A Study on Radiation Heat Transfer and Characteristics of Oxygen Enriched Double Inversed Diffusion Flame

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ABSTRACT

An experimental study of oxygen enriched double inversed diffusion flame was conducted to understand the flame characteristics and radiation heat transfer. The infrared radiation meter was used to measure of various combination of fuel, air and pure oxygen. The results show that oxygen enriched double inversed diffusion flame is very effective to increase of thermal radiation and proper addition of pure oxygen in air flow can intensify thermal radiation of flame. And it can be found that oxygen enriched double inversed diffusion flame could give benefits of cost effective and very high energy

Keywords : oxygen enriched double inversed diffusion flame, radiation heat transfer.

INTRODUCTION

Recently, manufacturing processes that need high heat or mainly use radiation heat transfer (glass manufacturing, billet manufacturing in the iron mill, ladle heating, etc.) tend to change their fuel from liquid fuel to LNG because of high price of crude oil. LNG is known to be a gas fuel that is low in cost, has low emission, and easy to store and carry. And the radiation heat transfer in most manufacturing processes is normally provided in a form of diffusion flame.

The two sources of thermal radiation in the diffusion flame consist of non-luminous flame radiation and luminous flame radiation. Non-luminous flame radiation is the molecular radiation from the combustion products CO_2 and H_2O, and Luminous flame radiation is caused mostly by the blackbody radiation from the soot that emits bright light. The radiation fraction of this diffusion flame varies from a few percent to greater than 50% according to the type of fuel and the flow condition.

Methane is selected as fuel in this paper since it possesses more than 86.7% of LNG. But it produces a low amount of soot, which results in less amount of radiation heat transfer[1]. To overcome this low radiation characteristic of methane-air flame, oxygen-methane flame is considered in this paper since it' s heating rate is very high due to high adiabatic flame temperature and it has also the higher radiation heat transfer by the more amount of soot created mostly in the rich mixture ratio.

And above process also requires the high heating rate, i.e, high load combustion rate. As means to achieve above high load heating rate, Hasegawa suggested that the fuel gas should be introduced between two high-speed oxidants(air or oxygen), which results in the high turbulence mixing rate of the fuel and oxidants for adequate flow fields during high load combustion.

Thus an oxygen-enriched double-inverse diffusion flame, which has the combustion characteristics of oxygen-fuel flame and represents a high-load combustion flow field, can be expected to achieve maximum radiation heat transfer Hence, in this research, experiments were performed to find out the basic characteristics of radiation heat transfer and the combustion of the oxygen enriched double-inverse diffusion flame. In addition, we investigated to see how much economical profit we could get from the high heating rate through the use of oxygen compared to when normal air is used as the oxidant.

THE CHARACTERISTICS OF OXYGEN ENRICHED FLAME

High flame temperature of the oxygen flame

From Fig.1 which shows the adiabatic flame temperature according to the addition of oxygen (P), it can be seen that the adiabatic flame temperature of the oxygen-methane (P=1) flame is 3076K, which is about 800K higher than that of the air-methane (P=0) flame. This high temperature will bring a greater advantage in the increase of radiation energy.

The value of P (Oxygen Participation) of equation (1) is defined as the fraction of total amount of oxygen required.

$$P(Oxygen\ Participation) = \frac{PureOxygen}{PureOxygen + 0.21Air}$$

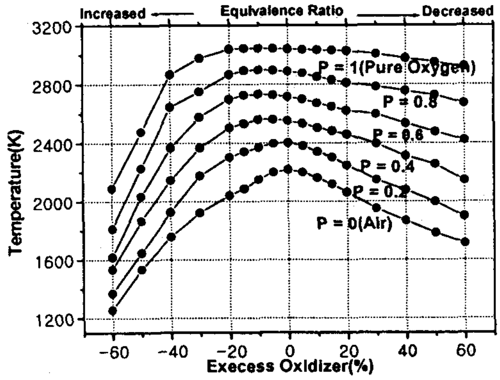


Fig.1 Adiabatic Flame Temperature of Methane-Oxygen Flame(Program STANJAN for chemical equilibrium calculations was used)

The increase of radiation heat transfer

Fig.2 represents the mole concentration of the combustion product produced during oxygen-enriched combustion, and it can be depicted that the oxygen-methane flame shows a much higher concentration of CO_2 and H_2O than the air-methane flame, that

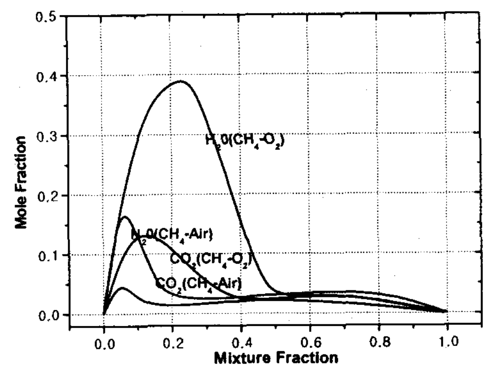


Fig.2 Mole Fraction of Methane-Air/ Methane-Oxygen Flame CO_2, H_2O (Program PRE-PDF2.4 calculations was used)

will make molecular radiation increase [5-9].

Besides, according to the research of Homan[2], the soot is generally produced in an area with high temperature and rich mixture ratio, and in the case of the oxygen-methane flame, the high heat transfer and the reduction of the dilution effect of nitrogen due to the use of oxygen produces a large amount of soot which contributes mainly to blackbody radiation.

The controllability of the flame

The ignition temperature of the oxygen-methane flame is 540K, which is 100K lower than the air-methane flame, and the flammability region of the oxygen-methane flame is ~59% while it is 5.3~14% for the air-methane flame of which the flammability region is more than 4 times wider. Also, in Fig.1 it can be seen that the oxygen-methane flame maintains high temperature under a wide equivalence ratio.

