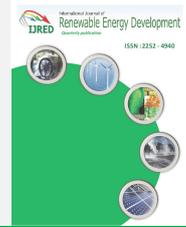




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Research Article

Thermodynamic Study of Palm Kernel Shell Gasification for Aggregate Heating in An Asphalt Mixing Plant

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ABSTRACT. This study evaluated thermodynamically the performance of conversion of palm kernel shells into combustible gas through gasification technology for aggregate heating in a hot-mixed asphalt production plant by developing a thermodynamic model using licensed Aspen Plus v.11 software. The effects of the equivalence ratio (ER) in the gasification process and the amount of combustion air to combustible gas to attain the required aggregate temperature were investigated. The thermodynamic model showed a good agreement with the experimental results based H₂ and CO contain in producer gas which provided by maximum root mean square errors value of 8.82 and 6.42 respectively. Gasification of 30–35 kg of palm kernel shells in a fixed-bed gasifier reactor using air as a gasifying agent at an ER of 0.325–0.350 generated gaseous fuel for heating 1 ton of aggregate to a temperature of 180–200°C with combustion excess air 10%–20%. ©2020. CBIORÉ-IJRED. All rights reserved

Keywords: thermodynamic study, gasification, palm kernel shell, aggregate, hot-mixed asphalt

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1. Introduction

In recent years, the utilization of renewable energy has received more attention due to the depletion of fossil fuels. Almost all sectors in terms of industry, civilization and transportation still relies on various fossil fuels as their main energy sources. According to Indonesia Presidential Decree No. 79 of 2014 for a national energy mix policy, the total contribution of new and renewable fuels as the main energy source shall be 23 % by 2025. For this reason, many research have been conducted to discover potential renewable energy resources (Cheng & Hu, 2010); (Erinofiardi et al., 2017); (Ki, Kurniawan, Lin, Ju, & Ismadji, 2013); (Nasruddin et al., 2016); (Silitonga et al., 2011). As reported, the renewable energy resource in Indonesia with the most potential is palm oil (Indrawan et al., 2017), as Indonesia's palm oil production supplies almost 62% of the world's palm oil demand (Febriansyah, Setiawan, Suryopratomo, & Setiawan, 2014). Meanwhile, the production of 1-ton palm oil can produce many types of solid waste, such as 0.3 ton of palm kernel shell (PKS), 1-ton of empty fruit bunch (EFB), or 0.7 ton of palm mesocarp fiber (PMF) (Husain, Zainac, & Abdullah, 2002). PKS has the highest calorific value compared to the other solid wastes (PKS: ± 15 MJ/kg; EFB: ± 5 MJ/kg; PMF: ± 11 MJ/kg) and can potentially be used to replace fossil fuels as the main energy source for many purposes. Recently, some PKS, together with PMF, has been used as a fuel for

boilers to produce heating steam and electricity, but some is exported outside Indonesia (Wirawan, 2007).

Asphalt Mixing Plant (AMP) industries that support highway construction are likely to use PKS for the heating of aggregates before mixing with hot asphalt through gasification technology. Traditionally, this heat is supplied by many types of fossil fuel combustion. It is obvious that increasing highway construction activities require more energy for aggregate heating. Every ton of hot-mixed asphalt (HMA) consumes about 315 MJ or approximately 7.6–11.41 L of diesel fuel (Kristjánssdóttir, Muench, Michael, & Burke, 2007). PKS gasification offers a flexible and reliable technology to minimize the dependence on fossil fuel for producing HMA. With a total production of 34.71 million tons of palm oil in 2018, around 11.5 million tons of PKS also will be available for fuel substitution in AMP industries in Indonesia (Husain et al., 2002). A block diagram of a proposed AMP process production system combined with a PKS gasification unit is shown in Figure 1.

PKS enters the gasifier from the belt conveyor and screw feeder. A limited amount of air as a gasifying medium is also added into the gasifier to produce combustible gas with typical composition: 19.5% H₂; 22.3% CO; 3.07% CH₄; 12.4% CO₂; and 3.46% H₂O (Kirsanovs et al., 2017). The gas should be cooled to condense the water content and cleaned to remove unwanted particulates by

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feeding the gas into a water scrubber. The purpose is to maintain the calorific value of the gas. If there is water (vapor) and undesired particulates in the gas, the calorific value of the gas decreases. At the same time, aggregate from the stockpile is fed into the rotary dryer and heated to the required temperature. The heat is generated as the result of combustion between the producer gas and combustion air. After heating, hot aggregate is mixed with the hot asphalt to produce the HMA. In order to deliver good quality HMA, a temperature of 150–200 °C should be achieved (Peinado, de Vega, García-Hernando, & Marugán-Cruz, 2011). Thus, the optimum operating condition of the gasification and heating processes should be controlled properly.

