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# Co-firing of Rice Straw and Natural Gas in Fluidized Bed Furnace

# الحرق المشترك لقش الأرز والغاز الطبيعى في فرن ذى مهد مميع

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## الملخص:

هذا البحث يقدم دراسة عملية للاحتراق المشترك لقش الأرز والغاز الطبيعى فى فرن ذى مهد مميع. تم تصميم الفرن المستخدم بحيث يتيح أسلوب تشغيل مبتكر للمهد المميع بالإضافة إلى الأسلوب التقليدى. الفرن أسطوانى الشكل قطره الداخلى ٣٠٠ مم وإرتفاع ٣٣٠٠ مم ، ومزود بأنبوب نفاث عند محورالفرن قطره الداخلى ٣٨,١ مم. فى حالة إستخدام المهد ذو النافث النافورى (النظام المبتكر) يتم إمرار وقود الغاز الطبيعى مختلطا بالهواء اللازم لحرقه من خلال الأنبوب النفاث مما يؤدى إلى إنتاج منفوث جاهز للإشتعال، بينما يمرر الهواء اللازم لحرق قش الأرز من خلال موزع الهواء أسفل المهد. بينما فى حالة التشغيل بنظام المهد التقليدى فيتم خلط الغاز الطبيعى مع الهواء اللازم لحرق كل من قش الأرز والوقود الغازى من خلال موزع الهواء. وفى كلا النظامين يتم تغذية قش الأرز على شكل كريات صغيرة الحجم أعلى المهد بارتفاع قدره ١٥٠٠ مم.

وقد أوضحت النتائج التى تم التوصل إليها إلى أن إستخدام المهد ذو النافث النافورى يحقق أداءا أفضل من حيث أن عملية الحرق المشترك لقش الأرز والغاز الطبيعى تتم بأسلوب سلس وتعمل على تجنب حدوث إحتراق إنفجارى لمحتوى الفقاعات كما هو الحال فى حالة المهد التقليدى.

كما أوضحت النتائج أنه عند تشغيل الفرن بنظام المهد ذى النافث النافورى تنخفض درجات الحرارة فى المنطقة الحرة أعلى المهد حيث تقوم حبيبات النافث النافوى باكتساب جزء كبير من الحرارة الناتجة من اللهب المحيط بها وتعمل على نقلها إلى المهد. وقد تم التحقق من ذلك من خلال قياس حمل التبريد داخل المهد والذى زادت قيمته بنسبة كبيرة مقارنة بنظيره فى حالة المهد التقليدى. كما أوضحت النتائج أيضا إنخفاض نسب تركيز الإنبعاثات المختلفة والتى تشمل كلا من أول أكسيد الكربون، وأكاسيد النيتروجين وثانى أكسيد الكبريت، كما نقص معدل الكربون الثابت المفقود، مما أدى إلى إرتفاع ملحوظ فى كفاءة الاحتراق، وذلك عند تشغيل الفرن بأسلوب المهد ذى النافث النافورى.

وقد أوضحت النتائج أيضا أن زيادة درجة الحرارة المهد له تأثير إيجابى من حيث تحسين كفاءة الاحتراق والحد من إنبعاث أول أكسيد الكربون، وفى تقليل معدل فقد الكربون الثابت. بينما كان التأثير سلبيا على إنبعاث أكاسيد النيتروجين اذ أدى الى زيادته. من ناحية أخرى وجد أن هناك درجة حرارة معينة للمهد ينخفض عندها إنبعاث ثانى أكسيد الكبريت.

## Abstract

Experimental study on co-cofiring of rice straw and natural gas has been performed in a fluidized bed. The used combustor allows the novel, jetting-fountain configuration and the conventional operation as well. The experimental apparatus is mainly a bubbling fluidized bed of 300 mm ID and 3300 mm height equipped with a 38.1 mm ID jet-pipe located at the combustor center. In jetting-fountain configuration, natural gas premixed with the air required for its combustion proceeds through the jet pipe to create jet-fountain zone. Whereas only the air required for rice straw combustion passes through a gas distributor.

The findings of the experiments confirm that smooth combustion of natural gas with rice straw can be performed in the jetting-fountain fluidized bed. This avoids acoustic effects and explosions of burning bubbles that occurs in conventional operation.

The performance of the combustor has been found much better when operates at the jetting-fountain configuration. Temperature measurements in the freeboard demonstrate that the jetting-fountain fluidized bed dampens greatly the freeboard overheating. The fountain-particles absorb a great part of heat released in freeboard and recover it back to the bed. The later hypothesis is confirmed by measuring the in-bed cooling load that was found considerably increase, in particular, at lower bed temperature.

There is also a considerable reduction in different emissions including carbon monoxide, nitric oxides and sulfur dioxide. The fixed carbon loss reduces as well. Combustion efficiency records higher values with jetting-fountain configuration.

