層流対向流場に形成されるn-decane噴霧火炎中のすす生成特性に噴霧特性が与える影響

Effects of spray characteristics on soot formation of n-decane spray flame stabilized in the laminar counter-flow field

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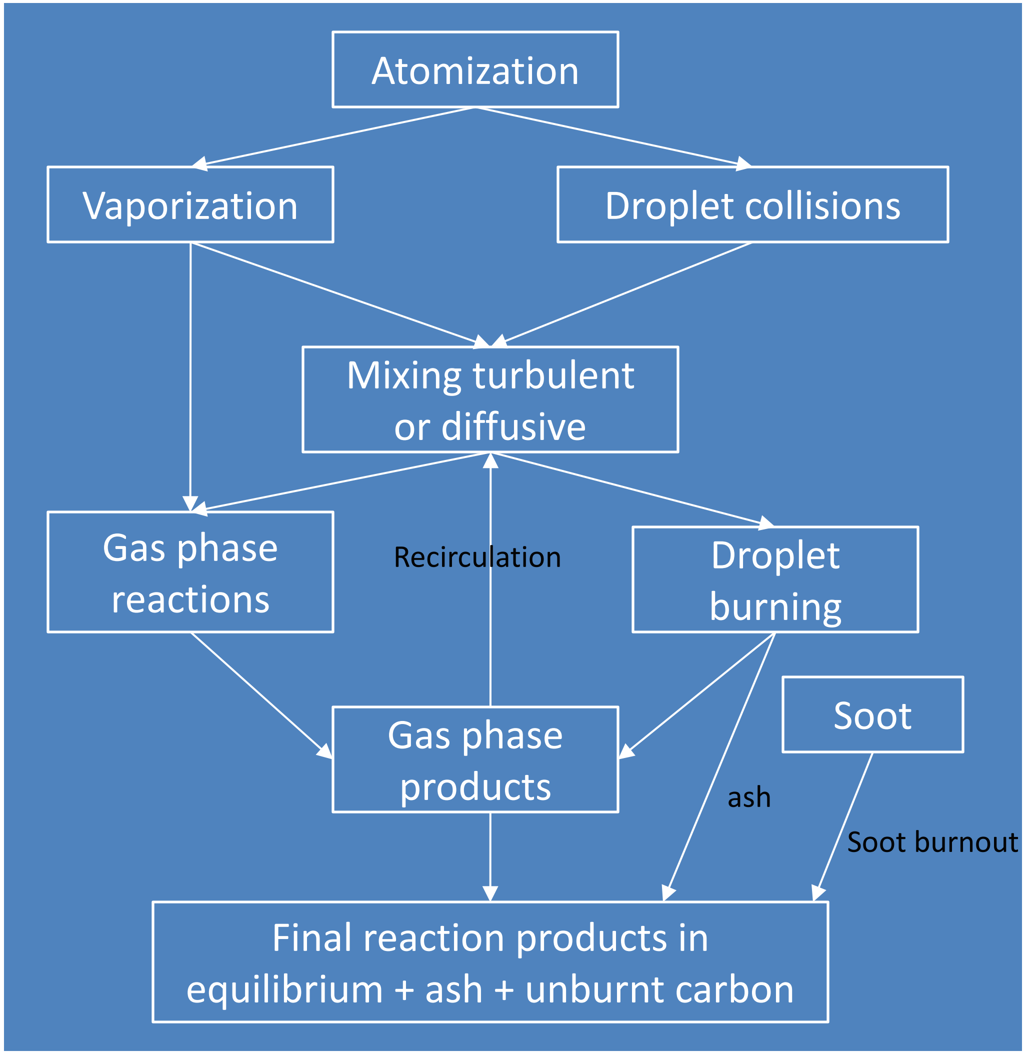
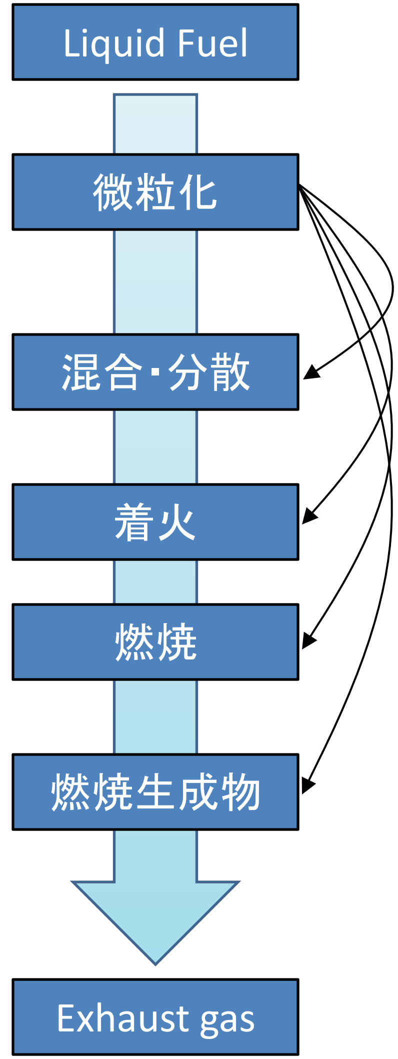
赤松　史光（大阪大学）

燃焼器における噴霧燃焼のステップ

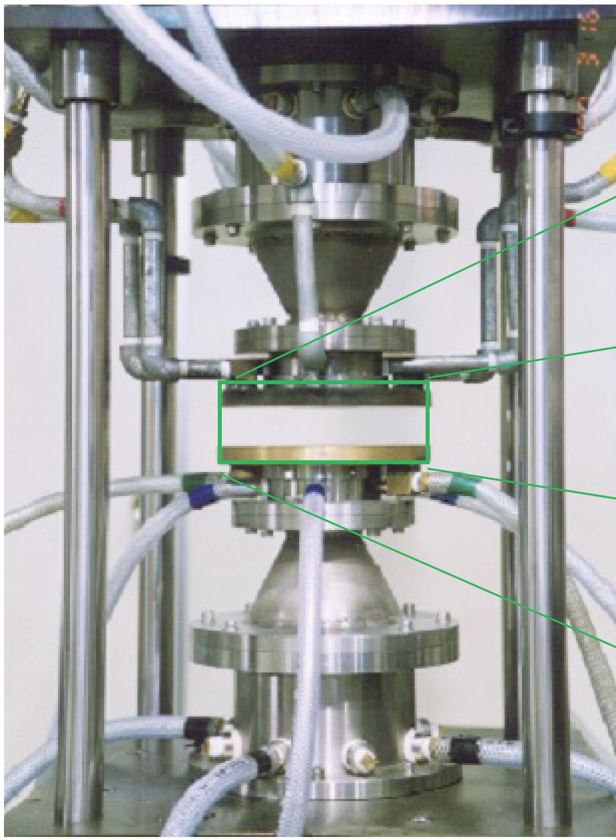




微粒化により噴霧特性が決定され，すべての過程に影響を与える.

