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Numerical Study of the Complexity of the Velocity Field at the Nucleation Site in Water Saturated Nucleate Boiling

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Abstract: ***This study presents a numerical investigation of bubble growth during nucleate boiling in water using the finite element method via COMSOL Multiphysics. The analysis focuses on the evolution of the velocity field at the nucleation site under varying wall heat fluxes. Shannon entropy is employed to quantify the randomness of the velocity field, thereby capturing the complexity during the bubble formation and departure stages. Results show that the entropy values fluctuate during the initial phase and tend to stabilize, with higher heat fluxes leading to greater complexity. These findings provide insights into flow behavior near the boiling surface and enhance the understanding of the phase change processes.***

Keywords: nucleate boiling; bubble growth; heat flux; Shannon entropy

1. Introduction

Nucleate boiling efficiently transfers large amounts of heat with a minimal temperature difference. It has found wide applications in industry. An experimental study of the nucleate boiling of saturated HFE7100 [1] under the condition of atmospheric pressure was carried out, and it was found that the heat transfer coefficient was significantly enhanced after adding nanoparticle. Nucleate boiling experiments were conducted using a copper heater, and structured surfaces were fabricated on the copper heater, resulting in a significant enhancement in thermal performance [2]. A mechanism based on the concept of vapor recoil force was provided to explain boiling crisis phenomena [3]. Based on the topography of the boiling surface and the heterogeneous nucleation principle, a theoretical model was provided to calculate the heat transfer coefficient during the transition from convection to nucleate boiling [4]. Nucleate boiling experiments were conducted on rough and ultra-smooth surfaces, and it was found that the best thermal performance happened by using ultra-smooth surfaces with a small number of imperfections as the heat fluxes increased [5].

The finite element method [6] has been employed to solve a variety of engineering problems in which exact closed-formed solutions are difficult or impossible to obtain, and approximate numerical solutions are needed. In this paper finite element method is used to simulate the growth of the single bubble in water nucleate boiling, and the simulation platform is Comsol Multiphysics.

Shannon entropy [7] is a parameter that qualitatively measures the randomness of a signal. In this paper it is used to measure the randomness of the velocity filed at the nucleation site during the nucleate boiling process.

This paper aims to numerically analyze the evolution of velocity field complexity during single bubble growth in water nucleate boiling using Shannon entropy under different heat flux conditions.

Understanding the complexity of velocity fields during bubble nucleation provides valuable insights for designing efficient heat exchangers and boiling systems. This study offers a novel perspective by integrating entropy-based analysis with numerical simulation.

2. Mathematical Modeling

To model the process of nucleate boiling, Navier-Stokes equation is employed, and phase field equation is also employed to consider the movement of the interface between the liquid and the vapor.

The incompressible Navier-Stokes equation is used to describe the behavior of the liquid phase.

$$\rho_L \frac{\partial \mathbf{u_L}}{\partial t} + \rho_L(\mathbf{u_L}\cdot\nabla)\mathbf{u_L} = \nabla\cdot[-p_L\mathbf{I} + \eta_L(\nabla\mathbf{u_L} + (\nabla\mathbf{u_L})^T)] + \rho_L g \tag{1}$$

$$\nabla\cdot\mathbf{u_L} = 0 \tag{2}$$

where the letter L denotes the liquid phase, ρ_L is the density of the liquid, $\mathbf{u_L}$ is the velocity of the liquid, η_L is the viscosity of the liquid, which measure the resistance of the liquid to deformation, g is the gravitational constant.

As to the description of the behaviour of the vapor phase, the compressible Navier-Stokes equation is used.

$$\rho_v \frac{\partial \mathbf{u_v}}{\partial t} + \rho_v (\mathbf{u_v} \cdot \nabla)\mathbf{u_v} = \nabla \cdot [-p_v \mathbf{I} + \eta_v (\nabla \mathbf{u_v} + (\nabla \mathbf{u_v})^T) - \left(\frac{2}{3}\eta - k_{dv}\right)(\nabla \cdot \mathbf{u_v}) I] + \rho_v g \quad (3)$$

$$\frac{\partial \rho_v}{\partial t} + \nabla \cdot (\rho_v \mathbf{u_v}) = 0 \quad (4)$$

where the letter $\mathbf{v}$ denotes the vapor phase.

