

# Combustion Characteristics Of A Small-Sized Burner'S Single Diesel Droplet in Different Atmosphere Pressures

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**Abstract.** On the plateau, atmospheric pressure is reduced, which effects diesel combustion feature prominently. Combustion process of diesel oil droplet under different environment pressure were calculated by theoretical programming and numerical simulation method. Considering droplet drag and air flow relative motion, burning time and motion path of diesel single droplet have been conducted by programming calculation. Burning regulation of different initial particle droplet size were received, including burning time, Droplet drag. The relationships between different atmospheric pressure and burning time or motion path are found respectively. Combining with the experiments of macroscopic scale flame, follow the micro level of droplet combustion, change Mechanism of macro flame shape in different sub-atmosphere were analysed. In the low-pressure environment, both burning time and burning path of diesel droplets are longer in sub- atmosphere environment.

## 1. Introduction

Low-pressure atmospheric environment is always referred to the pressure of environment which below the atmospheric pressure (101kPa, the corresponding elevation: 0m). Common low-pressure environment such as at high altitudes, cargo and other aircraft, an air pressure range is generally 45 ~ 100kPa (corresponding to altitude: 0 ~ 5000m) [1]. Liquid spray combustion under low-pressure environment, has been widely used in rocket engines, aircraft engines, internal combustion engines, gas turbines and fuel boilers and other power and energy equipment [2]. In order to research the mechanism issue of the spray combustion process more deeply, the scholars dedicated to the study of the droplet combustion. Ulzama S et al [3] simulated combustion of n-heptane droplets under different oxygen concentration environment. They Summarized change rules of droplet radius, the radius of the flame and evaporation rate separately. Awasthi Inkant et al [4] investigated the influence rule of droplet combustion under different initial droplet (n-heptane) diameter and ambient temperature conditions respectively by numerical method. There are few conclusions about droplet combustion state at low pressure environment. There was a large altitude changes in vast plateau region, especially in China Qinghai-Tibet Plateau. With increasing altitude, atmospheric pressure and oxygen concentration would go down, therewith the flame shape was varied. Understand the changes in the law may provide the basis for engineering design. Mechanism of flame change will be solved at the level of the droplets in this paper.



This paper mainly studied a single diesel droplet combustion in theoretical aspects. Spray droplets Riello G40 burner was the original model. The spray cone angle is  $60^\circ$ , injection pressure 1.2MPa, Droplet size distribution were range from  $20\mu\text{m}$  to  $100\mu\text{m}$ . Burn time and path length of a single diesel droplet will be analyzed under different environmental pressure parameters.

## 2. Theoretical calculation model and method

### 2.1. Droplet combustion basics model

In order to calculate the actual forced air combustion regularity of droplet, the liquid-drop model of combustion process must be established firstly in a relatively static environment. Figure.1 is a schematic diagram of single droplet evaporation and combustion model. Heat flow that passed to the droplet by the heat conduction in unit time is equal to the heat of droplet evaporation taken away [5]. That can be written as:

$$4\pi r^2 \lambda_g \frac{dT}{dr} = m[C_{pg}(T - T_s) + H] \quad (1)$$

In the formula above:

$m$  - The vaporization quantity of the droplet surface per unit time,  $\text{m}^2 / \text{s}$ ;

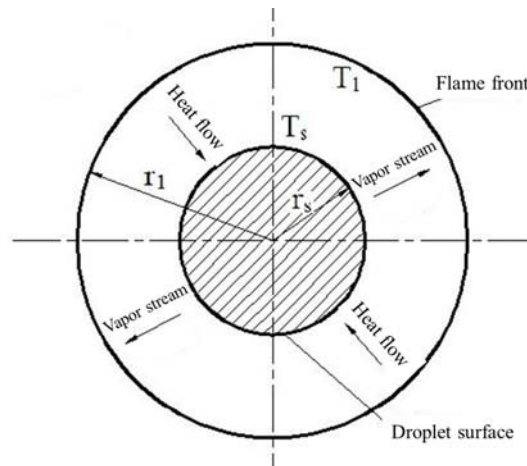
$C_{pg}$  - Diesel heat capacity,  $\text{kJ} / (\text{kmol} \cdot \text{K})$ ;

$\lambda_g$  - Thermal conductivity,  $\text{W} / (\text{m} \cdot \text{K})$ ;

$T_s$  - The droplet surface temperature,  $\text{K}$ ;

$T$ -- Surrounding medium temperature,  $\text{K}$ ;

$H$ -- Surface latent heat of vaporization when droplet evaporation,  $\text{J} / \text{kg}$ .



