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Fluidized Bed Combustion of an Agriculture Waste Case Study: Combustion of Rice Straw.

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FLUIDIZED BED COMBUSTION OF AN AGRICULTURE WASTE CASE STUDY : COMBUSTION OF RICE STRAW

حرق المخلفات الزراعية في فرن ذي مهد مميع

دراسة حالة قش الأرز

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ملخص البحث

توجد في مصر وفرة من المخلفات الزراعية والتي مازالت لها اثار سلبية على البيئة، وبصفة خاصة قش الأرز. ويمكن تلاشى أضرار هذه المخلفات بتوظيفها كأحد مصادر الطاقة المتجددة ، وهذا البحث يركز على دراسة خصائص احتراق قش الأرز في الفرن ذي المهد المميع والذي يعد أحد أفضل البدائل الواعدة لحرق المخلفات الحيوية و استعادة طاقاتها.

ونظرا لأن قش الأرز منخفض الكثافة وغير منتظم الشكل فقد تم تجهيز عينات لاستخدامها كوقود يسهل تغذيته إلى داخل الفرن، وذلك باستخدام وحدة بسيطة أعدت خصيصا لذلك. وعينات الوقود التي تم تجهيزها عبارة عن قطع صغيرة من قش الأرز اسطوانة الشكل قطرها ١٢ مم وطولها حوالي ١٠ مم وكثافتها حوالي ٠،٧٣ جم/سم^{٣}.

وقد أجريت سلسلة من التجارب لدراسة خصائص احتراق قش الأرز باستخدام فرن ذي مهد مميع قطره الداخلي ٣٠٠ مم وارتفاعه حوالى ٣٣٠٠ مم وكذلك دراسة تأثير عوامل التشغيل المختلفة عليها. وفى أثناء التجارب تم ملاحظة سلاسة الأداء من حيث تغذية الوقود ومستوى تميع حبيبات الوسط أو تكتلها كنتيجة لوصولها درجة حرارة التلدن أو نتيجة لانصهار رماد الوقود، كذلك تم رصد ومشاهدة اللهب داخل الفرن بالعين مباشرة من خلال نظارة زجاجية.

وقد تناولت الدراسة بالشرح والتحليل تأثير عوامل التشغيل المختلفة على كفاءة الاحتراق، والإنبعاثات المختلفة، كما تم أيضا رسم منحنيات توزيع درجات الحرارة في كلا الاتجاهين القطري والمحوري داخل الفرن. شملت عوامل التشغيل كل من سرعة التميع، وارتفاع المهد المميع، ودرجة حرارة المهد المميع ، ونسبة الهواء إلى الوقود .وتفيد النتائج التي تم التوصل إليها إلى أن عملية حرق قش الأرز في فرن ذي مهد مميع تتم بكفاءة في حدود ٩٨%وان نسب تركيز أول اكسيد الكربون و اكاسيد النتروجين في حدود من ٢٠٠- ٣٣٠ جزئ في المليون ومن ١٧٥-٢٧٠ جزئ فى المليون ، على الترتيب.

ABSTRACT

In Egypt there is abundance of agriculture byproducts and residues that is still provoking environmental problems, in particular, rice straw. Utilizing of biomass for energy production alleviates the growing waste disposal problems and preserves the diminishing conventional fossil fuels. The present work is dedicated to investigate the combustion characteristics of rice straw in a fluidized bed.

Rice straw has been prepared as pellets of diameter 12mm and length 10 mm by virtue of chopping and compression processes. The rice straw pellets have been burnt in an atmospheric bubbling fluidized furnace of diameter 300 mm and height 3300 mm. The experiments have been carried out under steady state conditions and by means of over-bed fuel feeding system.

Experimental results demonstrate that combustion of rice straw in fluidized bed is successful with high efficiency. Post-combustion of volatile over bed is evidence that results in a peak temperature in freeboard. The peak temperature degree and location are sensitive to the operating parameters, especially fluidization velocity and excess air. CO and NO_x level are relatively low ranging from 200 to 330 ppm and 175 to 270 ppm respectively. The obtained results show that at high level of the studied operating parameters (fluidization velocity, bed height, bed temperature and excess air), NOx emission increases with different degrees.

