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Study of Atomization and Micro-Explosion of Water-in-Diesel Fuel Emulsion Droplets in Spray within a High Temperature, High Pressure Bomb

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ABSTRACT

The lump fashion micro-explosion of water-in-diesel fuel emulsion spray in eddy scale was observed by a multi-pulsed ruby laser holocamera with an off-axis image-plane optical path and a high speed camera in a high temperature, high pressure constant volume bomb. The environmental temperature has strong influence on the occurrence and strength of micro-explosion. A no-water layer evaporation model for single emulsion droplet was introduced into the computational simulation of the micro-explosion of the droplets, based on the observation of the micro-structure of emulsion droplets, the analysis of the velocity field in the droplet and Hill vortex theory. In this model, a rapid-mixing zone exists in the outer region of the moving droplet. The vaporization characteristics of an emulsion droplet in the spray are investigated by using this model under the experimental conditions, which has very good agreement with experimental results.

INTRODUCTION

The technique concerned with introducing water into engine combustion chamber was proposed by Prof. B. Hopkinson (1)* in 1913, to make better internal cooling of the gas engine and to increase the engine output. Furthermore, the technique was developed to improve the thermal efficiency and reduce exhaust emissions, or used as the safety fuel (2). Many different methods had been employed to introduce water into combustion chamber, e.g. water-injection in inlet manifold, mixing water and fuel as emulsions by mechanically stirring, steam-jet or ultrasonic equipments. But they were not developed enough to be applied in engineering application until the discovery of the micro-explosion phenomenon in 1965 (3), and the commercializations of ultrasonically-emulsifying technique and the emulsifying stabilizer in 1970s. More utilization of water-in-oil emulsions, both stabilized and unstabilized emulsion, with or without stabilizer, are applied in combustion chambers, and more attention on the fundamental research has been paid to understand the combustion characteristics and the combustion mechanism of the water-in-oil emulsion. By the emulsified fuel, an obvious advantage of economic benefit has been found in both fuel consumption and air pollution; the effect of soot cleaning has also been found in the field of industrial furnaces using crude oil or residual oil, which clears the soot deposited on the inner-face of the furnaces. Certain effects of the utilization of emulsified fuel on energy saving and the reduction of Nitrogen Oxides are also obtained for internal combustion engines, especially for old-fashion direct injection (D.I.) diesel engines.

The early fundamental researches were mostly focused on the combustion of single droplet or a limited number of droplets of 0.3 to 1.0 mm in diameters, which are suspended by one or a cluster of very fine quartz fibre or Platinum fibre, under an environmental condition of atmospheric pressure and higher temperature (4). A droplet generator was also employed to generate small droplets floating on upward heated air (or Nitrogen) stream to eliminate the coagulation of water, the internal phase, due to the suspending fibre in the later work (5). In most experimental works, the evaporation, the micro-explosion and the combustion processes were recorded by high-speed micro-photography. Some observations on the micro-explosion of emulsion spray were also made by high-speed photography, schlieren photography and shadowgraph macroscopically in a constant vessel of 0.5 MPa (6). However, the higher environmental pressure has a tendency to restrain the occurrence of the micro-explosion. The droplet diameters, the environmental temperature and the interaction of droplets have significant effects on the combustion process, so the characteristics of micro-explosion in dense spray with much smaller droplets in diesel engine combustion chamber are hardly identified from the experimental data mentioned above. Does the micro-explosion take place in practical engine combustion chambers with pressure of 3.0 MPa or more? Is the explosion energy strong enough to improve the combustion process and clear the deposited soot? How much benefit can be obtained by the utilization of water-in-fuel emulsion? How to explain the phenomena that both beneficial and adverse effects are observed in engine tests? These questions were still hardly known a few years ago. The knowledge from the theoretical research can hardly explain the facts in engine applications, and the results from engine tests are not comprehensive enough to direct practical applications.

