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Technical Section

A new approach to boiling simulation using a discrete particle based method ☆

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ABSTRACT

We present a discrete particle based method capable of realistically representing the entire boiling process including nucleation, bubble formation, growth, bursting, vapour and steam formation at the fluid free surface. The underlying fluid simulation is based on the mesh-free Smoothed Particle Hydrodynamics method. Vapour bubbles are created at nucleation sites when they reach suitable superheat temperatures above the boiling point. Rising bubbles grow or shrink in the fluid depending on the local superheat of the fluid. The bubbles burst at the fluid free surface and create jets of steam particles and small sprays of liquid drops. This model contains significant bubble scale physics and allows the capturing of key processes that cannot be directly modeled by traditional methods. The method provides the visual artist control over several key aspects of the bubble nucleation, generation, growth and interaction with fluid and other species allowing a broader range of boiling behaviour to be realistically and easily animated. This is demonstrated by examples showing the variation in bubble creation, growth and distribution with temperature and nucleation density. The utility of this model for realistic animation is demonstrated by the boiling of some eggs in a water filled glass pot heated on a cook top.

1. Introduction

The phenomenon of boiling occurs in several environmental, industrial and domestic circumstances. The boiling is accompanied by flow of liquids. Examples include the boiling of molten lava as it flows after a volcanic eruption, the pouring of molten metal in a factory, bubbling of water in hot mineral springs and the boiling of eggs in water in a pan. A model that can easily simulate such a wide range of boiling environments should have the ability to replicate the real process with sufficient physical accuracy to be visually convincing as well as provide the visual artist with a strong degree of control over the key parameters used in the simulation process.

A discrete particle based method is presented here that can realistically represent the entire boiling process including nucleation, bubble formation, growth, bursting, vapour and steam formation on the fluid free surface. The method allows for the generation of tiny gas bubbles in the liquid from nucleation sites on the heated surface. Surface tension causes the small bubbles to stick to the nucleation sites until they are large enough such that their buoyancy overcomes the surface tension forces. These bubbles then start rising through the liquid. Rising bubbles grow or shrink in the liquid depending on the local superheat of the liquid. The rate of change of bubble size is determined by the Rayleigh solution for inertial controlled bubble growth [1]. The motion of the discrete bubbles includes bubble collisions and two way drag interactions with the liquid. Once the vapour bubbles reach the liquid surface they burst and create jets of fine vapour particles that can be rendered as steam. Sprays of fine liquid drops are also created by the bursting bubbles.

The underlying liquid simulation is based on the mesh-free Smoothed Particle Hydrodynamics method originally developed by Gingold and Monaghan in 1977 [15]. The method was used first for animating liquids by Desbrun and Gascuel [2]. Since this early implementation in visual effects the method has been widely used in several related applications. Ihmsen et al. [20] provide a comprehensive report on the state-of-the-art in SPH simulations in the visual effects domain. Cleary [13] and Cleary and Monaghan [8] extended the method to include heat transfer. This has been used to simulate various heat transfer related problems including lava flow modelling [3], melting [4,5] and metal casting [16]. In this

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paper, we further extend the method by using a discrete bubble fluid dynamics model similar to the approach taken in [9]. This enables simulation of a broad range of boiling phenomenon. The model contains significant bubble scale physics and allows the capturing of the key boiling processes which cannot be created by traditional simulation methods. The method described and implemented here uses the weakly compressible implementation of SPH [15]. However it can relatively easily also be implemented in the context of other implementations of SPH such as predictive-corrective incompressible SPH in [21] or implicit incompressible SPH in [22].

Additionally, the method allows the visual artist to control several key attributes of the boiling process including rates and density of bubble nucleation, generation rates, growth rates and bubble sizes and interaction with fluids and other simulated entities. This enables a broad range of boiling behaviour to be convincingly animated. Some control elements are demonstrated through some simple examples showing the change in boiling with user specified fluid temperature and bubble nucleation density. Finally the method is used to animate the boiling of eggs in a pot of water. The water, the dynamic motion of the eggs, the bubbles, and the steam are all coupled. Realistic rendering of the simulated boiling process is achieved by using a Phong shader for the fluid and a combination of a Phong and dielectric Mentalray shader for the bubbles. This example shows the ability of the method to incorporate the interaction between dynamically moving objects (eggs) with the boiling phenomenon.

