



# An enthalpy method based on fixed-grid for quasi-steady modeling of solidification/melting processes of pure materials



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## ABSTRACT

We propose a quasi-steady enthalpy method based on fixed-grid to consider the latent heat of phase change during a solidification/melting process of a pure material. The latent heat of phase change released or absorbed at the solid-liquid interface disperses into a region at the interface in the proposed method. It is validated through comparing to the solutions obtained with the adaptive mesh method which is commonly accepted for its accuracy in modeling solidification/melting processes for pure materials. The effects of the dispersed region size and the phase change rate on the simulation accuracy of the proposed method are investigated. Based on the proposed method, a general form of the distribution function of the latent heat of phase change is proposed. The distribution of the latent heat of phase change in the dispersed region is controlled by selecting different forms of distribution function to improve the simulation accuracy. The selecting principle of the distribution function is proposed on the basis of concentrating the latent heat of phase change at the solid-liquid interface. By following the selecting principle, the accuracy can be controlled and the size of the dispersed region does not need to be determined in advance. Two distribution functions of the latent heat of phase change are investigated. Results show that the proper concentration of the latent heat of phase change at the solid-liquid interface is favorable for the simulation accuracy.

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## 1. Introduction

Solid-liquid phase change is of great importance in numerous industrial applications including crystal growth, metallurgy, casting, welding, and heat storage with phase change materials. When the phase of material changes, latent heat of phase change is released or absorbed at the solid-liquid interface whose location is unknown in advance. There are many numerical methods proposed for solid-liquid phase-change problems, which can be broadly classified into three categories: fixed grid methods [1–4], adaptive mesh methods [5], and mixed Eulerian-Lagrangian methods [6]. Enthalpy method is one of the most popular fixed grid methods to solve the solid-liquid phase-change problems. Since it does not need to solve additional equations or adjust the grid to track the interface, the enthalpy method is mathematically and computationally easier to be implemented than other methods. Additionally, it can deal with phase-change problems occurring in both cases at a fixed temperature and in a range of temperature [1,7]. Up to now, the enthalpy method has been widely applied for phase-change problems [8–10].

For the phase change of pure materials which occurs at a fixed temperature, the solid-liquid interface is an infinitely thin interface, rather than a finite region. When the enthalpy method based on fixed grid is applied for modeling solidification/melting processes of pure materials, neither the solid-liquid interface is the boundary of the computational domain nor there are specific meshes corresponding to the interface. Consequently, the shape and the location of the solid-liquid interface are not explicitly traced. The enthalpy method can only be applied for transient and steady modeling of the solidification/melting process of pure materials [9,11,12]. For the transient modeling of phase-change problems, detail information can be obtained for the whole process and the latent heat of phase change is considered. However, the transient simulation is very time-consuming when the phase-change process lasts a long time and the system is complex. For the steady modeling of phase-change problems, the thermal system is assumed in a steady state, and thus the governing equations are simplified by neglecting the transient terms. The steady modeling is consequently easy to be implemented and can save computational resources. Whereas, the phase change rate is ignored and the latent heat of phase change is not considered consequently [11]. However, the latent heat of phase change released or absorbed at the interface is often comparable with the

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conductive/convective heat transfer during a solidification/melting process, which has important effect on the thermal and flow fields [13,14]. Therefore, the latent heat of phase change should be taken into consideration.

Quasi-steady modeling is a compromise between the transient modeling and the steady modeling. It ignores the effect of the solid-liquid interface motion on the temperature and velocity fields, and is thus easier to be implemented than the transient modeling. In addition, the phase change rate is not ignored in order to consider the latent heat of phase change. However, the enthalpy method cannot be applied for the quasi-steady modeling of solidification/melting processes of pure materials. It is because that the latent heat of phase change released or absorbed at the solid-liquid interface cannot be considered since the solid-liquid interface is not explicitly traced. Therefore, it is necessary to investigate the implementation of the latent heat of phase change in the enthalpy method for the quasi-steady modeling of solidification/melting processes of pure materials.

In this study, we firstly propose a simple method for the implementation of the latent heat of phase change in the enthalpy method for the quasi-steady modeling of solidification/melting processes of a pure material. Secondly, a general form of the distribution function of the latent heat of phase change is proposed for this method.

## 2. Numerical modeling of a quasi-steady solid-liquid phase change process of a pure material

### 2.1. The enthalpy method based on fixed-grid for steady state modeling of a solid-liquid system

For the sake of simplicity, it is assumed that the liquid is an incompressible Newtonian fluid with the Boussinesq assumption. The governing equations of mass, momentum and energy for a steady solid-liquid phase change system are as follows [1]:

$$\nabla \cdot \vec{u} = 0 \quad (1)$$

$$\rho \vec{u} \cdot \nabla \vec{u} = -\nabla p + \mu \nabla^2 \vec{u} - \beta \rho \vec{g} (h - h_{ref}) / C_p + \vec{S}_u \quad (2)$$

$$\rho \vec{u} \cdot \nabla h = \nabla \cdot \left( \frac{k}{C_p} \nabla h \right) - S_h \quad (3)$$

where  $\vec{u}$  is the velocity,  $\rho$  is the density,  $p$  is the pressure,  $\mu$  is the dynamic viscosity,  $\beta$  is the thermal expansion coefficient of the fluid,  $\vec{g}$  is the gravitational acceleration,  $C_p$  is the specific heat,  $k$  is the thermal conductivity,  $h$  and  $h_{ref}$  are the sensible heat and reference sensible heat, respectively. The source term  $\vec{S}_u$  in Eq. (2) is the artificial source term, which is zero for the liquid phase region and it ensures that the velocity in the solid phase region is zero [1].