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Increasing bed temperature is beneficial for reducing carbon monoxide, decreasing fixed carbon loss and improving combustion efficiency. Existence of an optimum bed temperature for sulfur retention has been confirmed. As normal, nitric oxides has been found increases with bed temperature.

**Keywords:** Fluidized Bed Co-firing, Jet, Gaseous Fuels, Biomass.

# 1. Introduction

Biomass is recognized as a potential energy resource to mitigate emission greenhouse gases [1, 2]. Utilization of biomass energy at large scale could contribute to sustainable development on different fronts including, environmental, social, and economical [3]. Biomass is renewable and nearly $CO_2$ neutral fuel when managed in a sustainable manner [1, 4]. Moreover, using biomass for energy production assists to solve the waste disposal problem and avoid landfilling materials that ultimately decompose forming both $CO_2$ and methane, more harmful greenhouse gas [5]. Nowadays biomass contributes about 10 to 15% of total world energy demand [3, 6].

Co-firing with fossil fuels promotes the use of biomass and provides one alternative to achieve emission reductions. Among the other renewable energy options, co-firing is the lowest risk, least expensive and most efficient [7]. The addition of biomass to a coal-fired boiler has no or slightly impact on the overall generation efficiency of a coal fired power plant [8]. Co-firing of biomass and coal has been subjected to intensive studies that used essentially every major type of biomass (herbaceous, woody, animal wastes, and anthropomorphic wastes) combined with different rank of coal [9, 10, 11]. Contribution of biomass mainly reduces $CO_2$ emissions. Further, Co-firing of biomass with fossil fuels provides means to reduce $SO_2$, and it may also reduce NOx emissions [10, 11].

Open burning of rice straw is a serious problem in Egypt where smoke cloud is easily detected during the harvest season. Burning of rice straw in the field releases pollutants that contribute to greenhouse gases without energy gain. Utilization of rice straw and rice husk in energy production is a promising option. Combustion of rice by-products in fluidized bed has been carried out in different works [12, 13]. Many other works have successfully performed on co-firing with coal [14, 15] or bitumen [16,17].

In this work co-firing of rice straw and natural gas in fluidized bed has been investigated. However, the combustion of gaseous fuels in fluidized beds is characterized by acoustic effects and explosion risk [18]. Post-combustion of gaseous fuels in the freeboard is significant, in particular, at lower bed temperatures [18,19,20]. Post-combustion has been also found important in combustion of biomass [21] and liquid fuels [22-24]. In this respect, the ejected bed particles in splashing zone play an important role as they absorb and recover a part of the heat released in the freeboard back to the bed. These particles also act as a heat sink that contributes to controlling the freeboard temperature [17]. Moreover, other studies indicated that the contact between gas and solids is very poor in the main bed while it is very good in the splashing zone [25].

To avoid the shortcomings discussed above, a novel fluidized-bed configuration of fluidized bed developed by Okasha [26,27] has been applied for the present study. The novel configuration, namely jetting-fountain fluidized bed, is characterized by excellent gas-solids contact. This feature is, thanks to creating a jet in upper part of bed, establishing a fountain in the freeboard and moderating bubbles size in the main bed. Jetting-fountain configuration enables gaseous fuels to burn smoothly similar to a normal premixed flame avoiding acoustic effects and explosions risk. It enables a rapid reliable method for initial heating of fluidized bed reactor. The jetting-fountain configuration reduces considerably the power consumed in feeding gases to the combustor.

## 2. Experimental

### *2.1. Apparatus and technique*

A bubbling fluidized-bed combustor has been modified to adopt the jetting-fountain configuration as shown in Fig. 1. It consists of fluidization column of 300 mm ID and 3300 mm height. A nozzle-type plate is used to distribute the gases at the bottom of the fluidization column. These gases serve in fluidizing bed materials. A stainless steel tube of 38.1 mm ID is used to feed jet-gases vertically upward. It passes through the center lines of the plenum chamber and the gas distributor plate to the centerline of the fluidization column. The tube is designed to be movable in the vertical direction in order to adjust the location of the jet outlet regarding the bed surface.

In conventional operation all air pre-mixed with natural gas is delivered through the gas distributor. In jetting-fountain configuration, on the other hand, natural gas premixed with the air required to its combustion proceeds through the jet pipe to create jet-fountain zone. Whereas only the air required for rice straw combustion passes through the gas distributor, see Fig. 2.