The problems of using oxygen

The problems of oxygen-enriched flame are the reduction of convection heat transfer caused by the small amount of burnt gas (the reduction of the amount of N_2), and the increase in operational costs (the additional cost of using oxygen). However, it has an advantage in the process that mainly uses radiation heat transfer without contacting heated objects and/or in the process that necessities high temperature heating. And as for the operational costs, the cost of oxygen production is getting lower because of the development of oxygen production techniques (cryogenic air separation, cost effective pressure swing absorption).

Fig.3 shows the operating diagram of ladle-heating burner made by the American Combustion Corporation that uses oxygen and air. In case the required temperature is more than 800C under the condition of P=0.55 and (Φ=1, it is shown to be possible to gain an economic profit when the price ratio of oxygen/LNG is 0.2 or below. In case of the required temperature more than 1000℃, it is thought to be possible to gain an economic profit when the price ratio of oxygen/LNG is 0.35 or below. Also, in case the required temperature is more than 1200℃, it is possible to gain an economic profit when the price ratio of oxygen/LNG is 0.58 or below. In other words, it is possible to gain an economic profit under a wider range of temperature as the price of the oxygen lowers and in a process that requires high temperature even if the price of the oxygen is relatively high.

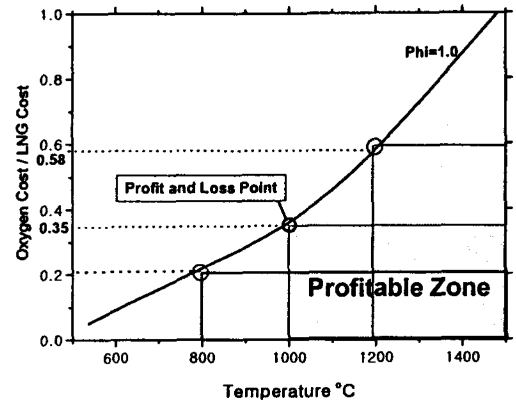


Fig.3 Profit and loss Point of Oxygen/LNG Cost Ratio versus Exhaust Gas temperature(AirCost/LNG-Cost=5%)

METHOD OF EXPERIMENT

The structure of the burner

The burner used in this research is shown in Fig.4. The burner was designed for a fuel flow of 5 l/min and to make a flame of the adequate size with turbulent characteristics, and this was designed by referring to the Moss experiment and through many pretest using burners of different sizes. Many combination of methane, oxygen, air, and air + oxygen was introduced into each of the burner nozzles, ①, ②, ③ in order to make many different kinds of diffusion flames. The areas of the burner nozzles of ①, ② was kept as much the same as possible and by changing the kind of oxidant and the position of the fuel, many types of flames can be made. The fuel, oxygen, air flux, and specifications of each nozzle are given in Table.1.

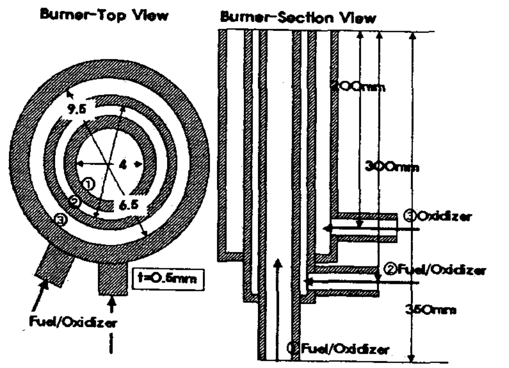


Fig.4 Schematic diagram of Double concentration Burner

Experimental schematics

The schematics of the experiment apparatus are as shown in Fig.5. The mass flow of the fuel and the oxidants(oxygen, air, oxygen + air) were controlled using the Mass Flow Meter (MKS Type-1179A). A digital camera was used to measure the luminous flame height and the general characteristics of the luminous flame according to each oxidant.

The measurement of thermal radiation heatflux

To compare the radiation intensity of each flame, the radiation heatflux was measured. PASCO' s radiometer model. TD-8549 to measure the radiation heatflux was used. The measuring wavelength range of this measuring machine, which spans the whole range of the infrared rays, is 0.6~30.0m and its sensitivity is 20 m/cm^2. As shown in Fig.6, by restricting the view angle of the radiometer to a small degree of θ=7.5 by the View-Restrictor with a water-cooling body, the radiation around the flame can be avoided and only the flame radiation of the measurement point emitted by the high temperature combustion gas of each flame can be detected. And the temperature of the View-Restrictor with a water-cooling body was controlled to maintain about 300K using

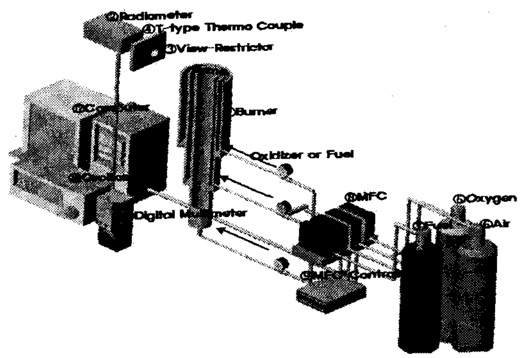


Fig.5 Schematic diagram of Experimental apparatus

Table.1 Flow Rate of Oxidizer and Fuel

	Gas	Flow Rate (L/min)	Area (mm^2)	Diameter Out/In(mm)
① Primary Oxidizer Or Fuel	Air	0~20	12.57	5/4
	Oxygen	0~20		
	Air+Oxygen	0~20+0~20		
	Methane	0~20		
② Fuel or Primary Oxidizer	Methane	0~10	13.55	7.5/6.5
	Air	0~1		
	Oxygen	0~20		
	Air+Oxygen	0~20+0~20		
③ Secondary Oxidizer	Air	0~60	16.70	12.5/9.5
	Oxygen	0~20		
	Air+Oxygen	0~20+0~60		

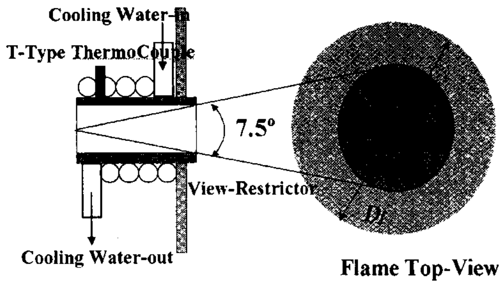


Fig.6 View-Restrictor

the T-type thermocouple.