Four years ago, the utilization of emulsion fuel was proposed as an alternative and economic fuel to save the fuel consumption due to the petroleum crisis in China. An objective evaluation must be made for making a decision to use emulsion fuel, a series of fundamental research had been done since that time. In the series, an advanced experimental technique — multi-pulsed laser holography was employed to microscopically detect the existence and the characteristics of micro-explosion of emulsion droplets in dense spray in a constant volume bomb filling with Nitrogen up to 4.0 MPa (7,8); the lump fashion micro-explosion was found. The phenomenon that the micro-explosion takes place in combustion process and has enough energy to expand the spray region, speeding up the flame propagation, was confirmed by high speed photography (8,9). A computer simulation was also made to predict the benefit in fuel consumption by the use of emulsion fuel in diesel engines, the combustion characteristics and the optimum water percentage in emulsion for different operating conditions had been discussed (8,10). The questions mentioned in the last paragraph are mainly answered by this series of work, an additional theoretical research to explain the mechanism of the micro-explosion was also successfully finished last year, which will be introduced in this paper.

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* Numbers in parentheses designate references at end of paper.

EXPERIMENTAL RESEARCHES

The details of the apparatus and the experimental method are mentioned in references (7,8,9). The interesting observations and computational simulation are all mentioned in the same references. Here some interesting points are repeated as the foundation of the theoretical model.

The testing conditions for both holography and high-speed photography are listed in Table 1, which simulate the environment in a high speed D.I. diesel engine with compression ratio of 16.5.

Table 1 Testing Conditions

Gas Pressure:	0.1 MPa, 2.4 MPa, 3.2 MPa, 4.0 MPa, 4.5 MPa, 5.0 MPa
Gas Temperature:	293 K, 723 K, 733 K, 753 K, 773 K, 823 K, 923 K
Injection pressure:	18 MPa, 22 MPa, 24 MPa
Injection Nozzle:	4 X 0.35 mm
Weight Percentages of Water:	0, 10, 12
Internal Phase Size:	0.002 -- 0.010 mm
Viscosity:	5 centistoke at 293 K

A constant volume bomb with controllable temperature and pressure up to 923 K and 6.0 MPa was employed to provide the environment for the experimental researches. Two pieces of quartz window with high optical quality are used as the path of object beam for off-axis holography. When the bomb is used for high-speed photography, one of the windows is covered by a piece of black paper to make a dark background. It is worth mentioning that the gas temperature in the bomb is much higher than the average gas temperature in the engine cylinder during its working cycle and the fuel injector in the bomb is working under single-shot condition without cooling by the flowing fuel. Therefore a cooling water jacket with a thermal insulating coat is used to cover the exposed part of the injection nozzle in the bomb to keep the working temperature under 353 K and to avoid the evaporation of the water in emulsion before the emulsion is injected into the bomb. This is very important for emulsion fuel study.

A ruby laser holocamera was employed to study the micro-explosion of emulsion droplets in spray during evaporation process microscopically. To avoid the burning of fuel, the bomb is filled with Nitrogen in this investigation. Since the fuel is injected into a high pressure vessel, the holographic plate is located at least 100 mm away from the spray for off-axis optical path. The droplets are too small to diffract strong signal for holographic plate, the direct recording method cannot provide enough resolution to measure the small droplets of 0.005-0.010 millimeters, so the image-plane method was employed to provide the highest resolution. A high optical quality convex lens of 25 mm in diameter is inserted into the path, between the spray and the holographic plate which is located at image-plane. The image is pre-magnified up to 3.5 times, and recorded on the holographic plate. The diameter of the convex lens determines the area of the field of view which is a thousand times of the micro-photography if they are in the same resolution level, so that the image of the fast moving droplets due to the explosion can be captured in the same picture. To avoid the speckle noise and obtain a uniform illumination in the field of view, a convergent white light beam is employed in the reconstruction system, any part of the field of view can be recorded as 2-D image on a negative colour film or black/white film by a 35 mm camera with macro lens. Then the images on negative film is re-magnified to the required sizes.

