EXPERIENCE USING INETI EXPERIMENTAL FACILITIES IN CO-GASIFICATION OF COAL AND WASTES

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ABSTRACT

The increase in energy demand and at the same time the generation of more and more wastes both caused by the growth of world population and higher standards of people's life puts several problems that need to be faced. The development of our society in a sustainable way demands, not only an effort to reduce and recycle the wastes generated, but also the application of new energy technologies to process in a useful manner, with lower environmental impact, the combustible wastes resulting from the industry, forestry and agricultural activities. The application of gasification technology to mixtures of coal and wastes relies on this perspective.

In the present work, co-gasification of coal, biomass and plastic wastes mixtures was studied. Experimental fluidised bed gasification tests were done in two facilities, a bench and a pilot scale, using air and steam mixtures. It was studied the effect of temperature and feedstock composition on different gasification parameters, such as, gas composition, gas yield, heating value and energy conversion.

The results obtained so far are encouraging, as they have shown that it is possible to co-gasify coal mixed with either pine and polyethylene wastes to values up to 40% (w/w) of wastes, being even possible to substitute one waste type by the other, whenever their availability is seasonally affected. However, the presence of pine led to the production of higher amounts of CO, while the presence of PE wastes favoured the release of hydrocarbons, which may be reduced by either an increase in gasification temperature or in air flow.

INTRODUCTION

With the increased concern about negative impacts caused either by the use of fossil fuels and growth amounts of wastes, there is a renewed interest to find innovative ways to convert the existing reserves with improved technology in order to limit the effect of such fuels on environment. There is already a large scientific knowledge on the requirements for a successful gasification of coal both with air and steam, but the application of this technology to other fuels like biomass or municipal solid wastes is still under development. The latter fuels are generally more difficult to process, due to variations in quality, availability and composition. One of the potential solutions is the co-gasification of coal mixed with wastes using different components and compositions, thus enabling the development of a more robust and versatile technology, that can both benefit from the advantages of the diverse compositions of the fuels involved while reducing the effects of their availability due to seasonal variations.

There is not much information available about co-gasification of coal with wastes. Therefore, co-gasification behavior of such mixtures needs to be further studied to understand the behaviour of both feedstock and the synergetic effects during co-gasification process. Kurkela and others [1] reviewed co-gasification of biomass and coal mostly in medium and large-scale systems and reported that biomass wastes could be used as an additional feedstock in large pressurised coal gasification plants – IGCC process or synthesis gas plant. Also, co-gasification of wood residues and coal has been successfully carried out in an 18 MW_t Pilot Plant of Enviropower in Finland [1]. Sjostrom [2], Chen [3] and Brage [4], found that co-gasification of mixtures of coal and wood led to higher gas yields and lower amounts of tars. Studies of co-gasification of biomass wastes with low-grade coals in two fluidised bed plants (1.7 and 2 MW) were reported by Reinoso et al. [5]. Due to difficulties in gasifying such coals alone (with high ash and sulphur contents), they were mixed with wood wastes. The results obtained showed that the gasification was improved by the addition of wood wastes to the coals, because biomass low ash content (usually lower than 2%), almost no sulphur and high volatile content, could counterbalance the negative effects of ash and sulphur present in coals [5].

On the other hand, Co-gasification of coal with plastic wastes was tested in the High Temperature Winkler Process (HTW) [6, 7]. The brown coal used helped to stabilize gasification conditions and to counterbalance the eventual negative effect of plastic wastes, due to its heterogeneous nature and changes in its characteristics. The results obtained were encouraging; as for each tonne of plastic wastes was produced 850 kg of synthesis gas, with higher benzene content and traces of naphthalene [6, 7].

In the present work, co-gasification of coal, biomass and plastic wastes mixtures was studied, analysing gas composition and yield. Experimental fluidised bed gasification tests were done using air and steam mixtures. Different optimisation strategies were tested to improve gas quality for each coal/biomass/plastic mixture studied, including: run temperature, fuel/gasifying agent ratio and air/steam ratio. Most of the fuel mixtures included between 60 to 80% coal, combined with different amounts of biomass, and polyethylene (PE) wastes.

This work aims the production of a gaseous product from coal and wastes that could be used either as a synthesis gas, (e.g. with higher H_2 and CO contents), or as a gaseous fuel so that its energy contents is maximized. This gas could also be used in solid oxide fuel cells for direct generation of electricity.