KEYWORDS

Combustion, Fluidized Bed, Biomass

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INTRODUCTION

The worldwide greenhouse issue, the protocol of Kyoto, the more stringent environmental regulations and the limited resources of fossil fuels guide toward growing utilization of renewable resources of energy. From this point of view, Biomass is expected to be one of the most important in the near future. Biomass is a renewable energy that is a CO_2 neutral fuel. Biomass, in all its forms, provides about 7% of the world annual energy consumption. In developing countries, it provides 35% of all the energy requirements [1- 3].

Fluidized bed combustion (FBC) is widely considered for burning different biomass fuels. The fluidized bed is a layer of inert material (like silica sand) that is being fluidized using air delivered through the bed via a distributor plate found at the furnace floor. The operation temperature is so low that all NOx emissions are generated from fuel nitrogen while the thermal contribution NOx is insignificant. The thermal inertia of the fluidized bed is large, which stabilizes and maintains combustion and allows very fuel flexible operation. In particular, the tolerance for fuel moisture variation clearly exceeds other combustion technologies. The advantages of the bubbling fluidized bed boilers may be summarized as: high boiler efficiency, high availability, excellent fuel flexibility, fast dynamic behavior, low maintenance costs, low auxiliary power consumption, low emissions and minimum operating personnel requirement [4-7].

In Egypt there is abundance of agriculture byproducts and residues that is still provoking environmental problems because most of them are burnt haphazardly without energy recovery. This performance is multiplying greenhouse effect due to adding emissions and heat to atmosphere. Alternatively, many of agriculture wastes can be utilized as a biomass fuel realizing two fundamental goals. Utilizing of biomass fuel preserves the diminishing conventional fossil fuels and alleviates the growing waste disposal problem. Another remarkable asset is its comparatively low impact on the environment. According to the Agriculture Engineering Researches Institute, the annual potential of agriculture wastes in Egypt is about 22.5 million ton [8]. About 35% of them are utilized as animal feeding and fertilizer and 65% are available for energy production which is 7 million ton oil equivalent (TOE)

Because rice straw represents the worst environment issue of agriculture wastes in Egypt, the current study is devoted to investigate combustion of rice straw in fluidized bed. The main objectives of this experimental work are:

- Preparation of rice straw in a form adequate for feeding and combustion.
- Assessment of the combustor behavior with regard to fuel feeding, fluidization, sintering and burnout.
- Measurement of the temperatures and gaseous concentrations at different points in the combustor.
- Evaluation of the influence of operation parameters on different emissions and combustion efficiency.

Special attention is given to the role of the freeboard in the combustion process by determining axial profiles of temperature.

EXPERIMENTAL

Test Rig

The experimental test rig used for the present work is an atmospheric bubbling fluidized bed. Figure 1 shows a schematic of the test rig. A detailed description of the test rig can be found elsewhere [9]. 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. By virtue of this system, 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 variable speed electric motor. Downstream the feeder, the pellets move to the combustor by gravity. A hopper to feed bed sand particles is located on the top of the combustor 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.

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 bed temperature.

Fuel Preparation and Characteristics

As receiving conditions, rice straw has a very low bulk density and relatively long and irregular shape. Because of these characteristics rice straw has very low energy content per unit volume and it is difficult to handle. Moreover, it has high transportation and storage cost. So, it is important to convert rice straw into a product of regular shape and of higher bulk density through the Briquetting process.

For the present work, a simple unit has been installed to densify rice straw. The unit should be piston type briquetting that mainly consists of a hydraulic press, pistons and different dies. The unit produces biomass fuel pellets in cylindrical form.

At first, rice straw has been chopped to about 3 cm length. The chopped rice straw is undergone pressure of 300 bar inside the die. The final product is rice sraw pellets of cylindrical shape. The pellet is of 12 mm diameter and about of 10 mm length. The 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. Figure 2 is a photograph of some briquette rice straw prepared by the unit. The proximate and ultimate analysis of rice straw are reported in Table 1

Test Procedure and Operating Parameters

After charging a quantity of sand corresponding to the required bed height, sufficient air premixed with LPG is delivered through the distributor to fluidize bed material. The bed is initially heated by burning LPG. At 650 °C the rice straw pellets are fed into the bed multiplying the rise rate of bed temperature. Flow rate is then adjusted at predetermined value. The bed temperature is controlled by adjusting the penetration length of heat exchanger tube inside the bed. When the desired temperature is attained feeding of LPG is stopped and the fuel feeding is totally switched to rice straw pellets. After the unit stabilizes at the prefixed steady state conditions, different measurements are carried out.

