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NUMERICAL SIMULATION OF BOILING PROCESS

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ABSTRACT

Main point of interest of our research is the numerical simulation of nucleate boiling. In this paper we present a model which can be used to simulate such processes. The model resolves the interface between (immiscible) phases and belongs to the family of interface capturing methods. It was validated using the cases for which the exact solutions exist. Some qualitative tests on several one- and two-dimensional cases were also performed.

Keywords: nucleate boiling, interface capturing, Plesset-Zwick solution

1. INTRODUCTION

Boiling as the phenomenon plays the important role for efficiency of many industrial technologies. It has great influence on the heat transfer from the wall to the liquid that boils, and depending on the regime of boiling, it can dramatically increase the heat transfer. Sometimes it is the only way to transfer heat away from critical components.

When we talk about regimes of boiling, we should note that in our research we are only interested in the regime called *nucleate boiling*.

The nucleate boiling is a type of boiling that takes place when the surface temperature is higher than the temperature of saturation by a certain amount, but where the heat flux is below the critical heat flux. This is illustrated on Figure 1 (image courtesy of www.thermalfluidscentral.org):

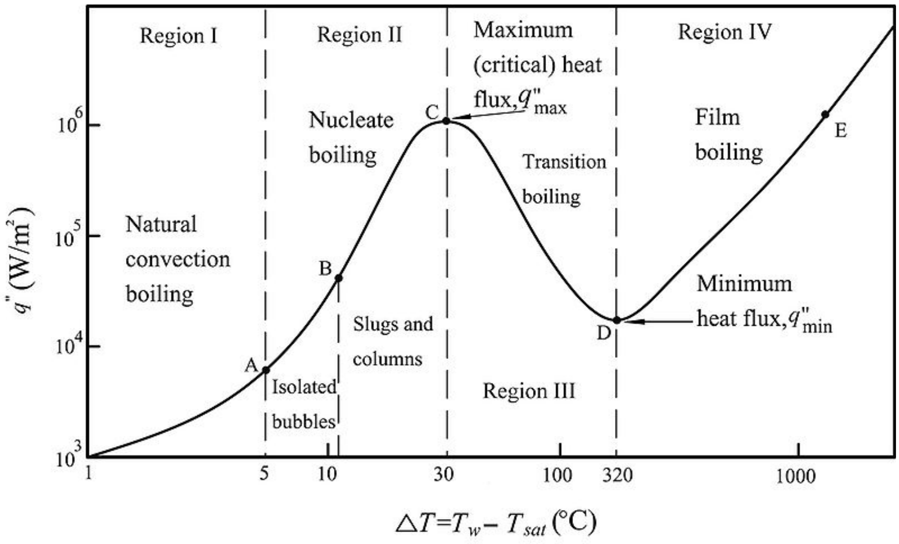

Figure 1: Pool boiling curve for saturated water

We can see here that the heat flux greatly depends on the regime of boiling.

2. MATHEMATICAL MODEL

The mathematical model is based on previous work of Mašić and Muzaferija [1]. Model’s key equations come from the conservation laws in physics. These are:

- The momentum conservation

$$\frac{\partial}{\partial t}\int_V \rho_m \boldsymbol{v}\, dV + \oint_S \rho_m \boldsymbol{v}\boldsymbol{v}\cdot d\boldsymbol{S} = \oint_S \boldsymbol{T}\cdot d\boldsymbol{S} + \int_V \boldsymbol{f}_b\, dV,$$

- The total mass conservation

$$\frac{\partial}{\partial t}\int_V \rho_m\, dV + \oint_S \rho_m \boldsymbol{v}\cdot d\boldsymbol{S} = 0,$$

- The phase mass conservation

$$\frac{\partial}{\partial t}\int_V \rho_i \alpha_i\, dV + \oint_S \rho_i \alpha_i \boldsymbol{v}\cdot d\boldsymbol{S} = \int_V s_{\alpha_i}\, dV,$$

- The specific enthalpy conservation

$$\frac{\partial}{\partial t}\int_V \rho_m h\, dV + \oint_S \rho_m h \boldsymbol{v}\cdot d\boldsymbol{S} = \oint_S \boldsymbol{q}\cdot d\boldsymbol{S} + \int_V s_h\, dV,$$

which are valid for an arbitrary solution domain of the volume V bounded by the surface S, with surface vector $d\boldsymbol{S}$ pointing outwards. Here, ρ_m is the mixture density, $\boldsymbol{v}$ is velocity, $\mathbf{T}$ is the Cauchy stress tensor, $\boldsymbol{f}_b$ is the momentum source, α_i is the volume fraction of phase i, h is the specific enthalpy, $\boldsymbol{q}$ is the local heat flux and s_h is the energy source.