EXPERIMENTAL

The experimental work was carried out under atmospheric pressure, in a bench scale fluidised bed gasifier, previously described [8] and the effect of the main experimental conditions on gas yield and composition was also tested in a pilot scale installation. In Table 1 are described the main characteristics of both installations.

Table 1: Characteristics of bench and pilot-scale installations.

Bench Scale characteristics	
Gasifier Total Height (mm)	500
Bed Diameter (mm)	70
Disengagement Zone Diameter (mm)	145
Disengagement Zone Height (mm)	190
Heating Method	Electric
Feeding Method	Calibrated Rotating Screw
Feeding Auxiliary Gas	Nitrogen
Pilot Scale characteristics	
Gasifier Total Height (m)	3.2
Bed Dimensions (m)	0.2 x 0.2
Heating Method	Electric
Feeding Method	Calibrated Rotating Screw
Feeding Auxiliary Gas	Air or Nitrogen

The gas produced in both installations left the reactor, passing through a cyclone to remove particulates. In pilot plant, tars and condensable liquids entrained by the gas were removed in a scrubbing system. After the scrubber, the gas went to a flare system. A continuous gas sample passed through a sampling system, before being introduced to CO, CO_2 and H_2 on-line analysers to monitor the process. The produced gas was also analysed by gas chromatography to determine hydrocarbons content. The amounts of condensable liquids were also determined.

In Tables 2 and 3 are shown the operating conditions used in both installations.

Table 2: Bench scale operating conditions.

Reaction temperature (ºC)	750 - 900
Freeboard temperature (ºC)	750 - 900
Fuel mixture flow rate (g daf/min)	4.4 – 8.2
Particle size (μm)	1250 - 2000
Pressure	Atmospheric
Steam flow rate (g/min)	3.8 – 5.0
Air flow rate (g/min)	0 - 13
Steam/fuel mixture ratio	0.7 - 1.3

Table 3: Pilot scale operating conditions.

Reaction temperature (ºC)	750 - 900
Freeboard temperature (ºC)	750 - 900
Mixture flow rate (kg/h)	4.8 – 6.8
Particle size (μm)	1250 - 3000
Pressure	Atmospheric
Steam flow rate (kg/h)	3.8 – 5.0
Steam/fuel mixture ratio	0.7 - 1.3

It was studied the effect of run temperature and the influence of different blendings of biomass, coal and plastic wastes on products yields and gas composition. As biomass wastes was selected pine, the most abundant biomass species in Portugal. The main plastic present in municipal solid waste, polyethylene (PE) was selected for gasification studies. In Table 4 the analysis of the three components of the blends is presented.

Table 4: Fuel Analysis.

	Coal	**Pine**	**PE**
Elemental Analysis			
Carbon Content (% daf)	77.3	51.6	85.7
Hydrogen Cont. (% daf)	5.31	4.9	14.3
Sulphur Content (% daf)	1.27	-	-
Nitrogen Content (% daf)	1.93	0.9	-
Oxygen Content (% daf)	14.2	42.6	-
Proximate Analysis			
Fixed Carbon (% w/w)	37.3	13.6	-
Volatiles (% w/w)	24.9	74.5	-
Ash (% w/w)	32.3	0.3	-
Moisture (%w/w)	5.5	11.6	-
HHV (MJ/kg daf)	30.65	20.2	46.1

RESULTS AND DISCUSSION

Bench Scale Facility

Effect of temperature

The effect of gasification temperature, it was studied for different blends. In Figure 1 is presented, on a dry-inert basis, the gas composition for a blend containing 60% of coal, 20% of pine and 20% of PE (w/w), using a mixture of steam/air as gasifying agent. These results were obtained with a steam/fuel ratio of 1.05 (g/g daf) and an oxygen/fuel ratio of 0.27 (g/g daf). The temperature effect was very pronounced giving at higher temperatures, a mixture with greater hydrogen and lower methane and heavier hydrocarbon contents. The contents of CO and CO_2 presented a small variation, although CO increased with temperature, as thermodynamically expected. This gave rise to a higher CO/ CO_2 ratio obtained at higher temperatures. The increase in temperature clearly promoted the steam reforming of the gaseous hydrocarbons.

