An Expression Model of Blood Drying Process Based on SPH Method

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***Abstract*— Expression related to blood such as bloodshed and "blood splashes" is often used in "Computer Graphics field like game and movie". With the improvement of the performance of machines and technics, we able to express blood adhering to the object, however, there is few examples expressing the change of blood states over time. In this paper, we mainly focus on the coffee ring effect seen when blood is dried and we propose a method to simulate changes in the blood states like coffee ring effect, discoloration, over time and aim for more realistic representation of blood using the SPH method.**

Keywords*— Expression of blood; SPH method; Evaporation model; Coffee ring effect; Clotting; Discoloration.

I. Introduction

Smoothed Particle Hydrodynamics (SPH) method [1] was used mainly for simulating the dynamics of continuum media, such as fluid flows. However, SPH method has not been applied to small scale fluid flows, for example water droplets. There have been proposed several models to apply the SPH method to such small scale fluid flows.

Models proposed by Abe [2] et al., and by Sato [3] et al. made it possible to express shapes and movements of small scale fluid flows such as water droplets. Hirayama et al proposed a model which can express shrinkage processes of water droplets based on evaporation of water droplets.

However, changes in the states of fluid flows over time are missed such as deposition, coagulation and discoloration of colloidal particles found in colloidal solutions such as blood can't be expressed. In this paper we verify whether our method of state change of blood over time is effective

II. Previous Work

We describe proposed several previous study for modeling shapes of water droplets based on the SPH method [1].

A. Water drop shape model

1. Interfacial tension model

In order to express the shapes of actual water droplets, Abe et al. [2] proposed an "interfacial tension model" by extending the SPH method. This model made it possible to represent the shapes of the water droplets with different contact angles and the flat shape.

2. Dynamic contact angle model

Abe's interfacial tension model [2] made it possible to represent various water droplet shapes. However, Abe's model is only applicable to the shape of a water-drop in a stationary state. Sato et al. [3] proposed an extended shape model of Abe's model, considering dynamic behavior of water droplets. They realized a shape model including the dynamic contact angles of a water droplet in motion. Their model can express the shape of a water droplet in the stationary states but also in the motion.

B. Phase transition model

1. Phase transition model

Kim et al [4] propose a freezing model of water to generate complicated shape like the tip of an ice pillar by using the Stefan problem under the limited water conditions. Generated 3D models of icicles seem to be similar shapes to real objects. However, its algorithm is very complicated.

2. Heat transfer and phase transition among particles (freeze and evaporation)

In order to represent the frozen water, *i.e.*, icicles, Sato et al. proposed a heat transfer system between the particles [4]. Let the temperature of water particle $\boldsymbol{i}$ be t_i. In this model, air, water, and ice particles are not distinguished. Interfaces between air, water and ice are not set. The amount of heat transfer between two particles i and j is described as q_{ij} of the Equation (1).

$$q_{ij} = k_{ij}A_{ij}(t_j - t_i). \qquad (1)$$

The definition of 'neighboring particles' is as follows (see Fig.1). We choose any particle i, and call this particle as the current particle. Then we select other particles around in the current particle i in its effective region. These particles in the effective region are called as "neighboring particles". In this case, we can select three particles as neighboring particles of the current particle i.

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Here, k_{ij} is the specific heat transfer coefficient between the particles i and j. A_{ij} is their contact area. Q_i is the total of heat transmitted to the particle i, which is obtained by the Equation (2).

$$Q_i = \sum_{j=0}^{N_i} q_{ij} = \sum_{j=0}^{N_i} k_{ij} A_{ij}(t_j - t_i). \qquad (2)$$

Here, N_i is the number of particles near the particle i. When the temperature of the water particles becomes 0°C or below, the phase transits to ice. In this case, particle i will be condensed and lose latent heat. By using Hirayama's model [5], in addition to the heat conduction between neighboring particles, the temperature of the water particles is raised by heat transfer between the air, the floor surface and the water particles. Expression of water droplet evaporation and contraction is expressed by extinguishing particles by exceeding the temperature limit value of water particles.

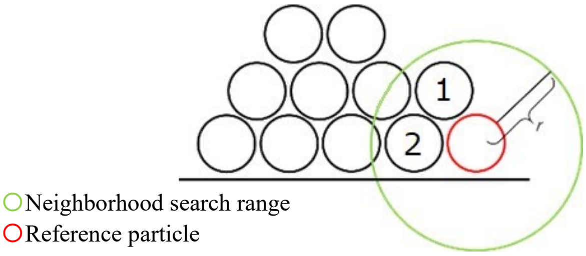

Fig. 1. Definition of neighboring particles

III. PROPOSED METHOD

In this paper, based on the model of Sato et al [3] and Hirayama et al [5], we propose a method to express state change including phase transition of colloid solution like blood.

