Effect of air-steam agent on co-gasification of biomass and coal

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Abstract. The goal of the study is to investigate the impact of adding steam as a gasification agent for the co-gasification of biomass and coal. Study has been performed with ASPEN PLUS simulation, and has been confirmed by experimental findings. The coal and biomass ratio of 60% was gasified at an equivalent ratio of 0.29 and 0.35. The addition of steam was as much as 0%, 25%, 50%, 75%, and 100% for each equivalence ratio difference. The findings demonstrate that the best quality of fuel gasses such as CO and H₂ is obtained by applying up to 75% steam where the temperature of the reactor can still be held at 770°C. The cold gas efficiency and carbon combustion efficiency where equivalent ratio ranged from 0.29 to 0.35 at 75% steam to air ratio are 61.2-67.3% and 77-79%, respectively. Co-gasification between coal and biomass with a combination of air and steam may technically be a replacement for biomass gasification with air.

1. Introduction
Biomass has been used for food processing, plant-based products and the advancement of renewable energy to meet basic human needs. However, non-food biomass is an attractive option for energy applications because, apart from being renewable, carbon neutral and there is no fear of competing directly with human food needs. There are several forms of non-food biomass from agricultural and agroforestry activities [1,2] as well as from waste biomass materials [3] which are usually not recycled or reused directly that are interesting to exploited as renewable energy feedstocks. The problem is that this form of biomass is typically of low heating value and its sources are spread around different regions. In the meantime, while coal is not renewable, there is still a lot to be found in some regions. Coal has a calorific value and other energy properties that are greater than that of biomass. It is also very likely to mix up alternative fuels, coal and biomass.

Biomass and coal are less desirable for transport in their dense form. In their application, both types of fuel are not very versatile compared to liquid and gas applications. However, study and application of the conversion of biomass or coal to gas and liquid fuels continues to increase. Technologies that are widely used for converting solid fuels to gas or liquid are devolatilization, liquefaction and gasification. The comprehensive method of converting from solid to liquid or gas is also different with the blending process of biomass and coal. In addition, the use of gasification is economically more desirable than incineration for the treatment of biomass from municipal solid waste to electricity [4].

There are many possible chemical reaction routes for converting carbon-containing solid fuels to gas, such as devolatilization, Boudouard, steam gasification, carbon oxidation, water gas reaction, or methanation. Some of them are heterogeneous and homogeneous reactions as the following. Heterogeneous reactions:

\[ \text{Biomass} \rightleftharpoons \text{char} + \text{volatiles} \quad (C_xH_{2x} + C_xH_2 + H_2O + H_2S + H_2 + CO_2 + \text{Tar}) \quad (1) \]
\[ C_{(s)} + O_2 \rightleftharpoons CO_2 \quad \Delta H_{298}^o = -394 \text{ kJ/mol} \] (2)
\[ C_{(s)} + \frac{1}{2} O_2 \rightleftharpoons CO \quad \Delta H_{298}^o = -110.5 \text{ kJ/mol} \] (3)
\[ C_{(s)} + CO_2 \rightleftharpoons 2CO \quad \Delta H_{298}^o = 172.5 \text{ kJ/mol} \] (4)
\[ C_{(s)} + H_2O \rightleftharpoons CO + H_2 \quad \Delta H_{298}^o = 131.3 \text{ kJ/mol} \] (5)
\[ C_{(s)} + 2H_2O \rightleftharpoons CO_2 + 2H_2 \quad \Delta H_{298}^o = 77 \text{ kJ/mol} \] (6)
\[ C_{(s)} + 2H_2 \rightleftharpoons CH_4 \quad \Delta H_{298}^o = -74.5 \text{ kJ/mol} \] (7)

Homogeneous reactions:
\[ CO + \frac{1}{2} O_2 \rightleftharpoons CO_2 \quad \Delta H_{298}^o = -41.2 \text{ kJ/mol} \] (8)
\[ H_2 + \frac{1}{2} O_2 \rightleftharpoons H_2O \quad \Delta H_{298}^o = -241.5 \text{ kJ/mol} \] (9)
\[ CO + H_2O \rightleftharpoons CO_2 + H_2 \quad \Delta H_{298}^o = -41.2 \text{ kJ/mol} \] (10)
\[ CO + 3H_2 \rightleftharpoons CH_4 + H_2O \quad \Delta H_{298}^o = -205.8 \text{ kJ/mol} \] (11)
\[ CO_2 + 4H_2 \rightleftharpoons CH_4 + 2H_2O \quad \Delta H_{298}^o = -164.6 \text{ kJ/mol} \] (12)
\[ CH_4 + H_2O \rightleftharpoons CO + 3H_2 \quad \Delta H_{298}^o = 206 \text{ kJ/mol} \] (13)

