle agglomeration. The thermophysical parameters of the nanofluid are calculated as shown in
 14 the following equations(Aktary et al. 2025; Zhou et al. 2022b):

$$\rho_{nf} = (1 - \phi) \rho_f + \phi \rho_p \quad (4)$$

$$\mu_{nf} = \frac{\mu}{(1 - \phi)^{2.5}} \quad (5)$$

$$(\rho c_p)_{nf} = (1 - \phi)(\rho c_p)_f + \phi(\rho c_p)_p \quad (6)$$

$$\lambda_{nf} = \frac{\lambda_f \left[(\lambda_p + 2\lambda_f) - 2\alpha(\lambda_f - \lambda_p) \right]}{(\lambda_p + 2\lambda_f) + \alpha(\lambda_f - \lambda_p)} \quad (7)$$

15 where ϕ is the volume fraction of the nanofluid; ρ_f is the density of the base fluid, kg/m³; ρ_{nf} is
 16 the density of the nanoparticles, kg/m³; μ is the dynamic viscosity of the base fluid, kg/(m·s); μ_{nf} is
 17 the dynamic viscosity of the nanofluid, kg/(m·s); $(c_p)_{nf}$ is the specific heat capacity of the nanofluid,

1 $J/(kg \cdot K)$; $(c_p)_f$ is the specific heat capacity of the base fluid, $J/(kg \cdot K)$; $(c_p)_p$ is the specific heat
2 capacity of the nanoparticle, $J/(kg \cdot K)$; λ_f is the thermal conductivity of the base fluid, $W/(m \cdot K)$; λ_p
3 is the thermal conductivity of the nanoparticles, $W/(m \cdot K)$.

4 **3. Solution method and model validation**

5 **3.1 Solution method**

6 This study is accomplished using computational fluid dynamics methods. The finite volume
7 method is used to numerically explore the fluctuation characteristics at free surface of a nanofluid
8 in an annular pool. The laminar flow model was chosen to calculate the flow of the nanofluid
9 because the velocity of the fluid is quite small. PISO method is used to solve pressure velocity
10 coupling. The Least Squares Cell Based method was chosen for the spatial discretization of the
11 gradient. The second-order upwind format was used for the pressure discretization. Momentum and
12 energy are discretized using the QUICK method. In the calculations, all four edges of the annular
13 pool are wall type boundaries. Where the inwall, outer wall and bottom face of the pool are standard
14 no-slip boundaries and the free surface is a shear boundary with a surface tension coefficient of -
15 $7.55 \times 10^{-5} N/(m \cdot K)$. Constant temperature is chosen to be used as the thermal boundary condition
16 for the inner and outer faces of the annular pool. The temperature of the outer wall surface is 298.15
17 K for cooling the nanofluid and the temperature of the inner wall surface is 318.15 K for heating
18 the nanofluid. The bottom surface of the annular pool and the free surface are adiabatic boundaries.
19 The detailed boundary types of the model are shown in **Table 1**. Silicone oil-copper nanofluid is the
20 medium used for the simulation. The thermophysical properties of silicone oil base fluid and copper
21 nanoparticles are shown in **Table 2**(Chen et al. 2025).

22 **Table 1** Numerical boundary condition

Category	Boundary name	Momentum condition	Thermal condition
Boundary condition	Inwall	Standard & No slip	Constant temperature { $T_h=318.15K$ }
	Outwall	Standard & No slip	Constant temperature { $T_c=298.15K$ }
	Free surface	Shear condition	Adiabat{ $q=0$ }
	Bottom surface	Standard & No slip	Adiabat{ $q=0$ }

1

2

3

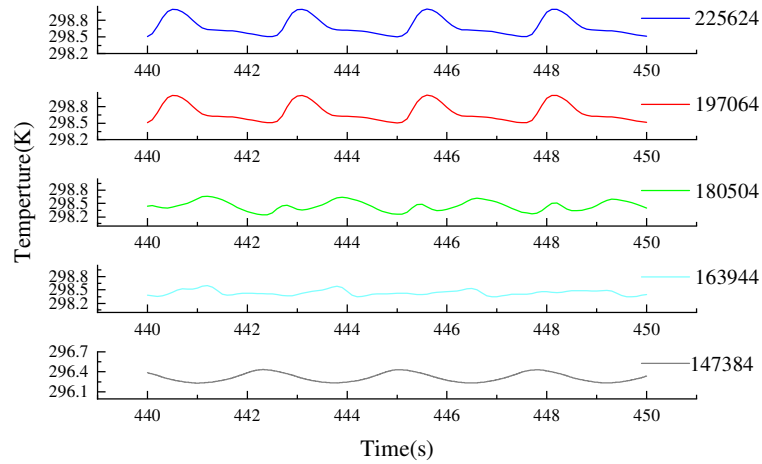
Table 2 Nanofluid thermophysical parameters

thermal properties	Base fluid (silicone oil)	Copper particles
Density, kg/m^3	818	8978
Dynamic viscosity, $kg/(m \cdot s)$	8.18×10^{-4}	381
Specific thermal capacity, $J/(kg \cdot K)$	1975	/
Thermal conductivity, $W/(m \cdot K)$	0.11	387.6

3.2 Grid independence analysis

Before simulation, the geometry was divided into a hexahedral structured mesh for mesh verification in order to eliminate the negative influence of the mesh on the simulation results. The five types of grids were constructed with the cell numbers of 147384, 163944, 180504, 197064 and 225624, respectively. **Fig. 2** shows the temperature variation at free surface measurement point 1 for meshes with different number of cells. It can be observed that all six meshes exhibit periodic fluctuations in the range of 440 s to 450 s, but the temperature fluctuation period of the mesh with cell number 147384 is 2.0 s, while the temperature fluctuation period of the other four meshes is 2.6 s. In addition, the temperature fluctuations of the meshes with cell numbers 147384, 163944 and

1 180504 have different waveforms until the number of cells of the mesh increases to 197064 the
 2 shape change of temperature fluctuations basically no longer changes. Therefore, in order to ensure
 3 the accuracy of the results and to fully utilize the computational resources, the mesh with 197,064
 4 cells is finally selected for the calculation.



5
 6 **Fig. 2.** Temperature variation with time at free surface at measurement point 1

7 3.3 Model validation

8 The critical temperature difference is an important parameter in the study of thermocapillary
 9 convection. Here the results of the computational model are compared with the thermocapillary
 10 convection critical temperature difference measured by Kang in an annular pool(Kang et al. 2019a).

11 **Fig. 3** shows the comparison of simulated and experimental critical temperature difference under
 12 liquid pool conditions with different volume ratios. From the figure, it can be seen that in the range
 13 of volume ratio less than 0.905, the relative error between simulation and experiment is basically
 14 within 15%, which verifies the validity of the simulation method. At this time, the corresponding
 15 liquid layer thickness is 10.86 mm, which provides a reference for the selection of the thickness of
 16 the geometric model. However, when the volume ratio exceeds 0.905, the error between the
 17 simulated and experimental results increases significantly. This is because the thickness of the liquid

layer increases as the volume ratio increases. The buoyancy effect starts to become significant when the layer thickness is too large, and stronger buoyant convection dominates the heat transfer mechanism inside the fluid, which leads to a more uniform distribution of heat inside the fluid, thus weakening the effect of thermocapillary convection. In this case, the simulation results deviate from the experimental results. Therefore, in order to ensure the validity and reliability of the simulation and to minimize the influence of the buoyancy effect, a fluid layer with a thickness of less than 10 mm was finally chosen for the simulation. This can study the intrinsic mechanism of thermocapillary convection more accurately and provide a reliable numerical basis for subsequent studies.

