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論文内容要旨

【Chapter 1 Introduction】 Spray combustion is widely utilized in industrial combustors. Since environmental destruction such as acid rain caused by NO_x emission is serious problem, advanced spray combustion is required. Advanced spray combustion is super low-NO_x emission (under 30 ppm at 0%O_2 concentration) and high efficiency combustion. An important points for advanced spray combustion are (1) the mixing between spray and air, (2) atomization (secondary atomization of emulsified fuel) and (3) advanced numerical simulation. This work focuses on above points. Focusing on numerical simulation, an experimental and numerical investigation were carried out to achieve the advanced spray combustion.

【Chapter 2 Numerical simulation of spray combustion for low-NO_x emission】 The effect of the mixing of air and spray on combustion behavior and exhaust NO mole fraction was investigated by numerical simulation with k-ε two-equation model. The configuration of combustion chamber is shown in Fig. 1. Kerosene was used and air ratio was 2.0. Fig. 2 shows the effect of inlet nozzle diameter on predicted temperature distribution and

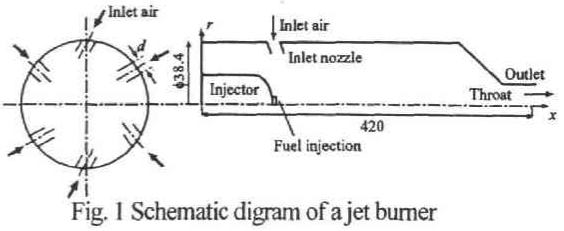

Fig. 1 Schematic digram of a jet burner

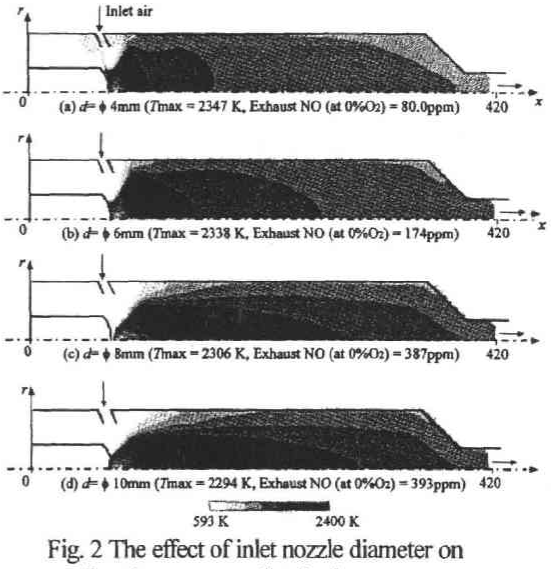

Fig. 2 The effect of inlet nozzle diameter on predicted temperature distribution

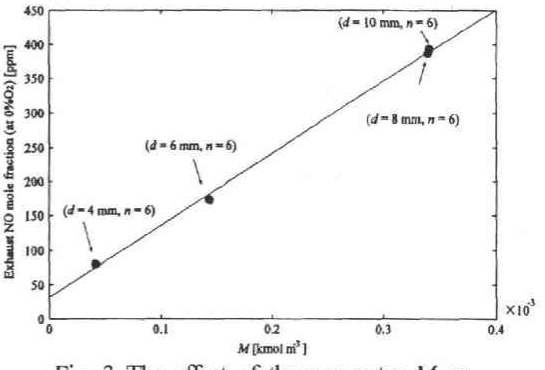

Fig. 3 The effect of the parameter M on exhaust NO mole fraction

exhaust NO mole fraction. When the diameter of air inlet nozzle decreases, exhaust NO mole fraction decreases because the residence time in the high temperature region drastically decreases due to the improvement of mixing of spray and air. It is shown that the mixing process of the fuel and the air had an important effect on low-NO_x combustion. The exhaust NO mole fraction is also related with not only the residence time t_h but also the NO formation reaction rate. Therefore, the product of the residence time and the laminar NO formation reaction rate in high temperature region (M) is defined.

Fig. 3 shows the effect of the parameter M on the exhaust NO mole fraction. The relationship between exhaust NO mole fractions and the parameter (M) is highly linear.