From reconstructed pictures (7,8), the image of droplets of 0.005 mm can be clearly identified after 10 times re-magnifying. The water dots of 0.001 mm in emulsion droplets can also be recognized, a no-water layer is found near the surface of the droplet (Fig.1). The micro-explosion of droplets takes place in the lump fashion of eddy-scale. The explosion region is near the outer layer of the spray, and the explosions occur in individual lumps, and at different moments and with different strengths. The environmental temperature plays an important role in the occurrence of the explosion. The micro-explosion can hardly be observed below 733 K. If the explosion takes place, the energy of the explosion at this temperature is much smaller than that at 773 K. At 823 K, the explosion takes place early and is slightly weaker. In lower gas pressure cases, the velocity of torn fragments of droplets after explosion is much higher than that in higher gas pressure due to lower gas density.

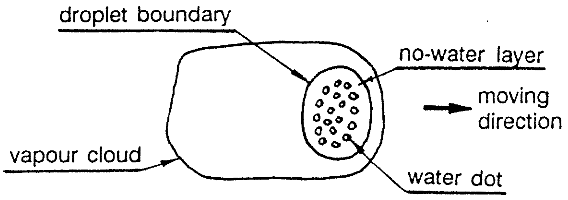

Fig.1 Micro-structure of the evaporating emulsion droplet

To study the combustion process of emulsion, the ignition delay, the flame propagation, and the macro effects of micro-explosion, a 16 mm HYSPEED high speed camera with CANON 10/100 mm video camera zoom was employed (8,9). The field of view here was about 55 mm in diameter. In this investigation the bomb was filled with fresh air. Before injection, the air was heated up to 733 – 923 K and the pressure was 3.2 – 5.0 MPa.

The angle and the area of the emulsion flame are larger than those for pure fuel, the edge of the emulsion flame is unclear and irregular. This phenomenon can be regarded as the macro effect of the micro-explosion. Inside the flame region, many burning lumps can be seen, they are different from the case of the pure fuel flame. When the initial gas pressure is reduced, the micro-explosion becomes stronger, the flame angle becomes larger. If the initial temperature in the bomb varies, the combustion processes of the emulsion change greatly. When the temperature is 873 K, the effect of the explosion is less than that at 823 K, the explosion occurs earlier and closer to the injection nozzle, and the pictures are also more similar to the pure fuel's. When the temperature is down to 773 K, the rates of burning and heat release of emulsion are greatly reduced in the first period of combustion. The lump-fashion flame is much more significant.

PHYSICAL DESCRIPTION

When emulsion fuel is just injected into the bomb, the gas temperature around the droplets is lower and the heating rate of the droplets is slow. The shear-stress due to the relative velocity difference between gas and droplets reduces the droplet speed and induces an internal circulation, Hill vortex, in the droplets (Fig.2). The circulation strength is much stronger in the outer layer of the droplets, but very weak in the inner core. Since the shear-stress is not an axially symmetrical stress, it may rotate the droplet, and then form a rapid-mixing zone — a no-water layer (refer to Fig.1). In this layer the water dots will be moved onto the surface of the droplets and rapidly evaporate before the water dots are heated up to the saturation temperature (523.5 K at 4.0 MPa), and form a steam cloud around the droplet. The oil is also evaporating, but it is much slower than water. The diffusion rate of the steam is much higher than that of oil vapour. Meanwhile, the thermal diffusion effect makes the heavier oil molecules move towards the droplets, so the diffusion rate of diesel fuel is much lower than water, a no-water layer is formed under this condition. The circulation inside the core is not strong enough to homogenize the temperature field and the water dot distributions in the whole droplet since the Hill vortex still exists to form new no-water layer if the droplet is moving in the air, but the inner core itself can be assumed as a homogeneous phase. The no-water layer is very important to the micro-explosion of emulsion droplets, it remains an unbalanced situation inside the droplet. The water dots in the core are easily heated up to the superheat state, a pseudo-stable state, if the environmental temperature is proper. When the water dots near the outer layer achieve the limit of superheat (e.g. 583 K at 4.0 MPa) and gasify, and lead to that the other superheated water dots also gasify and expand rapidly at the same moment, and thus tear the fuel droplet, which is called micro-explosion. The micro-explosion takes place more easily in a big droplet than in a small one since the unbalanced situation is more easily kept in a big droplet.