Ref.) A. Williams, Combustion of liquid fuel sprays, (1990), Butterworths.

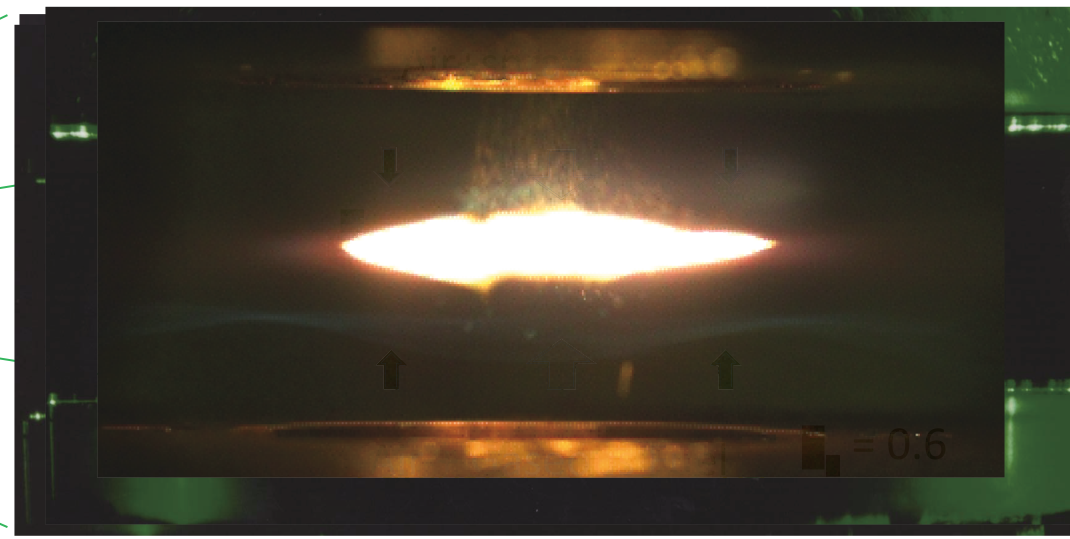
Laminar Counterflow Burner



Spray

- Flow rate
- Drop size distribution

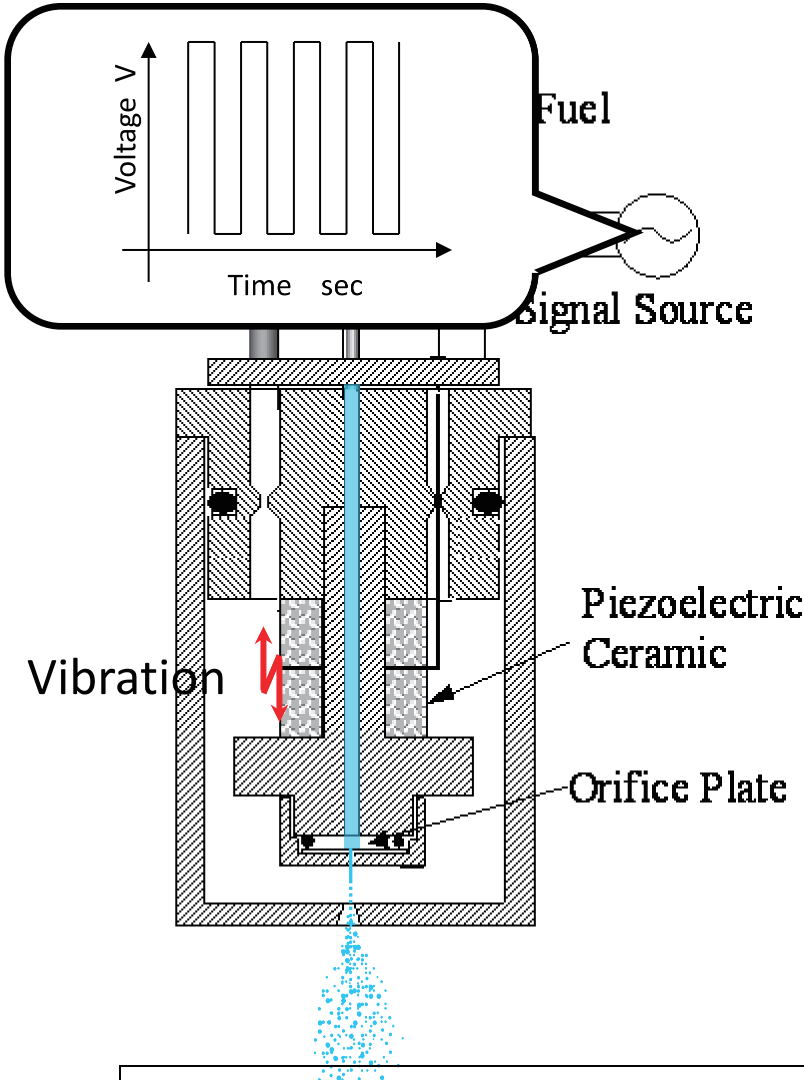
} controlled

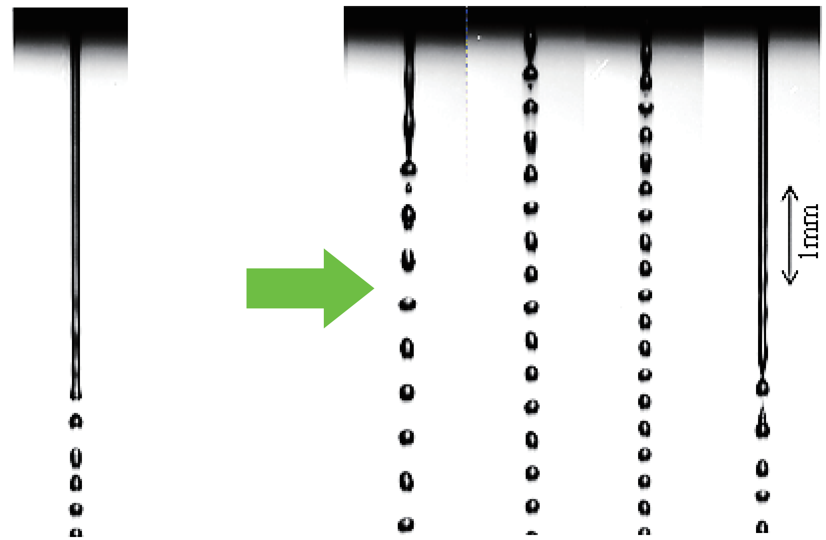


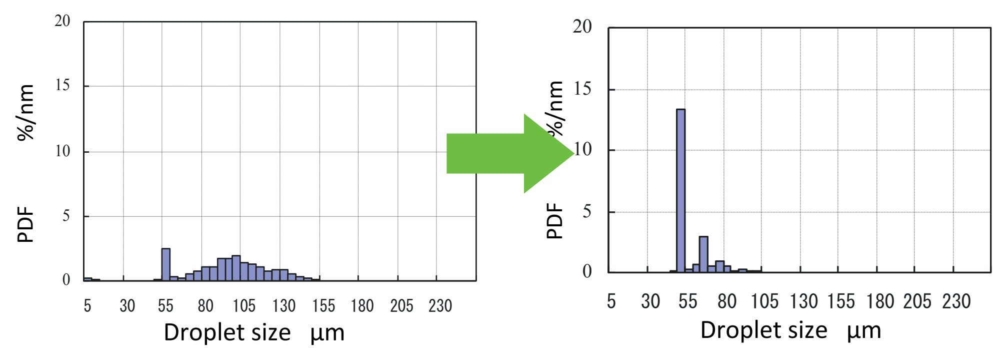
・Flat gaseous flame is stabilized.

・It simulates a situation of combustor in which fuel spray is entering the high temperature region.