To find out where the variation of heat radiation according to the distance between the flame and the radiometer is the smallest, the radiation heat flux by increasing the ratio of D_r (measuring diameter) on the basis of D_f (the width of the visible flame)was measured. And the mechanical milling table was used to measure the distance between the radiometer and the measuring flame. From Fig.7, which shows the variation of radiation energy according to distance, it can be found that there was almost no variation in radiation heat flux between D_r/D_f=0.4~0.6. So the measuring area was set to D_r/D_f=0.5.

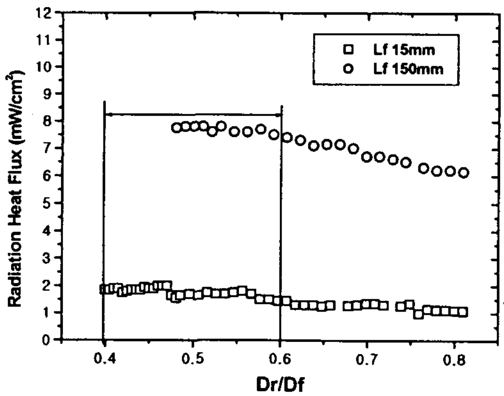


Fig.7 Mwasurement of radiaion Heat Flux by D_r/D_f ratio (DIFP05,P=0.5,Φ=1.0,Qr=3.327kw)

The 2D plane distribution characteristics of the soot using the LII (Laser Induced Incandescence) technique

To find out characteristics of the soot distribution that occupy large part of the radiation heat transfer in the diffusion flame, the LII (Laser Induced Incandescence) technique was adopted to measure the soot distribution of each flame. LII technique can measure the instantaneous soot concentration in the very transient combustion phenomenon such as turbulent flame.

The LII technique is based on the fact that the intensity of blackbody radiation is in proportion to soot concentration. The blackbody radiation is emitted from soot particles in over 4,000K during heating and then cooling when a high energy density laser beam is irradiated onto the soot particles within flame for a few ns. Its advantage is that it can measure the concentration and the particle size distribution of the soot particles in nearly real-time. To simplify the interpretation of the results, it is assumed that laser sheet has the same energy flux.

Fig.8 depicts the experimental diagram of the soot distribution measurement apparatus using the LII technique. The experiment apparatus mainly consists of the optical equipment that make the plane laser sheet of the Nd:Yag pulse laser and the light receiving section which detects the LII signal. For the optical equipment, a 25.4×5.4mm^2 cylindrical lens and a spherical lens with a diameter of 101.6mm were arranged to make a sheet beam of 100mm in height and under 5mm in width, using the secondary harmonic wave (532nm) of the Nd:Yag laser and the plain mirror, beam splitter, and the pin hole which control the laser beam.

For the light receiving section, a 400, 532 nm band pass filter and a ICCD camera were used.

The energy density of the laser beam was set to 5×108w/cm2 which can produce the LII signal, and the interval between each pulse is 5~7ns. And it is important in LII measurements to adequately set the incipient laser's wavelength and the measuring wavelength and also the delay time, which is used to

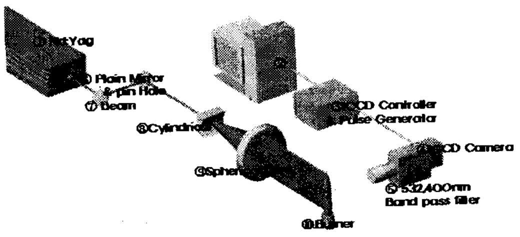


Fig.8 Schematic diagram of LII Experimental apparatus

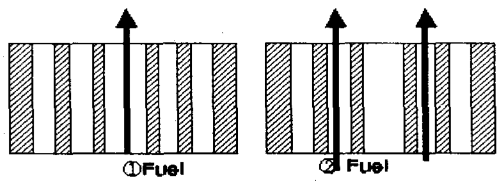


Fig.9.a.1 NDF Fig.9.a.2 ADF

Fig.9.a. Fuel Flow Only

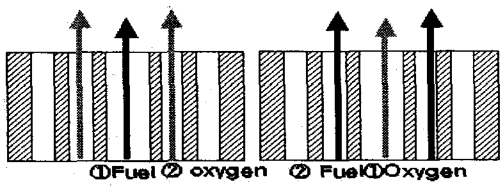


Fig.9.b.1 CDF Fig.9.b.2 IDF

Fig.9.b Fuel+Primary Oxidizer(Oxygen)

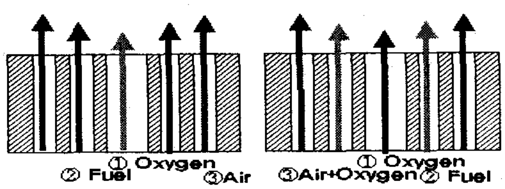


Fig.9.c.1 DIFP Fig.9.c.2 DIFP-MIX

Fig.9.c Fuel+Primary+Secondary Oxidizer

Fig.9 Combination of Fuel and Oxidizer

remove the noise beside the LII signal. The fluorescent noise induced by C_2 by high power laser is especially serious when a laser frequency close to 532nm is used. To reduce the effect of noise like this, the LII signal has to be detected in a wavelength outside of the 460~560nm range, and generally the 360~440nm range is widely adapted. In this paper, the LII signal measurement was made using a 400nm filter.

