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Staged Combustion of Rice Straw in a Fluidized Bed.

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STAGED COMBUSTION OF RICE STRAW IN A FLUIDIZED BED

"الإحتراق المرحلى لقش الأرز فى فرن ذى مهد مميع"

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ملخص البحث

مازال لمخلفات قش الأرز وقع سلبى على البيئة والذى يتضح جليا مع ظاهرة السحابة السوداء من كل عام، ولم يتضح بعد وجود حل جذرى لهذه المشكلة. ويعد توظيف هذه المخلفات الحيوية المتجددة فى إنتاج الطاقة إحدى البدائل المطروحة بقوة، وهو ما يمثل إمتدادا طبيعيا لاستخدامات الماضى ولكن مع توظيف تقنيات حديثة، ويعتبر ثانى أكسيد الكربون الناتج عن عمليات الإحتراق فى هذه الحالة هو بمثابة توازن طبيعى مع ذلك الممتص أثناء عملية البناء الضوئى.

فى هذا البحث تمت دراسة حرق قش الأرز فى المهد المميع مع تجزئ الهواء إلى مرحلتين وهو أسلوب معروف لتقليل أكاسيد النيتروجين الناتجة عن عمليات الإحتراق. وقد أجريت التجارب فى فرن ذى مهد مميع قطره الداخلى 30 سم، وارتفاعه 330 سم، حيث تم تغذية الهواء الأساسى من خلال الموزع فى أسفل الفرن، أما الهواء الثانوى فقد تم إدخاله أعلى المهد على إرتفاع 150 سم من الموزع. تم تغذية قش الأرز المضغوط على صورة قطع أسطوانية صغيرها، قطرها 12 مم، وطولها حوالى 10 مم.

وتناولت الدراسة بالشرح والتحليل التأثيرات المختلفة لإجراء تجزئ الهواء على أداء عملية الإحتراق، حيث تم تحديد توزيع درجات الحرارة وتركيز الغازات المختلفة فى الإتجاه المحورى للفرن، كما أظهرت النتائج تأثير تجزئ الهواء على إنبعاثات كلا من أكاسيد النيتروجين و ثانى أكسيد الكبريت، كذلك التأثير على كفاءة الإحتراق. ومن خلال الدراسة والتحليل استخلصت النتائج التالية:

- تزداد نسبة المواد التى تحترق فى المنطقة الحرة فوق المهد مع تجزئ الهواء وخاصة عند زيادة نسبة الهواء الثانوى ويظهر ذلك فى إرتفاع درجة الحرارة القصوى مع الإزاحة إلى أعلى.
- اظهر أسلوب تجزئ الهواء فعالية فى تقليص أكاسيد النيتروجين المنبعثة عن عملية الإحتراق، خاصة مع تشغيل المهد عند درجات حرارة مرتفعة، والتى تصل تحت بعض ظروف التشغيل إلى 50%.
- أدى تجزئ الهواء إلى تقلص طفيف لإنبعاث ثانى أكسيد الكبريت عند النسب القليلة للهواء الثانوى لكن الإنبعاث إزداد عند النسب المرتفعة للهواء الثانوى.
- لتجزئ الهواء تأثير إيجابى على كفاءة الإحتراق عند القيم المنخفضة والمتوسطة لنسبة الهواء الثانوى، إلا أن كفاءة الإحتراق تسجل تراجعا عند القيم المرتفعة لنسب الهواء الثانوى بعد بلوغ قيمة قصوى، وجدير بالذكر أن مدى نسب الهواء الثانوى والتي تتزداد معه كفاءة الإحتراق يتسع مع ارتفاع درجة حرارة التشغيل.

ABSTRACT

Staged combustion of rice straw has been investigated using a fluidized bed combustor of 300 mm ID and 3300 mm height. With air staging, secondary air is fed higher up in the freeboard at 1500 mm above the distributor of primary air. Rice straw is fed as cylindrical pellets with 12 mm diameter and 10 mm length.

The obtained results indicate that staged combustion is an effective way to reduce NO_x emissions, in particular, at higher operating temperatures. NO_x typically reduces by 50% when secondary air ratio becomes 30% at 850°C bed temperature. Staged operation has a slight, non-monotonic effect on SO_2 emissions. Combustion efficiency increases with increasing secondary air ratio reaching a maximum value that is mainly attributed to a reduction in fixed carbon loss. However, combustion efficiency decreases after a maximum as a result of growing exhausted carbon monoxide and fixed carbon loss. The range of secondary air, over which combustion efficiency increases, widens at higher operating temperature.

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KEYWORDS
Staged Combustion, Fluidized Bed, Biomass

INTRODUCTION

Utilization of biomass waste in energy production is a promising option since biomass is a renewable and CO_2 neutral fuel. Utilization of biomass fuel preserves the diminishing conventional fossil fuels and alleviates the growing waste disposal problem [1-8].

Fluidized bed combustion (FBC) is widely considered for burning different biomass fuels. In FBC, NO_x emissions originate mainly from the fuel nitrogen. Oxygen plays a major role in most of intermediate reactions involving in formation and reduction of NO_x. Accordingly, O_2 concentration, particularly in the lower zone, has an important impact on NO_x emissions. Air staging, therefore, is considered an effective technique to reduce NO_x emissions [9-13]. The species containing nitrogen during volatile releasing are not only sources of NO_x but may also act as reducing agents of NO_x. More of these reducing agents will be present at low O_2 concentration that enhances the reduction of NO_x. With a correct design and operation of fluidized bed combustors, it is possible to direct the volatiles acts as reducing agent more than with conventional operation [9]. This latter may be more visible in the case of biomass burning that has a high volatile content (greater than 60%) and a considerable portion of combustion processes completes in freeboard.

