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CFD Analysis of Effective Human Motion for Whipping Heavy Cream by Hand

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This study observed human motions of whipping conducted by five expert confectionery hygiene mistresses, because mixing performance can be easily estimated by change of physical properties in heavy cream. Mixing state of heavy cream was evaluated by an overrun which indicates the amount of gas phase in the cream. Rheological properties of the cream were also measured for mixing state estimation. Agitating behaviors were recorded by a high-speed camera. Fluid flow motion was numerically observed by the Moving Particle Semi-implicit (MPS) method. The experts' motions were classified into two patterns, i.e. vertically elliptical rotation and horizontally reciprocating. Numerical analysis suggested that these motions with large amplitude produced large disturbances and high shear on the liquid surface and consequently enhanced the uptake of air as fine bubbles. It is considered that elliptical and reciprocating motions are effective for whipping because the shearing on fluid and efficient air uptake improve the whipping performance.

1. Introduction

Mixing of ingredients is one of the most important unit operations in food industries. Mixing is used to not only obtain uniform mixture but also enhance heat and mass transfer, control properties of food substances and so on. Due to the complex rheological properties, mixing of food substances is one of the most difficult unit operations in food processes. As Lindley (1991) pointed out, therefore, although mixing is widely used in food processing, there is a total lack of fundamental understanding, design and development of mixing devices are still seen as an art without a general systematic procedure being available. This study focused on a “tacit knowledge” or “tacit knowing” on agitating motions in cooking. The “tacit knowledge” firstly introduced by Polanyi (1967) can be defined as skills, ideas and experiences that people have in their minds and are difficult to access because it is often not codified and may not necessarily be easily expressed (Chugh, 2013). In cooking agitation, cooking experts agitate food substances by their unique methods combined with rotating, reciprocating, and/or swinging motions. If the effective agitating motions from these cooking experts can be extracted, new fundamental understanding can be obtained for design and development of mixing devices. Hara et al. (2018) revealed that phase difference of motions among elbow, wrist and whisk was observed and the time-series of displacement showed rather complex and chaotic in the expert’s motions. Furthermore, it has been found that the expert agitates with small motion putting snap on the whisk. They also found that horizontally reciprocating motion by the expert produced disturbance on the surface of cream due to heavy collision of fluid with fast moving whisk wires. This intense disturbance due to heavy collision of fluid elements enhances not only the uptake of air, but also breaking up the fat globules of cream. Consequently, an appropriate state of whipping cream containing large amount of fine air bubbles can be obtained.

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This study experimentally investigated agitating behaviors within a cooking bowl by five expert confectionery hygiene mistresses, and tried to classify their motions. Numerical simulation using MPS method was also conducted to elucidate effective motions of whisk on the surface of cream.

2. Experimental

Experimental procedure in this study is the same as Hara et al. (2018). Research subjects for the motion analysis consisted of five female confectionery hygiene mistresses as experts. One subject was left-handed and the other subjects were right-handed. Fresh cream (Fresh Cream 47, Takanashi Milk Products Co., Ltd., Yokohama, Japan) was used as an agitated substance. A conventional whisk having the length of 270 mm and the maximum head diameter of 71 mm was used. 200 mL fresh cream was poured into a metal bowl with the inner diameter of 210 mm. This cooking bowl was immersed into another metal bowl with the diameter of 240 mm filled with iced water. Agitating behaviors within the cooking bowl were recorded by a high-speed video camera system (VW-6000, KEYENCE Co., Osaka, Japan).

After a certain time of agitating, viscosity of sampled fresh cream was measured by a rheometer (Physica MCR 301, Anton Paar Co., Ashland, Virginia, USA). Whipping state (mixing state) was evaluated by the following volume increasing ratio, ΔW [-], called “overrun”,

$$\Delta W = \frac{W_0 - W}{W} \times 100 \qquad (1)$$

Here W_0 [kg/m^3] is the initial density of heavy cream and W [kg/m^3] is the density of sampled heavy cream after agitation. Incidentally, it is said that larger than 100% of ΔW gives a good whipping state.

