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Combustion behaviour of Olive pruning/animal manure blends in a fluidized bed combustor

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Abstract

Olive pruning and animal manure blends were burned in a fluidized bed system, in order to investigate their valorization for thermal energy production. Combustion performance was studied in terms of efficiency and emissions under various operating conditions.
Both fuels burned mostly within the bed. The maximum temperature of animal manure was 50 °C lower than that of olive pruning, however efficiency was nearly 99%. CO emissions were low, SO_2 emissions were negligible, whereas NO_x emissions of blends exceeded legislation limits, when excess air ratio was over 1.4. Decreasing excess air from 50 to 30%, or reducing reactor loading, resulted in improved burnout. The optimum performance for the blends was achieved when the feed rate was 0.6 kg/h and excess air was 30%.

Keywords: Environmental science, Chemical engineering

1. Introduction

Animal manure, produced from livestock feedlots, is traditionally used for land application, or as fertilizer. However, this kind of application could create environmental problems, due to the limited number of disposal sites, air pollution from greenhouse gases and organic compounds, as well as contamination of soil

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and ground water by heavy metals, nitrates and other substances [1, 2]. European Union Directives 1991/31/EC and 1991/676/EC imposed a reduction in the amount of biodegradable wastes going to landfill [3]. On the other hand, European Union has set the target to increase the percentage share of biomass fuels on the primary energy consumption, in order to substitute depleting traditional fossil fuels [4]. Among the various biomass fuels, wastes are considered as promising secondary fuels for energy recovery by the power generation sector across the world, increasing at the same time economic returns to rural communities.

Animal manure is a low quality fuel, heterogeneous in nature with high moisture and problematic elements in ash [5, 6, 7]. Therefore, its co-combustion with higher quality materials is suggested. As such, olive pruning, among other agricultural residues, is readily available in large quantities in Mediterranean countries and its calorific value is higher than most low rank coals. In Greece, about 1.5 millions dry tons of olive pruning are annually produced, whereas about 41 million cubic meters of animal wastes, due to the highly developed animal breeding activity [4, 8]. In Crete, the largest Hellenic island, the annual production of olive pruning is 270000 tons [9], part of which are used for household heating, while the greatest amount is wasted in the dump creating environmental problems. Considering an availability factor of 0.35, this agricultural waste could oversupply the energy needs of the island. As the increase of energy demand in Crete is very high due to the tourism industry, the embodiment of combustion technologies using waste materials in the local energy system seems a feasible long term solution. Furthermore, small or big enterprises are highly interested in using own by-products together with agricultural wastes, for producing heat or power for their needs.

A great number of studies have been devoted to the combustion of agricultural residues, such as kernels from olive and fruit trees, rice husks, cotton, straw and wood chips [10, 11, 12, 13]. These studies have mainly focused on flue gas emissions, efficiency and ash related problems, such as fouling and agglomeration. Carbon monoxide emissions have been reported to increase for fuels with high volatile matter content and control of fuel feeding, excess air, residence time or secondary air has been suggested for their minimization. On the other hand, SO_2 emissions have been found to be very low for agricultural wastes, whereas NO_x emissions have been shown to vary greatly, depending on the nitrogen content of the fuel, the bed temperature, the excess air and other system design parameters [10, 12, 13, 14, 15, 16]. Fluidized bed system has been the preferable among dedicated combustion technologies, due to its inherent advantages, such as fuel flexibility, good mixing and temperature control, high efficiency and low pollutant emissions [10, 12]. On the other hand, there is limited information on the performance of animal manure as a fuel. Pyrolysis, combustion and co-combustion have been studied only with coal in thermogravimetric analysis systems [6, 17, 18]. Gasification has been investigated in lab-scale fluidized bed using catalysts

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[19]. In a previous work by the author [20] the co-combustion of this waste with olive kernel was studied in a fluid bed unit.

The heterogeneous nature and variable composition of biomass materials implies a thorough knowledge of their behaviour in thermal systems. Their different characteristics influence handling and feeding, primary and secondary air required, temperature profiles, flue gas emissions, ash issues, burnout time and combustion efficiency. When mixtures of fuels are used, the blends may not burn in the same way as single fuels do and interactions can occur that may or may not be beneficial for the process. Thus, in order to avoid fuel combinations with unwanted properties, the performance of any particular mixture has to be properly evaluated for the effective design and operation of the conversion units. Obviously, even for the same type of experimental system, the results depend strongly on operating conditions.

