

Theoretical and Experimental Studies of Droplet Evaporation in High-Temperature Air

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Abstract: This paper is deal with the evaporation rules of single droplet in a “hot” ambient environment. equipment is designed and CCD high-speed camera is used to attain the evaporation rules of suspended droplet with the diameter in range of 1.6 to 1.8mm in the high- temperature air. At the same time, a simplified evaporation models is developed for numerical simulation based on the so-called ‘film theory’, and the comparison of vaporization history indicates that, traditional D^2 -law is not followed by drop evaporation in “hot” air and simplified evaporation models are in close agreement with experiments; The evaporation of a single droplet provides certain foundation for the further evaporation mechanism research with model of smaller droplet in high-temperature air.

Keywords: High-temperature air; Droplet; Evaporation rules; Studies

1. Introduction

Evaporation of small liquid droplets in a form of sprays and mist is encountered in numerous technologically important applications such as spray combustions, evaporative cooling, suppression of building fires, at present, most documents^[2-9]are deal with evaporation combustion characteristics based on single particles of diesel engine fuel droplet in “hot” surroundings, the membrane theory (Namely that the process of droplet evaporation, heat and mass transfer occur in a layer of gas "film" which is between the droplet surface and high temperature gas; heat and mass transfer resistance in droplet surface is respectively indicated by dimensionless quantity $F(B_r), F(B_m)$, which express the relative change of film thickness) has been applied by Abramzon and Sirignano^[6]for numerical computation of fuel droplet and for accurate prediction of evaporation time, evaporation rate and other parameters. With the development of steel industry, Spray evaporative cooling technology of gas with different component is applied more and more, but it has been rarely reported of the research on the droplet evaporation mechanism against this background. This paper studies the evaporation rules of single droplet in

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the high temperature air. Considering the effect of thermophysical parameters varied with temperature in the gas film, Stefan flow and Spalding heat and mass transfer number, a simplified evaporation model was developed based on the so-called film theory;At the same time, the experiment is designed and CCD high-speed camera is used to obtain the effect-laws of gas temperature and initial diameter on vaporization rate. This paper provides certain foundation on the further evaporation mechanism research on model of smaller droplet under higher temperature.

2. Experimental equipment and method

2.1 Experimental equipment

This experiment separately researched the rule of evaporation rate and drop diameter with time under different initial diameter and different temperature ambient. The air is provided by compressed gas cylinders. Experimental device is shown in Fig.1,

cylinder① supplies the gas, and rotameter② measures the flow rate. ④ means platinum-rhodium thermoelement with 0.3mm; water droplet is suspended from a thermoelement node through a feed buret, while thermoelement is fastened by a jib③. Platinum-rhodium thermoelement⑤ is used to monitor outlet temperature

of furnace, and temperature value is displayed in the temperature regulation⑥. High-speed camera⑧ films the whole process of evaporation. Furnace⑦ is fastened by support frame⑨, and various devices are connected by plastic tube⑩.

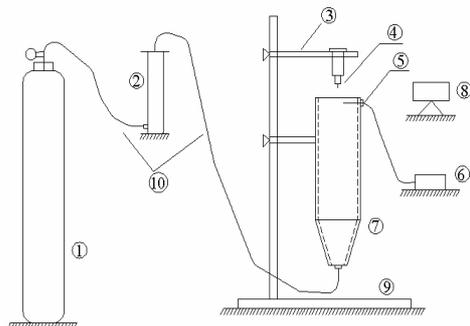


Figure 1. Diagram of equipments

2.2 Experimental method

The ceramic regenerator balls which are heated to

1000K in their surface before experiment hold 2/3 volume of the furnace⑦, The gas flows from cylinders through the rotameter to bottom entry of the furnace⑦, and the highest temperature of air in the outlet of the furnace⑦ could be 800K after heat exchange with regenerator balls. Air flow is controlled and kept steady by rotameter and valve of cylinders. Thermoelement hanging the drop is about 8mm away from the mouth of furnace. Water drop is suspended a thermoelement node through a microburet. The jib ③ which fixed the suspender could rotate and move. Because high-speed camera films the whole process of evaporation of water droplet, the video image offers exact droplet size of all time. The whole experimental system is open, so ambient pressure is one standard atmosphere. As indicated in Fig.2. When the velocity of air is 3.0m/s and temperature is 673K, the high-speed camera records the whole evaporation process of a droplet whose initial diameter is 1.9mm.