Temperature is not sufficient to reduce heavier hydrocarbons content, some of which could condense out as tars on the cooling the gas. It may be necessary to use catalysts to achieve a greater reduction of these hydrocarbons, for this reason, it is not justified the use of very high gasification temperatures, because this would increase investment cost, due to the materials needed for the construction of the gasifier and the operating costs would also be higher.

The results obtained for co-gasification of coal mixed with wastes may be compared to those obtained for gasification of coal only, Figure 2. As it was expected the effect of temperature is similar, as the rise of this parameter also led to an increase in H_2 released and a decrease in hydrocarbons concentration. However, the presence of wastes led to a gas richer in hydrocarbons contents even at the highest temperature tested, which may mean that the gas needs further treatment depending on gas application. The higher hydrocarbons content of the gas obtained with co-gasification of coal and wastes were probably mainly due to the presence of PE wastes in the feedstock. The higher temperatures promote hydrocarbons further decomposition, through cracking and reforming reactions, but were not enough to bring their contents to the levels obtained with coal. In fact, the presence of 20% (w/w) of pine wastes and 20% (w/w) of PE wastes led to a gasification gas 32% richer in methane than the gas produced by gasification of coal alone, whilst the heavier hydrocarbons content was 3.6 times higher than the one obtained with coal.

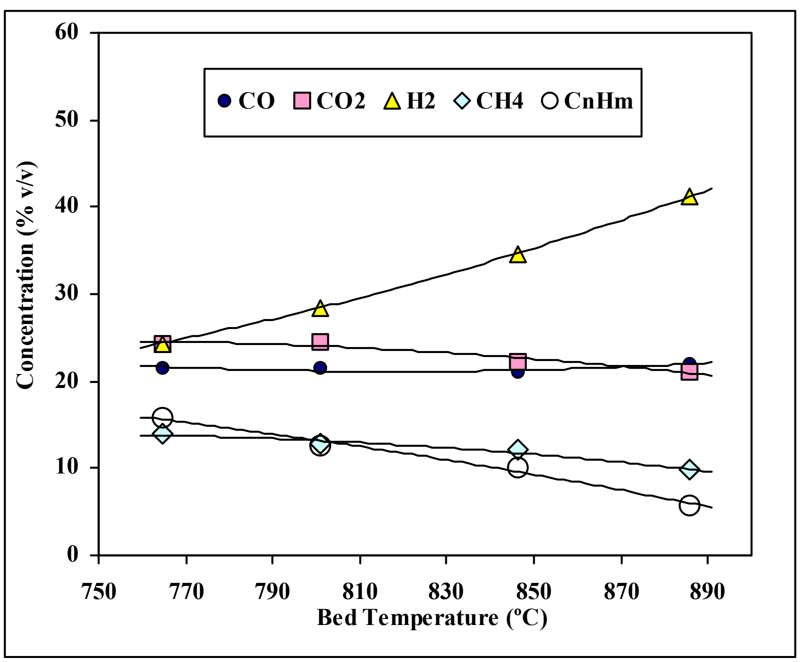

Figure 1 Effect of bed temperature on gas composition for co-gasification
of 60% (w/w) of coal mixed with 20% (w/w) of pine wastes and 20% (w/w) of PE wastes.

In relation to tars content and the amount of char remaining in the bed it was detected that the rise of temperature led to a decrease in both of these parameters, either when coal was gasified alone or mixed with wastes. The presence of wastes in the feedstock also favoured the formation of tars and of char.