Based on the above, the objective of the present work was to evaluate the co-combustion of the principal agroresidue of Greece with an animal waste, both of which remain unexploited, for energy production. The performance of the fuels and their blends was examined in terms of efficiency and emissions as a function of operating conditions.

2. Experimental

2.1. Raw materials and fuel analyses

The agricultural wastes selected for this study were olive pruning (OP), as being abundant in South European countries and an animal manure (AM) from swine breeding, provided as received from Creta Farm industry in the island of Crete. After air drying, olive pruning was ground in a cutting mill and animal manure in a jaw crusher and ball mill, both to a final size of 1–2.8 mm. Following homogenization and riffling, the fuels were pre-dried overnight in the oven. (in large scale furnaces the fuels could be dried by the flue gases or other waste heat). Mixtures with blending ratios 30, 50 and 70% of animal manure by weight in the mixtures were also prepared for the co-combustion tests.

Fuel analyses (proximate, ultimate, calorific value) were performed according to the European standards CEN/TC335. Chemical analysis of ashes was performed by an inductively coupled plasma mass spectrometer type ICP-MS 7500cx. Phosphorous and silicon measurements were conducted using a spectrophotometer type *UV–vis* Hach 4000 V and an atomic absorption spectrometer (AAS) Analyst-100 of Perkin Elmer, respectively. For sample preparation, the procedures of $Li_2B_4O_7$ fusion or acid digestion ($HCl/HF/HNO_3$) were used, depending on the element under determination. The base-to-acid ratio and the alkali index [21] were adopted to predict the deposition tendencies of ashes.

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The inert material of the fluidized bed reactor was a Na-feldspar $NaAlSi_3O_8$ with an average particle size of 421 μm, since this has been found to diminish bed agglomeration problems [11, 13].

2.2. Fluidized bed combustion experiments

Combustion tests were carried out in an atmospheric lab-scale fluid bed reactor, with an inner diameter of 70 mm and a total height of ~2 m, as described in detail in a previous work [22]. A schematic diagram of the system is shown in Fig. 1. The main parts are 2 silos with screw feeders, one dosimetric followed by one rotating faster and delivering the fuel into the bed (2 cm above the diffuser), water jacket and minor nitrogen flow in second silo to avoid biomass pyrolysis prior to the reactor as well as flue gas back flow, reactor body equipped with controlled heating furnace, seven K-type thermocouples and a differential pressure transducer, a cyclone of tangential flow type (cut size 10 μm, operating velocity ~4 m/s), a gas heat exchanger, a tar condenser and a multi-component gas analyzer.

For each fuel or mixture, feed rate and excess air were selected as the principal independent variables. Feed rates were 0.6 kg/h and 0.72 kg/h, whereas excess air ratios varied between 1.3 and 1.5. The minimum fluidization velocity (0.16 m/s) was determined by measuring the pressure drop across the bed and air diffuser plate versus the superficial air velocity, using a cold reactor model. Depending on fuel and operating conditions, air flow rates ranged between 3.2 and 5.5 m^3/h.

After charging the inert material into the reactor (static bed height-to-internal diameter ratio ~2.9), the fluidizing air was preheated at about 550 °C. Thereafter,