Two types of particles water and component particles(hereinafter referred to as nonaqueous particles) are used to express the temporal phase transition of the colloidal solution at the time of drying and the deposition of colloidal particles by the coffee ring effect. In the colloidal solution, after evaporation of the water particles, the nonaqueous particles are attracted to the edges of water drop and produce a coffee ring effect. At the same time, the nonaqueous particles oxidize and coagulate / discolor.

The simulation flow is shown in Fig.4. Steps 2, 3, 4, and 8 use the models of Sato and Hirayama et al[3] [5]. In this chapter, Step 1, 5, 6, and 7 will be described in detail below.Abbreviations and Acronyms

Step 1 Generating Particle

Generate particles in the simulation space. Since the ratio of water to red blood cells in the blood is about 1: 1, it is generated so that the amounts of the two kinds of particles, water particles and nonaqueous particles, are also 1: 1. Also, when generating particle, it is generated so that the position becomes random so that two kinds of particles mix.

Step 5 Particle evaporation e

We expand Hirayama's model [5] to exert the coffee ring effect when nonaqueous particles evaporate. Particles inside a sphere of a radius r centered on a certain particle P are defined as neighboring particles of P. The particle is determined to be at the edge of the droplet when the number of neighboring particles is equal to or smaller than the threshold μ. When the water particles P on the edge of the water drop evaporate, a force toward the water particles P is applied to the nonaqueous particles in the vicinity thereof (Fig. 2). By this action, the nonaqueous particles are attracted to the edge of the water drop, and when all of the water particles finally evaporate, the nonaqueous particles express a coffee ring effect that accumulates more at the endpoints of the droplets.

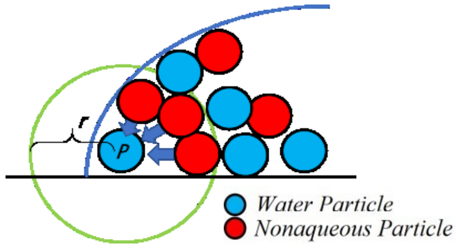

Fig. 2. Force acting on evaporation

Step 6 Particle coagulation

The blood coagulation is controlled by parameter X representing the degree of oxidation possessed by nonaqueous particles. X increases by increment ΔX for each update. ΔX varies depending on the number of neighboring particles N_i. When the degree of oxidation X of the particles exceeds the threshold , attract non-water particles in the vicinity towards. As a result, water particles are reduced and a lot of nonaqueous particles are gathered, so blood coagulation is expressed

.

Step 7 Particle Discoloration

Blood turns discolored by oxidation [6]. In order to reproduce this, discoloration is carried out according to the parameter O representing the amount of oxygen contained in the nonaqueous particles. O decreases by ΔO with time. ΔO also fluctuates according to the number of adjacent particles N_i . Discoloration of the particles according to the value of O to express discoloration. The color of the particle follows a color chart of 5 stages created based on the color chart prepared by Shihana et al [7] experiment.