**Figure 1.** Droplet combustions model schematic.

Droplet diameter from actual burner nozzle is quite small [6] of the order of micron, so for such infinitely small droplets, formula (1) can be rewritten as:

$$\frac{mC_{pg}}{4\pi\lambda_g} \frac{dT}{dr} = \frac{d}{dr} \left( r^2 \frac{dT}{dr} \right) \quad (2)$$

Integrating the above equation from the surface of the droplets to the flame front, i.e.,  $r = r_s$ ,  $T = T_s$  to  $r = r_l$ ,  $T = T_l$  formula (3) can be obtained.

$$\frac{mC_{pg}}{4\pi\lambda_g}(T - T_s) = -\left[(r^2 \frac{dT}{dr})_{r=r_s} - (r^2 \frac{dT}{dr})_{r=r_l}\right] \quad (3)$$

Further available, the formula (4) has been accomplished from above formula by identical deformation.

$$(r^2 \frac{dT}{dr})_{r=r_s} = m \frac{H}{4\pi\lambda_s} \quad (4)$$

In the formula,  $\lambda_s$  is thermal conductivity at the droplet surface temperature  $T_s$ , W / (m · K).

Simultaneous equations (3) and (4), so as to obtain evaporation rate  $m$  :

$$m = \frac{4\pi\lambda_g}{C_{pg}} \frac{r_s r_l}{r_l - r_s} \ln\left[1 + \frac{\lambda_s}{\lambda_g} \frac{C_{pg}}{H} (T_l - T_s)\right] \quad (5)$$

This theory is difficult to determine the relative position between the flame front and droplet surface, namely flame front radius  $r_l$ . Spalding D.B [7] adopted another simple way to dispose this problem. We assume that combustion occur in the atmosphere of the droplet surface, Spalding represented droplet evaporation rate by the formula (6):

$$m = \frac{2\pi\lambda_g d_s}{C_{pg}} \ln(1 + B) \quad (6)$$

In the formula (6), B is the number of the exchange, it may be expressed as:

$$B = \frac{Q}{H} \frac{M_{O_2}}{i} + C_{pg} \frac{T_g - T_s}{H} \quad (7)$$

In the formula,  $Q$  represents heat of combustion;  $M_{O_2}$  is mass fraction of oxygen in the air;  $i$  represents the stoichiometric ratio;  $T_g$  indicates the temperature of the external environment.

## 2.2. Calculation of droplet burning time

Droplet is spherical, the mass can be expressed as:

$$m_s = \frac{4\pi r_s^3}{3} \rho_l \quad (8)$$

In formula (8),  $\rho_l$  is density of droplet component, kg / m<sup>3</sup>

In order to conclusively the complete combustion time of the single droplet, Formula (8) is differentiated primarily. Under actual conditions, the droplet diameter is small, i.e.,  $r_1 \gg r_s$ . A specific infinitesimal droplet evaporated burning time is calculated as follows:

$$dt = - \frac{C_{pg} \rho_l r_s dr_s}{\lambda_g \ln[1 + \frac{\lambda_s}{\lambda_g} \frac{C_{pg}}{H} (T_1 - T_s)]} \quad (9)$$

The formula (9) is integrated, and ultimately obtained:

$$t = \frac{C_{pg} \rho_l (r_s^2 - r^2)}{2 \lambda_g \ln[1 + \frac{\lambda_s}{\lambda_g} \frac{C_p}{H} (T_1 - T_s)]} \quad (10)$$