The influences of the most important operating parameters have been studied. Static bed height has been varied between 20 cm to 40 cm. Bed temperature has been ranged between 700 °C to 900 °C. To have good mixing of bed material with moderate bubble size, fluidization velocity range is chosen to be 0.3-0.7 m/s (about 5-10 time U_{mf}). Excess air range is 10%-30%.

RESULTS AND DISCUSSION

Performance of Operation

Steady state Experiments have been performed at different operating conditions. The feeding of the fuel pellets was usually successful, however, in few cases the system is blocked. This problem may be overcome by using a vibrating feeding system or by passing secondary air through the fuel-feeding pipe. During the combustion the fluidization behavior was normal and no problem has been encountered. Saving analysis of bed materials doesn't demonstrate agglomerating or sintering.

Direct observation showed the occurrence of the flame in the freeboard. This behavior is expected as rice straw has a high volatile content. A significant part of volatile escapes the bed to complete combustion in the freeboard. This characteristic of biomass fuel combustion has been recognized by different researchers [10-13]. The measurements of axial temperature confirm the existence of peak temperature in the freeboard. The peak temperature degree and position are varied according to the operating conditions. The collected materials in the cyclone were found relatively small.

Temperature Profiles

Temperature distribution in axial direction has been measured at different operating conditions. The obtained profiles are plotted in figures 3-5. The temperature of the bed zone is nearly uniform, however, there is temperature rise in the freeboard above the expanded bed. In fact the temperature profiles reflect the occurrence of the post combustion in freeboard for all runs. A considerable part of volatile surpasses the bed without combustion because of short residence time and lack mixing with oxygen. The position of intensive combustion zone in freeboard moves according to the operating conditions.

The influence of fluidization velocity on axial temperature profile is plotted in figure 3. The temperatures of the bed and splashing zones are more uniform at higher fluidization velocity due to the higher rigorous mixing of bed particles. However, the freeboard temperature becomes higher with fluidization velocity increase and flue gases leave the combustor at higher temperature as well. It is obvious that increasing fluidization velocity enlarges the volatile combustion in freeboard zone and shifts the peak temperature up along the combustor height. These results should be ascribed to the shorter gas residence time in the bed. It is the average time period that a unit volume of gas remains in the bed and is defined as the ratio of the expanded bed height to the fluidization velocity.

Figure 4 shows the influence of bed height on the axial temperature profile. The freeboard temperature becomes higher while decreasing the bed height. Further the peak temperature moves down. The profiles indicate that more heat is released in freeboard due to post-combustion. With decreasing bed height, the gas residence time becomes shorter and more volatiles bypass the bed without combustion. On the other side, decreasing the bed height reduces the heat transfer to the cooling tubes inside the bed.

To study the effect of excess air maintaining fluidization velocity nearly constant, the fuel flow rate is varied while holding the airflow rate constant. In Figure 5, the axial temperature profile is presented as a function of excess air factor. It is noticed that with increasing the excess air factor the peak temperature moves down while the temperature of gases leaving the freeboard reduces. Increasing excess air implies that the oxygen available for reaction becomes greater and the rate of combustion reaction becomes higher. At excess air factor 1.3, the combustion rate is the highest. Under these conditions, the majority of combustibles burn inside the bed. The combustion of escaping volatiles takes place in freeboard zone close to the bed. This is evident as the peak temperature is being adjacent to the bed. At excess air factor 1.2 the available oxygen decreases and reaction rate decelerates. Consequently, the amount of combustibles that burns inside the bed lessens while the peak temperature becomes higher. The same trend and justification may be referred to when decreasing excess air to 1.1. It is worth noting that the temperature profile ends higher for lower excess air factor. Under the condition of lower excess air, the reaction rate is slower. Accordingly, the flame stretches and the combustion process continues releasing significant heat along the combustor height.

Gaseous Emissions

From environmental point of view, it is important to determine different emissions issuing from the combustion process. Keeping the emissions under the recommended national limits becomes mandatory. Measurements of CO and NOx have been reported at different operation conditions.

Carbon monoxide

The influences of operating parameters on the carbon monoxide concentration in flue gases have been plotted in figures (6-9). CO concentration is found to be reduced with decreasing fluidization velocity, increasing bed height, increasing bed temperature and increasing excess air factor. Excess air factor has the highest impact on CO whereas the bed height has the lowest effect.