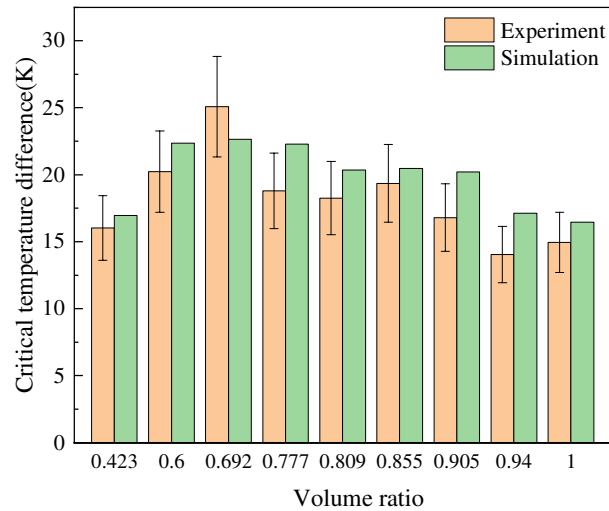


Fig. 3. Comparison of simulated and experimental critical temperature difference

4. Results and Discussion

4.1 Oscillatory characteristics of thermocapillary convection

Temperature behavior at free surface of the annular nanofluid pool is captured in numerical simulations. **Fig. 4** shows the temperature variation with time at four measurement points along the radial direction for different temperature differences. The graphical results reveal the key properties of thermocapillary convection by observing the temperature variations of radial measurement points with time at different temperature differences. At a temperature difference of 20 K, the temperatures

1 at all four measurement points (located at 10 mm, 15 mm, 20 mm, and 25 mm, respectively) show
2 a stable periodic oscillatory behavior after about 104 seconds. This indicates that the flow reaches
3 a regular state under this condition. On the contrary, when the temperature difference increases to
4 30 K, 40 K and 50 K, the temperatures at each measurement point show unpredictable and non-
5 stationary signals, and the temperature fluctuations become more drastic as the temperature
6 difference increases. This implies that the system may have entered a chaotic or turbulent state.

7 In addition, measurement point 1 (10, 0, 2.5) near the heated wall consistently maintains the
8 highest temperature, indicating that the heat is mainly transferred to the interior of the fluid through
9 the heated wall. As the location of the measurement point moves away from the heated wall, the
10 temperature decreases and the fluctuation of the temperature decreases. This is because the
11 temperature gradient decreases with increasing radial distance. It is interesting to note that as the
12 temperature difference increases, the point temperature begins to fluctuate significantly earlier. This
13 suggests that higher temperature difference accelerates the development of flow instability, leading
14 to earlier onset of periodic or non-periodic oscillations. Since the main purpose of this study is to
15 deeply explore the signal fluctuations under free surface periodic oscillations, the boundary
16 condition with a temperature difference of 20 K will be uniformly adopted in the subsequent analysis
17 in order to ensure the controllability and regularity of the research object, so that the periodic
18 oscillations can be analyzed and investigated more deeply.

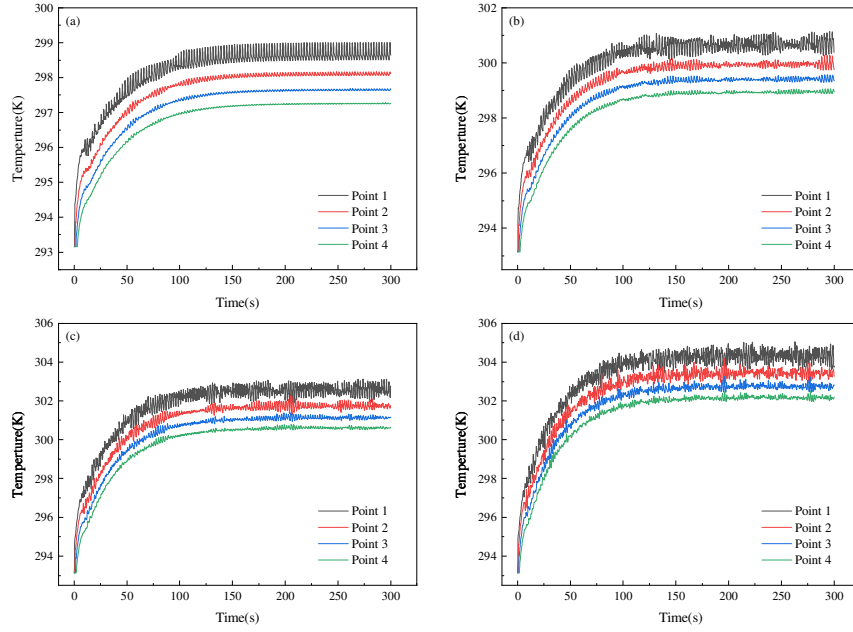


Fig. 4. Temperature variation over time at radial measuring points under various temperature difference conditions. (a. $\Delta T=20$ K, b. $\Delta T=30$ K, c. $\Delta T=40$ K, d. $\Delta T=50$ K, $\phi=0\%$)

In order to analyze the temperature variation of the free surface more intuitively, **Fig. 5** shows the temperature and tangential velocity fluctuation contour plot of the free surface for different temperature differences. The fluctuation value here is the difference between the instantaneous and time-averaged values of the free surface signal. It can be seen from the figure that the amplitude of the fluctuations in tangential velocity and temperature increases significantly with increasing temperature difference. At lower temperature differences ($\Delta T=20$ K), the free surface fluctuation patterns are relatively simple and the fluctuations are less intense. It shows a more regular radial distribution, especially near the surface of the heated wall showing alternating positive and negative fluctuation mode transition regions, resembling a fan-shaped pattern. This fan-shaped structure indicates the existence of a periodic flow pattern at free surface, which is related to the annular flow driven by the surface tension gradient. As the temperature difference increases the fluctuation contour plot becomes more complex, the fluctuations in tangential velocity and temperature exhibit

1 more localized extremes and the intensity of the fluctuations increases significantly. This implies
2 that the flow becomes more unstable and thermocapillary convection is more intense, while vortex
3 structures of various scales emerge. The fluid motion driven by thermocapillary forces at higher
4 temperature differences is more intense, which leads to more complex perturbations of the surface
5 temperature and velocity fields.

6 In addition to the increase in the fluctuation amplitude, it is observed that the spatial
7 distribution of the high and low temperature regions and the high and low velocity regions becomes
8 more irregular, which suggests that the flow is gradually transitioning to a turbulent state. The more
9 intense fluctuations in the region near the heated wall at higher temperature differences indicate that
10 the heat is mainly transferred directly from the heated wall to the free surface, and stronger
11 thermocapillary convection is induced in this region. This phenomenon further verifies the
12 important influence of the heated wall at free surface flow and suggests that the thermocapillary
13 instability within the thermal boundary layer at higher temperature differences is a key factor in
14 triggering surface fluctuations and complex flow structures. At the same time, the fluctuations in
15 the region away from the heated wall are enhanced, indicating that the influence of thermocapillary
16 convection is expanding, but the overall intensity is still lower than that in the region close to the
17 heated wall. This hierarchical fluctuation intensity distribution reflects the energy transfer from the
18 heated wall to the whole free surface.