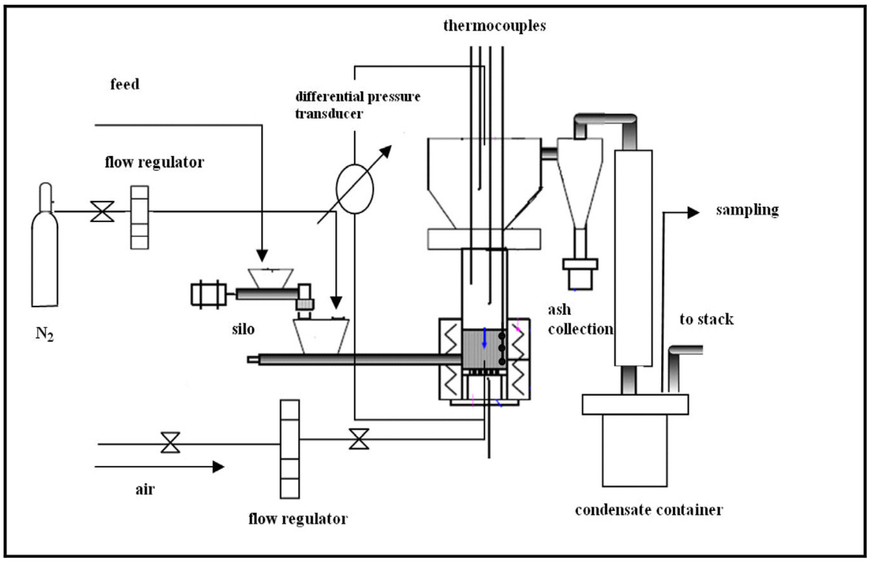

Fig. 1. Schematic diagram of the fluidized bed system.

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operating conditions were set and when furnace temperature reached steady state the fuel was fed continuously to the bed, 2 cm above the air diffuser, at the predetermined rate. Temperatures along the reactor height and pressure drop were measured throughout the tests. The product gas was cleaned from particulates in the cyclone, cooled in the heat exchanger, further cleaned from particles, tars and moisture in a gas conditioning unit and finally analyzed on line by the analyzer (Madur Ga-40plus of Sick-Maihak), every 5 seconds. All data was displayed and logged on a PC via a data acquisition unit. The results of two replicates were subjected to statistical analysis.

At the end of each experiment, bed material and fly ash were drained, weighed and analyzed for unburned carbon, in order to calculate combustion losses in the bottom (L_{ba}) and fly ash (L_{fa}). Inert material was sieved to remove ash and attrited particles and made up with fresh feldspar prior to be used in the following test.

3. Results and discussion

3.1. Fuel analyses

Table 1 compares the proximate and ultimate analyses of the fuels under study. Animal manure, having lower volatile matter and higher ash content than olive pruning, had a lower calorific value. However, due to the lower oxygen content of the former, the gross calorific value is significant and it is 3–4 times greater than that of digested swine manure reported in literature [23]. The sulphur and chlorine contents of both fuels, being related to emissions, fouling and corrosion in boilers, were low. On the other hand, the concentration of nitrogen in animal manure is quite high, implying increased toxic NO_x emissions during combustion.

The results of the chemical analyses of the ashes are presented in Table 2. Both ashes were rich in Ca, Si, Mg and P, while olive pruning in K too, elements known to be plant nutrients and soil improvement agents [24]. The domination of Ca and P in swine manure is typical of animal sludges [25]. The base-to-acid ratio (Table 2) is a useful index, because a high percentage of basic oxides lowers the melting ash temperature. When $R_{b/a} < 0.5$ deposition tendency is low and when $R_{b/a} > 1$ deposition tendency is high. The alkali index (Table 2) expresses the quantity of alkali oxides in the fuel per unit of fuel energy. When AI values are in the range

Table 1. Proximate and ultimate analyses and calorific value of the samples (% dry weight).

Sample	Volatile matter	Fixed carbon	Ash	C	H	N	O	S	Cl	GCV[a] (MJ/kg)
Animal manure	60.9	11.7	27.4	43.3	6.5	4.3	17.4	1.15	0.08	18.0
Olive pruning	79.4	17.1	3.5	48.6	6.3	0.4	41.1	0.03	0.07	19.2

[a] Gross calorific value.

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Table 2. Chemical analysis of ashes in main oxides (%).

Sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	P_2O_5	MnO	SO_3	B/A*	AI**
Animal manure	10.0	3.0	2.0	26.2	12.3	3.0	3.3	22.8	0.14	9.6	3.58	0.97
Olive pruning	4.7	3.4	1.0	28.8	2.6	19.3	0.5	8.5	0.05	1.8	6.4	0.36

* B/A = (Fe_2O_3+ CaO+ MgO+ K_2O + Na_2O)/(SiO_2+ Al_2O_3+ TiO_2).
** AI = kg(K_2O + Na_2O)/GJ.