3. Numerical simulation

Conventionally grid methods such as finite element method finite difference method have been used for CFD analysis. In these grid methods, however, it is difficult to express this free surface of fluid flow, and various methods such as the VOF method (Volume Of Fluid Method) have been proposed. Many methods based on the grid method are weak in calculating fluids with complex liquid surface shapes. On the other hand, the MPS method without mesh based on Lagrange expression developed by Koshizuka and Oka (1996) can easily express the large deformation of fluid surface, and liquid splitting and coalescing. As described in Introduction, the disturbance on the surface of cream due to heavy collision of fluid is crucial important. Hence, this study used a commercial MPS code, Particleworks (KOZO KEIKAKU ENGINEERING Inc., Tokyo, Japan), for numerical simulation.
The following incompressible continuity equation and Navier-Stokes equation were used;

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} = 0 \qquad (2)$$

$$\frac{\mathrm{D}\vec{u}}{\mathrm{D}t} = -\frac{1}{\rho}\nabla P + \nu\nabla^2\vec{u} + \vec{F} \qquad (3)$$

where ρ = density, t = time, u = velocity, P = pressure, ν = kinematic viscosity and F = external force. Numerical simulation was conducted by discretizing the governing equation by replacing the gradient, divergence and Laplacian appearing in Eqs. (2) and (3) to the corresponding interparticle interaction model. Numerical conditions are shown in Table 1. As whipping heavy cream is a non-Newtonian fluid, a power low model $\eta = 0.1558\dot{\gamma}^{-0.1584}$ was used. Detailed geometrical information will be described in the following Results and discussion. A particle model was used for the whipping heavy cream, the wall of bowl and the surface of wwhisk were expressed by lattices, and a polygon model without particles inside the wall was used (Harada et al., 2008). The no-slip condition was imposed on the wall boundary conditions.

Table 1: Numerical conditions

Physical properties	Numerical values
Density [kg/m^3]	970
Surface tension coefficient [N/m]	0.04154
Contact angle [deg]	60
Particle distance [mm]	0.8
Number of particles [-]	394000

4. Results and discussion

4.1 Performance and classification of experts' agitating motions

Figure 1 shows the time variation of the overrun, ΔW, where E1 – E5 represent the five expert confectionery hygiene mistresses, while N1 and N2 are the two non-expert female students. The data of N1 and N2 were obtained by Hara et al. (2018). In the case of the expert confectionery hygiene mistresses, the overrun rapidly increased and reached a peak value at about 3 – 4 min after starting agitation. The peak value is more than 100%, which indicates that the whipping state is appropriate for cooking. On the other hand, the value of overrun of the two non-experts slowly increased until about 6 min, and then decreased. The peak values of the two non-experts were remarkably smaller than that of the experts. These results indicate that the experts can whip heavy cream much better in almost two times shorter time than the non-experts and that all these five experts show almost the same performance for agitating cream.

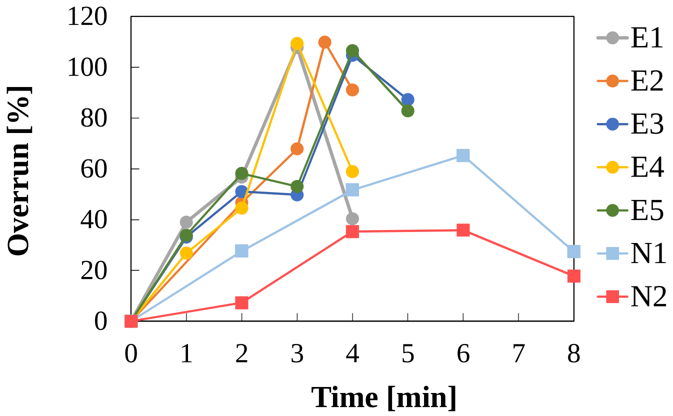


Figure 1: Time variation of overrun

Although the five experts show the same performance as each other, it has been found that their agitating motions are classified into two patterns. Figure 2 shows schematics of two agitating patterns and their corresponding photographs with the orbit of whisk head. As shown in Figure 2, the experts, E1 – E4, performed long elliptical motion in the longitudinal direction passing through the liquid every half period to scoop the whipping cream against the inclination of the ball. On the other hand, E5 horizontally reciprocated the whisk near the surface of cream without detaching from the liquid surface. The orbit of whisk head for the elliptical motions by E1 – E4 show narrower agitating region than that for E5.