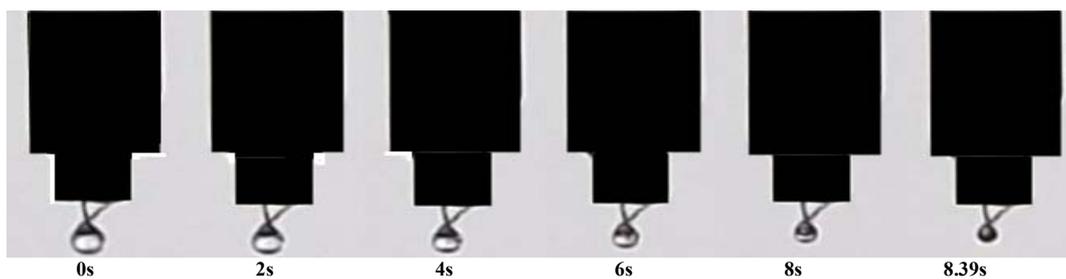


Figure 2. Process of droplet evaporation

3. Theoretical simulation

3.1 Physical model

When high-temperature air flows through the hanging drop, heat and mass transfer is carried out and droplet turns into water vapor. Principle hypothesizes are as follows:

- 1) Droplet remains spherically symmetric;
- 2) Thermophysical property of high temperature gas and droplet keeps uniform;
- 3) Flow field is of laminar and axisymmetric;
- 4) The effect of gravity, viscous dissipation, temperature gradient within the droplet and thermal radiation is

ignored;

- 5) Temperature of droplet surface is uniform and varies with time.

3.2 Mathematical models

According to "film theory", the concept of film thickness is introduced to represent the resistance of heat and mass transfer between air flow and droplet surface. Stefan flow produced by drop evaporation can have an influence on film thickness^[6], so the relative change of film thickness produced by that should be represented by reintroduced parameters F_T 、 F_M . Existing study by Hubbard^[11] and others show that instantaneous change of

thermophysical parameters with time in the film have a negligible impact on evaporation process. In this paper, $T_r = T_s + A_r(T_\infty - T_s)$ is used as reference temperature in the simulation of thermophysical

parameters in the film, whereas Yuen^[4] gives $A_r = 1/3$, or so-called "1/3-law". In conclusion, mathematical model followed:

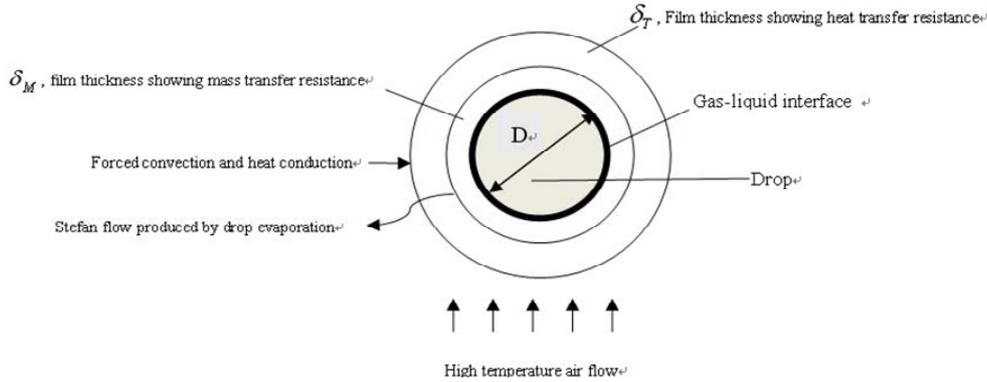


Figure 3. Physical model of droplet evaporation based on film theory

1) For a single droplet, the instantaneous evaporation rate is^[8]:

$$\dot{m} = 2\pi\rho_g D_g D_s \text{Sh} \ln(1 + B_M) \quad (1)$$

$$B_M = \frac{Y_{Fs} - Y_{F\infty}}{1 - Y_{Fs}} \quad (2)$$

$$\text{Sh} = 2 + (\text{Sh}_0 - 2)/F_M \quad (3)$$

where ρ_g is gas density; D_g is diffusion coefficient of vapor in gas; B_M is Spalding mass transfer coefficient; $Y_{Fs} - Y_{F\infty}$ are Mass percentage of water vapor respectively in drop surface and gas; P is gas pressure around droplet; P_{Fs} is saturated pressure of vapor in drop surface; Y_{Fs} is confirmed by $Y_{Fs} = [1 + (\frac{p}{P_{Fs}} - 1) \frac{M_g}{M_F}]$,

where M_g and M_F is respectively the molar mass of gas and water droplets; p_{Fs} can be calculated by the formula as Clausius-Clapeyron equation:

$$p_{Fs} = \exp\left[-\frac{\Delta H_{vap}}{R} \left(\frac{1}{T_s} - \frac{1}{373}\right)\right],$$

where $\Delta H_{vap} = 40.7 \text{kJ/mol}$ is evaporation enthalpy;

$$R = 8.31 \text{J/mol.K is gas constant; } \text{Sh}_0 = 2 + 0.552 \text{Re}^{1/2} \text{Sc}^{1/3} \quad (7)$$

$$F_M = (1 + B_M)^{0.7} \frac{\ln(1 + B_M)}{B_M} \quad (8)$$

2) Assuming that temperature of droplet surface is uniform and varies with time according to literature^[8], the temperature is expressed as:

$$m_p C_L \frac{dT_p}{dt} = \pi D_p^2 h (T_g - T_p) - \frac{dm_p}{dt} L + \pi D_p^2 \sigma \overline{\theta}_a \theta_R^4 \quad (9)$$

According to an assumption that thermal radiation and temperature gradient within the droplet are ignored, formula (9) is written as:

$$\frac{dT_p}{dt} = \frac{6\lambda_f}{D_p^2 \rho_L C_L} [(T_\infty - T_p) Nu - \frac{L}{C_{pf}} \frac{dm_p}{dt} \frac{C_{pf}}{\pi D_p \lambda_f}] \quad (10)$$

where Nu is introduced to correct the expression of Nu_0 by Ranz^[8], and determined by the formula:

$$Nu = 2 + \frac{(Nu_0 - 2)}{F_T} \quad (11)$$

$$Nu_0 = 2 + 0.552 \text{Re}^{1/2} \text{Pr}^{1/3} \quad (12)$$

$$F_T = (1 + B_T)^{0.7} \frac{\ln(1 + B_T)}{B_T} \quad (13)$$

where ρ_L is the density of droplet and C_L is specific heat; T_∞ , T_p is respectively the temperature of air and drop surface; C_{pf} , λ_f are respectively the specific heat and thermal conductivity under the reference temperature of mixed gas in the film. According to literature^[7], $\varphi = \frac{C_v}{C_g} \left(\frac{\text{Sh}}{Nu}\right) \frac{1}{Le}$, and C_v , C_g are respectively the specific heat of vapor and air. $B_T = (1 + B_M)^\varphi - 1$

3) Formula (1) shows the change of drop diameter with time:

$$\frac{dD_p}{dt} = \frac{2\lambda_f}{\rho_L D_p C_{pf}} \text{Sh} \ln(1 + B_M) \quad (14)$$

4. Results and Discussions

With experiments and theoretical simulation, this paper gives the rule of evaporation rate, drop diameter and surface temperature with time under some terms, which including that initial diameter is in range of 1.6 to 1.8mm, air temperature is 553 to 773K and its pressure is one standard atmosphere, and rule is represented in Fig. 4. Results of experiments and simulation are as follows:

4.1 Rule of evaporation rate in high-temperature air and the compare of experiments and theoretical calculation

4.1.1 Rule of evaporation rate and drop diameter with time

Fig.4 and 5 respectively give time-dependent curves of drop diameter and evaporation rate, where initial diameter $D_0=1.7mm$ and air temperature $T_0=663K$. Fig.6 gives time-dependent curve of theoretical temperature in drop surface under different air temperature and $D_0=1.7mm$. At the beginning of a very short time (about 0.5s) shown here, low evaporation rate is less than heated expanding rate and drop diameter slightly increases. After that period, with the increasement of evaporation rate and droplet evaporation, droplet size became smaller. At the initial step (about 4s), small change of diameter shows that the heat absorbed is basically used to raise the surface temperature (shown in Fig.6), and evaporation process is in rapid-heating stage until its rate reaches a maximum. However, after that step, surface temperature remains steady and is same as saturation temperature under working pressure; as is shown in Fig.6, evaporation process is in stationary stage and its rate decreases with reduction of droplet. It's clear that evaporation no longer follows the traditional D^2 -law.

4.1.2 Comparison of experiments and theoretical calculation

As are shown in Fig.4-5, the evaporation time predicted by the simplified mathematical model based on membrane theory is in well accordance with experiments. In the theoretical simulation, the paper made the assumption that thermal radiation and temperature gradient within the droplet are ignored in order to simplify the model. As for the evaporation in "hot"

surroundings, the capacity of air to radiate and absorb radiation is weak, so air medium is supposed to not participate in heat radiation. Predicted evaporation time is less than real, because the temperature gradient within the droplet and a little absorbed heat used for internal temperature rise, is thought to exist in real process; while in the model, this part of absorbed heat is used for evaporating. However, the error for both is less than 5% (shown Fig.4)

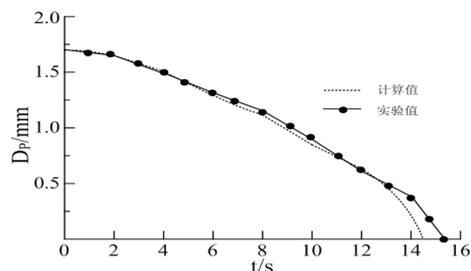


Figure 4. Experimental and calculated values of droplet diameter with time ($D_0=1.7mm, T=663K$)

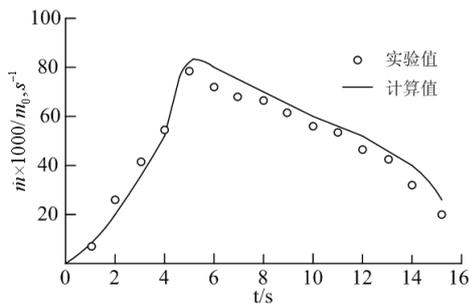


Figure 5. Experimental and calculated values of evaporation rate with time ($D_0=1.7mm, T=663K$)

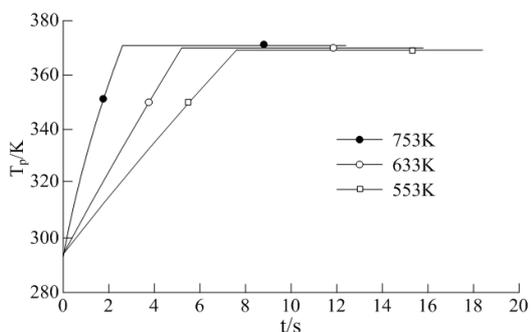


Figure 6. Curve of surface temperature under different air temperature ($D_0= 1.7mm$)

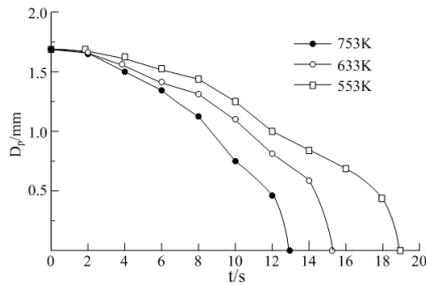


Figure 7. Diameter-change curve under different air temperature ($D_0=1.7\text{mm}$)