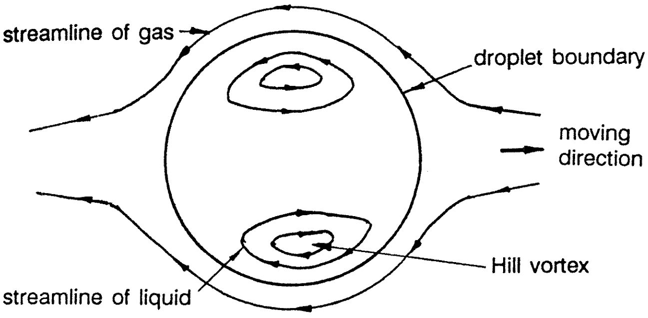

Fig.2 Schematic diagram of Hill vortex

If the environmental temperature is not high enough, the water dots in the droplets will not be superheated and will evaporate gradually, or evaporate completely before water dots are heated into the superheated state, no explosion will take place (Fig 3). If the temperature is much higher, the heat transfer between gas and droplets is strong enough, the temperature gradient in the droplets is steep, some of the water dots will be over the limit of superheat earlier than that in lower temperature conditions, the micro-explosion will also take place earlier and the water dots in the droplet will not be all superheated and explode at that moment. Therefore the strength of explosion is not very strong. If the environmental temperature is proper, the water dots in the droplets will be all rapidly heated into superheated state and then explode. In this case, the explosive strength will be strong enough to emit fragments of torn droplets several millimeters away from spray, and greatly expands the spray region in a macroscopic point of view.

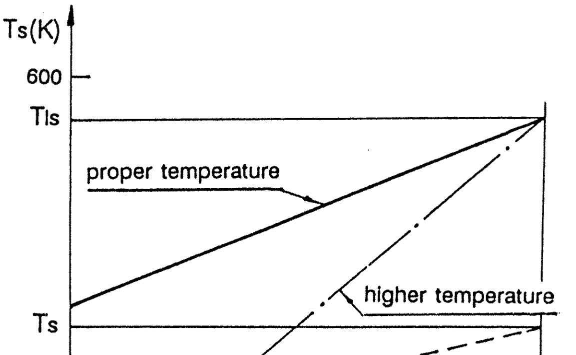

Fig.3 The influence of environmental temperature on the droplet heating process

T_{ls}: Limit of superheat (583 K at 4.0 MPa)

T_s: Saturation temperature (523.5 K at 4.0 MPa)

In fact, since the emulsion droplets do not exist individually, the turbulent eddies in spray also play an important role in micro-explosion process, and make the explosion in the lump fashion of 2 – 3 mm scale. When injecting, the spray entrains air in the lump fashion (that is also confirmed by holograms) and expands at about 20 degree of spray angle. The air entrained forms a number of lump-fashion eddies. In the same eddy the emulsion droplets are in a similar superheated state. If a droplet is exploding, the explosion wave and the fragments of the torn droplet may induce the other droplets in the same eddy to explode — an avalanche of the micro-explosion — which is so called the lump-fashion explosion. The micro-explosion is able to expand the spray region and homogenize the fuel-air mixture. But the occurrence of the explosion and the explosion strength is closely related to the environmental temperature, water percentage, etc., and the effect of micro-explosion is also related to the environmental pressure — gas density. Because of that, the positive influence of the emulsion is fully conditional on the applied situation, and sometimes the influence may be negative. It is the reason why the economic benefits to engine application reported by different researchers are often different, some are even worse than pure fuel, owing to the different testing conditions.

MATHEMATICAL DESCRIPTION

Many simulation models, e.g. infinite conductive limit model, conductive limit model, have been made to describe the behaviour of emulsion droplets in high temperature conditions (11,12,13), but these works are all based on still droplet condition, which is different from the condition of moving droplets in spray. According to W.A.Sirignano's theory (14), the shearing effect between air and the droplet induces an internal circulation – Hill vortex, which has an important influence on the concentration and temperature distribution in the droplet. A vortex model has been developed to describe the phenomenon, and had very good results, comparing with infinite conduction limit model and conduction limit model (15).