Considering that the LII signal is affected by the delay time according to the average molecule diameter, the gate time of the ICCD camera was set to 100ns after the laser was irradiated on the flame. This is because the effects of the surrounding noise can be minimized if the delay time is given more than 80ns.

To analyze the precise distribution characteristics of the soot within the methane-air flame, which produces only a small amount of soot, 50 LII images were overlapped. Since the flame shape is bigger than the sheet beam, which is 100mm in height and below 0.5mm in width, the distribution of the soot was measured in sections with high concentrations of the soot.

RESULTS AND DISCUSSIONS

Reference Flames a(fuel flow only), Diffusion Flame (NDF) and the Annular Diffusion Flame (ADF)

Prior to the oxygen enriched double inverse diffusion flame experiment, NDF and ADF of Fig.9.a were established to measure the radiation heat transfer of normal diffusion flame according to the different location of the fuel introduced in still air as reference flames. Fig.10 shows ADF is wider than NDF and NDF is longer than ADF.

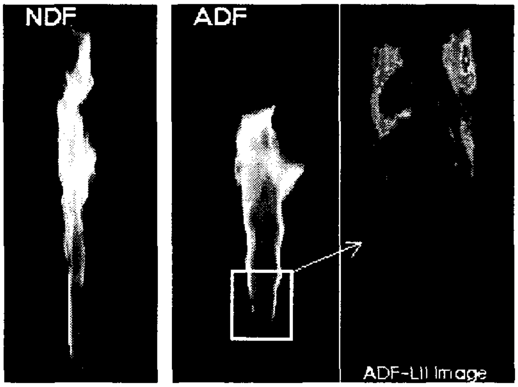


Fig.10.1 NDF Fig.10.2.a ADF Fig.10.2.b LII image of ADF

Fig.10 Photograph of NDF, ADF(Qr=3.327kw)

And Fig.10.2.b shows the soot distribution of the squared region of picture of the ADF in Fig.10.2.a. It can be seen that the distribution of the soot is generally distributed in a ring shape around the flame.

Fig.11 shows the radiation heatflux according to the flame length direction (Lf) between NDF and ADF under the same heating power(Qr=3.327kw). From the results, it can be seen that the wider ADF has the better mean and the maximum value of radiation heat flux so that the fuel flow in the form of a ring is more efficient for higher radiation heat transfer.

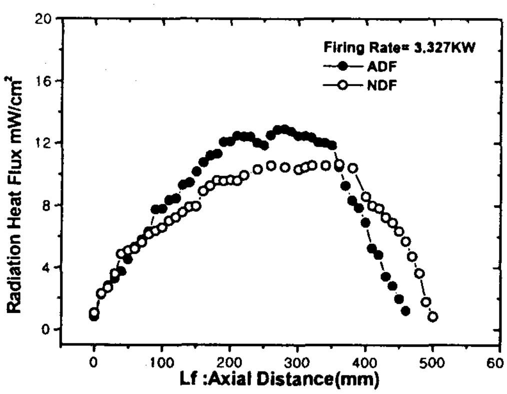


Fig.11 Comparison of Radiation Heat Flux results with NDF,ADF (Qr=3.327kw)

Reference flames b(Fuel and Oxygen), Coannular Oxygen Diffusion Flame (CDF) and Oxygen Inverse Diffusion Flame (IDF)

To find out the effects of oxygen introduction instead of still air in reference flame A and the location of fuel and oxygen flow, we established CDF that supplies oxygen to the outer side of the fuel flow in central tube as shown in Fig9.b.1, and IDF that introduces oxygen to the central tube as shown in Fig9.b.2.. It is observed in Fig12.1 that the luminous area is distributed on flame surface of CDF. In case of the IDF of Fig13.1, it can be seen to be formed in a ring shape around the bottom center axis of the flame and its intensity is much higher than that of CDF. And the visible length of the flame of the IDF is much longer than that of CDF. As for the soot distribution of Fig12.2, the soot is distributed on flame surface in case of CDF. In case of IDF as seen in Fig13.2, soot is concentrated on the luminous zone of ring shape observed in Fig. 13.1. It is thought that the luminous zone is produced by blackbody radiation due to soot formation by the reaction of oxygen and inner side of fuel jet layer.

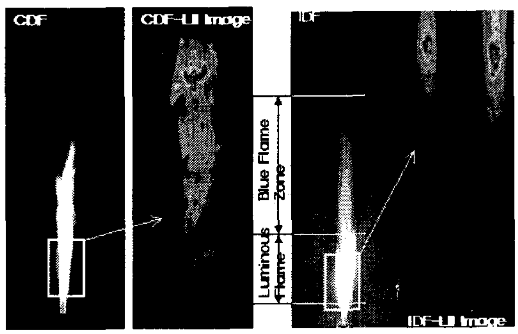


Fig.12.1 Fig.12.2(LII) Fig.13.1 Fig.13.2(LII)

Fig.12 Photograph of CDF (Qr=3.327kw,P=1.0,Φ=1.0) Fig.13 Photograph of IDF (Qr=3.327kw,P=1.0,Φ=1.0)

Fig.14 shows comparison of overall radiation of CDF and IDF with same oxygen

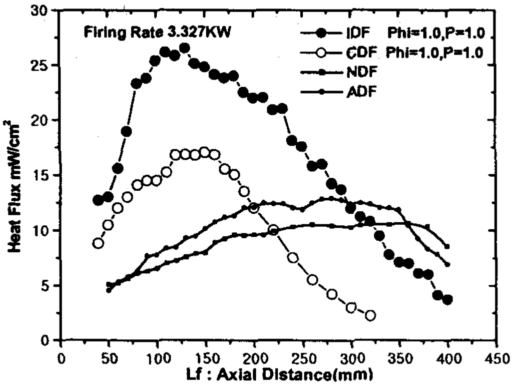


Fig.14 Comparison of Radiation Heat Flux results with IDF, CDF, NDF, ADF(Qr=3.327kw)