Figure 6 presents the influence of fluidization velocity on CO concentration. The concentration of CO increases with fluidization velocity. At the lower range of fluidization velocity, up to 0.5 m/s, The measured CO concentration is in the range (175-240 ppm) and the increment is low. However, at higher range of fluidization velocity, the increment multiplies resulting in relatively high concentration of CO in flue gases. This trend of results should be attributed to the residence time effect on combustion processes. The residence time either in bed or in freeboard becomes longer at lower values of fluidization velocity. Hence CO and O_2 have prolonged time for diffusion, mixing and reaction to produce carbon dioxide. Further, lower fluidization velocity produces smaller bubbles which have slower rising velocity. These consequences enhance mass transfer between bubble and emulsion phases improving combustion processes. At lower fluidization velocity almost all CO converts to CO_2 inside the combustor.

The influence of bed height on CO concentration is plotted in figure 7. As shown in the figure CO concentration slightly reduces with bed height increase. Increasing bed height improves slightly the combustion process due to the longer residence time inside the bed.

In figure 8, CO concentration is presented as a function of the bed temperature. It is obvious that increasing the bed temperature improves the combustion process and reduces the carbon monoxide. The reduction is significant at lower part of temperature range. For higher bed temperature more than 850 °C, the reduction of CO becomes insignificant. It is well known that the temperature rise increases the rate of chemical reaction. Moreover, diffusion of gases somewhat enhances with temperature rise. These may be the reasons of CO reduction with bed temperature rising.

Figure 9 illustrates the influence of excess air factor on carbon monoxide concentration. The figure shows that reducing excess air factor less than 1.2 has high impact on the combustion process where high level of CO escapes the combustor. At excess air factor 1.1 the carbon monoxide concentration records about 1550 ppm. On the other side increasing excess air factor more than 1.25 does not lead to further considerable reduction in CO concentration.

Nitrogen Oxides, NOx

Oxides of nitrogen from biomass fluidized bed combustion originate almost exclusively from fuel bound nitrogen. Once the volatiles are released, the nitrogen amine fragments ($-NH_2$) either oxidize to NO or are stripped of the hydrogen atoms and form N_2. The percentage oxidized is a function of the combustion environment, with volatile nitrogen conversion to NO ranging from 8% to 40% depending upon combustion technology and combustion conditions [14].

Measurements of NO_x emission in flue gases have been carried out and presented against the operating parameters in figures 6-9. The NO_x level is relatively low ranging from 175 to 270 ppm. The figures indicate that at high level of the studied operating parameters (fluidization velocity, bed height, bed temperature and excess air), NO_x emission rises with different degrees. It appears that the concentrations of NO_x have converse trend comparing to CO concentrations (except in the case of fluidization velocity). In other words, the conditions that improve the combustion process results in higher level of NO_x concentration. It is likely that carbon monoxide reduces NO to elemental nitrogen via the following mechanism [15,16]:

$$2CO + 2NO \rightarrow 2CO_2 + N_2$$

Moreover, under the conditions that intensify the combustion process the concentration of carbon char in the bed lessens. Consequently, the rate of reduction of NO_x by carbon char decreases via the following process [15,16].

$$2C + 2NO \rightarrow 2CO + N_2$$

In figure 6, higher fluidization velocity results in rising CO concentration that should ameliorate NO_x reduction, however, NO_x emission increases slightly with fluidization velocity. The results seem to have some contradiction. The contradiction can be elucidated when considering the role of gas residence time. At higher fluidization velocity, gases have shorter residence time inside the combustor. Thus NO_x have shorter time for reduction process. The obtained result is the sum of these two counteracting consequences.

Excess air has been found to have the highest impact on NO_x emission Variation of excess air has two reinforced combined effects. Increasing the excess air multiplies the formation of NO_x due to high level of available oxygen. Moreover, the combustion process enhances and the reduction of NOx via the two mechanism mentioned above decelerates.

Fixed Carbon Loss

The particulates elutriated by flue gases have been collected using a cyclone. The collected materials have been weighed and analyzed. The obtained data have been shown in figures 10 where the carbon loss ratio is plotted against operating parameters. The carbon losses ratio is calculated as the ratio between the rate of collected carbon in cyclone to the feed rate of fuel fixed carbon.