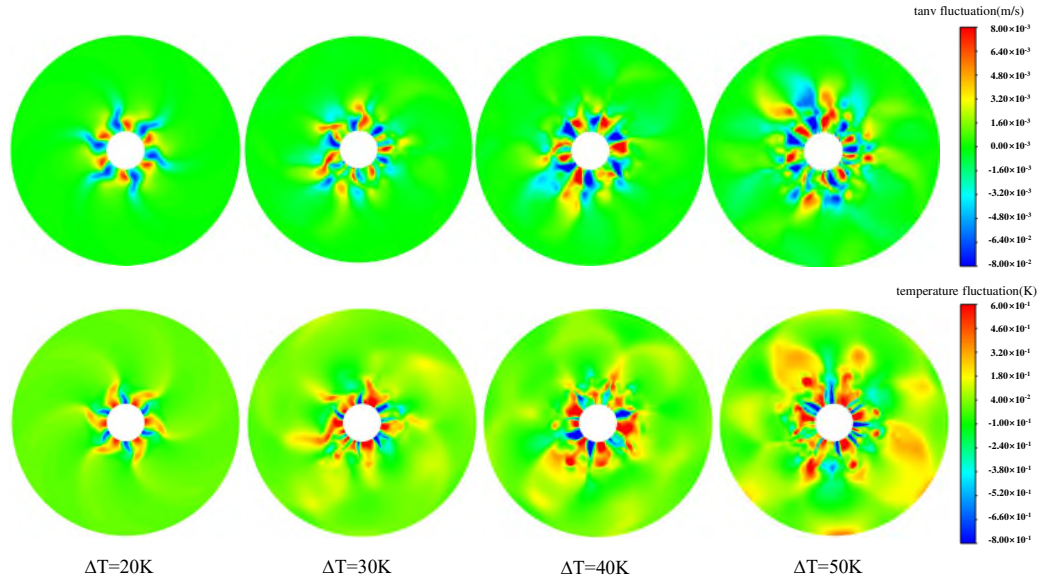
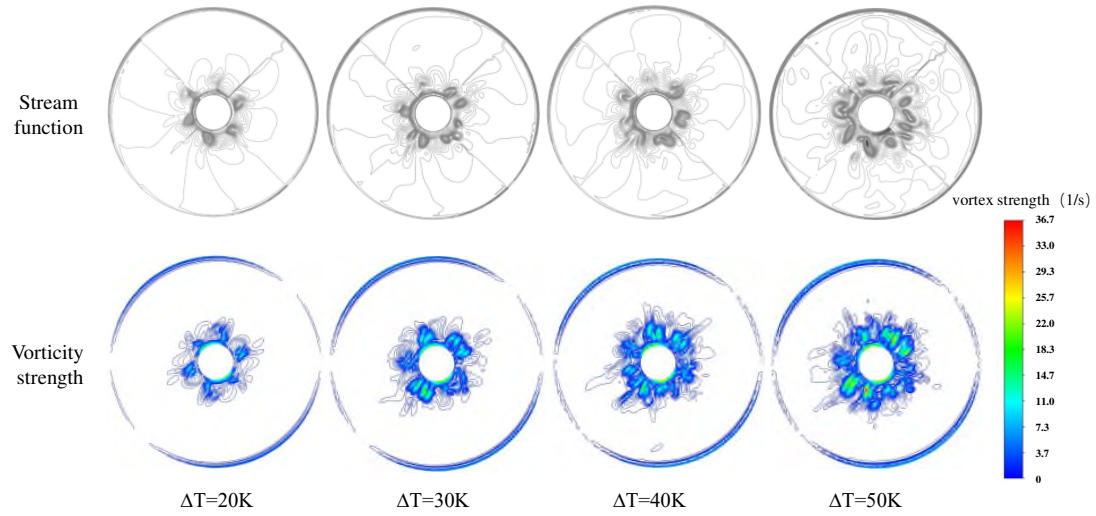


Fig. 5. Temperature and tangential velocity fluctuation contour plot of free surface with different temperature difference. ($\varphi=0\%$, $d=2.5$ mm, $G=0.001$ g).

Figure 6 shows the distribution of the stream function and vorticity strength in the horizontal cross-section ($d = 1.25$ mm) of the liquid layer. At temperature differences of 20 K and 30 K, the flow function contour lines in the liquid layer cross-section are sparse, and several elliptical vortex cells exist near the heating wall. As the temperature difference increases to 40 K and 50 K, the liquid layer flow becomes progressively disorder. Streamlines of the vorticity function become distorted, and the number of vortex cells increases significantly while they are more densely packed. At the same time the circular flow structure extends radially toward the outer wall. The vorticity function reveals the overall circulation structure of the liquid layer, while the vorticity intensity reflects the local rotational strength of the fluid. From the distribution of vorticity strength, it can be observed that the vorticity strength is weak at low temperature differences. As the temperature difference increases, the vorticity strength increases greatly, and small-scale vortex structures bloom near the hot wall. This intuitively reflects the fluid rotation effect induced by the temperature gradient through changes in surface tension. In addition, the uneven distribution of vorticity strength is also

1 an important reason contributing to the irregular shape of the vortex cells in the flow function.



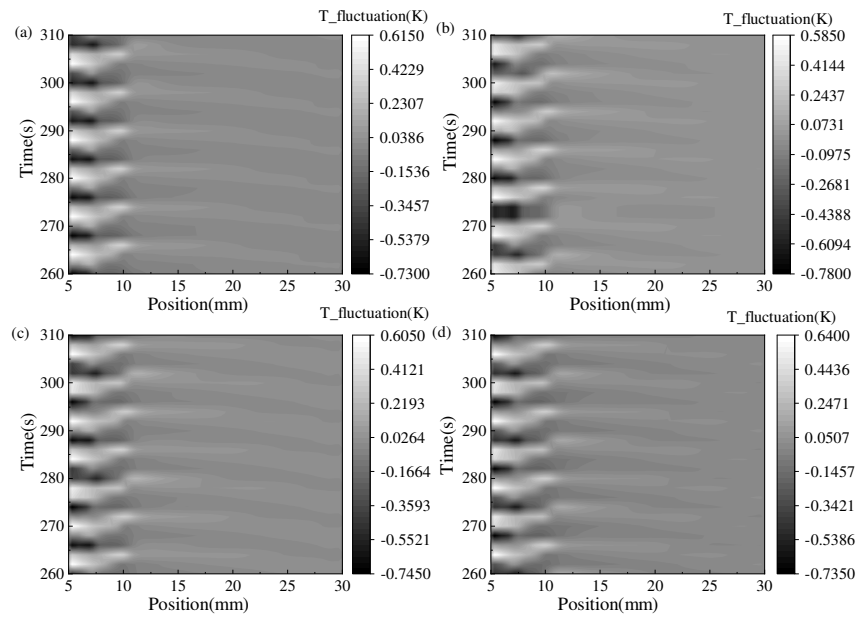
2
3 **Fig. 6.** Stream function and vorticity strength of $d=1.25$ mm under various temperature
4 differences. ($\phi=0\%$, $d=2.5$ mm, $G=0.001$ g).

