第１４回数値流体力学シンポジウム
<A05-2>

ミルククラウンの形成に関する研究
Analysis on Breakup in Coronet

張　　彦　東京工業大学院創造エネルギー専攻,目黒区大岡山 2-12-1 E-mail: yzhang@es.titech.ac.jp
島田　賢司 東京工業大学工学部機械科学科,目黒区大岡山 2-12-1 ,E-mail: simadake@stu.mech.titech.ac.jp
中川　順達 東京工業大学院機械物理工学専攻,目黒区大岡山 2-12-1 ,E-mail: nakagawa@mech.titech.ac.jp
矢部　孝　東京工業大学院機械物理工学専攻,目黒区大岡山 2-12-1 ,E-mail: yabe@mech.titech.ac.jp
Yan ZHANG, Dept. of Energy Sciences, Tokyo Institute of Technology, 2-12-1,O-okayama,Meguro-Ku,152-8552
Kenjii SHIMADA, Dept. of Mechanical Sciences and Engineering, Tokyo Institute of Technology
Masamichi NAKAGAWA, Dept. of Mechanical Sciences and Engineering, Tokyo Institute of Technology
Takashi YABE, Dept. of Mechanical Sciences and Engineering, Tokyo Institute of Technology

The coronet or the so-called milk-crown has been investigated mostly by experiments that already revealed many interesting features and physics. We have performed three-dimensional simulations on breakup of thin film leading to coronet in order to examine its mechanism in situations. Surprisingly, the wavelength of the breakup sensitively depends on the density of ambient gas and increases with density although the density has been believed to be too small to affect the dynamics. The simulation suggests that the breakup is due to competing between the breakup driven by Rayleigh-Taylor and stabilization effect owing to ambient gas flow. And we have also performed experiment of coronet..

1. INTRODUCTION

The milk-crown of the coronet is one of the most fascinating phenomena ever since the pioneering work by Worthington and is always keeping attention of people over a hundreds years. Therefore it is natural that it has been investigated by quite a lot of experiments that already revealed many interesting features and physics. The splashing of drops on liquid layers has a wide variety of applications. Engineering applications of drop impact are spray cooling, ink-jet printing, and GDI (Gasoline Direct-Injection) engine. Thin coatings can be obtained on surfaces by spray coating and spray painting. Levin and Hobbs applied their results to thunderstorm electrification and to the buildup of space charge during rainfall. In agriculture the prevention of soil erosion due to rain plays an important role. Brodie has demonstrated that the importance of the splashing of the raindrops in soil erosion and the dispersal of seeds and microorganisms. A knowledge of the spreading behavior of pesticides of foliage enables a reduction of the quantity of pesticides applied per unit area. Further, splashed pesticide droplets can be blown away by wind and pollute neighboring places. Splashing raindrops provide mechanisms for the dispersal of fungus spores. Atmospheric and oceanographic sciences investigate phenomena connected with rain formation and the interaction of rain with the surface of the ocean. High pressure occurring during meteor impacts can cause a fluidization of the rocky material. The resulting flows may lead to the formation of central peaks in craters that can be found on the moon. And, in criminalistics the study of the characteristics of stain patterns of impacted blood drops can be of significance in reconstructing crimes.

In contrast, simulation of the milkcrown has long been a dream in the field of computational physics because it can not only demonstrate the power of the scheme but also can investigate the physics of the milkcrown formation by choosing a situation which is hard to realize experimentally. Several interface capturing schemes have been proposed to attack this problem. Although the present-day technique is already close to this goal, nobody reported the three-dimensional milkcrown formation before except for a preliminary three-dimensional work, and several two dimensional works pioneered by Harlow and Shannon, in which instability and therefore breakup of rim leading to the milkcrown were not simulated. This is because the milkcrown is not merely a consequence of a free surface problem but we must treat ambient gas as well. This requires a special treatment at the complex boundary of the milkcrown where density ρ changes by 1000 times. In solving pressure p, it is quite a difficult task to guarantee the continuity of force $(\nabla p)/\rho$ across the complex interface having very large density ratio, otherwise quite a large acceleration can occur because of the change of denominator from 1 to 0.001 g/cm^3 across the interface.