Vibratory Orifice Atomizer –droplet size distribution control-

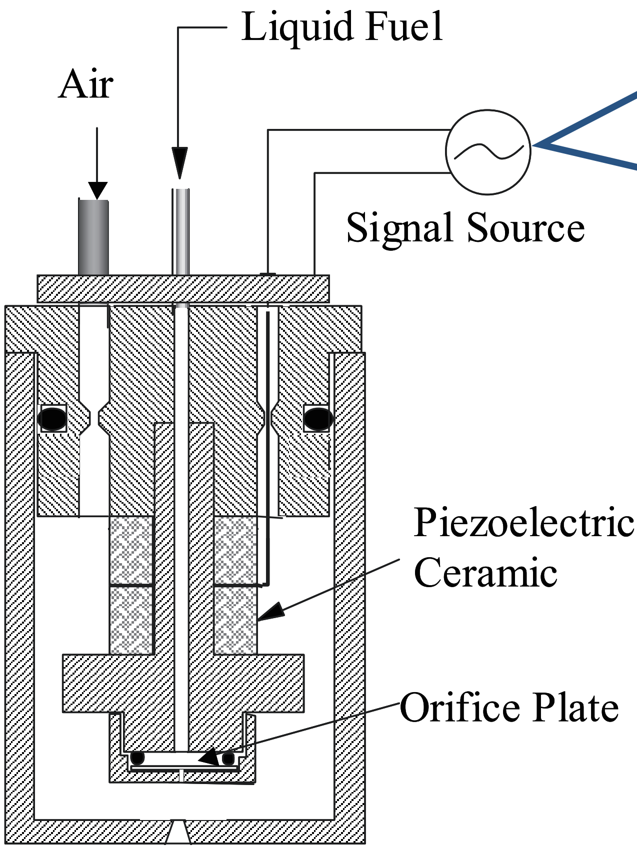


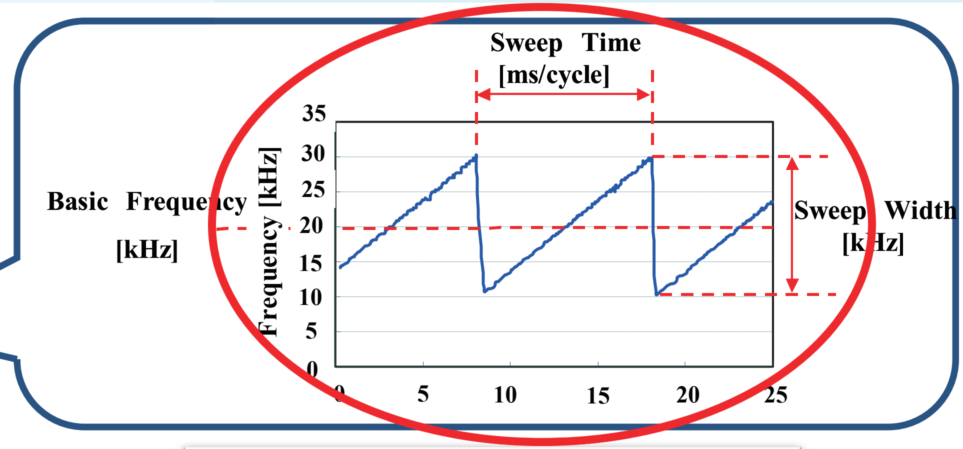


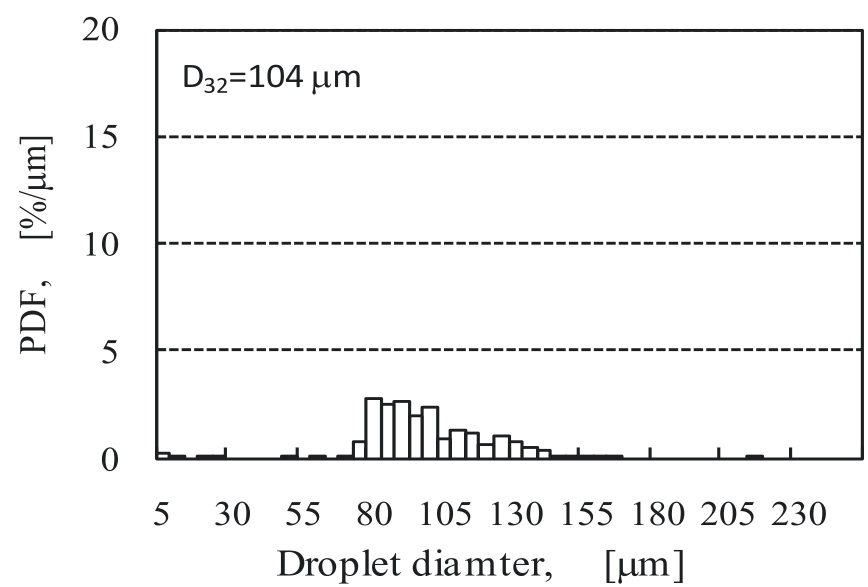


