RAP 84069

Buell, Thomas

From: Buell, Thomas
Sent: Friday, July 2, 2021 10:23 AM
To: 'Mark Bowers'
Subject: FW: AltEn
Attachments: Alten Waste Proposal.pdf; AltEn tire proposal.pdf; AltEn Waste Management G Zang 2019.pdf

Mark:
Please see the email below and the attached information. We will inform the sender that the AltEn Facility Response Group has joined the VCP and we would direct future proposals to them.

Please let me know if you have any questions.
Thanks,
Tom

Tom Buell
DIVISION ADMINISTRATOR, MONITORING AND REMEDIATION DIVISION

Nebraska Department of Environment and Energy
P.O. Box 98922
Lincoln, Nebraska 68509-8922

DIRECT: (402) 471-4270 / MAIN OFFICE (402) 471-2186

From: Adrian Lanser <adrianlanser@gmail.com>
Sent: Thursday, July 1, 2021 1:34 PM
To: Macy, Jim <jim.macy@nebraska.gov>
Cc: Carol Blood <cblood@leg.ne.gov>; Al Ratner <albert-ratner@uiowa.edu>; Teresa Brown <tbrown4iowa@hotmail.com>; Jeremy Granquist <jgranquist@larsonengr.com>
Subject: AltEn

Mr. Macy,

I have been referred to you by State Senator Carol Blood. My company, Independence Energy Company, has summarized a plan for the disposal of the solid material at the AltEn site in Mead using our proprietary technology. We have shared the summary with, among others, Sen. Blood. Attached below are our summaries and one of the white papers published pertinent to the performance of our technology.

We would ask: if you know of any entity, public or private, that is considering disposal options? If so then: to whom and in what format should we make our proposal known?

I thank you for your time and attention to our request.

Best Wishes,

Adrian Lanser

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Adrian Lanser, CEO and Chairman
Independence Energy Company
Direct dial 770.606.4403

Des Moines, IA, USA

INDEPENDENCE ENERGY™

Proposal for AltEn Waste Disposal

Given the recitations of indisputable and admitted facts set forth in *State of Nebraska et al v. AltEn, LLC, District Court of Saunders County, Nebraska, Case No. D06C1210000036, March 1, 2021* the ecological contamination occurring at the AltEn site in Mead, Nebraska is exceedingly precarious. The seed corn waste, both solid and liquid, presents a significant and imminent physical harm to plant life, animal life and human life. The scope of the harm has yet to be determined although broad reaching adverse impact may well be expected.

The solid seed corn waste must be mitigated. Traditionally waste was disposed of by dumping, landfilling or incineration. AltEn, through one of its subsidiaries, unsuccessfully attempted incineration which was simply not hot enough to eliminate the toxins. Additionally, the air pollution control associated with incineration is prohibitively expensive. Landfilling the solid seed corn waste presents three significant problems: 1) finding a willing recipient for the toxic waste and 2) transporting the toxic waste across public highways and 3) the cost. To avoid the challenges attendant to landfilling or incineration technological innovation must step in.

Independence Energy Company (IEC) has proprietary technology the has demonstrated the disposal of seed corn and the neutralization of the toxic pesticides, herbicides and fungicides. The core technology is gasification. The proprietary components of the IEC technology allow for an economically sound process. Further, the IEC innovation has a component of modularity. This means, in the present case for example, the IEC can bring its disposal hardware to the waste at the scale needed to do the job. The process hardware will be exactly tailored to the disposal objective. That level of hardware precision constitutes a high operational efficiency which yields a substantial cost saving.

IEC has assembled a highly competent team of hardware, software and engineering specialists to support the deployment of the IEC innovation. Essentially IEC need only be presented with material for disposal; we'll manage the rest.

IEC, therefore, proposes the following. IEC will dispose of the solid seed corn waste (WDGs and unprocessed seed corn) for $250 per ton. Within ninety days of the execution of a suitable agreement IEC will have enough hardware on site to commence disposal. Within ninety to one hundred twenty days thereafter IEC's disposal operation at the AltEn site will be at full capacity. The projected timeline for the complete disposal of the solid waste is twelve to eighteen months. And the disposal process will comport with all prevailing environmental standards.

Briefly, IEC suggests that the disposal of the liquid waste will require the composition of a separate engineering plan based on data assessments gathered from the site. IEC has begun to create a preliminary plan but in the absence of access to the site IEC cannot take any more next steps.

IEC submits that given the short list of disposal options IEC presents the most economically and environmentally sound alternative to the mitigation of the AltEn waste problem.

Please refer any question to:

Adrian Lanser, CEO
IEC
adrianlanser@gmail.com
770.606.4403

INDEPENDENCE ENERGY™

Tire and Distiller Grain Conversion Proposal

June 24, 2021

Currently the presence of chemical toxins, in both solid and liquid states, at the AltEn site in Mead, NE is well known to a broad range of stakeholders including the general public. The scope of the harm caused to date and which made be caused going forward in time is not known with specificity thus requiring serious and competent study. Intuitively, however, it seems as though a good case can be made, for instance, that 84,000 tons of fungicide and pesticide ladened distillers grains sitting in a concentrated pile, open to the weather and on bare ground could cause a sufficiently bad outcome so as to warrant immediate action.

Independence Energy Company (IEC) has previously distributed a proposal for disposal of the solid matter at the site. The proposal announces a cost per ton that comports with (and may well be cheaper than) alternative means of disposal. IEC proposes an added benefit of on site disposal; our technology eliminates the need to transport the solid toxic matter across public highways or rail lines.

IEC has also learned of potential hazard in Alvo, NE. In or in proximity to that village lies a pile of some 300,000 tires which present a fire risk and offers a breeding ground for insects including predominantly mosquitos. It seems sensible to dispose of those tires.

IEC technology can convert those tires into energy both cost effectively and environmentally soundly. A highly regarded peer review scientific journal has published research findings in support of IEC's claim pertinent to tire conversion. A copy of the published article is attached. The energy yield from the tires could be used in the IEC technology to aid in the efficiency of the disposal of the AltEn distillers grains.

IEC proposes the following. IEC will convert 300,000 tires into energy at the AltEn site concurrent with disposal of the distillers grains. A public entity, either State or local, will negotiate the cost of disposal with the owner and possessor of the tires. As a show of good faith and environmental stewardship as well as our desire to use the enhanced energy value in the distillers grains' disposal IEC will donate the tire disposal fee to an entity or entities identified by either the State or local government. This tire conversion proposal rests, of course, on the contractual commitment made to IEC to dispose of the distillers grains.

IEC submits that a problem as complex as environmental clean up requires not only sophisticated technological innovation and expertise but business innovation that accounts for a convergence of interests both technical and of the various affected communities. While synergy may be an over wrought word it nonetheless applies to our proposal. Given the many benefits of disposing of the tires and the distillers grains in one process it simply makes

Please refer all inquiries to:

Adrian Lanser, CEO
IEC

adrianlanser@gmail.com

770.606.4403

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Modeling and economic analysis of waste tire gasification in fluidized and fixed bed gasifiers

Guiyan Zang [a], Junxi Jia [b], Yunye Shi [c], Tejasvi Sharma [a], Albert Ratner [a,*]

[a] Department of Mechanical Engineering, The University of Iowa, Iowa City, IA 52242, USA
[b] College of Power and Energy Engineering, Harbin Engineering University, Harbin 150001, China
[c] Engineering and Physics, St. Ambrose University, Davenport, IA 52803, USA

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ABSTRACT

Waste tires have an organic-matter composition of more than 90% and have been proposed as an excellent calorific fuel material. The objective of this study is to find an economic and efficient pathway for producing syngas by waste tires gasification. To achieve this goal, two most commonly used gasifier types of fluidized bed and fixed bed have been simulated and compared by using a semi-empirical model and a one-dimensional kinetics model, respectively. Moreover, economic analysis of the levelized cost of syngas is used to compare economic indicators of different gasifiers. Results show that the lower heating value of the tire-syngas product is 2.5–7.4 MJ/Nm^3, moreover, equivalence ratio and tire mixture ratio have negative impacts on syngas heating value and syngas efficiency. Furthermore, the levelized cost of syngas of tire gasification is 0.33–0.60 ¢/kWh that is lower than the market price of natural gas at 0.68 ¢/kW, which indicates tire gasification is a potential technology for syngas production. Finally, compared with the fluidized bed tire gasification, the fixed bed tire gasification has worse performance but better economic indicators, indicating that fixed bed gasification is an economic pathway for the syngas product.