5 4.2 The effect of volume fraction on thermocapillary convection

6 4.2.1 Dynamic evolution characteristics at free surface

7 Spatial-temporal evolution diagrams are graphs that show the pattern of temperature changes
8 over time and space in thermocapillary convective systems, which can help researchers gain insight
9 into the dynamic behavior of fluids, the development of instabilities, and the mechanisms of heat
10 transfer. Fig. 7 shows the Spatial-temporal evolution diagram of temperature fluctuations of
11 nanofluid at different volume fractions. From the figure, it is shown that when observing
12 temperature fluctuations over time at a fixed spatial location, persistent alternating black-and-white
13 ripples are found. This indicates a possible composite pattern within the system, where propagating
14 traveling waves superimpose upon local oscillations. The distinct diagonal stripes observed between
15 270s and 290s further validate the presence of traveling waves, propagating at a constant speed
16 through space. Overall, the temperature fluctuations exhibit continuous and smooth evolution,

1 indicating the system has established a relatively stable wave pattern. It is noteworthy that in the
 2 spatial-temporal map temperature fluctuations vary across different locations. Near the hot wall
 3 surface ($5 \text{ mm} < r < 10 \text{ mm}$), temperature fluctuations reach 0.70 K. As distance extends radially
 4 toward the cold wall surface, these fluctuations gradually diminish. Near the cold wall surface (25
 5 $\text{mm} < r < 30 \text{ mm}$), fluctuations are only 0.20 K. Furthermore, as the nanofluid concentration
 6 increases, temperature fluctuations near the cold wall surface become increasingly weaker.



7
 8 **Fig. 7.** Temperature fluctuation spatial-temporal evolution diagram along the radial direction at
 9 free surface under different volume fractions(a. $\varphi=1.0\%$, b. $\varphi=1.5\%$, c. $\varphi=2.0\%$, d. $\varphi=2.5\%$; $\varphi=0\%$,
 10 $d=2.5 \text{ mm}$, $G=0.001 \text{ g}$).

11 **Figure 8** shows the temperature distribution and power spectrum distribution of nanofluid with
 12 different volume fractions at measurement point 1 at free surface. The temperature distribution plot
 13 reveals distinct peaks and troughs in the temperature time series, exhibiting sawtooth-like periodic
 14 fluctuations. The average temperature fluctuation across all volume fractions is 298.823 K. However,
 15 the amplitude of temperature fluctuations at volume fractions ranging from 1% to 2.5% is 0.528 K,
 16 0.554 K, 0.568 K, and 0.614 K, respectively, with higher volume fractions exhibiting greater

1 amplitude. Additionally, the phase of temperature fluctuations at 1.5%, 2%, and 2.5% exhibited
2 delays of 0.3s, 0.8s, and 1.2s, respectively, compared to the 1%. In the power spectral distributions,
3 the vertical axis is logarithmically scaled to highlight differences between groups. The dominant
4 frequency of the power spectrum for 1% and 1.5% is 0.379 Hz, corresponding to a temperature
5 fluctuation period of 2.64 s, while the dominant frequency for 1% and 1.5% is 0.359 Hz,
6 corresponding to a temperature fluctuation period of 2.78 s. The fluctuation dominant frequency
7 decreases slightly with increasing volume fraction. Nanofluid with higher volume fractions exhibit
8 greater viscosity and enhanced thermal conductivity. These changes of physical properties increase
9 resistance to fluid motion and weaken the intensity of thermocapillary convection, thereby reducing
10 the periodic oscillation frequency of the free surface temperature. In the low-frequency range of
11 0~0.4 Hz, the 1.50% exhibits the strongest fluctuation energy, while the 2.00% concentration shows
12 the weakest. Particularly in the mid-frequency range of 0.4~1 Hz, the 2.00% and 2.50%
13 concentrations demonstrate spectral power peaks significantly higher than other concentrations. In
14 the high-frequency range of 1~5 Hz, the high-frequency components of the power spectrum
15 gradually increase with rising volume fraction. Concurrently, the power spectrum flattens relatively,
16 with the dominant frequency peak no longer prominent. The increased energy contribution from
17 high-frequency components also indicates growing nonlinear effects, suggesting the flow becomes
18 more complex.

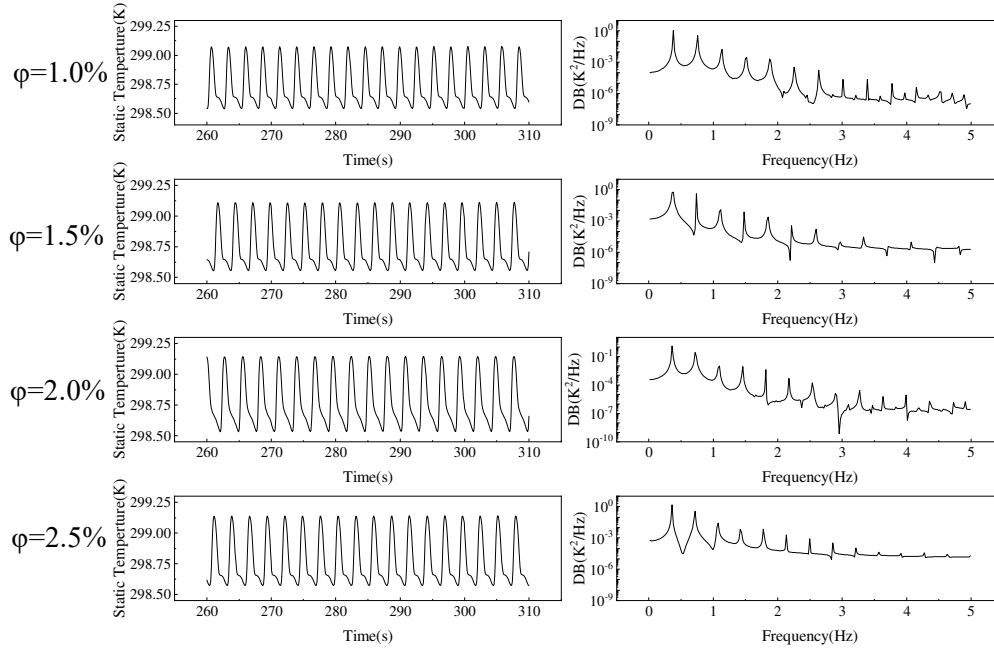
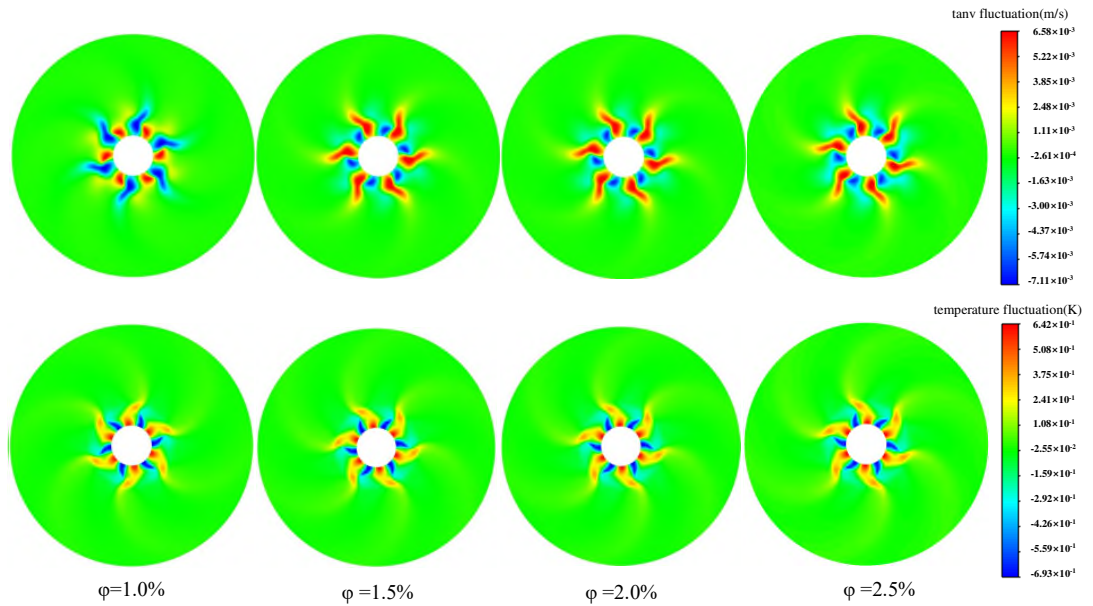