Control of Mean droplet size through changing frequency of electric signal

Vibratory Orifice Atomizer –droplet size distribution control-



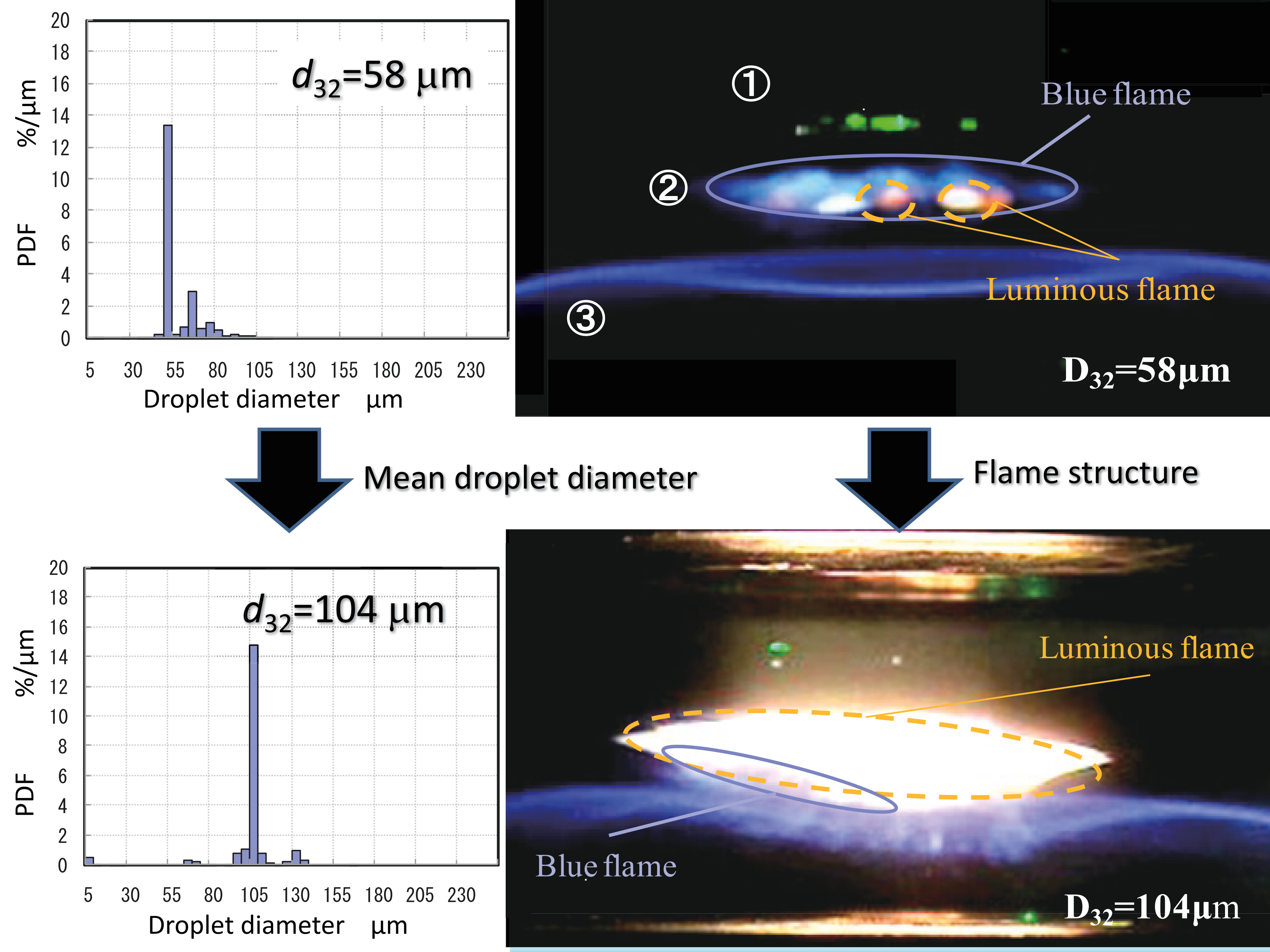




It can control droplet size distribution independently!!