Recently we simulated formation process of milkcrown by CIP method which can treat very large density change keeping the continuity of $(\nabla p)/\rho$ at the interface without any special boundary condition. This capability is essential for the application to the instability during the dynamics of milkcrown formation.

And we are preparing the experiments on milk-crown to verify our simulation results.

2. SIMULATION OF MILKCROWN

Figure 1 shows an iso-surface contour of density in which 100 $\times$100(horizontal)$\times$34(vertical) fixed, equally spaced Cartesian grids are used with D/16 grid spacing. A thin liquid film of D/4 thick is placed on a solid plate and a liquid drop of diameter D impacts from the top at a speed of U and $Re = UD/\nu = 8400$. We solved gas as well as liquid and the density ratio at the interface is almost 1000 as already mentioned. As shown in Fig.1 at t=4.92 and 8.2D/U, the irregular ring, which we call "finger" of the milkcrown, appears at first and then laminar belt develops below the finger later on.

We can estimate the deceleration of the motion to be $a = 2.5U^2/$D and from typical wavelength 0.42D (kD = 15) of the irregularity along the rim during deceleration we get the growth rate of $\gamma_{RT}=(ak)^{1/2} = 6.12U/D$ for the R-T (Rayleigh-Taylor) instability. This growth rate seems to be sufficient to account for the evolution of the irregularity because of $\gamma \Delta t$ = 3.67 during the deceleration time Δt=0.6D/U. At t = 1.80D/U ,the deceleration is largely reduced and from this time on, because of the lack of the instability, laminar belt of the milkcrown begins to develop just below the finger. Thus the well-known double structure consisting of the finger on top of the laminar belt is formed as observed in typical experiment of the milkcrown.

The above observation looks reasonable. Since the computer capability is limited, we can not check the validity of the theory by largely changing the parameters. The easiest and most interesting way to alter the situation is to change the gas density ρ_{gas}. Although the denser gas seems to be unrealistic, it may help

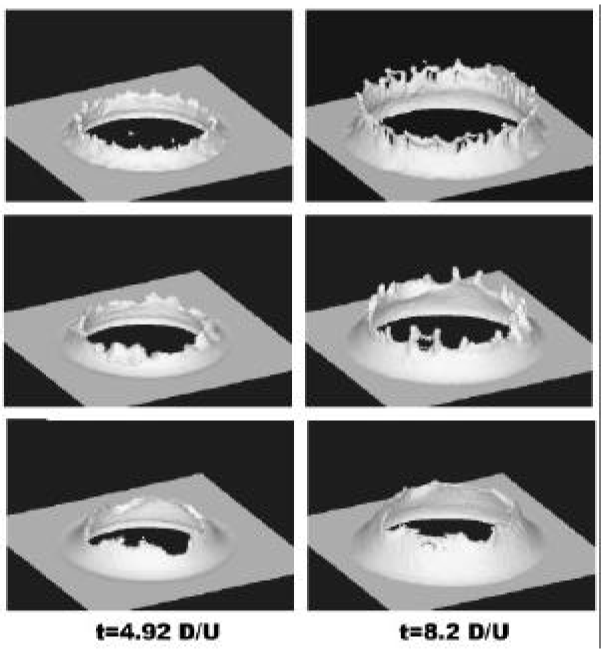


FIG. 1 Water surface plot in the milkcrown formation process. ρ gas/ ρ liq=0.002(top) and 0.02(middle)0.03 (bottom).

to check the physics in a situation which can be realized only by computer simulation. Since the gas density is 1000 times less than liquid, it does not seem to contribute to the evolution of the milkcrown. Surprisingly, however, it sensitively changes the evolution as shown in this paper.