【Chapter 3 An experimental investigation of secondary atomization and spray combustion of emulsified fuel】 The occurrence of micro-explosion and puffing is widely accepted to explain the decrease in CO and soot emission. In this chapter, the characteristics of emulsified fuel were investigated by the single droplet experiment and the spray combustion experiment. The amount of the surfactant added in the emulsified fuel was 0.75 vol%. Water content was 10 vol%. The step in preparing the W/O emulsified fuel was to add the water and the emulsifying agent into kerosene and the mixture was stirred by the supersonic homogenizer.

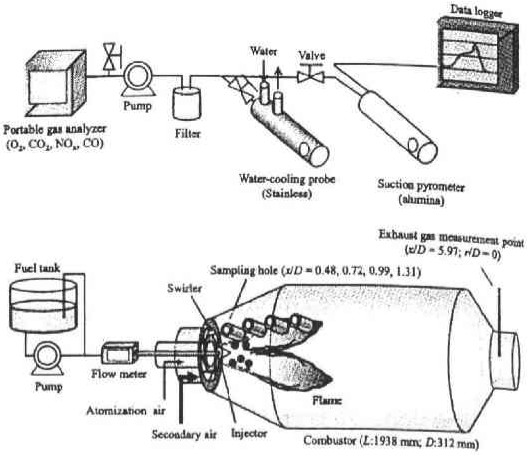

Fig. 4 Schematic diagram of experimental apparatus for spray combustion

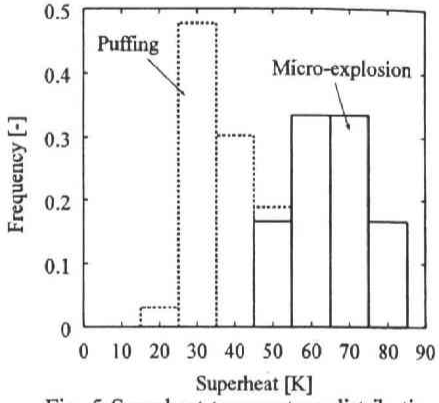

Fig. 5 Superheat temperature distribution just before the occurrence of puffing and micro-explosion

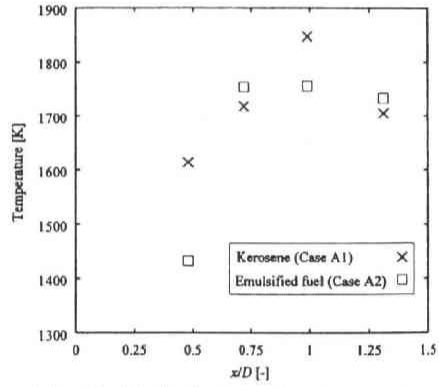

Fig. 6 Axial distribution of gas temperature

A single droplet suspended from an R-type thermocouple was heated in an electric furnace, and the droplet during heating was observed using a high-speed video camera. Fig. 4 shows schematic diagram of experimental apparatus for spray combustion. A twin fluid atomizer was used in the combustor. Air ratio was 1.18. Fig. 5 shows superheat distribution just before the occurrence of puffing and micro-explosion obtained from single droplet experiment. It is found that the probability of the micro-explosion increases with an increase in the superheat temperature. Fig. 6 shows the axial distribution of gas temperature in the combustor. When the emulsified fuel is used, the gas temperature is reduced by about 200 K at $x/D = 0.48$. However, the gas temperature increases rapidly at $x/D = 0.72$ and there is no peak of the gas temperature. It is shown that micro-explosion

and puffing enhanced the combustion reactions although the additional water causes ignition delay

[Chapter 4 Development of mathematical model for micro-explosion and puffing] Numerical simulation of spray combustion of emulsified fuel exhibits complex features. The main problem is that micro-explosion or puffing occurs when the emulsified fuel droplet is heated. Since micro-explosion is instantaneous phenomenon, it can be assumed that droplet changes vapor rapidly at the occurrence of micro-explosion. However, puffing occurs continuously. In this chapter, the mathematical model for puffing which was simple to apply the numerical simulation of spray combustion was proposed. Puffing is that water vapor is blown out from the droplet surface with fine droplets. Therefore, the mass change equation of emulsified fuel droplet during puffing is given as:

$$\frac{dm_{d,i}}{dt} = \frac{dm_{d,\text{evaporation},i}}{dt} + \frac{dm_{d,\text{puffing},i}}{dt} \quad (i = \text{F, W}). \tag{1}$$

It is assumed that $(dm_{d,\text{puffing}}/dt)$ is expressed as follows:

$$\frac{dm_{d,\text{puffing},i}}{dt} = A\frac{m_{d,i}}{m_{d,F} + m_{d,W}}\frac{dm_{d,\text{evaporation,w}}}{dt} \quad (i = \text{F, W}), \tag{2}$$

where A is experimental parameter. In the single droplet calculation, the equations of the rate of mass change and heating of a droplet are solved with the explicit Euler method. The time step is set to 1 μs.