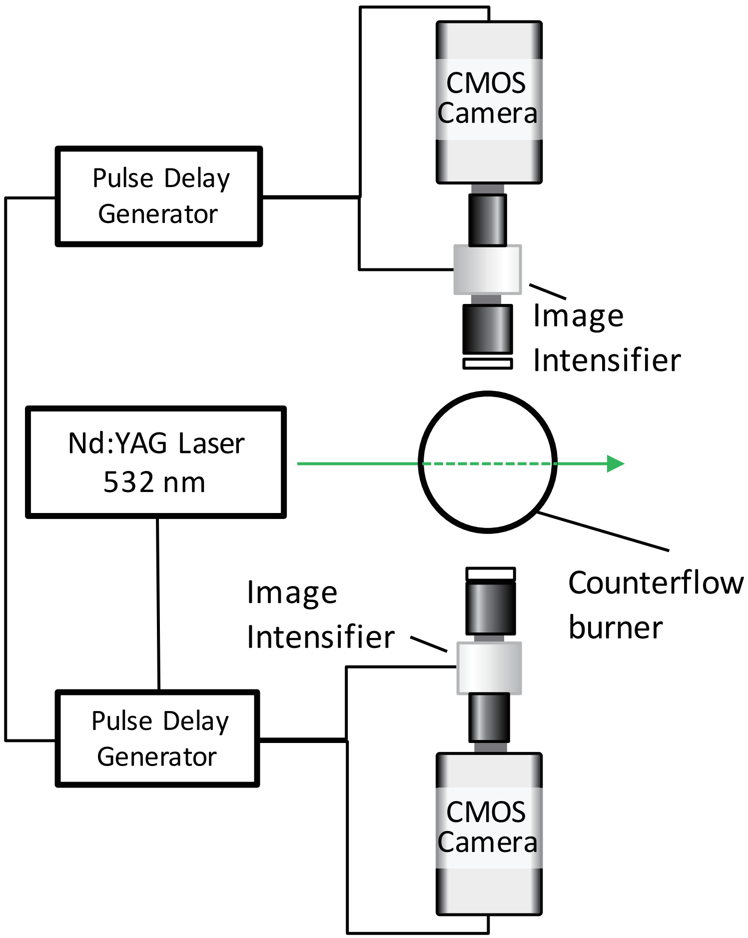
Experimental Conditions

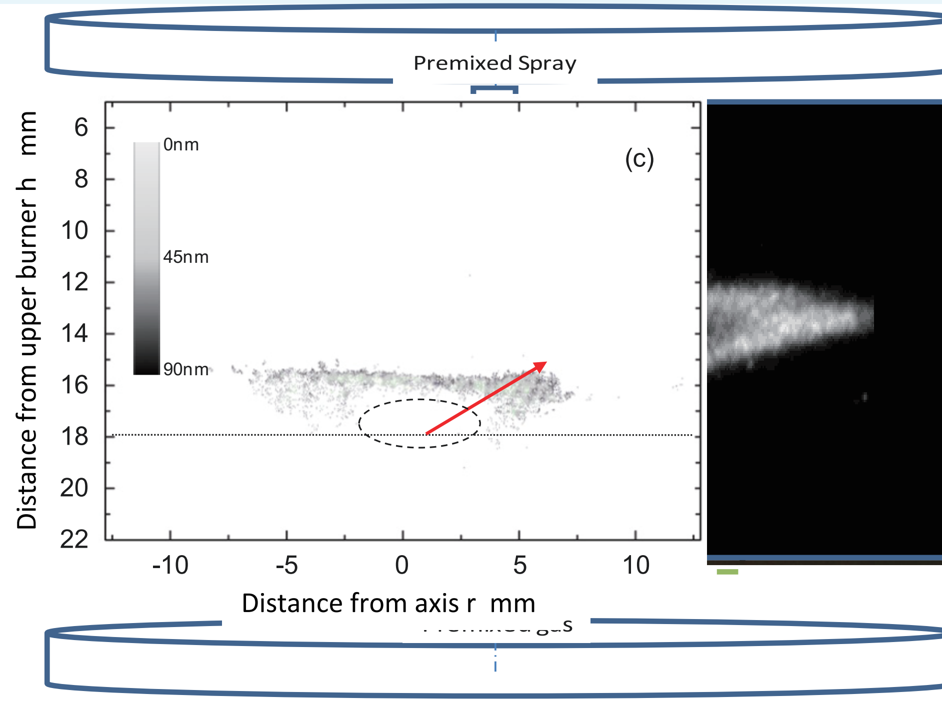
Item	Value
Fuel	*n*-decane
Sauter mean diameter (d_{32})	58 ~ 110 μm
Liquid Fuel Equivalence Ratio	$\phi_l = 0.106$
Droplet size distribution (DSD)	**Quasi Mono-DSD ～ Poly-DSD**
Measurement	LII (for soot)
	PDA (for droplets)