The concept of staged combustion consisting of injecting secondary air downstream of a first staged combustion zone that will change its characteristics. With air staging, not only the environment composition of the first zone will be changed but also the hydrodynamic characteristics, in particular, fluidization velocity and bubble sizes. The aim of the present work is to investigate the impacts of air staging on combustion performance of rice straw in a fluidized bed. The combustion performance is characterized in terms of: i) axial profiles of temperature and species concentration; ii) NO_x and SO_2 emissions; iii) combustible losses and combustion efficiency.

EXPERIMENTAL

Apparatus

The apparatus used for the present work is an atmospheric bubbling fluidized bed combustor. Figure 1 shows a schematic of the apparatus. A detailed description of the apparatus can be found elsewhere [14,15]. The combustor is a cylindrical column of 300-mm inner diameter and 3300 mm height.

A nozzle type plate is used to distribute the primary air at bottom of the combustor. The air serves in fluidizing bed materials and burning fuel.

The column is implemented with 21 portals to insert probes for measuring purposes. The fluidized bed section contains a heat exchanger system consists of three radial movable pipes, where, bed temperature can be controlled by adjusting the pipes penetration lengths into the bed, and accordingly heat removal rate.

The combustor is equipped with a continuous over-bed fuel pellets feeding system using a paddle shaft. The shaft is driven by a variable speed electric motor. Downstream the feeder, the pellets move by gravity through an inclined pipe flanged with the combustor at 1500 mm above the air distributor. The pipe has 152 mm ID and it is inclined 60° with horizon. Secondary air is also introduced through this latter pipe. A hopper to feed bed sand particles is located on the top of the column.

Flue gases coming out from the fluidization column pass through a cyclone to separate and to collect the entrained particulates. Column parts are all insulated using blankets of thermal wool.

Radial and axial temperatures profiles of the combustor are measured using type K thermocouples. The flue gas concentrations are carried out using GA-40 plus gas analyzer, which is able to measure O_2, CO_2, CO, SO_2 and NO_x concentrations.

Materials

Silica sand with a narrow size distribution (0.25-0.5 mm) has been used as bed material. Its experimental minimum fluidization velocity is 5.6 cm/s at 850 °C, typical operating temperature of fluidized bed.

Rice straw is reproduced to be suitable for handling and feeding, more details are found elsewhere [9]. Rice straw is prepared as pellets of cylindrical shape. The pellet is of 12 mm diameter and 10 mm length. The average bulk density of pellets is about 0.73 g/cm^3 whereas the initial bulk of raw rice straw is about 0.05 g/cm^3. The proximate and ultimate analysis of rice straw are reports in Table 1.a. The analysis of rice straw ash is also given in table 1.b.

RESULTS AND DISCUSSION

A series of experimental tests has been performed to investigate air-staging effects on the combustion performance of rice straw in a fluidized bed. The experiments have been carried out under steady state conditions. The static bed height was fixed at 30 cm and excess air factor was kept at 1.2, considering total air, for all tests. Ratio of secondary air to total air was varied from 0 to 40% while maintaining the total air rate constant. The fluidization velocities were chosen high enough to ensure a good fluidized bed (u/u_{mf}>5).

Combustion behavior was good in all tests. As the rice straw has a high volatile content, a considerable part of combustion took place in freeboard. This behavior was recognized by direct observation inside the combustor through a glass window. It is also confirmed by axial temperature profiles inside the combustor where the peak temperature occurred in the freeboard. The concentrations of different species have been measured along the freeboard and at the stack, as well. The measurements have been performed at different radial positions to have an average value over the cross section. The collected materials in cyclone were analyzed to assess the elutriated fixed carbon. Saving analysis of bed materials doesn't demonstrate agglomerating or sintering.

Axial Profiles of Temperature and Species Concentration

Figure 2 shows the axial temperature profiles inside the combustor for conventional and staged operation at different secondary air ratios. The bed temperature was kept nearly constant by varying the cooling load of the in bed-tubes. In all cases, the bed zone has fairly uniform temperature due to intensive mixing of bed material. On the other side, there is a temperature rise in freeboard, evidently, due to post combustion. Actually, because of the high volatile content of rice straw, a considerable portion of combustion is completed in freeboard. The degree of post combustion in freeboard depends on the ratio of secondary air.

As shown in figure 2 the temperature profile and the peak value vary with secondary air ratio. With conventional operation (no secondary air) the temperature gradually increases with height due to post combustion reaching a maximum value, and then, it steadily decreases due to heat transfer through walls. On the other side, with staged operation (a portion of air is introduced as a secondary air) the temperature profiles become different and have two distinct parts. In the freeboard zone under secondary air entrance, the temperature becomes lower compared with conventional operation. This result should be mainly ascribed to the shortage of oxygen as shown in Fig. 3. In fact, due to the lack of oxygen, a higher quantity of CO is produced (see Fig. 4), and consequently, the heat released reduces in the lower zone. Conversely, the gas temperature develops into higher in the freeboard zone above the secondary air entrance. Evidently, a significant quantity of heat releases due to combustion of carbon monoxide to CO_2 thanks to the oxygen associated with secondary air. Figure 4 demonstrates the high reduction rate of CO at the secondary air entrance (1500 mm above the distributor), mainly due to conversion and partially due to dilution. These consequences are in accordance with Fig. 5 where CO_2 concentration rapidly grows at the secondary air entrance after a sudden drop owing to dilution effect. The latter trends caused by introducing secondary air become more pronounced with increasing its ratio. At secondary air entrance, the gas temperature doesn't record a significant increment and it may also yield a slight drop. This finding is reasonable since the secondary air is un-preheated and requires energy to reach the combustor temperature.