1. Introduction

Waste tires have an organic-matter composition of more than 90% and have been proposed as an excellent calorific fuel biomass material (Abdul-Raouf et al., 2010). The United States generated approximately 4 million tons of waste tires in 2017, about 18% of which were still land-disposed, resulting in 60 million tires accumulated in stockpiles in the United States (U.S. Tire Manufacturers Association, 2018). The rubber component in tires is water resistant and abrasion resistant and takes more than 100 years to be destroyed by micro-organisms (Czajczyńska et al., 2017), leading to heavy pollution of the environment.

To reduce land-disposed pollution of waste tires, they have been proposed for fuel production due to their high organic-matter composition. The three most-used technologies for tire-derived fuel production are incineration, pyrolysis, and gasification (Laboy-Nieves, 2014). Incineration generates electricity by burning waste tires in ovens but releases emissions of CO_2, hydrocarbons, pyrolytic oil, and heavy metal compounds (Mozafari et al., 2017). In contrast, pyrolysis method decomposes tire rubber at different temperatures from 500 to 600 °C with a char yield in the range of 33% to 42% (Khiari et al., 2018; Saleh and Gupta, 2014), which only converts 10% of the waste tire mass into syngas. Therefore, gasification, which has the potential to reduce the hydrocarbons and pyrolytic oil emissions from incineration (Mozafari et al., 2017) and produce more syngas than pyrolysis (Basu, 2010), has been developed as an attractive waste tire conversion technology for syngas production (Labaki and Jeguirim, 2017).

Gasification is a partial oxidation process in which air, steam, or oxygen reacts with waste tires to produce syngas for utilization in a gas turbine or a fuel cell (Luz et al., 2015; Oboirien and North, 2017). Previous studies on laboratory or pilot scale tire gasification were conducted in either a fluidized bed gasifier or a fixed bed gasifier (Oboirien and North, 2017). Results showed that in the fluidized bed gasifier, when the equivalence ratio (ER), which is the ratio of the actual air/fuel ratio to the stoichiometric air/fuel ratio, ranges from 0.29 to 0.60, the lower heating value (LHV) of the

Abbreviations: CCF, Capital charge factor; CCR, Carbon conversion ratio; CF, Capacity factor; ER, Equivalence ratio; LCOE, Levelized cost of electricity; LCOS, Levelized cost of syngas; LF, Levelization factor; LHV, Lower heating value; NETL, National Energy Technology Laboratory; NGCC, Natural gas combined cycle; NPV, Net present value; TOC, Total overnight cost; TPC, Total plant cost.

* Corresponding author at: Department of Mechanical and Industrial Engineering, The University of Iowa, 2401 Seamans Center for the Engineering Arts and Sciences, Iowa City, IA 52242, USA.

E-mail address: albert-ratner@uiowa.edu (A. Ratner).

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syngas product is between 1.8 and 8.0 MJ/Nm^3 (Kaewluan and Pipatmanomai, 2011; Karatas et al., 2013; Leung and Wang, 2003). While in a fixed bed gasifier, the gas yield is improved by the introduction of the nickel/dolomite catalyst (Elbaba and Williams, 2013; Vonk et al., 2019). Even though these experimental results indicated the feasibility of tire gasification in either the fluidized bed gasifier or the fixed bed gasifier, it is hard to determine which gasification technology is more suitable for syngas production without further technical and economic comparison.

Process simulation and economic analysis are two effective tools for technical comparison (Khan et al., 2016; Vonk et al., 2019). When conducting process simulation, fluidized bed gasification models are usually based on kinetic rates or chemical equilibrium (Hejazi et al., 2017; Machin et al., 2017; Násner et al., 2017; Sreejith et al., 2015). However, because the kinetic parameters of tire gasification are hard to determine and the chemical equilibrium model has large errors for predicting methane and hydrocarbon products, none of them are suitable for simulating tire gasification in a fluidized bed gasifier (Puig-Arnavat et al., 2010). To overcome these problems, Hannula and Kurkela have proposed a semi-empirical model, which fits well to the experimental data by using Aspen Plus software without complex kinetic calculations (Hannula and Kurkela, 2010). But its simulation results are limited to sawdust gasification, no study has used the semi-empirical model for tire gasification simulation up to date.

Different from the fluidized bed gasifier, the fixed bed gasifier does not have good mixing characters (Ma et al., 2012), which results in the chemical equilibrium model is not suitable for the fixed bed gasification simulation (Patra and Sheth, 2015). Therefore, a combined model of reaction kinetics and chemical equilibrium has been widely used to simulate the fixed bed gasification process (Ratnadhariya and Channiwala, 2009; Roy et al., 2009). Even though the combination model has been successfully used to simulate the gasification of wood and animal manure, it has not been applied for the gasification of tire yet (Jia et al., 2015, 2018; Roy et al., 2009, 2010).

Another tool for comparison is the discounted cash flow economic analysis method. The net present value (NPV) and levelized cost of electricity (LCOE) have been used to analyze the economic indicators of biomass gasification's application for power generation (Arena et al., 2011; Hadidi and Omer, 2017; Shen et al., 2017). However, for electricity generation, the commercial application scale of fluidized bed gasifier based on the gas and steam turbines' combined cycle is 10 MW, while that of the fixed bed gasifier using internal combustion engine is lower than 0.1 MW (Sansaniwal et al., 2017), which results in the difficulties for their comparison. Because NPV is the difference between the present value of cash inflows and outflows with the unit of M$, it is not suitable for the comparison of different scale projects (Malek et al., 2017). Furthermore, if using one gasifier to drive a internal combustion engine or a combined cycle to generate power, the lower efficiency of the smaller engine will result in the unfair economic comparison result of LCOE (in the unit of ¢/kW-electricity generation) (Luz et al., 2015). According to the physical similarity of the syngas product from different gasifiers and the low syngas transport cost, comparing different gasification technology based on syngas parameters will avoid bias (Ahmad et al., 2016). Therefore, levelized cost of syngas (LCOS) based on syngas LHV (in the unit of ¢/kW-syngas LHV) is more appropriate for the comparison of fluidized bed and fixed bed gasifiers.

The objective of this study is to find an economic and efficient pathway for the syngas product derived from waste tires gasification process. To achieve this goal, two most commonly used gasifier types of fluidized bed and fixed bed have been simulated by using a semi-empirical model (Hannula and Kurkela, 2010) and a one-dimensional kinetics model (Roy et al., 2009), respectively. These two models indicate the impacts of ER, moisture component, and tire mixture ratio on all the major syngas parameters such as composition, LHV, and efficiency. Furthermore, the economic analysis method developed by the National Energy Technology Laboratory (NETL) (Zang et al., 2018a) is used to analyze the LCOS of different syngas production pathways. This study has two innovations: (a) tire gasification processes happened in the fluidized bed gasifier and the fixed bed gasifier are simulated by a semi-empirical model and a one-dimensional kinetics model, respectively, which integrates previous models to provide tire gasification details (Hannula and Kurkela, 2010; Jia et al., 2018; Roy et al., 2009; Zang et al., 2018b); (b) LCOS is used as the major indicator for the economic comparison to avoid the unfair comparison for different gasification scales (Ahmad et al., 2016).

2. Material and methods

2.1. Gasification model description and assumptions

2.1.1. Fluidized bed gasification model

The fluidized bed tire gasification is simulated by using a semi-empirical model (Hannula and Kurkela, 2010). This model uses Aspen Plus software to assist the simulation process with the schematic shown in Fig. 1, which includes nine units. In the biomass decomposition unit, tire or the mixture of tire and wood is decomposed into carbon, hydrogen, nitrogen, oxygen, sulfur, and ash based on proximate and ultimate analysis results. Then the ash and unreacted carbon are separated in the ash removal unit and carbon conversion unit. In the volatiles separator, the mixture (Stream 3) is separated into fixed carbon (Stream 4) and volatiles (Stream 5). The fixed carbon is further gasified in the gasification unit, while the volatiles flow through the heat exchanger and hydrocarbon formation units to produce CH_4, C_2H_2, C_2H_4, and C_2H_6 according to experimental results. Then part of CH_4 and all of C_2H_2, C_2H_4, and C_2H_6 of Stream 7 are separated into Stream 9 and then mix with Stream 11 as the final syngas product. Meanwhile, other components left in Stream 8 are gasified in the gasification unit. The gasification unit is the core of this model, in which fixed carbon (Stream 4) and unreacted volatiles (Stream 8) react with air and steam following the reactions list in Table 1 (Zang et al., 2018b) to generate syngas (Stream 11) under chemical equilibrium. Detailed simulation processes of each unit are described as following:

Biomass decomposition (Unit 1): Tire or mixture of tire and wood is defined as nonconventional material, which is determined by the proximate and ultimate analysis results. Biomass decomposition unit is a Ryield reactor that converts tire or mixture into carbon, hydrogen, nitrogen, oxygen, sulfur, and ash according to the material analysis data (Nikoo and Mahinpey, 2008).