a) Elliptical motion b) Reciprocating motion

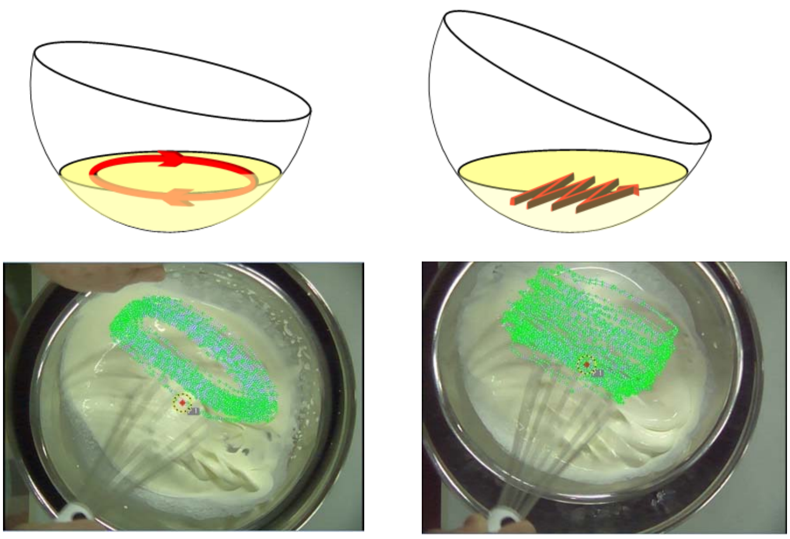
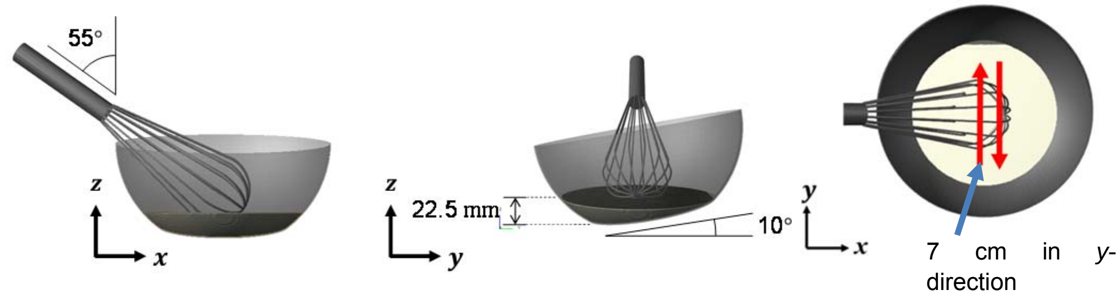


Figure 2: Schematics of two agitating patterns and their corresponding photographs with the orbit of whisk head

4.2 Geometric models of the experts' agitating motions

By taking advantage of the results described in the previous section, this study constructed geometric models of the experts' agitating motions for CFD analysis, as shown in Figure 3. The bowl was tilted by 10° with respect to the horizontal direction and the whisk was arranged at 55° in the vertical direction. The volume of liquid was 200 mL which was the same as the experimental condition and the deepest liquid height was 22.5 mm. In the case of elliptical motion, the elliptical orbit consists of amplitudes of 7 and 5 cm in *y*-direction and *z*-direction, respectively. On the other hand, in the case of reciprocating motion, whisk is reciprocated in *x*-direction with amplitude of 10 cm. The period of one cycle of motion was 0.2 s in both cases. Whipping width, *L*, which is perpendicular to whisk motion was set at two cases, i.e. wide and narrow cases, for each motion pattern. In the elliptical motion, *L* in wide and narrow cases were 180 and 100 mm, respectively. On the other hand, in reciprocating motion, *L* in wide and narrow cases were 170 and 110 mm, respectively.