Nitric Oxides

The effectiveness of staged combustion as a technique for NO_x reduction has been studied. Figure 6 shows the impact of staged combustion on axial profile of NO_x concentration (as measured dry ppm) in freeboard. However, direct comparison on the figure isn't easily noticeable because of dilution effect in the first stage with changing secondary air ratio. Alternatively, in figure 7, NO is plotted in terms of emission index (NO_x moles/kg fuel) that is independent of the dilution effect. As shown in the figures NO_x emission greatly reduces along the combustor height. It appears that NO_x rapidly reaches a peak due oxidization of fuel nitrogen then it reduces with height due to chemical destruction of NO_x, most likely by char, NH_3, and CO [16,17]. The reduction of NO_x is evident with staged operation, in particular, at higher value of secondary air ratio. With staged operation, less air is fed through the distributor resulting in a lower O_2 concentration and creating more reducing conditions in the bottom zone. Under these conditions the formation rate of NO decreases and the peak has a lower NO_x concentration. Moreover, at lower O_2 concentration, the reducing agents, such as NH_3, CO, char will have more concentrations that enhance NO reduction as well. On the other side, from a dynamic point of view, introducing lower air in the bottom zone decreases fluidization velocity and reduces bubbles sizes. Consequently, gas residence time increases and mass transfer processes improve inside the bed. Those later consequences should result in a further enhancement of NO reduction.

Figure 8 illustrates the influence of secondary air ratio on the NO_x concentration in exhausted gases for different bed temperatures. Evidently, the NO_x emission with staged combustion is considerably lower than that measured with conventional operation. As shown in the figure, NO_x reduction increases with increasing secondary ratio. The figure also indicates that the staged operation becomes more effective in reducing NO_x at higher bed operating temperature. It appears that the shortage of oxygen and reducing conditions created with staged operation counteract the consequences of rising bed operating temperature. NO_x is reduced by about 28, 39 and 50% at bed temperature of 750, 800, 850 °C, respectively, when 30% of the combustion air is introduced in the freeboard.

Sulfur Dioxide

SO_2 concentration was measured and reported in figure 9. It is noted that the reported values of SO_2 emission is less than the theoretical concentration that would correspond to the total sulfur content of fuel. The theoretical SO_2 concentration is about 900 ppm under the considered conditions. This major reduction in SO_2 concentration confirms the occurrence what is known sulfur self-retention. Actually, fuel sulfur is partly retained by mineral matters found in fuel ash acting as a sorbent. The sulfur retention efficiency is calculated and it ranges 35-55% based on the values reported in Fig. 9.

Figure 9 also shows the effect of bed temperature on the SO_2 emission. The emission decreases with temperature until a minimum and then it grows again. This implies that sulfur self-retention improves with temperature, reaching an optimum at about 800 °C, since reactivity increases with temperature. Further increasing in bed temperature leads to a drop in sulfur retention that is attributed to the decomposition of CaSO4 at higher temperatures [18, 19].

The impact of staged operation on the SO_2 emission is also cared about and presented in figure 9. The obtained results indicate that the effect of air staging on the SO_2 emission is not straightforward. At the lowest considered secondary air ratio, 10%, SO_2 emission somewhat reduces that may be attributed to the hydrodynamic effect of staged operation where residence time becomes longer and bubble size becomes smaller. Those latter are favored sulfur self-retention processes. Rising secondary air ratio to 20% or more yields an increase in SO_2 emission. At this end the reducing condition created by staged operation starts to have the major role and favors $CaSO_4$ decomposition that exceeds the beneficial of hydrodynamic effect [18].

Combustible Losses

CO concentration in exhaust gases has been measured and reported in figure 10. The figure shows the influence of staged operation on CO concentration for different operating bed temperatures. CO concentration steadily increases with increasing secondary air ratio. It appears that the combustor height above the secondary air entrance is not sufficient to ensure intimate mixing and complete burning, in particular, when secondary air is not well distributed over the combustor cross section. The higher bed temperature is beneficial in reducing CO emissions, in particular, at greater secondary air ratio (see Fig. 10).

Figure 11 shows the fixed carbon loss as a function of secondary air ratio and bed temperature. The reported fixed carbon loss is calculated as a ratio between the rate of elutriated fixed carbon to the rate of fed fixed carbon. The figure indicates that fixed carbon loss reduces with staged operation in the lower range of secondary air ratio. With staged operation the fluidization velocity decreases because a portion of air is introduced in the freeboard. Consequently, char comminution (attrition and fragmentation) lessens as the bed becomes less turbulent. Moreover, a lower percentage of particulates with terminal velocities less than the fluidization velocity will be entrained out of the bed. In the higher range, increasing secondary air ratio has insignificant effect or even a negative impact on the fixed carbon loss. Under these conditions the rate of char burning decreases due to the lower concentration of oxygen, and consequently, the char concentration in the bed grows to be higher. Consequently, the rate of char comminution increases producing higher percentage of elutriable particulates. Moreover, the char concentration in the bed boosts up at lower bed temperature as reactivity of char combustion reduces. This outcome is demonstrated in Fig. 11 where the fixed carbon loss reaches a minimum value earlier in the case of the lowest considered temperature compared with the higher ones.

Figure 11 also shows that rising bed temperature significantly reduces the fixed carbon loss. As discussed above, the reactivity of char combustion increases with rising bed temperature that results in lower char concentration in the bed. And consequently, the comminution and entrainment rate of char fines becomes lower.

Combustion Efficiency

Combustion efficiency is calculated on an energy basis assuming that the fuel hydrogen is completely burned. It is mathematically determined according to the following expression.

$$\eta = \frac{E_i - E_l}{E_i} \qquad (1)$$

where E_i is the energy rate of fed fuel which is given as

$$E_i = M_F (HV)_F \qquad (2)$$

where M_F is the fuel feeding rate and $(HV)_F$ is the fuel heat value.

