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Combustion Characteristics of Anthracite in a Vertical Cyclone Combustor

Soo Young No*
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Isothermal, gas combustion and coal tests were undertaken in order to characterise a vertical cyclone combustor for burning anthracite. Inert particles (alumina cement) were used during the first two series of tests, in order to characterise chamber temperatures, material collection efficiencies and size distribution of particles. Mixture ratios from 0.4 up to 1.6 were tested in steps of 0.2. Under isothermal conditions, an optimum penetration length of vortex finder into the combustion chamber was found to be approximately 10 % of the chamber length. The highest temperature can be obtained in the lower section of the combustion chamber both in gas and in coal combustion. The collection efficiency of the cyclone combustor in the various modes of operation was found to be excellent. For coal tests, mixed firing with coal and gas was adopted to sustain the flame in the combustor. The mixed fuels investigated here contain 60, 70 and 80 % by mass of coal, and the 70% case was found favorable in the context of carbon burnout and collection efficiency.

Key Words: Cyclone Combustor, Anthracite, Collection Efficiency, Mixed Firing, Carbon Burnout

1. Introduction

The cyclone combustor has been developed for the combustion of materials that are normally considered difficult to burn efficiently such as vegetable refuse, high ash content coals, high sulfur oils, low calorific value waste gases, certain mineral ores and as part of MHD combustors (Agrest, 1965; Ali, Claypole and Syred, 1983; Demski and Yeh, 1979; Lawn, 1987; No, 1990; Syred et al., 1977). Cyclone combustors used centrifugal forces to suspend burning fuel particles according to their size in equilibrium against the drag of inwardly spiralling air, thus increasing their residence time relative to that of the gas. Large particles may, however, be flung to the walls before being completely burnt. Conversely, some fine particles may be convected out of the system very rapidly. Thus, the penetration length of vortex finder into the combustion chamber is one of important parameters in designing of cyclone combustors.

Cyclone combustors can be classified as slagging and non-slagging units. Slagging devices must usually operate with temperatures of at least 1500 ℃ to remove ash as a liquid slag and to ensure efficient slag removal. Non-slagging cyclone combustors operate in such a way that the ash can be collected in particulate or sintered form. This may be achieved by maintaining the wall temperature of chamber below 1200 ℃ in order to avoid ash fusion (Lawn, 1987). Cyclone combustors can be also considered in two types in configuration, horizontal and vertical (Lawn, 1987). The vertical units require less swirl leading to reduce the fan power requirements than that of horizontal ones. It has also advantages to handle coals of high ash content. The vertical cyclone combustor is, therfore, selected here, as anthracite is considered for coal combustion.

One important parameter for cyclone combustor is the configuration of the tangential inlet and

* Dept. of Agricultural Machinery Engineering, Chungbuk National University, Cheongju 360-763, Korea

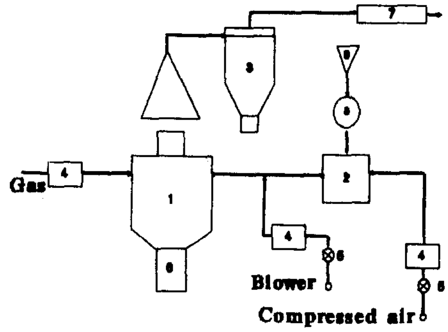
its area relative to the exhaust nozzle and main cyclone chamber. Experience shows that an exhust nozzle about 0.5 of the cyclone chamber diameter gives the best compromise for combustion performance and low pressure drop (Gupta, Lilley and Syred, 1984). Data in the literature show that an operating inlet velocity range of between 30 and 75 m/s gives quite a good flow turndown erosion which may be operated with moderate pressure drops (MacGregor, No and Syred, 1987).

Most Korean coals belong to low grade anthracite. Anthracite is normally considered difficult to burn efficiently. Accordingly, cyclone combustor is suitable for burning of low grade anthracite due to high ash content. System aerodynamics in a cyclone combustor are well understood, having been characterised under combustion conditions with gas, oil and coal, mostly bituminous coal (Lawn, 1987). There, however, has been a few work on the combustion of anthracite in cyclone combustors (Marshak, Chernavski and Kuvaev, 1967).

