Pellet plant energy simulator

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Abstract. The Pellet Plant energy simulator is a software based on advanced algorithms which has the main purpose to see the response of a pellet plant regarding certain location conditions. It combines energy provided by a combined heat and power, and/or by a combustion chamber with the energy consumption of the pellet factory and information regarding weather conditions in order to predict the biomass consumption of the pellet factory together with the combined heat and power, and/or with the biomass consumption of the combustion chamber. The user of the software will not only be able to plan smart the biomass acquisition and estimate its cost, but also to plan smart the preventive maintenance (charcoal cleaning in case of a gasification plant) and use the pellet plant at the maximum output regarding weather conditions and biomass moisture. The software can also be used in order to execute a more precise feasibility study for a pellet plant in a certain location. The paper outlines the algorithm that supports the Pellet Plant Energy Simulator idea and presents preliminary tests results that supports the discussion and implementation of the system.

1. Introduction

Wood pellets are a modern form of densified biomass fuel with consistent quality (low moisture content, high energy density and homogeneous size and shape). Consistent fuel quality makes pellets a suitable fuel type for producing electricity and/or heat for all areas of application, from stoves and central house heating systems to large scale plants, with practically complete automation in all these capacity ranges [1].

Before the wood pellets leave to their final destination they have to be produced in a pellet factory. In order to ensure the maximum profitability for a pellet factory, the wood pellets should have a quality according to international standards [2], and the pellet production should reach the nominal capacity during the entire working period.

Before erecting the pellet plant, instead of sizing the pellet factory according to the annual average of biomass moisture content, of ambient relative humidity and temperatures, instead of selecting the dryer using the average evaporation rate at average conditions of the location ambient, a better approach is to dimension the pellet factory according to historical weather data [3] from the respective location, or by using the data from a trustworthy weather forecast.

By using this weather data [3] the pellet factory can be sized better ensuring a longer working period at the nominal power. This can be possible by using the Pellet Plant energy simulator.
The idea of Pellet Plant Energy Simulator depicted in this paper combines information regarding location’s historical weather data [3] (temperature, relative humidity), biomass availability, biomass moisture content [4] and pellet production [5] in order to:

- Calculate the amount of biomass consumption for the next simulating period on simulation step basis;
- Calculate the amount of pellets that can be produced for the next simulating period on simulation basis;
- Calculate the thermal energy required to evaporate the water from the biomass in order to reach the desired pellets humidity;
- Simulate the psychometric diagram [6], [7], [8] for calculating the required dryer inlet thermal energy, temperature and volumetric air flow rate;
- Calculate the biomass consumption of the combined heat and power plant and/or combustion chamber;
- Calculate the produced thermal energy and volumetric flue gas, with its temperature and enthalpy by the combined heat and power plant and/or combustion chamber;
- Calculate the electrical energy produced by combined heat and power plant (in case of using it);
- Calculate the percentage of the charcoal amount into the amount of biomass combusted in the combustion chamber (in case of using a down draft gasification plant [9] as combined heat and power plant);
- The combustion chamber working range (partial load/maximum load).

The Pellet Plant Energy Simulator can be used by investors as a tool in helping to execute a more precise feasibility study, or by pellet and dryer manufacturers for a better dimensioning of pellet factory machinery.

2. Overview of the system
The following diagram (Figure 1) depicts the overall idea of the Pellet Plant Energy Simulator.

![Figure 1. Pellet Plant Energy Simulator Overview](image-url)
The necessary information and how it is being used can be described as follows:

1. The inputs are inserted by the user regarding:
   a) Biomass chemical composition (Figure 3A) plus charcoal chemical composition (Figure 3A) in case of using a downdraft gasification plant (information obtained after Instituto de Carboquimica from Zaragoza, Spain, was analyzing the samples of biomass and charcoal) in order to calculate the biomass heating value [10];

   ![Figure 3A. Biomass and Charcoal chemical composition](image)

   ![Figure 3B. Pellet Plant Location data](image)

   b) Combined heat and power plant data (Figure 4) for calculating the electrical and thermal energy produced. As a combined heat and power plant was used a downdraft gasification plant [11] combined with a gas engine [12];
c) Data about the pellet factory (Figure 5) (e.g. pellet production and operating hours, the drier’s temperature ranges) in order to ensure that the quality of pellets is following European standards [2];

![Figure 5. Pellet Factory input data](image)

d) Location (Figure 3B).

2. The weather data (Figure 1) is either entered manually, either downloaded from a website [3] for providing the system with information regarding the weather such as temperature or humidity conditions during the simulation period in order to calculate the enthalpy of the ambient air flow and of the inlet and outlet dryer air flow [13].