E_l is the energy loss rate in the exhausted combustibles that include both of fixed carbon and carbon monoxide that is calculated as:

$$E_l = M_{CO}(12/28)(HV)_{CO} + M_{cl}(HV)_C \qquad (3)$$

where M_{CO} is the mass rate of carbon monoxide in flue gases, $(HV)_{CO}$ is the heat value of carbon monoxide when burned to carbon dioxide , M_{cl} is the mass rate of elutriated fixed carbon and $(HV)_C$ is the heat value of carbon when completely burned to carbon dioxide

The combustion efficiency is shown in Fig. 12 as a function of secondary air ratio and bed temperature. Combustion efficiency increases with staged operation in the lower range of secondary air ratio. The gain in combustion efficiency is mainly attributed to the reduction in fixed carbon loss. Combustion efficiency reaches a maximum, and then it reduces with further increase in secondary air ratio. This latter is due to the higher concentration of CO and a slight increase in fixed carbon loss in the higher range of secondary air ratio (see Fig.s 10 and 12). The combustion efficiency can be maximized by overcoming the above drawbacks. CO concentration may be reduced by introducing secondary air uniformly over the cross-section and by increasing the combustor height above the entrance section. The collected particulates can be recirculated back to combustor or fed to a carbon burn-up cell, which is operated at a higher temperature and a lower fluidization velocity.

The positive effect of bed temperature on combustion efficiency is evident in figure 12 as combustion efficiency is greater at higher temperature. Moreover, at higher temperature, the combustion efficiency improves over a wider range of secondary air ratio.

CONCLUSIONS

In the course of the present work the effects of air staging on the combustion performance of rice straw has been investigated. The combustion performance is characterized by axial profiles of temperature and species concentrations, NO_x and SO_2 emissions, combustible losses and combustion efficiency. The obtained results lead to the following conclusions:

- Applying staged operation intensifies the post combustion in freeboard, increases the peak temperature and displaces up the hotter zone. CO concentration multiplies in the lower zone with increasing secondary air ratio.
- The results demonstrate that staged operation is as an effective method to reduce the NO_x emission, in particular, at higher operating temperature. The created reducing conditions decelerate the formation rate of NO_x from fuel nitrogen and promote production of reducing species like CO that enhance reduction of NO_x to

N_2. NO_x emissions significantly reduce with increasing secondary air ratio.

- The effect of air staging on SO_2 isn't straightforward. SO_2 slightly reduces in lower range of secondary air ratio that is attributed to hydrodynamic behavior, specifically, decreasing fluidization velocity and bubble sizes. On the other side, it slightly increases in higher range of secondary air ratio due to the impact of reducing conditions.
- Combustion efficiency improves with staged operation in the lower range of secondary air ratio mainly due to the reduction in fixed carbon loss. However, combustion efficiency decreases after a maximum as a result of increasing fixed carbon loss and carbon monoxide. Rising bed temperature increases the combustion efficiency and widens the range of secondary air ratio over which combustion efficiency improves.

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Table 1.a. Analysis of rice straw

Proximate Analysis (as received)	
Moisture, %	8.9
Volatile matter, %	63.13
Fixed carbon, %	18.1
Ash, %	9.87
Ultimate Analysis (dry basis)	
Carbon, %	42.04
Hydrogen, %	6.26
Nitrogen, %	1.23
Sulphur, %	0.64
Oxygen, %	39
Ash	10.83
Pellet density, kg/m^3	0.9
Lower calorific value, kJ/kg	19441

Table 1.b. Analysis of rice straw ash

Analysis of rice straw ash, %										
CaO	K_2O	Na_2O	SiO_2	Al_2O_3	FeO	TiO_2	MnO	MgO	BaO	P_2O_5
9.23	38.92	2.16	44.72	1.13	0.14	0.03	0.04	1.96	0.04	P_2O_5