Based on the experimental observation and theoretical analysis, a single droplet model for emulsion evaporation — no-water layer model is developed as follows:

a) the droplet is treated as a sphere containing two zones, zone 1 — the inner core of the droplet, zone 2 — the rapid-mixing zone — the no-water layer (Fig.4);

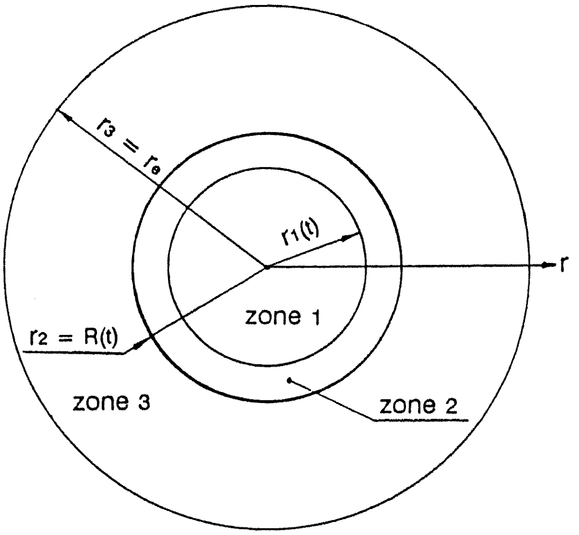

Fig.4 No-water layer model

r_e: equivalent radius

b) zone 1 is considered as a uniform phase, the physical property of the mixture is determined by the weight percentage of water;

c) zone 2 is formed by Hill vortex and the temperature in zone 2 is equal to the droplet surface temperature;

d) the droplet and zone 3 — the gas phase around the droplet construct the system, the gas phase is spherically symmetrical and quasi-stable because the residence time of gas phase in boundary layer is one thousandth of the droplet life time.

The basic equations in spherical coordinates are:
Temperature distribution in zone 1,

$$\frac{\partial T_1}{\partial t} = \alpha_1 \frac{\partial^2}{\partial r^2}(r\ T_1) \qquad (0\leq r<r_1, t>0)$$

$$T_1(r,t) = T_s(t) \qquad (r=r_1, t>0)$$

$$\frac{\partial T_1(r,t)}{\partial r} = 0 \qquad (r=0, t>0)$$

$$T_1(r,t) = T_0 \qquad (t=0) \qquad (1)$$

Energy equation for zone 2,

$$\dot{Q}_3 - \dot{Q}_1 = \dot{m}\ L + \rho_l\, C_{pl}\, V_2 \frac{dT_s}{dt}$$

$$T_s(t) = T_0 \qquad (t=0) \qquad (2)$$

Temperature distribution in zone 3,

$$\frac{\partial}{\partial r}\left(r^2 \frac{\partial T_3}{\partial r}\right) = \frac{\dot{m}}{4\pi \alpha_g \rho_g} \frac{\partial T_3}{\partial r} \qquad (R(t)\leq r<r_e)$$

$$T_3 = T_\infty \qquad (r\rightarrow r_e)$$

$$T_3 = T_s \qquad (r=R(t)) \qquad (3)$$

where: $r_e = R/(1-2/Nu)$

Concentration distribution in zone 3,

$$\frac{\partial}{\partial r}\left(r^2 \frac{\partial Y_f}{\partial r}\right) = \frac{\dot{m}}{4\pi D_f \rho_g} \frac{\partial Y_f}{\partial r} \qquad (R(t)\leq r<r_e)$$

$$Y_f = 0 \qquad (r\rightarrow r_e)$$

$$Y_f = Y_{fs} \qquad (r=R(t)) \qquad (4)$$

where: $r_e = R/(1-2/Sh)$

The evaporation rate,

$$\frac{\dot{m}}{4\pi R^2} = \rho_l \frac{dR}{dt} = \frac{D_f \rho_g}{1-Y_{fs}} \left.\frac{\partial Y_f}{\partial r}\right|_{r=R} \qquad (5)$$