Ash removal (Unit 2), volatiles separator (Unit 4), and carbon conversion (Unit 3): They are simulated by Sep separators in Aspen Plus. The ash removal unit removed all the ash components as ash output, the volatiles separator separates all the volatiles from fixed carbon, and the carbon conversion unit separates part of the carbon as unreacted char product. Eq. (1) defines the carbon separation ratio of the carbon conversion unit.

$$r = \dot{m}_{uC}/\dot{m}_C \tag{1}$$

where r is the separation ratio, $\dot{m}_{uC}$ is the mass flow rate of the unreacted carbon, and $\dot{m}_C$ is the carbon mass flow rate of tire or mixture.

Heat exchanger (Unit 5) and hydrocarbon formation (Unit 6): The heat exchanger receives heat from the gasification process to increase the volatiles temperature, then in the hydrocarbon formation unit, the volatiles are converted into CH_4, C_2H_2, C_2H_4, and C_2H_6

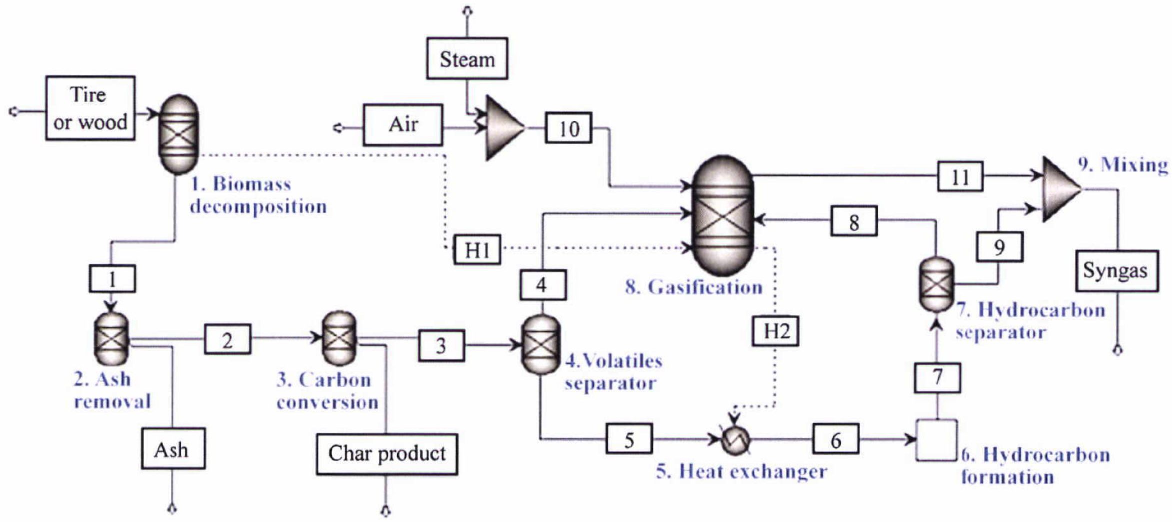

Fig. 1. Semi-empirical model of fluidized bed tire gasification.

Table 1
Waste tire gasification reactions.

Reaction name	Reaction equation	Heat (MJ/kmol)	Number
Water shift reaction	$CO + H_2O \leftrightarrow CO_2 + H_2$	−41	R1
Methanation reaction	$C + 2\ H_2 \leftrightarrow CH_4$	−75	R2
Boudouard reaction	$C + CO_2 \leftrightarrow 2\ CO$	+172	R3
Water gas reaction	$C + H_2O \leftrightarrow CO + H_2$	+131	R4
Methane reforming reaction	$CH_4 + H_2O \leftrightarrow CO + 3\ H_2$	+206	R5
Combustion reactions	$C + 1/2\ O_2 \leftrightarrow CO$	−111	R6
	$CO + 1/2\ O_2 \leftrightarrow CO_2$	−283	R7
	$H_2 + 1/2\ O_2 \leftrightarrow H_2O$	−242	R8

according to experimental result. A FORTRAN model is used to evaluate the NH_3 and hydrocarbon conversion ratios in the hydrocarbon conversion process. The target NH_3 and hydrocarbon compositions are from the experimental data, which have linear relationships with equivalence ratio as shown in Eqs. (2)–(6) (Zang et al., 2018b). More detailed Aspen plus unit definition and the FORTRAN code are provided in the Supporting information (Fig. S1 and Page S2 to S3).

$$NH_3 = 0.118 - 0.2 * ER \tag{2}$$

$$CH_4 = 10.13 - 16.67 * ER \tag{3}$$

$$C_2H_2 = 0.46 \tag{4}$$

$$C_2H_4 = 1.45 - 3.25 * ER \tag{5}$$

$$C_2H_6 = 0.21 - 0.4 * ER \tag{6}$$

where ER is the equivalence ratio defined in Eq. (7) (Guo et al., 2013), NH_3, CH_4, C_2H_4, and C_2H_6 are the target NH_3 and hydrocarbon compositions in the unit of %.

$$ER = \left(\frac{mass\ of\ actual\ air}{mass\ of\ biomass}\right)/\left(\frac{mass\ of\ stoichiometric\ air}{mass\ of\ biomass}\right) \tag{7}$$

Hydrocarbon separator (Unit 7): The hydrocarbon separator is another Sep reactor applied in the simulation process, in which all NH_3, C_2H_2, C_2H_4, and C_2H_6 are separated to the Stream 9 shown in Fig. 1. However, only part of CH_4 is separated to Stream 9 to ensure the CH_4 composition in the final syngas product is the same as the test result by using Aspen Plus Design Spec definition (Hannula and Kurkela, 2010).

Gasification (Unit 8): The gasification unit is an RGibbs reactor, which calculates the syngas product based on chemical and phase equilibrium by Gibbs energy minimization. The gasification reaction temperature and pressure are defined by experimental results and the adiabatic efficiency is assumed to be 90% (Doherty et al., 2009).

Mixing (Unit 9): The last unit in the simulation model is mixing, which is used to mix the gasification product Stream 11 with NH_3 and hydrocarbons in Stream 9 (Zang et al., 2018a).

2.1.2. Fixed bed gasification model

The fixed bed tire gasification is simulated by a one-dimensional kinetic model with the structure shown in Fig. 2 (Roy et al., 2009, 2010). In this model, the gasifier is reorganized into the combustion zone and the reduction zone. The combustion zone uses equilibrium assumptions to simulate the processes of drying, pyrolysis, and combustion, whereas the reduction zone uses a kinetic model to calculate the final syngas product (Jia et al., 2015).

The major assumption of the combustion zone is that the syngas products at the end of this zone satisfy chemical equilibrium. The global reaction is:

$$\begin{aligned} &CH_mO_n + \frac{w*(12+m+8n)}{18*(100-w)(100-\alpha)}H_2O \\ &+\frac{1+0.25m-0.5n}{ER}(O_2+3.76N_2) \\ &= x_1H_2 + x_2CO + x_3CO_2 + x_4H_2O + x_5CH_4 + x_6N_2 + x_7C \end{aligned} \tag{8}$$

where m, n, w, and α are derived from the ultimate and proximate analysis results; and x_1 through x_7 are the molar products of one mole of fuel. The following seven equations are used to solve the global reactions:

$$x_2 + x_3 + x_5 + x_7 = 1 \tag{9}$$

$$2x_1 3.762x_4 + 4x_5 = \mathrm{m} + \frac{2*w*(12+m+8n)}{18*(100-w)(100-\alpha)} \tag{10}$$

$$x_2 + 2x_3 + x_4 = \mathrm{n} + \frac{w*(12+m+8n)}{18*(100-w)(100-\alpha)} + 2*\frac{1+0.25m-0.5n}{ER} \tag{11}$$