Figure 1 also includes the iso-surface contour of the calculations with various density of ambient gas. Interestingly, unstable wavelength becomes longer when gas density is increased. Furthermore, at $\rho_{gas} = 0.03 \rho_{liq}$ the rim inclined inwardly ,which shows the apparent effect of ambient gas.

Even if this difference is taken into consideration, the effect of ambient gas can not be resolved because the gas density comes into the R-T growth rate as the Attwood number =$(\rho_{liq} - \rho_{gas})/(\rho_{liq}+\rho_{gas})$ but it is too small already to change the number even for denser gas of ρ_{gas}/ρ_{liq} =0.03.

If the instability is caused by the K-H (Kelvin-Helmholtz) instability, the growth rate[13] is $\gamma_{KH} = k|V|(\rho_{liq}\ \rho_{gas})^{1/2}\ (\rho_{liq}+\rho_{gas})$, where V is the relative velocity between gas and liquid, and can be affected by the ambient gas density by a factor of 3 for 10 times difference of density. However, the growth rate is larger for denser gas and contradicts with the simulation result.

Here we propose one possible explanation to this result. At first, let us derive the R-T growth approximately. Equation of motion in the x-direction (which corresponds to the radial direction) is written as $\rho_{liq}\ \partial u/\partial t \sim -\partial p/\partial x$. If the perturbation is in the y-direction (which corresponds to the azimuthal direction along the rim) and its wavenumber is k, the pressure perturbation $\partial\ \delta p/\partial x \sim -k\ \delta p \sim -\rho_{liq}\ ak\ \xi$, since divergence-free motion gives the mode of exp(-kx)exp(iky) and perturbed gravitational potential changes the pressure as $\delta p \sim -\rho_{liq} ak\xi$. Thus

$$r_{Liq}\frac{\partial^2 x}{\partial t^2} = r_{Liq} akx \qquad (1)$$

is derived with the help of $\partial \xi/\partial t = u$.
From this equation we get the growth of the R-T instability to be $\xi \sim \exp[(ak)^{1/2}t]$.

Nextly, we include the effect of ram pressure. Since the wind of ambient gas blows towards the rim radially in the moving frame of the rim, it can act to stabilize the R-T instability like a wall. If this wind velocity is U_0, then the effect of the ram pressure should be added to Eq.(1) in the perturbed form of $\partial \rho_{gas} U^2_0/\partial x$ which is roughly $\rho_{gas} U_0\ \partial\ (\xi/\Delta t)/\ \partial x \sim \rho_{gas} U_0 k\ \xi\ \gamma_{RT}$,, Δt being $1/\gamma_{RT}$,. Thus Eq.(1) is modified to be

$$r_{Liq}\frac{\partial^2 x}{\partial t^2} = r_{Liq} g^2_{RT} x - r_{gas} U_0 kxg_{RT} \qquad (2)$$

Therefore the criteria for the growth of perturbations will be

$$g_{RT} > \frac{r_{gas}}{r_{Liq}} kU_0 \qquad (3)$$

In the simulation, we have included the kinematic viscosity for water and air to be UD/ν = 8400 and 560 , respectively. Since the viscosity effect appears in a form of kinematic viscosity in the R-T and K-H instability, the effect of the ambient density will not explicitly appear in the result.

We have tested the effect of surface tension as shown in Fig.2 for $We = \rho U^2 D/\sigma = \infty$, 1216, 608. Actually, the break up of the rim tends to be reduced for larger surface tension although some implication of the droplet formation is seen at the top of the rim for We =1216. The impact Reynolds numbers in these cases are 448 and 377, and correspond to those that generate 20-30 fingers as seen from the experimental results. We compared our simulation results with experimental results in Fig.3