The source term  $S_h$  in the Eq. (3) is a phase related term. According to Voller and Prakash [1], the steady/quasi-steady form of  $S_h$  is given as follows:

$$S_h = \nabla \cdot (\rho \vec{u} \Delta H) \quad (4)$$

where  $\Delta H$  is the latent heat. Whereas, Galione et al. [15] concluded that the convection of latent heat  $\Delta H$  should not be considered since only the liquid phase is transported between cells. Thus  $S_h = 0$  is also applied as the steady/quasi-steady form of  $S_h$  in our study.

The above equations describe the principles of the enthalpy method for a steady solid-liquid phase change system in which the latent heat of phase change is not considered since the phase change rate is ignored. However, the latent heat of phase change absorbed or released at the solid-liquid interface during a solidifi-

cation/melting process must be considered in a quasi-steady modeling.

### 2.2. Implementation of the latent heat of phase change in a quasi-steady modeling of solid-liquid phase change process

#### 2.2.1. A simple method for the implementation of the latent heat of phase change

As the solid-liquid interface is not explicitly traced in the enthalpy method, the latent heat of phase change cannot be directly implemented at the interface as additional heat flux as implemented in the adaptive mesh method [16,17] in the quasi-steady modeling of solid-liquid phase change process. In the proposed simple method, the latent heat of phase change is considered as a volumetric heat source in a specific region in the vicinity of the solid-liquid interface. The specific region is defined as the dispersed region where the latent heat of phase change disperses. For the sake of simplicity, it is assumed that the phase change rate is equal along the solid-liquid interface. The energy conservation equation considering the latent heat of phase change is modified as follows:

$$\rho \vec{u} \cdot \nabla h = \nabla \cdot \left( \frac{k}{C_p} \nabla h \right) - S_h + S_L \quad (5)$$

where  $S_L$  is the source term considering the latent heat of phase change.

To obtain the form of  $S_L$ , a two-dimensional solidification process is investigated for the sake of simplicity. Fig. 1(a) shows the schematic of the implementation of the latent heat of phase change. The isothermal line  $T_m$  is the solid-liquid interface.  $V_{sl}$  is the moving velocity of the solid-liquid interface, whose value is equal to the phase change rate  $V_g$ . As shown in Fig. 1(a), it is assumed that the latent heat of phase change at the solid-liquid interface disperses into the dispersed region (shadow area) where the temperature ranges from  $T_m$  to  $T_m + \Delta T$ . Thus the source term  $S_L$  can be described as:

$$S_L = g_L S'_L \quad (6)$$

where  $g_L$  is introduced to define the dispersed region where the latent heat of phase change disperses, and it is given as follows:

$$g_L = \begin{cases} 0 & T < T_m \text{ or } T > T_m + \Delta T \\ 1 & T_m \leq T \leq T_m + \Delta T \end{cases} \quad (7)$$

In order to determine the form of  $S'_L$ , the distribution of the latent heat of phase change at the solid-liquid interface is analyzed. As shown in Fig. 1(a), the latent heat of phase change  $Q_L$  generated at the element AB of the interface is described as follows:

$$Q_L = \rho V_g L \Delta A_{\perp} \quad (8)$$

where  $\Delta A_{\perp}$  is the projection length (projection area in 3D case) of element AB on the surface perpendicular to  $V_{sl}$ . According to Fig. 1(a), the latent heat of phase change  $Q_L$  is assumed to disperse into the micro region  $ABB'A'$  where  $AA'$  and  $BB'$  are parallel to  $V_{sl}$ .

Fig. 1(b) shows two elements (similar to micro region  $ABB'A'$  in Fig. 1(a)) with the same length  $\Delta A_{\perp}$  in the dispersed region.  $\Delta z_1$  and  $\Delta z_2$  are the heights of the element 1 and element 2 along the direction of  $V_{sl}$ , respectively. The latent heat of phase change generated in elements 1 and 2 are given as follows:

$$Q_L = \rho V_g L \Delta A_{\perp} = S'_{L1} \Delta z_1 \Delta A_{\perp} = S'_{L2} \Delta z_2 \Delta A_{\perp} \quad (9)$$

where  $L$  is the specific latent heat of phase change,  $S'_{L1}$  and  $S'_{L2}$  represent  $S'_L$  in element 1 and element 2, respectively. Eq. (9) can be transformed as follows:

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