Boiling can take place only in the proximity of the liquid-vapor interface. The rate of evaporation/condensation is modeled as:

$$\dot{m} = K\cdot(T - T_{sat}),$$

where K is a scaling factor and T_{sat} is the saturation or boiling temperature. In our present model K is calculated as

$$K = \frac{m c_p}{h_{lv}\Delta\tau},$$

where m is mass of liquid in the case of evaporation or mass of vapor in the case of condensation present in the control volume, c_p is specific heat, h_{lv} is specific latent heat, and is timescale of the phase change. The rate of evaporation results in additional source terms in the energy and phase volume-fraction transport equations.

3. NUMERICAL IMPLEMENTATION

Numerical procedure is based on the finite volume method, as described in [2]. It uses Cartesian coordinates to define unstructured meshes of arbitrary cell topology (Figure 2).

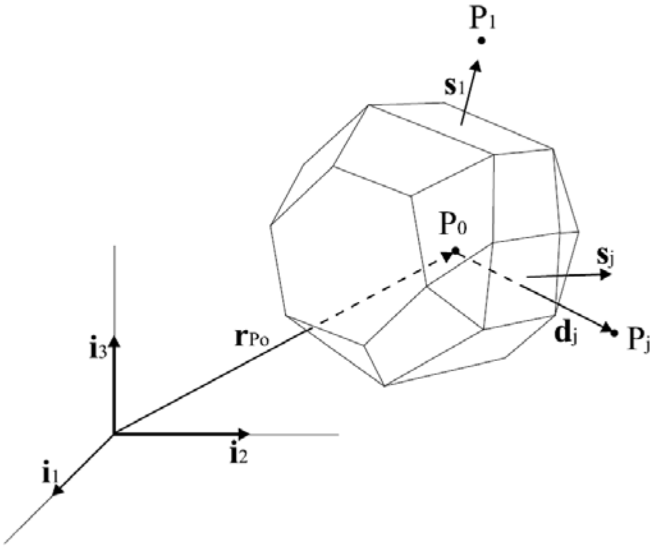

Figure 2: Arbitrary cell

All variables are calculated in cell's centers. Special discretization scheme for convective term was developed - the main goal there was to keep the interface sharp. Pressure is calculated using SIMPLE algorithm.

4. RESULTS

The boiling model is validated using the Stefan problem [3], where we study 1D evaporation in a semi-infinity solution domain. Initially the liquid is at the saturation temperature. The heated wall is at the temperature ΔT above the saturation temperature. The liquid evaporates as it heats up and the newly created vapor pushes the liquid to the right and the vapor column grows displacing the liquid out of the domain. Both phases are incompressible.

The temperature of the liquid phase is constant throughout the simulation, and equal to the initial saturation temperature T_{sat}, while the vapor temperature satisfies the following equation

$$\frac{\partial T}{\partial t} = \frac{k_v}{\rho_v c_{pv}} \frac{\partial^2 T}{\partial x^2}, \quad for\ 0 \le x \le s(t).$$

k_v, ρ_v and c_{pv} are thermal conductivity, density and specific heat of vapor. The position of the interface between the liquid and its vapor $s(t)$ is a function of time. The boundary conditions for the portion of the solution domain occupied with vapor are

$$T(x = s, t) = T_{sat},$$
$$T(x = 0, t) = T_{sat} + \Delta T.$$

The speed v_s at which the interface travels follows from the condition

$$\rho_v v_s h_{lv} = -k_v \left.\frac{\partial T}{\partial x}\right|_{x=s(t)}.$$

The position of the interface $s(t)$ is given by the following expression:

$$s(t) = 2\lambda\sqrt{\alpha t},$$

where α is the thermal diffusivity of the vapor:

$$\alpha = \frac{k_v}{\rho_v c_{pv}}.$$

Parameter λ is the solution of the transcendental equation

$$\lambda e^{\lambda^2} erf(\lambda) = \frac{c_{pv}\Delta T}{h_{lv}\sqrt{\pi}},$$

where the error function is defined as

$$erf(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt.$$

In our simulation ΔT is 25K, and material properties of vapor are $k_v = 0{,}0257$ W/(m·K), $c_{pv} = 1007$ J/(kg·K) and $h_{lv} = 2{,}2 \cdot 10^6$ J/kg. Figure 3 shows the results of our simulation for different values of density of liquid and vapour. Analytical solution was perfectly reproduced.