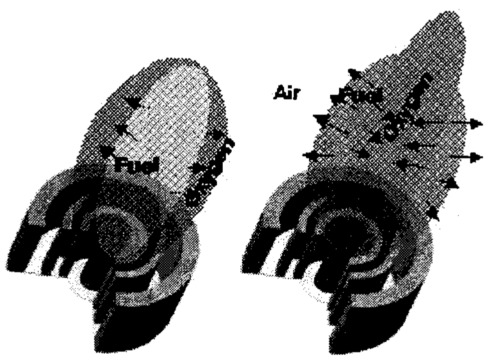


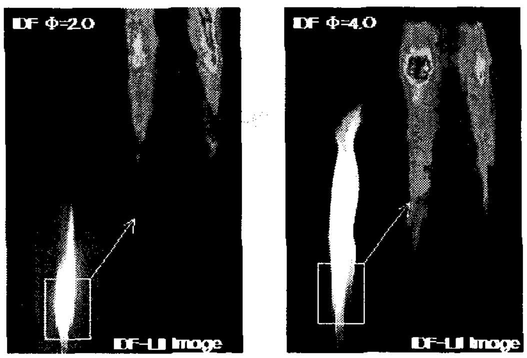
Fig.15.1 CDF Fig.15.2 IDF
Fig.15 Flame Structure of CDF, IDF

under the same heat release according to the length direction (Lf). And it also shows the axial radiation distribution of NDF and ADF that used only fuel. From the distribution results of the radiation heatflux in the above, IDF and CDF represents much higher maximum and mean value of radiation heatflux compared to the ADF and NDF which supply only fuel gas into the surrounding still air. It seems that the high temperature and reduction of the fuel dilution effect of nitrogen by using oxygen would increases the amount of soot and then increases blackbody radiation. Also the increase in the concentration of CO_2 and H_2O intensifies molecular radiation resulting in higher radiation heat transfer.

Under the same amount of oxygen, the IDF showed a higher value of radiation heatflux than did the CDF.

It seems that these characteristics can be explained in Fig.15. In case of CDF, the oxygen surrounds the fuel as shown in Fig.15.1, while in the case of IDF, the fuel surrounds the inner oxygen as shown in Fig.15.2. In the latter case, inside flame sheet of high temperature is formed according to the inverse diffusion reaction between fuel and the oxygen at inside of the fuel and outside fame sheet is established through reaction between still air and out side fuel layer. Therefore, this double flame sheets overlap heat release rate and make radiation intensity of flame more intense.

Now it is important to know effect of amount of the oxygen in IDF on the radiation heat flux. Thus Fig. 13 and Fig.16.1,2 shows the characteristics of radiation heat transfer according to the increase of pure oxygen on IDF (this means the increase of cost). The increase in the amount of oxygen means a decrease of equivalence ratio, Φ and thus the amount of pure oxygen can be expressed as



16.1 IDF at Φ=2.0 16.2 IDF at Φ=4.0

Fig.16. Photograph of IDF by Φ
(Increased Pure Oxygen, Qr=3.327kw,P=1.0)

value of Φ. In case Φ is greater than 2, the flame shows the normal diffusion flame in Fig.13.1. Its luminous region is distributed all over the flame sheet. But as Φ decreases to Φ=2 (Fig.16.1), very luminous zone become to appear(100mm≤Lf≤200mm) in the lower part of the flame. This intense radiating zone maintains itself even if Φ becomes less than 2.0.

The flame length measurement result of Fig.17 shows that the flame length is the shortest near Φ=2, regardless of the firing rate (Qr). Within the range of Φ<2 (Fig.13 and Fig.16.1), this luminous region is maintained at almost constant size but the overall length of the flame increases because of the increase of the length of the blue flame in the upper part of the flame.

As for the distribution of the soot, it can be seen that as the value of Φ decreases to Φ less than 2.0, the distribution of the soot is concentrated at luminous zone of the lower part of the flame and is annular distributed. Fig.16.1 is the distribution of the soot when Φ=2 and Fig.13.2 is the distribution of the soot when Φ=1. From the Figures, both of them seems to have nearly the same distribution in the lower part of the flame. From the measurement results of the radiation heat flux in Fig. 18 and 19, that the maximum value of radiation heat transfer from Φ=4.0 to Φ=2.0 moves toward the lower part of the flame. Interestingly, it is found that in ranges where Φ<2 (increase of oxygen) the distribution, mean, and the maximum value of radiation heatflux maintains at almost same value.

These results show that according to the increase of the use of oxygen a lot of soot is created in the lower part of the flame and then most of the radiation heat flux is produced in this area. And it is found that the radiation heat transfer increases according to the increase in the amount of pure oxygen. (decrease of Φ) But, when the amount of pure oxygen exceeds the amount of oxygen that corresponds to Φ=2, there is not any noticeable difference of the radiation heat flux, which meant that a limit of value of pure oxygen necessary to increase of radiation heat flux exists.

Above results also represents that oxygen-methane reaction at slight fuel rich condition(Φ=2) seems to be more effective to generate the soot to help increase the radiation heat flux.