Fig. 8. Temperature curves and power spectral distributions at point 1 for nanofluid with different volume fractions. ($d=2.5\text{mm}$, $\Delta T=20\text{ K}$, $G=0.001\text{ g}$).

4.2.2 Fluctuation characteristics of nanofluid at free surface

Figure 9 shows the variation in tangential velocity and temperature fluctuations at free surface of nanofluid with different volume fractions. The fluctuations in tangential velocity and temperature exhibit a regular radial petal-like structure. Six distinct sectors are observed near the heated wall surface. Within this concentration range, the thermocapillary convection fluctuation pattern remains relatively stable and is strongly influenced by the heated wall surface. When $\phi \leq 1.0\%$, the viscosity and thermal conductivity of the nanofluid exhibit minimal alteration, with flow behaviour approximating that of the pure base fluid. At this stage, the development of nanofluid instability closely resembles pure fluid patterns, manifesting as counter-clockwise surface wave structures. When $\phi \geq 1.5\%$, the viscosity and thermal conductivity undergo significant modification, inducing a reversal in the overall flow structure, which then exhibits clockwise characteristics. As

1 the volume fraction increases from 1% to 2.5%, both temperature and tangential velocity
2 fluctuations become significantly more pronounced, with an accompanying increase in fluctuation
3 amplitude. At a volume fraction of 1%, the interface fluctuations are relatively gentle, with broad
4 trough structures in the tangential velocity. At volume fractions of 1.5% and 2%, the tangential
5 velocity exhibits sharper peaks, and the trough regions significantly narrow, forming a denser
6 alternating structure. When the volume fraction increases to 2.5%, the tangential velocity
7 fluctuations show a slight radial development. Notably, temperature and velocity fluctuations
8 remain highly spatially coupled throughout, with positive and negative fluctuation regions perfectly
9 corresponding.



10 $\varphi=1.0\%$ $\varphi=1.5\%$ $\varphi=2.0\%$ $\varphi=2.5\%$

11 **Fig. 9.** Temperature and tangential velocity fluctuation contour at free surface for nanofluid with
12 different volume fractions. ($d=2.5\text{mm}$, $\Delta T=20\text{ K}$, $G=0.001\text{ g}$).

13 4.3 The effect of the thickness of nanofluid on thermocapillary convection

14 4.3.1 Dynamic evolution characteristics at free surface

15 **Figure 10** shows the spatiotemporal evolution of temperature fluctuations along the radial
16 direction of the free surface of nanofluid with different thicknesses, specifically 2.5 mm, 5 mm, 7.5

1 mm, and 10 mm. From the spatiotemporal diagram, it can be observed that the thickness of the nanofluid significantly influences the behavior of temperature fluctuations at free surface. At a thickness of 2.5 mm, the spatiotemporal map exhibits regular stripes, with thermocapillary convection continuing in both the temporal and spatial dimensions, and heat transfer at free surface remaining highly stable. When the thickness increases to 5 mm, individual stripe regions become larger and their boundaries more blurred, causing the thermocapillary convection pattern at free surface to transition from periodic oscillations to turbulence. As the thickness of the nanofluid continues to increase, the dominant role of thermocapillary convection gradually diminishes. At a thickness of 7.5 mm, stripe structures are no longer discernible in the spatial-temporal diagram, with only sporadic temperature fluctuation regions remaining, and periodic thermocapillary convection has become extremely weak. When the thickness reaches 10 mm, temperature fluctuations have completely disappeared, and the spatiotemporal map becomes uniformly gray with no stripes. In thicker nanofluid layers, heat transfer along the axial direction is significantly higher than radial transfer, resulting in a substantial decrease in the temperature gradient at free surface. Compared to thinner nanofluid layers, the formation and development of thermocapillary convection are thus suppressed.

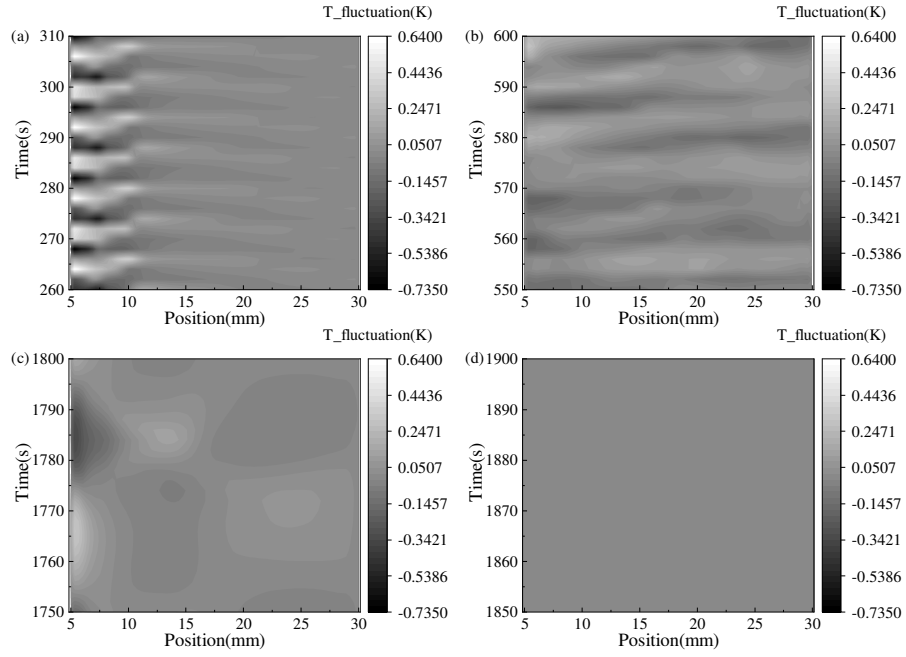
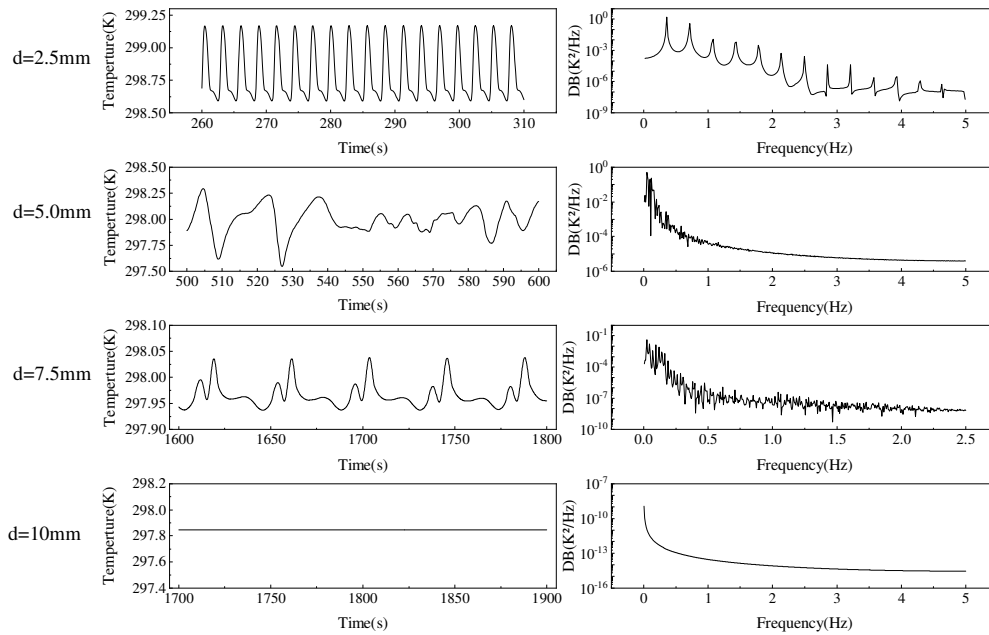


