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Energy and Exergy Analysis on Bubbling Fluidized Bed Gasifier Using Aspen Plus Simulation

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Abstract: In this study, exergy and energy analysis were investigated for gasification of almond shell in bubbling fluidized bed gasifier by using Aspen Plus simulation. The effect of temperature and steam/fuel ratio, which are important parameters for the gasification process, on energy and physical exergy values of syngas were examined. The results of the simulation showed that the exergy and energy values of the syngas were significantly affected by the change in gasifier temperature and steam/fuel ratio. Increasing the steam/fuel ratio influenced the energy and exergy value in a negative manner. However, H_2 and CO compositions in the syngas and energy and exergy values of the syngas increased with the enhancement of temperature. The developed bubbling fluidized bed gasifier model will create knowledge for researchers interested in the gasifier process.

Keywords: Gasification, bubbling fluidized bed gasifier, energy and exergy analysis, Aspen Plus, biomass.

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INTRODUCTION

Due to global concerns, researchers have focused to develop new and more efficient energy systems in order to supply the increasing energy demands in a sustainable way (1). Among renewable energy sources, biomass is getting considerable attention because of its low environmental impact, reducing carbon emissions, and the handle of converting organic-based wastes to useful energy (2). Biomass resources can be found in different forms such as forest residues, agricultural residues and crops, and municipal wastes. Biomass properties such as heating value, elemental composition, moisture, ash content, and volatile matter content are used to select proper biomass type for certain applications (3).

Biomass gasification is a promising process that converts biomass into synthesis gas (syngas) under different atmospheres such as O_2, CO_2, air and/or steam. Generally, the syngas can be used for generation of fuels, chemicals, and power, it produced in the gasification process is a combination of carbon monoxide (CO), methane (CH_4), carbon dioxide (CO_2) and hydrogen (H_2). Compared with air gasification, steam gasification obtains a better performance owing to more combustible gases are produced (4, 5). The gasification process takes place in the gasifier which is divided into three main groups with respect to their working principles, namely fixed bed, fluidized bed, and entrained flow gasifiers (6). They are selected according to operational conditions, fuel amounts, fuel properties such as shape, size, ash and moisture content (7). Bubbling bed gasifier is the type of fluidized bed, it has excellent heat and mass transfer, higher working capacity, and flexibility for the particle size of fuel (8).

Energy is conserved with respect to the first law of thermodynamics; it flows in or out of a system with heat transfers, mass flows, and work interactions. Exergy is the useful work potential of a certain amount of energy at specified state. Exergy measures and compares the ability to do work between energies of the same form. Energy consumption and losses of the system are evaluated by using the first law of thermodynamics. Exergy analysis is related to the second law of thermodynamics that also provides information about the system's internal inefficiency (9-12). The destroyed exergy is related to the generated entropy. Exergy analysis can provide to design thermal system more efficient by decreasing the present inefficiencies.

Aspen Plus is a reliable software for designing and optimization of thermochemical processes. Researchers try to improve the gasification process for different operational conditions using by Aspen plus simulator based on the Gibbs free energy minimization. Biomass gasification technique is complex, and the process performance can be influenced by several parameters (13). Modeling and simulation can help to understand and analyze the effects of different parameters on the outcome variables (14, 15). Researchers have used Aspen Plus to model the gasification process. Beheshti et al.(16) modeled a bubbling fluidized bed gasifier under the steam-air atmosphere to evaluate effect of operational parameters on the syngas composition and hydrogen yield by using Aspen Plus. Begum et al. (17) examined the performance of the fixed bed gasifier model while the air-fuel ratio, gasifier temperature changed for different biomass feedstocks under steady-state condition via Aspen Plus simulation. Acar et al. (18) recently discussed the almond shell gasification process which used chemical equilibrium and restricted chemical equilibrium models. They compared the two models with experimental results and investigated the influence of gasification conditions on the syngas composition and lower heating value of syngas.