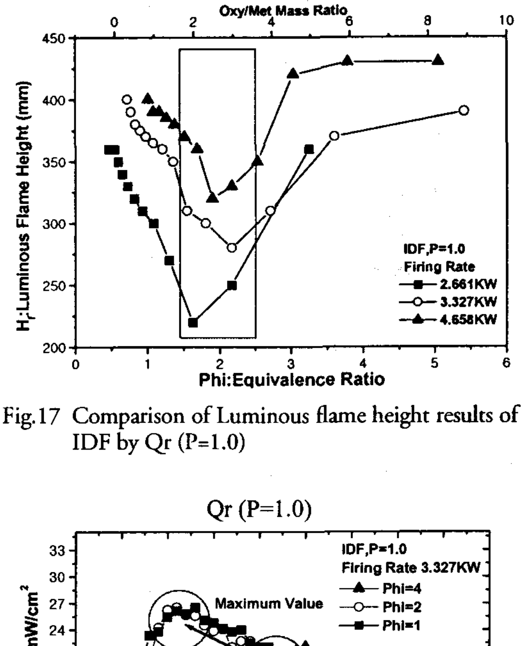


Fig.17 Comparison of Luminous flame height results of IDF by Qr (P=1.0)

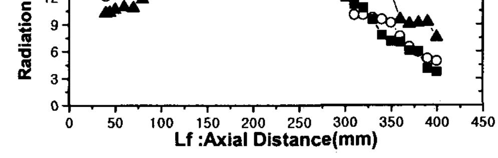


Fig.18 Comparison of Radiation Heat Flux results with IDF by Φ(Qr=3.327kw,P=1.0)

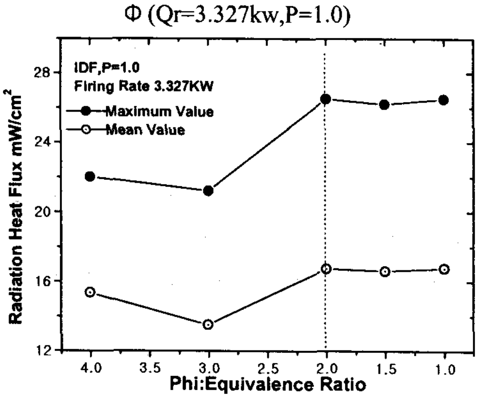
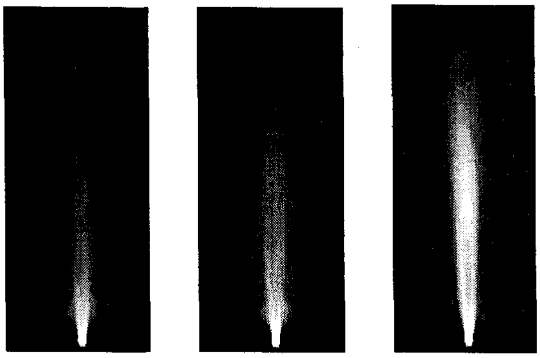


Fig.19 Comparison of Radiation Heat Flux results with IDF by Φ(Qr= 3.327kw,P=1.0)

Oxygen Enriched Double Inverse Diffusion Flame (DIFP)



20.1.DIFP035 20.2.DIFP5 20.3.DIFP065

Fig.20. Photograph of DIFP by Increased P (Qr=3.327kw, Φ=1.0)

The DIFP shown in Fig.9.c is basically based on IDF structure which supplies oxygen in central tube and has outstanding radiation heatflux. Moreover it has additional outside tube to supply the air to oxidize the soot formed in oxygen-fuel reaction and maximize radiation heat transfer. Therefore the increase of P in DIFP means the increase of pure oxygen and the reduction of air, which is supplied in outer side of burner. When value of P becomes P=1.0, it corresponds to IDF.

From the results of the previous IDF experiment, in range where Φ<2, the radiation heatflux showed no variation. As for the relation between pure oxygen and the fuel, when Φ=2 the IDF had the same structure as DIFP, so we experimented with DIFP with P=0.5 as the basis.

Fig.20 represents the picture of the flame according to the variation of the value of P of DIFP, and it shows that the double flame surface is formed in an annular structure.

Fig.21 shows the radiation heatflux according to the value of P in condition of overall equivalence Φ=1. It is seen that as p is increased, the mean and the maximum values of radiation heat flux increase. The increase in the value of P means that the increase in the amount of the use of pure oxygen (and this in turn increases the temperature and reduces nitrogen), increases the radiation heatflux. In general, it showed a higher value than ADF, which used only fuel. Fig.22 shows according to the variation of the equivalent ratio. It shows that as the mixture ratio becomes more and more rich, the radiation heat flux increases.

This structure of DIFP is shown in Fig.23. If air is supplied under the overall condition of Φ=1, the equivalent ratio of only pure oxygen and fuel becomes Φ>1 and mixture ratio becomes rich. The formation of fuel-rich zone and high temperatures by pure oxygen is thought to produce the lots of soot at oxygen-fuel flame zone. This is explained by the distribution of the luminous radiation in the lower part of the flame. The reaction area, which air is solely supplied, is called the fuel lean zone. It is expected that the reaction area completely combusted through the reaction of unburned fuel and soot because mixture ratio of oxygen fuel is rich and lots of soot is formed in oxygen-fuel. Through this process the soot will probably be oxidized and this combustion process can be in a kind of a staged combustion type.

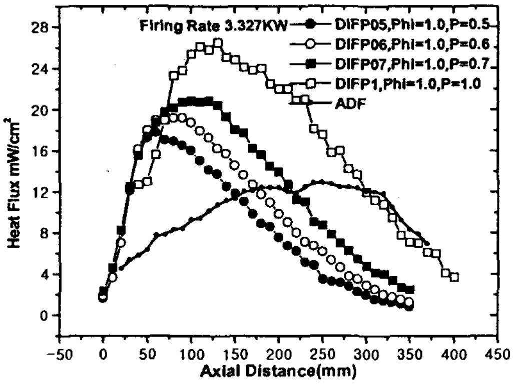


Fig.21 Comparison of Radiation Heat Flux results with DIFP and ADF by P(Qr=3.327kw)

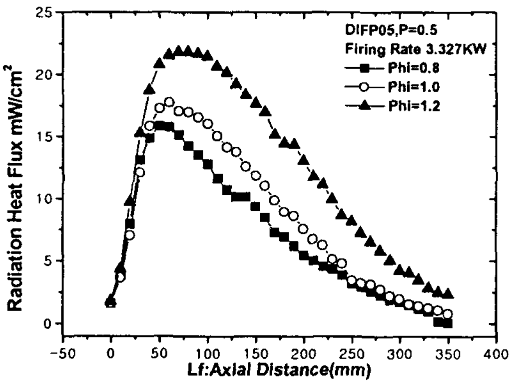


Fig.22 Comparison of Radiation Heat Flux results with DIFP05 by Φ(Qr=3.327kw,P=0.5)