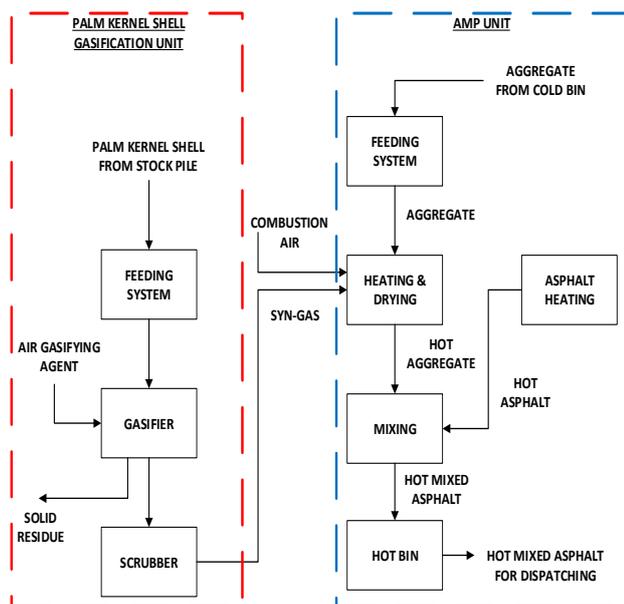


Fig. 1 Block Flow diagram of PKS gasification for aggregate heating in AMP

There are two equilibrium approaches widely used for thermodynamic modelling: a stoichiometric method based on chemical reaction equilibrium constants and (Zogała, 2014). In this study, the non-stoichiometric equilibrium approach was used for gasification process modelling because the several complicated chemical reactions that take place in the process (Table 1). By using this approach, these reactions and their equilibrium constants are not considered in the model (Baruah & Baruah, 2014). Many investigators have reported that this approach delivers a good agreement between simulation and experiment (Doherty, Reynolds, & Kennedy, 2009); (Hannula & Kurkela, 2012); (Adnan, Susanto, Binous, Muraza, & Hossain, 2017); (Adnan & Hossain, 2018); (Puig-Gamero, Argudo-Santamaria, Valverde, Sánchez, & Sanchez-Silva, 2018); (Gu, Tang, Yao, & Chen, 2018). Many similar types of research with special purposes, object studies, parameter studies, and feedstocks have been performed by previous investigators. A thermodynamic study of coal gasification in an entrained gasifier for generating electricity with burner type and input nozzle angle as parameters study has been performed (Lee et al., 2012), while rice straw gasification with variations in gasification medium and ER was also studied

thermodynamically (Gu et al., 2018). The effects of gasifier temperature and ER in two fixed-bed municipal solid waste gasifiers was investigated to determine the most suitable gasification conditions (Chen, Jin, Yan, & Chi, 2013). A thermodynamic study on microalgae gasification reported a relative error of less than 10% (Adnan & Hossain, 2018); (Adnan, Xiong, Hidayat, & Hossain, 2019). PKS gasification in a circulating fluidized bed gasifier was modelled to investigate the effects of gasifier temperature and steam/biomass ratio on producer gas composition (Hussain, Tufa, Azlan, Yusup, & Zabiri, 2016). This work examines the effects of equivalence ratio (ER) for gasification and combustion of producer gas on aggregate temperature by developing a thermodynamic model with Aspen Plus software.