In this study, isothermal, gas combustion and coal tests were undertaken in order to characterise the system. The purpose of isothermal test was mainly to find an optimum penetration length of vortex finder into the chamber. To simulate the combustion conditions, gas combustion was performed. Especially, the mixed firing with coal and gas was introduced in coal combustion due to the ignition problem of anthracite itself. To find the combustion limit as well as slagging and non-slagging characteristics of the cyclone combustor, operation between mixture ratios of 0.4 and 1.6 was used.

2. Experimental Apparatus

A schematic diagram of the experimental apparatus is shown in Fig.1. Compressed air enters the ejector with a 2.5 mm diameter hole to produce a high velocity jet. The fuel, which is fed through another port connected to the rotary feeder and hopper, mixes with the compressed air. At exit from the ejector, the premixed fuel and air encounters an additional air supply (primary air) which is introduced into a cyclone combustor via a tee junction. Throughout the tests a constant check is made which ensures that negative pressure prevails in the fuel feed system. This prevents any combustible gases escaping to atmosphere through ejector.



1. Cyclone Combustor 2. Ejector
3. Cyclone Separator 4. Flowmeter
5. Valve 6. Ash removel pooket
7. Fan 8. Coal feeder
9. Hopper

Fig. 1 Schematic diagram of test facility

The premixed fuel and air are introduced via a single tangential inlet mounted circumferentially adjacent to the vortex finder. Within the chamber particles are kept in suspension close to the wall by centrifugal forces. In the oxygen rich layer close to the wall a further combustion process occurs. Particles will remain in the region until they are sufficiently small to follow the gas flow to the oxygen deficient central outward flow or are collected by ash removal pocket beneath the chamber.

3. Experimental Procedure

Isothermal, gas combustion and coal tests were undertaken in order to characterise the system. The research has examined the combustor seeded with inert solid particles to simulate the behaviour of a coal fired unit without the complication of reduction in particle size as the material burns and independent of the coal reaction kinetics. Realistic assessments of particulate dynamics and seperation characteristics were then

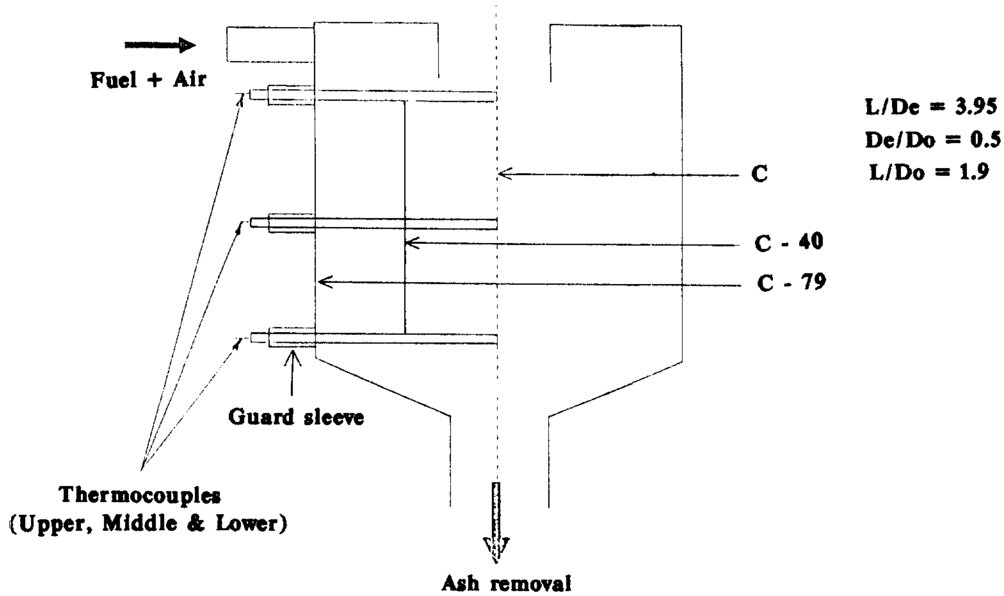


Fig. 2 Schematic of cyclone combustor and positions of temperature readings

made with high temperature flow fields produced by coal combustion being simulated by gas combustion.