Of the several potential reactions mentioned above, there are two common reagents or carbon-reacting agents in producing gas from biomass and coal, namely oxygen (air) and water vapor (steam). In the gasification process, the analysis of biomass into syngas, using steam or air individually, as well as coal feedstocks, has been carried out. Syngas is a synthetic gas consisting of hydrogen (H₂), methane (CH₄) and carbon monoxide (CO) with different ratios produced from biomasses and it can be produced by gasification technology. The typical composition of syngas by steam agent includes 50-52% of hydrogen, 25-28% of carbon monoxide, 16-19% of carbon dioxide, 4-6% of methane, and traces of sulphur dioxide [5]. In contrast, the combustible gas composition of syngas by air agent includes [6] 11.2-18.6% of hydrogen, 21-26% of carbon monoxide, and 4-8% of methane which is lower than produced by steam gasification.

However, the use of a mixture of steam and air in the co-gasification of biomass and coal has increased interest since both agents has their own advantages that can complement each other. The purpose of this study is therefore to investigate the effect of a mixture of air and steam on biomass and coal co-gasification. Research focuses on the composition, efficiency and temperature of the syngas. In the analysis, two similar ratio variables were also used.

2. Materials and Method
The material used was a blend of biomass and coal with a moisture content of 10%. The ultimate and proximate analysis of the two materials can be seen in the table 1. Air and steam were the gasification agents used. Steam was supplied by boiler at a temperature of 200°C.

| Feedstocks | Proximate (wt%, db) | Ultimate (wt%, db) | LHV (MJ/kg) |
|------------|---------------------|--------------------|-------------|
|            | FC | VM | Ash | C | H | O | N | S |          |
| Sawdust Biomass | 15.63 | 73.84 | 10.53 | 52.30 | 5.17 | 41.70 | 0.40 | 0.43 | 17.52 |
| Coal       | 49.10 | 35.20 | 15.70 | 61.40 | 5.30 | 28.20 | 0.90 | 4.20 | 25.63 |

Simulation studies have been carried out using ASPEN PLUS with the validation of previous experimental results [7]. Co-gasification was carried out by having a coal-to-biomass feedstock ratio of 60:40. The gasification used was a fluidized bed with a height of 3.5 m and a diameter of 0.153 m. Meanwhile, the amount of bed used was 4 kg of silica sand.

Biomass and coal were dried and devolatilized in the pyrolysis reactor with a working pressure of 0.1 MPa. The feedstock mass flow rate was kept fixed at 18.8 kg/h. In the pyrolysis reactor, biomass and coal were being devolatilized into char and gases. The pyrolyzed gas containing tar was then separated and followed by cracking of the tar by means of oxidation. So that enough air is needed to...
break the tar. In the meantime, the chars were streamed into the char reactor, which then reached the
gases from the tar cracking and mixed in the gasification reactor.

In order to simulate biomass, coal, char, and ash in ASPEN PLUS, they were estimated using
non-conventional components. The enthalpy and density for non-conventional components was
determined using HCOALGEN and DCOALIGT models. The biomass-coal co-gasification process has
been modelled within three main stages: drying and devolatilization reactor, tar cracking reactor, and
gasification reactors. The biomass-coal co-gasification flowsheet is shown in figure 1. In
devolatilization reactor and tar cracking reactor, non-conventional biomass and coal, char, and tars were
decomposed into conventional components using RYield block. Meanwhile, the gasification process
was performed using power law kinetics. The ASPEN PLUS model was validated with the experiments
of previous study [7].