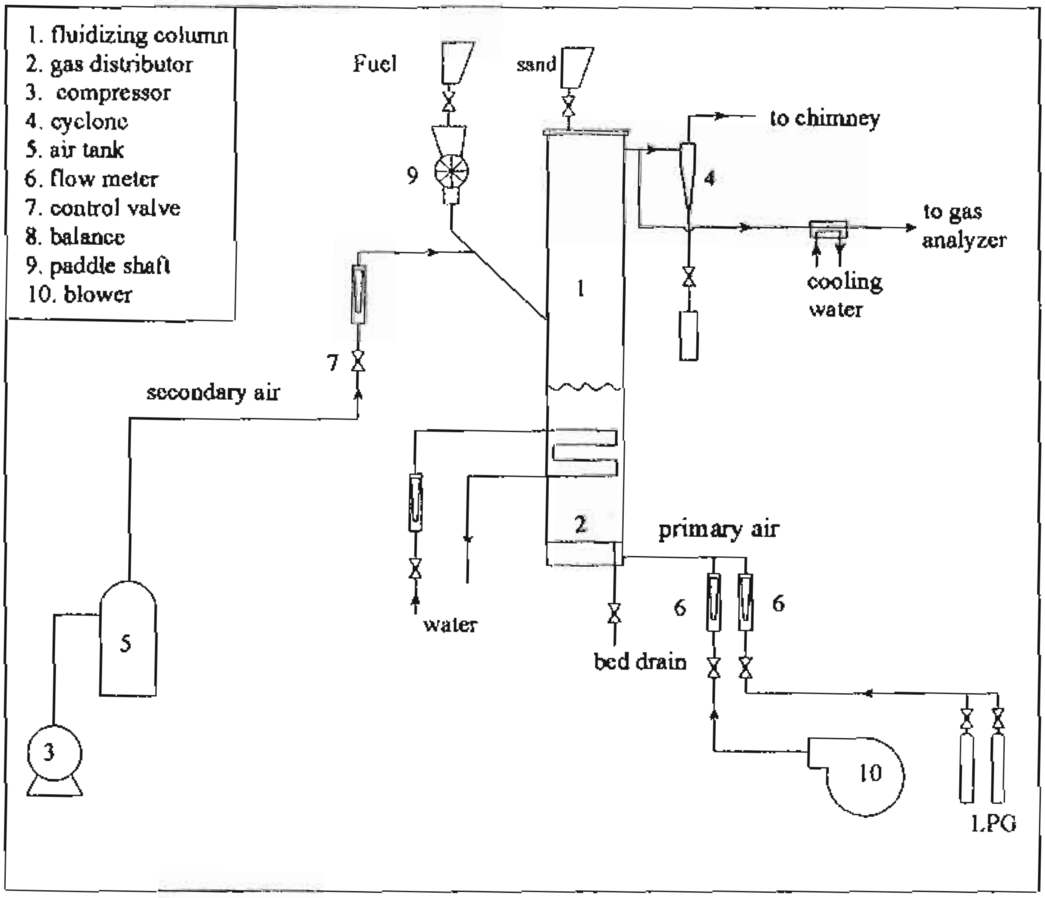

Figure 1. Schematic of the experimental apparatus

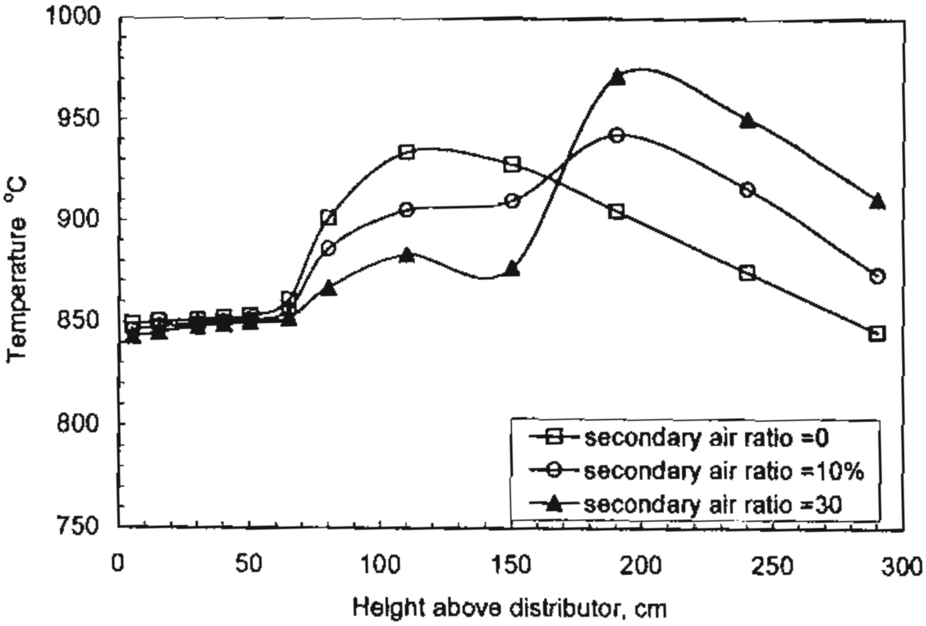

Figure 2. Influence of secondary air ratio on axial temperature profile

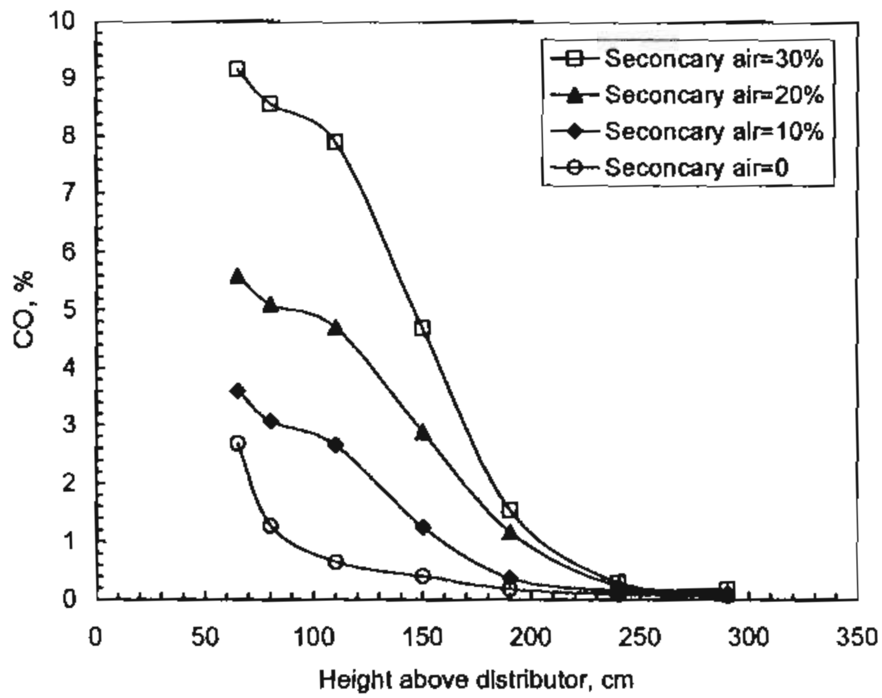

Figure 3. Effect of secondary air ratio on axial profile of CO