Fluidization velocity has the highest impact on the carbon loss, see figure 10a. When fluidization velocity increases the drag force increases and coarser particulates can be entrained with flue gases.

Figures 10b-10d demonstrate that the carbon loss slightly reduces with increasing bed height, bed temperature and excess air. As discussed above, the high levels of these operating parameters intensify the combustion process. Accordingly, the concentration of chars lessens in the bed. Moreover, entrained char fines have smaller size by virtue of higher combustion rate.

Combustion Efficiency

An important objective of this investigation is to assess the conditions under which rice straw could be burned efficiently in fluidized bed. 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.

$$\eta = \frac{M_F(HV)_F - M_{CO}(12/28)(HV)_{CO \rightarrow CO2} - M_{el}(HV)_{C \rightarrow CO2}}{M_F(HV)_F}$$

Where M_F is the feeding rate of fuel. $(HV)_F$ is the heat value of fuel. M_{CO} is the mass rate of carbon monoxide in flue gases. $(HV)_{CO \rightarrow CO2}$ is the heat value of carbon monoxide when burned to carbon dioxide , M_{el} is the mass rate of elutriated fixed carbon and $(HV)_{C \rightarrow CO2}$ is the heat value of carbon when completely burned to carbon dioxide

Influences of operating parameters on calculated combustion efficiency have been illustrated in figures 11. Among the studied parameters fluidization velocity has the greatest impact on combustion efficiency. The drop in combustion efficiency at higher fluidization velocity is mainly attributed to increasing carbon loss within the elutriated char and partially to carbon monoxide, see figures 6 and 10a. Combustion efficiency improves with increasing bed height, bed temperature and excess air, as shown in figures 11b-11d. Increasing these parameters results in reducing carbon monoxide and carbon losses as illustrated in figures (7-9) and (10b-10d), respectively.

CONCLUSIONS

Rice straw has been successfully burned in a bubbling fluidized bed. Fuel feeding, fluidization behaviour and combustion processes are stisfactory. Based on the obtained experimental results the following conclusions may be drawn:

- A simple technique has been utilized to convert rice straw into form of pellets which is suitable for feeding and burning. The pellets have a bulk density, at least, 10 times more compared to its primary state.
- A considerable amount of heat is released in the freeboard zone due to the post-combustion of volatiles. The peak temperature occurs in the freeboard zone. Its degree and location are dependent on operating conditions.
- Burning of rice straw has been realized with combustion efficiency above 96% over a wide range of operating conditions. Combustion efficiency is found to be improved with increasing bed height, bed temperature and excess air.
- Fluidization velocity has a negative impact on carbon loss and combustion efficiency.
- The NOx level is relatively low ranging from 175 to 270 ppm. The studied operating parameters (fluidization velocity, bed height, bed temperature and excess air) somewhat promote NOx emission.

NOMENCLATURE

EA	excess air factor
Hbs	static bed height, (m)
Tb	bed temperature, (K)
u	fluidization velocity, (m/s)
U_{mf}	minim um fluidizition velocity, (m/s)

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Table 1. Analysis results 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
Lower calorific value, kJ/kg	19441