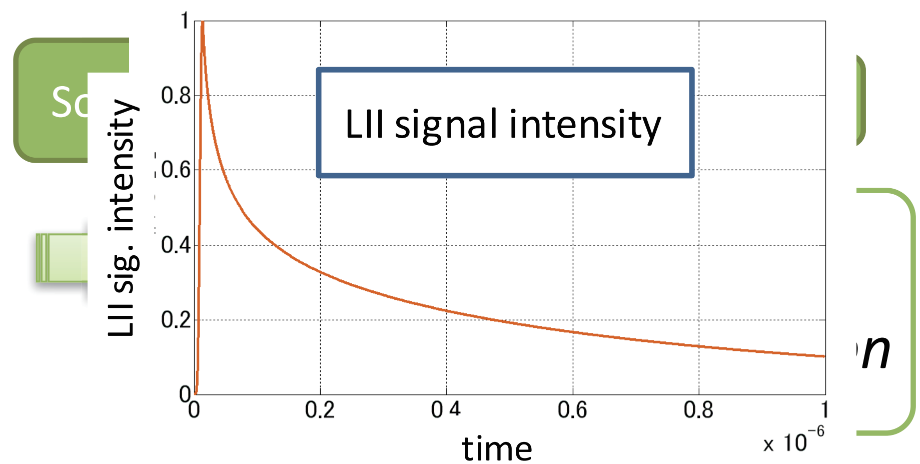


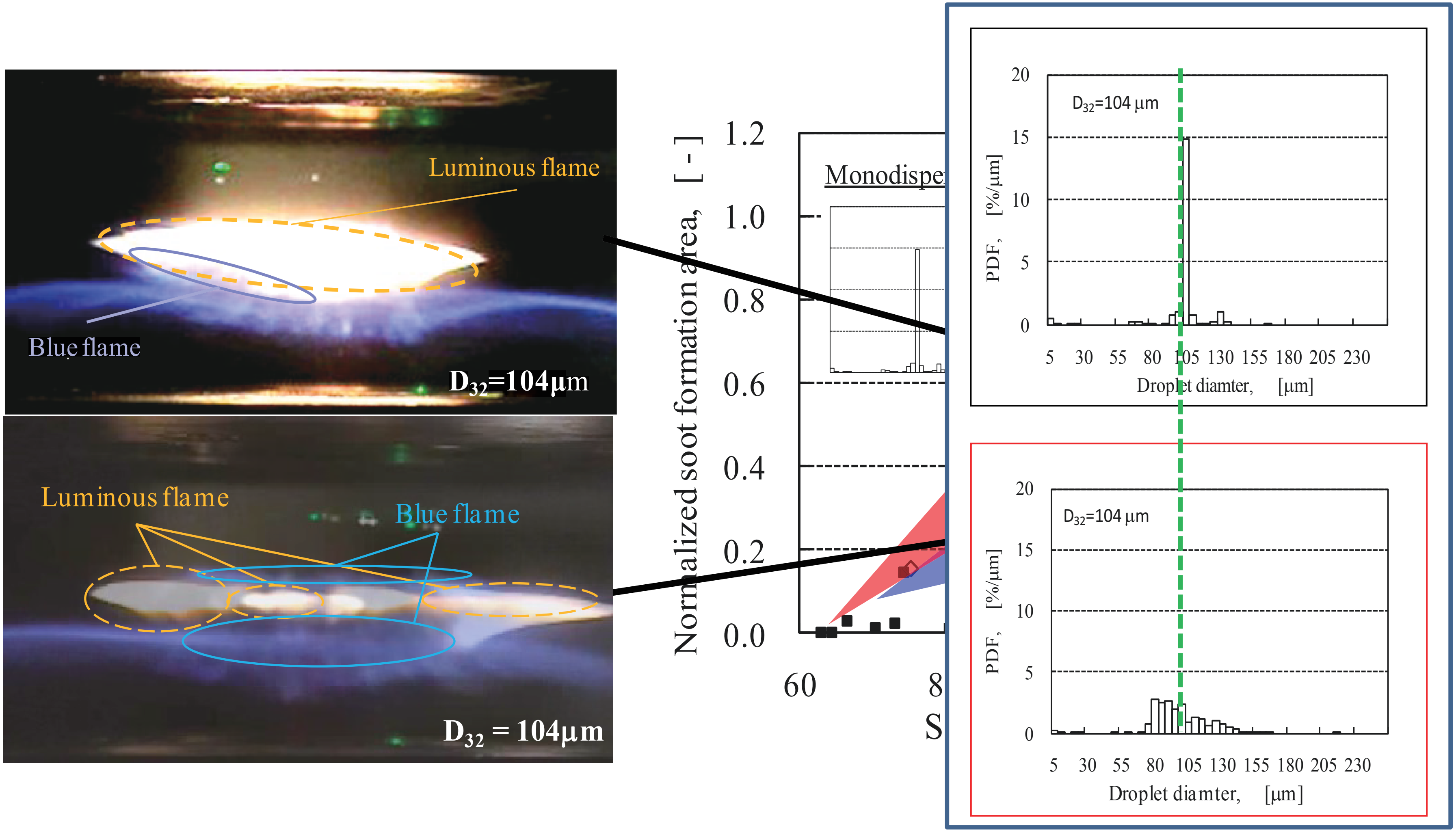
d32=58 μm
PDF %/μm
Droplet diameter μm
①
②
③
Blue flame
Luminous flame
D32=58μm
Mean droplet diameter
Flame structure
d32=104 μm
PDF %/μm
Droplet diameter μm
Luminous flame
Blue flame
D32=104μm

Laser Induced Incandescence (LII) for soot volume fraction








Luminous flame
Blue flame
D32=104μm
Luminous flame
Blue flame
D32 = 104μm
Normalized soot formation area, [-]
1.2
1.0
0.8
0.6
0.4
0.2
0.0
60
Monodispe
20
15
10
5
0
D32=104 μm
PDF, [%/μm]
5 30 55 80 105 130 155 180 205 230
Droplet diamter, [μm]
20
15
10
5
0
D32=104 μm
PDF, [%/μm]
5 30 55 80 105 130 155 180 205 230
Droplet diamter, [μm]

支配方程式

気相

質量保存式
$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_j}\rho u_j = S_m$$

運動量保存式
$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial}{\partial x_j}(\rho u_i u_j + P\delta_{ij} - \sigma_{ij}) - \rho g_i = S_{u_i}$$

エネルギ保存式
$$\frac{\partial \rho h}{\partial t}+\frac{\partial}{\partial x_j}\left[\rho u_j h - \rho\lambda\frac{\partial h}{\partial x_j} + \sum_{k=1}^{n} h_k(\rho\lambda - \rho D_k)\frac{\partial Y_k}{\partial x_j}\right] = S_h$$

化学種保存式
$$\frac{\partial \rho Y_k}{\partial t}+\frac{\partial}{\partial x_j}\left(\rho u_j Y_k - \rho D_k\frac{\partial Y_k}{\partial x_j}\right) = S_{combu,k} + S_{Y_k}$$

油滴

位置
$$\frac{dx_{d,i}}{dt} = u_{d,i}$$

速度
$$\frac{du_{d,i}}{dt} = \frac{f_1}{\tau_d}(u_i - u_{d,i}) + g_i$$

温度
$$\frac{dT_d}{dt} = \frac{Nu}{3Pr}\left(\frac{c_p}{c_{p,d}}\right)\left(\frac{f_2}{\tau_d}\right)(T_g - T_d) + \frac{1}{m_d}\left(\frac{dm_d}{dt}\right)\frac{L_V}{c_{p,d}} + \frac{1}{m_d c_{p,d}}[A_d\varepsilon_d(\pi I - \sigma_{sb}T_d^4)]$$

f_1とf_2はそれぞれ油滴の蒸発による効力と熱伝達に関する修正係数

質量
$$\frac{dm_d}{dt} = -\frac{Sh}{3Sc}\frac{m_d}{\tau_d}ln(1+B_M) \qquad B_M = \frac{Y_{F,S} - Y_F}{1 - Y_{F,S}} \qquad \tau_d = \frac{\rho_d d_d^{\,2}}{18\mu}$$