Fig. 10. Temperature fluctuation spatial-temporal evolution diagram along the radial direction at free surface of nanofluid with different thickness. (a. $d=2.5$ mm, b. $d=5.0$ mm, c. $d=7.5$ mm, d. $d=10$ mm; $\phi=2.5\%$, $\Delta T=20$ K, $G=0.001$ g).

Figure 11 shows the temperature curves and power spectrum diagrams of measurement point 1 at free surface of nanofluid with different thicknesses. When the nanofluid thickness is 2.5 mm, the thermocapillary convection at free surface is relatively stable, and a regular periodic temperature fluctuation curve is obtained at the measurement point. The corresponding power spectrum diagram shows a prominent main frequency peak and a series of harmonic peaks in the lower frequency region, with the temperature fluctuation energy primarily concentrated in a single frequency component and its harmonic components. As the thickness increases to 5 mm, the periodicity of the temperature curve significantly weakens. The dominant frequency peak disappears in the power spectrum diagram, and multiple frequency fluctuations coexist. The spectrum curve is no longer a single curve but becomes a broadband, with temperature fluctuation energy more dispersed. When the thickness continues to increase to 7.5 mm and 10 mm, the temperature fluctuations at free surface

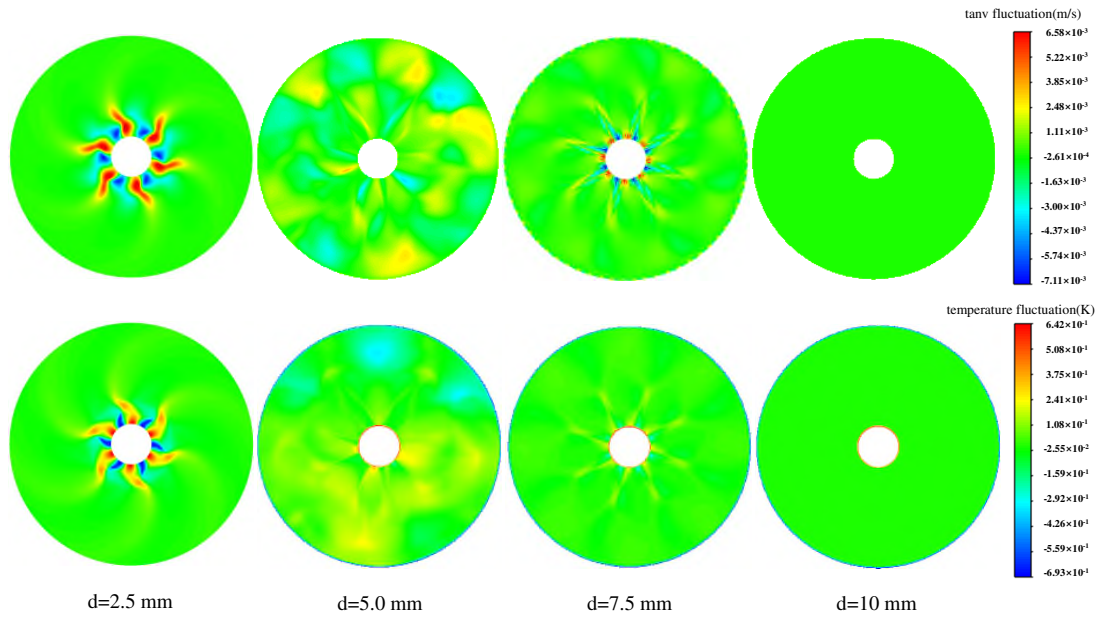
1 become weak, and the temperature curve almost becomes a straight line. In the power spectrum
 2 corresponding to 7.5 mm, the energy level further decreases, though some fluctuations remain in
 3 the low-frequency region, making it difficult to identify a clear dominant frequency. At 10 mm, the
 4 power spectrum approaches a horizontal line, indicating that temperature fluctuations have almost
 5 completely disappeared. It can be concluded that thermocapillary convection is completely
 6 suppressed at this thickness, with heat transfer primarily dominated by axial heat conduction.
 7 Therefore, the thickness of the nanofluid layer is critically important for the formation and stability
 8 of thermocapillary convection. Thinner liquid layers are conducive to the formation and stability of
 9 thermocapillary convection, while excessively thick liquid layers suppress thermocapillary
 10 convection.



11
 12 **Fig. 11.** Temperature curves and power spectral distribution at point 1 for nanofluid with different
 13 thickness. ($\Delta T=20$ K, $\varphi=2.5\%$, $G=0.001$ g).

14 4.3.2 Fluctuation characteristics of nanofluid at free surface

1 **Figure 12** shows the fluctuations in tangential velocity and temperature at free surface of
 2 nanofluid with different thicknesses. When the thickness of the nanofluid increases from 2.5 mm to
 3 5 mm, the fluctuating modal region of the fan-shaped structure at free surface disappears. At this
 4 point, thermocapillary flow becomes disordered, and the fluctuations in tangential velocity and
 5 temperature are distributed more uniformly across the entire free surface. In **Fig. 11** the temperature
 6 fluctuation amplitude of the 7.5 mm nanofluid temperature curve is approximately 0.1 K, which is
 7 lower than that of the 5 mm nanofluid. In this case the tangential velocity and temperature
 8 fluctuations at free surface still exist but are very weak, and thermocapillary convection continues
 9 to play a role. However, when the thickness increases to 10 mm, the fluctuations in tangential
 10 velocity and temperature at free surface disappear, and thermocapillary convection is completely
 11 suppressed, consistent with the conclusions from the time-series analysis.