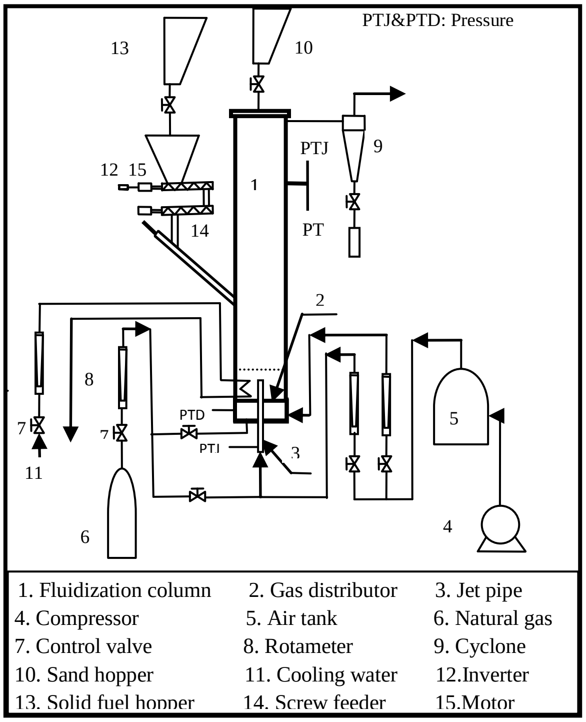

Fig.1 Bubbling fluidized bed combustor adopting jet-fountain configuration

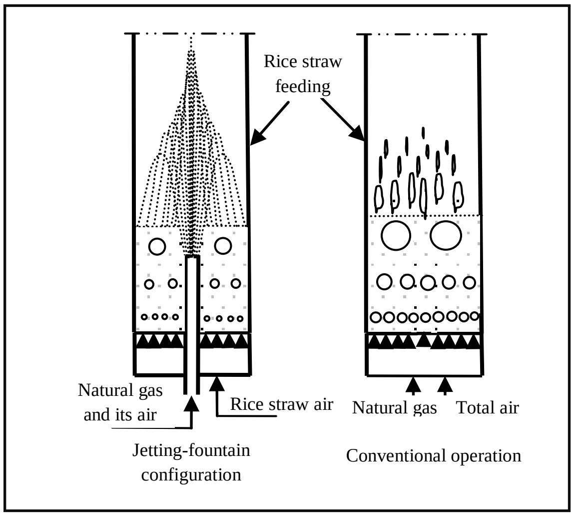

Fig. 2 Methods of feeding gases and rice straw pellets

The combustor is equipped with a continuous over-bed fuel feeding system using a screw feeder consists of two stages, the first screw which conveys the fuel pellets from the hopper into the second screw is calibrated and driven by a variable speed electric motor. The second screw feeder is used to drive the fuel pellets to an inclined pipe flanged with the combustor at 1500 mm above the air distributor.

The combustor also contains a heat exchanger system consisting of three horizontal movable pipes. By virtue of this system, bed temperature can be controlled by adjusting the pipes penetration lengths into the bed. In-bed cooling load can be determined by measuring the inlet and outlet temperatures in addition to the water flow rate.

The column is implemented with 21 portals to insert probes for measuring purposes. It is also furnished with two eyeglasses to enable visualizing the freeboard of fluidization column. Two taps, PTD are used to measure the pressure drop from the plenum to the freeboard. Two additional taps, PTJ, are used to measure the pressure drop from the jet pipe entrance to the freeboard. PTD and PTJ taps in the freeboard are located at 240 cm above the distributor.

Jetting-fountain configuration enables a rapid and reliable method for initial heating of fluidized bed reactor. Gaseous fuel partially premixed with air is fed through the jet pipe. The remaining part of air is fed through the distributor plate to fluidize bed solids. When the bed reaches a preset temperature the operating parameters are regulated to predetermined values of a designed test. In particular, the bed temperature is regulated by adjusting penetration lengths of the heat exchanger pipes inside the bed. When the unit stabilizes at the preset temperature, different measurements are carried out.

Temperatures have been measured in bed using various thermocouples of type K at heights of 50, 150, 300, 400, 500, 650, 800, 1100, 1500, 1900, 2400 and 2900 mm above the distributor. Measurements of gases concentrations and temperature in the freeboard have been carried out using LANCOM III gas analyzer, which is able to indicate $O_2$, $CO_2$, CO, $SO_2$ and $NO_x$ concentrations as well as gas temperature.

### *2.2. Materials*

Silica sand of (0.5-0.8 mm) range size and (2650 kg/m$^3$) density has been used as bed material. Rice straw in the pellet form is used. The pellets are of a 12 mm diameter and 10–15 mm lengths. The average bulk density of the pellets is about 0.73 g/cm$^3$. Proximate and ultimate analyses of rice straw are reported in Table 1a. Analysis of rice straw ash is also given in Table 1b. The chemical analysis of used natural gas is reported in Table 2.