In this study, a new developed bubbling bed gasifier model was used to conduct almond shell gasification process under steam atmosphere by using Aspen Plus program. Unlike other literature studies, the main objective is to investigate the effect of temperature and steam/biomass ratio on the H_2 and CO composition of syngas accordingly exergy value. Performance of the gasification process of almond shell was evaluated where exergy issue is considered, and optimum operational conditions were determined for new developed bubbling bed gasifier model using Aspen Plus software.

MATERIALS AND METHODS

The determination of the biomass properties such as proximate, ultimate analysis and heating value is important to achieve efficient gasification performance. Almond shell is agricultural waste and has high energy potential to be used as feedstock in the bubbling fluidized bed gasifier (19). Ultimate and proximate analysis results of the almond shell, wood pellet, and tire have been used as feedstock in the developed model and validation respectively are presented in Table 1.

Table 1. Proximate and ultimate analysis of almond shell (20), wood pellet(21) and tire(22).

		Almond Shell	**Wood Pellet**	**Tire**
Proximate Analysis (wt %)	Volatile Matter	76.1	80.6	64.21
	Ash	3.04	0.89	6.68
	Moisture	7.85	9.8	0.68
	Fixed Carbon	20.86	18.51	29.11
Elemental Analysis (wt%)	Sulfur	0.03	0.004	2.48
	Oxygen	40.1	41.36	2.62
	Hydrogen	5.98	7.09	7.97
	Carbon	50.14	50.57	80.1
	Nitrogen	0.74	0.089	0.15

A bubbling fluidized bed gasifier model for the steam gasification of almond shell was conducted in the Aspen Plus process simulator through the combination of reactors, mixers, heat exchangers, and separators. Stream and block information were specified, and the thermodynamic property method was selected as Soave-Redlich-Kwong to perform the simulation, where HCOALGEN and the DCOALIGT models as a physical property method was selected to calculate the enthalpy and density of almond shell. Steam was selected as a gasifying agent. The bubbling fluidized bed gasifier model is shown in Figure 1.

Gibbs's free energy minimization was implemented in the developed model. Bubbling fluidized bed gasifier was modeled under some assumptions:

- The model is in a steady-state, gasification parameters do not change with time.
- All gases are ideal.
- There is no pressure decrease in the gasifier.

- The ash in the almond shell is inert and does not participate in the gasification reactions.
- The temperature distribution is uniform in the gasifier.
- All the reactions reach equilibrium.

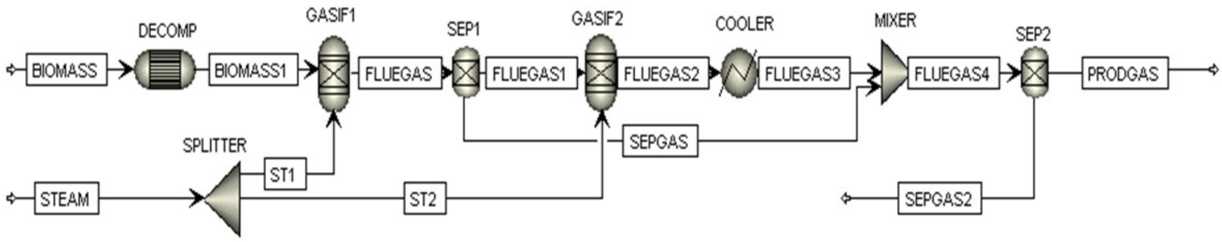


Figure 1: Bubbling fluidized bed gasifier flowsheet in Aspen Plus.

Almond shell was introduced with its proximate and ultimate analysis results as nonconventional component to the stream named BIOMASS temperature at 20 °C with 25 kg/h flow rate. In DECOMP reactor, RYIELD type reactor was selected and the feed was decomposed into its conventional components based on the sulfur, proximate, and ultimate analyses of the almond shell. RGIBBS reactor was used to represent pyrolysis and gasification zones. Low and high temperature pyrolysis takes place in the GASIF1 the temperature around 300 °C. SEP1 block separates the certain amount of CH_4 and CO before the gasification part. Gasification reactions are formed in GASIF2 reactor and operation temperature changes between 700-1000 °C. Steam flow rate is changed between 10-40 kg/h and flow is split into two streams equally to create a steam atmosphere in the GASIF1 and GASIF2 by using SPLITTER. COOLER is used to cool or keep constant the syngas temperature at 800 °C after GASIF2 reactor. SEPGAS and FLUGAS3 is mixed in the MIXER. Water, ash, and H_2S were separated from FLUEGAS4 to clean product gas via SEP2 block. Gasification reactions which take place in bubbling bed gasifier are submitted in Table 2 (23).