Table 1
Typical gasification reactions at 25°C

Reaction	ΔH_R° (kJ/kmol)	ΔG_R° (kJ/kmol)
Carbon reactions:		
$C + CO_2 \leftrightarrow 2CO$	+172.0	+120.00
$C + H_2O \leftrightarrow CO + H_2$	+131.0	+91.41
$C + 2H_2 \leftrightarrow CH_4$	-74.8	-50.50
$C + \frac{1}{2}O_2 \rightarrow CO$	-111.0	-137.20
Oxidation reactions:		
$C + O_2 \rightarrow CO_2$	-394.0	-394.40
$CO + \frac{1}{2}O_2 \rightarrow CO_2$	-284.0	-257.20
$CH_4 + 2O_2 \leftrightarrow CO_2 + 2H_2O$	-803.0	-801.12
$H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O$	-242.0	-228.61
Water-gas shift reaction:		
$CO + H_2O \leftrightarrow CO_2 + H_2$	-41.2	-28.59
Methanation reactions:		
$2CO + 2H_2 \rightarrow CH_4 + CO_2$	-247.0	-170.50
$CO + 3H_2 \leftrightarrow CH_4 + H_2O$	-206.0	-141.91
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$	-165.0	-113.32
Steam-reforming reactions:		
$CH_4 + H_2O \leftrightarrow CO + 3H_2$	+206.0	+141.91
$CH_4 + \frac{1}{2}O_2 \rightarrow CO + 2H_2$	-36.0	-86.70

2. Materials and methods

2.1 Model development

This work develops a non-stoichiometric thermodynamic model of PKS gasification in a downdraft fixed-bed gasifier for aggregate heating with ER and combustion excess air as parameters. This is based on Gibbs free energy minimization on Eq. (1) where n_i is the mole of species i and μ_i is the chemical potential of species i which is given by Eq. (2). It should be defined that $\Delta G_{f,i}^0$ is the standard Gibbs free energy of formation of species i , R is universal gas constant, T is the reaction temperature, f is fugacity coefficient, P_i is the pressure of species i .

$$G^t = \sum_{i=1}^N n_i \mu_i \quad (1)$$

$$\mu_i = \Delta G_{f,i}^0 + RT \ln \left(\frac{\theta P_i}{p^0} \right) \quad (2)$$

During gasification reactions, it is assumed at ambient pressure that a gas ideal approach is reasonable then Eq. (2) is rewritten to be Eq. (3).

$$\mu_i = \Delta G_{f,i}^0 + RT \ln (y_i) \quad (3)$$

with y_i is mol fraction of species i in the producer gas. Substitution Eq. (3) to Eq. (1) results Eq. (4).

$$G^t = \sum_{i=1}^N n_i \Delta G_{f,i}^0 + \sum_{i=1}^N n_i RT \ln (y_i) \quad (4)$$

Eq. (4) should be differentiated towards n_i and set the value to zero which is minimization of Gibbs energy at certain values of n_i . This results a number of differential equations as many as the involved species. Elemental balances of carbon, hydrogen and oxygen atoms in the reaction system should also be constructed as expressed on Eq. (5) and summed over all the atoms k , it is rearranged into Eq. (6) where a_{ik} is the number of k -th atom of element present in each species i , and A_k is total number of k -th atom of element in the system.

$$\sum_i n_i a_{ik} = A_k \quad (5)$$

$$\sum_k \lambda_k (\sum_i n_i a_{ik} - A_k) = 0 \quad (6)$$

where λ_k is Langrange multipliers. This equation is then added to Eq. (4) without changing the value of G^t as expressed on Eq. (7).

$$F = \sum_{i=1}^N n_i \Delta G_{f,i}^0 + \sum_{i=1}^N n_i RT \ln (y_i) + \sum_k \lambda_k (\sum_i n_i a_{ik} - A_k) \quad (7)$$

Furthermore, Eq. (7) should be differentiated towards n_i and minimization of this equation created a number of algebraic equations. There would be 5 (five) total Gibbs free energy as expressed on Eq. (8) to (12) which represent all considered components.

CH₄:

$$\frac{\Delta G_{f,CH_4}^0}{RT} + \ln(y_{CH_4}) + \frac{\lambda_C + 4\lambda_H}{RT} = 0 \quad (8)$$

H₂:

$$\frac{\Delta G_{f,H_2}^0}{RT} + \ln(y_{H_2}) + \frac{2\lambda_H}{RT} = 0 \quad (9)$$

CO:

$$\frac{\Delta G_{f,CO}^0}{RT} + \ln(y_{CO}) + \frac{\lambda_C + \lambda_O}{RT} = 0 \quad (10)$$

CO₂:

$$\frac{\Delta G_{f,CO_2}^0}{RT} + \ln(y_{CO_2}) + \frac{\lambda_C + 2\lambda_O}{RT} = 0 \quad (11)$$

H₂O:

$$\frac{\Delta G_{f,H_2O}^0}{RT} + \ln(y_{H_2O}) + \frac{2\lambda_H + \lambda_O}{RT} = 0 \quad (12)$$

Elemental balance equations of atom carbon, hydrogen and oxygen should also be determined from palm kernel shell ultimate analysis (Table 2). The elemental balances of each element are formulated on Eq. (13) – (15). Finally, 8 (eight) unknown variables namely λ_C , λ_H , λ_O , n_{CO} , n_{H_2} , n_{CO_2} , n_{H_2O} dan n_{CH_4} at a certain temperature could be determined by simultaneously solving 8 (eight) algebraic equations.