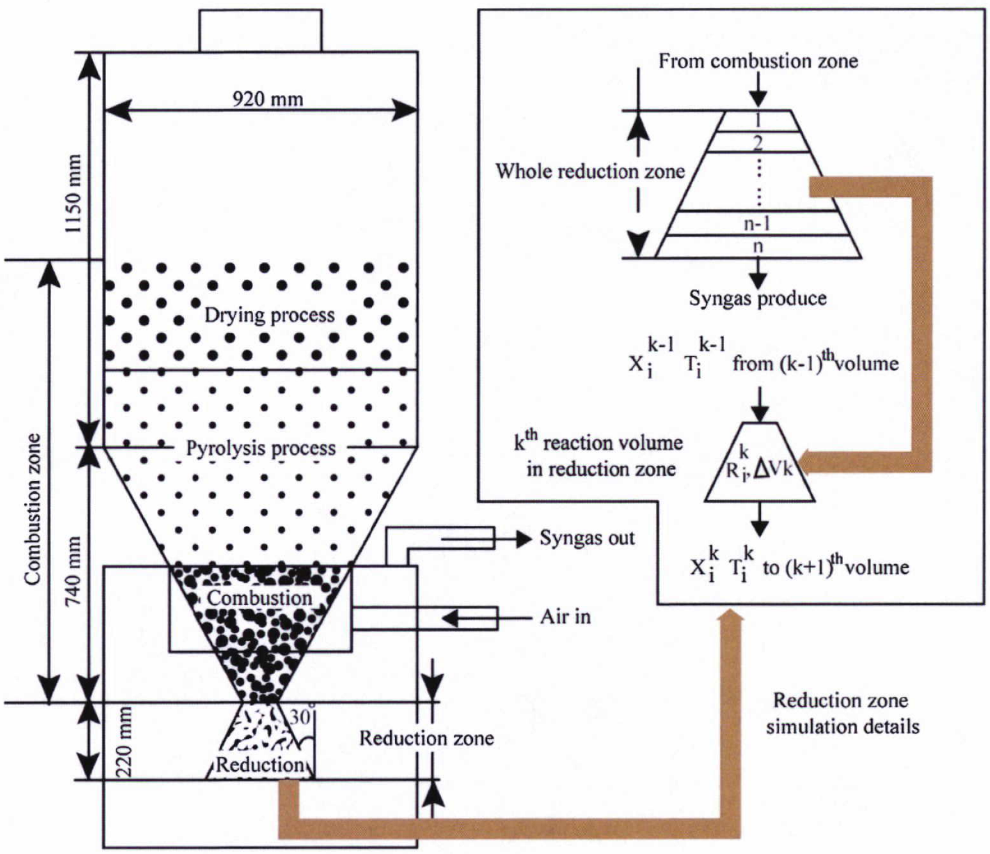

Fig. 2. One-dimensional simulation model of downdraft fixed bed tire gasification.

$$x_6 = 3.76 * \frac{1 + 0.25m - 0.5n}{ER} \tag{12}$$

$$lnK_1 = ln\frac{x_1x_3}{x_2x_4} = \frac{\bar{g}^0_{CO}}{RT} + \frac{\bar{g}^0_{H_2O}}{RT} - \frac{\bar{g}^0_{CO_2}}{RT} - \frac{\bar{g}^0_{H_2}}{RT} \tag{13}$$

$$lnK_2 = \ln(\frac{x_5}{x_1{}^2}\sum_{i=1}^{6} x_i) = 2\frac{\bar{g}^0_{H_2}}{RT} - \frac{\bar{g}^0_{CH_4}}{RT} \tag{14}$$

$$x_5 + x_7 = \frac{FC}{C} \tag{15}$$

Eqs. (9)–(12) are the mass balance of carbon, hydrogen, oxygen, and nitrogen. Eqs. (13) and (14) are derived from the chemical equilibrium of the water gas shift reaction (R1 in Table 1) and the methanation reaction (R2 in Table 1). K is the equilibrium constant, $\bar{g}^0_i$ is the Gibbs function of different syngas components i, and R is 8.314 kJ/mol·K (Jarungthammachote and Dutta, 2007). Eq. (15) assumes that the fixed carbon is translated into solid carbon and methane; FC is the fixed carbon from the proximate analysis, and C is the carbon content of the ultimate analysis. T is the temperature at the end of the combustion zone, which is determined by the energy balance shown in Eq. (16) (Roy et al., 2009).

$$\bar{h}^0_f + \frac{w*(12+m+8n)}{18*(100-w)(100-\alpha)}\bar{h}^0_{H_2O} + Q_{lost} = \sum_{i=1}^{6} x_i\left(\bar{h}^0_i + \int_{T_0}^{T} c_{p,i}dT\right) + (x_7c_{p,7} + m_{ash}c_{p,ash})(T - T_0) \tag{16}$$

where $\bar{h}^0_i$, $\bar{h}^0_f$, and $\bar{h}^0_{H_2O}$ are the syngas, fuel, and water's formation enthalpy. Q_{lost} is the heat loss, andT_0 is the standard temperature of 25 °C. $c_{p,i}$ is the specific heat of gaseous species$i$, m_{ash} is the ash mass flow rate, and$c_{p,7}$ and $c_{p,ash}$ are the specific heats of solid char and ash, which are assumed to be 21.86 kJ/kmol·K and 0.84 kJ/kg·K, respectively (Sharma and Sheth, 2016).

In the reduction zone, the total reaction area is separated into finite reaction elements (Fig. 2). The combustion zone products enter the first control volume of the reduction zone with the components shown in Eq. (17).

$$X^0_i = \frac{m_f(1 - 0.01\alpha)}{12 + m + 8n}x_i, i = 1 \ to \ 7 \tag{17}$$

where X^0_i is the initial mole flow rate of the gaseous species i, and m_f is the feedstock flow rate of 20 kg/hr (Jia et al., 2018).

Then, for a specific control volume k (Fig. 2), the product mole flow rate is X^k_i, which is calculated by Eq. (18).

$$X^k_i = X^{k-1}_i + R^k_i\Delta V_k \tag{18}$$

whereX^{k-1}_i is the initial mole flow rate of the kth control volume, ΔV_k is its volume, and R^k_i is derived from the reaction rates ofr_2, r_3, r_4, and r_5 listed in Table 2 (Wang and Kinoshita, 1993) according to Eqs. (19)–(25) (Roy et al., 2009).

$$R^k_1 = r^k_4 - 2r^k_2 + 3r^k_5 \tag{19}$$

$$R^k_2 = 2r^k_3 + r^k_4 + r^k_5 \tag{20}$$

$$R^k_3 = -r^k_3 \tag{21}$$

$$R^k_4 = -r^k_4 - r^k_5 \tag{22}$$

Table 2
Reduction zone reaction calculation.[a]

Equilibrium constants	Reaction rates	A (1/s)	E kJ/mol
$lnK_2 = 2\frac{\bar{g}^0_{H_2}}{RT} - \frac{\bar{g}^0_{CH_4}}{RT}$	$r_2 = C_2A_2exp\left(\frac{-E_2}{RT}\right)\left(y^2_{H_2} - \frac{y_{CH_4}}{K_2}\right)$	0.00419	19.21
$lnK_3 = \frac{\bar{g}^0_{CO_2}}{RT} - 2\frac{\bar{g}^0_{CO}}{RT}$	$r_3 = C_3A_3exp\left(\frac{-E_3}{RT}\right)\left(y_{CO_2} - \frac{y^2_{CO}}{K_3}\right)$	36.16	77.39
$lnK_4 = \frac{\bar{g}^0_{H_2O}}{RT} - \frac{\bar{g}^0_{CO}}{RT} - \frac{\bar{g}^0_{H_2}}{RT}$	$r_4 = C_4A_4exp\left(\frac{-E_4}{RT}\right)\left(y_{H_2O} - \frac{y_{CO}y_{H_2}}{K_4}\right)$	15170	121.62
$lnK_5 = \frac{\bar{g}^0_{CH_4}}{RT} + \frac{\bar{g}^0_{H_2O}}{RT} - \frac{\bar{g}^0_{CO}}{RT} - 3\frac{\bar{g}^0_{H_2}}{RT}$	$r_5 = C_5A_5exp\left(\frac{-E_5}{RT}\right)\left(y_{H_2O}y_{CH_4} - \frac{y^3_{H_2}y_{CO}}{K_5}\right)$	0.073	36.15

[a] A_i, E_i, and y_i are the pre-exponential factor, activation energy, and mole fraction of species i.