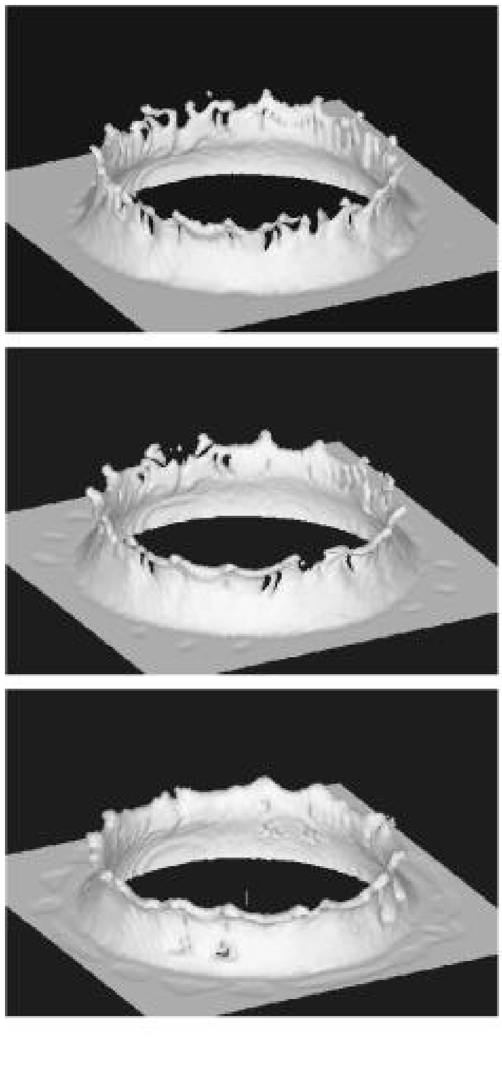


FIG. 2. Effect of surface tension.
We = $\rho U^2 D/\sigma = \infty$ (top), 1216(middle), 608(bottom)

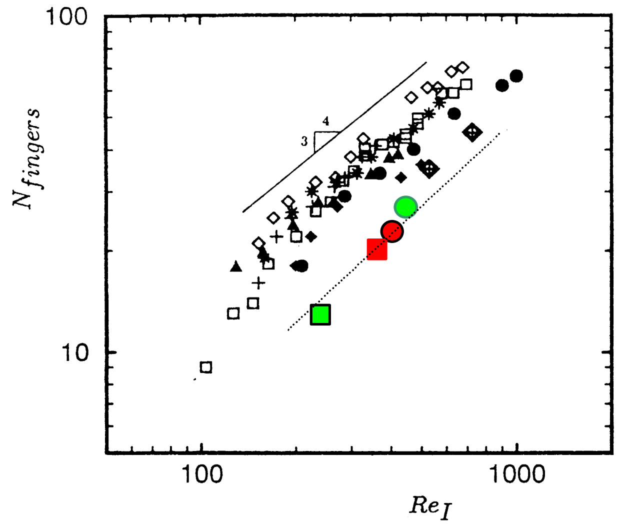


FIG. 3. Comparison with experimental results
Color Marks are simulation results while white-black marks are experimental results.

3. EXPERIMENT OF MILKCROWN

Experimental set up is shown in Fig.4. We initially set higher pressure in the injector which is used to drive a droplet. The open-close valve between injector and cylinder is electromagnetically controlled.

In Order to get a clear form of milk-crown, we chose a thin film of milk to which a droplet of milk will collide. Milk of 3 cm^3 is put into a culture dish (Shale). If we estimate the thickness of milk by tile surface area of shale, it gives 0.409 mm thick film. This estimation has some error owing to meniscus of circumference and therefore the absolute value of thickness is not accurate. We have repeated the experiments by 5 times for each condition and found that the phenomena are reproducible. Therefore, we conclude that tile thickness of milk is well controlled by this procedure. The droplet size and injection speed were measured by high-speed video camera (FASTCAM1) with the speed of the 2250 frames per sec and are estimated to be 2.74 mm in diameter and 1.97 m/sec. We have used 3.7 fat milk.

Figure5 shows milk-crown photographs taken by the high-speed video camera.