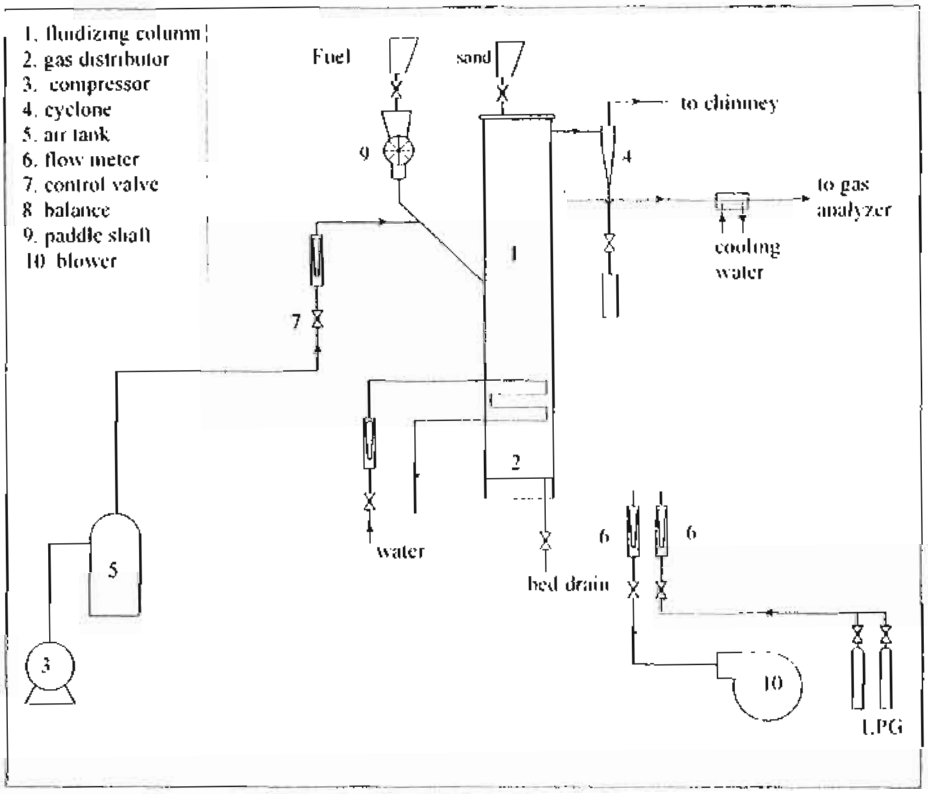


Figure 1. Schematic of test rig

Figure 2. A photograph of rice straw pellets

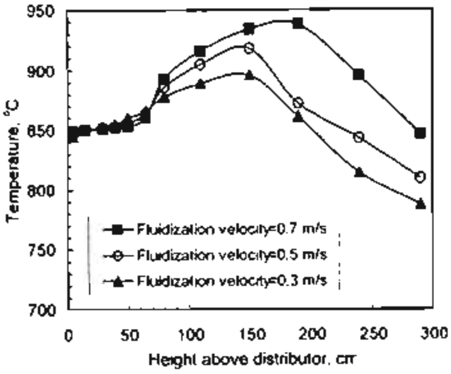


Figure 3. Influence of fluidization velocity on axial temperature profile (Hbs=30 cm & EA=1.2)

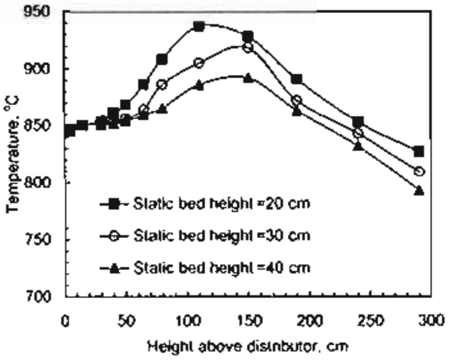


Figure 4. Influence of bed height on axial temperature profile (u=0.5 m/s, Tb=850 °C & EA=1.2)

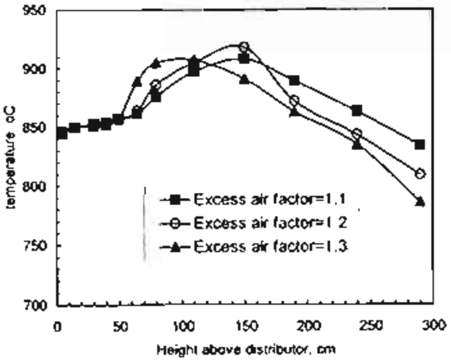


Figure 5. Influence of excess air on axial temperature profile (u=0.5 m/s, Hbs=30 cm &Tb=850 °C)

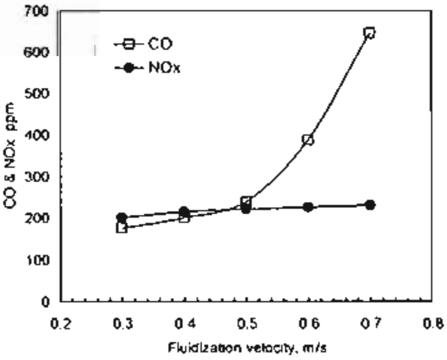


Figure 6. Influence of Fluidization velocity on CO and NO_x emissions. (Hbs=30 cm, Tb= 850 °C & EA=1.2)