The heat conduction in the vapor phase is described by the following equation:

$$\rho_v C_p \frac{\partial T_v}{\partial t} + \rho_v C_p (\mathbf{u_v} \cdot \nabla) T_v = -\nabla \cdot k_v \nabla T_v \quad (5)$$

In the process of boiling, the boundary condition becomes complicated because at the interface, the velocity of the liquid phase is not necessarily equal to the velocity of the vapor phase.

$$\mathbf{u}_{\mathbf{interface}} = \mathbf{u_L} - \frac{\dot{m}}{\rho_L}\mathbf{n} \quad (6)$$

$$\mathbf{n}.\rho_v \mathbf{u_v} = \dot{m}(1 - \frac{\rho_v}{\rho_L}) + (\mathbf{n}.\rho_v \mathbf{u}_L) \quad (7)$$

If no phase change happened (that means $\dot{m} = 0$), it can be known from eq (6) and eq (7) that

$$\mathbf{u}_{\mathbf{interface}} = \mathbf{u_L} = \mathbf{u}_v \quad (8)$$

The balance of the forces acting on the liquid phase is the following:

$$\mathbf{n}.[-p_L \mathbf{I} + \eta_L (\nabla \mathbf{u_L} + (\nabla \mathbf{u_L})^T)] = \dot{m}(\mathbf{u}_L - \mathbf{u}_v) + \sigma k \mathbf{n} + \mathbf{n}.[-p_v]$$

(9)

where the term $\dot{m}(\mathbf{u}_L - \mathbf{u}_v)$ describes the reaction force which is the consequence of the escape of the vapor phase from the liquid surface. The term $\sigma k \mathbf{n}$ is the surface tension. The term $\mathbf{n}.[-p_v \mathbf{I}]$ describes the pressure exerted on the liquid by the vapor. The term $\mathbf{n}.[\eta_v (\nabla \mathbf{u_v} + (\nabla \mathbf{u_v})^T)]$ describes the viscous force exerted on the liquid by the vapor.

The temperature at the interface is the saturation temperature, which is a function of the ambient pressure.

$$T = T_{saturation}(P_{ambient}) \quad (10)$$

The mass flux escaping from the vapor phase is determined as the following:

$$\dot{m} = -\left(\frac{M_v}{\Delta H_{lv}}\right)\mathbf{n} \cdot k_v \nabla T_v \quad (11)$$

where M_v is the molecular weight of the vapor, ΔH_{lv} is the vaporization enthalpy.

The phase-field method [9] is used to describe interface behavior in boiling flows.

The water saturation temperature is 100 °C and the ambient pressure is 1atm. The density of the liquid water is 1000 kg/m^3 and its viscosity is 10^{-3} Pa.s, and the water vapor is assumed to be subject to ideal gas law.

In the simulation a mesh of triangles is employed. The mesh independence verification has been conducted. In the platform of Comsol Multiphysics, the choice of 'fine' in the meshing section is made. The time step is 0.02 second.

Figure 1 shows the simulation result of the bubble growth at the nucleation site.

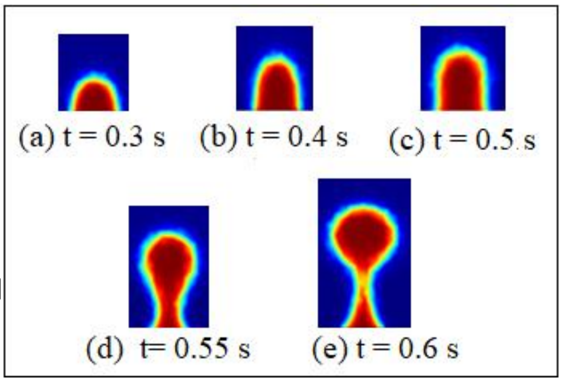

Figure 1: Bubble growth and departure from the heater wall

Figure 2 shows the configuration of the nucleate boiling, in which liquid phase, vapor phase, and the interface are included. Figure 3 shows the sampled area to calculate the Shannon entropy at the nucleation site. The sampled area is a square with side length of 10mm.