$$R^k_5 = r^k_2 - r^k_5 \tag{23}$$

$$R^k_6 = 0 \tag{24}$$

$$R^k_7 = -r^k_3 - r^k_4 - r^k_2 \tag{25}$$

In the reduction zone, the main assumption is that there is no heat transfer in the small control volume, so the temperature at the end of the k[th] control volume is determined from the energy balance (Sharma and Sheth, 2016), which is calculated by Eq. (26).

$$\begin{aligned}&\sum_{i=1}^{6} X_i^{k-1}\left(\bar{h}_i^0 + \int_{T_0}^{T_{k-1}} c_{p,i}dT\right) \\ &\quad + \left(X_7^{k-1}c_{p,7} + m_{ash}c_{p,ash}\right)\left(T^{k-1} - T_0\right) \\ &= \sum_{i=1}^{6} X_i^{k}\left(\bar{h}_i^0 + \int_{T_0}^{T_{k}} c_{p,i}dT\right) \\ &\quad + \left(X_7^{k}c_{p,7} + m_{ash}c_{p,ash}\right)\left(T^{k} - T_0\right)\end{aligned} \tag{26}$$

2.2. Thermodynamic and economic analysis properties

Proximate and ultimate analyses of wood and tire are shown in Table 3 (Machin et al., 2017; Zang et al., 2018b). The feedstock flowrate of the fluidized bed gasifier is 5400 kg/hr, which is for a typical commercial application scale of 10 MW electricity generation (Zang et al., 2018a). Meanwhile, the biomass input flowrate of the fixed bed gasifier is 20 kg/hr according to the downdraft gasification test (Jayah et al., 2003). Gas yield, gas LHV, carbon conversion ratio (CCR), syngas efficiency, and char efficiency are the primary thermodynamic properties compared in this study and are defined in Eqs. (S1)–(S5) in the Supporting information (Prins, 2005).

Table 3
Proximate and ultimate analyses of wood and tire.[a]

Proximate analysis (by mass, %)	Wood	Tire
Fixed carbon	16.8	27.04
Volatile matter	83.12	66.3
Ash	0.08	6.66
Ultimate analysis (by mass, %)	Wood	Tire
Carbon	51	81.74
Hydrogen	6	7.06
Oxygen	42.8	2.42
Nitrogen	0.08	0.3
Sulfur	0.04	1.82
Moisture content	16	0.9
LHV (MJ/kg)	16.9	37.1

[a] All the data in Table 3 are from the material analysis results in the work of Machine et al. and Zang et al (Machin et al., 2017; Zang et al., 2018b). To show the differences between wood and tire clearly, the tire analysis results have been calculated to the dried base scale which is the same with wood analysis results.

The power plant cost estimated in this paper is based on the methodology employed by NETL (Black, 2013; Gerdes et al., 2011), which assumes that the tire gasification process is high risk with a capital expenditure period of 5 years and an operation period of 30 years. The capital depreciation of the gasification project is 20 years with 150% declining balance, and the distributions of total overnight cost (TOC) are 10%, 30%, 25%, 20%, and 15% in the construction years with a debt period of 15 years. The LCOS is chosen as the cost metric defined in Eq. (27).

$$LCOS = LF \times (CCF \times TOC + OC_{fix} + CF \times OC_{var})/(CF \times MWH) \tag{27}$$

where LF is the levelization factor, CCF is the capital charge factor, TOC is the total overnight cost, CF is the capacity factor, MWH is the total energy of syngas output at full capacity, and OC_{fix} and OC_{var} represent the fixed and variable operating costs, respectively. As shown in our previous work, the values of LF, CCF, and CF are 1.268, 0.124, and 0.8, respectively (Zang et al., 2018a).

The costs of wood and tire are assumed to be 50 $/ton and −50 $/ton, while the TOC is the summation of the total plant cost (TPC) and the owner's cost. The TPC of the fixed bed gasifier and the fluidized bed gasifier are based on the work of Jia et al. (2018) and Zang et al. (2018a), while the TPC of tire pretreatment is derived from the equipment cost of the pretreatment subsystem designed in this study. The equipment cost of the feedstock pretreatment is scaled by Eq. (28).

$$C = C_0 \times (S/S_0)^f \tag{28}$$

where C_0 and S_0 are the equipment cost and capacity of the reference plant (Caputo and Pelagagge, 2002), C is the equipment cost, S is the capacity of the designed process, and f is the scaling exponent for each equipment.

2.3. Model validation

The experimental results used for the validation of the fluidized bed and the fixed bed gasification process are from the research of Gil et al. (1999) and Jayah et al. (2003). Fig. 3 shows the comparison between the experimental and simulation results. In Fig. 3, the percent error of the fluidized bed gasifier is lower than 3.5%, and that of the fixed bed gasifier is no more than 3.6%. Moreover, the root-mean-square error of the fluidized bed and the fixed bed are 3.4% and 2.2%, respectively. The error analysis results show that both the semi-empirical model of the fluidized bed gasifier and the one-dimensional kinetic model of the fixed bed gasifier are reliable.

3. Results and discussion

3.1. Effects of ER value

Fig. 4-(a) and -(b) illustrate the ER effects on the dry-based syngas composition. Similar to the test result of the bubbling fluidized bed (Gil et al., 1999), when ER increases from 0.22 to 0.50, the per-

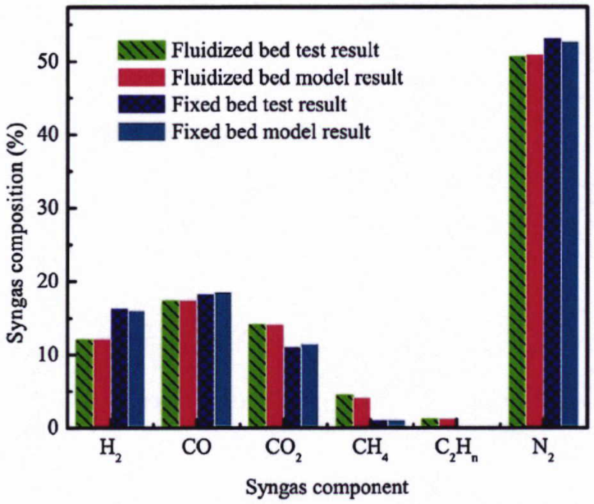

Fig. 3. Model validation of fluidized bed and fixed bed gasifiers.

centages of CO_2 and N_2 increase while all the other compositions' percentages decrease. The reason is that increasing ER value results in more air in the reactions, which inputs more N_2 and produces more CO_2. Considering the combustion reaction of R7 and R8 in Table 1, the compositions of CO and H_2 decrease with the increase in the ER value. Furthermore, because the higher ER value raises the gasification temperature, the hydrocarbon products from both gasifiers decrease. Compared to the fixed bed gasifier, the fluidized bed gasifier has a higher CO product at a lower ER value whereas a higher H_2 product at a higher ER value. This is because the fluidized bed is more closed to the chemical equilibrium state than the fixed bed gasifier, which results in the water shift reaction (R1) impact being deeper in the fluidized bed gasifier.

Fig. 4-(c) and -(d) show the effects of ER on other parameters of tire gasification: gas yield and CCR increase and other parameters decrease when the ER increases. Higher ER results in more air in the reaction, which makes the gas yield increase from 3.1 to 5.5 Nm^3/kg, while the gas LHV decreases from 7.4 to 2.8 MJ/Nm^3. Compared with the natural gas' LHV of 35.8 MJ/Nm^3, the LHV of tire-syngas is much lower, but still can be either reacted in a solid oxide fuel cell or combusted in a microturbine for power generation (Corrêa Jr et al., 2019; Jia et al., 2018). Moreover, because the gasification temperature increases with the growth of the ER value, more fixed carbon takes part in the gasification reaction, which enhances CCR and decreases the char efficiency. Char is the major by-product of the gasification process including 17.8% to 29.3% of carbon from feedstock. Previous studies showed the biomass gasification derived char can be used as cleaning catalyst, soil amendment, and in direct carbon fuel cell (Ahn et al., 2013; Qian et al., 2015). Finally, compared with the fixed bed gasifier, the fluidized bed gasifier has higher gas yield, gas LHV, CCR, and syngas efficiency as a result of having a higher gasification temperature and being more closed to the chemical equilibrium state.