**Table 1a Analysis of rice straw**

| **Proximate analysis (as received.)** | % |
|---|---|
| Moisture, % | 8.94 |
| Fixed carbon, % | 18.2 |
| Volatile, % | 62.98 |
| Ash, % | 9.88 |
| **Ultimate analysis (dry basis)** | |
| Carbon, % | 42.16 |
| Hydrogen, % | 6.24 |
| Nitrogen, % | 0.79 |
| Sulphur, % | 0.64 |
| Chlorine, % | 0.09 |
| Ash, % | 10.9 |
| Oxygen, % | 39.18 |
| Low heating value, MJ/kg (as received) | 14.1 |

**Table 1b Analysis of rice straw ash**

| **Rice Straw Ash Analysis, %** | | | | | |
|---|---|---|---|---|---|
| CaO | $K_2O$ | $Na_2O$ | $SiO_2$ | $P_2O_5$ | FeO |
| 9.23 | 38.92 | 2.16 | 44.72 | 1.63 | 0.14 |
| $TiO_2$ | MnO | MgO | BaO | $Al_2O_3$ | |
| 0.03 | 0.04 | 1.96 | 0.04 | 1.13 | |

**Table 2 Analysis of natural gas**

| $N_2$+$O_2$ | $CH_4$ | $CO_2$ | $C_2H_6$ | $C_3H_8$ |
|---|---|---|---|---|
| 0.211 | 92.19 | 0.718 | 3.962 | 1.143 |
| ISO-C4H10 | N-$C_4H_{10}$ | ISO-$C_5H_{12}$ | N-$C_5H_{12}$ | $C_6$+ |
| 0.602 | 0.383 | 0.336 | 0.178 | 0.277 |

# 3. Results and Discussion

A series of steady state experimental tests have been performed to investigate co-firing of rice straw and natural gas. It gives a comparison between the jetting-fountain configuration and the conventional operation. In conventional operation all air premixed with natural gas are fed through the gas distributor. On the other hand, in the jetting fountain fluidized bed, only air required for burning rice straw is fed through the distributor. While natural gas premixed with the air required to its combustion is fed via the jet pipe creating a large fountain zone in the freeboard. In this series of experiments, the blending ratio of the rice straw and natural gas is 50%:50% based on the thermal load.

In all tests the static bed height is fixed to 30 cm and excess air percent is kept around 20%. The calculated fluidization velocity and jet velocity for all tests are reported in Tables 3 and 4. The fluidization velocity is calculated at the corresponding bed temperature while the jet velocity is calculated at a mean value of the bed and the ambient temperatures.

**Table 3 Fluidization ($U_F$) and jet ($U_J$) velocities at different bed temperatures for conventional and jetting fountain configuration**

| Configuration | Conventional operation | | Jetting fountain configuration | |
|---|---|---|---|---|
| Bed Temp., °C | $U_F$ m/s | $U_J$ m/s | $U_F$ m/s | $U_J$ m/s |
| 700 | 1.41 | 0.0 | 0.59 | 33.4 |
| 800 | 1.55 | 0.0 | 0.64 | 36.1 |
| 850 | 1.62 | 0.0 | 0.68 | 37.4 |
| 900 | 1.70 | 0.0 | 0.71 | 38.7 |

**Table 4 Fluidization ($U_F$) and jet ($U_J$) velocities at different bed temperatures for different fuels blending ratios**

| Fuel Contribution | U m/s | Bed Temp.,°C | | | |
|---|---|---|---|---|---|
| | | 700 | 800 | 850 | 900 |
| RS 100%<br>NG 0% | $U_F$<br>$U_J$ | 1.17<br>0.0 | 1.29<br>0.0 | 1.35<br>0.0 | 1.41<br>0.0 |
| RS 75%<br>NG 25%$_J$ | $U_F$<br>$U_J$ | 0.88<br>16.7 | 0.97<br>18.0 | 1.01<br>18.7 | 1.05<br>19.3 |
| RS 50%<br>NG 50% | $U_F$<br>$U_J$ | 0.59<br>33.4 | 0.64<br>36.1 | 0.68<br>37.4 | 0.71<br>38.7 |
| RS 25%<br>NG 75% | $U_F$<br>$U_J$ | 0.29<br>50.2 | 0.32<br>54.1 | 0.34<br>56.1 | 0.35<br>58.0 |

Temperature distributions have been measured in the axial direction along the combustor height. These serve in assessing the overheating of the freeboard above the bed temperature. The in-bed cooling load is estimated by measuring the inlet and outlet temperatures of cooling water. The in-bed cooling load implies the amount of heat absorbed by bed material from gases.

Concentrations of different species have been measured at the combustor exit. Materials collected in cyclone were chemically analyzed to assess elutriated fixed carbon. Fixed carbon loss is calculated as a ratio between the rates of elutriated and fed fixed carbon. Combustion efficiency, $\eta_C$, is calculated on an energy basis assuming complete burning of hydrogen. It is mathematically determined according to the following expression:

$$\eta_c = (E_i - E_o)/E_i \qquad (1)$$

where $E_i$ is the energy content in fed fuel and $E_o$ is the energy content in exhausted combustibles including fixed carbon and carbon monoxide.

General observations have been noted during these tests. The conventional operation of the combustor is characterized by relatively high acoustic effects due to burning bubbles explosions. A relatively rigorous vibration of the combustor is recognized. Post-combustion in the freeboard is also observed. On the other hand, jetting-fountain configuration is characterized by smooth combustion, less vibration. A jet-fountain-flame zone was also observed.