a) Elliptic motion



b) Reciprocating motion

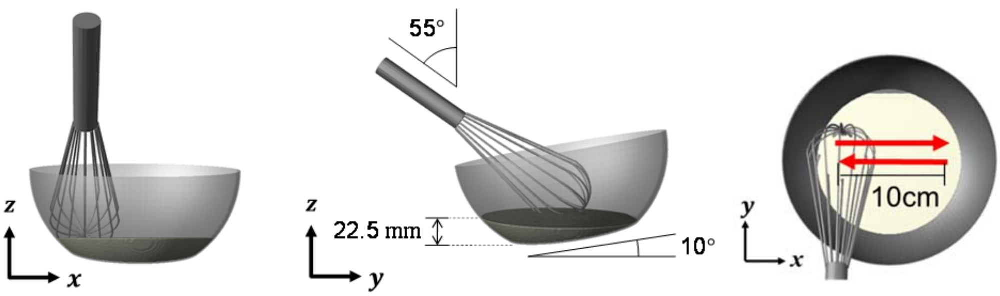


Figure 3: Geometric models of the experts' agitating motions

4.3 Numerical estimation of liquid surface state

Figure 4 shows surface images obtained by numerical simulation. In the elliptical motion, it has been found that narrower *L* gives more disturbed liquid surface. In the case of wider *L*, it is considered that the turbulence of the liquid surface could not be amplified because the amount of fluid to be lifted from the surface was smaller than in the case of narrower *L*. On the other hand, the reciprocating motion with narrower *L* can disturbed only the limited liquid surface at the portion through which the whisk passed, whereas the reciprocating motion with wider *L* can disturbed relatively wide range even at the part where the whisk did not pass. These results indicate that liquid lifted up from the surface collide with the liquid surface again occurs in the entire bowl in the case of reciprocating motion with wider *L*. Figure 5 shows liquid surface area calculated by numerical simulation. It has been found the elliptic motion with narrower *L* gives higher surface area than that with wider *L*, while the reciprocating motion with wider *L* gives higher surface are than that with narrower *L*. As described in the previous experimental results section, the orbit of whisk head for the elliptical motions by E1 – E4 show narrower agitating region than that for E5. Hence, numerical results suggest that the agitating motions by the experts are quite reasonable to obtain a good whipping state.

Raw heavy cream contains a lot of emulsified fat globules. According to Ueno et al. (1998), by agitating, initially these emulsified fat globules form a network structure and air bubbles are taken from the gas-liquid interface into this network structure. At this stage, the overrun gradually increases due to the uptake of air bubbles. Higher overrun means that finer bubbles are entrapped. By continuing to agitate, the fat globules finally break up and