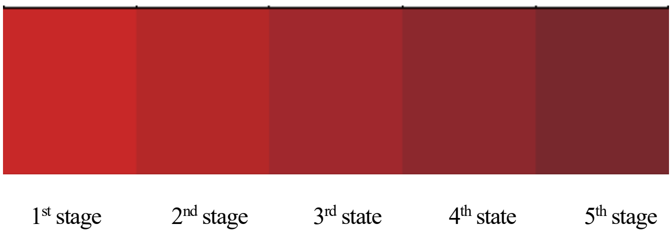

Fig. 3 Five stages of discoloration

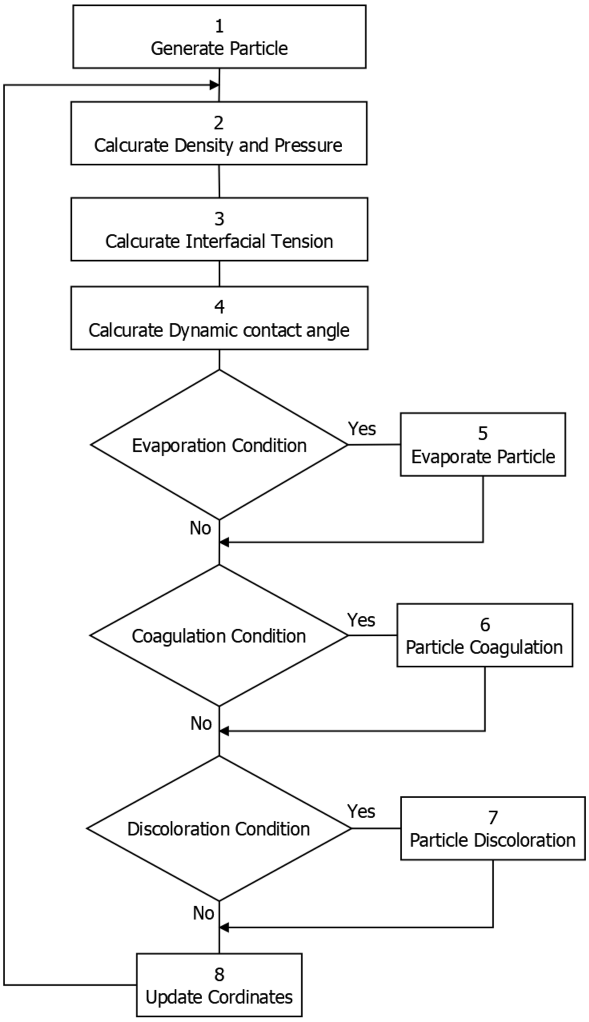

Fig. 4 Flowchart for Simulation

IV. Simulation Results

1. Coffee Ring Effect

As the colloidal solution dries, colloidal particles settle and ring marks remain on the edge of the droplet (Figure 5). This phenomenon is known as the coffee ring effect, and the same effect is known to occur in the blood [8] [9].

In order to confirm that the deposit of nonaqueous particles due to the coffee ring effect can be expressed by the process of Step 5 in the previous chapter, simulation was performed by generating and arranging the particles in annulus shape, imagining the bottom of the coffeecup. The distribution of the nonaqueous particles immediately after formation is shown in Fig. 6, but water particle is also generated, but it finally evaporates, so it is not descrived in the figures after Fig. 7. In the simulation, the nonaqueous particles change color depending on the number of adjacent particles (Fig. 7).The number of neighboring particles is large in order of red, green and blue. By this indication method, the state of each nonaqueous particle and its distribution state are displayed in an easily understandable manner.

As shown in Fig. 6, most of the particles were red at the time of production. However, over time, water evaporates and decreases, and red and green particles increase. Particles are drawn toward the outer circle which is the circle of the ring and the inner circle. As a result, the area inside the annulus was blue particles with few neighboring particle, or cavities (Fig. 7). From this, it can be seen that as time passed, most of the nonaqueous particles migrated to the edges of the annulus and deposited. As a result, it can be said that the coffee ring effect was reproduced.

Fig. 5 Coffee Ring

2. Coagulation and Discoloration

When the blood comes into contact with air, multiple chemical changes occur and fibrin is formed. Fibrin draws and coagulates red blood cells each other [10]. On the other hand, the color of blood changes with the amount of oxygen carried by hemoglobin. When blood touches the air, it oxidizes and hemoglobin loses its capacity to carry oxygen, the amount of oxygen carried by hemoglobin decreases. As a result, as shown in Fig. 4, the blood color change from bright red to dark brown [6].

This process can be simulated by the process of steps 6 and 7 of the proposed method. Over time, coagulation and discoloration proceed. The results of changing the color of the particles according to the color chart (Fig.4) are shown in Fig 8. From Fig 8, it can be said that it is possible to simulate the state change of the blood over time. Based on this series of simulation results, the final rendering result is shown in Fig 9.

V. Conclusion

Expanding the SPH method, it was possible to more realistically express the coffee ring effect caused by drying, and the state change of blood such as coagulation and discoloration.

The future task is taking into consideration physical characteristics such as viscous resistance and intermolecular force, we want to move the behavior of blood closer to the real one.