3. By using the temperature and relative humidity from weather data, using the wood equilibrium moisture content formula [4] (Figure 1), the biomass moisture content [4] is estimated in order to calculate the mass flow rate of dry biomass and to calculate the heat together with its specifications required for drying the biomass.

4. The overall efficiency of the system is reported according to the annual biomass consumption of the plant (Figure 1).

5. The air flow entering in the combustion chamber for ensuring a total combustion of the biomass and charcoal, comes mainly from the syngas cooling system and from the engine cooling system. The air flow entering in the combustion chamber is adjusted with the help of outside air. If the amount of inserted outside air for adjusting the air mass flow coming from cooling the syngas and the engine is negative (described as failure in Figure 1), it means that a part of the heat recovered form syngas and engine cooling systems is given away resulting in a decrease of the overall efficiency of the system. In order to minimize the wasted heat, the inlet temperature of the dryer has to be decreased until the amount of inserted outside air becomes 0 or positive.
The Pellet Plant Energy Simulator is based on advanced algorithm that is using all the information depicted above in order to calculate and predict the pellet plant biomass consumption (pellets raw material plus biomass consumption of the combined heat and power plant and of the combustion chamber) more accurate than the conventional methods. It can also calculate which thermal energy source has to be used at each step of the simulation (only the combustion chamber at certain percentage from its maximum capacity, or both the combustion chamber at a certain percentage from its maximum capacity together with the combined heat and power plant) resulting in indicating the simulation steps when it is recommended to plan the maintenance of the combined heat and power plant (the charcoal cleaning of the gasification plant and maintenance of the engine).

In the end, the user is able to analyze the amount of biomass required in each simulation step in order to produce enough thermal energy necessary for a certain production of pellet by using the most energy efficient source.

The entire software has been developed using Visual Basic Application from Microsoft, mostly because of the good communication with Excel, a software used in feasibility studies.

Features of the Pellet Plant Energy Simulator:

1. Design Parameters page (Figure 2), containing 49 inputs (regarding location, biomass, pellet production, dryer, combustion chamber, biomass and charcoal chemical composition (section II.1.a.) and finally the gasification unit together with the engine) and 2 option buttons for selecting the dryer type (with or without recovering system).
2. Quick Results page (Figure 6), containing 68 results and 2 buttons:
   - “Gasifier ON”: When this button is activated the gasification plant is operating and when is deactivated it is not operating;
   - The second button called “Show results” is displaying 68 results of a quick simulation (33 results for the hottest day, another 33 results for the coldest day), the required part load for the combustion chamber and the maximum amount of extra air flow rate at the end of the dryer in order to keep a constant flow of the flue gas coming from the dryer so the silo can ensure lower polluting emissions in the atmosphere;
   - The white boxes are displaying the results regarding the hottest day during the future simulation, and the blue boxes are displaying the results regarding the coldest day during the simulation;
   - “%Chamber Min/Max” represents the required part load for the combustion chamber;
   - “Cleaning ventilator Maximum air flow rate” (Figure 6) represents the maximum amount of extra air flow at the end of the dryer in order to keep a constant flow of the flue gas coming from the dryer for ensuring low amount of polluting emissions in the atmosphere.
Figure 6. Pellet Plant Energy Simulator - “Quick Results” page

3. Simulation Diagram page (Figure 7):
   - One Button for activating or deactivating the gasification plant operation;
   - One combo box for seeing the simulated values according to the date for which the weather data was defined (See Related accessories, described above);
   - One diagram showing the system and the simulated parameters for each component.

Figure 7. Pellet Plant Energy Simulator - "Simulation Diagram" page

4. Charts page (Figure 8)
   - The first box called “Simulation Charts”, represents the list of charts of different results according to the simulated period;
- The second box called “Range charts” contains a list of charts showing the response of the pellet factory with or without the gasification plant according to three main parameters (Ambient Temperature, Ambient Relative humidity, and Biomass Moisture Content);
- Finally the selected chart is displayed.

![Pellet Factory Energy Simulator](image)

**Figure 8.** Pellet Plant Energy Simulator - "Charts" page

5. “Simulation” button for running the simulation according to the inputs entered on the design parameters page (point 1).

3. Software Development

The main idea behind Pellet Plant Energy Simulator is how to estimate/predict more accurate biomass consumption in a pellet plant in order to execute a more precise pellet plant feasibility study and a better management of the biomass acquisition in such plant.

After getting all information depicted above (Section II), the software can decide the best approach in calculating when it is more energy efficient to the combustion chamber with or without the combined heat and power plant unit.

First step of the calculations starts from the pellet production and the biomass consumption of the combined heat and power plant data, together with the initial and final biomass moisture content in order to calculate the mass flow rate of dry biomass through the drier.