C: $n_{CH_4} + n_{CO} + n_{CO_2} - 1 = 0 \quad (13)$

H: $2n_{H_2} + 2n_{H_2O} + 4n_{CH_4} - 1,513 = 0 \quad (14)$

O: $n_{CO} + 2n_{CO_2} + n_{H_2O} - 0,665 = 0 \quad (15)$

Table 2
Characterization of PKS

Description	Content
Total Moisture (weight/weight)	13.60%
Proximate Analysis (weight/weight dry basis):	
Moisture content	9.50%
Volatile matter	70.50%
Fixed carbon	18.30%
Ash content	1.70%
Ultimate Analysis (weight/weight dry basis)	
Carbon	47.60%
Hydrogen	6.37%
Oxygen	43.93%
Nitrogen	0.31%
Sulphur	0.09%
High Heating Value (MJ/kg dry basis)	18.668

The analysis of gasification process is divided into four stages: drying, decomposition, gasification, and combustion. The PKS is considered as a non-conventional compound with a composition based on the proximate and ultimate analysis. A biomass feed of 30 kg was applied in the simulation for the production of 1 ton of HMA. The PKS drying process is carried out at 105°C in the STOICHIOMETRY REACTOR (MODEL ID: DRY-REAC) to evaporate the moisture content (MC). In this reactor, the stoichiometric of MC in biomass was determined according to Eq. (16).

$$MC \text{ Biomass} = 1/18 H_2O \quad (16)$$

The H₂O formed in this reactor model is separated from the dry biomass by 2-phase FLASH SEPARATOR (MODEL ID: SEP). Water and dry shell exit the flash separator as top and bottom products, respectively. After that, the dry shell decomposes into its single components, C, H, O, N, S, and ash, in a YIELD REACTOR (MODEL ID: DECOMP). The heat needed for drying and decomposition are obtained from the combustion of biomass in the GASIFIER (MODEL ID: Q-DRY, Q-DECOMP). The output from the YIELD REACTOR is fed into the RIGIBSS REACTOR (MODEL ID: GASIFIER) to produce producer gas using limited air according to the ER calculation. A non-stoichiometric equilibrium approach applies in this gasifier by minimizing the Gibbs free energy. Cooling water flows around the gasifier to keep the temperature below the ash fusion temperature. The combustion of producer gas takes place in the RIGIBSS REACTOR (MODEL ID: BURNER) to produce flue gas for aggregate heating at a temperature of 150–200°C, while combustion air is controlled appropriately. The aggregate is defined as a non-conventional compound, following the HCGEN model for general heat capacity and the DENGGEN model for general density. Several assumptions are made in this simulation: steady-state operation, non-adiabatic processes, ideal gas behavior prevailing, negligible tar and char formation at the high temperature of the gasification process, and heat loss ignored.

2.2 Model validation

Experimental data from previous laboratory-scale experiments in fixed bed downdraft gasifier (Jayah, Aye, Fuller, & Stewart, 2003); (Gai & Dong, 2012); (Svishchev, Kozlov, Donskoy, & Ryzhkov, 2016); (Biagini, Barontini, & Tognotti, 2016); (Maneerung, Li, Li, Dai, & Wang, 2018); (Kuhe & Aliyu, 2015) were used to validate the model. The validation also conducted by experiments in the plant. By comparing the H₂ and CO content in the producer gas as the result of experimental data and the model, root mean square error (RMSE) values were calculated to check the accuracy of the model (Gu et al., 2018). This value is defined by Eq. (17), where *N* represents the number of data.

$$RMSE = \sqrt{\frac{\sum_i^n (Experiment_i - Model_i)^2}{N}} \quad (17)$$

ER plays a significant role in the gasification process, as expressed in Eq. (18). A proper ER

$$ER = \frac{\text{mole actual air}}{\text{mole stoichiometric air}} \quad (18)$$

A high ER indicates more oxidation to gasify the biomass; a lower ER produces more char due to pyrolysis. As reported by (Upadhyay, Sakhiya, Panchal, Patel, & Patel, 2019), the optimum ER value is 0.24–0.36. Thus, in the present study the ER value varied from 0.25 to 0.35. By calculating the stoichiometric quantity of air for complete biomass combustion, the value of the ER can be determined for suitable producer gas composition for heating aggregate in the AMP.

