Computations of Boiling in Microgravity

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ABSTRACT

The absence (or reduction) of gravity, can lead to major changes in boiling heat transfer. On Earth, convection has a major effect on the heat distribution ahead of an evaporation front, and buoyancy determines the motion of the growing bubbles. In microgravity, convection and buoyancy are absent or greatly reduced and the dynamics of the growing vapor bubbles can change in a fundamental way. In particular, the lack of redistribution of heat can lead to a large superheat and explosive growth of bubbles once they form. While considerable efforts have been devoted to examining boiling experimentally, including the effect of microgravity, theoretical and computational work have been limited.

Here, the growth of boiling bubbles is studied by direct numerical simulations where the flow field is fully resolved and the effects of inertia, viscosity, surface deformation, heat conduction and convection, as well as the phase change, are fully accounted for. Boiling involves both fluid flow and heat transfer and thus requires the solution of the Navier-Stokes and the energy equations. The numerical method is based on writing one set of governing transport equations which is valid in both the liquid and vapor phases. This local, single-field formulation incorporates the effect of the interface in the governing equations as source terms acting only at the interface. These sources account for surface tension and latent heat in the equations for conservation of momentum and energy as well as mass transfer across the interface due to phase change. The single-field formulation naturally incorporates the correct mass, momentum and energy balances across the interface. Integration of the conservation equations across the interface directly yields the jump conditions derived in the local instant formulation for two-phase systems. In the numerical implementation, the conservation equations for the whole computational domain (both vapor and liquid) are solved using a stationary grid and the phase boundary is followed by a moving unstructured two-dimensional grid. While two-dimensional simulations have been used for preliminary studies and to examine the resolution requirement, the focus is on fully three-dimensional simulations.

The numerical methodology, including the parallelization and grid refinement strategy is discussed, and preliminary results shown. For buoyancy driven flow, the heat transfer is in good agreement with experimental correleations. The changes when gravity is turned off and/or fluid shear is added are discussed, as well as the difference between simulations of a layer freely releasing bubbles versus simulations using only one wavelength initial perturbation. Figure 1 shows the early stages of the formation of a three-dimensional bubble from a thin vapor layer. The boundary conditions are periodic in the x and y direction, the bottom is a hot and the top allows a free outflow. The jagged edge of the surface close to the bottom of the computational domain is due to some of the surface elements being on the other side of the domain and some elements not plotted by our plotting routine. In the second figure, we show the temperature distribution through two perpendicular planes.

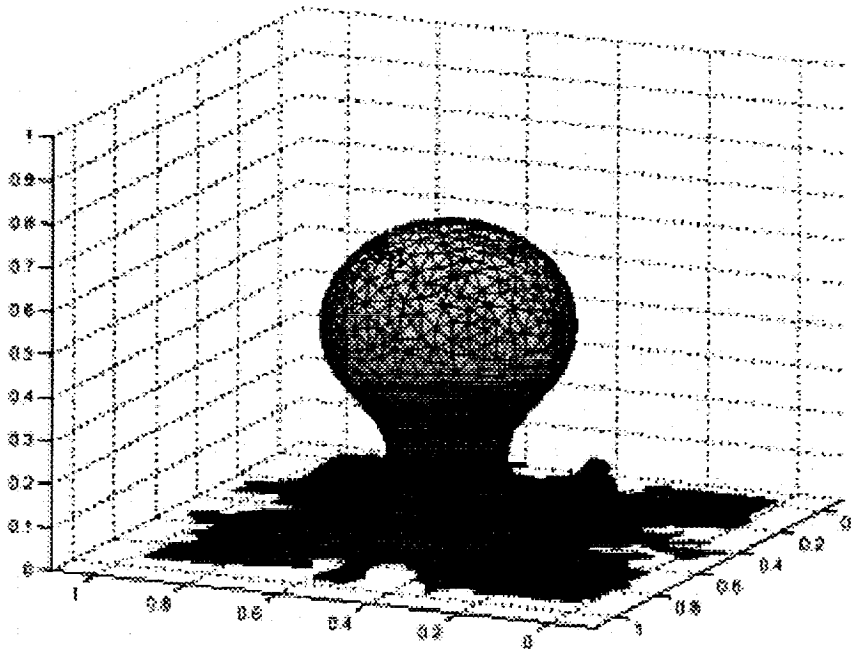

Figure 1. The formation of a bubble from a thin vapor layer. The grid representing the phase boundary is shown after the bubble has formed. The jagged edges of the front are an artifact of plotting of the periodic boundaries.

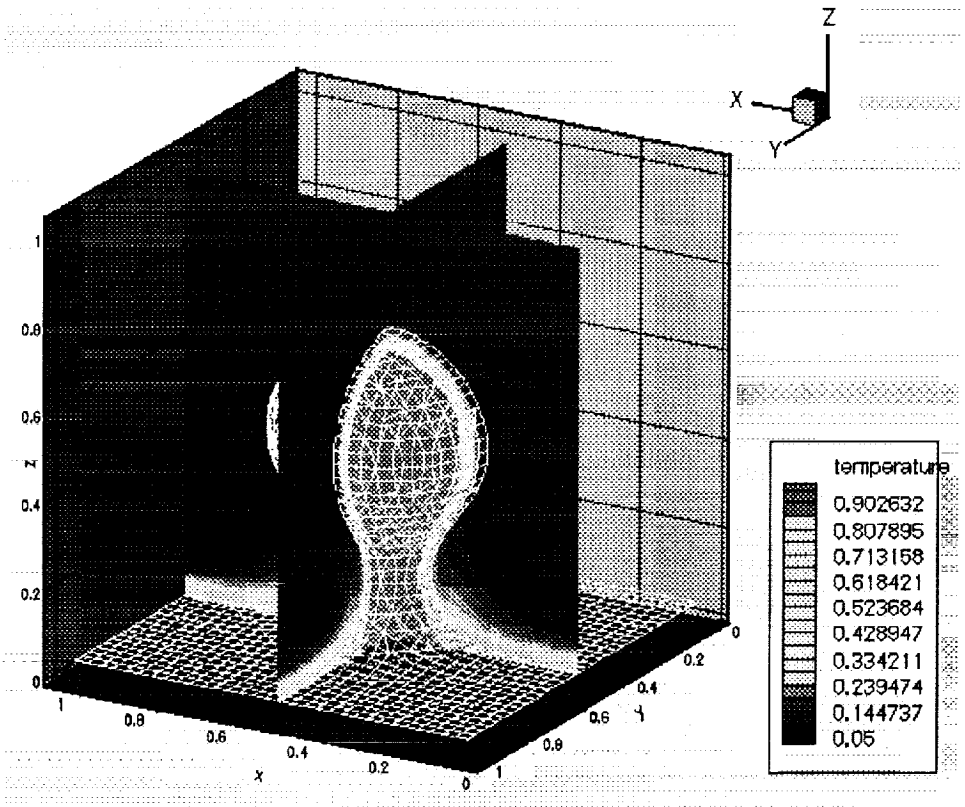

Figure 2. The temperature distribution in a bubble rising from a thin vapor layer. The high temperature in the bubble is represented by a light shades of gray.

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Title

Computations of Boiling Flows

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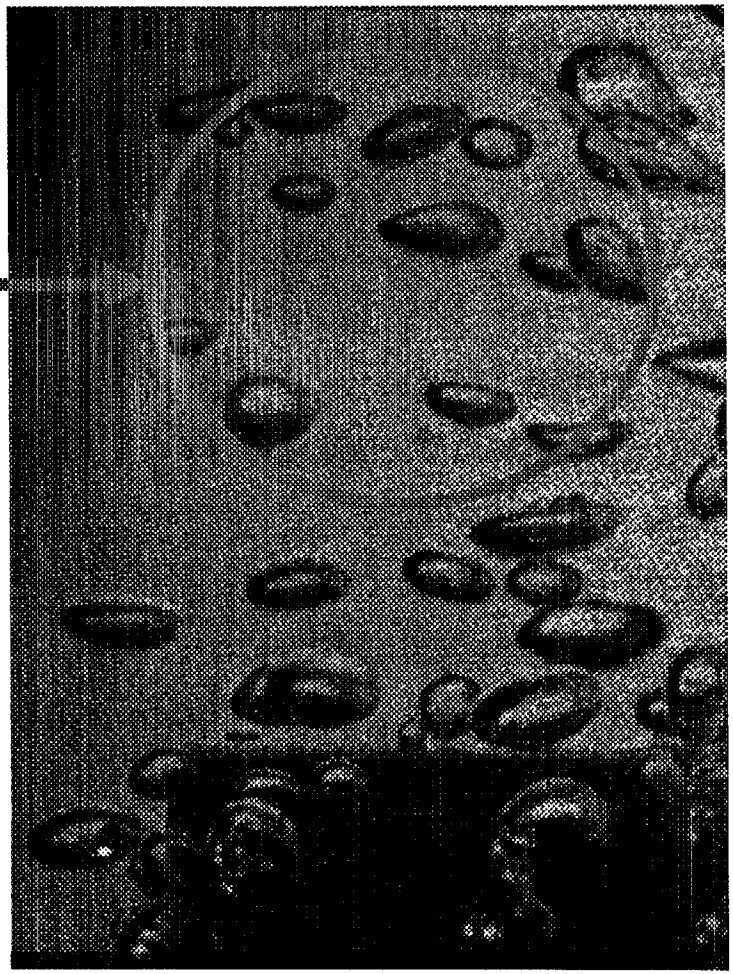
Motivation

Phase change is the most efficient way of transporting heat (as in boiling and refrigeration). However, the results of design or operator error can be catastrophic.

Effect of gravity, flow, binary solute, thermocapillary, surfactants, electric fields, acoustic, and so on are important but still poorly understood.