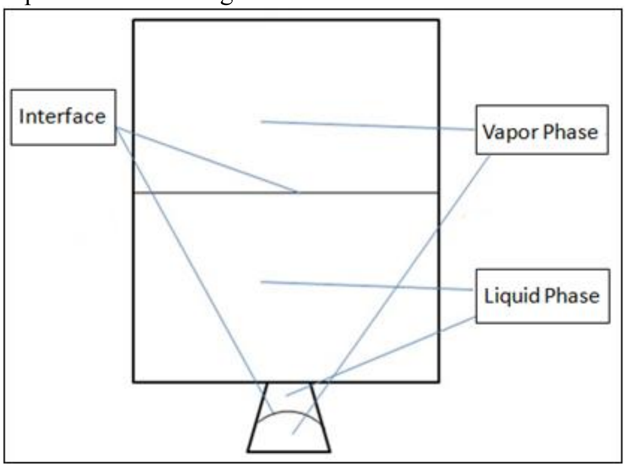

Figure 2: Configuration of the nucleate boiling

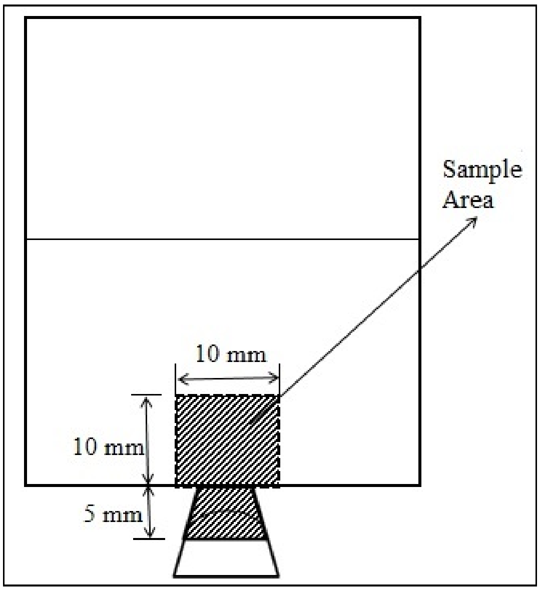

Figure 3: Sampled Area at Nucleation Site

Figure 4 shows a bubble generated at a nucleation site. The red and blue colors correspond to the vapor and liquid phases respectively.

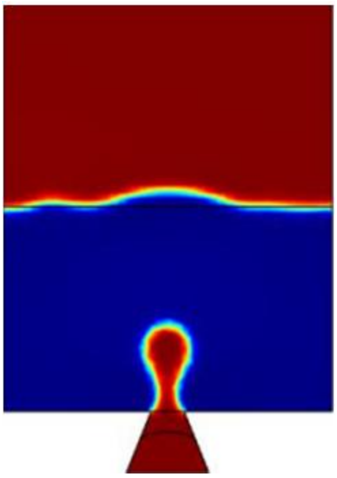

Figure 4: Bubble Generated at Nucleation Site

3. Shannon Entropy

Shannon entropy serves as a qualitative parameter to measure uncertainties of events. If the probability of an event is 1, the uncertainty the event gives to the observer is 0, and the larger is the probability, the smaller is the uncertainty. Mathematically, the definition of Shannon entropy is

$$H = -\sum_i p_i \cdot \log_2 p_i = \sum_i p_i \cdot \log_2 \frac{1}{p_i} \quad (12)$$

where H is the Shannon entropy, p_i is the probability of the i th possible value of the event.

4. The time evolution of the Shannon entropy of velocity field at the nucleation site under the conditions of different wall heat fluxes

Figures 5 to 8 show the time evolutions of the Shannon entropies of the velocity fields at he nucleation site under the conditions of the heat fluxes of 0.8W/m^2, 1.1W/m^2, 1.3W/m^2, and 1.7W/m^2 respectively. The data shows that the Shannon entropies fluctuate approximately between 3 and 6. In the first 0.2 seconds it decreases significantly and then oscillates under the conditions of the heat fluxes of 0.8W/m^2, 1.1W/m^2, and 1.3W/m^2. The Shannon entropy finally converges to about 5 under the condition of the heat flux of 1.7W/m^2.

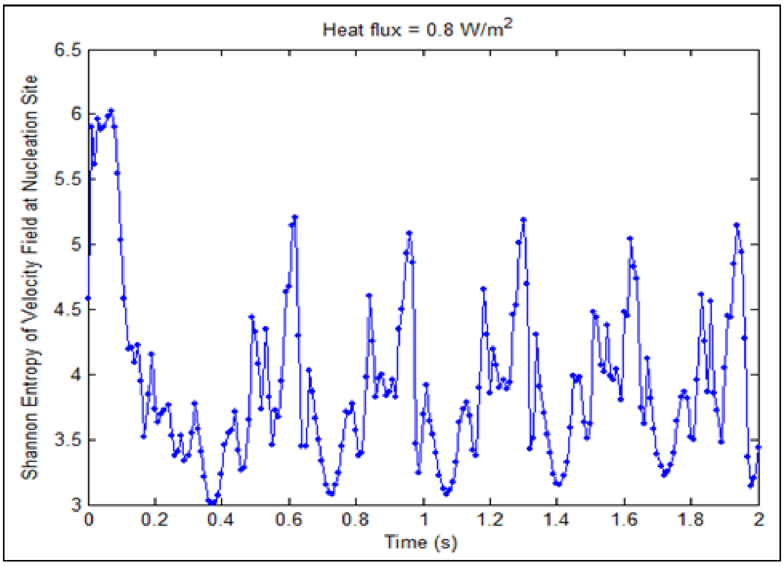

Figure 5: The change of the Shannon entropy of the velocity field at nucleation site under the condition of wall heat flux of 0.8W/m^2