Gasification agent, biomass properties, and operating conditions affect the gasification reactions directly.

Table 2. Gasification reactions in bubbling fluidized bed gasifier

$C+2H_2 \leftrightarrow CH_4$ (methane formation reaction)	(1)
$C + 1/2O_2 \rightarrow CO$ (partial oxidation reaction)	(2)
$CO + H_2O \leftrightarrow CO_2 + H_2$ (water gas shift reaction)	(3)
$C + CO_2 \leftrightarrow 2CO$ (Boudouard reaction)	(4)
$H_2 + S \rightarrow H_2S$	(5)
$C + H_2O \leftrightarrow CO + H_2$ (water gas reaction)	(6)
$CH_4 + H_2O \leftrightarrow CO + 3H_2$ (steam reforming reaction)	(7)
$C + O_2 \rightarrow CO_2$ (complete oxidation reaction)	(8)
$H_2 + 0.5O_2 \rightarrow H_2O$ (hydrogen oxidation)	(9)

The model in this study was simulated between the gasifier temperature 700-1000 °C, and the steam flow rate 10-40 kg/h to investigate the effect of operational conditions on the syngas composition and exergy value. Sensitivity analysis was implemented to conduct parametric studies.

RESULTS

Model Validation

The developed model was successfully validated with two data sets from literature. In the first data (21), the wood pellet was used as a feedstock and gasification process carried out at 800 °C under air atmosphere. The model was also validated with steam gasification data (22), where tire samples were used as fuel under steam atmosphere in bubbling fluidized bed gasifier. The syngas composition of the model is approximate to experimental gas composition as shown in Table 3.

The model validation results from literature as seen on Table 3 show that the model is robust and have worked properly. However, CH_4 compositions are quite different from experimental results in the literature, while H_2, CO, and CO_2 compositions are very close. Because the model works thermodynamic equilibrium based and residence time could be different in the Aspen Plus model and experimental study.

Parametric Study

Sensitivity analysis was applied to conduct parametric studies after model validation. The effect of gasifier temperature and steam/biomass ratio on the syngas composition and exergy value have been examined.

Table 3. Model validation results with air (21) and steam (22) gasification data sets.

Model validation result with air (21) experimental data set		
Wood Pellet	Fuel (kg/h)	34
Gasifier - 800°C	Air (Nm³/h)	37
Gas Composition	**Literature (%)**	**Model (%)**
H_2	14.5	15.67
CO_2	16	16.44
CO	13.8	13.91
CH_4	4	9.09
Model validation result with steam(22) experimental data set		
Tire Sample	Fuel (kg/h)	0.876
Gasifier – 770°C	Steam (kg/h)	0.331
Gas Composition	**Literature (%)**	**Model (%)**
H_2	48.81	47.87
CO_2	3.30	3.56
CO	3.89	3.2
CH_4	26.37	14.3

Effect of Temperature on Syngas Composition
Gasifier temperature affects the syngas composition as seen in Figure 2. Because of endothermic reactions occurring in the gasifier, syngas composition changes with increasing temperature.

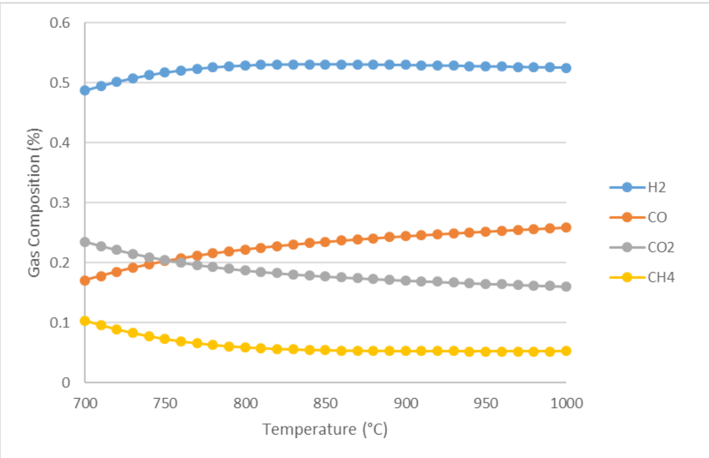


Figure 2. Effect of temperature on the syngas composition.