The movement equation of droplet,

$$\frac{dv_l}{dt} = -\frac{3C_D}{8R} \frac{\rho_g}{\rho_l} v_l^2 \qquad (6)$$

Equations 1 – 6 are the basic equations. Considering the rotation of the droplet, the radius of inner core is determined by the zero point of the angular-velocity ($\sqrt{2}/2$ R) in the droplet from the stream function of Hill vortex

$$v_\theta = -\ Ar\ (R^2-2r^2)\ \sin^2\theta \qquad (7)$$

When the no-water layer is formed, the water content in the layer has been moved onto the surface of the droplet by the vortex and evaporated, so the droplet radius is less than the initial radius:

$$R^3 = R_0^3 - (R_0^3 - r_1^3)\, Y_w\, \rho_w/\rho_f \qquad (8)$$

Since there is a forced convection between the droplet and environment, the Stefan flow around droplet is not spherically symmetrical, an equivalent radius is also introduced here for convenience in calculation. After the derivation of the equations by Duhamel integral, the equations are solved by Runge-Kutta method, some variables are treated by quasi-stable principle. Some parameters e.g. Y_{fs}, Nu, Sh, D_f, etc. are determined by empirical formulae. The surface temperature of droplet Ts(t), droplet radius r(t), droplet velocity v(t) are obtained from calculation. From Ts(t), the temperature field in the droplet can be calculated, and the temperature of individual water dot at different moments is known, considering the heat transfer between the continuous phase — oil and discrete phase — water. According to this result, the time of micro-explosion occurrence is obtained, and the explosion energy is calculated by the residual water mass times the expanding work during the gasifying process. The speed and the penetration of the fragments of torn droplet is also obtained. The detailed description of the model and the computation procedure was mentioned in reference (16).

COMPUTATION RESULTS

To evaluate the accuracy of the new model — no-water layer model, the calculations for pure hexane, decane, hexadecane has been made in the same operating conditions as Aggarwal's work (15). The surface temperature and diameter of the droplet is very good, comparing with vortex model and infinite conductive limit model (Fig.5), especially in the second half of the heating period, in which the droplet reaches the saturation temperature. Therefore the inaccuracy of the model has small influence on micro-explosion.

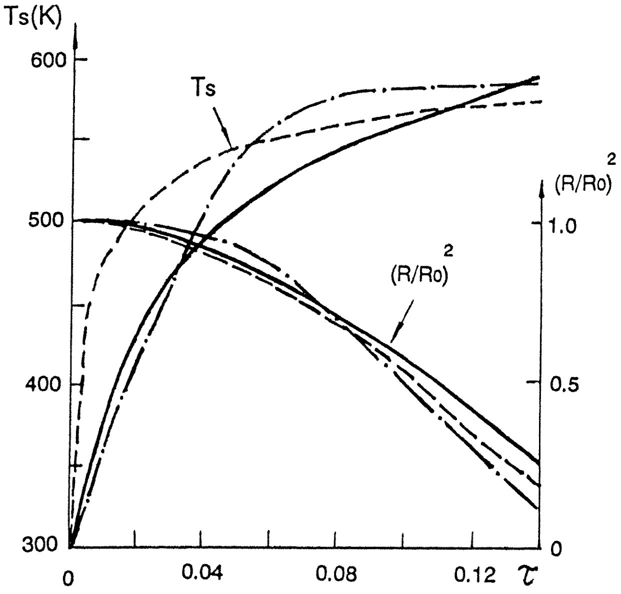

Fig.5 The histories of the surface temperature and diameter of Hexadecane droplet
—— no-water layer model
– – – vortex model
—·— infinite conductive limit model
$\tau = \alpha_1 t/R_0^2$, dimensionless time

The no-water layer model is applied for the simulation of water-in-diesel emulsion fuel. The operating conditions are simulating the experimental research in constant volume bomb, and the influence of the environmental temperature and pressure, the initial velocity and diameter of droplet, and water percentage on the occurrence and energy of the explosion are studied. The results are very close to experimental results, and a much more comprehensive understanding of the mechanism of micro-explosion is obtained.

a) The environmental temperature is the key factor on the occurrence of micro-explosion (Fig.6). If the pressure and temperature are p=3.2 MPa and T=773 K, the droplet surface temperature will achieve 583 K at t=2.2 ms, micro-explosion will take place. If the temperature is T=823 K, micro-explosion will take place at t=1.4 ms. If T=723 K, the droplet will evaporate completely when the surface temperature reaches 576 K, no micro-explosion will take place. In this case, the minimum environmental temperature for micro-explosion is 733 to 773 K. The simulated results have very good agreement with the experimental results.