The air supply to the system was held constant, and the mixture was varied by altering the feedrate of the material. The mixture ratio was defined by the ratio of actual air fuel ratio to stoichiometric air fuel ratio. The primary air from the blower was fixed to 1500 l/min. Using calibration chart from previous work and measuring the ejector pressure, a conversion of 300 mmH_2O to 97 l/min for the compressed air was taken. Some variance in ejector pressure was experienced, but this was not great enough to significantly affect the results. Thus 1597 l/min of air was used in total during all tests. This is equivalent to the inlet velocity of approximately 50 m/s.

The alumina cement was chosen as the nonreactive fuel for the tests due to its ability to absorb heat and yet suffer no significant changes of state or phase. It has high ash fusion temperature, is inflammable and does not decompose under severe heating. The cement has a wide particle size range which remained constant throughout the tests. The particle distribution of sample was calculated by Rosin-Rammler equation and analyzed by GRANULOMETRE(CILAS 715E628), then average particle size was 120 μm. The LPG was used to preheat the combustion chamber and to simulate the behaviour of coal fired combustion flame as the inert solid fuel is introduced in the gas combustion test.

Figure 2 shows the schematic of cyclone combustor and positions of temperature readings. Temperature levels in the cyclone chamber were measured at three different vertical sections; (1) just below the vortex finder, (2) half-way down the cyclone chamber, (3) near the baseplate. In each vertical section, temperature profiles were taken at three different horizontal positions,i.e. at center (C), at middle (C-40) and at wall (C-79). Tempereaure measurements were made with platinum/platinum rhodium thermocouples (R type).

For an effective ash removal system, penetration of the flow along the length of the chamber, and particularly to the back wall, is required. To find an optimum penetration length of vortex finder into the chamber, three sizes of vortex finder (V_1 = 15 mm, V_2 = 40 mm, V_3 = 60 mm below the top of chamber) were chosen and tested.

Table 1 gives the ultimate analysis of anthracite samples tested. In coal combustion, it was impos-

Table 1 Ultimate analysis of coal samples used

	C	H	O	N	S	Ash
Dry basis (WT %)	37.5	0.94	0.29	0.72	0.70	59.86

sible to ignite anthracite itself over the mixture ratios considered in this experiment. The mixed firing with coal and gas was, therefore, introduced instead of preheating the primary air. The mixed fuels investigated here contain 60, 70 and 80% by mass of pulverised coal.

4. Results and Discussion

4.1 Isothermal(cold) test

The main purpose of the isothermal tests in this paper was to examine the material collection aspect of the cyclone combustor for different vortex finders. Figure 3 shows the material percentages collected in the collector pocket against the mixture ratios for three vortex finders. This figure shows that the cyclone combustor operate well between the 0.8 to 1.2 mixture ratios for all vortex finders tested. In case of vortex finder V_2, there is especially little variation of collection efficiency according to the variation of mixture ratios. The collection efficiency was defined by the ratio of the mass of collected particle by the collector pocket and the mass of total particle. The effect of mixture ratio between 0.8 to 1.2 on the mean particle size collected is, therefore, shown in Fig. 4. For vortex finder V_3, the mean particle size collected by the collector pocket is decreasing sharply with the increasing the mixture ratio, whilst mean particle diameter curves for V_1 and V_2 reveal the small variance. Those results indicate that the penetration of vortex finder by approximately 10% of combustion chamber is required to prevent the partially burnt particles leaving the chamber prematurely. Accordingly, vortex finder V_2 was selected for gas and coal combustion test hereafter.