0.17–0.34 kg/GJ fouling or slagging is probable, while when these values are greater than 0.34 fouling or slagging is virtually certain to occur. These empirical slagging/fouling indices indicate that the fuels, especially animal manure, could create ash problems if burned in boilers at high temperatures, due to the substantial amounts of alkali they contain. These are known to produce molten salt mixtures on accessible surfaces via vaporization, condensation or secondary reactions [26]. On the other hand, previous work by the author [26] has shown that alkali metals in the materials under study were bound in carbonates and phosphates, so that they were not available for formation of chlorides, HCl or Cl_2.

3.2. Combustion performance of raw fuels and their mixtures at same operating conditions

3.2.1. Axial temperature profiles

The temperature profiles along the height of the reactor of the two fuels and their blends, after steady state was reached, at a feed rate of 0.6 kg/h and excess air ratio λ=1.4, are illustrated in Fig. 2. As can be seen, both fuels burned drastically in the

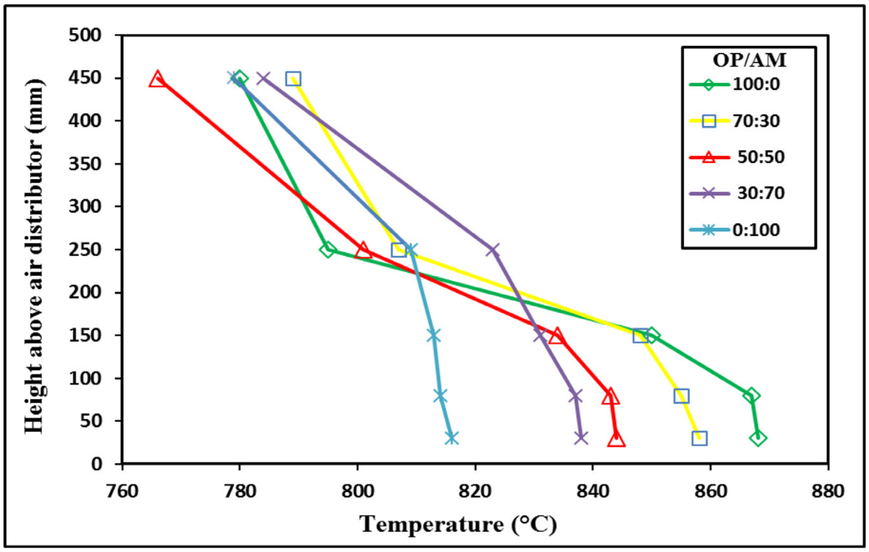

Fig. 2. Temperature profiles of the fuels and their blends along the reactor height at F = 0.6 kg/h and λ = 1.4.

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lower part of the reactor column, attaining the maximum temperature just 30 mm above the air distributor plate within the bed. For olive pruning, which was richer in volatile matter and carbon, maximum temperature (868 °C) exceeded that attained by animal manure by 52 °C (816 °C). The temperature remained quite uniform inside the bed and then decreased gradually along the freeboard zone. The decrease was greater for olive pruning toward the end of the expanded bed (> 250 mm), revealing ceasing of volatiles combustion.

When animal manure was mixed with olive pruning, Fig. 2 clearly indicates that combustion temperatures were reduced inside the furnace with increasing blending ratio, because this waste had lower volatiles and fixed carbon, whereas a much higher ash content than olive pruning. Maximum temperatures were reached within the bed, as for the individual fuels. In this region, the temperatures of the mixtures varied between 831 °C and 858 °C, while in the freeboard between 766 °C and 823 °C. In the conical section of the reactor (not shown in the graph), flue gas temperatures were around 375 to 471 °C. Temperature values were in between those corresponding to the combustion of the individual fuels, suggesting an additive behaviour. Finally, no signs of segregation, or defluidization were observed during the tests. Inspection of bed material after the experiments did not show agglomerates or fused material, because of the rather low temperature (< 870 °C), as well as the presence of a high amount of calcite in ashes.