Afterwards the absolute humidity of the biomass at the drier inlet (dry basis) is calculated from the initial biomass moisture. Similar to how the absolute humidity of biomass at the drier inlet was calculated, by using the final biomass moisture content the absolute humidity of biomass (dry basis) at the drier outlet it is calculated (eq. 1).

\[
\text{AH}_{\text{biomass (dry basis)}} = \frac{\text{Biomass moisture content}}{100 - \text{Biomass moisture content}} \times 100 \tag{1}
\]

The absolute humidities and enthalpies of drier inlet and outlet flue gases were calculated by generalizing the psychometric chart [6], [7], [8] and using the known values of ambient temperature and relative humidity together with the inlet and outlet temperatures of the drier.
By using the biomass mass flow rate, and by knowing the absolute humidity of biomass at the inlet and at the outlet of the drier, and from the absolute humidities of drier inlet and outlet flue gas, the dry air mass flow rate is calculated using a mass balance on the solvent [14] (eq. 2).

\[
M_{f, \text{air}} \times (AH_{\text{out}} - AH_{\text{in}}) = M_{f, \text{biomass}} \times (AH_{\text{biomass, in}} - AH_{\text{biomass, out}})
\]

(2)

From the enthalpies of the drier inlet and outlet flue gas, and from the dry air mass flow rate the gross heat is calculated (3). Then the efficiency of the drier is taken into consideration (4).

\[
Q_{\text{gross}} = M_{f, \text{air}} \times \Delta H
\]

(3)

\[
Q_{\text{net}} = Q_{\text{gross}} \times Eff
\]

(4)

Next, by using the heat recovered from the gasification plant [11] (heat recovered from the syngas cooling system and the heating value contained by the charcoal) and from the gas engine [12] (heat recovered from the engine cooling system and from the exhaust gases), using first law of thermodynamics the total amount of thermal energy recovered from the combined heat and power plant is calculated (5).

\[
Q_{\text{CHP}} = Q_{\text{charcoal}} + Q_{\text{syngas}} + Q_{\text{engine}} + Q_{\text{exhaust}}
\]

(5)

By knowing the amount of thermal energy required by the drier and by knowing the amount of energy produced by the combined heat and power plant, the energy required to be produced by the combustion chamber it is calculated (6).

\[
Q_{\text{combustion chamber}} = Q_{\text{dryer}} - Q_{\text{CHP}}
\]

(6)

Next, according to the biomass chemical composition and the heat required to be produced by the combustion chamber, the biomass flow into the combustion chamber is calculated (7).

\[
MF_{\text{biomass into combustion chamber}} = \frac{Q_{\text{combustion chamber}}}{\text{Biomass Low Heating Value}}
\]

(7)

From the biomass and charcoal flow into the combustion chamber the air flow rate required for a full combustion of the biomass and charcoal is calculated (8).

\[
M_{f, \text{combustion air}} = \text{excess air ratio} \times \frac{1.04 \times C + 1.55 \times H + 0.70 \times S - 0.70 \times O}{0.11}
\]

(8)

Where C, H, S and O represents the biomass and charcoal chemical composition.

After comparing different configurations of the recovered heat flows, the most efficient way is found to be when most of the air flow required for a full combustion comes from the low temperature heat recovered from the combined heat and power plant. This is because the air mass flow will be reduced, resulting in higher temperatures which are offering the possibility to work also with high temperature driers.

The resultant flue gas coming from the combustion chamber is mixed with the engine exhaust gases and if it is necessary the temperature of the resultant flue gas is regulated with outside air in order to respect the working temperature ranges given by the manufacturer of the components.
4. Test Results

Four different tests were made, using the Pellet Plant Energy simulator in order to see which configuration of a pellet plant fits better in Vaggeryd, Sweden. This location was chosen due to the surrounding biomass availability and due to the relatively low ambient temperature, which increased the differences in the systems efficiencies. Afterwards the Vaggeryd weather data was downloaded and inserted into the software, and the inputs were entered (as in section 2).

Four different tests were made:
1. Pellet plant with constant dryer inlet volumetric air flow rate during the simulation period;
2. Pellet plant with constant dryer inlet temperature during the simulation period;
3. Pellet plant with a varying inlet temperature during the simulation period;
4. Pellet Plant with a dryer with recovering system up to 30% from dryer outlet volumetric air flow rate.

The test results were compared with the traditional method used in industry were the pellet plants were dimensioned according to annual average of dryer evaporation rate reported to normal ambient conditions, biomass moisture content, location relative humidity and temperature.