Motivation

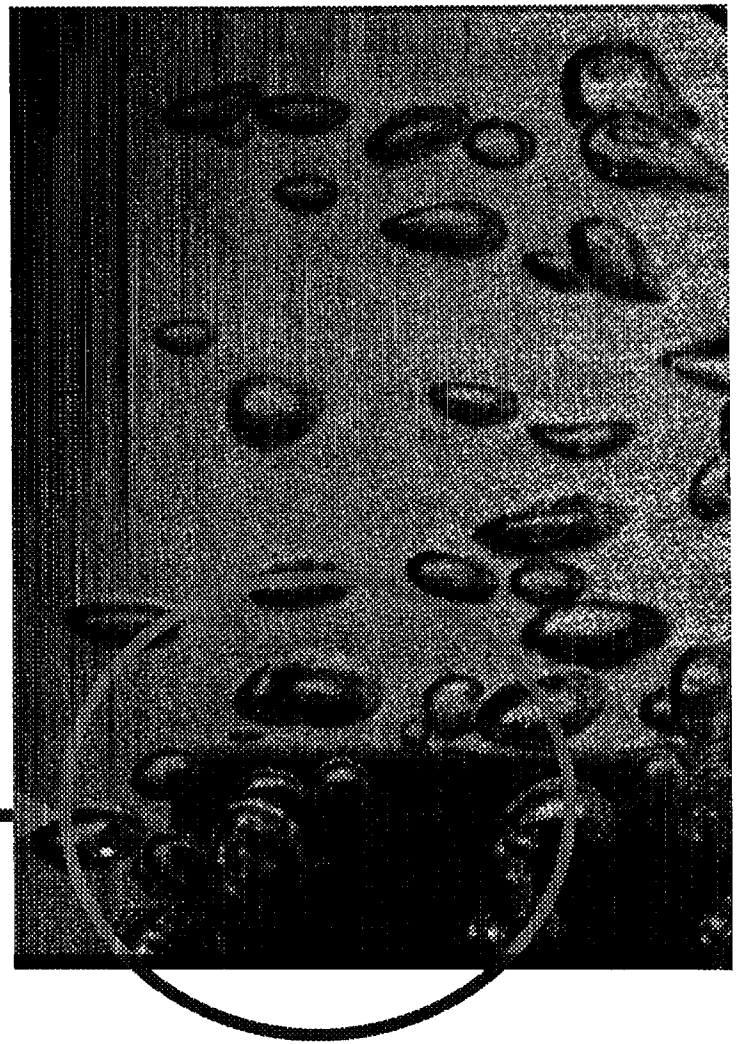
Direct numerical simulations of bubbly flows now allow relatively routine predictions of bubbly flows.



Motivation

Motivation

The formation of bubbles is the critical part of boiling



Boiling Flows—Background

2D simulations by:

D. Juric and G. Tryggvason. Computations of Boiling Flows. *Int'l. J. Multiphase Flow*. 24 (1998), 387-410.

G. Son and V.K. Dhir. Numerical simulation of film boiling near critical pressures with a level set method. *J. Heat Trans*. 120 (1998), 183-192.

S.W.J. Welch and J. Wilson. A volume of fluid based method for fluid flows with phase change. *J. Comp. Phys*. 160 (2000), 662-682.

Governing Equations

Momentum (conservative form, variable density and viscosity)

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \rho \mathbf{u}\mathbf{u} = -\nabla p + \mathbf{f}$$

$$+ \nabla \cdot \mu\left(\nabla \mathbf{u} + \nabla^T \mathbf{u}\right) + \underbrace{\int_F \sigma \kappa \mathbf{n} \delta\left(\mathbf{x} - \mathbf{x}_f\right) dA}_{\text{Singular Interface Term}}$$

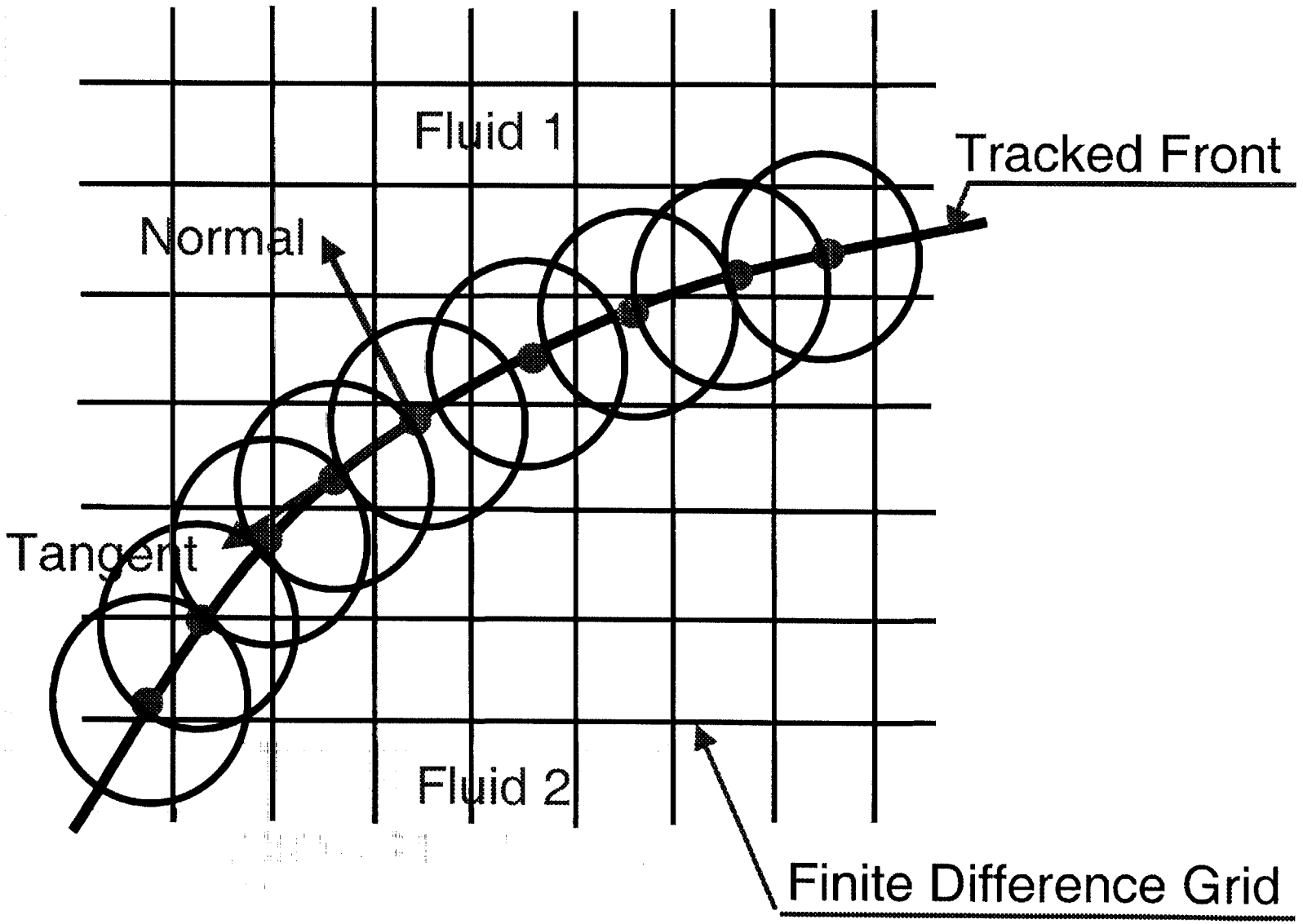
Mass conservation (incompressible flows)

$$\nabla \cdot \mathbf{u} = 0$$

Equations of state (properties of each fluid remain constant)

$$\frac{D\rho}{Dt} = 0; \quad \frac{D\mu}{Dt} = 0$$

Numerical Method

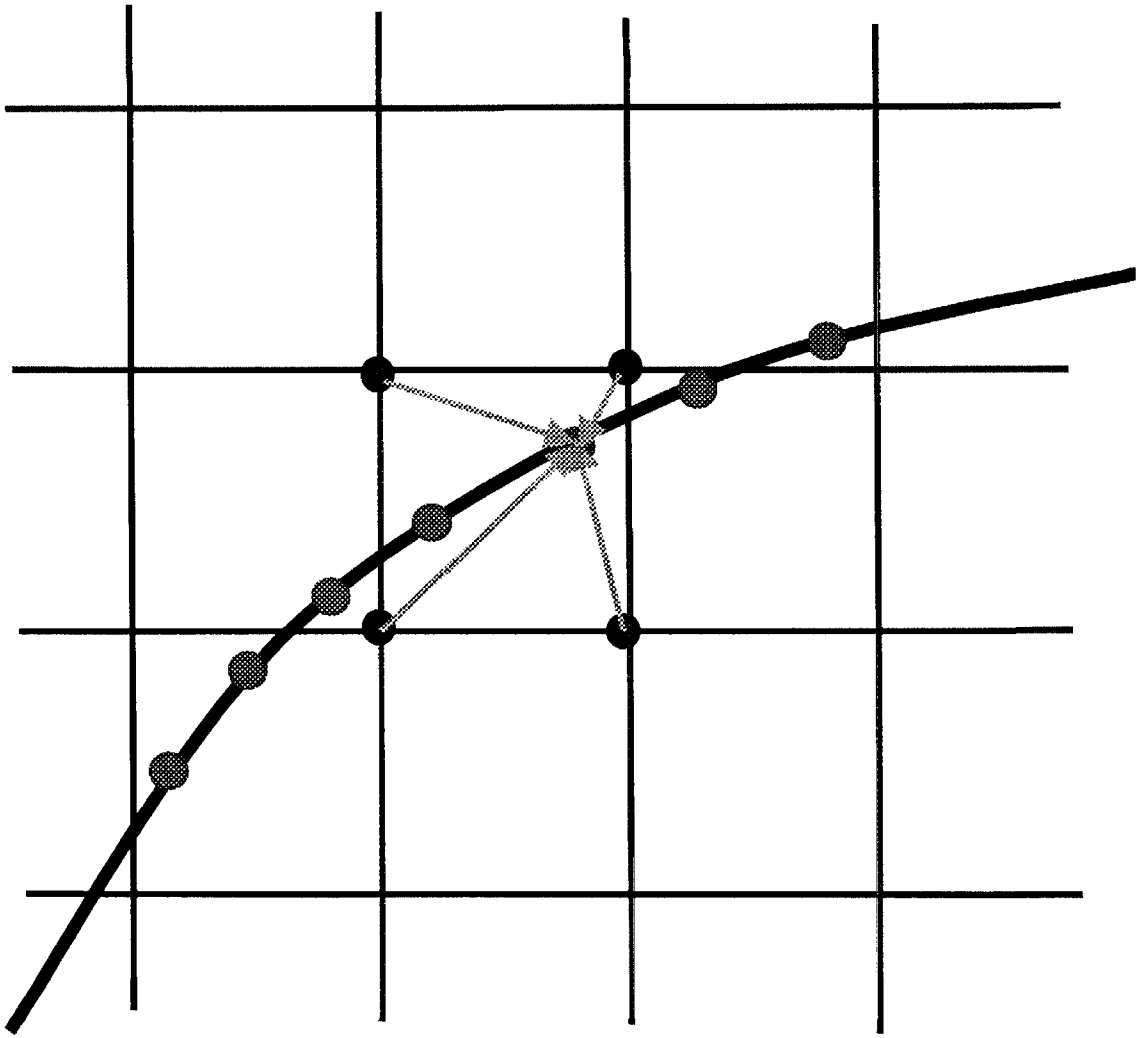


Interpolating from grid

The velocities are interpolated from the grid:

$$\phi_{ijk} = \sum \phi_l w_{ijk}$$

the weights w_{ijk} can be selected in several different ways



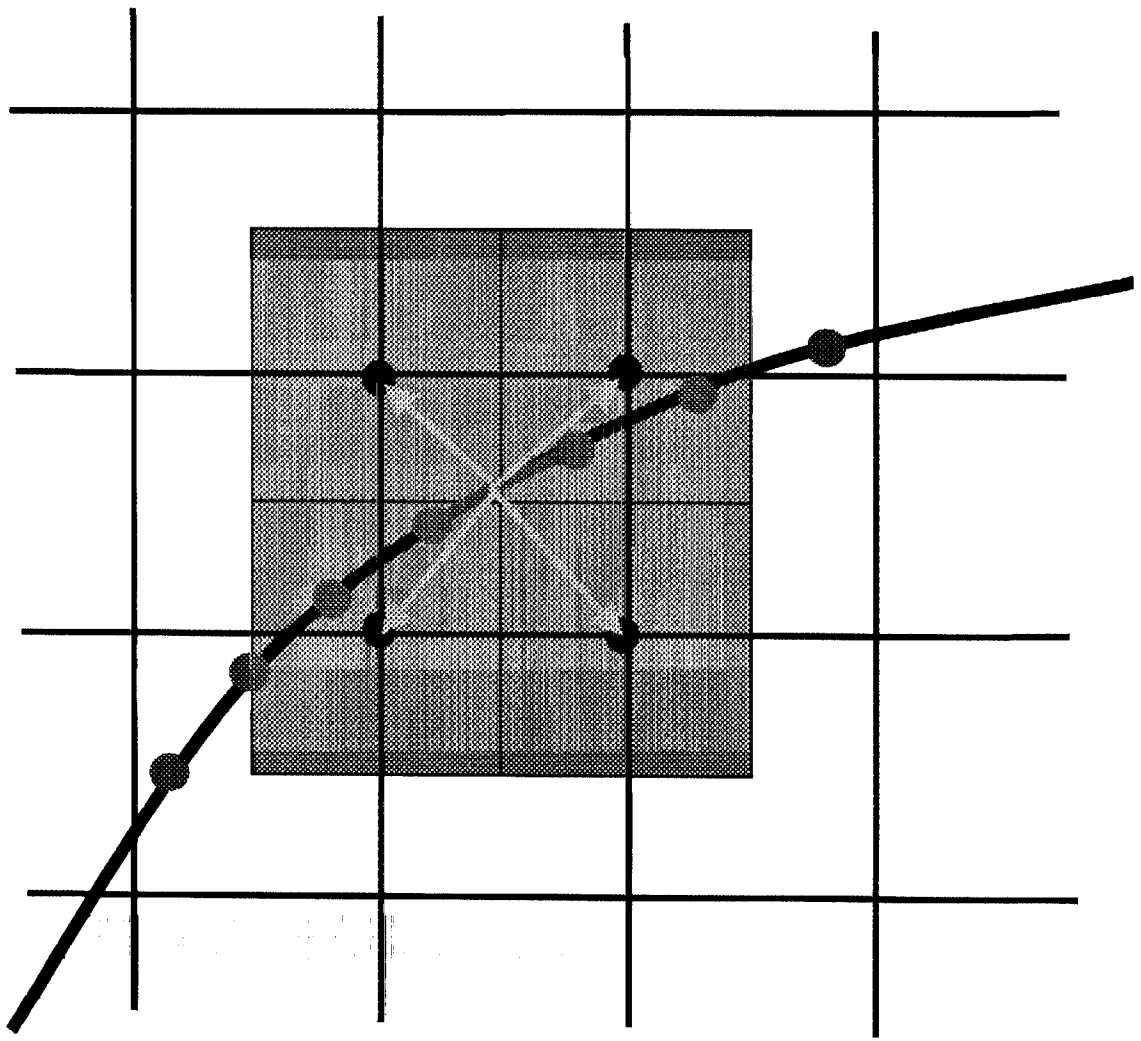
Approximating singular terms

The front values are distributed onto the grid by

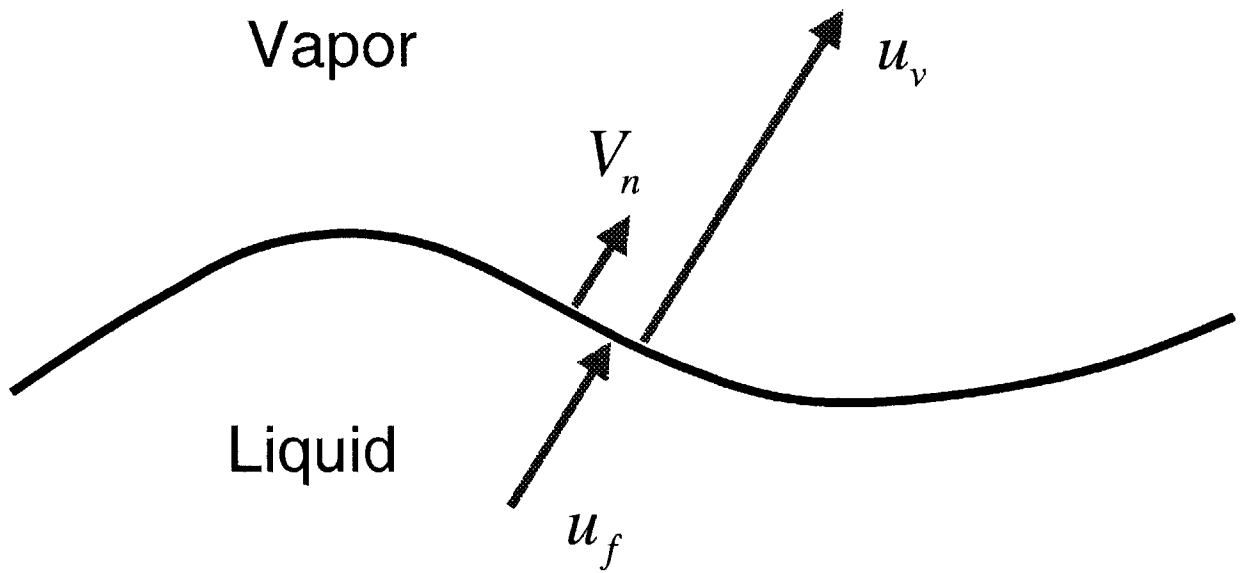
On the front: per length
On the grid: per volume

To conserve integrated value

$$\phi_{ijk} = \sum \phi_l w_{ijk} \frac{\Delta s_l}{h^3}$$



Phase boundary



Phase boundary

Mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{u} = 0$$

The Rankine-Hugoniot conditions give:

$$-V_n\left(\rho_f - \rho_v\right) + \left(u_f \rho_f\right) - \left(u_v \rho_v\right) = 0$$

where

V_n :Velocity of phase boundary

Rewrite:

$$\rho_f\left(u_f - V_n\right) = \rho_v\left(u_v - V_n\right) = \dot{m}$$

Phase boundary

$$\frac{\dot{m}}{\rho_f} = u_f - V_n \quad \text{and} \quad \frac{\dot{m}}{\rho_v} = u_v - V_n$$

Volume Source (subtract)

$$Q = u_f - u_v = \dot{m}\left(\frac{1}{\rho_f} - \frac{1}{\rho_v}\right)$$

Velocity of phase boundary (add)

$$V_n = \frac{1}{2}\left(u_f + u_v\right) - \frac{\dot{m}}{2}\left(\frac{1}{\rho_f} + \frac{1}{\rho_v}\right)$$

Phase boundary

The mass transfer at the phase boundary is proportional to the heat source

$$\dot{m} = \frac{\dot{q}}{L}$$

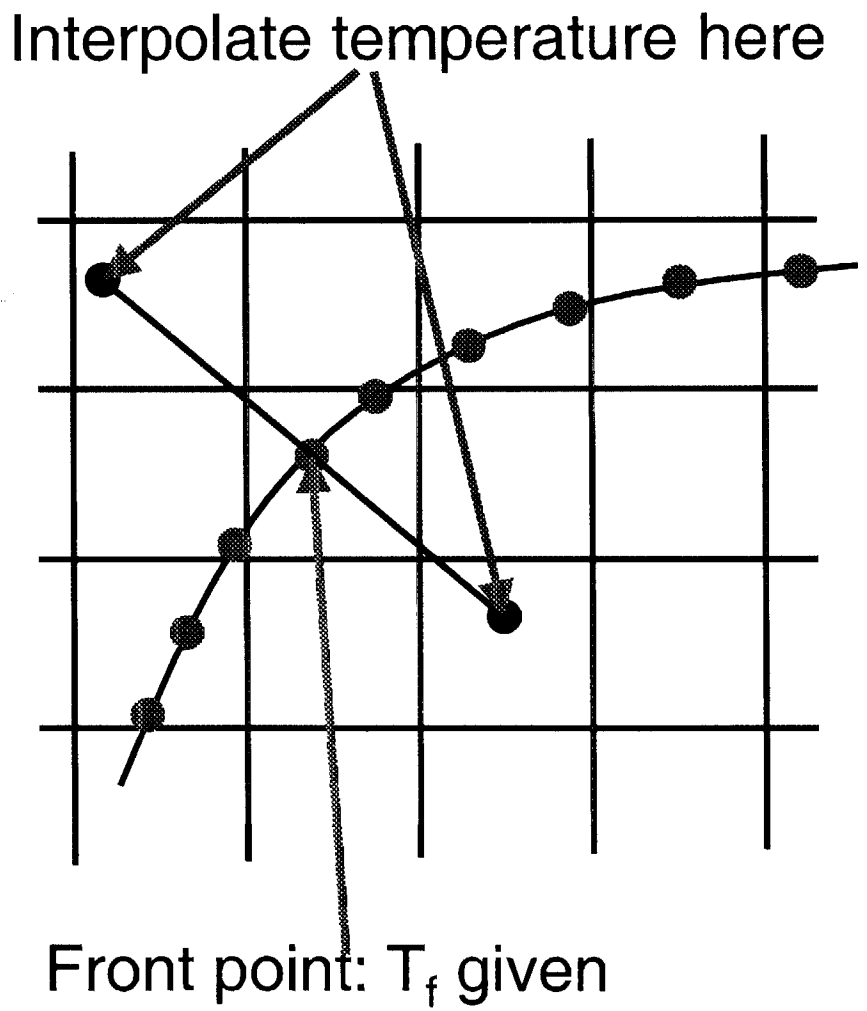
where

$$\dot{q} = k\frac{\partial T}{\partial n}\bigg|_1 - k\frac{\partial T}{\partial n}\bigg|_2$$