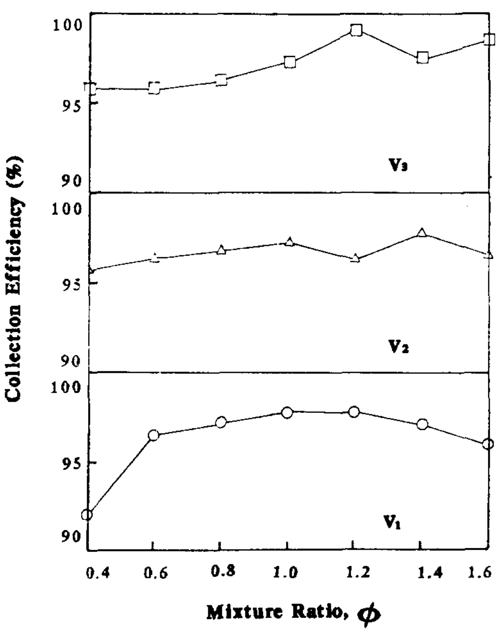


Fig. 3 Effect of mixture ratio on collection efficiency for three vortex finders (isothermal test)

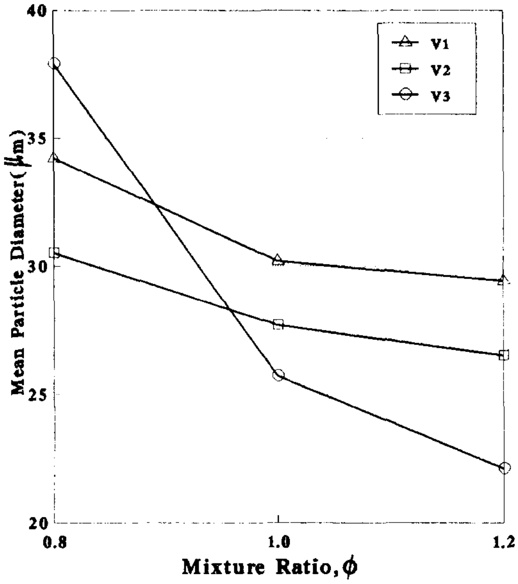


Fig. 4 Effect of mixture ratio on particle diameter collected (isothermal test)

4.2 Gas combustion

The LPG and the alumina cement was used in the gas combustion test. Figure 5 shows the variation of temperature with measuring sections at different chamber position at mixture ratio of typically 1.2. Comparing the temperatures in the upper, middle and lower sections, the highest temperature flow field was estabilished in the middle section. In Fig.6 the effect of mixture ratio on chamber temperature typically at upper section is shown. In this figure, it is found that the temperature is higher in fuel lean condition than that of fuel rich condition. In addition, the center of chamber exhibit the highest temperature over all mixture ratio considered. However, it is clear that the temperature differences between the center and middle position was small enough to ignore. Difficulties were sometimes encountered with the fluctuation of temperature, especially section (1) and dust build-up on the thermocouples. There is, however, clear evidence that the hot material is increasing temperature levels in the base region of the combustor. The gas temperature near the base plate reveals 1300~1400 K at mixture ratio of 1.2.

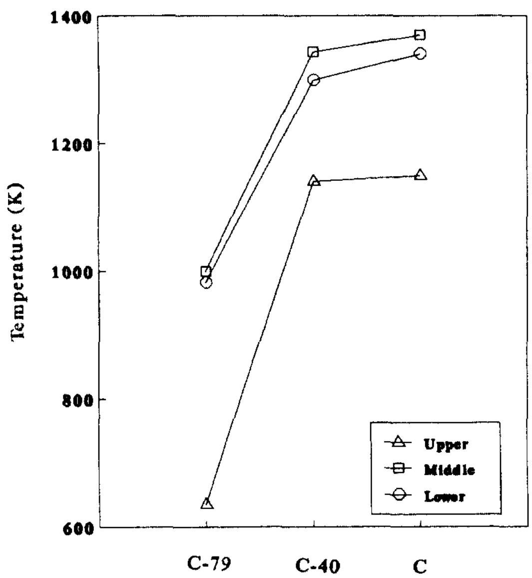


Fig. 5 Variation of temperature with measuring section at different chamber position (gas combustion, $\phi = 1.2$)

The effect of mixture ratio on the collection efficiency in gas combustion tests is shown in Fig. 7. From a mixture ratio of 0.4 to 1.6 the efficiencies stay relatively constant. The poor performances of the collector pockets for mixture ratios of 0.4, 0.8, 1.2 and 1.4 are probably caused by the relatively high levels of deposition. Overall separation performance, therefore, reveals the similar trend with that of collector pocket. Comparing the collection efficiencies between inert condition (Fig. 3) and gas combustion (Fig. 7) over the