3.2.2. Flue gas emissions

The pollutant concentrations from the combustion of olive pruning, animal manure and their mixtures, at steady state (average values ±standard error) and at a feed rate of 0.6 kg/h and excess air ratio λ=1.4, are compared in Fig. 3. SO_2 emissions are not shown in this graph, because they were practically null (< 6 ppm_v). Although it was expected olive pruning to present lower CO concentration in the flue gas, as it was burning at higher temperatures than the animal manure, the opposite occurred. The increased CO levels of olive pruning are most probably attributed to its greater amount of volatiles which boost hydrocarbons concentration in the reactor, inhibiting further conversion of CO to CO_2. Nevertheless, CO emissions of both fuels were well below legislation limits (4000 ppm) for small scale fluid bed systems [27, 28]. These values (804–1385 ppm) were similar or lower to those reported for other biomass fuels burned in small-scale fluid bed units, which varied between 100 and 23000 ppm [10, 11, 14, 15]. When animal manure was mixed with olive pruning, CO concentration in the flue gas was raised with the share of animal manure, due to the lower combustion temperatures attained in this case and the higher ash content of the latter, which weakened oxygen penetration to the char particles. The sensitivity of CO oxidation to temperature is the main reason for the small fluctuations observed.

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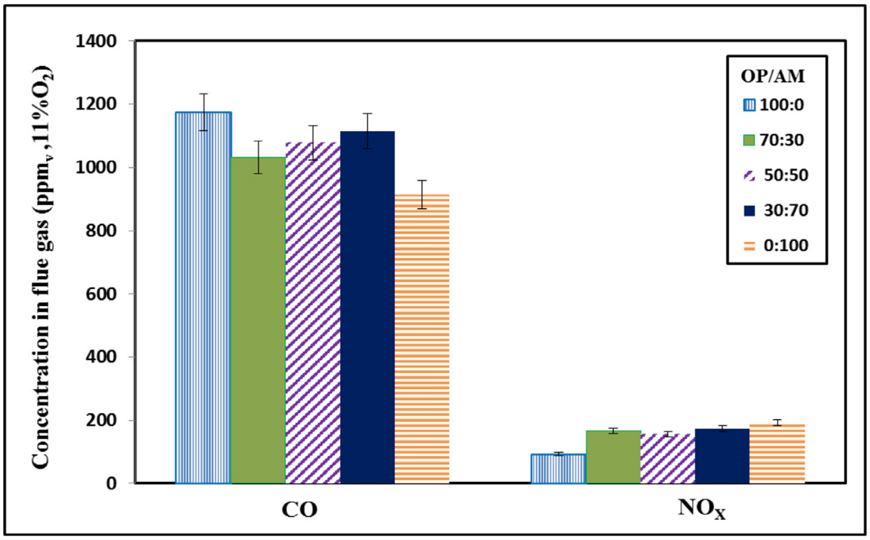

Fig. 3. Average (± standard error) flue gas emissions of the fuels and their blends at F = 0.6 kg/h and λ = 1.4.

As concerns NO_x emissions, Fig. 3 indicates that olive pruning, which had much lower fuel-N content, released small NO_x amounts (91–97 ppm) during its combustion, following the fuel-N mechanism [29], which were lower than literature data (100–1200 ppm) for woody fuels [10, 11, 12, 13, 14, 15, 16]. Additionally, the large amount of volatiles of this woody fuel could have created a temporary reducing environment, favouring NO_x decomposition. The values obtained for animal manure under the conditions mentioned above, were slightly over the limits allowed by some countries, including Greece [28, 29, 30]. Therefore, some measures such as air staging, or flue gas treatment would be required in this case to meet legislation. For mixtures, it can be seen that NO_x levels increased with blending ratio of animal manure, as expected, however these were within emission guidelines for small biomass units [29].

3.2.3. Combustion efficiency

The combustion efficiencies of the fuels and their blends at a feed rate of 0.6 kg/h and excess air ratio λ=1.4 are presented in Table 3. Net efficiency was calculated by equation (1):

$\eta = 100 - L_{CO} - L_{ba} - L_{fa}$ (%) (1)

where, L_{CO} was the loss caused by incomplete combustion:

$L_{CO} = \alpha\ CO(\%)/[CO(\%) + CO_2(\%)]$ (2)

CO and CO_2 in equation (2) were the volume concentrations in the combustion gases and α was a factor specific for a given fuel. L_{ba} and L_{fa} were the losses

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Table 3. Fluidized bed combustion performance of fuels at different excess air ratios and feed rate 0.6 kg/h.