Numerical method

Computing the heat source at the phase boundary

$$\dot{q} = k\frac{\partial T}{\partial n}\bigg|_1 - k\frac{\partial T}{\partial n}\bigg|_2$$



Governing equations

Momentum equation

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \rho \mathbf{u}\mathbf{u} = -\nabla p + \mathbf{f}$$

$$+ \nabla \cdot \mu\left(\nabla \mathbf{u} + \nabla^T \mathbf{u}\right) + \int_F \sigma \kappa \, \mathbf{n} \delta\left(\mathbf{x} - \mathbf{x}_f\right) dA$$

Energy equation

$$\frac{\partial c_p \rho T}{\partial t} + \nabla \cdot c_p \rho \mathbf{u} T = \nabla \cdot k \nabla T$$

$$+ \int \dot{q} \delta(\mathbf{x} - \mathbf{x}_f) dA$$

Governing equations

Mass conservation

$$\nabla \cdot \mathbf{u} = \int \dot{m} \left(\frac{1}{\rho_f} - \frac{1}{\rho_v} \right) \delta(\mathbf{x} - \mathbf{x}_f) dA$$

Thermodynamic

$$T_b = T_v(P):$$

Heat source

$$\dot{q} = L\dot{m} \left(\frac{1}{\rho_f} - \frac{1}{\rho_v} \right)$$

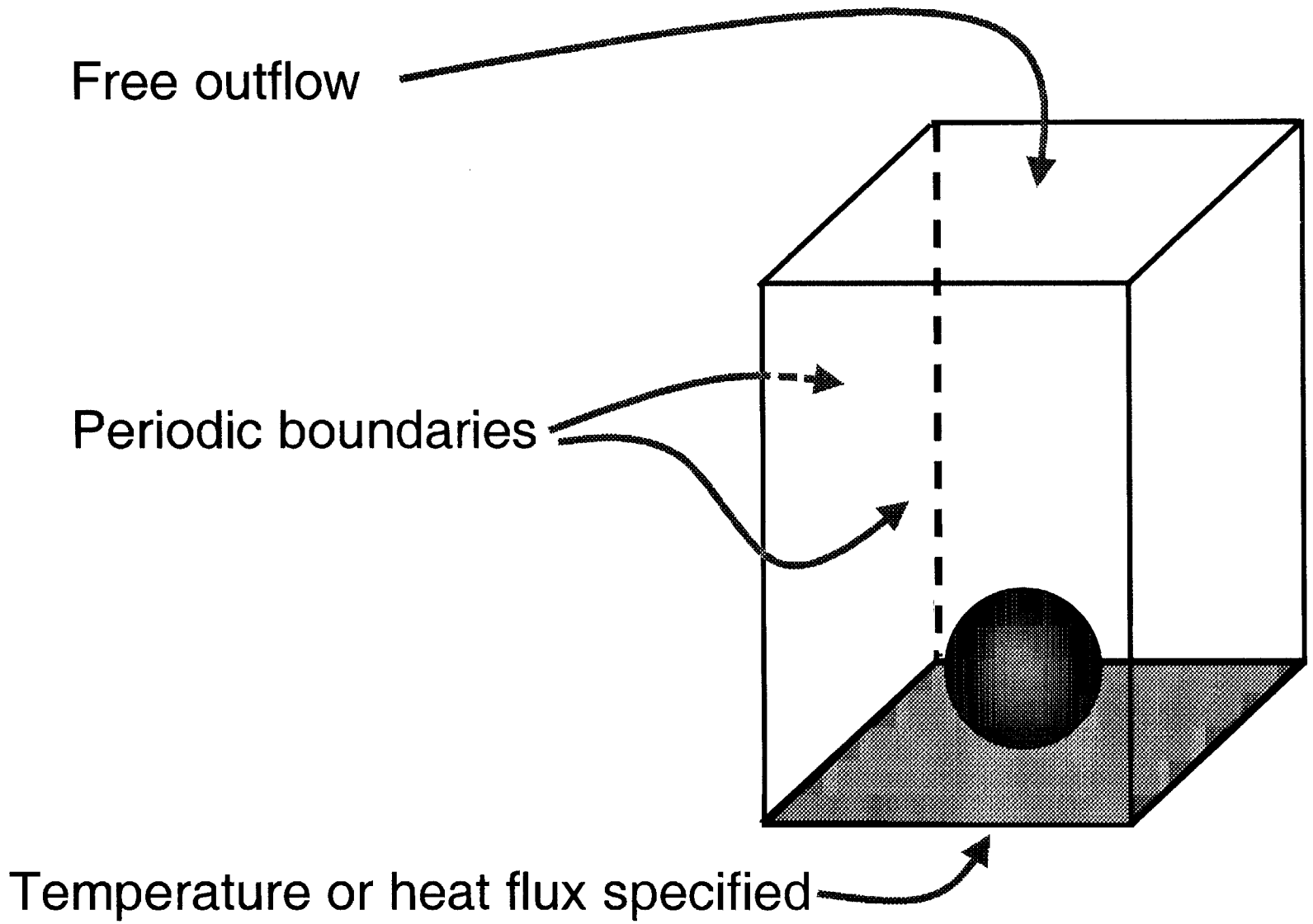
Normal velocity of boundary

$$\frac{d\mathbf{x}_b}{dt} = V_n \mathbf{n}$$

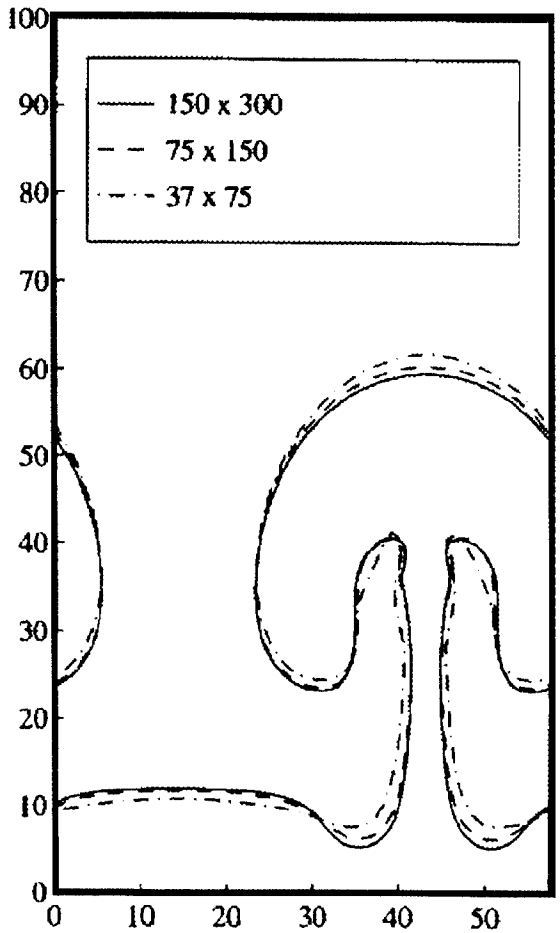
Algorithm

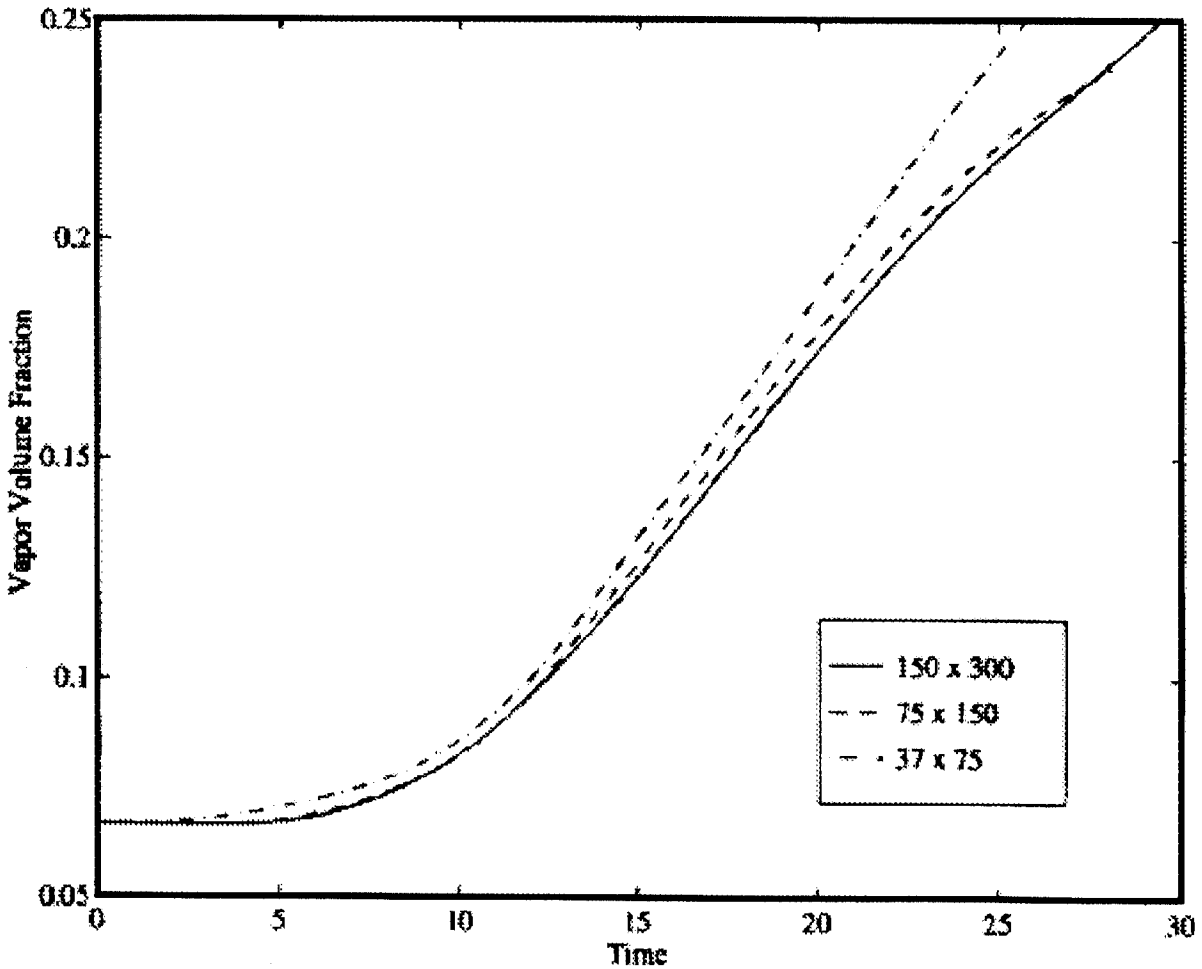
- Find heat source at phase boundary
- Interpolate velocity
- Add evaporation to the velocity
- Advance front to new position
- Update material properties
- Smooth heat source onto grid
- Find temperature at next step by solving the energy equation
- Find unprojected velocity
- Smooth volume source onto grid
- Solve for pressure
- Find corrected velocity