H_2 and CO composition increased with increasing temperature. On the other hand, CH_4 and CO_2 compositions showed an opposite tendency versus gasifier temperature. This is because higher temperature favors the steam and methane reforming reactions. Boudouard reaction also promotes CO formation, while the CO_2 concentration decreased with enhancing the temperature due to that is more effective when the temperature is higher than 800 °C. H_2 composition reached the maximum value at 850 °C. Increasing temperature above 850°C affected the H_2 concentration negatively. Former studies in the literature show the similar results for effect of temperature on the syngas composition (24-26).

Effect of Temperature on Exergy Value of Syngas
Exergy value is utilized to evaluate system performance. Figure 3 shows the change of syngas exergy value with the temperature in the bubbling fluidized bed gasifier. The studies about the syngas exergy value was discussed in the literature and our results show consistency with them (27, 28).

Exergy value of the syngas is the total value of chemical and physical exergies. Gasifier temperature is associated with physical and chemical exergies as increasing potential energy value and combustible components such as H_2 and CO in the syngas. H_2 concentration change showed the same trend with the exergy value of syngas. Both reached the maximum value at 850°C.

Sensitivity analysis results in Aspen Plus simulation for syngas exergy value according to temperature change were presented in Figure 4.

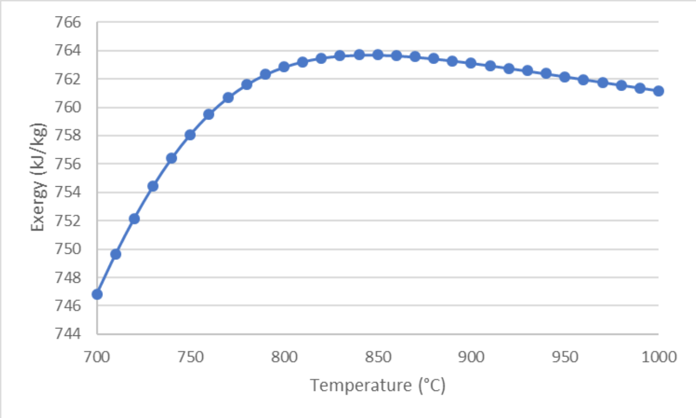


Figure 3. Effect of temperature on the syngas exergy value.

Effect of steam flow rate on the syngas composition

The steam flow rate is an important parameter for steam gasification. Enrichment of the steam flow rate affected the synthesis gas composition as shown in Figure 5. H_2 and CO_2 increased and CH_4 and CO decreased with increasing steam flow rate.