Sample	Excess air ratio λ	Bed temperature (°C)	Flue gas emissions (ppm_v)			Heat losses (%)			Efficiency η (%)
			CO	SO_2	NO_x	L_{CO}	L_{ba}	L_{fa}	
OP	1.3	850-869	1166	-	91	1.26	0.15	0.10	98.49
	1.4	850-868	1175	-	93	1.27	0.20	0.10	98.43
	1.5	849-863	1189	-	97	1.28	0.25	0.12	98.35
OP/AM 70:30	1.3	850-862	875	-	126	1.12	0.15	0.25	98.48
	1.4	848-858	1032	-	167	1.36	0.15	0.25	98.24
	1.5	843-854	1269	-	215	1.37	0.20	0.30	98.13
OP/AM 50:50	1.3	841-850	901	-	133	0.98	0.11	0.14	98.77
	1.4	834-844	1079	-	156	1.17	0.13	0.18	98.52
	1.5	832-841	1361	-	198	1.47	0.15	0.20	98.18
OP/AM 30:70	1.3	834-840	923	0.9	149	1.0	0.10	0.17	98.73
	1.4	831-838	1114	5.9	173	1.21	0.11	0.18	98.50
	1.5	828-831	1387	2.3	229	1.51	0.13	0.20	98.16
AM	1.3	815-817	804	-	166	0.91	0.07	0.20	98.82
	1.4	813-816	914	-	192	1.02	0.09	0.23	98.66
	1.5	809-813	1385	-	240	1.51	0.10	0.25	98.14

originating from unburned carbon in the bottom and fly ashes, respectively and were determined experimentally. As can be seen, heat losses due to incomplete combustion (L_{CO}) of flue gases in the freeboard area dominated in the heat balance, thus affecting the efficiencies achieved. Combustion loss resulting from the fly ash (L_{fa}) had in principle the largest portion in the total loss in ash (L_{fa} and L_{ba}). For mixtures with higher CO emissions, combustion efficiency was somehow lowered. However, all values were high, ranging between 98.4 and 98.7%. Previous investigations on small-scale fluid bed units have reported efficiency values between 93 and 99.8% [10, 11, 12, 13, 16].

A comparison of the present results with those of our previous work [20], where olive kernel (OK) was used instead of olive pruning, shows great differences in the CO and NO_x emission values for both raw fuels and their mixtures with animal manure. In contrast to olive pruning, the concentration of CO in the flue gas in the case of olive kernel was lower than that of the animal waste, as the temperature in the furnace was higher. Also, at a feed rate of 0.6 kg/h, olive kernel presented higher NO_x emissions than animal manure, while olive pruning much lower and when the feed rate was 0.72 kg/h, NO_x values of olive kernel and animal manure coincided, while this was not valid in the case of olive pruning. Additionally, for

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OK/AM mixtures, at a loading of 0.6 kg/h and λ=1.4, NO_x levels exceeded emission guidelines, whereas for OP/AM mixtures these values were within limits.

4.1. Combustion performance of raw fuels and their mixtures as a function of operating conditions

4.1.1. Axial temperature profiles

The effect of air stoichiometric ratio on the axial temperature distribution within the furnace is shown in Table 3. As can be noticed, for all fuel combinations when excess air was raised from 30% to 50% combustion temperature was reduced at all locations inside the reactor. Thus, the dilution of the flue gas at the higher flow of air caused its cooling, which however did not exceed a 10 °C drop in temperature. In the freeboard area, for λ between 1.3 and 1.5, the temperature was seen to be quite high for all feedstocks (741–828 °C), since their combustion was continued along this region.

Fig. 4 compares the distribution of temperature along the reactor height at constant excess air ratio (λ=1.3) and as a function of fuel feed rate. All temperature profiles were similar. Both individual fuels and their mixtures attained a maximum temperature just 30 mm above the air distributor within the bed, which then followed a diminishing trend outside the bed toward the freeboard zone. When the feeding rate was increased from 0.6 kg/h to 0.72 kg/h, combustion temperature everywhere in the furnace was slightly increased. For olive pruning the maximum temperature was 873 °C at the higher loading, whereas for animal manure it was 823 °C.