4.2 Effect of air temperature on lifetime of droplets

Fig.7 gives the diameter-change curve under some experimental conditions, which including $D_0=1.7\text{mm}$ and temperature are 553K, 633K and 753K. It also can be obtained from the Fig.7 that evaporation time decreases with the increase of air temperature, and a temperature rise of 200K reduces the evaporation time by 6s. Rapid-heating stage of evaporation lasts for 2s when air temperature is 753K while it extends to 8s when air temperature is 553K. Subsequently, the evaporation enters upon a stationary phase, whose duration is about 11s and differs little at different air temperature (shown in fig.7) evidently, the effect of air temperature on evaporation time mainly reflects in the rapid-heating stage.

4.3 Effect of initial diameter on evaporation time

In this paper, experiments of evaporation are studied under $T_\infty=753\text{K}$ and divided into three groups, diameters are 1.6mm, 1.7mm, 1.8mm, respectively. Diameter-change curve under different initial diameter is obtained (shown in Fig.8). Meanwhile, under $T_\infty=1000\text{K}$ and applying the proven simplified mathematical model, diameter-change curve with $D_0=100\mu\text{m}$, $200\mu\text{m}$ and $300\mu\text{m}$, is obtained (shown in Fig.9). As is shown in the Fig.9 in higher-temperature air, the evaporation rules of smaller droplet in theoretical calculation is basically consistent with experimental results. But from the eye of evaporation of small droplet, it is obvious that, in high-temperature air, the smaller the droplet, the steeper is the diameter-change curve and less visible are the two

phases of evaporation process (shown by $100\mu\text{m}$ -curve in Fig.9) which show the character of violent evaporation. Furthermore, an initial diameter increase of 2 times extends the evaporation time by 9 times, so initial diameter greatly impacts on evaporation time. In practical, the research of nozzle technology which determines the spray droplet size, is one of the main directions of our research.

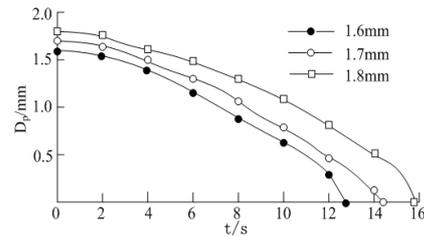


Figure 8. Diameter-change curve under different initial diameter ($T_\infty=753\text{K}$)

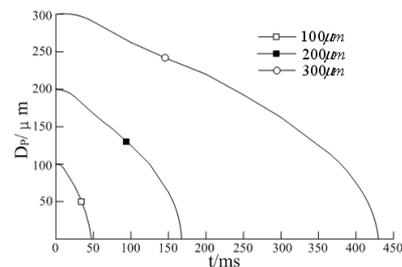


Figure 9. Diameter-change curve under different initial diameter by theoretical calculations ($T_\infty=1000\text{K}$)

5. Conclusions

1) Evaporation of single droplet in high-temperature air does not follow the traditional D^2 -law but divides into two phases, which are rapid-heating and stationary-evaporating. In the rapid-heating stage, the absorbed heat used as an increase in temperature is greater than used as evaporating, the temperature of droplet goes up and the length of this stage depends on air temperature. However, stationary-evaporating stage takes up the most time of evaporation process; at a certain working pressure, both initial diameter and air temperature do not affect surface temperature throughout stationary-evaporating stage, viz., saturation temperature of droplet under working pressure.

2) For high-temperature ambient and Reynolds number is less than 2000, the simplified mathematical

model based on membrane theory is suitable.

3) Air temperature and initial droplet diameter will affect the evaporation process, in which initial diameter has a greater impact, so in practical, the research of nozzle technology which determines the spray droplet size, is one of the main directions of our research.

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