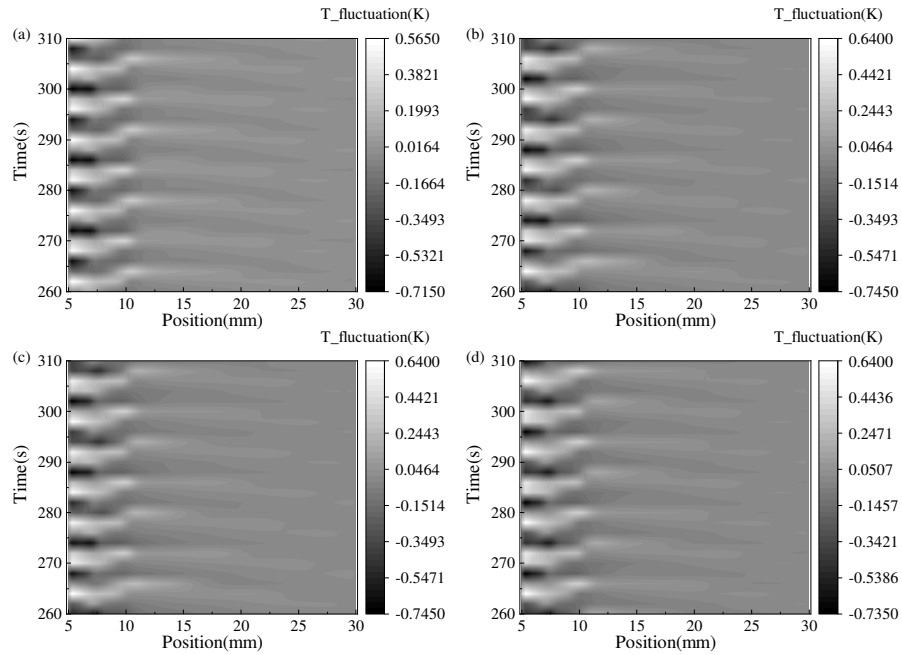


12 **Fig. 12.** Temperature and tangential velocity fluctuation contour at free surface for nanofluid with
 13 different thicknesses. ($\Delta T=20$ K, $\phi=2.5\%$, $G=0.001$ g).

15 4.4 The effect of gravity level on thermocapillary convection

16 4.4.1 Dynamic evolution characteristics at free surface

1 **Figure 13** shows the spatial-temporal evolution of temperature fluctuations in the radial
2 direction of the free surface of the nanofluid at different gravity levels. The evolution of free-surface
3 temperature fluctuations at different gravity levels is almost identical, and the black and white
4 fluctuation stripes are mainly concentrated near the heated wall from 5 mm to 10 mm, while the free
5 surface near the cooled wall from 25 mm to 30 mm is a homogeneous and stable state with almost
6 no fluctuations. This is because the heat input in the region near the heating wall is higher than the
7 dissipated energy, which leads to the temperature fluctuation mainly concentrated in the hot end.
8 The temperature gradient near the cooling wall surface is smaller and uniform at a temperature
9 difference of 20 K, so it is difficult to maintain significant fluctuations in the thermocapillary force.
10 They both have almost the same evolution process of thermocapillary convection.



11
12 **Fig. 13.** Temperature fluctuation spatial-temporal evolution diagram along the radial direction at
13 free surface of nanofluid with different gravity. (a. $G=g$, b. $G=0.1$ g, c. $G=0.01$ g, d. $G=0.001$ g;

14 $\varphi=2.5\%$, $d=2.5$ mm, $\Delta T=20$ K).

15 **Figure 14** shows the temperature profile and power spectral density plot of the detection point

1 of the free surface of the nanofluid under different gravity conditions. The thermocapillary
2 convection at free surface of the nanofluid is stable under standard gravity conditions, and the
3 temperature profile shows regular periodic fluctuations. The corresponding power spectrogram
4 shows that there are obvious main frequency peaks and overtone harmonic peaks in the low
5 frequency interval. With the gradual decrease of gravity, the temperature profile still has good
6 periodicity, and the fluctuation amplitude of the profile is not much different from that of the normal
7 gravity condition. The main frequency peaks in the power spectral distribution plot are still
8 significant, and the frequencies of the main peaks are the same as 0.359 HZ even though the gravity
9 level decreases, which indicates that the change of gravity does not affect the period of the
10 fluctuation. The difference with normal gravity is that the density curve of the power spectral
11 distribution under microgravity becomes slightly flat, the proportion of the curve in the high-
12 frequency interval becomes more, and the energy level of the temperature fluctuation also rises,
13 which is caused by the energy dispersion due to the increase of the nonlinear effect of
14 thermocapillary convection under the microgravity condition.

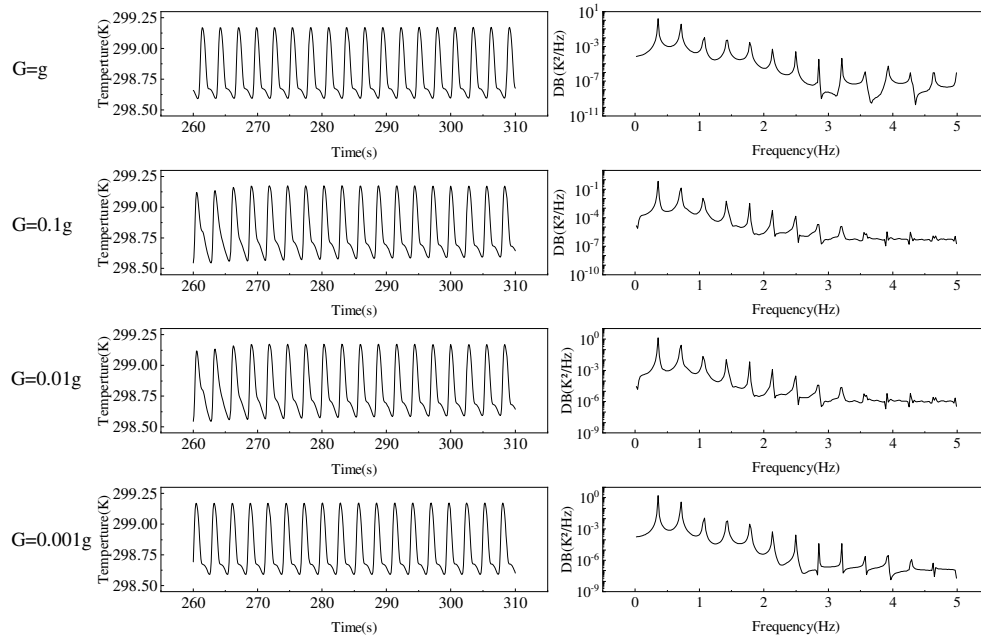
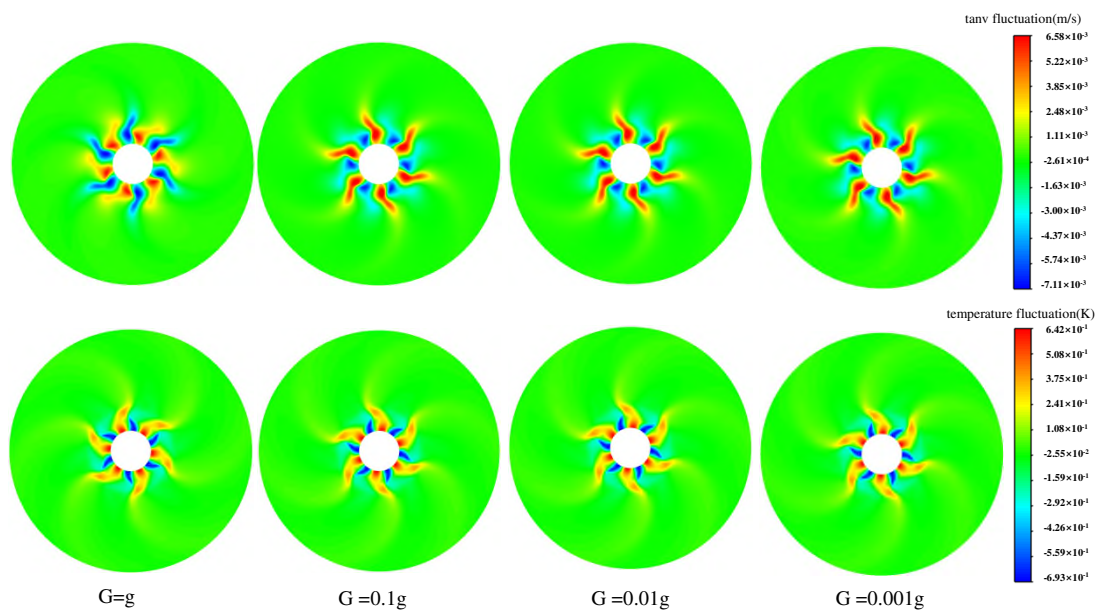