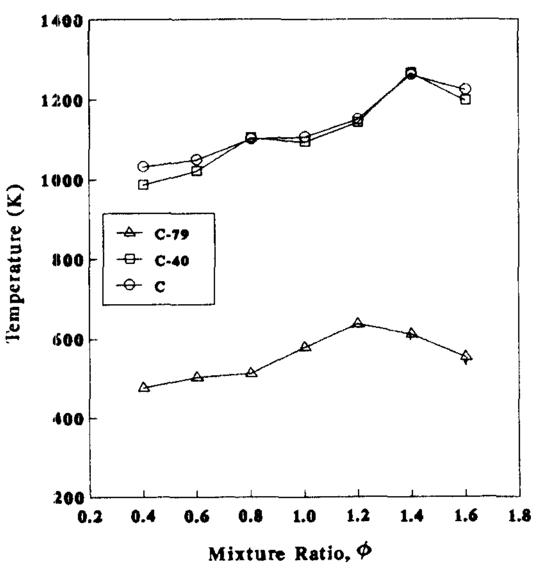


Fig. 6 Effect of mixture ratio on chamber temperature at upper section (gas combustion)

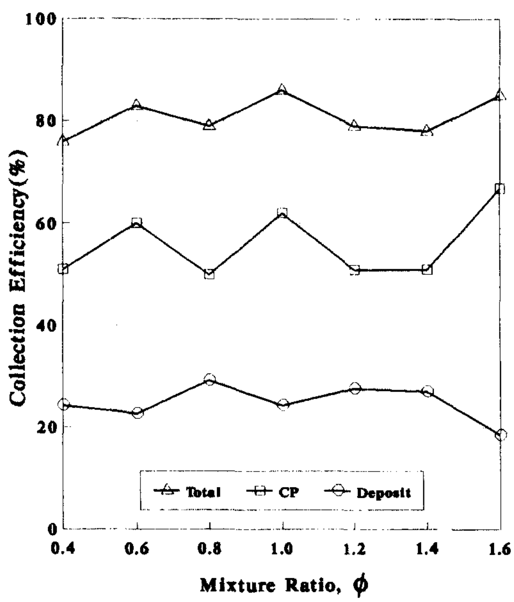


Fig. 7 Effect of mixture ratio on collection efficiency (gas combustion)

mixture ratio considered here suggests that the efficiency of isothermal test are better than that of gas combustion. This is caused by the large reduction of swirl number with combustion due to the large increase of axial flux of axial momentum as the fuel burns and the gases expand (Gupta, Lilley and Syred, 1984; Lawn, 1987).

Figure 8 shows the effect of the mixture ratio on the mean particle diameter collected at the collector pocket in the gas combustion case. It can be seen in this figure that the mean particle diameter collected is increasing with the increase of mixture ratio, notably between 0.8 and 1.2. From the comparison of Figs. 4 and 8, it is found that changes in aerodynamic flow structure by the large reduction of swirl number with combustion due to the large increase of axial flux of axial momentum as the gas burns and the gases expand. Under isothermal and combustion conditions the inlet angular momentum to the cyclone chamber remains approximately constant. However, the axial momentum of the outlet stream is considerably increased as a result of the expansion of the flow due to combustion which also caused a considerable reduction in swirl number.

4.3 Coal combustion

The variation of collection efficiency between collector pocket and deposit in coal combustion for the different coal loading rates is detailed in Fig. 9. The collection efficiencies in collector pocket for the 70 and 80% coal loading stay relatively constant, whilst those in the case of 60% loading are decreased sharply with the increase of mixture ratio. This result is clear from the variation of the collection efficiency in deposit in this figure. It is now found that there exist mixture ratios giving slagging of coal combustion within the chamber for mixture firing rate individually. Operation between mixture ratios of 0.8 and 1.2 reveals such problems.