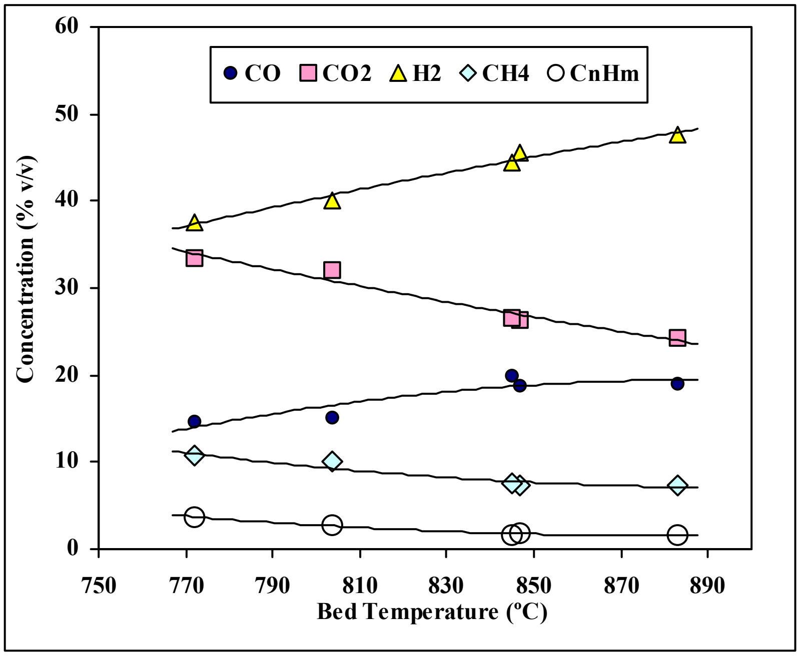

Figure 2 Effect of bed temperature on gas composition for gasification of coal.

It was also analysed the effect of bed temperature on gas yield, gas high heating value (HHV) and energy conversion. Gas yield was calculated based on the production of inert-free gas per weight of dry-ash-free feedstock. High heating value is the gross calorific value of the inert-dry-free gas on a volumetric basis. The energy conversion was defined as the ratio between the energy content in the produced gas and the energy of the feedstock that enters the gasifier.

Higher gasification temperatures of only coal enabled the production of greater amounts of gas and with increased energy conversions. The HHV values of the gaseous product conversely show a small decrease from 13.5 to 12.4 kJ/Nl, which was mainly due to the reduction of the amounts of methane and heavier hydrocarbons, as may be observed in Figure 2.

The presence of pine and PE wastes mixed with coal, led to higher gas yields, with greater energy conversion of more than 90%. The rise of temperature clearly decreased the heating value of the gas, however, these values were found to be greater than those obtained for gasification of only coal, due to higher hydrocarbons contents in the gas.

The effect of temperature on gasification performance and gas composition agrees fairly well with results obtained by other authors [10 to 11], though similar tendencies were obtained, values were different, mainly due to different systems and equipments used.

Effect of fuel mixture composition

Considering that there are several components that can be gasified in mixtures with coal, the effect of the presence of up to 40% plastic wastes (polyethylene-PE) and biomass (pine) in mixtures with coal was also tested. The temperature of 850ºC was chosen, and the steam/fuel mixture ratio and oxygen/fuel mixture ratio were equivalent to those considered in Figure 1.

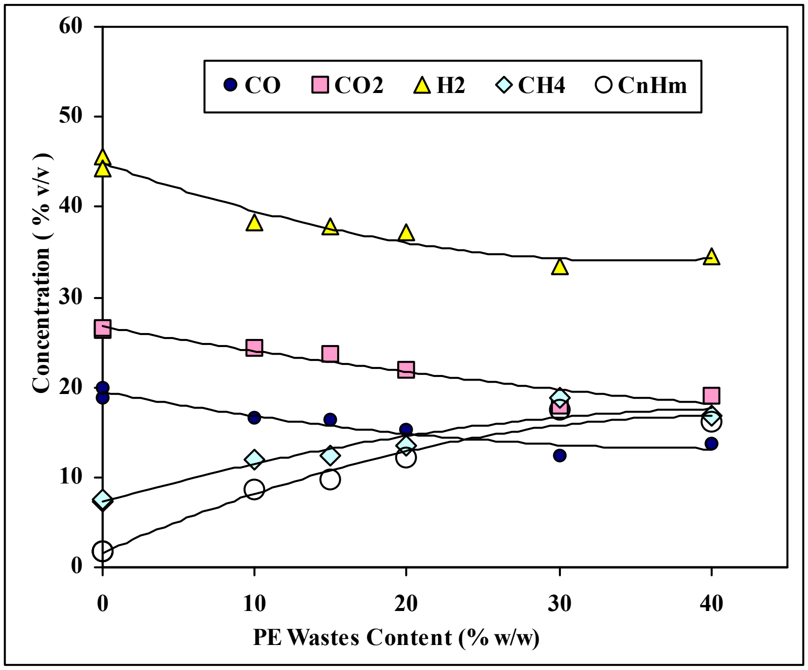

Figure 4 Effect of PE wastes content on gas composition for co-gasification with coal at 845 ºC.