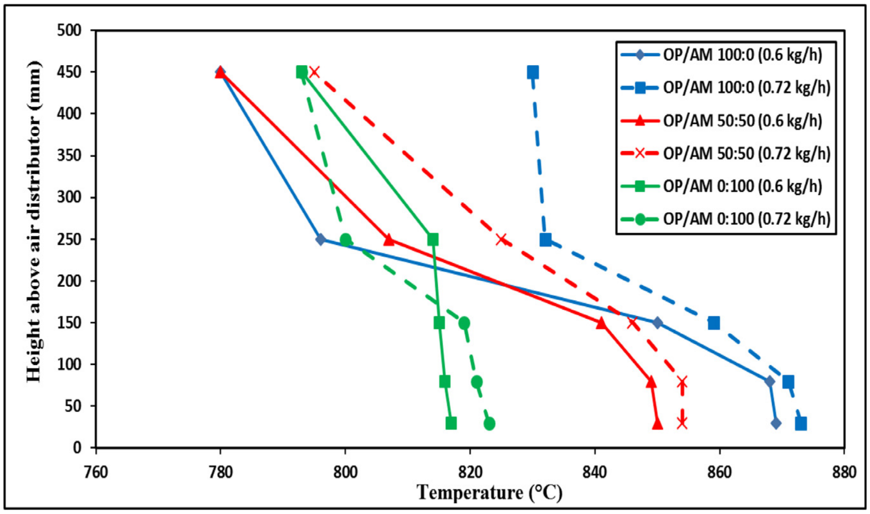

Fig. 4. Temperature profiles of the fuels and their blends along the reactor height at λ = 1.3, as a function of feed rate.

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4.1.2. Flue gas emissions

As previously discussed, when excess air ratio was increased reactor temperature was lowered. This resulted in higher CO emissions, as seen in Table 3. Nevertheless, all values were well below legislation limits [27, 28]. Furthermore, when excess air was raised from 30 to 50% NO_x emissions were increased, despite the reduced temperature and the dilution effects of air. This confirms the occurrence of the fuel- NO_x formation mechanism. For animal manure and its blends with olive pruning, NO_x values obtained at $\lambda > 1.4$ exceeded emission guidelines [28, 30]. As already mentioned, SO_2 emissions from all fuels were negligible.

The effect of fuel loading on pollutant concentrations is illustrated in Fig. 5. When the feed rate was higher (at constant λ coefficient), CO levels were generally dropped, due increased combustion temperatures and thus improved burnout. Accordingly, NO_x levels were seen to increase as more fuel was fed into the combustor. Although CO values were in accordance to guideline limits independently of the feed loading studied, NO_x values at a feed rate of 0.72 kg/h and $\lambda > 1.4$ for animal manure and its mixtures with olive pruning (~380–480 mg/Nm^3), were outside legislation limits [28, 30]. Once again, even at the higher fuel rate SO_2 emissions were practically null.

4.1.3. Combustion efficiency

Table 3 illustrates that combustion efficiencies for individual fuels or their blends were improved with diminishing excess air, because of the higher temperatures reached in the furnace, which resulted in lower heat losses due to incomplete

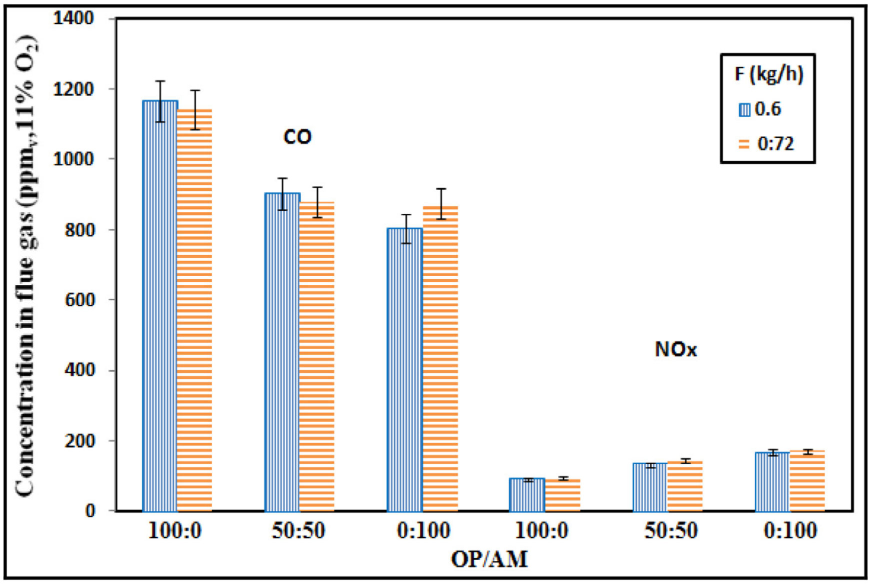

Fig. 5. Average (± standard error) flue gas emissions of the fuels and their blends at λ = 1.3, as a function of feed rate.