### *3.1 Axial Temperature Profiles*

The axial temperature distributions for the jet-fountain configuration in comparison with the conventional operation at different bed temperatures are shown in Figs. 3-6. The horizontal and vertical dashed lines represent the static bed heights and the nominal bed temperatures, respectively. Fig. 3 indicates that operation with the conventional configuration at lower bed temperature (700 $^{o}$C) causes high overheating in the freeboard (about 168 $^{o}$C). This result is in agreement with the previous findings [18,19,21]. At lower bed temperatures natural gas mainly burns in the freeboard [18,19] while a great part of biomass volatiles escapes the bed to burn in the freeboard [21]. Alternatively, operation with the jetting-fountain configuration greatly dampens the freeboard overheating (about 48 $^{o}$C). Delivering natural gas premixed with air via the jet pipe creates a large fountain of particles that obviously absorb a great part of combustion heat released in freeboard and recover it back to the bed.

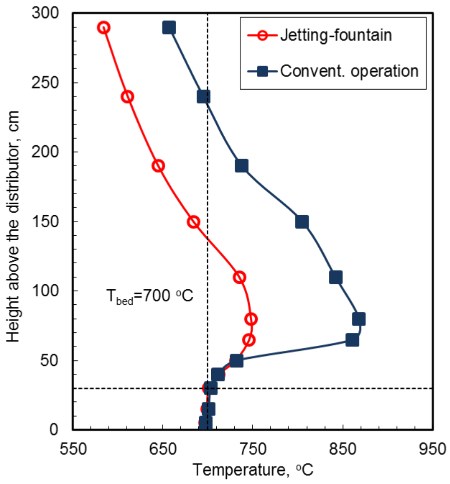

**Fig. 3** Axial temperature distribution ($T_b$=700 $^{o}$C).

Another factor that could play an important role in this respect is the fluidization velocity. In conventional operation, all air required for combustion in addition to natural gas are fed through the gas distributor. Therefore, the fluidization velocity is higher as reported in Table 3. The generated bubbles are, then, larger with higher velocities while the residence time of gases within the bed becomes smaller. All these consequences have negative impact on combustion processes within the bed. On the other hand, in the case of the jetting-fountain configuration, only the air required for rice straw combustion is fed through the gas distributor that results in lower fluidization velocity, see Table 3. Therefore the bubbles are smaller and slower. As residence time of gases becomes longer the combustion processes have a greater chance to be completed within the bed.

The same discussion is still valid for Figs. 4 and 5 that reports the results at 800 $^{o}$C and 850 $^{o}$C bed temperatures nevertheless the overheating becomes smaller. Obviously, greater part of gaseous fuel burns inside the bed with increasing its temperature. At bed temperature of 900 $^{o}$C the overheating is almost the same for the two configurations, see Fig. 6.