3. Results and discussion

Figure 2 describes the developed thermodynamic model of PKS gasification using air as gasifying agent for heating aggregate using licensed Aspen Plus v.11 software which was developed for woody and shell biomass chemical characteristics feedstock. This model was applied for calculating H₂ and CO in industrial scale (Table 3). It showed that RMSE values of H₂ and CO are in the range of 0.80 – 2.15 and 0.21 – 5.83 respectively as described in Table 3. Using the same feedstock, flowrate and gasification operating conditions, the model prediction of H₂ and CO composition in producer gas were compared with the experimental results of each investigator. The highest RMSE values of H₂ and CO content in producer gas are 8.82 and 6.42 respectively (Table 4). These values are in a good agreement with similar studies (Gu et al., 2018), (Adnan & Hossain, 2018), (Omar, Munir, Ahmad, & Tanveer, 2018), (Atnaw, Sulaiman, & Yusup, 2013), (Galindo et al., 2014); thus, the model is feasible in predicting H₂ and CO content in the producer gas resulted from biomass gasification process in a downdraft gasifier for heating aggregate. Then, the model was also reliable for predicting H₂ and CO content in a producer gas as the results of palm kernel shell gasification in an Asphalt Mixing Plant with capacity of 800 kg/batch (AMP-800).

Table 3
 Model validation with experimental data in the plant

Parameter	run-1	run-2	run-3
Flow rate, kg/h	250	250	250
Air flow rate, m ³	790	665	544
Air temperature, C	44	44	43
RMSE-H ₂	0.81	2.15	1.09
RMSE-CO	0.21	2.06	5.83