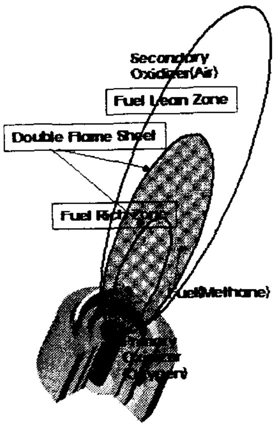


Fig.23 Flame structure of DIFP

The Oxygen Enriched Double Inverse Diffusion Flame that increased the oxygen concentration of the supplementary oxidizing agent (air) (DIFP-MIX)

The increase in the use of pure oxygen naturally brings the increase of radiation heat transfer but also accompanies an increase in cost. Therefore, to maximize the use of oxygen in case of P=0.5(DIFP05) when 50% of the oxygen is supplied with pure oxygen and the other 50% with oxygen within the air, we supplied a part of the 50% pure oxygen to the air of the supplementary oxidizing agent. This method was based on the results of the previous IDF that indicated the existence of a limit to oxygen as a main oxidizing agent. While maintaining the overall oxygen consumption amount, the method is used to reduce the consumption of pure oxygen within a range while its role as a main oxidizing agent would not be affected. Furthermore, it can be thought that the increase in the concentration of oxygen within the supplementary oxidizing agent, air, thereby increases the flame strength of the flame surface. So the adequate conditions on which this method can be used was investigated. Here volume percentage of pure oxygen that is added to the air, MIX, was defined.

$$MIX = \frac{Oxygen_{inSecondaryOxidizer}}{Total\ Oxygen} \quad (2)$$

As it can be seen in Fig.24, the structure of the flame looks similar to that of DIFP. The increase in the value of MIX here brings the increase in the amount of oxygen in air and

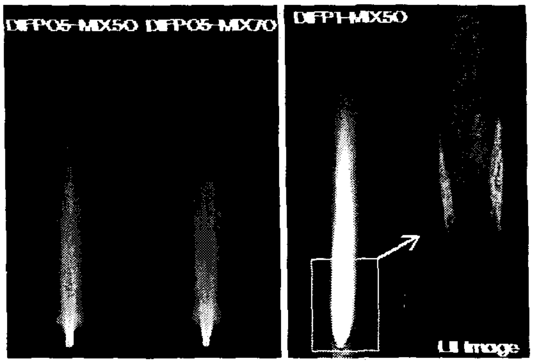


Fig.24.1 DIFP05-MIX50 Fig.24.2 DIFP05-MIX70 Fig.24.3 DIFP1-MIX50

Fig24. Photograph of DIFP-MIX by P and MIX ($Qr=3.327kw$, $\Phi=1.0$)

reduces the amount of pure oxygen. In particular, Fig.24.3 is a case where 100% pure oxygen was used as an oxidizing agent by the same amount both on the main and supplementary oxidizing agents. The distribution of soot is the same as IDF where it is distributed in an annular form in the lower part of the flame. The distribution of the radiation heat flux also showed that the maximum value was positioned in the lower part of the flame.

Fig. 25 and 26 show the mean and maximum values of the radiation heatflux of DIFP-MIX, which has been made by increasing P and the value of MIX; in other words, by increasing the oxygen concentration of the supplementary oxidizing agent(air). The results in this case show that regardless of the value of P, in areas where MIX<30 it increases; in areas where 30<MIX<70 it shows a steady increase or decrease, and in areas where MIX>70, it decreases. It can also be seen that it shows the maximum value when MIX=50, and generally, it has a higher value than the DIFP(MIX=0).

The proper combination of oxygen + air, oxygen, and fuel can make a more effective condition of heat radiation. So to show the saving effect of fuel we compared each combustion mode of radiation heat flux under the same amount of fuel in Fig. 27 and 28. From the comparison, the DIFP05-MIX50 with increased oxygen concentration of the supplementary oxidizing agent (air) had the highest radiation heat flux. The maximum radiation of DIFP05 also is about 1.4 times better than ADF. The DIFP05-MIX50 with increased oxygen concentration of the supplementary oxidizing agent (air), showed that when Qr=3.327KW(5l/min), the maximum value is 1.6 times and the average is about 1.2 times higher than those of ADF. In addition, 4.77KW(7l/min) of ADF has the same average radiation heatflux as 2.661kw (4l/min) of DIFP05-MIX50 with increased oxygen concentration of the supplementary oxidizing agent (air), and can bring the effect of reducing the amount of fuel by more than 40%. If the fuel cost that corresponds to the cost of oxygen (cost of oxygen/LNG≈0.2~0.33) consumed is substracted from total cost, then a total of about 27% reduction of fuel can be possible.

To express more definitely, the following equation to calculate the total cost as is adapted. In equation (3), the cost of fuel is set to 1

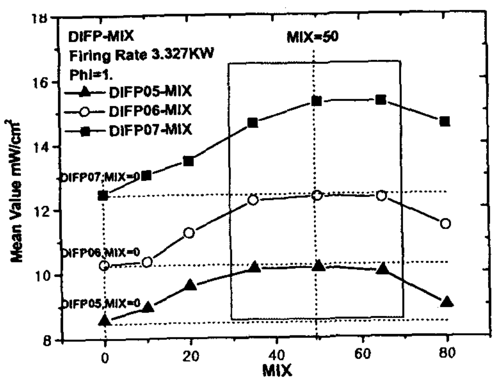


Fig.25 Comparison of mean Radiation Heat Flux results with DIFP-MIX by increased MIX ($Qr=3.327kw$, $\Phi=1.0$)