2. Related work

Boiling is a type of phase transition in fluids which is primarily produced by heating the fluid. Müller et al. [10] proposed a method to model fluid–fluid interaction based on the SPH method and as an application simulated boiling of water by changing the densities of particles dynamically according to their temperatures. They solved the diffusion equation on the particles to simulate the exchange of temperature as previously demonstrated in [3]. For boiling, they changed the density of probabilistically chosen liquid particles close to the heated object surface and converted them into air particles. In their simulation the air particles start rising immediately after they are formed. In real boiling the air bubbles have to reach a certain size to overcome the effect of surface tension before they can rise through the liquid. Bubble growth in their simulation is purely a function of the amount of compressibility allowed for the SPH gas phase and did not have any relationship with the temperature. Since the liquid is converted into air, the size of bubbles from boiling was constrained to be the size of liquid particles. The volume of bubbles created was also constrained by the volume of liquid in the system. This approach is not able to include sub-liquid particle-scale bubbles or to produce realistic nucleation behaviour for boiling.

The work of Mihalef et al. [11] is the best example of realistic physics based boiling as applied in graphics. Their model consisted of a coupled two-phase flow version of the Coupled Level Set and Volume of Fluid (CLSVOF) method augmented with a temperature field and a mass transfer mechanism. In their method the bubbles were initially seeded at an arbitrary frequency on selected nucleation sites on object surfaces. The bubbles grew until the buoyancy forces balance the surface tension forces during boiling. The detached bubbles then rise through the fluid and burst when they reach the liquid surface. The minimum size of the gas bubbles generated in this method is linked to the minimum grid size used for the simulation. This would necessitate the use of very fine grid sizes for representing the smaller bubbles resulting in prohibitive computational times. Once the bubbles burst on the surface this model did not account for any steam or spray formation as is found in real liquid boiling.

Kim and Carlson [7] proposed a different modular approach, where the thermal effects specific to boiling such as thermal diffusion and convection is handled in a separate simulation, and then loosely coupled to an existing particle level set solver. This modular design decoupled the bubble dynamics from the water surface dynamics and allowed the two features to be run at different resolutions, with decoupled time steps. They used a particle level set method for the underlying fluid flow calculations. For the boiling module a coupled map lattice model following on from [17] was used. In the examples provided they have shown indirect effects such as the breaking up of a smooth stream of water due to the imposition of the boiling model. However, the creation of bubbles, their detachment, and growth during a typical boiling process were not shown. This method appears to be computationally cheap and produces visually plausible results but lacks the flexibility and detail that is needed for high quality boiling animation.

Recently Cleary et al. [9] presented a discrete bubble fluid dynamics model to simulate the bubbling and frothing behaviour of aerated drinks such as beer, carbonated soft drinks and champagne. In a similar but more unified approach Ihmsen et al. [25] used a method of combining SPH with what are called diffuse particles to represent feature such as foam, spray and bubbles. In this approach the authors compute the diffuse particles post SPH simulation which then reduces computational effort and also provides artistic flexibility. The current work is an extension of the model implemented in Cleary et al. [9] and includes a significant amount of additional physics pertinent to the boiling mechanism including conductive and convective heat transfer, thermally variable nucleation site activity for bubble generation, bubble growth based on degree of local superheat and bursting of bubbles with subsequent generation of vapour and steam.

The proposed SPH/discrete boiling model has the following key elements:

- Discrete bubbles are used to represent the gas phase. This means extremely tiny and small (sub-fluid particle size) bubbles can be included in the simulation.
- The nucleation sites have variable activity which depends on the local temperature of the heated surfaces and on the nucleation site diameters. This is important to achieve realistic numbers and distributions of bubbles on surfaces whose temperature can vary spatially and can change dynamically during the animated sequence.
- The bubbles stick to surfaces at the nucleation sites until they become large enough for the buoyancy force to overcome the surface tension.
- There is no restriction on the number of bubbles created during the boiling process.
- Bubble collisions and coalescence are easily included.
- Bubbles burst on the free surface creating eruptions of steam and fine sprays of droplets.
- Bubbles grow naturally in the liquid and is accounted for by using an inertial controlled growth model that depends on the local superheat of the fluid through which the bubble travels. The size of the bubble then controls their rise speed in the usual way. This combination results in realistic bubble motion and interaction with the surrounding fluid.
- The two way coupling between the SPH liquid and the discrete bubbles allow the violent large scale free surface motion found in boiling to be well captured.

This removes the need for the user to specify potentially time varying nucleation rates on heated surfaces and allows a full