![Flowsheet diagram of biomass-coal co-gasification](image)

Figure 1. Flowsheet diagram of biomass-coal co-gasification

The gasification reactor operated with an air and steam agent with a customizable ratio of 0%,
25%, 50%, 75%, and 100%. The amount of the air and steam rates were modified in such a way that the
equivalent ratio (ER) of 0.29 and 0.35 can be validated with previous laboratory testing results [7]. ER
is specified as the actual ratio of the gasifying agent supplied during gasification to the stoichiometric
gasifying agent needed for the complete combustion of the feedstock.

\[
ER = \frac{\text{(mass flow of air/fuel) actual}}{\text{(mass flow of air/fuel) stoichiometry}}
\] (14)

The gas found is composed of hydrogen, methane, carbon monoxide and carbon dioxide. The gas
content of the syngas will then be used to calculate the calorific value of the syngas using the formula
[7].

\[
LHV_{\text{syngas}}(kJ/Nm^3) = 4.2 \left[ 25.7 \times H_2 + 30.0 \times CO + 85.4 \times CH_4 + \\
151.3 \times (C_2H_2 + C_2H_4 + C_2H_6) \right]
\] (15)

Where \(H_2\), \(CO\), \(CH_4\), \(C_2H_2\), \(C_2H_4\), and \(C_2H_6\) account for vol percent of each of these components in the
syngas.

Other indicators are related to gasification performance, namely the efficiency of cold gas (CGE) and
the efficiency of carbon conversion (CCE). CGE is a measure of the potential of chemical energy
contained in syngas compared to the energy contained in feedstocks. CCE is, meanwhile, a ratio between
the carbon content of the syngas and the carbon content of the feedstocks. CCE is therefore the power
of a gasifier to transform carbon into combustible gas in the feedstocks. The gasification reactor runs at
ER 0.29 and 0.35 and an operational pressure of 0.1 MPa in the co-gasification analysis. Coal and biomass in the feedstocks were varied from 0 percent, 25 percent, 50 percent, 75 percent and 100 percent. 

\[
CGE = \frac{\text{mass flow of syngas} \times LHV_{\text{syngas}}}{\text{mass flow of feedstocks} \times LHV_{\text{feedstocks}}}
\] (16)

\[
CCE = \frac{\text{carbon content in syngas}}{\text{carbon content in feedstocks}}
\] (17)

3. Results and Discussion

3.1. Validation of ASPEN PLUS simulation results with experimental data

Figure 2 shows the hydrogen, CO, CH₄, CO₂ composition of syngas and the rest is nitrogen. Flammable gases include H₂, CO, and CH₄. The combustible gas contents that are concentrated in CO and H₂ are between 10.23-15.41 %v in the variation of ER 0.29 and 0.35, while CH₄ concentration is only low, namely 1.7-2.6%. It can also be seen that there is a small influence of ER 0.29 and 0.35 on the composition of the gas in the syngas. There is only a slight variation in the simulation results of the experiment, and this is because the reactions that occur in actual gasification are very complex. CGE from the simulation results is also validated with the results from the experiment in addition to the gas concentration, as can be seen in the figure 3. Also, the CGE from the experimental results is not that different from the results of the CGE simulation, although the results of the CGE simulation are still little bit lower than those of the experiments on both ERs.

3.2. Effect of gasifying agent composition

Combustible gases such as H₂, CH₄, and CO are formed by oxidation and partial oxidation reactions between the carbon in the feedstocks and their concentrations are less than 12.5 percent, 2.6 percent and 15.4 percent, respectively. In the meantime, non-combustible gases such as CO₂ and N₂ are found in syngas in high quantities. As a consequence, there is a low heating value for the syngas generated from gasification with air agents. The lower heating value of syngas is varying between 2.76-6.35 MJ/Nm³.

The use of steam as a gasification agent is also attractive, as steam can react with carbon to become combustible gases such as CO and H₂. The amount of nitrogen in syngas is also decreased by the addition of steam. Too much steam, however, causes the gasification reactor temperature to decrease, which can adversely affect the rate of the gasification reaction itself. The key cause is a water gas reaction of an endothermic form. Therefore, it can be seen that keeping down the steam allows the hydrogen content to increase by up to 39.2 percent, which is up to 75 percent when the steam is applied. It is much easier to produce hydrogen in syngas using ER 0.29 than using ER 0.35. Interestingly, other

![Figure 2. Gas composition in syngas from experiment and simulation study of biomass and coal co-gasification using air as an agent.](image)

![Figure 3. Cold gas efficiency of biomass and coal co-gasification using air as an agent obtained from experiment and simulation.](image)
studies have shown that there is a synergistic phenomenon in co-gasification [8]. A positive synergistic effect was observed at ER < 0.3 because several forms of biomass ash and coal with ER < 0.3 produced minerals that were catalytic and were able to increase the concentration of combustible gas in syngas. In the co-gasification of biomass and air, the hydrogen content in the water-steam agent is still much higher than using air alone. The hydrogen content of different biomasses, such as oak, olive pruning waste and grape marc, was also found to be higher than other research on the use of air as an agent, which ranged from 2.89% to 14.0% [9–12].