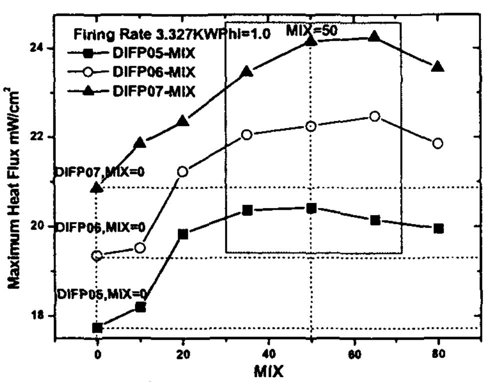


Fig.26 Comparison of maximun Radiation Heat Flux results with DIFP-MIX by increased MIX (Qr=3.327kw, Φ=1.0)

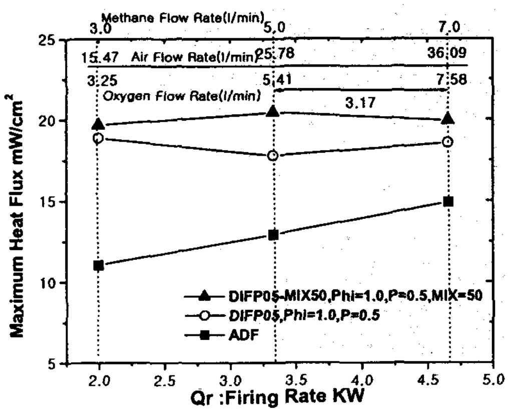


Fig.28 Comparison of maximum Radiation Heat Flux results with DIFP05-MIX50, DIFP05, ADF by Qr

and the cost ratio of oxygen/LNG is approximately 0.266.

$$TotalCost = 0.266 \times Oxygen_{Flowrate} + Fuel_{Flowrate} \quad (3)$$

Fig.29 and 30 represent the mean and maximum values of radiation heatflux in comparison with the total cost, and the dotted line means the same amount of fuel. The radiation heatflux value of DIFP05-MIX50 with increased oxygen concentration within air is higher than other flames under the same total cost. The area with dashed lines in Fig.29 and 30 shows the increase of radiation energy of

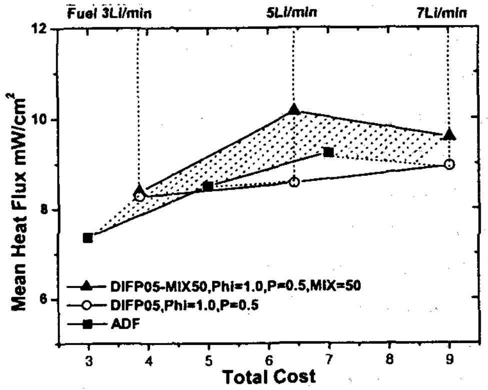


Fig.29 Comparison of mean Radiation Heat Flux results with DIFP05-MIX50, DIFP05, ADF by Total Cost

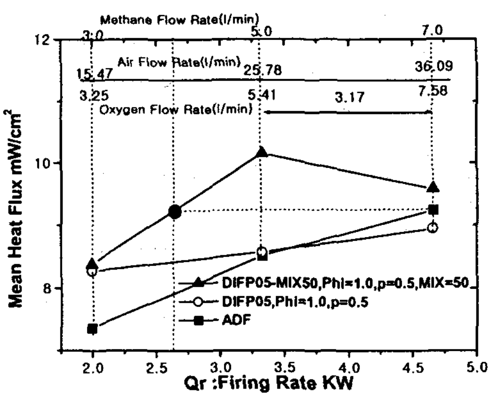


Fig.27 Comparison of mean Radiation Heat Flux results with DIFP05-MIX50, DIFP05, ADF by Qr

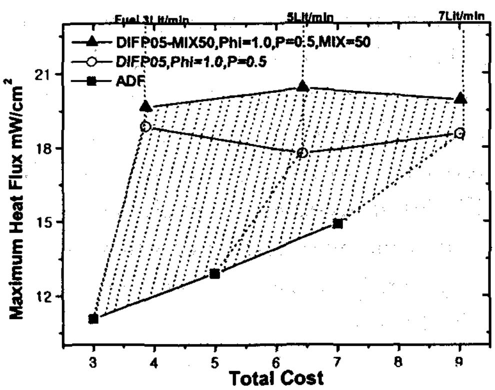


Fig.30 Comparison of maximum Radiation Heat Flux results with DIFP05-MIX50,DIFP05, ADF by Total Cost

DIFP05-MIX50 under the same total cost. In other words, when creating the same amount of radiation energy, the cost of the DIFP05-MIX50 structure with increased oxygen concentration within is much lower.

CONCLUSION

1) In diffusion flames, the soot distribution characteristics are closely related to the radiation heat transfer of the flame. The use of oxygen as an oxidizing agent and the method of creating the flow field of the oxidizing agent can change and increase the distribution of the soot and the effects of radiation heat transfer. When using oxygen the shape of the inverse diffusion flame was outstanding.

2) The DIFP, which was based on the IDF structure, is a form of flame that emits higher radiation energy compared to normal oxygen diffusion flames. This resulted from the following: an overlapping effect of heat release caused by double-flame surfaces; the high temperature condition according to an increase in molecular radiation; the increase of CO_2 and H_2O due to the use of pure oxygen; and, an increase in blackbody radiation caused by the increase in the amount of soot.

3) The intensity of radiation energy becomes strongest when pure oxygen is shared to air by 50%(MIX=50) in the DIFP. This seems that addition of oxygen to air side makes heat release rate of the fuel-air flame sheet more intense.

4) Under the same cost (fuel + oxygen), the DIFP was much better in radiation energy emission compared to other normal oxygen-enriched diffusion flames. Thus it is thought that the DIFP can is properly used in processes that need high radiation energy since it will bring a much larger saving in energy costs.

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