The results of overall collection efficiency for three coal loading rates considered here is shown in Fig. 10. Here overall collection efficiency includes those in collector pocket and in deposit. Overall collection efficiency for 80% of coal loading is higher than those for other coal loadings over the mixture ratios considered and shows similar trend with that of 70% coal loading. For 60% of loading, the efficiency stay ralatively constant over the mixture ratio except 0.4 of it. It

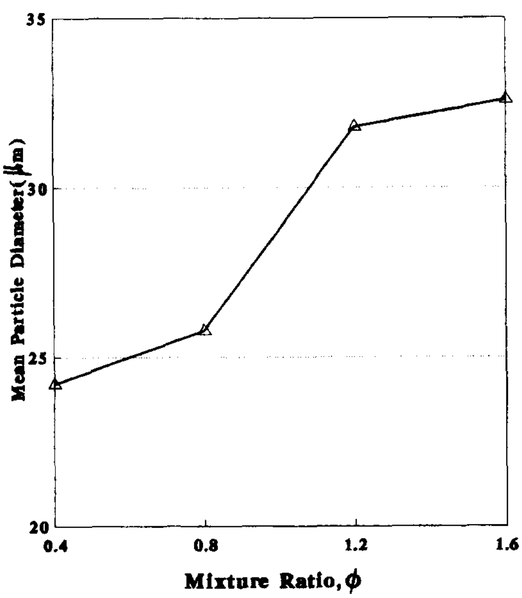


Fig. 8 Effect of mixture ratio on mean particle diameter collected (gas combustion)

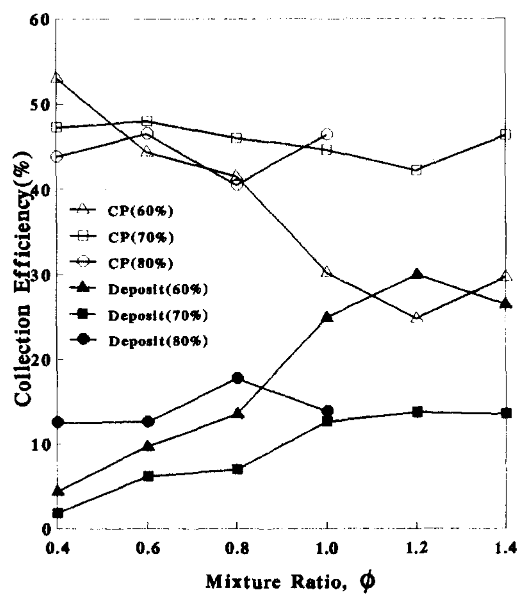


Fig. 9 Variation of collection efficiency in collector pocket and deposit for three coal loadings

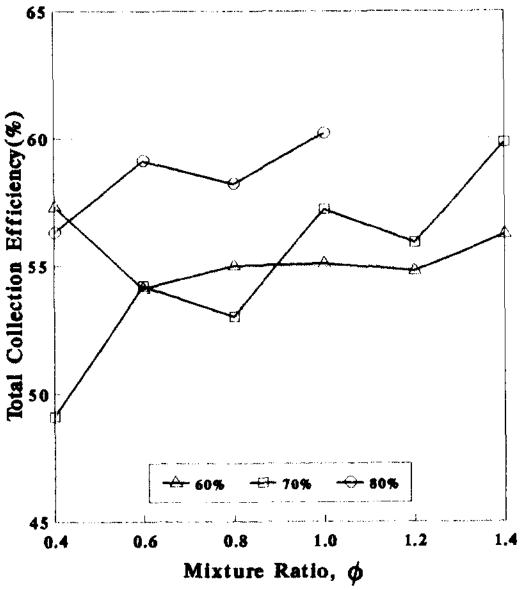


Fig. 10 Variation of overall collection efficiency for three coal loadings

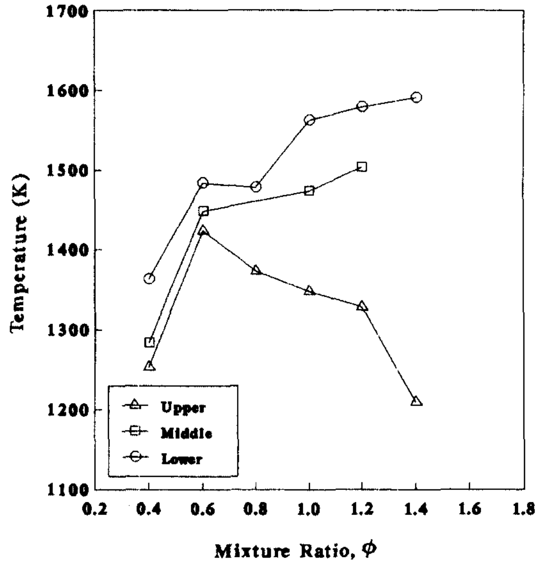


Fig. 11 Effect of mixture ratio on chamber temperature with different measuring section (70% loading, chamber position = C)