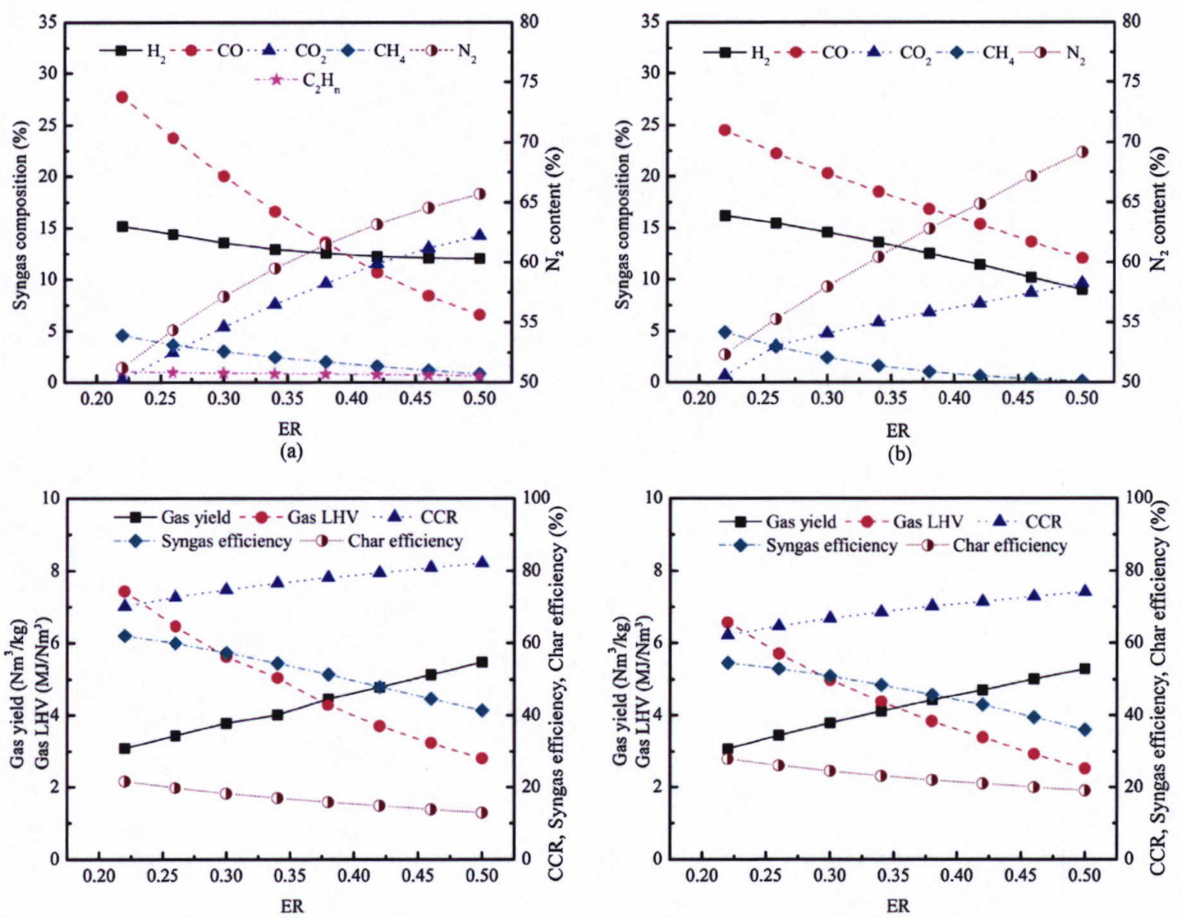

Fig. 4. ER effects on (a) syngas composition of fluidized bed, (b) syngas composition of fixed bed, (c) other parameters of fluidized bed, (d) other parameters of fixed bed.

3.2. Effects of moisture component

Fig. 5-(a) and -(b) illustrate the moisture component effects on the dry-based syngas composition: when the moisture component increases from 0.9% to 30%, the percentages of CO_2 and hydrocarbon increase while all the other compositions' percentages decrease. This simulation result has similar variation trends with the experimental result (Lv et al., 2004). The reason is that increasing the moisture component results in more water in reactions, which reduces the gasification temperature and improves the water shift reaction (R1). Compared with the fixed bed gasification process, in the fluidized bed gasifier, the moisture components' impacts on CO and CO_2 composition are larger because the water shift reaction in the fluidized bed is closer to the equilibrium state.

Fig. 5-(c) and -(d) show that the moisture component has a small impact on the other parameters of tire gasification. The effects of the moisture component are much lower than those of ER.

3.3. Effects of tire mixture ratio

Even though tire has a higher LHV than wood, its rubber structure results in the CCR of the gasification process is lower than 82% (Figs. 4 and 5). To increase the CCR, a lot of researches have used the mixture of wood and tire to replace the pour tire gasification. This section will discuss the effects of tire mixture ratio (r_{tire}) on the gasification parameters, which is defined in Eq. (29).

$$r_{tire} = \dot{m}_{tire}/(\dot{m}_{tire} + \dot{m}_{wood}) \tag{29}$$

where, $\dot{m}_{tire}$ is the mass flow rate of the waste tire feedstock, and $\dot{m}_{wood}$ is the mass flow rate of the wood material.

Fig. 6-(a) illustrates the tire mixture ratio effects on the dry-based syngas composition in the fluidized bed gasifier. When the tire mixture ratio increases from 0% to 100%, the percentages of CO_2 and H_2 reach maximums, while the CO percentage declines to a minimum at 10%. This is similar to test results in a fluidized bed (Kaewluan and Pipatmanomai, 2011). In addition, the percentage of N_2 increases and those of hydrocarbons decrease. This is because raising the tire mixture ratio reduces the carbon conversion ratio, which prevents the syngas production. Fig. 6-(b) illustrates the tire mixture ratio effects on the dry-based syngas composition in the fixed bed gasifier: when the tire mixture ratio increases, the percentage of N_2 increases and those of all other components decrease. The reason is that, in the fixed bed gasifier, the CCR is lower than that of the fluidized bed gasifier.

Fig. 6-(c) and -(d) show the effects of tire mixture ratio on the other parameters of tire gasification: gas yield and char efficiency increase and other parameters decrease with the growth of the tire mixture ratio value. A higher tire mixture ratio results in more carbon in reactions, which also requires more air to keep the ER value constant; therefore, the syngas yield increases with the growth of the tire mixture ratio. The lower CCR results in higher char efficiency when the tire mixture ratio is increased. Compared to the fixed bed gasifier, the fluidized bed gasifier has higher CCR and