As shown in Figure 4 the presence of different PE amounts in the coal has a strong influence on gas composition. In the gasification of only coal, very high hydrogen content was obtained and the methane and heavier hydrocarbon contents were small. Increasing amounts of PE in the blend caused a decrease in hydrogen, CO and CO_2 contents, while methane and heavier hydrocarbon contents increased to about 33% (v/v) when 40% (w/w) of PE was used. However, as could be verified, the gas composition remains almost unchanged for PE amounts beyond 20%.

As a consequence, there was a noticeable effect on the gasification performance due to the presence of PE in the feedstock, for PE contents till 20%. The rise of PE content led to gasification gases with a much higher HHV and energy conversion values. Gas yields also increased for higher PE amounts.

The effect of pine in the feedstock is presented in Figure 5. Compared with tests involving only coal, higher amounts of pine gave a gaseous mixture with lower H_2 and higher CO content. The contents of both methane and heavier hydrocarbons also increased. Although the same tendencies were obtained, the results were somewhat different from those when PE was used. For the same amount of waste, 40% (w/w), the presence of PE led to a decrease in hydrogen content of about 9%, but methane and heavier hydrocarbons concentrations increased 2 and 6 times, respectively.

Pine, when mixed with coal, caused some effect on gasification process, but not as strong as PE. The energy conversion values obtained were lower than when PE was used, but presented a strong increase for higher pine contents. Variations on the gases HHV were very small and the gas yields were similar to those obtained for the experiments done in presence of PE.

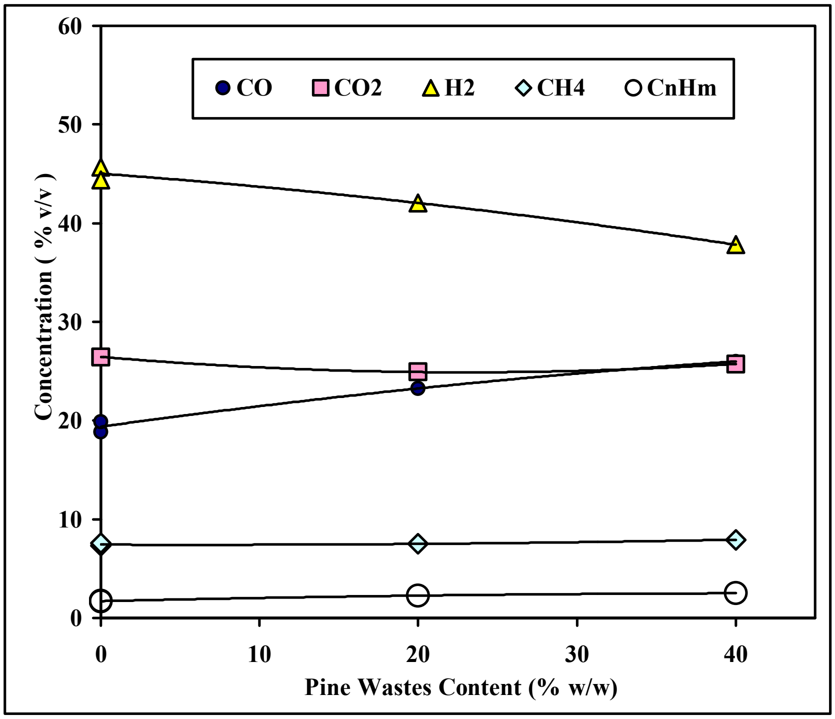

Figure 5 Effect of pine wastes content on gas composition for co-gasification with coal at 845 ºC.

Some gasification tests were done using coal mixed with pine and PE wastes with equal amounts of both. There was an almost linear relationship between mixtures having both pine and PE wastes and those involving only one of these wastes, e.g. for PE and pine (10%/10% and 20%/20%), the gas composition for each component fell always between the results obtained using 20% and 40% of each of these wastes. The component that seems to be most affected by the amount of PE on the feedstock was heavier hydrocarbons (C_nH_m). Hydrogen and CO productions were negatively affected by PE presence, whilst the addition of pine favoured higher CO productions. It could be concluded that the gas composition could easily be predicted based on the amount of each waste added to the blend. No adverse effects due to mixing of these two types of wastes in blend were observed. The presence of larger quantities of PE resulted in greater amounts of heavier hydrocarbons, which have to be dealt with by varying operating conditions, and probably by the addition of catalysts like dolomite.