Figure 6 shows sequential photographs of experimental results.

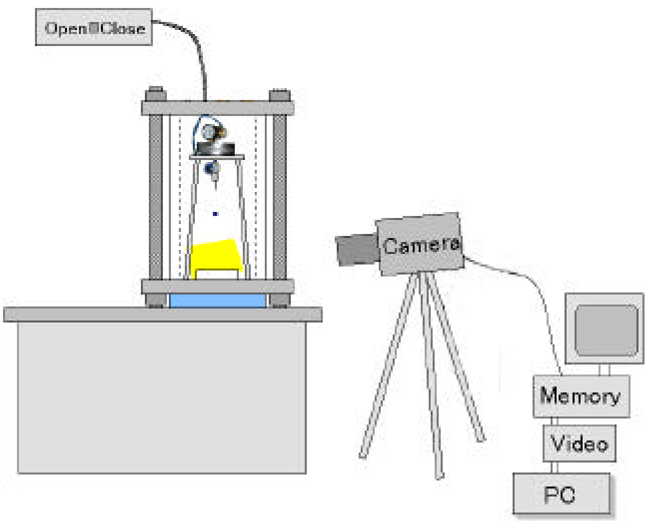


FIG. 4 Experimental setup

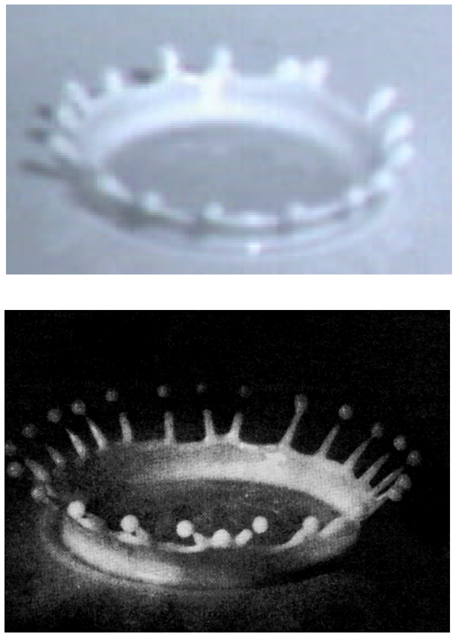
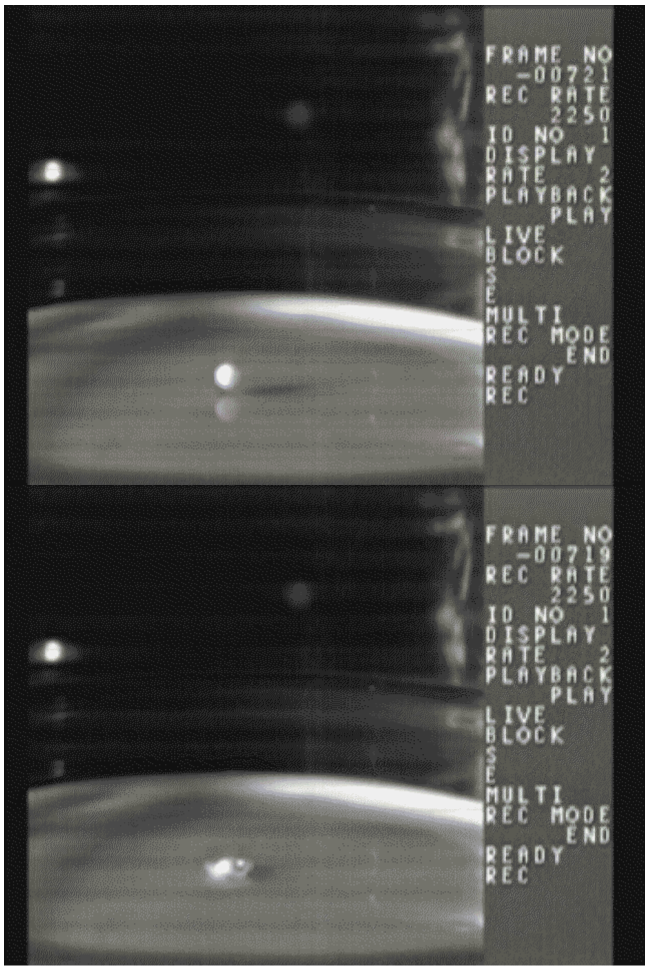