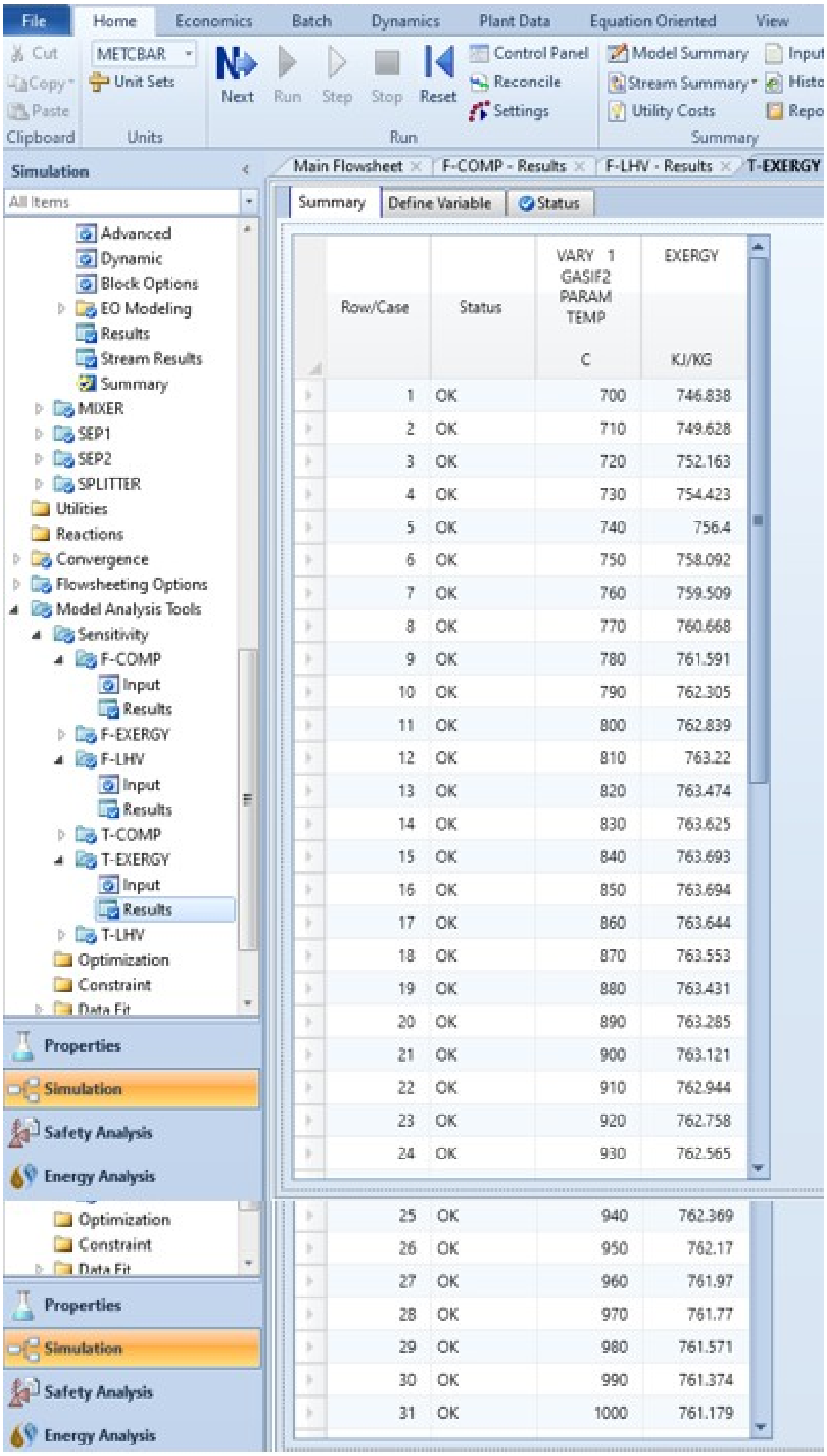
With the addition of steam, water-gas shift, water-gas, and steam methane reforming reactions shift to the product side according to Le Châtelier's principle (29). As a result of all reactions, H_2 concentration increased and CH_4 concentration decreased with steam increases. Increasing of steam flow rate is leading to more complete oxidation reaction, therefore, CO_2 concentration increases and CO concentration decreases. In this study, obtained results from Aspen Plus model show good agreement with the literature studies (30).

Effect of steam flow rate on the syngas exergy value

The effects of steam flow rate on the exergy of syngas were investigated. Figure 6 shows that syngas exergy value, from almond shell gasification under steam atmosphere, demonstrated an increasing trend with steam flow rate increases.

The trend in exergy increase from Figure 6 could be explained by encouragement of hydrogen formation as steam was supplied, which leads to higher exergy content at lower steam flow rate under 30 kg/h. The later increases in the exergy values were resulted from the decreases in the yields of CO. The results show that influence of steam flow rate on the syngas exergy value has similar behavior with literature studies (31).

The results are taken from Aspen Plus and presented in graphic 6 can be seen in the Figure 7 as screenshot in Aspen Plus simulation.