Langmuir-Knudsen 蒸発モデル —— 2次精度Adams-Bashforth法

物性値の取り扱い(熱力学特性と輸送係数)

利便性から熱力学特性や輸送係数を定数として取り扱う

↓

層流火炎で顕著な物性値の影響の精度を高めるため,
物性値の温度依存性を考慮

気相（O_2, N_2, CO_2, H_2O, $C_{10}H_{22}$）→CHEMKIN
液相（n- $C_{10}H_{22}$）

→温度の関数で表された推算式を使用

密度ρ_d	Gunn-Yamadaの方法
定圧比熱$c_{p,d}$	Sternling-Brown式
熱伝導率λ_d	Sato-Ridel法

気相ー液相　相関干渉項

⇒ PSI-Cellモデル

質量

$$S_m = -\frac{1}{\Delta V}\sum_{N_d} \dot{m}_d$$

運動量

$$S_{u_i} = -\frac{1}{\Delta V}\sum_{N_d}\left[\frac{m_d f_1}{\tau_d}(u_i - u_{d,i}) + \dot{m}_d u_{d,i}\right]$$

エネルギ

$$S_h = -\frac{1}{\Delta V}\sum_{N_d}\left[\frac{1}{2}\frac{d}{dt}(m_d u_{d,i} u_{d,i}) + Q_d + \dot{m}_d h_{F,d} + Q_{rad}\right]$$

化学種

$$S_{Y_k}\begin{cases} = -\frac{1}{\Delta V}\sum_{N_d}\dot{m}_d & for\ fuel\ (k = F) \\ = 0 & for\ other\ chemical\ species\ (k \neq F)\end{cases}$$

$$S_{combu\ ,k} = -\frac{n_k}{n_F}\cdot\frac{W_k}{W_F}\cdot R_F$$

すす生成モデル

すす生成過程の影響 - ①各過程の生成モデル，②flameletモデル

①核生成，凝集，表面成長，酸化

②前駆体：C_2H_2, 酸化剤：OH^*, O_2

混合分率の保存式

$$\frac{\partial \rho Z}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j Z - \rho D_Z \frac{\partial Z}{\partial x_j}\right) = S_Z \qquad (for\ C_2H_2, OH^*)$$

$$S_Z = -\frac{\phi}{\phi + Y_{O_2,air}}\left(\frac{1}{\Delta V}\sum_{N_d}\frac{dm_d}{dt}\right)$$

$$\frac{\partial \rho \phi}{\partial t} + \frac{\partial}{\partial x_j}\left(\rho u_j \phi - \rho D_s \frac{\partial \phi}{\partial x_j}\right) = S_\phi \qquad N = N_A \rho \phi_N, \qquad M = \rho \phi_M$$

N:すすの数密度

M:すすの質量密度

$$S_N = \frac{1}{N_A}\left[\left(\frac{dN}{dt}\right)_{Inc.} + \left(\frac{dN}{dt}\right)_{Coa.}\right]$$

$$S_M = \frac{M_p}{N_A}\left(\frac{dN}{dt}\right)_{Inc.} + \left(\frac{dM}{dt}\right)_{Gro.} + \left(\frac{dM}{dt}\right)_{Oxi.}$$

すす生成過程

Flamelet model ⇒ C_2H_2, OH^*, O_2

核生成
(inclination)

$$R_{inc.} = \left(\frac{dN}{dt}\right)_{Inc.} = c_1 N_A \left(\rho \frac{Y_{C_2H_2}}{W_{C_2H_2}}\right) e^{-\frac{21100}{T_g}}$$

凝集
(coagulation)

$$R_{coa.} = \left(\frac{dN}{dt}\right)_{Coa.} = -\left(\frac{24R}{\rho_{soot} N_A}\right)^{1/2} \left(\frac{6}{\pi \rho_{soot}}\right)^{1/6} T_g^{\,1/2} M^{1/6} N^{11/6}$$

表面成長
(growth)

$$R_{gro.} = \left(\frac{dM}{dt}\right)_{Gro.} = c_2 \left(\rho \frac{Y_{C_2H_2}}{W_{C_2H_2}}\right) e^{-\frac{12100}{T}} \left[(\pi N)^{1/3} \left(\frac{6M}{\rho_{soot}}\right)^{2/3}\right]$$

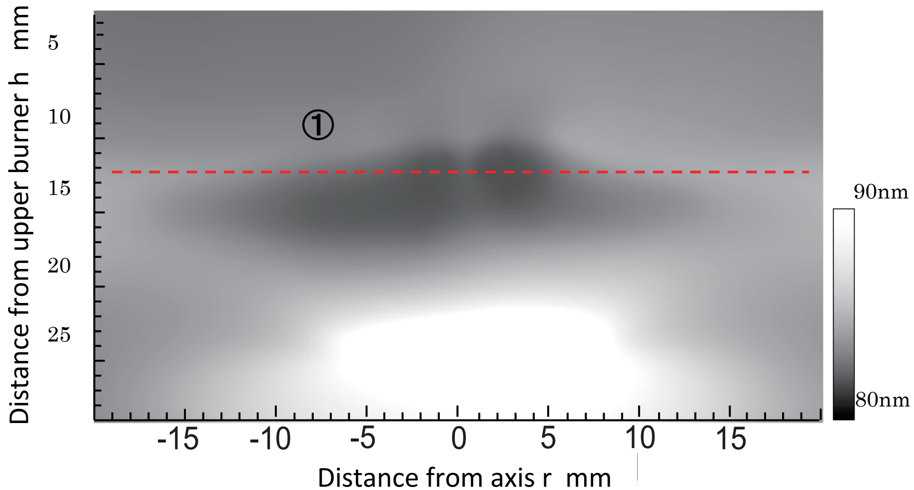
酸化
(oxidation)

