Effects of oxygen concentration on rapidly mixed type tubular flame combustion
(急速混合型管状火炎燃焼に及ぼす酸素濃度の影響)

Combustion affects almost every aspect of human activities, from heating and lighting our homes to powering the various modes of transportation vehicles. As a consequence of increased population and expansion of society, total energy consumption rapidly increases, which has led to increasing emissions of carbon dioxide which is believed to be responsible for global warming.

To save energy and reduce the carbon dioxide emissions, oxygen-enriched air combustion as well as pure oxygen combustion has received considerable attention in combustion research. In this study, an inherently safe technique of rapidly mixed tubular flame combustion, which has been developed once for air, has been attempted to extend to oxygen-enriched air as well as to pure oxygen combustion.

In Chap. 1, **Introduction**, the global environmental problem has been briefly reviewed and the importance of oxygen enhanced combustion has been addressed to achieve energy saving and low carbon dioxide emissions. Since oxygen enhanced combustion is very dangerous if it is used in a premixed mode, a new technique to ensure safety is indispensable. The rapidly mixed type tubular flame combustion has been reviewed and considered as a promising technique to accomplish the safety requirement. Objective of this study has been stated and the issues to be studied have been listed in detail.
In Chap. 2, **Experimental and Numerical Methods**, the experimental apparatus, measurement techniques as well as numerical methods to conduct this study are presented and described in details. Two stainless-made burners of slit width 2 and 1 mm, which give the swirl number of 6.28 and 12.56, are used for combustion tests; while with optically accessible quartz burners of slit width of 3, 2 and 1 mm, PIV measurements are conducted to analyze the mixing process inside the rapidly mixed tubular flame burner. The numerical calculations are performed by means of simulation of the one-dimensional, planar, adiabatic, steady, unstretched, laminar flame propagation through the software of Chemkin-PRO using the Chemkin Premix code.

In Chap. 3, **Flame Characteristics of Rapidly Mixed Oxygen Enhanced Tubular Flame Combustion**, experiments have been carried out by gradually adding oxygen into air stream, hence increasing the oxygen mole fraction in the oxidizer, to determine the flame appearances, stability limits as well as oscillatory combustion regimes under various oxygen mole fractions. The flame characteristics are separately presented from two aspects of oxygen-enriched air combustion and pure oxygen combustion.

For rapidly mixed methane/oxygen-air combustion (oxygen-enriched air), the following conclusions are obtained:

1. For methane/air, premixed and rapidly mixed combustion have been tested. The flame appearances of rapidly mixed type combustion are almost the same as those of premixed type, however, those in slit width of 1 mm perform better than in 2 mm slit burner due to higher swirling rate. And it is important to note that the rapidly mixed combustion can be achieved for standard flammable mixtures in the present burners.

2. When the oxygen mole fraction in the oxidizer is less than 0.4, rapidly mixed
tubular flame combustion of methane/oxygen-air could be achieved within flammable range, which has almost the same flame appearances as those of methane/air.

(3) When oxygen mole fraction exceeds 0.5, the circular tubular flame deformed as elliptical shape accompanied by intense vibration. With a decrease of equivalence ratio, stable circular tubular flame is obtained.

(4) When the oxygen mole fractions are further increased to 0.77, diffusion flames are anchored at the exits of the fuel slits, resulting in intense oscillatory combustion. Stable tubular flame is only obtained under very lean condition.

(5) Stable tubular flame ranges under various oxygen mole fractions are investigated with constant oxidizer flow rates in both burners of W=2 and 1mm. When oxygen mole fraction in oxidizer exceeds 0.4, with an increase of oxygen mole fraction, the tubular flame range in equivalence ratio becomes narrower and limited at the vicinity of lean limit.

(6) Pressure fluctuations above ±5 kPa are observed in oscillatory combustion with oxygen mole fraction of 0.661 and 0.868.

As for pure oxygen combustion of methane, experiments have been carried out under various flow rates in two burners of slit width 2 and 1 mm, respectively, the following conclusions are obtained:

(1) In the burner of W= 2 mm, diffusion flames are anchored at the exits of fuel slits. Under constant equivalence ratio while increasing the flow rate, hence increasing injection velocity, the diffusion flame is extended and becomes weaker, however, oscillatory combustion intensifies at high injection velocity.

(2) Keeping the oxygen flow rate constant, with an increase of the methane flow rate,
the diffusion flame become weak and the intensity of oscillatory combustion increase due to an increase of equivalence ratio.