Row/Case	Status	VARY 1 GASIF2 PARAM TEMP (C)	EXERGY (KJ/KG)
1	OK	700	746.838
2	OK	710	749.628
3	OK	720	752.163
4	OK	730	754.423
5	OK	740	756.4
6	OK	750	758.092
7	OK	760	759.509
8	OK	770	760.668
9	OK	780	761.591
10	OK	790	762.305
11	OK	800	762.839
12	OK	810	763.22
13	OK	820	763.474
14	OK	830	763.625
15	OK	840	763.693
16	OK	850	763.694
17	OK	860	763.644
18	OK	870	763.553
19	OK	880	763.431
20	OK	890	763.285
21	OK	900	763.121
22	OK	910	762.944
23	OK	920	762.758
24	OK	930	762.565
25	OK	940	762.369
26	OK	950	762.17
27	OK	960	761.97
28	OK	970	761.77
29	OK	980	761.571
30	OK	990	761.374
31	OK	1000	761.179

Figure 4. Sensitivity analysis results for effect of temperature on the syngas exergy value in Aspen Plus.

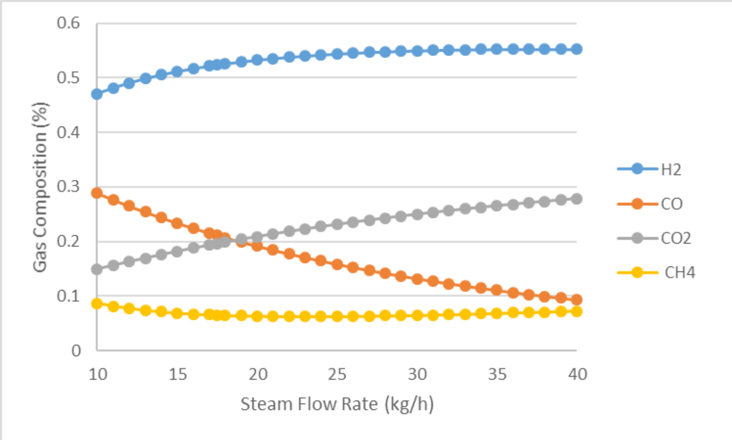


Figure 5. Effect of steam flow rate on the syngas composition.

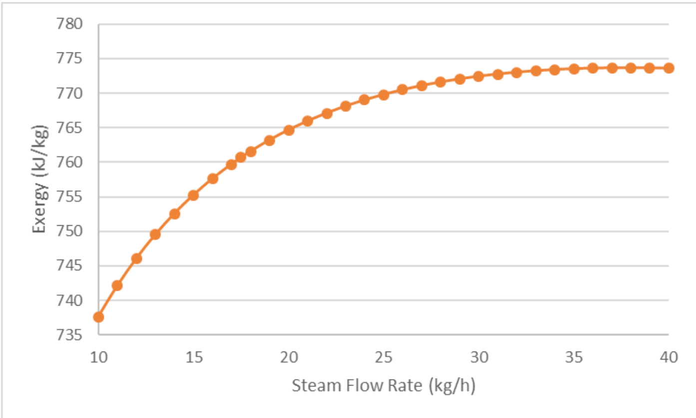


Figure 6. Effect of steam flow rate on the syngas exergy value.