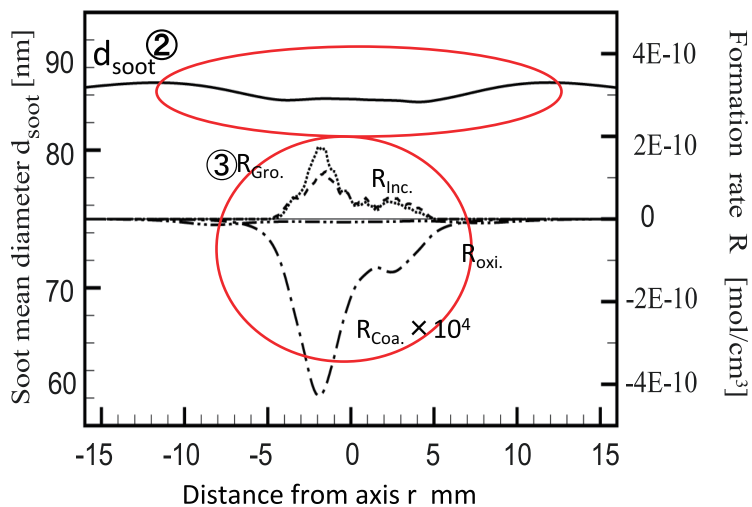
$$R_{oxi.} = \left(\frac{dM}{dt}\right)_{Oxi.} = -\left(c_3 \eta \rho \frac{Y_{OH}}{W_{OH}} + c_4 \rho \frac{Y_{O_2}}{W_{O_2}} e^{-\frac{19778}{T_g}}\right) T_g^{\frac{1}{2}} (\pi N)^{\frac{1}{3}} \left(\frac{6M}{\rho_{soot}}\right)^{2/3}$$

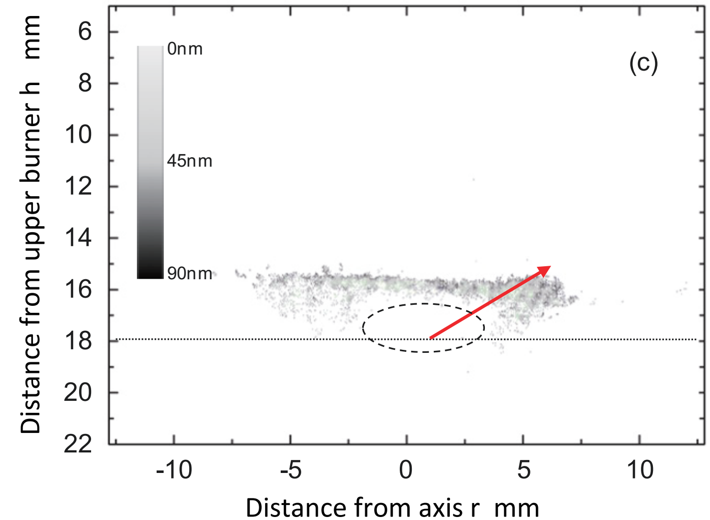
ρ_{soot}: 2000 kg/m^3, η: 0.13, c_1 : 54 s^{-1}, c_2: 9000.6 kg･m/(kmol･s), c_3: 105.81 kg･m/(kmol･K$^{1/2}$･s), c_4: 8903.51 kg･m/(kmol･K$^{1/2}$･s)

Soot formation

D_{32}=104μm, ϕ_l=1.26



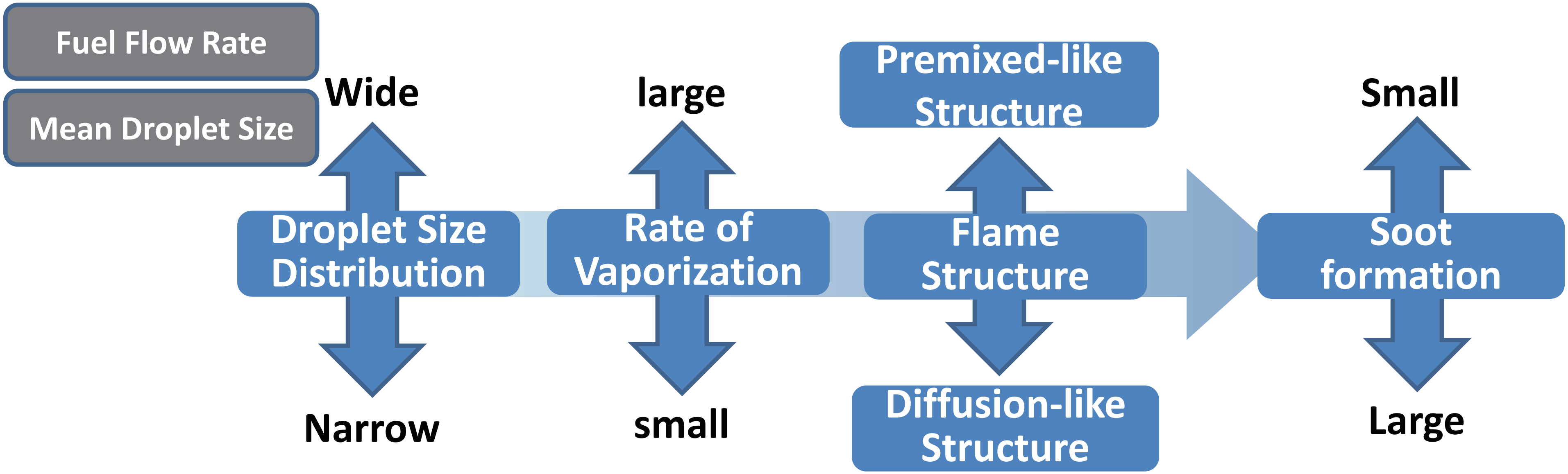




- ●不均一な生成領域
- ●すべての生成反応率が存在

- ●すす粒径が外周部で増大
- ●表面成長の生成反応率

Conclusion



- 噴霧火炎中におけるすす生成は，供給される燃料噴霧の平均粒径の増大に伴って増加する．また，**ザウタ平均粒径が等しい場合は，粒径分布の幅が広い多分散噴霧においてすす生成量が低下する**．

- 噴霧火炎中では，核生成，凝集，表面成長，酸化のすべての過程が同時に起こり，拡散的な噴霧火炎構造によって形成される高温領域の中心で，主に**表面成長の過程が生じることにより，外周部に置いて大粒径のすす粒子に成長する．**