The relationship between time and particle size can be expressed as:

$$t = \frac{d_s^2 - d^2}{K_1} \quad (11)$$

In the formula,  $d_s$  is initial droplet diameter,  $\mu\text{m}$ .  $K_1$  Refer to evaporation constant. Formula (12) was obtained by get identical deformation:

$$K_1 = \frac{8 \lambda_g \ln[1 + \frac{\lambda_s}{\lambda_g} \frac{C_{pg}}{H} (T_1 - T_s)]}{C_{pg} \rho_l} = \frac{4m}{\pi d_s \rho_l} \quad (12)$$

Calculation process of the droplet combustion constant described above was occurred in relatively static environment [8]. Furthermore, droplet combustion constant expression under forced air could be expressed as:

$$K_2 = K_1 (1 + \alpha_1 S_c^a R_e^n) \quad (13)$$

In the formula:  $K_1$  - a droplet evaporation constant under relatively stationary ambient air stream;  $\alpha_1 = 0.3$ ,  $a = 1/3$ ,  $n = 1/2$ .  $S_c$  - Schmidt number,  $S_c = \nu / D$ ,  $\nu$  - it is the kinematic viscosity of the gaseous medium, for air,  $\nu = 16.1 \times 10^{-6} \text{ m}^2 / \text{s}$ ,  $D$  is the diffusion coefficient.

$R_e$  - Reynolds, it is defined as follows:

$$R_e = \frac{d \cdot v_{gs}}{\nu} \quad (14)$$

$v_{gs}$  - Resultant velocity of air relative to a droplet,  $\text{m} / \text{s}$ ;

In this work, when the droplets are sprayed from the nozzle into the combustion chamber [9], droplet relative movement with air, and there is a certain angle. To obtain the resultant velocity of air relative to a droplet, droplet velocity  $v_s$  and the velocity of the gas  $v_g$  are determined respectively, then they were synthesized.

Relationship between nozzle exit velocity of droplet  $v_s$  and pressure differential  $\Delta P$  of nozzle [10] is as follows:

$$v_s = k_v \sqrt{\frac{2\Delta P}{\rho_l}} \quad (15)$$

In the formula,  $k_v$  value as 0.7;  $\rho_l$  is the density of fuel in a specific environment, kg / m<sup>3</sup>.

The calculation of air speed  $v_g$  is:

$$v_g = \frac{\alpha L_0 m}{A} \quad (16)$$

In the formula:  $\alpha$  - excess air coefficient,  $\alpha = 1.2$ ;

$L_0$  - Amount of air per unit fuel mass desired, m<sup>3</sup>;

$m$  - Air quality of per unit time and unit fuel consumption, kg;

$A$  - Air flow area, m<sup>2</sup>.

Xu G et al [11, 12] adopted experimental technique, measured droplet burn rate of n-decane were 1.15, 1.24 mm<sup>2</sup> / s when air temperatures were 300K and 633 K, respectively. They found that the initial droplet diameter has no influence on the value of  $k$  in a convection air.

To study an influence law between low pressure environment and a droplet combustion, but also to determine the effect of different particle size of droplets. Assuming ambient pressure  $P$  is 1atm, ambient temperature  $T$  is 273K. In calculating the variation of the droplet size over time, collate calculated formula of apiece theoretical parameters as follows:

(1) The average thermal conductivity  $k_g$  calculation is:

$$k_g = 0.4k_F(\bar{T}) + 0.6k_\infty(\bar{T}) \quad (17)$$

In the above formula,  $k_F(\bar{T})$  is thermal conductivity at a mean temperature of fuel oil;  $k_\infty(\bar{T})$  is thermal conductivity of air at an average temperature. These two parameters can be expressed as, respectively:

$$k_F(\bar{T}) = 8 \times 10^{-5} \bar{T} - 0.0123 \quad (18)$$

$$k_\infty(\bar{T}) = \{[(2 \times 10^{-8} \bar{T} - 6 \times 10^{-5}) \bar{T} + 0.1121] \bar{T} - 1.8686\} / 1000 \quad (19)$$

(2) Formula of heat capacity at constant pressure is obtained by fitting Heywood, JB obtained curve:

$$\bar{c}_p = 4.184(a_1 + a_2\theta + a_3\theta^2 + a_4\theta^3 + a_5\theta^{-2}) \quad (20)$$

In the formula,  $\theta$  --temperature,  $\theta = \bar{T} / 1000$ , K;

$\bar{T}$  --average temperature,  $\bar{T} = (T_{boil} + T_f) / 2$ , K;

$a_1, a_2, a_3, a_4, a_5$  - curve fitting coefficients, the values in the Table 1.