(3) Keeping the methane flow rate constant while increasing the oxygen flow rate, the diffusion flame becomes weak and the luminosity decreases due to decrease of equivalence ratio;

(4) For the burner of 1 mm slit width, when equivalence ratio is large, turbulent flame dominates the combustion; with a decrease of equivalence ratio, stable tubular flame combustion is obtained and remained until extinction. Under various oxygen flow rates with both 50 and 100 combustion tubes, the tubular flame range is examined, which is about 0.11 ~ 0.18 in equivalence ratios;

(5) The oscillatory combustions in W= 2 and 1 mm burners are tested, in which the pressure fluctuations are over ± 10 kPa and ± 20 kPa, respectively. For the case of tubular flame combustion in W=1 mm and L=50 mm, the pressure fluctuations are about ± 3 kPa;

(6) The concept of the first Damkohler number, which is the ratio of characteristic mixing time to characteristic reaction time, is proposed to quantify the establishment of tubular flame combustion.

In Chap. 4, Numerical Calculation of Burning Velocities and Reaction Time, numerical calculations have been made on the burning velocity as well as on the burned gas temperature of methane/oxygen/nitrogen mixtures with use of the Chemkin Premix code, in which 53 chemical species, 325 elementary reaction steps and detailed multi-component transport properties are taken into consideration. As for the burning velocity, good agreements have been obtained with experimental data available in the literatures.
Burning velocities and adiabatic burned gas temperature of the mixtures which sustain tubular flame in the rapidly mixed type combustion have been analyzed. When the oxygen mole fraction is around 0.4, burning velocity of 114 cm/s and adiabatic flame temperature of 2700 K could be achieved by rapidly mixed tubular flame combustion. With an increase of oxygen mole fraction, the maximum burning velocity and flame temperature for rapidly mixed tubular flame combustion decrease due to the formation of diffusion flame anchored at the exit of fuel slit.

In addition, the burning velocities and adiabatic flame temperature of CH₄/O₂-CO₂, H₂/O₂ and C₃H₈/O₂ are summarized for oxy-fuel combustion, respectively.

The laminar flame thickness is computed through the temperature profile obtained along with the burning velocity calculation. Based on these calculations, characteristic reaction times for various methane/oxygen/nitrogen mixtures have been obtained. For methane/oxygen mixture, with an increase of equivalence ratio, the reaction time reduces rapidly.

In Chap. 5, **Mixing Process Analysis in the Rapidly Mixed Type Tubular Flame Burner**, the mixing process in the rapidly mixed tubular flame burner has been carefully explored. With use of a PIV system, the mixing layers have been visualized and the individual thicknesses of the fuel stream and the oxidant stream have been determined precisely. Mixing time has been estimated based on the mixing layer thickness determined. The followings are concrete conclusions.

(1) It has been turned out that in the burner there coexist two types of flows, a boundary layer type flow near the exit of the slit, which develops along the wall, and an axisymmetric stretched flow more inside the wall.

(2) The mixing layer thickness in the boundary layer type flow is proportional to the
inverse square root of injection velocity; while for the axisymmetric flow, the thickness is in proportion to the inverse value of injection velocity.

(3) For the case of injection velocity of seeded flow half of that the non-seeded flow, the mixing layer thicknesses in boundary layer type flow are examined. The mixing layer thickness of the flow with lower injection velocity is thick and becomes the rate determining process for mixing. For the burners of slit width of 2 and 1 mm, the mixing thickness could be roughly calculated by the relations obtained under the same injection velocity but use the lower injection velocity. And this is further assumed to estimate the mixing layer thickness under various injection velocities of fuel and oxidant.

(4) For the boundary layer type flow, it has been validated that the determined relations in PIV measurement with low velocity could be applied to estimate the mixing layer thickness under high injection velocity even combustion tests.

(5) Mixing time can be calculated by the mixing layer thickness of the flow with lower injection velocity.

In Chap. 6, **Discussion on the Requirement for Rapidly Mixed Oxygen Enhanced Tubular Flame Combustion**, the requirement for the establishment of rapidly mixed tubular flame combustion has been discussed on the basis of the concept of the first Damköhler number, which is the ratio of the characteristic mixing time (estimated from Chap. 5) to the characteristic reaction time (calculated in Chap.4).

It is found that the Damköhler number calculated with the thickness of the boundary layer type flow gives useful insights on success/failure of rapidly mixed type tubular flame combustion; if the Damköhler number is less than unity, the mixing is completed before the onset of reaction, resulting in tubular flame combustion of