should be noted that combustion was no longer self-sustained over mixture ratio of 1.6 for 60 and 70% coal loading, 1.2 for 80% loading. As in the case of gas combustion, problems were encountered on temperature measurement at just below the vortex finder in coal combustion.

Figure 11 shows the effect of mixture ratio on chamber temperature with different measuring section in the case of 70% coal loading at the center of chamber. In this figure, it is clear that the highest temperature can be obtained in the lower section. This is due to the increase of temperature from coal combustion in the bottom. According to the increase of mixture ratio, the temperature in the middle and the lower section is increased, but that in upper section is decreased. This is probably due to gas combustion mainly in the upper section. The gas temperature near the base plate shows 1500~1600 K at mixture ratio of 1.2. Even though more attention is required to the measurement, certainly trends were coincided with gas combustion.

In Fig.12, the variation of carbon burnout for the different coal loading rates is shown. For 60 and 70% of coal loading, the carbon burnout is constantly increasing according to the increase of mixture ratio and shows maximum value at mixture ratio of 1.2. Best performance in terms of carbon burnout is obtained with 60% of coal

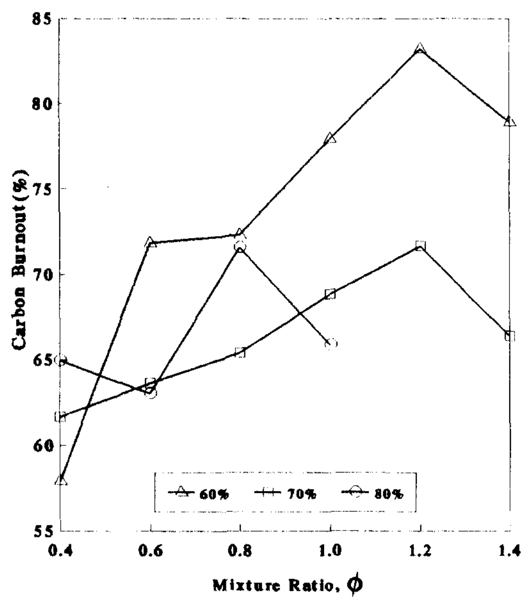


Fig. 12 Variation of carbon burnout for three coal loadings

loading at mixture ratio of 1.2. This result is similar with that of Morgan et al.(1988). The mixture ratio giving maximum carbon burnout moves down to 0.8 in the case of 80% coal loading. In this figure, it is found that the cyclone chamber mixture ratio and coal loading rate in mixed firing with gas are shown to have a dominant effect on carbon burnout.

3. Conclusions

A set of experimental investigation of a vertical cyclone combustor for anthracite coal has been undertaken. Isothermal, gas combustion with inert material and coal tests were performed in order to characterise the system. For isothermal tests, the optimum penetration length of vortex finder into the combustion chamber was found to be about 10% of chamber length to prevent the partially burnt particles leaving the chamber prematurely. Temperatures measured with gas and inert material combustion corresponded partly with temperature measurements made in the coal fired units. The highest temperature was obtained in the bottom and the vertically central part of the chamber, as expected.

Operation between mixture ratios of 0.8 and 1.2 revealed the slight slagging of coal combustion. The combustion limit existed at the mixture ratio of 1.4 for 60 and 70% coal loading, and at 1.0 for 80% loading. With a pulverised coal of 60 and 70% loading, operating normally fuel lean at the mixture ratio of approximately 1.2, good fuel burnout was obtained. Accordingly, recommendable coal loading for efficient burning of anthracite used was 70% coal loading.

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