**Table 1.** Coefficient of heat capacity at constant pressure curve

Fit coefficients	$a_1$	$a_2$	$a_3$	$a_4$	$a_5$
Numerical	-0.106	246.97	-143.7	32.329	0.0518

(3) For light diesel oil, calculation formula of boiling at different pressures is:

$$t_s = \frac{180}{1.648 - 0.225 \times \lg(p / 0.013)} + 273.15 \quad (21)$$

To calculate time variation low with different primary particle diameter under forced air conditions, initial conditions are listed below:

**Table 2.** The initial condition values

atmospheric pressure $P / (\text{MPa})$	External temperature $T / (\text{K})$	Nozzle pressure difference $\Delta P / (\text{MPa})$	Spray angle $\alpha / (^\circ)$	Fuel oil density $\rho_l / (\text{kg} / \text{m}^3)$	Synthesis rate $v_{gs} / (\text{m} / \text{s})$
0.01	273	0.01	60	978.7	29.23

In addition, in the calculation process, to study the influence of atmospheric pressure on the droplet burning, determine the ambient temperature is fixed to 273K. So that various physical properties of the fuel oil could be finalized. Fixed spray angle  $\alpha = 60^\circ$ , to determine the relative velocity  $v_{gs}$  at different pressures. Calculate the final resultant velocity at different pressures, as shown in Table 3:

**Table 3.** The relative airflow velocity at different ambient pressure

Environmental pressure $P / (\text{MPa})$	0.03	0.04	0.05	0.06	0.07	0.08	0.09	0.10
Relative airflow velocity $v_{gs} / (\text{m} / \text{s})$	24.02	25.85	27.57	29.20	30.76	32.24	33.67	35.05

### 2.3. Calculation of droplet burning path

Fuel emitted from the nozzle exit by the pressure differential applied force of nozzle. Under the influence of air resistance and thus atomized diesel oil was atomized into small droplets. Because of the pressure differential inside and outside of the nozzle so that the droplet has a certain relative velocity with air at the initial stage. As a consequence, the droplet is subjected to the action of the drag force. During the research of the external pressure influence on droplet drag, at ambient pressure  $P = 0.03 \text{ MPa} \sim 0.09 \text{ MPa}$ , pressure differential of nozzle was taken  $\Delta P = 0.8 \text{ MPa} \sim 1.4 \text{ MPa}$ , respectively. The initial condition of ambient temperature also is 273K, spray angle  $\alpha$  is same with  $60^\circ$ .

Under the action of the drag force drops, droplet having a certain acceleration, the acceleration of droplet decreases with diminishing of the particle size, finally reduced to zero due to the droplet evaporation and burn completely.

The drag of the droplet was calculated as  $F_d = C_d \rho_g v_{gs}^2 \pi d^2 / 8$ . Droplet mass expression is:

$m = \frac{4}{3} \pi \left( \frac{d}{2} \right)^3 \rho_e$ . So, the droplet acceleration can be calculated as:

$$a = \frac{F_d}{m} = \frac{3}{4} C_D \frac{\rho_{air}}{\rho_e} \frac{v_{gs}^2}{d} \quad (22)$$

Motion path at differentiation element time is:

$$dL = v_s dt \quad (23)$$

$v_s$  refer to the droplet speed in infinitesimal time  $dt$ , then the path of next infinitesimal time  $dt$  is:

$$dL = \left( v_s - \frac{3}{4} C_D \frac{\rho_{air}}{\rho_e} \frac{v_{gs}^2}{d} \right) dt \quad (24)$$