Computational Domain



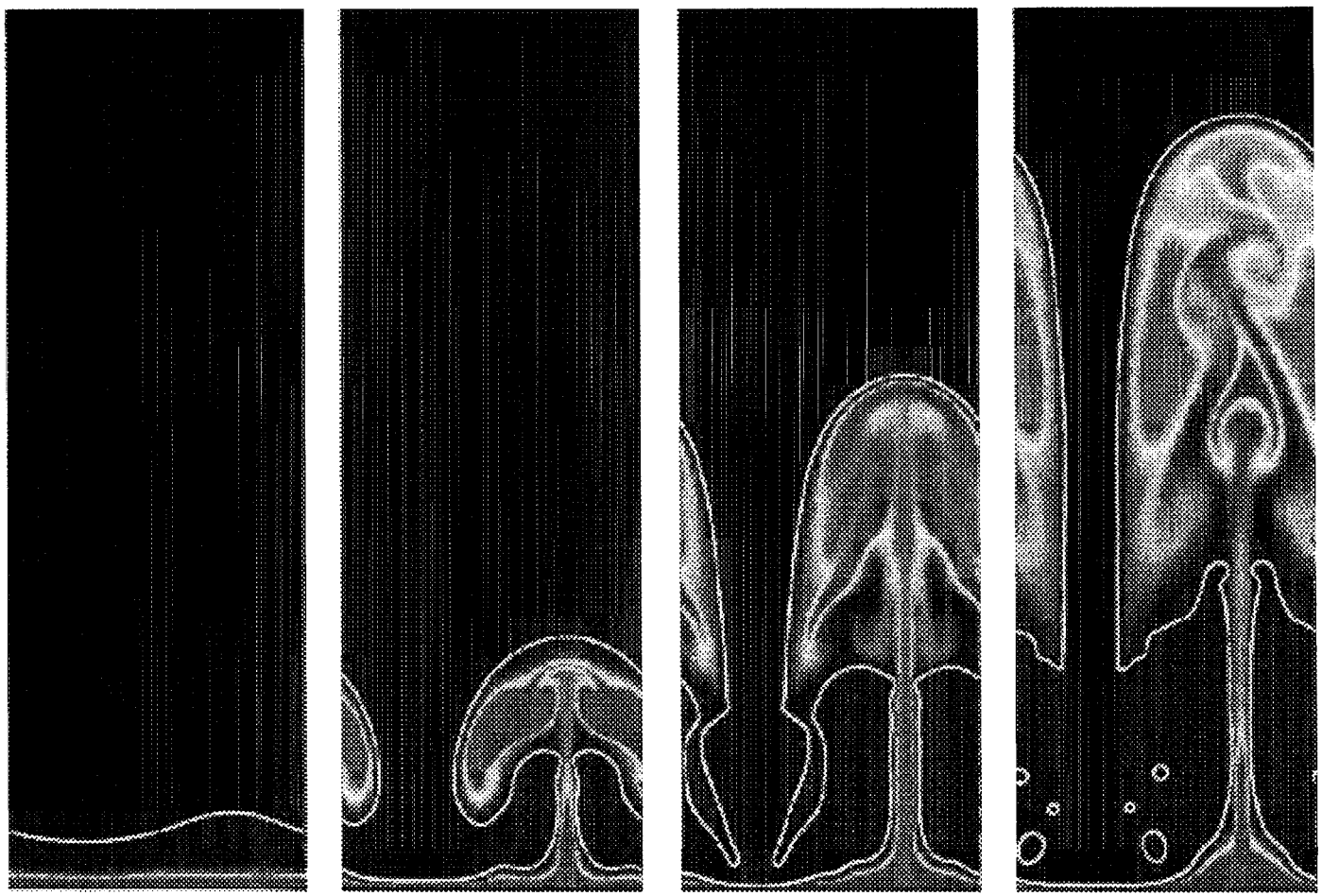
Resolution test



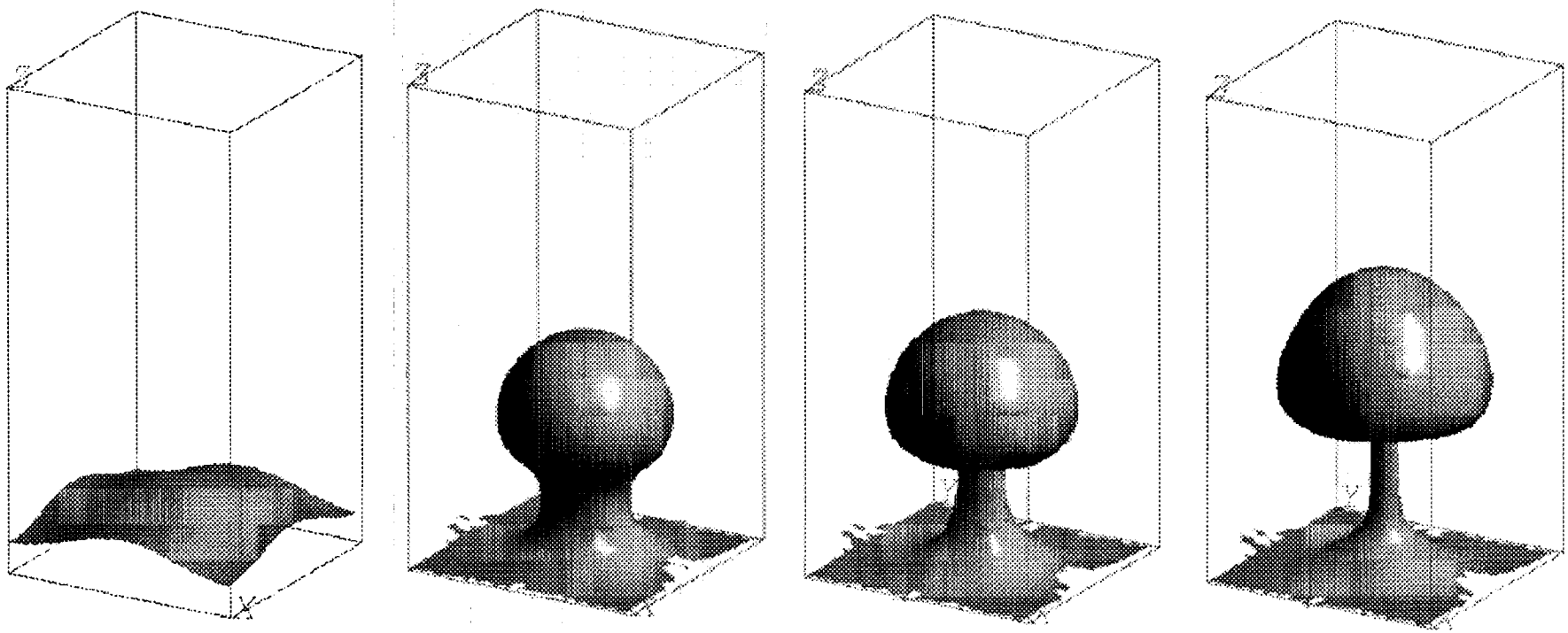


Film Boiling

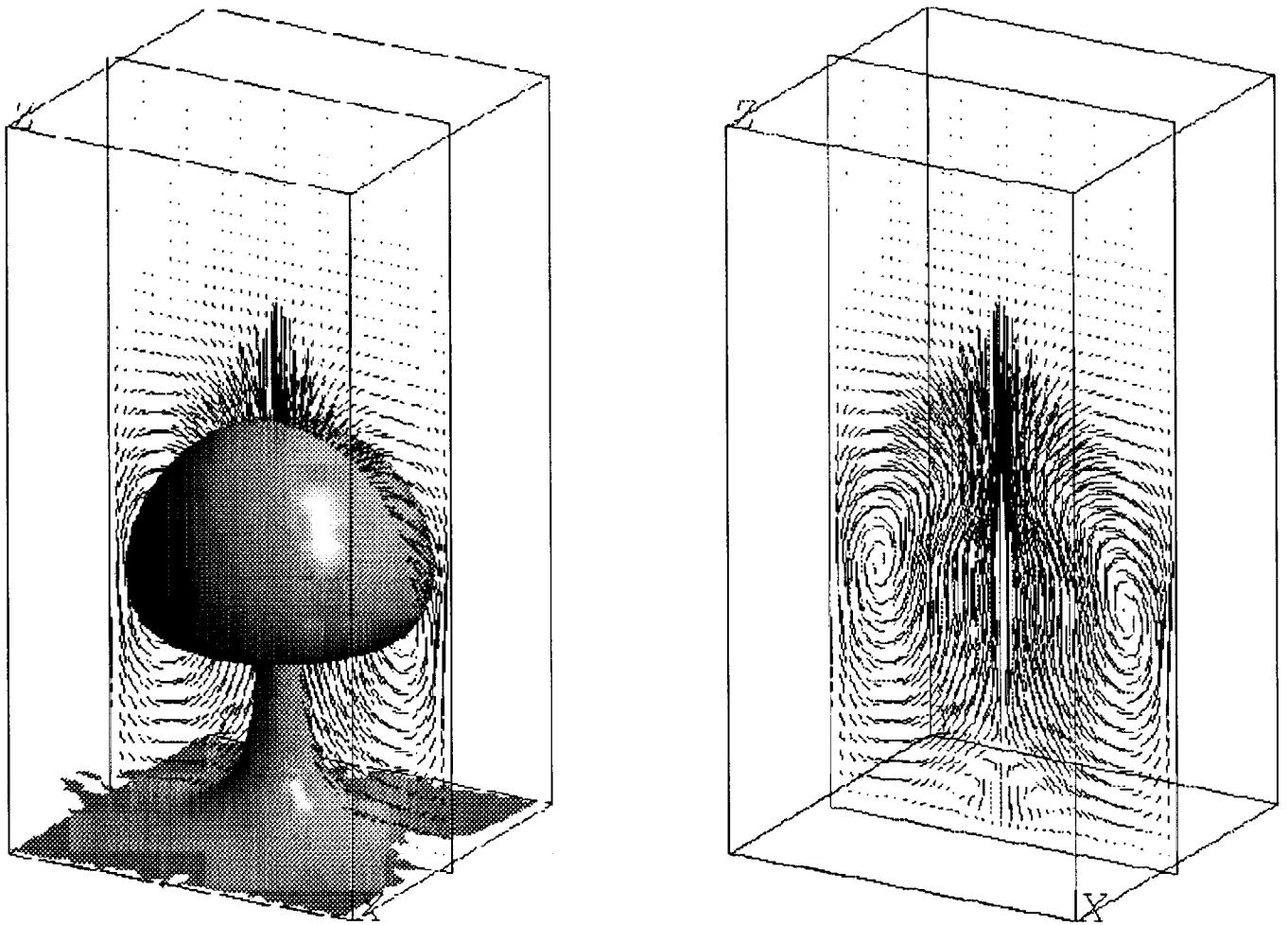
Four frames from a simulation of the boiling of hydrogen is shown to the right. The color represents temperature, with red hot and blue cold. The bottom wall has a constant heat flux.