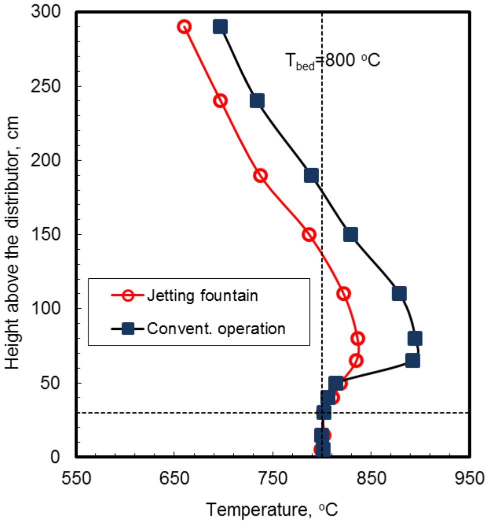

**Fig. 4** Axial temperature distribution ($T_b$=800 $^{o}$C).

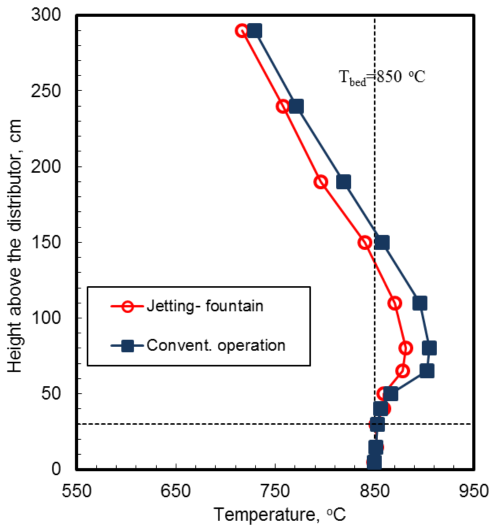

**Fig. 5** Axial temperature distribution ($T_b$=850 °C).

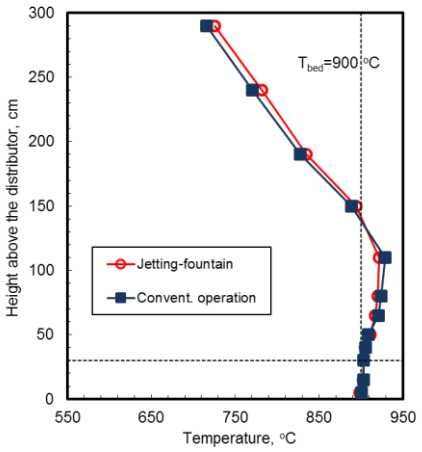

**Fig. 6** Axial temperature distribution ($T_b$=900 °C).

Figure 7 illustrates the maximum freeboard overheating of the jet- fountain configuration in comparison with the conventional as a function of bed temperature. The freeboard overheating is the difference between the maximum measured temperature in the freeboard and the bed temperature. The reported data confirm that the jetting-fountain configuration considerably dampens the overheating in freeboard, in particular, at lower bed temperatures. The figure also indicates that the overheating reduces with increasing the bed temperature. This is particularly for conventional operation where the combustion zone tends to move from the freeboard to the bed.

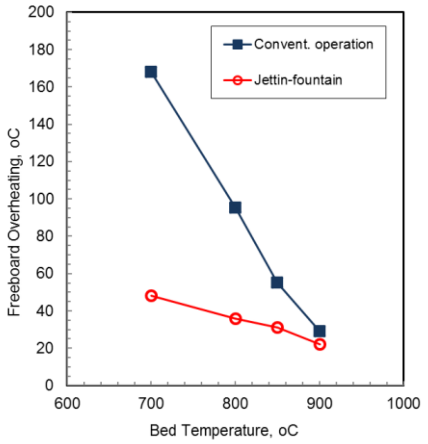

**Fig. 7** Freeboard overheating as a function of bed temperature.

### 3.2. Cooling Load

Figure 8 shows the in-bed cooling load as a function of bed temperature for the two configurations. The in-bed cooling load is estimated based on temperature rise and flow rate of cooling water**.** In general, jetting-fountain configuration exhibits greater amount of coaling load, in particular, at lower bed temperatures. It is

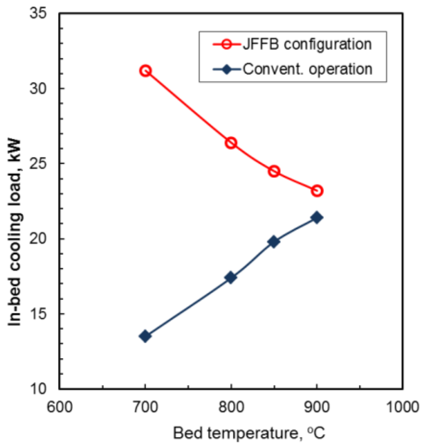

**Fig. 8** In-bed cooling load as a function of different bed temperature.

Obvious that the fountain-particles absorb a considerable part of released combustion heat in the freeboard and recover it back to the bed. With increasing bed temperature, the flue gases have higher enthalpy and heat transfer through the wall increases. Considering the same flow rates of the fuels, the in-bed cooling load reduces. Alternatively, in the case of conventional operation, in-bed cooling load multiplies with bed temperature as the combustion zone moves from the freeboard into the bed. Accordingly, bed particles absorb greater part of the heat released and transfer it to the cooling water.

### *3.3. Gaseous Emissions*

Sulfur dioxide emission as a function of bed temperature is shown in Fig. ٩. The figure is a comparison between convention operation and jetting-fountain configuration. It is noted that the reported values of $SO_2$ emission are less than the theoretical concentration that would correspond to the total sulfur content of the fed fuels. The theoretical $SO_2$ concentration is about 435 ppm under the considered conditions. Actually, sulfur is partly retained by mineral matters found in rice straw ashes, in particular, calcium and potassium oxides (see Table 1b). The sulfur retention efficiency is calculated based on the values reported in Fig. ٩. The sulfur retention efficiency ranges are 27–42% for jetting fountain configuration and 12-23% for conventional operation. The reduction in sulfur dioxide emission in the case of jetting-fountain configuration may be attributed to the hydrodynamic effect as the fluidization velocity is lower, see Table 3, residence time becomes longer and bubbles sizes become smaller. Those latter consequences favor sulfur self-retention processes [28]. Another factor could be important is the dilution effect. In conventional operation, all gases pass the bed that makes the concentration of $SO_2$ generated lower. Alternatively, in the jetting-fountain configuration, there are two distinct zones of combustion. The main bed and an outer part of the freeboard is a combustion zone for rice straw and its volatiles while the jetting-fountain zone in the inner part of the freeboard is the zone for natural gas combustion. As only the air required for rice straw combustion is delivered, the distributor when applying jetting fountain configuration. The concentration of $SO_2$ turns to be higher. It appears logical that the higher concentration of $SO_2$ accelerates the sulfur self-retention processes.