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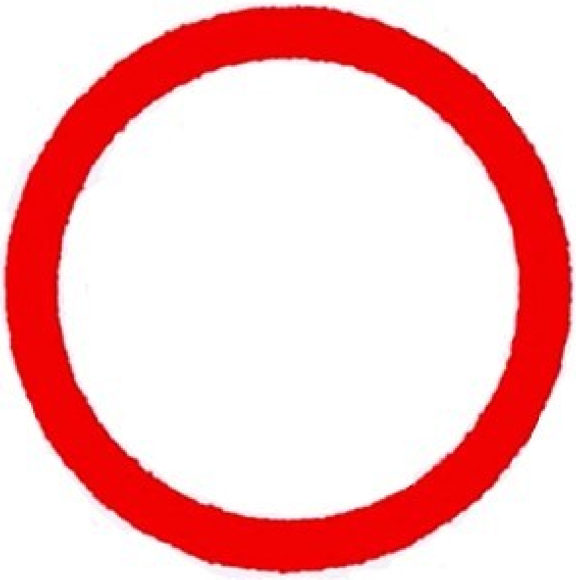

Fig. 5. Ring at generation

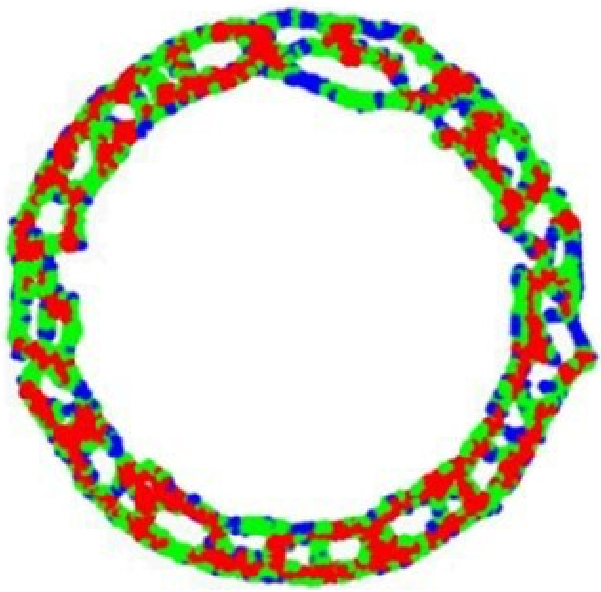

Fig. 6. .Ring after the passage of time

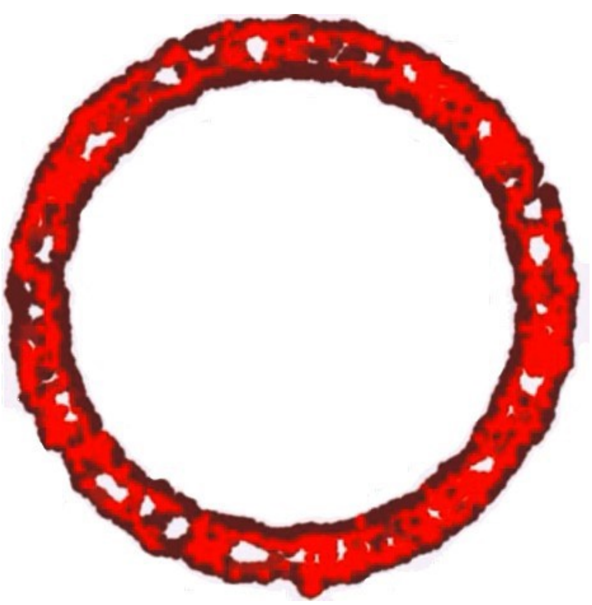

Fig. 7. Solidified and discolored ring

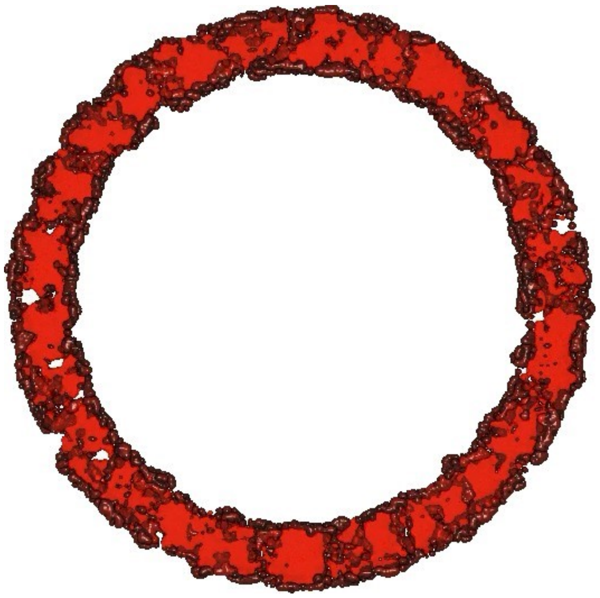

Fig. 8. Rendering result