FIG. 5 Experimental results under the gas pressure of 10^5Pa taken by Yabe Lab. in 2000 (top), and taken by Edgerton & Killian (MIT) with milk in 1987 (bottom)



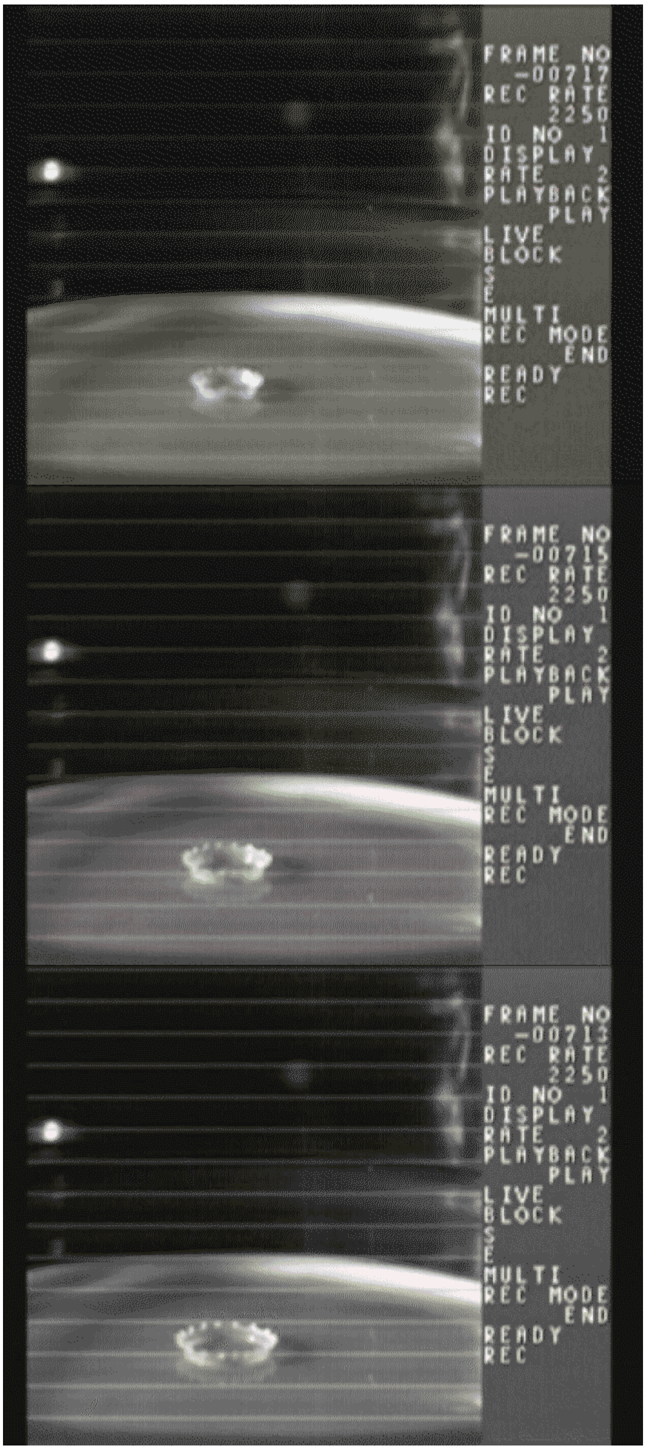


FIG. 6 Sequential photographs of experimental results

4. CONCLUSIONS

In summary, we have succeeded to simulate the three dimensional formation process of the milkcrown. The wavelength of the irregularity or finger along the rim depends on the density of ambient gas and increases with the density. This is due to competing between breakup owing to R-T instability and stabilization effect owing to ambient gas flow. Since the wavelength of the fingers along the rim strongly depends on the density of ambient gas, the finger formation observed here is not an artifact of finite grid size although it might have provided seeds of the instability. The present simulation has added important knowledge to the milkcrown formation physics by choosing the situation that would be hard to realize experimentally.