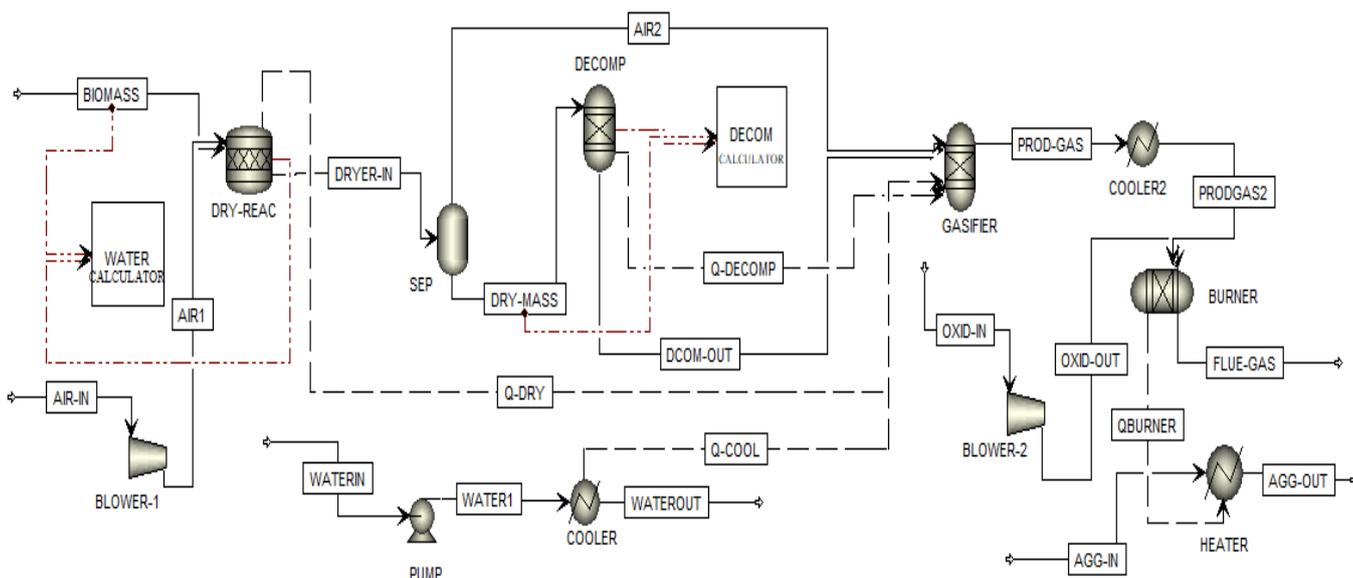


Fig. 2 Thermodynamic model of PKS gasification for aggregate heating

Table 4.
Model validation with previous experiment

Description	(Jayah et al., 2003)	(Gai & Dong, 2012)	(Kuhe & Aliyu, 2015)	(Biagini et al., 2016)	(Svishchev et al., 2016)	(Maneerung et al., 2018)
Biomass	Rubber Wood	Corn Cob	Groundnut shell	Wood Pellet	Wood	Red Wood Pellet
Feed rate, kg/h	20.90	-	-	-	-	-
ER	-	0.360	0.224	0.272	0.284	0.264
Air Fuel Ratio, kg/kg	2.37	-	-	-	-	-
RMSE-H ₂	0.30	4.92	0.51	7.56	1.46	8.82
RMSE-CO	1.31	6.42	4.36	1.33	3.73	3.09

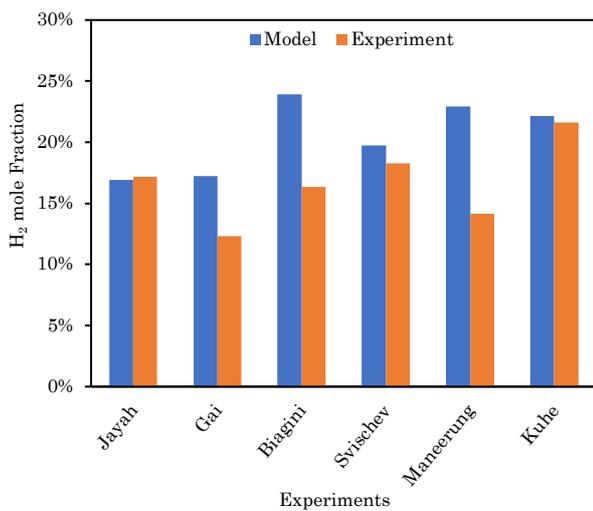


Fig. 3 H₂ composition in producer gas model vs experiment

There are two processes that take place in aggregate heating: combustion of the producer gas in air and drying the aggregate with heat generated from producer gas combustion. The parameters involved in this process are as follows: aggregate at ambient temperature, heat capacity of aggregate of 0.880 kJ/kg K (Peinado *et al.*, 2011), heat loss is ignored, and dry combustion air is applied. As reported by (Jarungthammachote, 2019), the adiabatic flame temperature for producer gas is around 1700°C, so in the present study, the burner temperature was assumed to be 1000°C. As shown in Figure 5, at an ER value of 0.250–0.350 with combustion excess air 10% Nm³, the aggregate temperature was below 150°C. This condition should be avoided because the aggregate temperature would not meet the required specification.

Even though at an ER value of 0.250–0.350 with combustion excess air below stoichiometric the aggregate was heated to a temperature of 150–200°C; this condition is not ideal because perfect combustion did not occur. This condition causes toxic pollutants such as CO to be generated in the flue gas. From the model, around 0.20–6.00 kg CO would be generated per ton of HMA produced. At combustion excess air 20%-30% with ER value 0.275–0.300 is also not suitable because the aggregate temperature would reach over 200°C, which would affect the quality of the HMA produced. As reported by (Yetkin,

Mansour, & Thomas, 2000) this higher aggregate temperature results in asphalt damage, construction problems and fume production. As can be seen in Figure 3, the optimum operating condition for palm kernel gasification for heating aggregate is an ER value of 0.325–0.350 with combustion excess air 10%–20%. The properties of producer gas at this ER value shown in Table 5. At combustion excess air above 30% the aggregate temperature is still within the range of required specification, but this condition is not chosen because it needs more energy (0.09 kWh/ton HMA) for delivering the air.