Figure 9 also shows the effect of bed temperature on the $SO_2$ emission. $SO_2$ concentration reduces with increasing bed temperature until a minimum value. This implies that sulfur self-retention improves with temperature, reaching an optimum at about 850 $^{o}$C, since reactivity of sorbents may increase with temperature. Further increasing in bed temperature, however, leads to an increase in $SO_2$ emission. This latter trend appears related to devolatilization process that intensifies with increasing bed temperature, and consequently, $SO_2$ tends to escape rapidly the burning pellet without retention. Additionally, with increasing bed temperature decomposition of $CaSO_4$ becomes more likely. Existence of an optimum temperature for sulfur self-retention was reported by some authors [29].

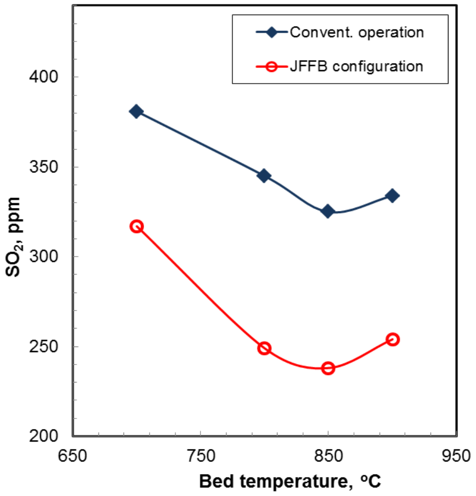

**Fig. 9 Sulfur** dioxide: a comparison between jetting-fountain configuration and conventional operation.

Nitric oxides concentration has been measured and reported as a function of bed temperature in Fig. 10. The jetting-fountain configuration exhibits less $NO_x$ emission compared to conventional operation. This may be ascribed to three main reasons. The first reason is hydrodynamic behavior. Introducing less air in the bottom zone leads to a decrease in fluidization velocity and in bubbles sizes. Therefore, gas residence time increases and mass transfer processes improve within the bed. Those later consequences should lead to an enhancement in NO reduction. Further introducing less air in the bottom zone leads to higher $NO_x$ concentration that should force toward $NO_x$ reduction. The lower freeboard overheating in the case of the jetting-fountain configuration, see Fig. 7, could be the third reason. Fig. 10 also indicates that increasing bed temperature leads to higher $NO_x$ emission, a well known trend.

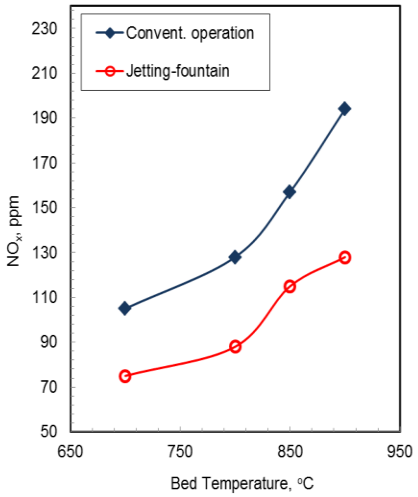

**Fig. 10 Nitric** oxides: a comparison between jetting-fountain configuration and conventional operation.

### *3.4 Combustible Losses*

Figure 11 presents carbon monoxide emission for jetting-fountain configuration in comparison with conventional operation. Carbon monoxide is reported as a function of bed temperature. Conventional operation exhibits much higher carbon monoxide emission compared to jetting-fountain configuration. This is more evident at lower bed temperature. These results may be explained as follow: In conventional operation, all air required for combustion in addition to natural gas are fed through the gas distributor. Hence, the fluidization velocity is considerably higher as reported in Table 3. The generated bubbles are, then larger with higher velocities while the residence time of gases within the bed becomes shorter. Therefore, the combustible and oxygen don't have sufficient time for intimate mixing and complete combustion. The situation appears worse for rice straw as biomass tend to concentrate near the bed surface during devolatilization period due to the draft effect of forming volatile bubbles [30]. Moreover, segregation of volatiles in bubbles decelerates mixing with oxygen. On the other hand, in the case of jetting-fountain configuration, only the air required for rice straw combustion is fed through the gas distributor that results in lower fluidization velocity, see Table 3. Therefore, the bubbles are smaller and slower. As residence time of gases becomes longer, the rice straw volatiles have a greater chance to burn within the bed. Moreover, natural gas mixed with the air required for its combustion is delivered via a jet pipe and burns in a jetting-fountain flame in a manner similar to conventional turbulent flame.