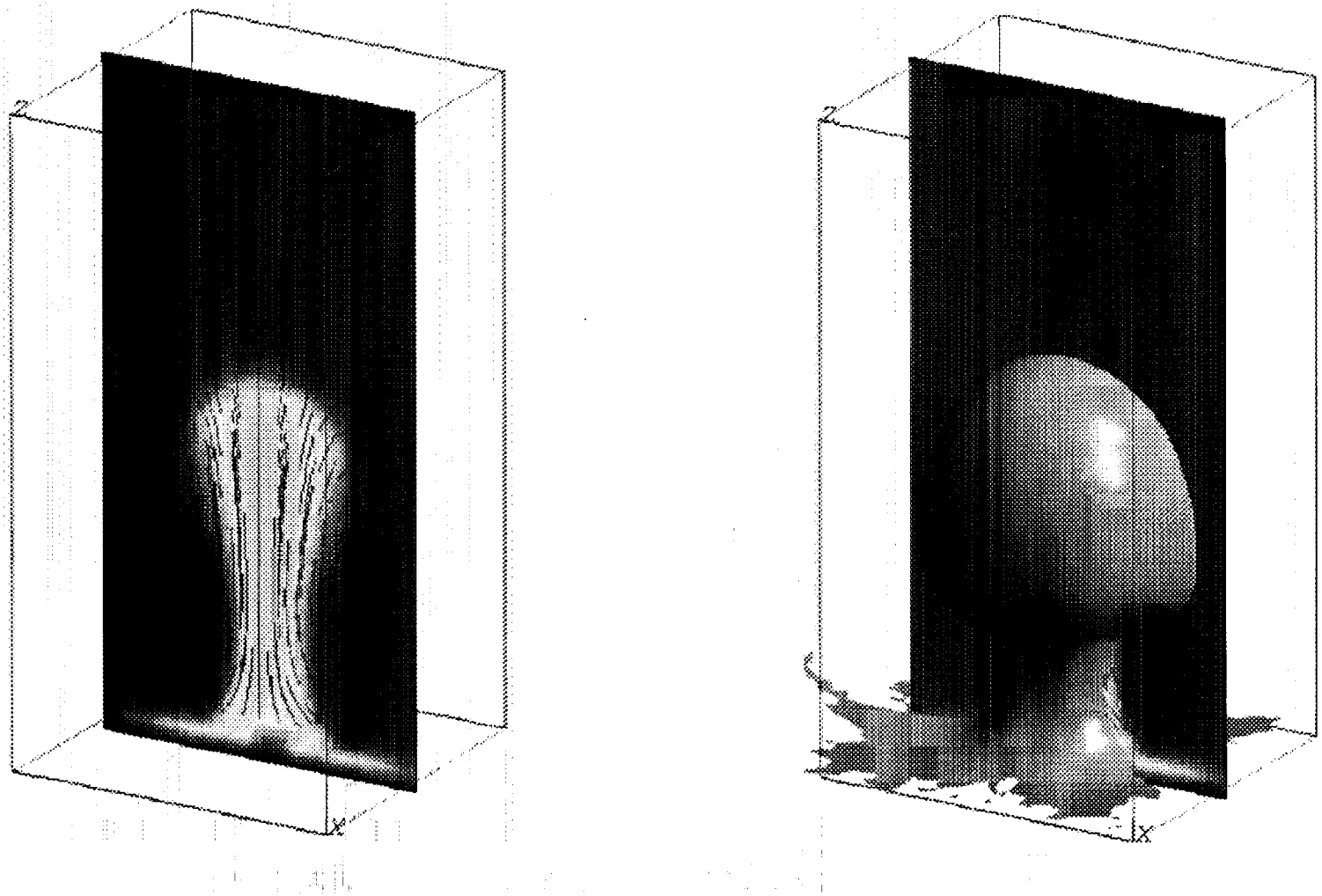
Film Boiling



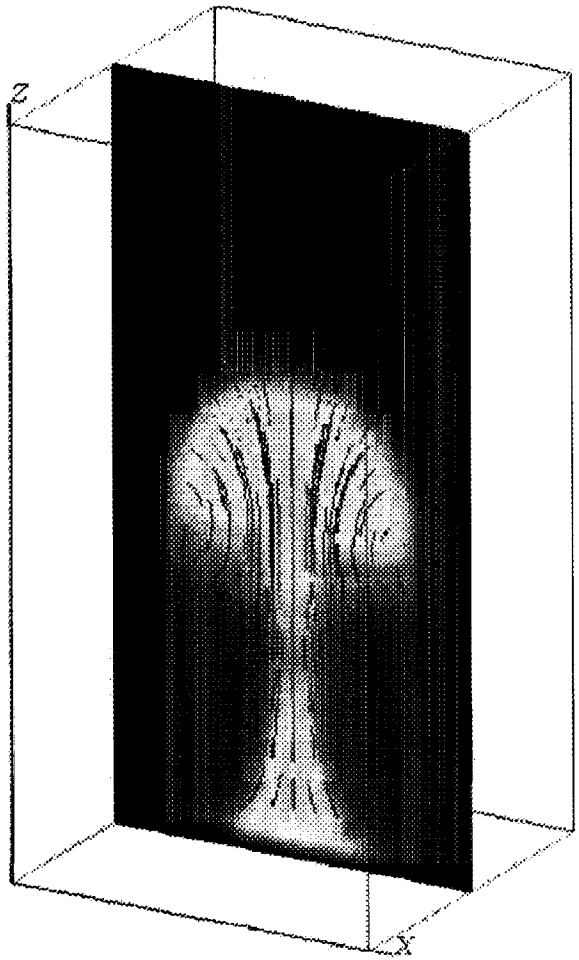
Film Boiling—Velocity

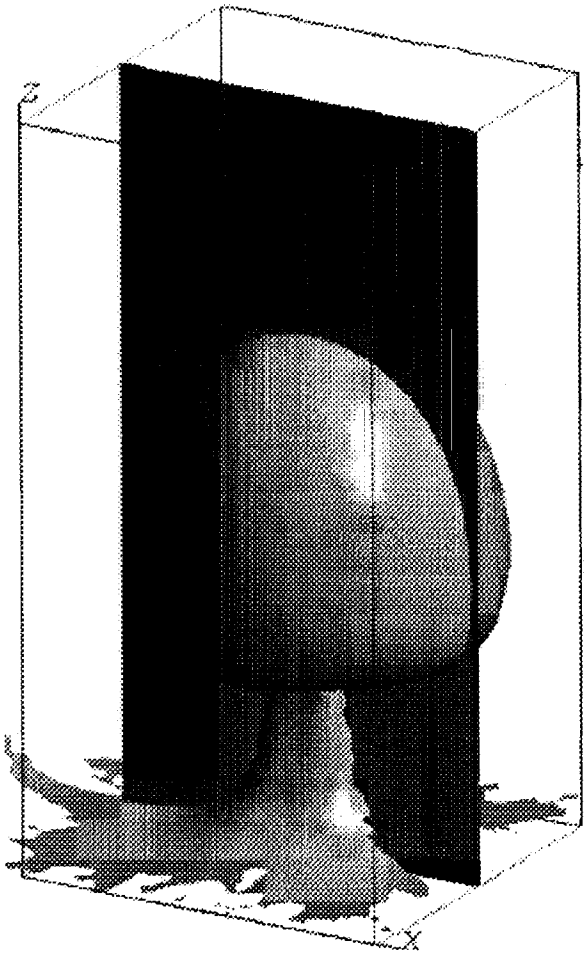


Film Boiling—Temperature

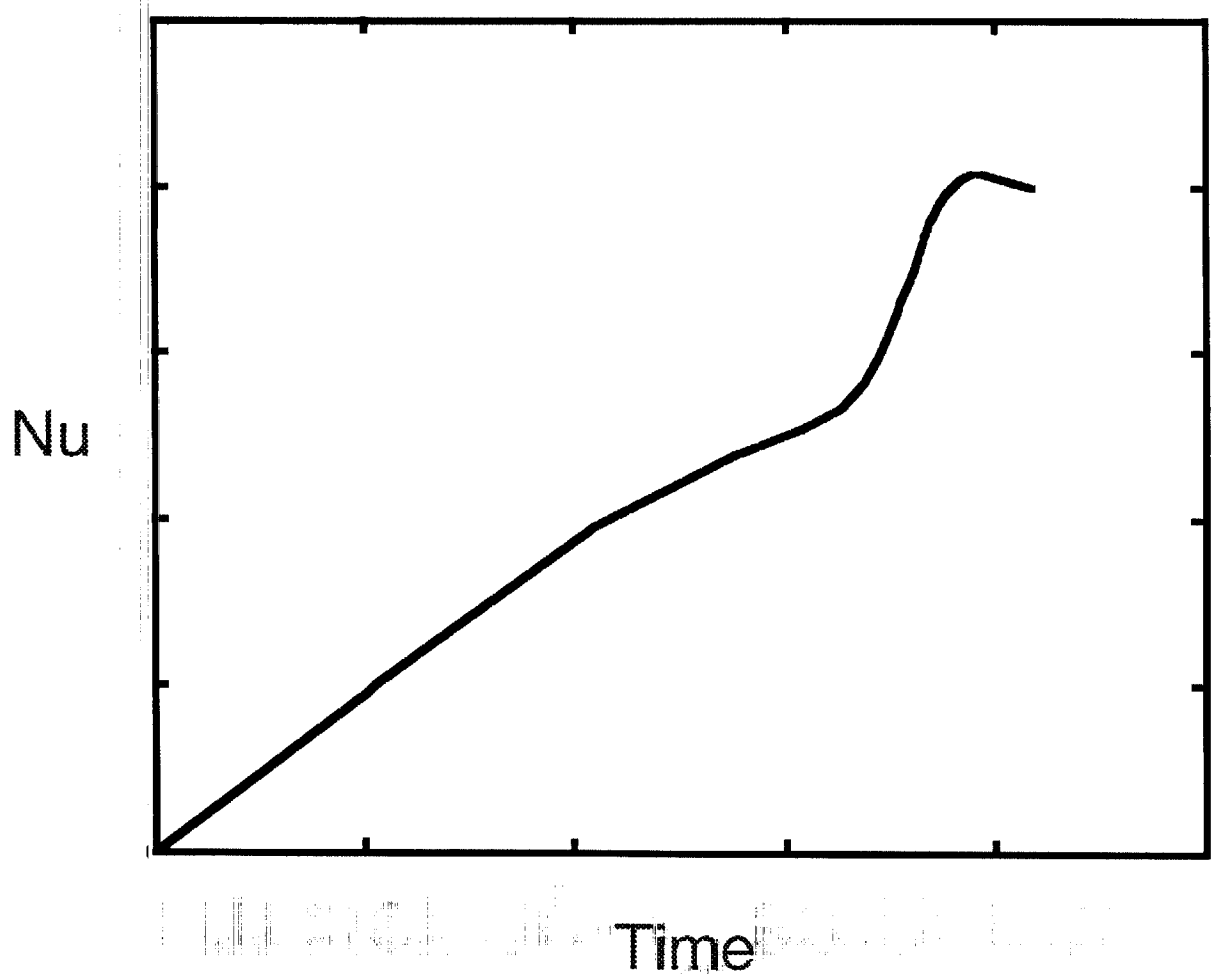


Film Boiling—Temperature

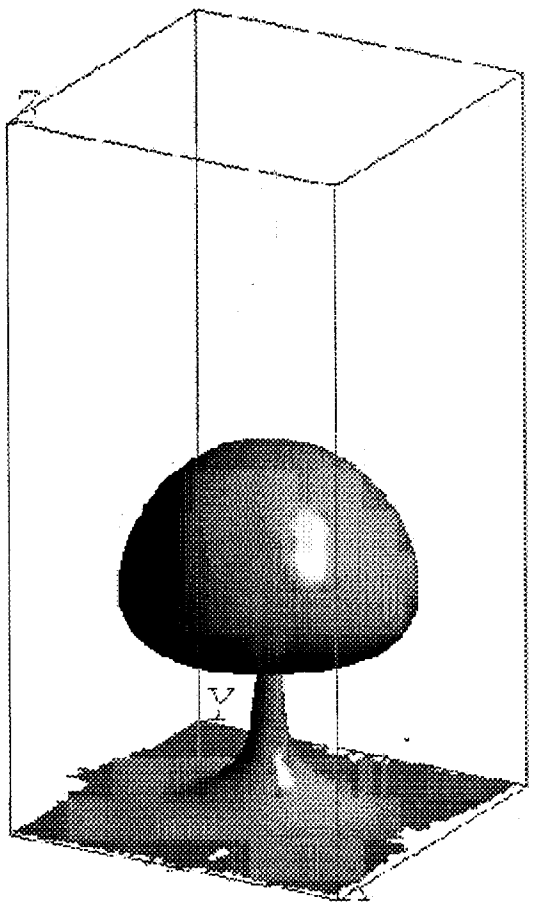




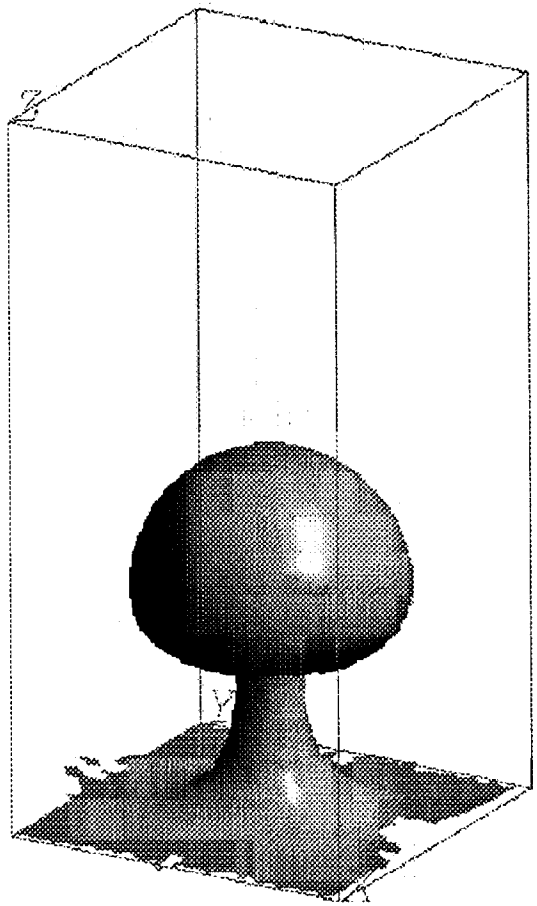
Film Boiling—Heat Flux



Film Boiling—Resolution

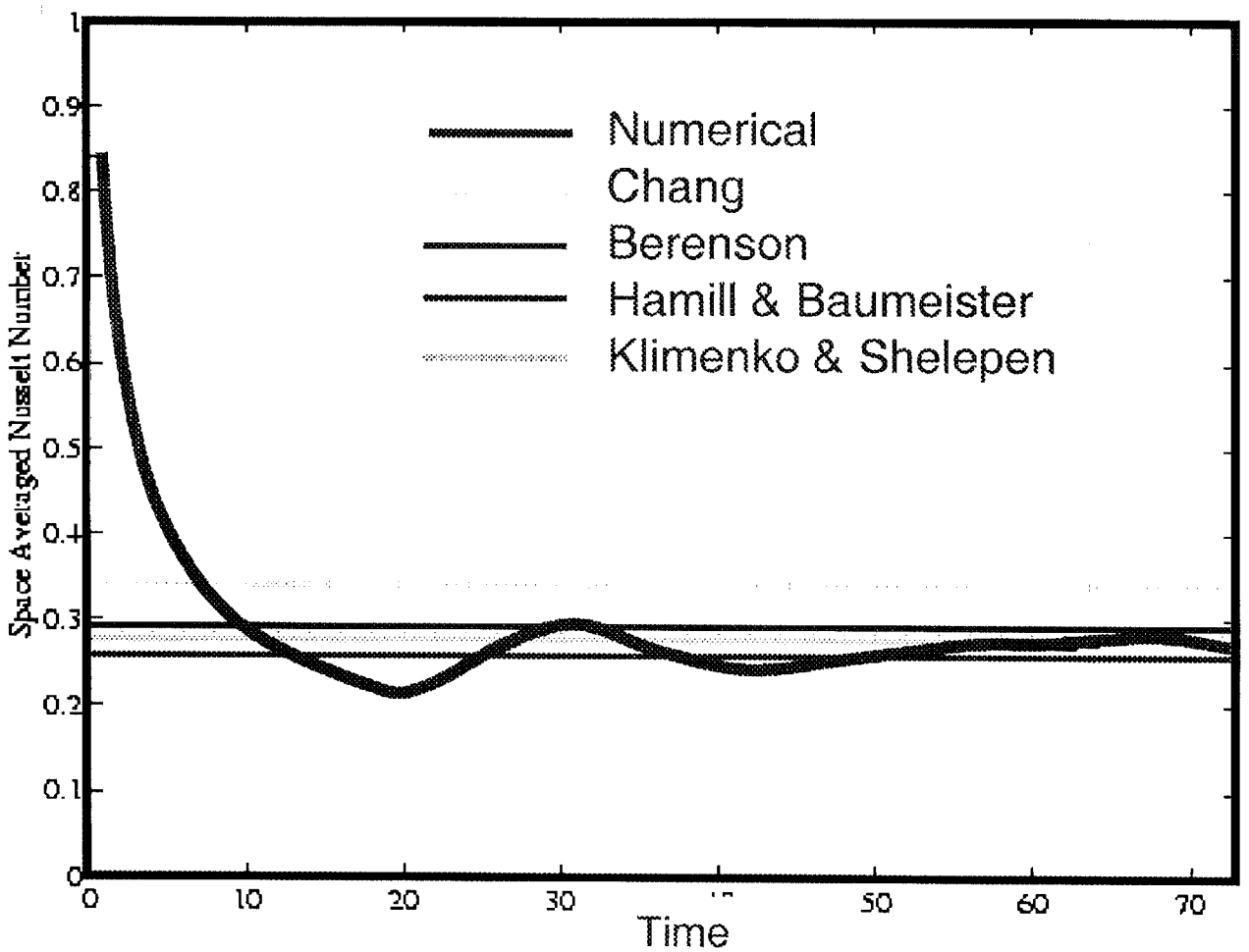


High resolution



Low resolution

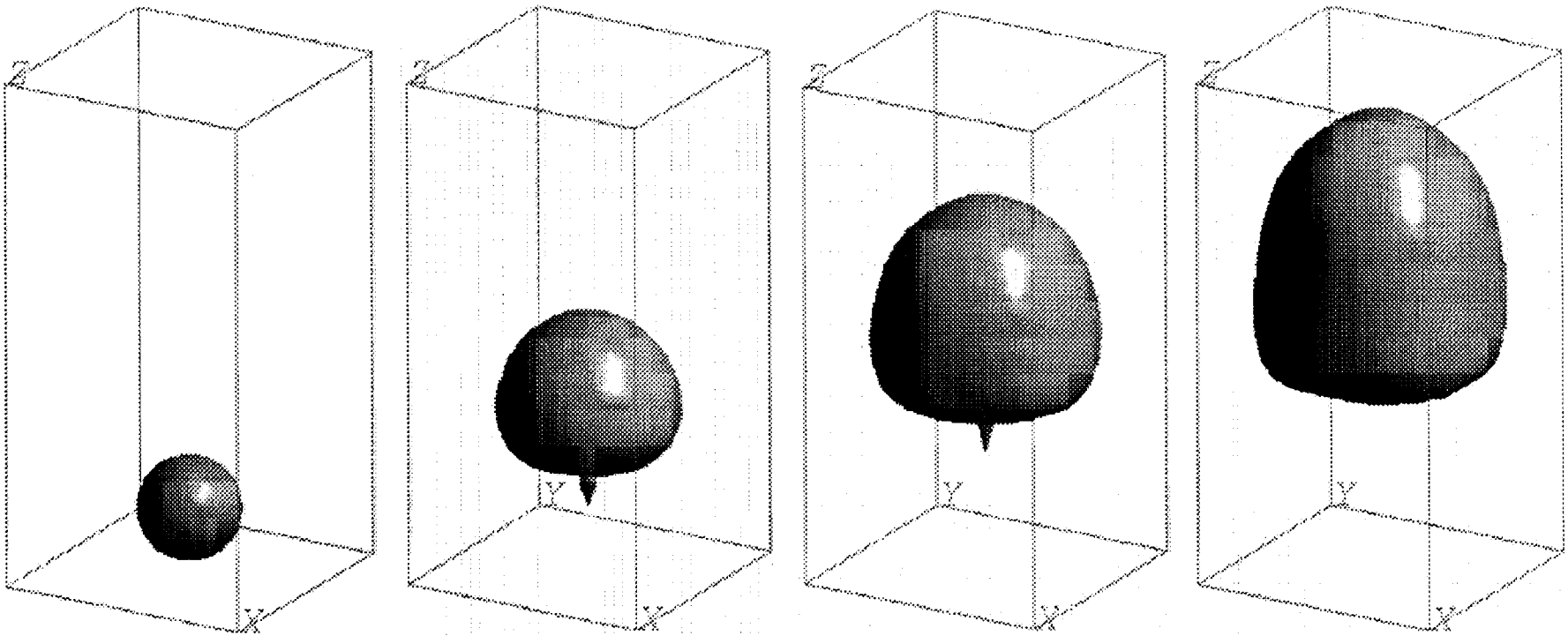