Highest gas yields were obtained with 40% (w/w) of pine wastes, which increased its value by 30% in relation with the gasification of only coal. However, higher amounts of PE led to higher energy conversion and gas HHV. For mixtures of coal with equal amounts of both pine and PE wastes, these gasification results were found to lie between those obtained for mixtures with the same amount of only one waste.

The gas yield was dependent in the wastes content of the blend, but not so much of the kind of waste, meaning that PE could replace at least part of pine wastes without severe adverse results, having in mind that in this case the gas quality might be somewhat different, indicating the need for small adjustments on experimental conditions to achieve similar results, mainly in gasification temperature and gasifying mixture fuel ratio.

Pilot Scale Facility

To study the effect of scale-up in co-gasification of coal mixed with PE and pine wastes the pilot-scale installation was used. In Figure 6 may be analysed the effect of temperature on co-gasification of 60% (w/w) of coal mixed with 20% (w/w) of pine wastes and 20% (w/w) of PE wastes. These results were obtained with an air flow of 4.6 kg/h, fuel flow of 5 kg/h (daf) and steam flow of 2 kg/h. The comparison of Figures 1 and 6 showed that the rise of temperature led to the same tendencies in gas composition, though different values were obtained, due to the lower steam flow used in pilot installation. In fact, the rise of temperature led to a higher hydrogen content, probably at the expenses of hydrocarbons further reactions of cracking and reforming, thus leading to a decrease in both methane and heavier hydrocarbons concentrations.

The run done in the pilot-scale installation at 850ºC and with a steam flow of 5 kg/h resulted in the following gas composition: H_2 = 36.1% (v/v), CO = 16.9 % (v/v), CO_2 = 23.4% (v/v), CH_4 = 14.5% (v/v), and C_nH_m = 9.1% (v/v). These results agreed fairly well with those obtained in the lab-scale installation, operating under similar experimental conditions. The gas composition obtained in the pilot installation at 750ºC was also similar to that produced in the lab-scale installation for the same experimental conditions. These results showed that scale-up effects were negligible for co-gasification of coal with pine and PE wastes, at least for the increase of scale tested.

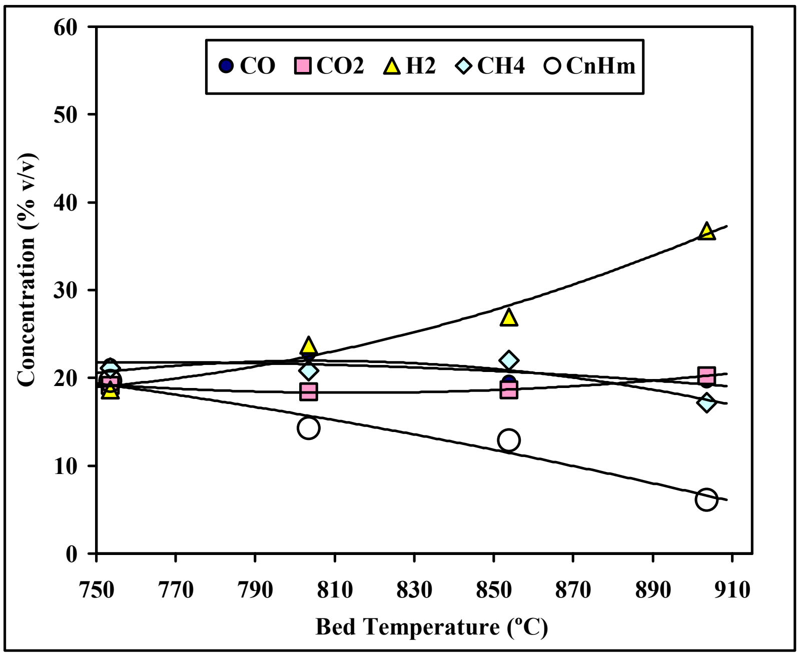

Figure 6 Effect of bed temperature on gas composition for co-gasification
of 60% (w/w) of coal mixed with 20% (w/w) of pine wastes and 20% (w/w) of PE wastes (pilot gasifier).

The rise of temperature led to a small growth of gas production but a great reduction in HHV values. This effect was basically due to the lower concentrations of hydrocarbons obtained at higher temperatures. This fact led to a decrease in the energy conversion with the rise of temperature.