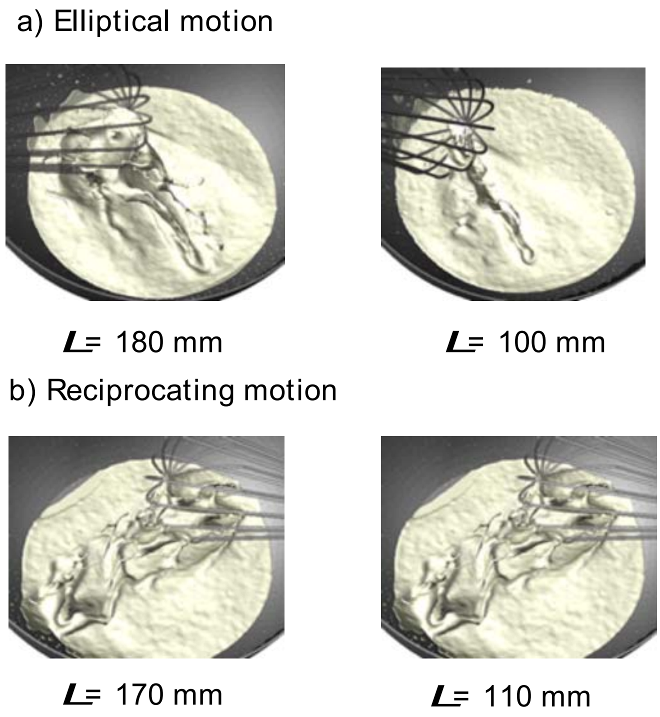


Figure 4: Liquid surface obtained by numerical simulation

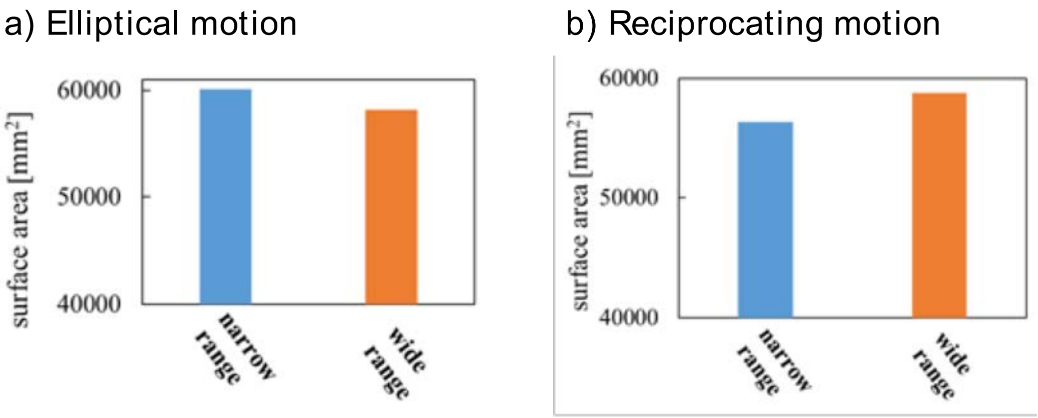


Figure 5: Liquid surface area

the network structure also breaks up. At this stage, heavy cream turns to a butter-like state and the entrapped bubbles released to the atmosphere, and the overrun rapidly decreases. By taking the above mechanism into consideration, not only large surface area produced by disturbance on the liquid surface but also high shear stress is also an important factor to uptake fine air bubbles. Figure 6 shows distributions of shear stress on the liquid surface. In the elliptical motion, the liquid surface is imposed high shear stress due to falling of whipping cream lifted up by the upward motion of whisk. The wider agitating region weaken the shear stress the amount of fluid to be lifted from the surface, as previously mentioned. On the other hand, the reciprocating motion produces relatively large shear stress on the surface by colliding fluids bouncing back against the wall and by colliding with each other fluid element. In addition, the shear stress is applied to the whole liquid surface by widening the agitating range.

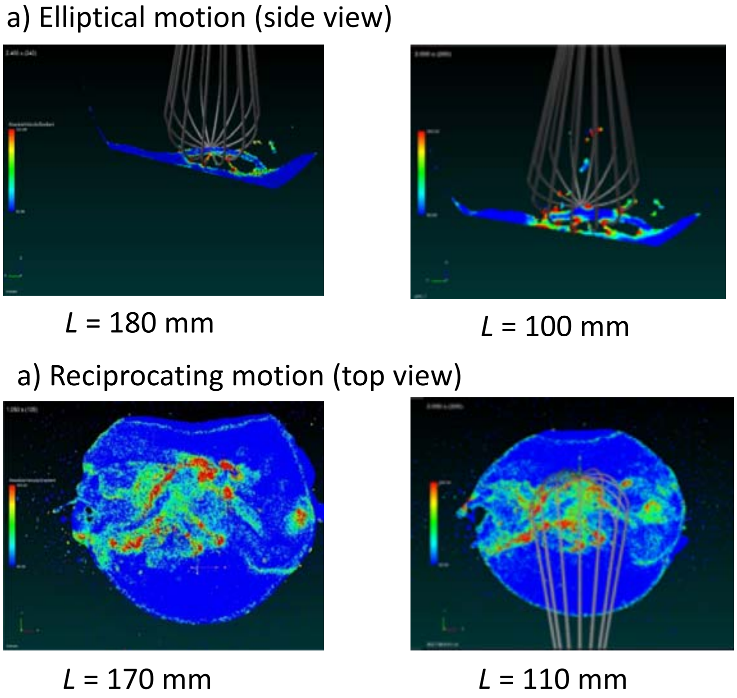


Figure 6: Distributions of shear stress on the liquid surface

5. Conclusions

This study experimentally observed human motions of whipping conducted by five expert confectionery hygiene mistresses. Fluid flow motion was numerically observed by the Moving Particle Semi-implicit (MPS) method. The experts' motions were classified into two patterns, i.e. vertically elliptical rotation and horizontally reciprocating by the experiments. In the elliptical motion, CFD analysis revealed that the liquid surface was imposed high shear stress due to falling of whipping cream lifted up by the upward motion of whisk and that the wider agitating region weaken the shear stress the amount of fluid to be lifted from the surface. On the other hand, the reciprocating motion produces relatively large shear stress on the surface by colliding fluids bouncing back against the wall and by colliding with each other fluid element. In addition, the shear stress is applied to the whole liquid surface by widening the agitating range. CFD analysis supported that he agitating motions by the experts are quite reasonable to obtain a good whipping state.

Acknowledgments

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