Film Boiling—Heat Flux



The average heat flux versus time. Predictions by various empirical correlations are shown by horizontal lines.

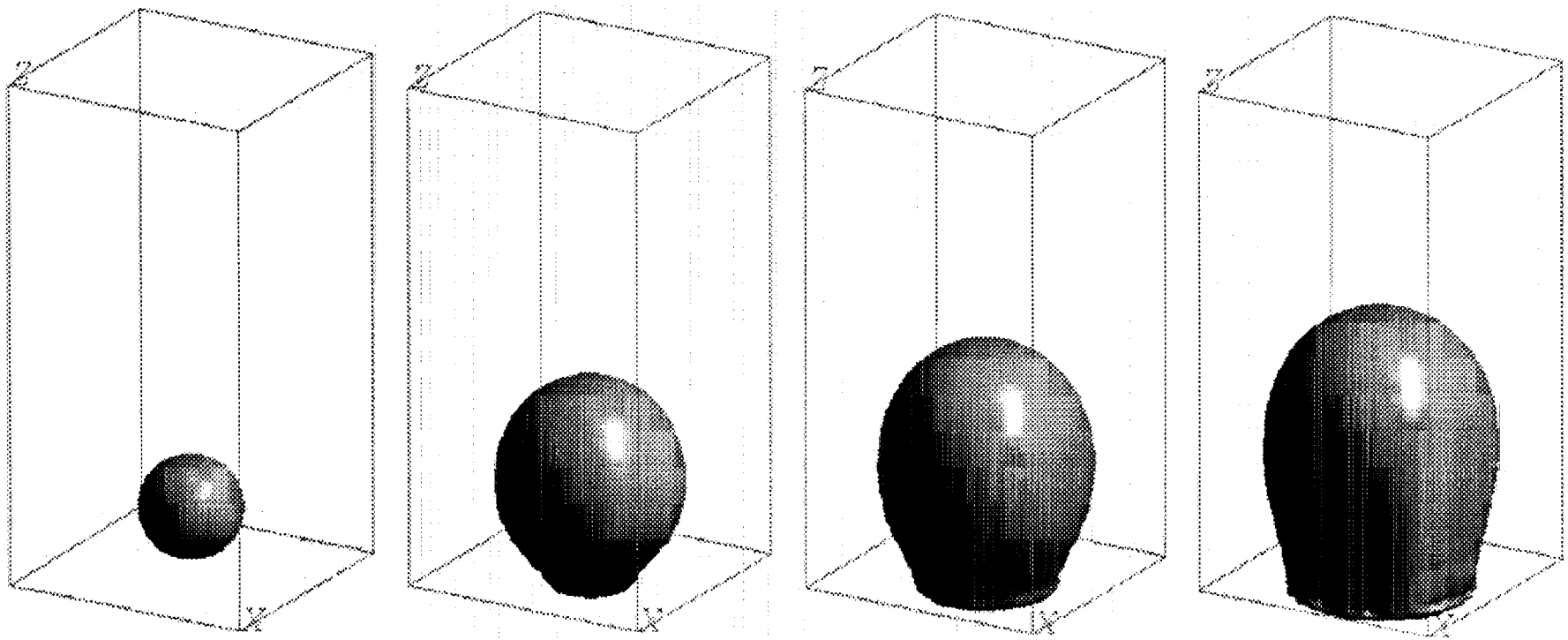
Nucleate Boiling

In gravity



Nucleate Boiling

Zero gravity



Other Phase Change Problems

Solidification and the effect of flow
on microstructure formation

The effect of flow on solidification

Dendrite growing in a uniform flow

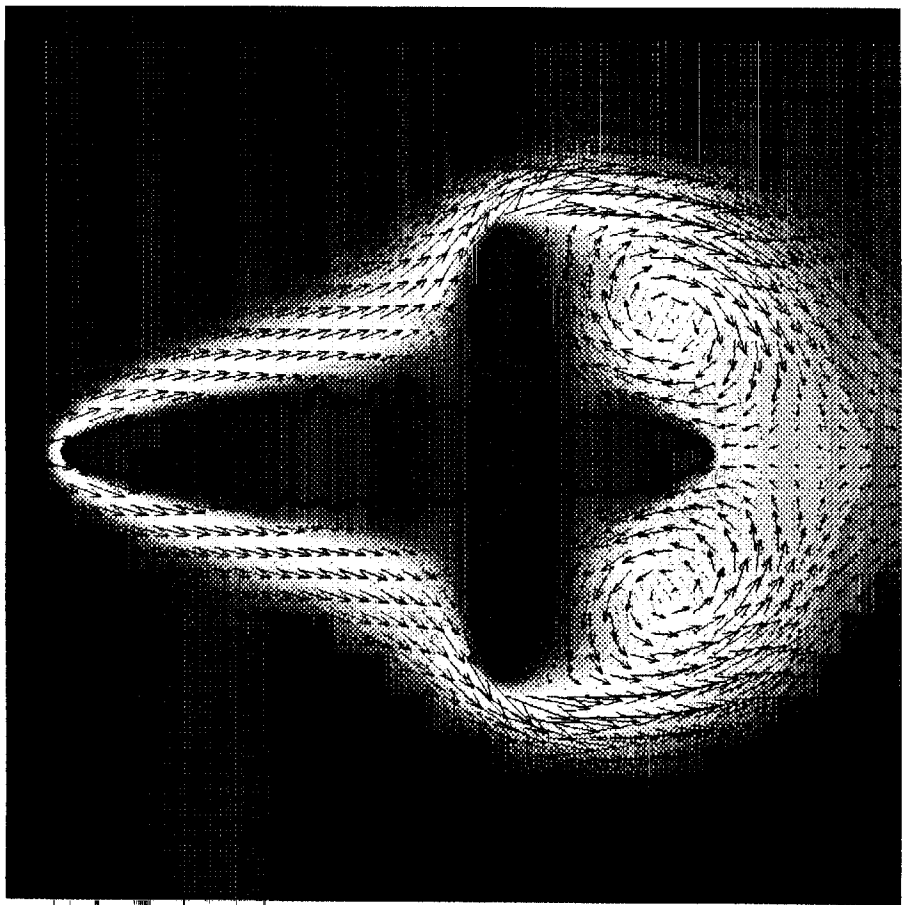
401 by 401grid

Anisotropy=0.4