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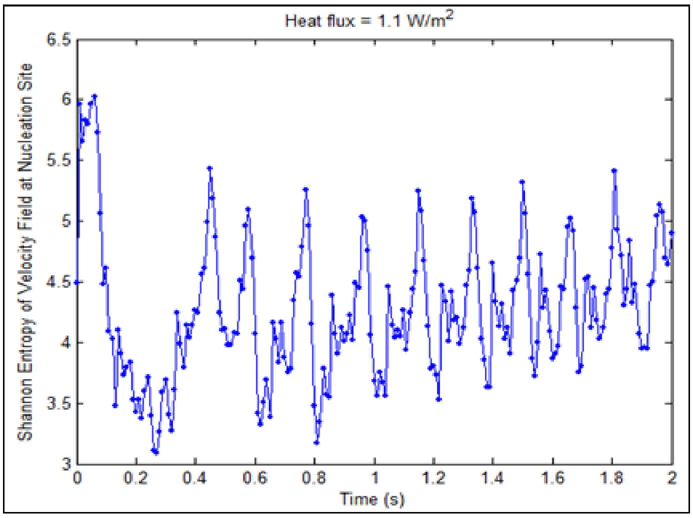

Figure 6: The change of the Shannon entropy of the velocity field at nucleation site under the condition of wall heat flux of 1.1W/m^2

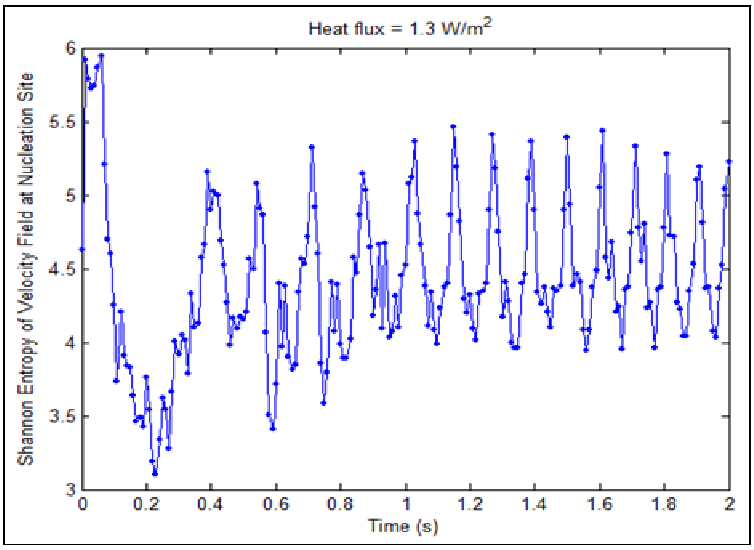

Figure 7: The change of the Shannon entropy of the velocity field at nucleation site under the condition of wall heat flux of 1.3W/m^2

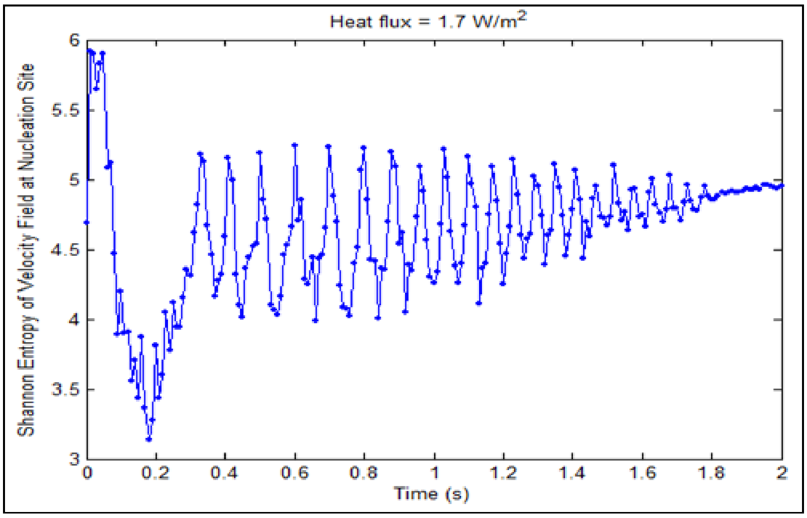

Figure 8: The change of the Shannon entropy of the velocity field at nucleation site under the condition of wall heat flux of 1.7W/m^2

5. Conclusion

This numerical study provides a detailed view of bubble dynamics and the associated complexity of the velocity field during nucleate boiling. By employing Shannon entropy, the study quantifies flow randomness under varying heat fluxes, demonstrating that higher fluxes lead to greater complexity and eventual stabilization. These insights contribute to a deeper understanding of phase-change heat transfer and support the optimization of boiling heat transfer surfaces for industrial applications.

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