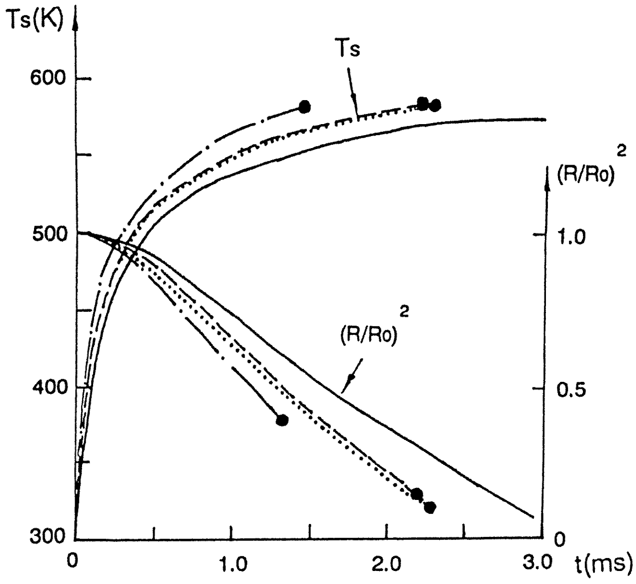

Fig.6 The histories of the surface temperature and diameter of emulsion droplet

—— T_∞=723 K, P=3.2 MPa, Y_w=10%
– – – T_∞=773 K, P=3.2 MPa, Y_w=10%
—·— T_∞=823 K, P=3.2 MPa, Y_w=10%
········ T_∞=773 K, P=3.2 MPa, Y_w=12%
● — micro-explosion occurs

b) The calculation shows that the lower the environmental pressure, the higher the explosive energy is, if the residual mass $(R/Ro)^2$ is the same when the explosion takes place. Therefore, if environmental pressure is raised, the surface temperature rises slightly faster, and the evaporation rate is slower since the high pressure reduces the diffusion coefficient of fuel (Fig.7). The residual mass in 4.5 MPa is 0.17, which is much higher than that of 0.13 in 3.2 MPa, if the temperature is 773 K and the initial droplet diameter is the same. But the speed and penetration of the fragments of torn droplet is much less than that in lower pressure conditions due to fast rising gas density in higher pressure cases. The increase of residual mass cannot compensate for the effect of increase of gas density on fragments penetration, which agrees very well with holographic observation. The micro-explosion occurs slightly earlier in higher pressure condition than that in lower pressure, which also agrees very well with the experiments.

c) The initial droplet diameter is another important factor on the micro-explosion. If the initial droplet is too fine, the residual mass is too small or has vanished before the droplet is heated up to saturation point, the explosion can hardly be observed in this condition. In fact, the injection pressure in experiments is kept in the nozzle open pressure (18 – 24 MPa). This result implies that the micro-explosion effect may be very helpful to the old-fashion bad-performance injection pump. The high initial velocity of droplet can speed up the heat and mass transfer and let the explosion occur earlier, but the residual mass varies slightly, the explosive energy changes little, if the initial diameter is the same.