By comparing the results (Figure 9) of the simulations it can be concluded that the most energy efficiency configuration is when the dryer with the recovery system is used, providing the lowest evaporation rate (average: 0.80 kW/water kg) during the simulation period. The worst results were obtained by the configuration which uses the normal dryer and the same dryer inlet temperature during the entire simulation period, (average: 1.03 kW/water kg). The dryer without the recovery system, but with a variant temperature and a variant volumetric air flow at the drier inlet during the year, provides the second lowest value for the evaporation rate (average: 0.88 kW/water kg) during the simulation period. Finally the dryer without the recovery system, with a variant inlet dryer temperature and constant volumetric air flow during the year provides an evaporation rate around 0.94 kW/water kg. By comparing the results (Figure 9) of the simulations with the traditional method, it can be seen that the traditional method has a significant error.
Regarding the viability of the plant, the best results (Figure 10 and Figure 11) are obtained with pellet plant with a dryer without recovery system and with the same volumetric air flow rate during the entire year, due to the reason that the partial load of the combustion chamber is down to 15% (from 5500 kg wood/h to 850 kg wood/h, representing the minimum partial load according to the manufacturer - point where all the other configurations were failing) and the maximum percentage of charcoal in biomass is 18% (from the experiments done, for a good ignition and combustion, the maximum percentage of charcoal presence in biomass was 20%).

A huge advantage in using the simulator can be seen at this point, because in the traditional method it is not taken into consideration that the combustion chamber in reality has to run at minimum partial load during the hottest days of the year, which sometimes is impossible to be reached.

**Table 1. Simulations results comparison**

|                           | Normal Dryer constant inlet V.f. | Dryer with recovering System 0% | Normal Dryer constant inlet temperature | Normal dryer varied inlet temperature | Dryer with recovering system | Unit | Error |
|---------------------------|----------------------------------|---------------------------------|----------------------------------------|--------------------------------------|------------------------------|------|-------|
| Operating hours per year  | 7 000                            | 7 000                           | 7 000                                  | 7 000                                | 7 000                        | h    | -     |
| Annual pellet production  | 50 000                           | 50 000                          | 50 000                                 | 50 000                               | 50 000                       | Tons | -     |
| Annual pellet raw material| 87 187                           | 87 666                          | 87 432                                 | 87 189                               | 77 917                       | Tons | 11%   |
| Evaporation rate          | 0.74-0.89                        | 0.82-1.10                       | 0.96-1.11                              | 0.82-0.99                            | 1.16                         | kW/kg| 27%   |
| Percentage charcoal in biomass | 36%                             | 18%                             | 18%                                    | 23%                                  | 4%                           | -    | 14%   |
| Combustion chamber partial biomass load | 10%                             | 15%                             | 12%                                    | 13%                                  | -                            | -    | -     |
| Annual combustion Chamber biomass consumption | 15 939                           | 21 140                          | 27 443                                 | 19 894                               | 26 047                       | Tons | 23%   |
| Annual biomass consumption | 103 126                          | 108 806                         | 114 875                                | 107 083                              | 103 964                      | Tons | 4%    |

**Figure 10.** Comparison between simulations biomass flows into the combustion chamber
Finally it can be concluded that regarding both energy efficiency and plant viability the most suitable Pellet Plant in cogeneration with a Down Draft gasification plant regarding the Vaggeryd in Sweden should include a normal rotary dryer using the same volumetric air flow rate during the entire period in order to avoid an external ventilator at the end of the dryer for cleaning the outlet volumetric air flow rate.

Using this configuration the evaporation rate will be around 0.94 kW/evaporated kg of water, and biomass consumption in the chamber around 21 000 tons/year, which together with the pellet raw material and the CHP plant biomass consumption results in a biomass consumption of the pellet plant of around 110 000 tons/year, and a production of 50 000 pellets/year.

5. Future Work
The system offers a number of interesting areas for future work. First of all because this is a preliminary version where the preventive maintenance is planned manually, but an automated feature can be included in the next version. In the actual state, the pellet plant has to be adjusted according to the outputs of the simulation by the plant operator, but by creating an interface to support actual hardware all this can be done by a user of the interface. Further on, can extend it with a website and/or applications for mobile phones or tablets, so that the system can be monitored remotely.

6. Conclusion
This paper shows the application of leading edge technology within the area of pellets and sustainable energy, implementing an autonomous system capable of predicting the response and the amount of biomass required for operating a pellet factory in cogeneration with a combined heat and power plant based on the weather collected data and on the weather forecast. An overview of the system has been presented as well as the key characteristics of the software. In the end different test results were compared (including the traditional method used in the industry). Those results together with the comparison between them demonstrates the valid behavior of Pellet Plant Energy Simulator.

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