Fig. 14. Temperature and power spectral distributions at point 1 for nanofluid under different gravity conditions ($\phi=2.5\%$, $d=2.5\text{mm}$, $\Delta T=20\text{ K}$).

4.4.2 Fluctuation characteristics of nanofluid at free surface

Figure 15 presents the tangential velocity and temperature fluctuations at free surface under different gravity conditions. From **Fig. 15**, it can be seen that the positive and negative fluctuations of the tangential velocity of the free surface under normal gravity have obvious boundaries, and the areas of positive and negative fluctuations are relatively close to each other, but the fluctuation pattern of the free surface changes with the reduction of the gravity level, the area of negative fluctuations decreases significantly, and the strength of positive fluctuations shows a gradual weakening trend. Positive temperature fluctuations at free surface behave similarly to tangential velocity fluctuations, both of which are gradually weakened with decreasing gravity. This phenomenon also reflects that the temperature and tangential velocity of thermocapillary convection are still highly coupled at free surface during the gravity change. Under normal gravitational

1 condition, buoyancy driven convection is stronger than thermal capillary convection, and it
 2 suppresses the clockwise oscillatory structures induced by changes in the physical properties of
 3 high-concentration nanoparticles. Thus, the oscillatory patterns revert to a state closer to the counter-
 4 clockwise oscillations observed in low-concentration or pure fluid systems. This demonstrates that
 5 buoyancy exerts a more dominant influence than nanoparticle property modulation in determining
 6 the selection of oscillatory modes. The shift in the fluctuation pattern is related to the attenuation of
 7 the buoyancy effect, which gradually loses its dominant role in the convective process due to the
 8 decrease in gravity, while the role of the thermocapillary effect gradually comes to the fore. The
 9 structure and distribution of the fluctuations at free surface are similar in microgravity, and the
 10 fluctuation pattern of thermocapillary convection is the same, but the boundaries of the positive and
 11 negative fluctuation regions at free surface become blurred, and the fan-shaped structure extends
 12 radially outward and the range of fluctuations is slightly enlarged. This indicates that the fluctuation
 13 is no longer limited to the center heating region under microgravity conditions, and the free surface
 14 thermocapillary convection becomes more complicated.



15 $G=g$ $G=0.1g$ $G=0.01g$ $G=0.001g$
 16 **Fig. 15.** Temperature and tangential velocity fluctuation contour plot of free surface with different

gravity of nanofluid ($\phi=2.5\%$, $d=2.5\text{mm}$, $\Delta T=20\text{ K}$).

5. Conclusion

In this study, the nanofluid thermocapillary fluctuation characteristics in an annular liquid pool in a microgravity environment are systematically investigated by numerical simulation methods. The influence of nanoparticles volume fraction, thickness, and gravity level, on the thermocapillary convection are revealed. The main conclusions are as follows:

(1) The volume fraction of nanofluid, the thickness of the liquid layer and the gravity level have a significant effect on the thermocapillary convection fluctuation pattern. As the volume fraction of nanoparticles increases from 1.0% to 2.5%, the amplitude of free surface temperature fluctuations shows an increasing trend. At the same time, there is a lag in the fluctuation phase, with a maximum lag of 1.2 seconds. Quantitative analysis of power spectrum shows that the dominant frequency has decreased from 0.379 Hz to 0.359 Hz, and the high volume fraction nanofluid has an extended fluctuation period due to increased viscosity. Under high volume fraction, the proportion of energy in the high-frequency region of the spectrum increases, the main peak tends to flatten, the nonlinear effects of the system are enhanced, and the flow structure tends to become more complex. The change in volume fraction of nanofluid affects the instability and energy distribution characteristics of thermocapillary convection.

(2) For the thickness of the liquid layer ($d<5\text{ mm}$), the free surface is dominated by thermocapillary convection, and the spatial-temporal evolution diagram of the temperature fluctuations shows black and white stripes. As the thickness increases, the heated wall transfers a large amount of heat along the axial direction, the temperature gradient at free surface decreases, the thermocapillary convection is thus suppressed, and the temperature fluctuations become

1 irregular from periodic until they disappear completely.

2 (3) The intensity of free-surface fluctuations increases when switching from normal gravity to
3 microgravity. When the gravity is reduced to 0.001 g in the microgravity environment, the
4 range of free surface fluctuations is slightly extended, and the dominant frequency of the
5 temperature power spectrum does not change, but it is more dispersed in the high-frequency
6 energy interval, which implies an enhanced nonlinear effect of thermocapillary convection.

7

8

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14 editing. Yuequn Tao: Investigation, Writing - review and editing. All authors reviewed the
15 manuscript.

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

18 **Declarations**

19 **Ethics approval** Not applicable (for studies not involving humans or animals).

20 **Consent to publish** Not applicable.

21 **Consent to participate** Not applicable.

22 **Competing interests** The authors declare no competing interests.

2 Nomenclature

$(c_p)_f$	the specific heat capacity of the base fluid, J/(kg·K)
$(c_p)_{nf}$	the specific heat capacity of the nanofluid, J/(kg·K)
$(c_p)_p$	the specific heat capacity of the nanoparticle, J/(kg·K)
d	thickness of nanofluid liquid layer, mm
e	the internal energy per unit mass of the nanofluid, J/kg
h	the static enthalpy per unit mass of the nanofluid, J/kg
p	pressure of the nanofluid, Pa
r	the inner diameter of annular liquid pool, m
R	the outer diameter of annular liquid pool, m
T	the temperature of the nanofluid, K
v	the velocity magnitude of the nanofluid, m/s;
$\vec{v}$	the vector velocity of the nanofluid, m/s

Greek symbols

λ_f	the thermal conductivity of the base fluid, W/(m·K)
λ_{nf}	thermal conductivity of nanofluid, W/(m·K)
λ_p	the thermal conductivity of the nanoparticles, W/(m·K)
μ	the dynamic viscosity of the base fluid, kg/(m·s)
μ_{nf}	the dynamic viscosity of the nanofluid, kg/(m·s)
ρ_f	the density of the base fluid, kg/m ³
ρ_{nf}	nanofluid density, kg/m ³

τ the time of continuous heating of the inwall, s

φ the volume fraction of the nanofluid

Subscripts

f fluid

p nanoparticle

nf nanofluid

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