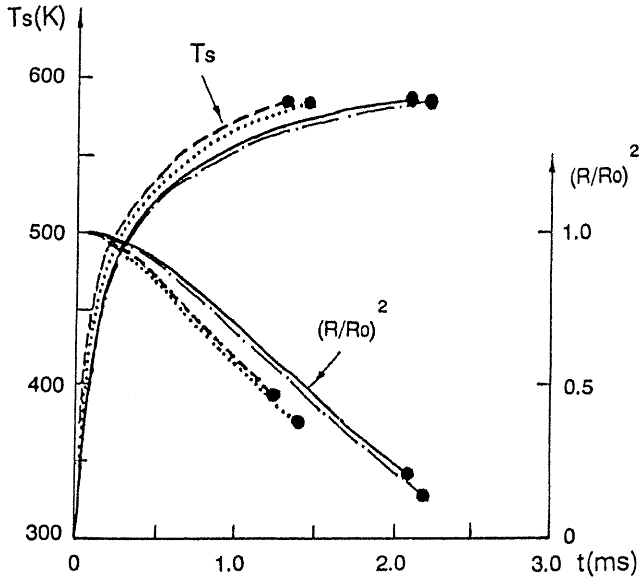

Fig.7 The histories of the surface temperature and diameter of emulsion droplet

—— T_∞=773 K, P=4.5 MPa, Y_w=10%
– – – T_∞=823 K, P=4.5 MPa, Y_w=10%
—·— T_∞=773 K, P=3.2 MPa, Y_w=10%
········ T_∞=823 K, P=3.2 MPa, Y_w=10%
● — micro-explosion occurs

d) By common sense, the higher the water percentage, the more the residual mass, and the larger the explosive energy is. However, if the initial diameter of the emulsion droplet is the same, the emulsion with much more water content will lose much more water and in droplet diameter, and thus lower the surface temperature when the no-water layer is formed at the beginning of evaporation (refer to formula 8 and Fig.6). The higher water percentage helps the injector to get finer fuel droplets and give the spray more initial momentum to improve the air-fuel mixing process. But when the explosion takes place the residual mass of water is not as high as that we expected due to the existence of the vortex and no-water layer. In our experiments, the water percentage has less influence on the occurrence of the micro-explosion.

It is worth mentioning that if the micro-structure of emulsion is not good, the water dots are not fine and uniform, this model may not be proper.

CONCLUSIONS

a) The Hill vortex effect separates the moving emulsion droplet into two zones: a rapid-mixing layer or so called the no-water layer near the surface of the droplet, and an inner core with lots of micro-water-dots. The heat and mass transfer in different zones are very different and form an unbalanced situation. The no-water layer concept when it is introduced into the emulsion evaporation model can describe this phenomenon successfully. This model indicates not only the relationship between environmental temperature, pressure and the micro-explosion, but also the influence of initial droplet diameter and water percentage on the explosive energy. All the explanations agree very well with the experimental observation, a much more comprehensive understanding on the mechanism of micro-explosion of emulsion droplets in spray is obtained from this research, which is very useful to direct the engine practice.

b) The temperature in the combustion chamber is the key factor of the utilization of emulsion, micro-explosion will take place in a certain temperature range and become stronger at a proper temperature. Higher pressure in the combustion chamber has little effect on the occurrence of the explosion, but the penetration of fragments of torn droplet will be much lower due to denser gas in the combustion chamber, it may weaken the effect of micro-explosion on the improvement of air-fuel mixing. The explosion will take place more easily for larger initial droplet diameters. The energy of explosion is strong enough to emit fragments of torn droplets to a distance several millimeters away from the spray boundary, if the gas temperature is suitable.

NOMENCLATURE

A = constant
C_D = drag coefficient
C_p = specific heat capacity at constant pressure
D = mass diffusivity
L = latent heat of vaporization
m = mass
Nu = Nusselt number, dimensionless
Q = heat (on unit area basis)
R = radius of emulsion droplet
r = radial distance
Sh = Sherwood number, dimensionless
T = temperature
t = time
V = volume
v = velocity
Y = mass fraction
α = thermal diffusivity
ρ = density
θ = angle

Subscripts
0 = initial condition
1 = zone 1, inner core of emulsion droplet
2 = zone 2, rapid-mixing zone
3 = zone 3, gas phase
e = equivalent
f = fuel
g = gas phase
l = liquid phase
s = surface
w = water
θ = angular direction
∞ = at infinity

Accent
• = time derivative

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