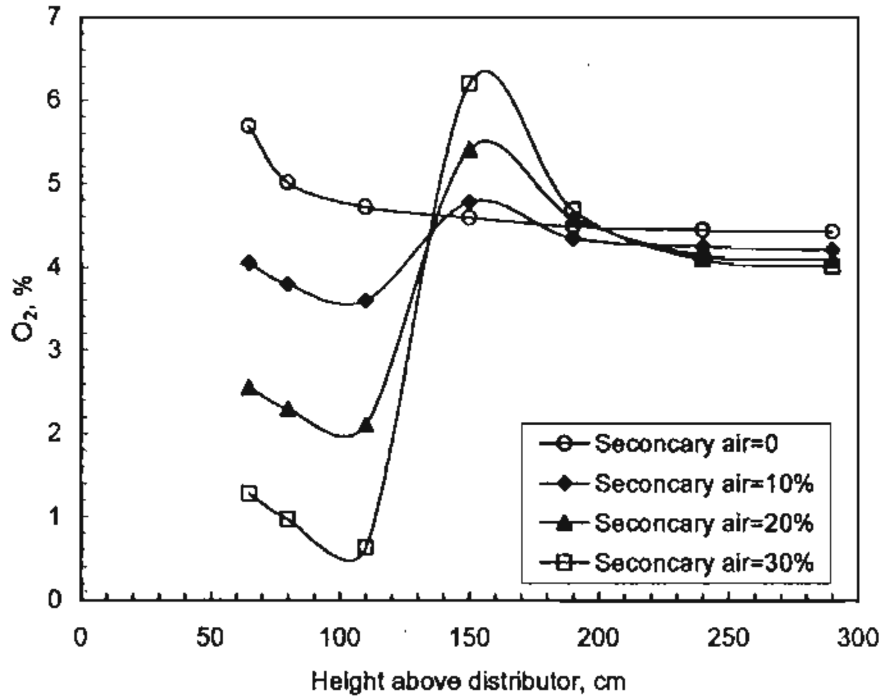

Figure 4. Effect of secondary air ratio on axial profile of O_2

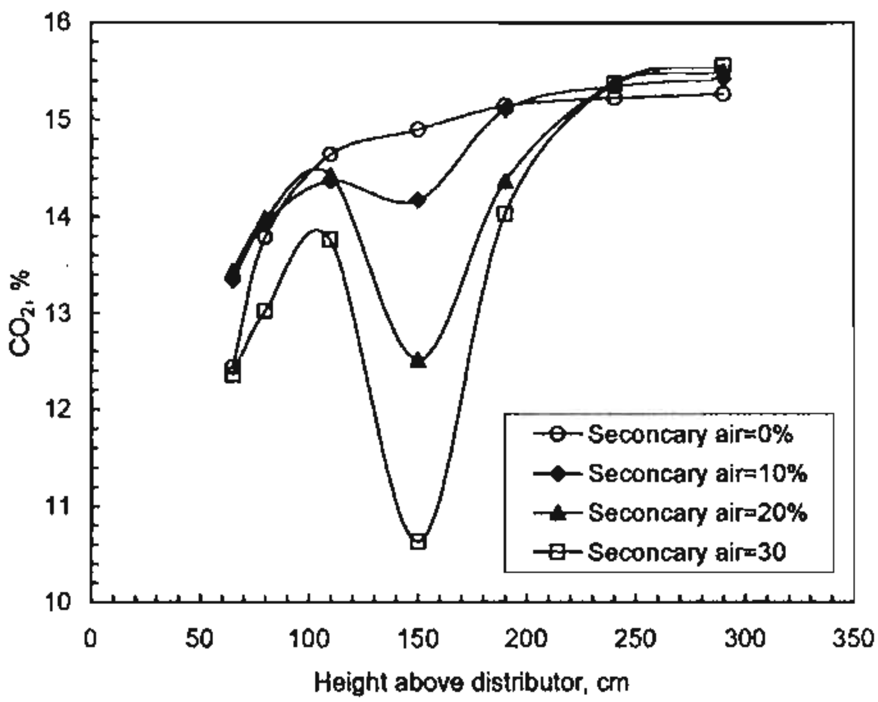

Figure 5. Effect of secondary air ratio on axial profile of CO_2

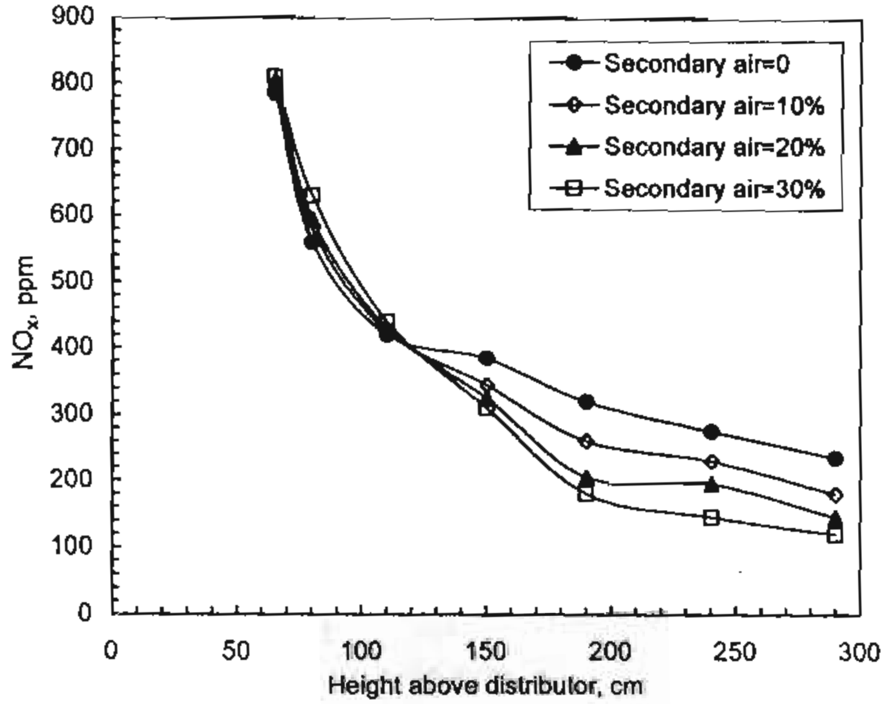

Figure 6. Effect of secondary air ratio on axial profile of NO_x

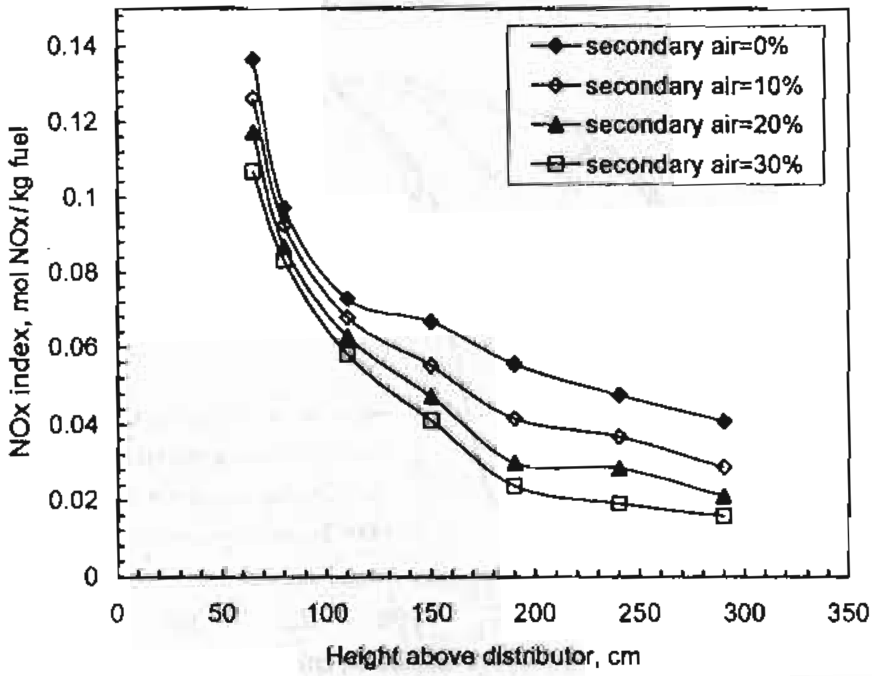