It can be seen in the figure 4 that adding steam causes the CH₄ content to drop drastically. CH₄ produced during the devolatilization, methanation, and oxidation tar removal processes will react with H₂O with the addition of steam to the gasifier or will undergo a methane reforming reaction. The transformation in CH₄ to CO and H₂ is the outcome of methane reformation. This is also why, as can be seen in the figure 4, the addition of steam causes hydrogen to increase while CH₄ to decrease as shown in figure 5.

During the process of adding steam to co-gasification between biomass and coal, the CO in syngas has a slight increase, especially by 75% and 100% in the addition of steam, as can be seen in the figure 6. The addition of 75% steam resulted in a rise in CO content from 14.7% to 16.8%. The shift in the ER from 0.29 to 0.35 causes the CO in syngas to decrease slightly.

Interestingly, the 25 percent and 50 percent addition of steam directly causes CO and CH₄ depletion. The addition of 25 percent and 50 percent steam allows the reaction of the water gas change to become more active in order to transform CO into CO₂ and H₂. As can be seen in the figure 4 and figure 7, H₂ and CO₂ are strongly increased by the addition of steam by 25 percent and 50 percent, followed by a sharp decrease in CO (figure 6). In the figure 7, it can be shown that the addition of steam
causes the CO₂ to be low and has a positive effect on the quality of syngas by up to 75 percent and 100 percent.

As can be seen in the figure 8, the quality of the syngas represented by the lower heating value (LHV) has decreased along with the increase in steam processing by up to 50 percent. The key cause is a rise in CO₂ and a decrease in the contents of CH₄ and CO. The highest LHV of syngas, namely 6.35 MJ/Nm³ at ER 0.29, is able to provide when the addition of 75 percent steam. The high LHV, with the addition of 75% steam, the result is high CGE. With the addition of 75% steam and ER 0.35, the highest CGE was reached at 67.25 percent as shown in figure 9. This LHV is comparatively similar to the results of previous biomass / coal co-gasification studies, namely 6.07 MJ/Nm³ [13].

The figure 10 shows CCE with steam addition from 0 percent to 100 percent. It can be seen that the CCE ranges from 77.0 to 86.2 percent. In co-gasification between biomass and coal, the addition of steam as a gasification agent causes a small decrease in the ability to convert carbon. This implies that oxygen in the air is more reactive than steam to carbon conversion, but it is also not automatic that air can be assumed to be better as a gasification agent because if viewed from other performance parameters,
the CGE, LHV, and combustible gas compositions in syngas are actually better formed when using a mixture of steam and air of 75% as a gasification agent compared to pure air or pure steam.

There is also a sharp drop in temperature along with the addition of steam as a gasification agent, aside from the numerous reaction behaviour influences and changes or shifts due to the addition of water vapor. For example, with the addition of 75% steam, the temperature of the gasification reactor becomes 770-776°C, as can be seen in the figure 11, since the presence of steam allows the endothermic reaction to become more active. This temperature is reasonably comparable to the findings of previous biomass-coal co-gasification tests, namely 650°C to 850°C [13]. Therefore, the benefit of using a mixture of air and steam as a gasification agent is that holding the reactor at a temperature of more than 700°C needs no additional energy, so this technique is assumed to be more effective and efficient than using pure steam if high-quality syngas with low contents of hydrogen are needed.

Figure 11. Syngas temperature of co-gasification between biomass and coal for a various steam-air mixtures and ER

4. Conclusions
Biomass co-gasification modelling has been done with coal where steam and air are the gasification agents used. At ER 0.35, the addition of up to 75 percent water vapor provided the best gasification efficiency. With the addition of steam, the combustible gases shift where the dominant reaction is endothermic reactions such as water gas reaction and methane reforming reaction in the presence of steam. In biomass and coal co-gasification, the use of pure water vapor is not recommended because it causes a substantial drop in temperature, so that the reaction rate, performance, and fuel gas also decrease. The cost effect of adding steam must be further investigated because steam with a temperature of 200°C is created from a boiler with a lot of fuel as opposed to free air.

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