$$\sigma = \frac{cT_m\gamma}{L^2 Z} =$$

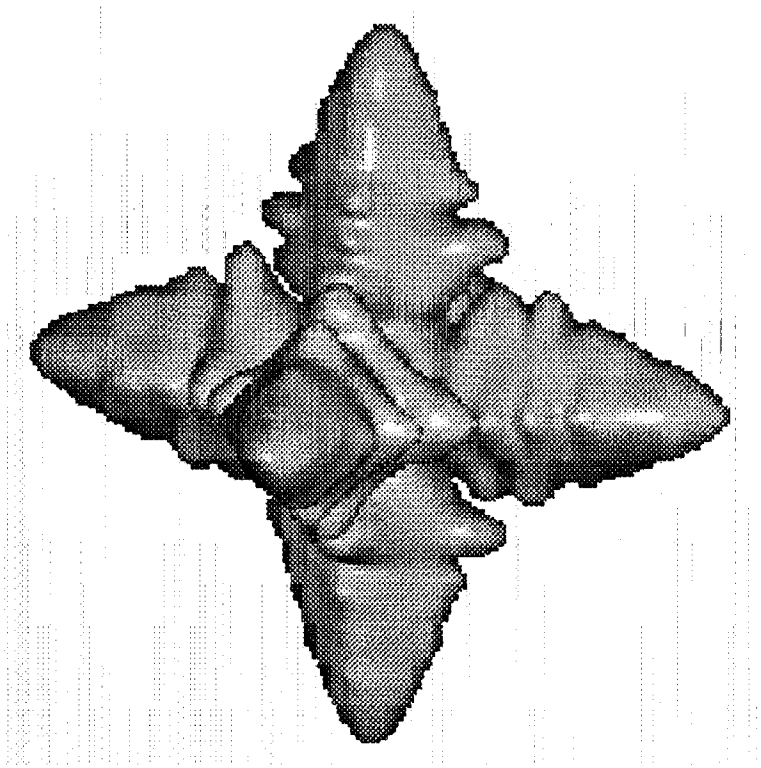
$$\mathrm{St} = \frac{c(T_\infty - T_m)}{L} = -0.3$$

$$\mathrm{Re} = \frac{\rho U Z}{\mu} = 600$$



From Nabeel Al-Rawahi

The effect of flow on solidification



From Nabeel Al-Rawahi

Next Step

- Implementation of the phase change method into our parallel code for fluid flow
- Add adaptive grid refinement capability
- Examination of the effect of gravity and flow on heat transfer
- Adding other effects (electric field, etc)