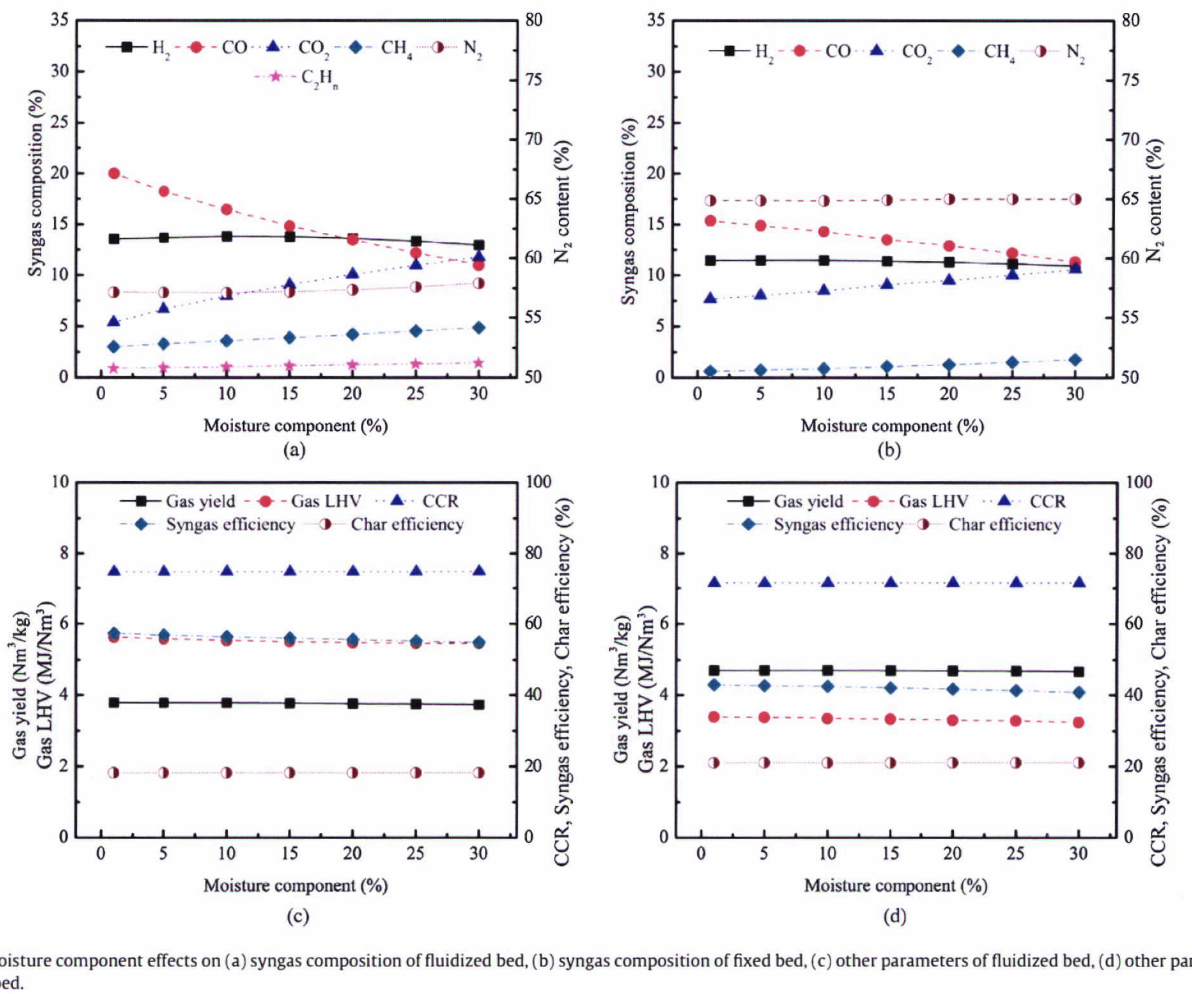

Fig. 5. Moisture component effects on (a) syngas composition of fluidized bed, (b) syngas composition of fixed bed, (c) other parameters of fluidized bed, (d) other parameters of fixed bed.

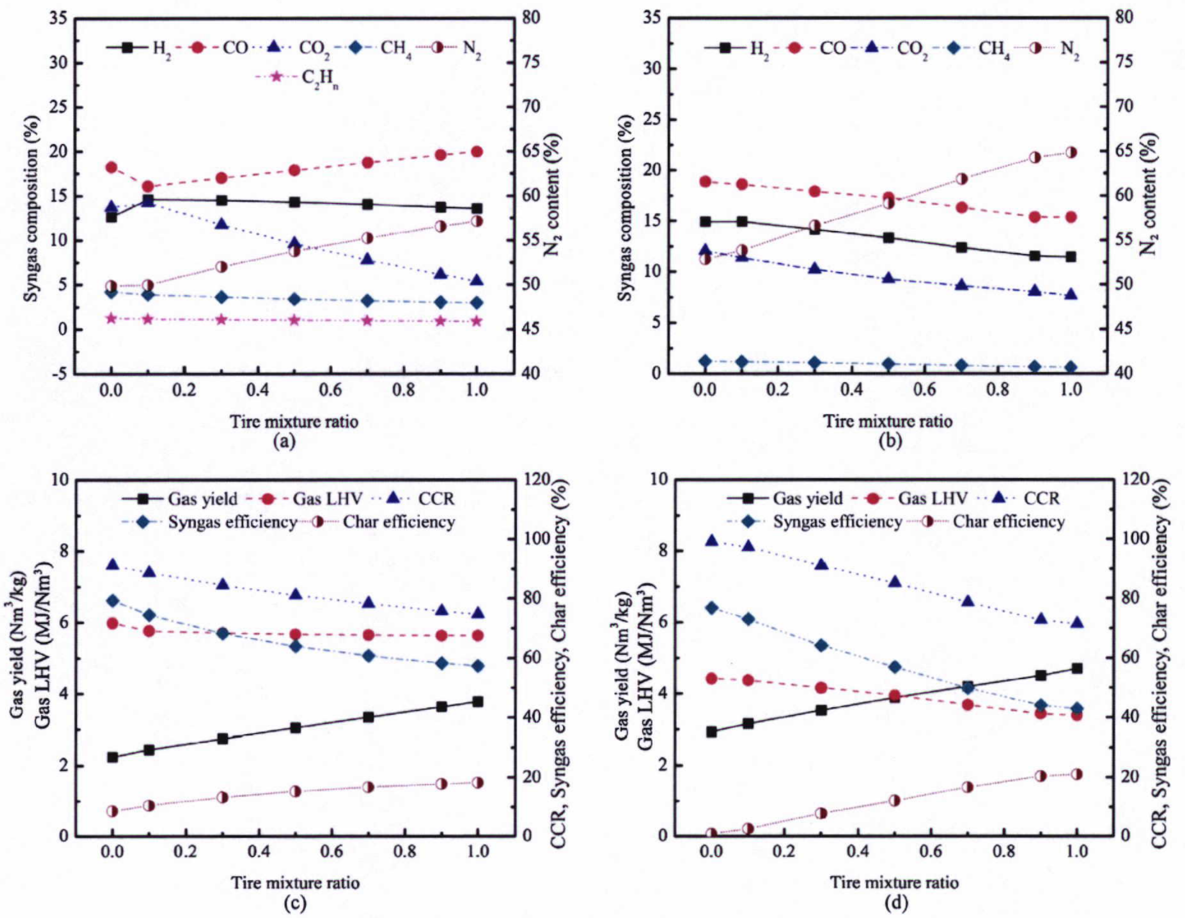

Fig. 6. Tire mixture ratio effects on (a) syngas composition of fluidized bed, (b) syngas composition of fixed bed, (c) other parameters of fluidized bed, (d) other parameters of fixed bed.

Table 4
Gasification cases design, energy balance, and performance results.

Gasifier type	Fluidized bed gasifier				Fixed bed gasifier			
Case number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Tire mix ratio	0	0.5	1	1	0	0.5	1	1
ER	0.3	0.3	0.3	0.42	0.42	0.42	0.3	0.42
Capacity [a](kg/hr)	5400	5400	5400	5400	20	20	20	20
Particle size (mm)	2	2	2	2	20	20	20	20
Total energy input (kW)	25,350	40,500	55,650	55,650	94	150	206	206
Pretreatment power needed (kW)	388	423	458	458	1	1	2	2
Syngas energy output (kW)	20,119	25,903	31,906	26,624	72	85	105	89
Char energy output (kW)	2195	6175	10,154	8272	1	18	51	43
Syngas energy efficiency (LHV%)	78.2	63.3	56.9	47.5	75.8	56.4	50.5	42.6
Char energy efficiency (LHV%)	8.5	15.1	18.1	14.7	0.9	12.0	24.3	20.9
Total energy efficiency (LHV%)	86.7	78.4	75.0	62.2	76.6	68.4	74.8	63.5
Syngas energy (MJ/kg-biomass)	13.41	17.27	21.27	17.75	12.99	15.37	18.87	15.93

[a] The capacity is the total input flowrate of the wood and the waste tire for different gasifiers. Because the gasifiers' structure does not change, the capacity keeps constant when the tire mix ratio and ER changing.

gas LHV, which shows the advantage of the fluidized bed gasifier over the fixed bed gasifier.

3.4. Economic analysis

To conduct the economic analysis, eight running models are selected from Figs. 4 and 6 based on three tire mixture ratios and two ER values. The case numbers and the configurations of these running models are listed in Table 4. Table 4 also illustrates the energy balance of these running models, in which the feedstock flowrate of the fluidized bed gasifier is 5400 kg/hr with particle size of 2 mm (Leung and Wang, 2003), while that of the fixed bed gasifier is 20 kg/hr having particle size of 20 mm (Pérez et al., 2012). Compared to the fixed bed gasification cases with syngas efficiency of 42.6% to 75.8%, that of the fluidized bed gasification cases are higher in the range of 47.5% – 78.2%.

The tire and wood pretreatment processes designed in this study use the work of Caputo and Pelagagge as a reference, with the equipment names and costs listed in Table 5 (Caputo and Pelagagge, 2002). The pretreatment of tire includes three stages: the initial milling and pelletizer stage (belt conveyor, hammer mill, pelletizer) cuts the initial tire waste into partials with a diameter of 40 mm; the impurities and metal removal stage (eddy current separator and magnetic separator) separates all the impurities from the raw tire material; and the final milling stage (hand-sorting shredder and trommel screen) grinds the cleaned tire material into the target size. Because the target feedstock size of the fluidized bed gasifier is 2 mm, two groups of final milling processes are installed in series. While the fixed bed gasifier tire pretreatment processes use one hand-sorting shredder and one trommel screen for the final tire milling to 20 mm. Wood chip production processes are similar to the tire pretreatment processes, the only difference is that the wood chip production processes do not include the eddy current separator and the magnetic separator.