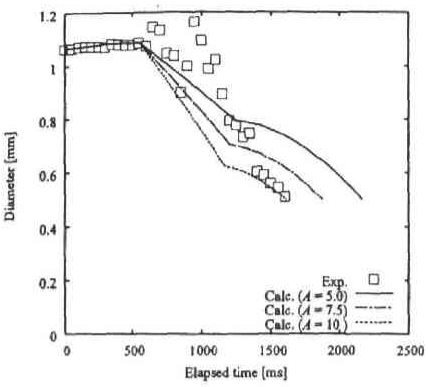

Fig. 7 Diameter history of single droplet evaporation (puffing)

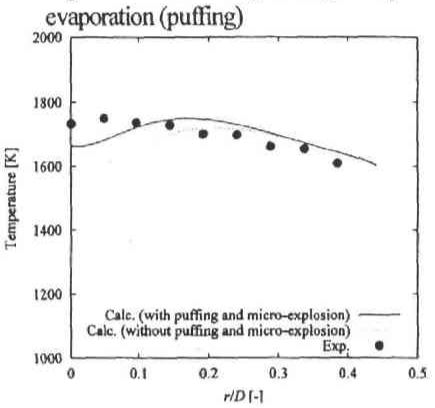

Fig. 8 Radial distribution of gas temperature

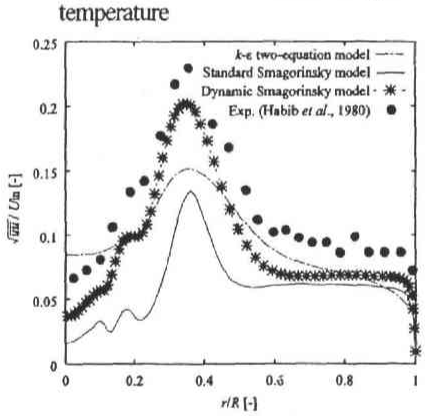

Fig. 9 Radial distribution of turbulent intensities

Fig. 7 show the evaporation characteristics of the emulsified fuel droplet when water content is 10 vol%. When puffing occurs continuously ($t \fallingdotseq 600$ ms), the droplet diameter drastically changes due to the generation of water vapor in the droplet. After the evaporation of the dispersed water is completed, the droplet diameter decreases smoothly. The calculated results with the parameter A varied from 5.0 to 10 are in good agreement with experimental ones.

[Chapter 5 Numerical simulation of spray combustion of emulsified fuel with considering puffing and micro-explosion] Numerical simulation of spray combustion of emulsified fuel with considering micro-explosion and puffing was carried out. The occurrence of micro-explosion and puffing is determined by the droplet temperature. The

temperature at the occurrence of puffing and micro-explosion is determined to each computational droplet by random numbers with probability function as shown in Fig. 5. When the temperature of droplet in which micro-explosion occurs reaches T_{micro}, a droplet is evaporated rapidly. When the temperature of droplet in which puffing occurs is higher than $T_{puffing}$, the mass change of a droplet is expressed by Eq. 1. Fig. 8 shows radial distribution of gas temperature. The calculated results of emulsified fuel without considering puffing and micro-explosion are different from the experimental ones. However, the calculated results using the proposed model are in good agreement with experimental ones.

【Chapter 6 Advanced numerical simulation for spray combustion】 In chapter 2 and 4, the steady calculation was carried out. However, steady calculation only provides the restricted information. The restricted information obtained from steady calculation precludes accurate prediction of combustion-induced instabilities and unsteady vortex dynamics. Alternatively, Large Eddy Simulation (LES) is attractive as it provides a compromise between accuracy and cost. This chapter presents LES of co-axial jet flows. Fig. 9 shows radial distribution of axial turbulent intensities. In LES, 1,282,752 CVs (Control Volumes) is used. When k-ε two-equation model is used, the turbulent intensities are quite different from the experimental ones. When the standard Smagorinsky model is used, calculated turbulent intensities are underestimated, and a lot of CVs are needed to predict the turbulent intensities accurately. When the dynamic SGS model is used, the calculated results are in good agreement with experimental ones. It is shown that the dynamic SGS model does not need a number CVs which is used in the calculation.