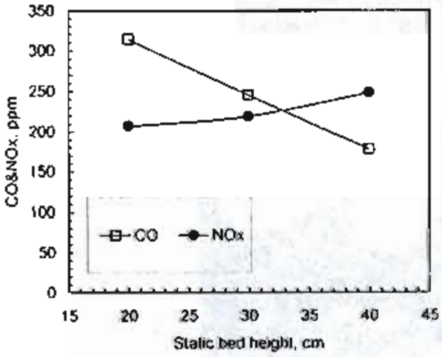


Figure 7. Influence of static bed height on CO and NO_x emissions. (u=0.5 m/s, Tb= 850 °C and EA=1.2)

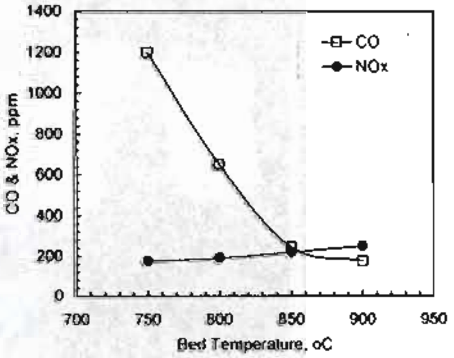


Figure 8. Influence of bed temperature on CO and NO_x emissions. (u=0.5 m/s, Hbs= 30 cm & EA=1.2)

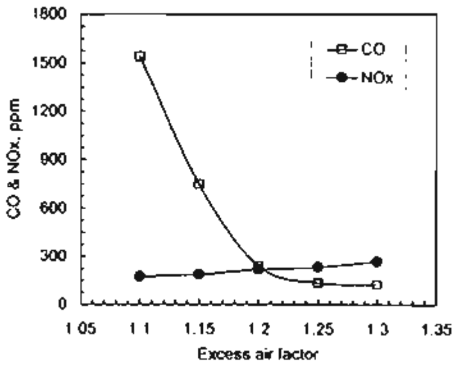


Figure 9. Influence of excess air on CO and NO_x emissions.

(u=0.5 m/s, Hbs= 30 cm & Tb= 850 °C)