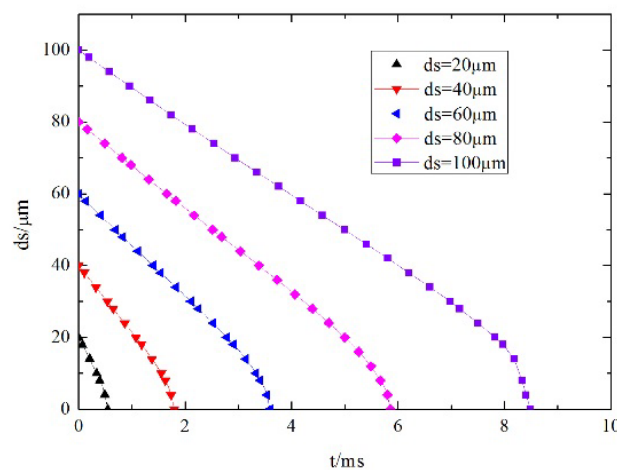
After the complete combustion of the droplet, the droplet path  $L$  could be integrated:

$$L = \int_0^{t_s} dL \quad (25)$$

### 3. Results and discussion

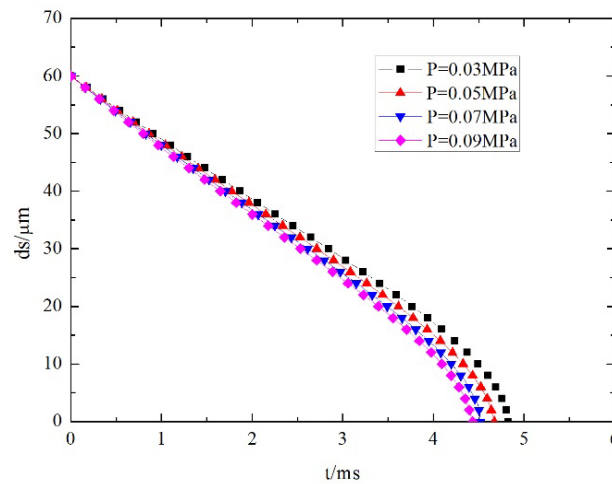
#### 3.1. Droplet burning time

Through utilizing formulas and the initial condition value above in Section 2, droplet combustion law of different initial droplet diameter can be acquired under the conditions of forced air by programming calculation. The results are shown in the Figure 2.



**Figure 2.** Different size droplets burning time curve under forced air conditions.

And the foregoing calculation formula in section 2.2 is calculated based on the initial programming conditions under different atmospheric pressure. The single diesel droplet burning time curve of different atmospheric pressure were shown as Figure 3.



**Figure 3.** Droplet burning time at different environmental pressure.

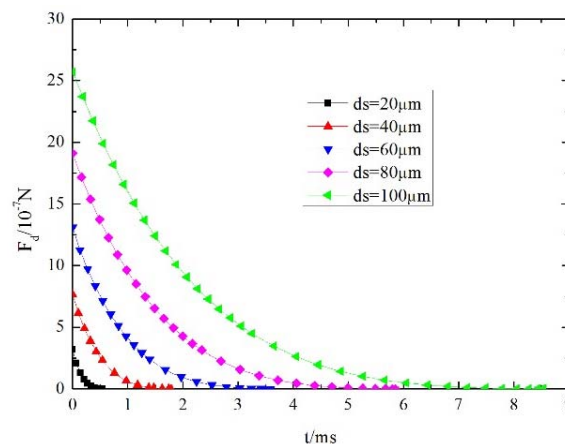
The droplet combustion regularity of a series of particular size substantially were almost identical at different pressures environments. With particle size progressively diminishing, droplet combustion rate gradually accelerated, i.e, performance of the slope gradually increases in Figure 2.

In addition, when external atmosphere pressure is lower, the droplet burning time became longer. When countless small liquid droplet formed droplet swarm, burning time will further lengthen. In the previous experimental research work [13] (the same initial conditions in this article), the flames elongate in a low-pressure environment. This is precisely explaining the conclusion of flame longer at the macro level under lower atmosphere pressure.

### 3.2. Droplet burning path

Before calculating the droplet path, calculation of the Droplet drags became significant. To study an influence law between low pressure environment and Droplet drag, but also to determine the effect of different particle size of droplets primarily.