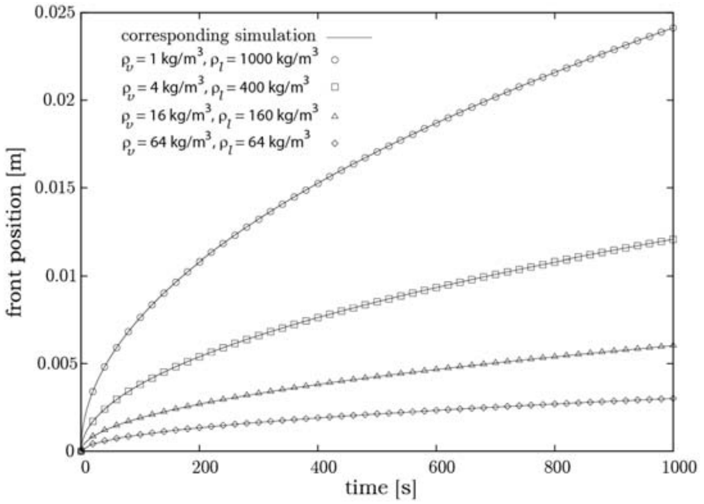

Figure 3: Position of the liquid-vapor interface as a function of time

Next case is the Plesset-Zwick solution [4]. It is a theoretical work on analytical solution for bubble growth in the infinite region of superheated liquid – figure 4 (image courtesy of thermopedia.com)

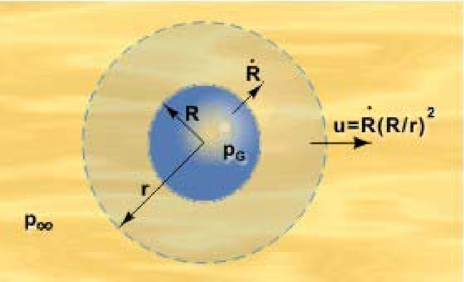

Figure 4: Bubble growth, Plesset-Zwick solution

The solution was derived using several approximations. One of those is the assumption that the thermal boundary layer around the bubble is thin. Taking into account all approximations, they arrived at the following solution for the time evolution of the bubble radius:

$$R(t) = \sqrt{\frac{3}{\pi}\cdot\frac{2k_l(T_\infty - T_{sat})}{h_{lv}\rho_v\sqrt{\alpha_l}}}\cdot\sqrt{t}$$

We performed simulation of this case and compared the results with the solution above. As you can see from figure 5, the agreement is not perfect. But this difference (less than 5%) is quite acceptable, because the Plesset-Zwick solution was derived under various approximations.

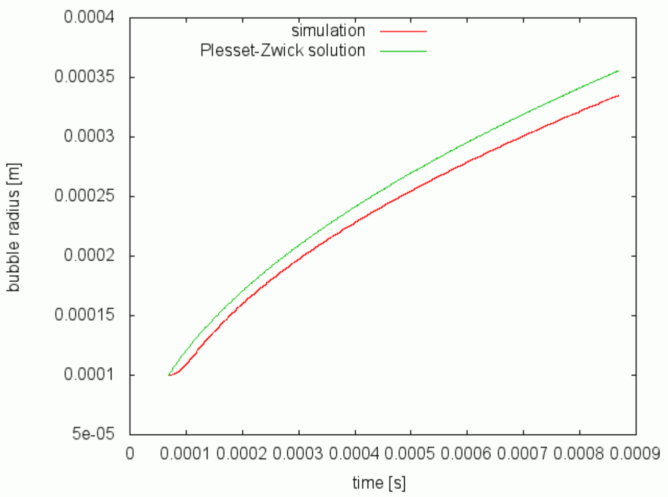

Figure 5: Bubble radius as a function of time

5. CONCLUSION

A boiling model capable of keeping the sharp interface between immiscible fluid phases was developed. It was tested using the Stefan problem and the Plesset-Zwick solution. In the case of Stefan problem perfect agreement with the analytical solution was achieved. Good but not perfect agreement appeared in the case of Plesset-Zwick solution. That could be expected due to all approximations in the Plesset-Zwick solution. All in all, the model passed these analytical (and some other qualitative) tests and it is ready for more complex applications.

6. REFERENCES

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