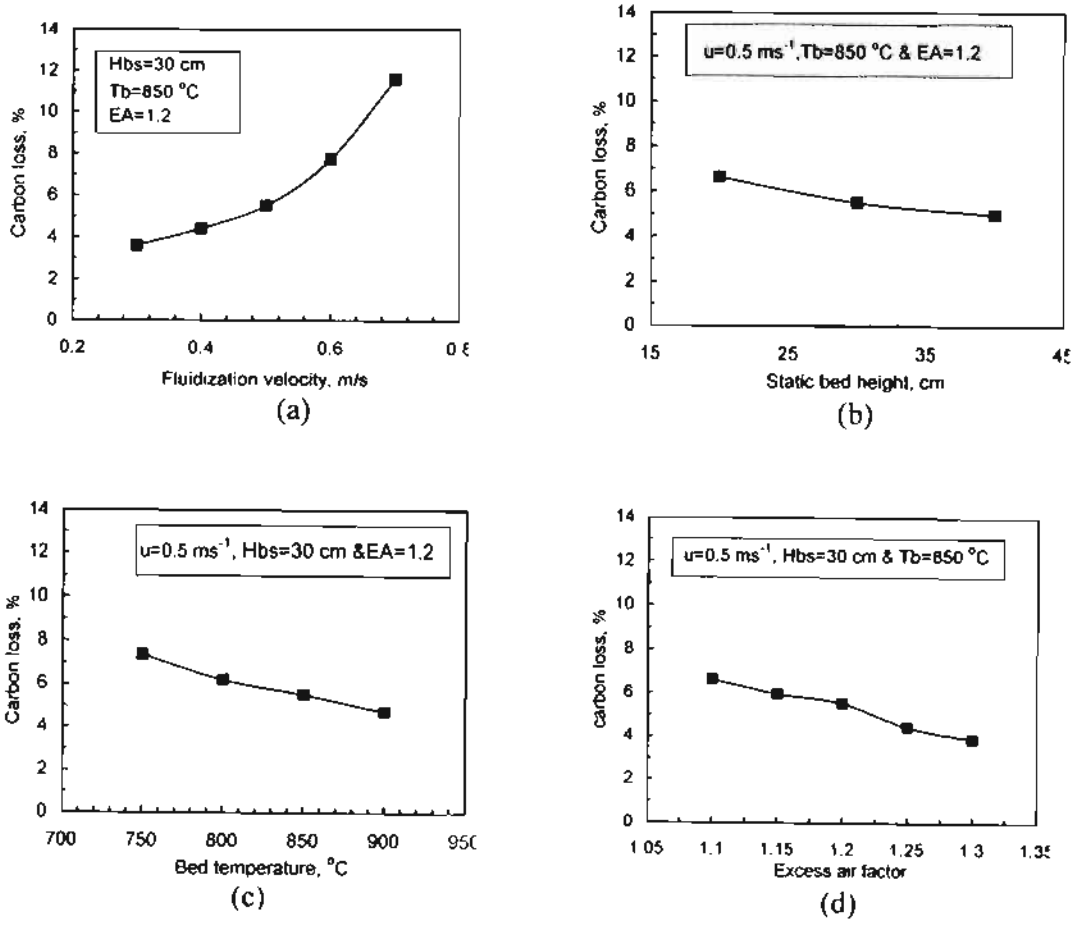
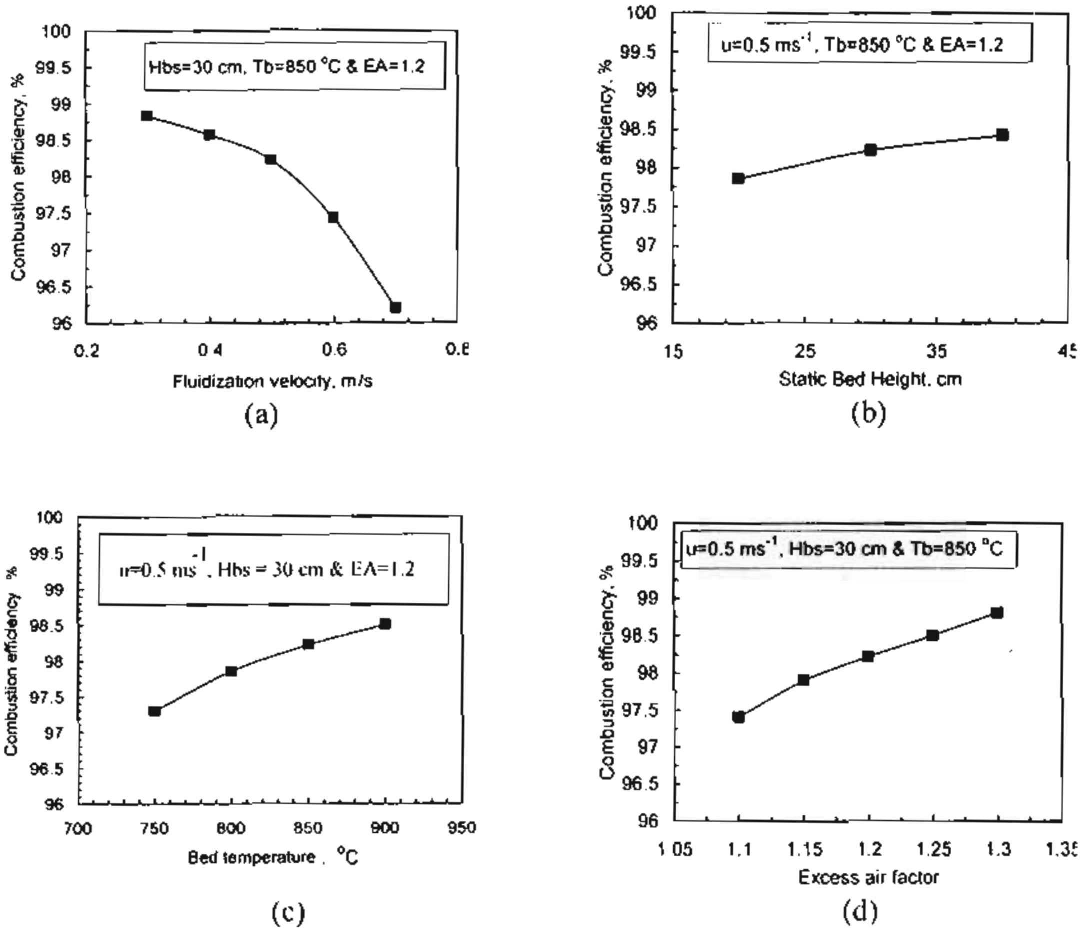


Figure 10. Influence of operating parameters on carbon loss



(a) (b)

(c) (d)

Figure 11. Influence of operating parameters on combustion efficiency