Figure 7. Effect of secondary air ratio on axial profile of NO_x

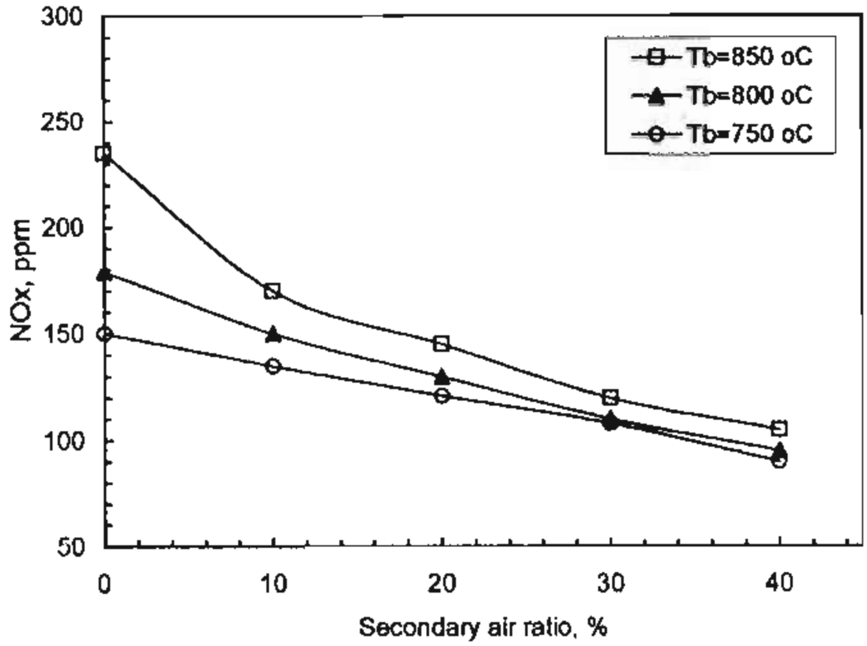

Figure 8. Effect of secondary air ratio on exhausted NOx at different operating temperature

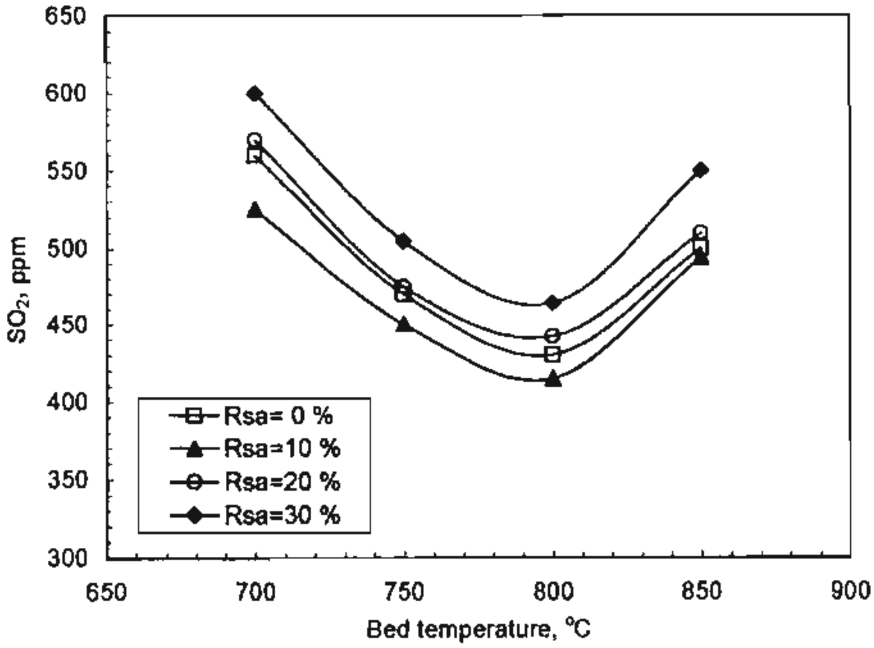

Figure 9. Exhausted SO_2 as a function of bed temperature and secondary air ratio