Table 5 also shows the calculation processes for the TPC of tire pretreatment. It is 2.07 times the total equipment cost. Table 6 shows the TPC scale data, and Table 7 shows the capital cost analysis result of the compared running models. In Table 7, although the TOC of running model 3 is 289 k$ higher than that of running model 1, the TOC of the unit energy output of running model 3 is 205 $/kW lower than that of running model 1 as a result of its higher syngas energy product (shown in Table 4). Fixed bed gasification processes have similar results, showing that the tire gasification process is more economical than sawdust gasification. In Table 7, the cost of running model 8's TOC is 43 $/kW lower than that of running model 4's, and the cost of running model 7's TOC is 32 $/kW lower than that of running model 3's, which shows the economic benefits of the fixed bed gasifier compared to the fluidized bed gasifier.

Fig. 7 presents the levelized cost of the syngas results, which shows that when the wood cost is 50 $/ton and the tire cost is −50 $/ton, the LCOS of the wood gasification is 3.76 ¢/kWh to 4.09 ¢/kWh and that of the tire gasification is 0.33 ¢/kWh to 0.60 ¢/kWh. Compared with the market price of natural gas, which is above 0.68 ¢/kWh, tire gasification has an attractive syngas product cost. Fig. 7 also shows that the fixed bed gasifier's LCOS is lower than that of the fluidized bed gasifier. These results indicate that even though the fluidized bed gasification technology has better performance indicators, the fixed bed gasification method can produce syngas more economically.

Table 5
Fluidized bed and fixed bed tire pretreatment system components and costs.

	Fluidized bed tire pretreatment				Fixed bed tire pretreatment			
Equipment	Capacity (kg/h)	Number	Cost (k$)	Operating cost ($/day)	Capacity (kg/h)	Number	Cost (k$)	Operating cost ($/day)
Belt conveyor	5400	1	25.41	16.93	20	1	0.16	0.11
Hammer mill	5400	1	237.24	711.92	20	1	1.54	4.62
Pelletizer	5400	1	338.93	142.54	20	1	2.20	0.92
Eddy current separator	5400	1	9.94	8.91	20	1	0.06	0.06
Magnetic separator	5400	1	49.72	5.28	20	1	0.32	0.03
Hand sorting Shredder	5400	2	135.32	51.74	20	1	0.44	0.34
Trommel screen	5400	2	119.30	20.10	20	1	0.39	0.13
Total equipment cost			915.88	957.43			5.11	6.21
Labor fee			540.37				3.02	
Eng'g CM fee			164.86				0.92	
Contingencies			274.76				1.53	
Tire pretreatment plant cost			1895.86				10.58	

Table 6
Total plant component and cost analysis assumption.

Fluidized bed gasifier	Plant component	Scaling parameter	C_0 (k$)	S_0	f
	Wood prepare to 2 mm	Biomass input, kg/hr	1070.76	5400	0.90
	Tire prepare to 2 mm	Biomass input, kg/hr	1895.86	5400	0.90
	Fluidized bed gasifier and cleaning up	Biomass input, kg/hr	7998.24	5400	0.75
Fixed bed gasifier	Plant component	Scaling parameter	C_0 (k$)	S_0	f
	Wood prepare to 20 mm	Biomass input, kg/hr	5.23	20	0.90
	Tire prepare to 20 mm	Biomass input, kg/hr	10.58	20	0.90
	Fixed bed gasifier and cleaning up	Biomass input, kg/hr	19.07	20	0.75

Table 7
Capital cost analysis results of compared running models.

Unit (k$ 2017)	1	2	3	4	5	6	7	8
Biomass preparation and handling	1071	1590	1896	1896	5	9	11	11
Gasifier system and cleanup	7998	7998	7998	7998	19	19	19	19
TPC	**9069**	**9588**	**9894**	**9894**	**24**	**28**	**30**	**30**
Owner's cost	2609	2363	2073	2073	8	7	6	6
TOC (k$ 2017)	**11678**	**11951**	**11967**	**11967**	**32**	**35**	**36**	**36**
TOC ($/kW)	**580**	**461**	**375**	**449**	**443**	**405**	**343**	**406**

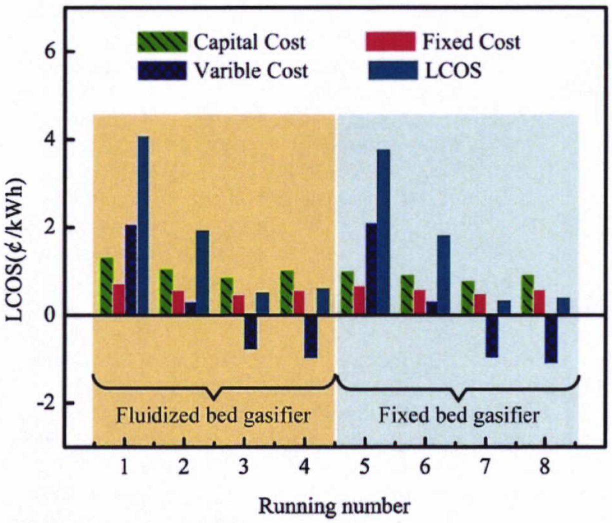

Fig. 7. Economic analysis results of running models.

3.5. Discussion and limitation

The simulation results indicate that compared with natural gas with an LHV of 35.8 MJ/Nm^3, the syngas product from the tire gasification process has a much lower LHV no more than 7.4 MJ/Nm^3, which results in their different commercial applications. For example, the primary use of natural gas is as fuel, as a source of hydrocarbons for petrochemical production and as the major source for elemental sulfur (Mokhatab et al., 2018). While the tire gasification derived syngas is more suitable for electricity generation and transport fuel production (Samiran et al., 2016). Therefore, according to the lower LCOS of tire-syngas, it is an attractive renewable syngas replacement for natural gas in electricity generation systems such as natural gas combined cycle (NGCC) and distributed household (Corrêa Jr et al., 2019; Khorshidi et al., 2016).

The designed capacity of the fluidized bed gasifier is 5400 kg/hr, which has the potential to drive a combined cycle to generate 10 MW of electricity by one gasifier (Zang et al., 2018a). However, the total plant cost of the fluidized bed gasifier is more than 9 million dollars (Table 7) and the tire gasification is not a mature technology, which result in the application of the commercial scale fluidized bed gasifier for tire-syngas production is limited (Oboirien and North, 2017). Different from the fluidized bed gasifier, the fixed bed gasifier's capacity is 20 kg/hr with a total plant cost no more than 30 thousand dollars. Considering the similarity components and thermal parameters of the syngas product from fluidized bed and fixed bed tire gasification, using fixed bed gasifier to produce tire-syngas distributed, and then transport syngas in pipes for central application is an easier pathway to apply the tire gasification technology in large commercial scale. Even though the LCOS results of this study have indicated the economic benefit of the fixed bed gasifier, our future work will use supply chain analysis method to optimize a 10 MW power plant based on distributed fixed bed tire-syngas supplement, and then compare it with standalone fluidized bed tire gasification power plant to have a deeper understanding on the differences between these two different processes.

The major limitation of this study is that the char remaining from the gasification process is not accounted for the economic analysis. For the tire gasification processes, the char by-product including 17.8% to 29.3% of the carbon from the tire feedstock. Even though char can be used as cleaning catalyst, soil amendment, and fuels, without detailed analysis it is hard to quantify how many credits will be added by accounting its production in the economic analysis process. Therefore, future work on char components, application, and economic analysis will replenish this study to be more comprehensive.

4. Conclusion

This study compares the tire gasification indicators in a fluidized bed gasifier and a fixed bed gasifier using process simulation and economic analysis. Results show the lower heating value of the tire-syngas product is 2.5–7.4 MJ/Nm^3, while equivalence ratio and tire mixture ratio have negative impacts on syngas heating value and syngas efficiency. Furthermore, the LCOS of tire gasification is 0.33–0.60 ¢/kWh that is lower than the market price of natural gas at 0.68 ¢/kW, which indicates tire gasification is an attractive technology for tire-syngas production. Finally, although the fluidized bed gasification technology has better performance indicators, the fixed bed gasification method can produce syngas with lower LCOS, which illustrates that fixed bed gasification is an economic pathway for the syngas product.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.wasman.2019.03.070.

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