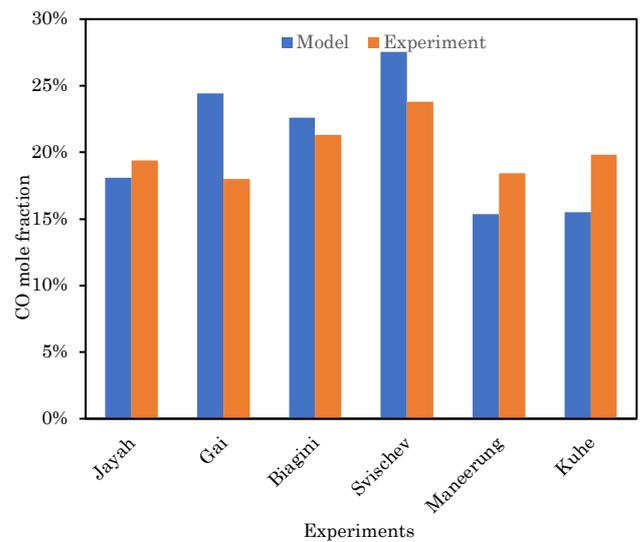


Fig. 4 CO composition in producer gas model vs experiment

Table 4
Producer gas properties at optimum operating condition

Parameter	ER: 0.325	ER: 0.350
Composition:		
H ₂	19.2%	17%
CO	19.8%	19.2%
CO ₂	9.3%	9.0%
N ₂	41.8%	43.5%
H ₂ O	9.9%	11.2%
LHV (MJ/Nm ³)	4.58	4.27

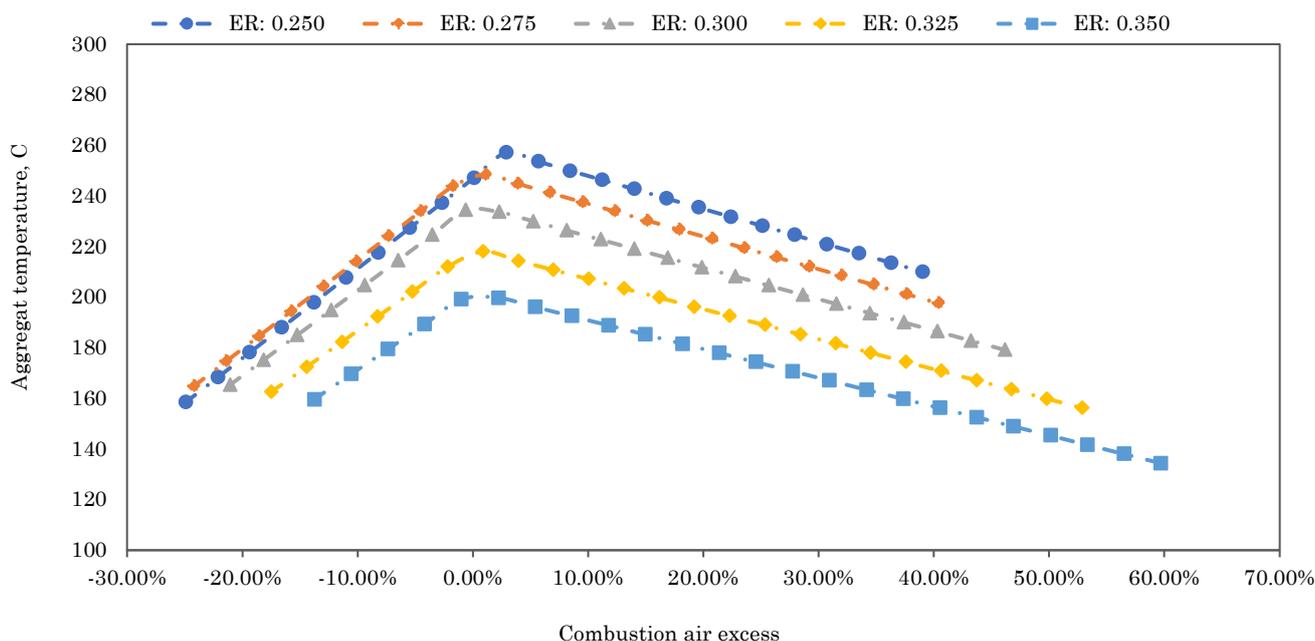


Fig. 5 Effect of combustion excess air on aggregate temperature at various ER

4. Conclusion

The thermodynamic model of PKS gasification using a fixed-bed gasifier for aggregate heating in an asphalt mixing plant is valid in predicting the operating conditions of the process to meet the aggregate temperature target with more efficient fuel and electricity consumption. The calculated cold gas efficiency which is defined as the ratio between energy flow of producer gas and energy content of feedstock based on equivalence ratio is in the range 67%–70%, which indicates a production of 2.6 – 2.7 Nm³ of producer gas from one kg PKS.

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