We are planning milkcrown experiment in high-pressure atmosphere to examine the result given by the authors[5].

Reference:

(1) A.M.Worthington: A Study of Splashes (Longman and Green, London 1908).
(2) H.E.Edgerton and J.R.Killian: Moments of Vision (MIT Press , Boston 1987).
(3) P.V.Hobbs and T.Osheroff: Splashing of Drops on Shallow Liquids; Science 158, 1184-1186(1967).
(4) H.Marmanis and S.T.Thoroddsen: Scaling of the fingering pattern of an impacting drop; Phys. Fluid 8,1344-1346(1996).
(5) Y.ZHANG and T.Yabe: Effect of Ambient Gas on Three-dimensional Breakup in Coronet Formation; CFD Journal, 8,378-382 (1999)
(6) T.Yabe: Interface Capturing and Universal Solution of Solid, Liquid and Gas by CIP Method; Proc.ISAC'97 High Performance Computingon Multi-Phase Flows, 19-24 (1997).
(7) T.Yabe, Y.Zhang and F.Xiao: A Numerical Procedure - CIP - to Solve All Phases of Matter Together; Lecture Note in Physics,Sixteenth International Conference on Numerical Methods in Fluid Dynamics, 439-457 (Springer, 1998).
(8) A.Prosperetti and H.N.Oguz: The Impact of Drops on Liquid Surfaces and the Underwater noise of rain; Annu. Rev. Fluid Mech. 25,577-602 (1993).
(9) F.H.Harlow and J.P.Shannon: The Splash of a Liquid Drop; J.¥ Appl. Phys.38,3855-3866 (1967).
(10)H.Takewaki, A.Nishiguchi, T.Yabe: The Cubic Interpolated Pseudo-particle Method (CIP) for Solving Hyperbolic-Type Equations; J. Comput. Phys. 61,261-268 (1985).
(11)T.Yabe and T.Aoki: A universal solver for hyperbolic equations by cubic-polynomial interpolation; Comput. Phys. Commun. 66 ,219-242 (1991).
(12)T.Yabe and F.Xiao: Simulation technique for dynamic evaporation processes; Nucl. Eng. & Design. 155,45-53 (1995).
(13)C.W.Hirt and B.D.Nichols: Volume of Fluid (VOF) Method for the Dynamics of Free Boundaries; J. Comput. Phys. 39,201-225 (1981).
(14)S.Osher and J.A.Sethian: Fronts Propagating with Curvature-Dependent Speed: Algorithms Based on Hamilton-Jacobi Formulations; J. Comput. Phys. 79,12-49 (1988).
(15)R.F.Allen: The Mechanics of Splashing; J. Colloid Interface Sci. 124, 309-316 (1988).
(16)S.Chandrasekhar: Hydrodynamic and Hydromagnetic Stability (Dover Pub., New York, 1961).
(17)S.Bodner: Rayleigh-Taylor Instability and Laser-Pellet Fusion; Phys. Rev. Lett. 33,761-764 (1974).
(18)T.Wakisaka, S.Takeuchi and J.H.Chung: A Numerical Study on the Mixture Formation Process in Fuel Injection Engines by Means of the CIP Method;CFD Journal, 8,82-90 (1999)
(19)M.Rein: Phenomena of liquid drop impact on solid and liquid surfaces; Fluid Dynamic Research 12,61-93(1993).
(20)Milk (Asakura Book Ltd, Tokyo 1964).