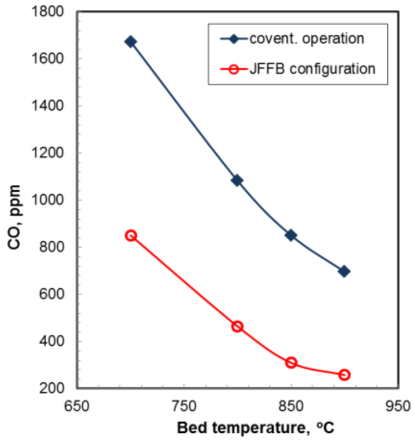

**Fig. 11 Carbon** monoxide: a comparison between jetting-fountain configuration and conventional operation.

Fig. 12 presents fixed carbon loss as a function of bed temperature. The figure indicates that fixed carbon loss considerably lower when the combustor operates at jetting-fountain configuration. These trends again may be attributed to the hydrodynamic behavior of the bed. As reported in Table 3, the fluidization velocity is lower in the case of the jetting-fountain configuration as only the air required for rice straw is fed through the distributor. 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. Fig. 12 also shows that rising bed temperature causes a significant reduction in the fixed carbon loss. With rising bed temperature the reactivity of char combustion increases that leads to a reduction in char concentration in the bed. And consequently, generation and entrainment rates of fine chars become also lower.

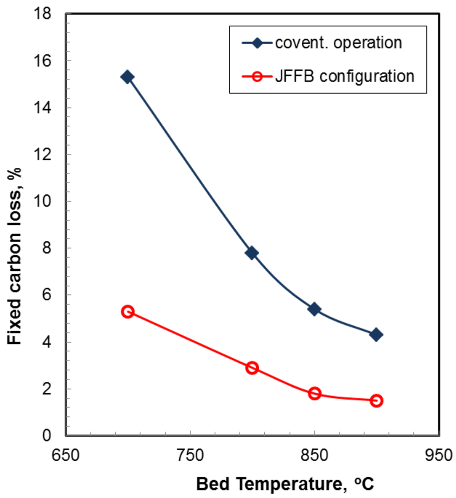

**Fig. 12 Fixed** carbon loss: a comparison between jetting-fountain configuration and conventional operation.

### *3.5 Combustion Efficiency*

The combustion efficiency is shown in Fig. 13. as a function of bed temperature. Combustion efficiency exhibits higher values with the jetting-fountain configuration. The gain in combustion efficiency is mainly attributed to the reduction in fixed carbon loss, see Fig. 12, and partially to the reduction in carbon monoxide concentration, see Fig. 11. The positive impact of bed temperature on combustion efficiency is evident in Fig. 13 as combustion efficiency becomes greater at higher bed temperature. Increasing bed temperature multiplies the reactivity of combustibles that reduces steadily fixed carbon loss and carbon monoxide as discussed above.

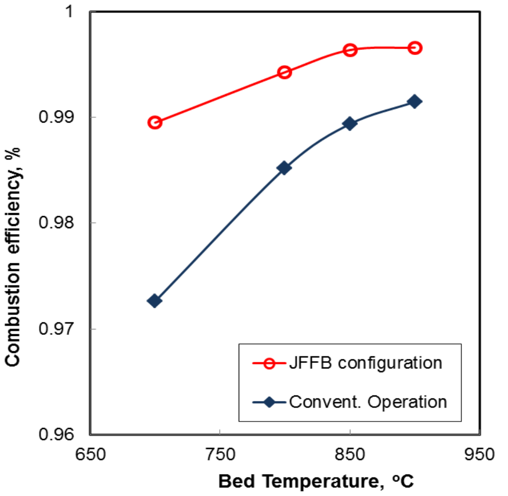

**Fig. 13.** Combustion efficiency: a comparison between jetting-fountain configuration and conventional operation.

## Conclusions

Experimental study on co-firing of rice straw and natural gas has been performed in a fluidized bed. The used combustor enables the novel, jetting-fountain configuration and the conventional operation as well.

The findings of the experiments confirm that smooth combustion of natural gas with rice straw can be performed in the jetting-fountain fluidized bed. This avoids acoustic effects and explosions of burning bubbles that occurs in conventional operation.

Temperature measurements in the freeboard demonstrate that the jetting-fountain fluidized bed dampens greatly the freeboard overheating, in particular, at lower bed temperatures. The fountain-particles absorb a great part of the heat released in the freeboard and recover it back to the bed. The later hypothesis is confirmed by measuring the in-bed cooling load that was found considerably increase, in particular, at lower bed temperature.

The performance of the combustor has been found much better when operates at the jetting-fountain configuration. There are great reduction in different emissions including carbon monoxide, nitric oxides and sulfur dioxide. This is, in particular, obvious at lower bed temperature. The fixed carbon loss reduces as well. Combustion efficiency records higher values with jet-fountain configuration.

Influences of bed temperature on combustion performance have been studied. Increasing bed temperature is beneficial for reducing carbon monoxide, decreasing fixed carbon loss and improving combustion efficiency. Existence of an optimum bed temperature for sulfur retention has been confirmed. As normal, nitric oxides has been found increases with bed temperature.

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