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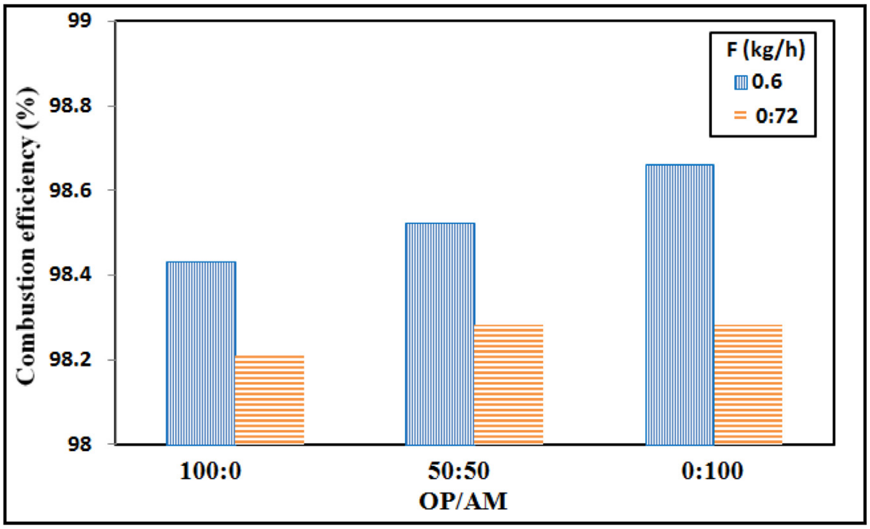

Fig. 6. Effect of fuel loading on combustion efficiency of fuels and their blends at $\lambda = 1.4$.

combustion or unburned carbon in fly and bottom ashes. The same was true for the lower feed rate, due to improved burnout as Fig. 6 shows. The highest efficiencies were obtained at the feed rate of 0.6 kg/h and excess air ratio 1.3 (98.5–98.8%). When the percentage of animal manure in the mixtures was higher and there was a drop in combustion temperature, efficiencies were also somehow reduced. However, all values were still high for olive pruning/animal manure blends, ranging from 98.1 to 98.8% under the conditions studied.

Once again, the performance of olive pruning and OP/AM blends, as a function of excess air and reactor loading, was different than that of olive kernel and OK/AM blends reported in our previous work [20]. Besides the temperature differences obtained along the reactor height when $\lambda \geq 1.3$ (at 0.6 kg/h), NO_x values of olive kernel and OK/AM blends exceeded emission guidelines, while this was true for olive pruning and OP/AM blends when $\lambda > 1.4$. Furthermore, when the feed rate was increased, CO levels of olive kernel and its blends were raised and NO_x levels dropped, contrary to olive pruning and its blends, as stated above. Finally, the combustion efficiency of olive kernel increased with fuel loading, as opposed to that of olive pruning, which was higher at the lower feed rate.

In conclusion, present results demonstrate the importance of investigating each fuel or fuel blends separately for the effective operation of thermal units and the environmental control of flue gas emissions.

5. Conclusions

Animal manure had lower volatiles and fixed carbon, whereas higher nitrogen and ash contents than olive pruning. Its ash was rich in Ca and P.

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During co-combustion of the fuels in the fluidized bed, maximum temperature was attained within the bed and for animal manure it was about 50 °C lower. CO levels were kept well below legislation limits and SO_2 emissions were negligible for all fuel combinations. NO_x emissions increased with blending ratio of animal manure and values at excess air ratio greater than 1.4 exceeded emission guidelines.

Decreasing excess air from 50 to 30% or reducing reactor loading resulted in improved burnout and generally lower emissions. An optimum combustion (~98.8%) and emission performance for all blends was achieved when the combustor was operated at a loading of 0.6 kg/h and excess air below 40%.

Declarations

Author contribution statement

Despina Vamvuka: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Nicolaos Alloimonos: Performed the experiments; Analyzed and interpreted the data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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