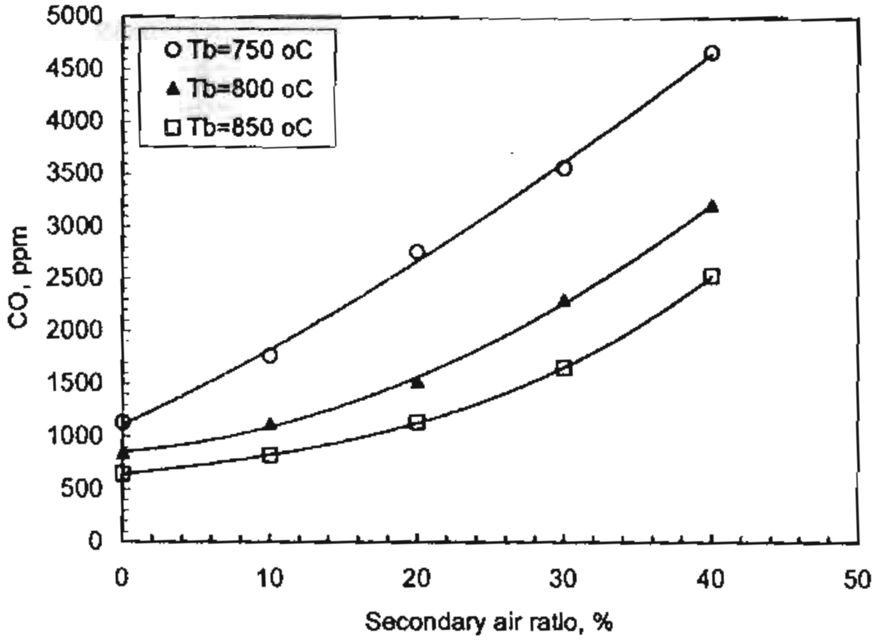

Figure 10. Effect of secondary air ratio on exhausted CO at different operating temperature

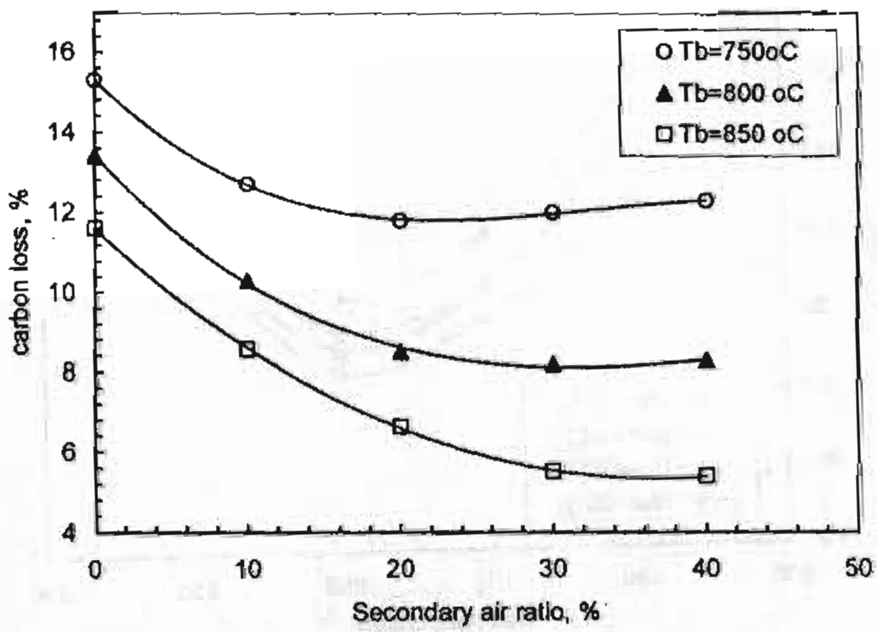

Figure 11. Effect of secondary air ratio on fixed carbon loss at different operating temperature

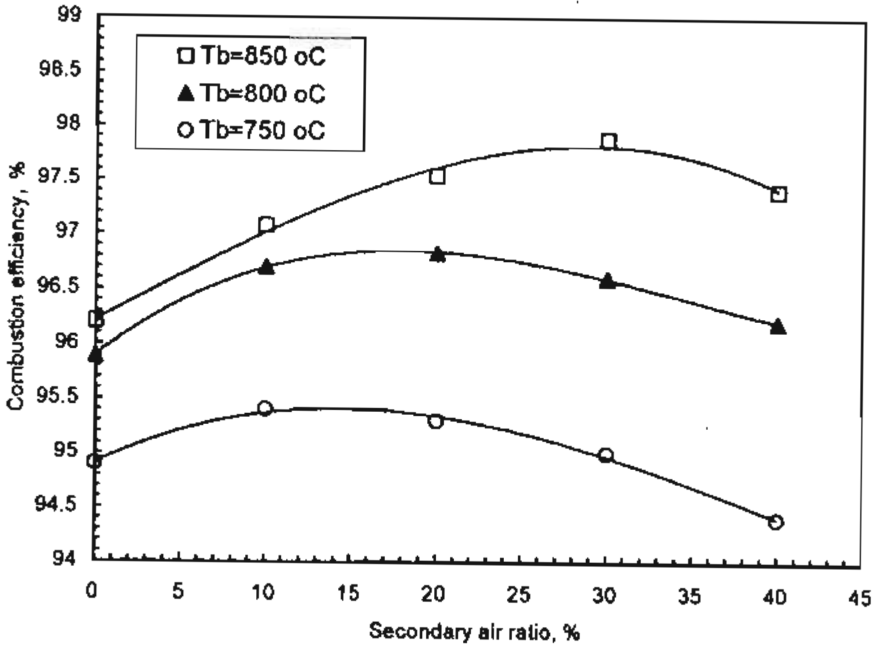

Figure 12. Effect of secondary air ratio on combustion efficiency at different operating temperature