【Chapter 7 Conclusions】 In this thesis, an experimental and numerical investigation were carried out. The main contribution of the present thesis is the development and application of numerical simulation for advanced spray combustion. The effective guide for the low-NO_x combustion was obtained and numerical simulation of spray combustion of emulsified fuel was developed.

論文審査結果の要旨

噴霧燃焼の高度化は新エネルギー開発に匹敵する重要性を持つ。噴霧燃焼の高度化を達成する上で重要な点は(1) 噴霧と空気の良好な混合、(2) 微粒化特性の向上 、(3) 数値シミュレーションの高度化の3点である。本論文は以上3点に焦点をあて、測定技術および数値解析を駆使し、各種検討および数学モデルの開発を行ったものであり、全編7章から成る。

第1章は緒論であり、本論文の目的、構成、背景について述べている。

第2章では、噴霧燃焼の低 NO_x 化を目的とした数値シミュレーションを行っている。実験結果と解析結果が良好に一致することを示した後、空気流入ノズル径および数を変更し、数値解析によるケーススタディを行っている。その結果、高温領域における燃焼ガスの滞在時間と NO 生成速度の積というパラメータと NO 排出濃度が直線関係にあることを数値解析的に示している。このパラメータは低 NO_x 型燃焼器の開発を行う上で重要な指針になることが予想され、本成果は工学的に高く評価できる。

第3章ではエマルジョン燃料の二次微粒化特性について実験的検討を行っている。まず、単一液滴の蒸発実験を行い、液滴全体が微細液滴に分裂するミクロ爆発と液滴の一部が分裂する puffing の二つの現象を観察している。これらの発生因子を検討し、過熱度が支配因子であることを明らかにしている。また、燃料と空気の混合をより促進するためには、二次微粒化発生までの待ち時間を短くすることが必要となる。そこで気泡核生成エネルギーを低下させるために CO_2 をエマルジョン燃料に溶かし、その特性について検討している。ガスを溶かして気泡核生成エネルギーを減少させ、二次微粒化発生を促進させるという研究例は極めて希少であり、興味深い知見が得られている。

第4章では、二次微粒化モデルを提案している。ミクロ爆発は瞬間的な現象であるため、即蒸発を仮定している。puffing は瞬間的な現象ではないため、その特性を表現することのできる数学モデルを提案している。提案した数学モデルは puffing による液滴の質量変化が油中水滴の蒸発速度と燃料と水分の質量分率に比例するというものである。本モデルを用いることでエマルジョン燃料滴の蒸発特性を良好に表現することができ、その妥当性が示されている。噴霧燃焼の数値シミュレーションに適合した二次微粒化モデルを提案したのは本研究が初めてである。

第5章では、二次微粒化を考慮したエマルジョン燃料の噴霧燃焼の数値シミュレーションを行っている。二次微粒化を考慮しない場合、解析結果は温度分布を過小に評価したが、第4章で提案した二次微粒化モデルを使用することで解析結果と実験結果は燃焼器下流部において良好に一致している。二次微粒化を考慮した噴霧燃焼の数値シミュレーションの研究例は僅少であり、有用な知見が得られている。

第6章では、同軸二重噴流を対象とした Large Eddy Simulation の解析結果に及ぼす計算格子数の影響について検討を行っている。dynamic SGS モデルを用いた場合、解析結果は計算格子数の依存性が比較的少なく、実験結果と良好に一致することが示されている。

第7章は結論であり研究全体の総括を行っている。

以上、本論文は噴霧燃焼の高度化を目的とし、数値解析的検討により低 NO_x 型燃焼器の開発指針を得ている。さらに、新規な数学モデルを提案し、今まで数値シミュレーションが適用されていなかった二次微粒化を伴う噴霧燃焼の数値シミュレーション手法を示すことに成功したものである。工学的に有用な知見を数多く得ており、本研究成果は噴霧燃焼の高度化に寄与するところが大きい。

よって，本論文は博士(工学)の学位論文として合格と認める。