In Figure 7 may be analysed the influence of fuel composition in gas composition produced during co-gasification of coal and wastes in the pilot installation. These results were obtained when a steam feeding of 2 kg/h and a fuel feeding of 5 kg/h (daf) were used for a gasification temperature of 850 ºC.

It could be concluded that when bigger amounts of PE were fed with the mixture, there was a rise of hydrocarbons formed, being the maximum reached when a mixture with 60% of coal and with 40% of PE was used. The opposite happened for CO and CO_2 contents, meaning that the levels released decreased when higher amounts of PE were used. When mixtures with higher amounts of coal were used the production of H_2 increased, while the mixture with more pine allowed the productions of a gas with lower levels of hydrocarbons, but richer in CO and CO_2.

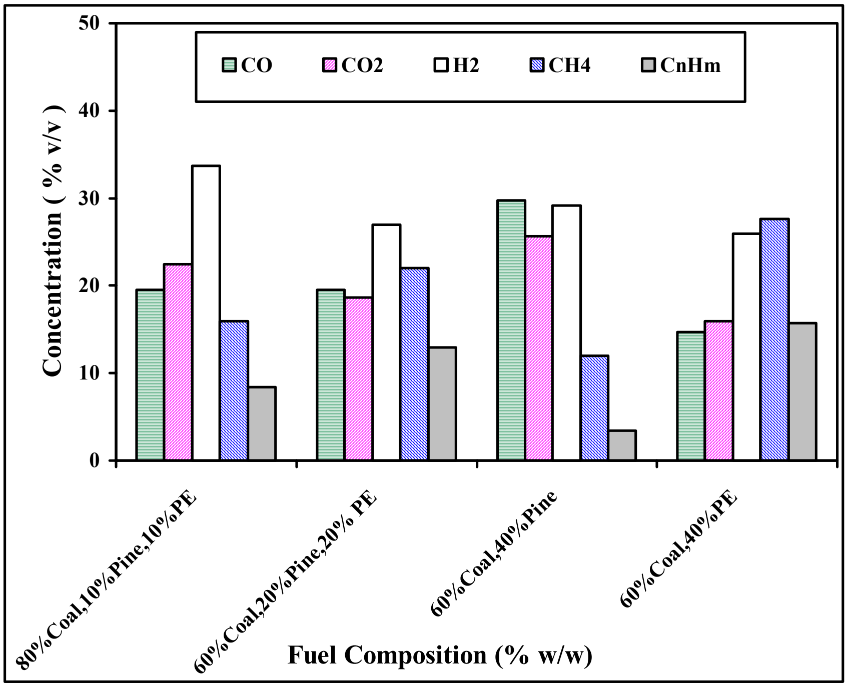

Figure 7 Effect of fuel composition on gas composition for co-gasification of coal with pine and PE wastes (850ºC)

CONCLUSIONS

The results obtained so far are very promising. Higher amounts of wastes in the mixtures produced greater gas yields, however, higher amounts of hydrocarbons were produced, mainly in presence of PE. While the presence of pine led to the production of higher amounts of CO, PE originated gases with higher methane and heavier hydrocarbons contents. Generally, pine increase considerably CO content, while PE give rise to great $CH_4$and C_nH_m contents. Both wastes leads to a significant decrease in H_2, specially PE Depending on the desired end-use application for the gases, the use of wastes mixed with coal may mean that the produced gas may need further cleaning treatment.

The use of higher gasification temperatures and higher air flows allowed to decrease tars and hydrocarbons concentrations, which may be advantageous for some gas applications. However, lower hydrocarbons contents also mean a decrease in HHV values, which is disadvantageous if the gasification gas is directly used for power generation.

The runs containing both wastes gave an intermediary composition in relation with the use of only one type of waste, without significant negative synergetic effects, indicating that at least part of one of the wastes can be replaced by the other without significant adverse effects. However, when higher amounts of PE were used the higher hydrocarbon contents of the gas, which also correspond to a higher tar formation, may be a negative factor in the cleaning step of the gas. These higher hydrocarbons can be partially reduced by the use of higher temperatures and a greater amount of oxygen on the gasifying mixture, although with higher operational costs.

In relation to the effect of the experimental conditions studied, the same tendencies were obtained for both bench and pilot scale installations, though, different values were obtained for either gas composition or gasification parameters. However, the results obtained so far, did not show appreciable scale-up effects for co-gasification of coal with pine and PE wastes, at least for the increase of scale tested.

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