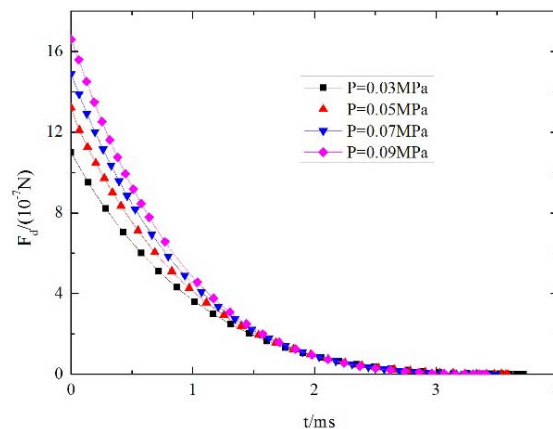
The pressure differential inside and outside of the nozzle  $\Delta P = 0.1 \text{ MPa}$ , fuel atomization spray cone angle  $\alpha = 60^\circ$ . Calculated to obtain an droplets relative velocity of initial flow:  $v_{gs} = 29.23 \text{ m/s}$ . and variational regularity of droplet drag with different initial particle size ( $d_s = 20\mu\text{m} \sim 100\mu\text{m}$ ) were calculated, as shown in Figure 4.



**Figure 4.** Different initial droplet diameter drag force over time variety curve.

Droplet drag overall showed a trend of decrease over time. Although forces are different, but the overall law curves of droplet drag can be seen from Figure 4. There were not affected by variation of primary particle diameter. Thus, when we research the effects of different atmosphere pressure on the droplet combustion process, particle diameter size of droplets could be ignored.

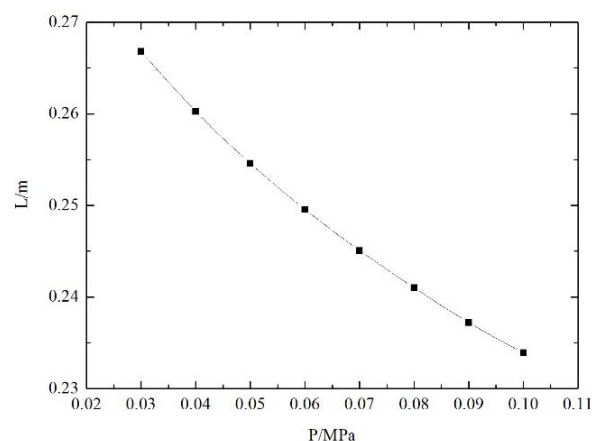
The data of droplet drag were obtained at different pressures drops according to the initial particle size  $60\mu\text{m}$  by programming calculation. Finally drag curve is shown in Figure 5.



**Figure 5.** Droplet drag variation with time at different ambient pressures.

As the burning time goes on, diameter of diesel droplet decreased, simultaneously, droplet drag was declined and its rate accelerates. Furthermore, droplet drag at the high ambient pressure is always higher than the drag at lower pressure drops. The higher drag force result in relative movement between the droplet and air flow become more obvious. That is to say the faster droplet evaporation rate and further presented as the flame length shorter macroscopically. Therefore, the droplets drag lows can also reasonable verify the conclusion that the length of the flame will be longer in lower pressure.

Combining these results of droplet drag, the change rule of single diesel droplet path with different pressures were analyzed as shown in Figure. 6.



**Figure 6.** Droplet path changes with ambient pressures.

For single droplet, the lower the pressure was, the longer the length of the motion path. The formation of a flame is made up of an infinite number of single droplet burning. Because of the droplet burning time and path became longer and longer at sub- atmospheric pressure, therefore it can be

extended to explain this phenomenon that is in the reduced ambient pressure the length of the flame was elongated.

#### 4. Conclusion

This paper mainly investigated the burning time and movement path of a single diesel droplet under different atmosphere pressures by theoretical research and programming analysis. The main conclusions are as follows:

(1) The burning time of single diesel droplet increases with the decrease of external atmospheric pressure.

(2) The droplet drag force increases with the increase of atmospheric pressure.

(3) The length of Diesel droplet movement path is shortened with the decrease of environmental pressure.

(4) Combining shorter droplet time and longer path length can explain the macroscopic flame length variation at reduced pressure atmosphere.

The burning mechanism of liquid drop is very complicated. The combustion characteristics of multi-droplet under different atmospheric pressure can be investigated deeply.

#### Acknowledgments

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