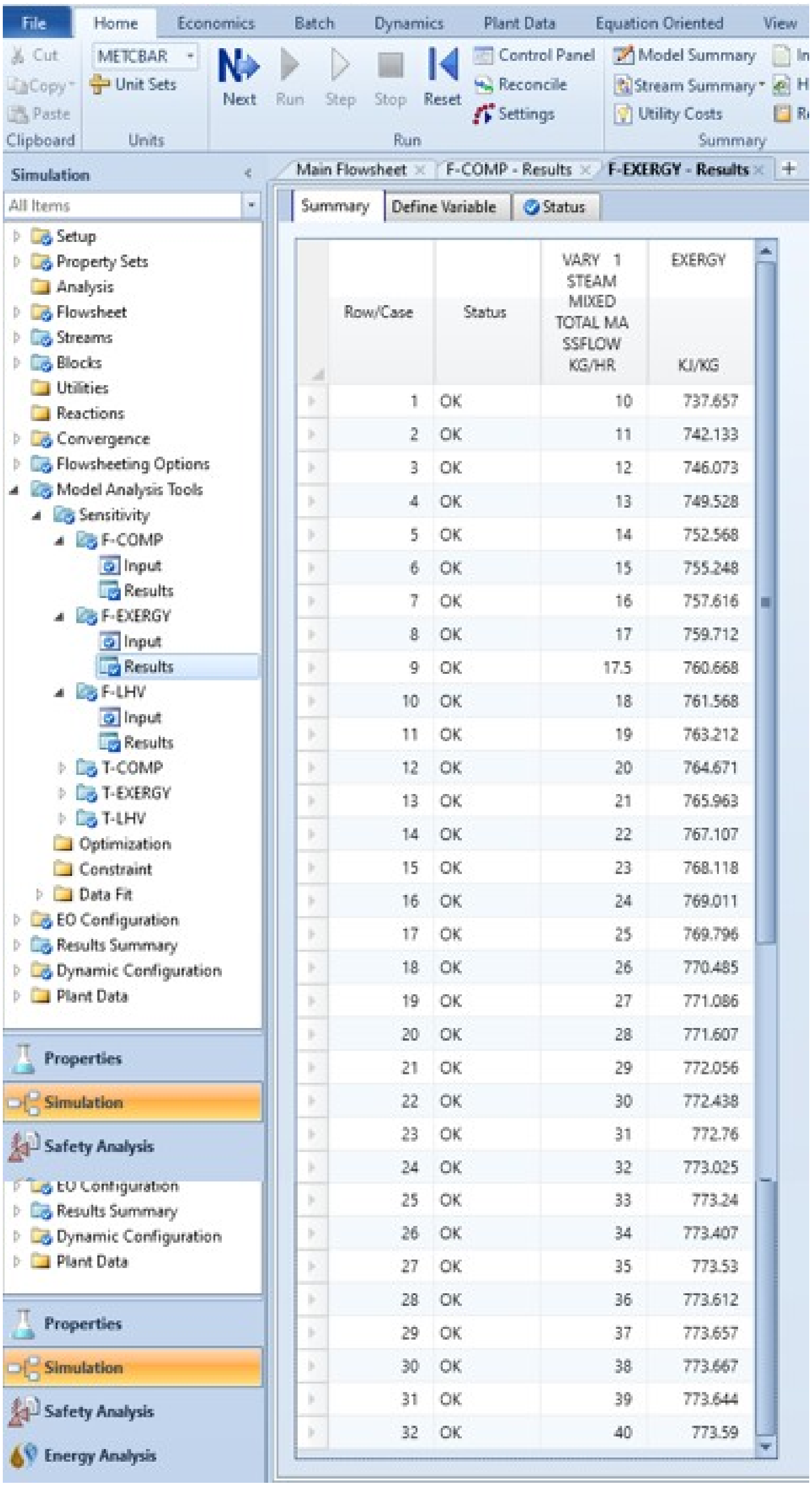


Figure 7. Sensitivity analysis results for effect of steam flow rate on the syngas exergy value in Aspen Plus.

CONCLUSION

The following conclusive remarks were drawn:

- The developed bubbling fluidized bed model was successfully validated with experimental data sets from literature.
- Changing the gasifier temperature showed a significant effect on the syngas composition. H_2 composition increased from 48.74% to 53.11% between the temperatures 700-850 °C, and reached the maximum value at 850 °C, while CO content in the syngas increased from 17.05% to 23.48%.

- Increasing the gasifier temperature enhanced the system energy potential, therefore, the exergy value of syngas increased from 746.83 to 763.70 kJ/kg between the temperature 700 and 850 °C.
- Results represented that the steam flow rate showed considerable effects on H_2 and CO composition in the syngas. H_2 content increased between %47 and %55 and CO content decreased from 28% to 9%, while the steam flow rate raised from 10 to 40 kg/h. Furthermore, the exergy value of syngas increased from 737 to 773 kJ/kg.

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