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Original article

Sorption-enhanced steam gasification of fine coal waste for fuel producing

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ABSTRACT

Improving the quality of syngas from fine coal waste using the sorption-enhanced gasification process is a novel technology in the production of H₂. The effect of CaO on CO₂ absorption and H₂ increase in the steam fine coal gasification process was determined in a fixed bed gasifier. The steam gasification process took place at 650 °C using bentonite and CaO as catalysts and absorbents. Steam increased the H₂ concentration in the syngas to 58 vol%. In-situ CO₂ absorption is more effective with the addition of CaO. The maximum percentage of CO₂ was absorbed when the Ca/C ratio 2 was 78.33 %. The H₂ content in the syngas after the CO₂ was absorbed increased rapidly to 75.80 vol% at a Ca-to-carbon-mole ratio (Ca/C) of 1.5 and a steam-to-feedstock ratio (S/F) of 1.5. CaO did not produce significant results for low heating value (LHV) or cold gas efficiency (CGE), with results of 12 MJ/Nm³ and 44.53 %. The dominant water gas shift reaction due to the influence of steam and CaO increased H₂/CO up to 9.11, which made the syngas from this work suitable for Fischer–Tropsch synthesis.

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1. Introduction

CO₂ emissions have caused global warming, which threatens the ecosystem. CO₂ emissions worldwide have been predicted to reach 35.3 Gton by 2020 (Safarian et al., 2020). Almost 87 % of CO₂ emissions from human activities worldwide are caused by the use of fossil energy (Wilberforce et al., 2021) and the cement industry. Emissions can be reduced by using carbon-neutral renewable materials (AlNouss et al., 2018; Aprianti et al., 2020; Srivastava et al., 2021), carbon capture technology (Bach et al., 2019; Cormos and Cormos, 2019; Gabrielli et al., 2020), and CO₂ absorption technology (Chen et al., 2019; Saladeen et al., 2020). Although coal is not a renewable energy source, it is still being used today because there are still reserves. Compared to natural gas and oil, coal is still abundant in nature, so reducing CO₂ emis-

sions from its use is still being considered. More than 30 billion metric tons of coal from 10 major coal-producing countries are also accompanied by fine coal problems. Fine coal is waste from the mining industry disposed of in landfills or tailing dams. Fine coal has no economic value and is buried in stockpiles and slurry ponds (Ramudzwagi et al., 2020). Fine coal is used as a generator fuel for power plants in coal mining, and direct burning has added to air pollution. With around 30 % of the total production, other uses of fine coal are converted into briquettes. Unfortunately, fine coal has not received much attention as a fuel source.

Gasification is one of the technologies for converting coal and other feedstock into fuel. The gasification method can be applied not only on an industrial scale but also on a small scale (Susastriawan et al., 2021). In addition to producing H₂ and CO as the main components of syngas, the coal gasification process also produces CO₂ and CH₄ in relatively high amounts (Parvez et al., 2021). The process of converting fine coal through gasification is still limited. In our previous work, about 40–50 vol% of H₂ was produced from the gasification of fine coal with and without a catalyst (Faizal et al., 2021a). Based on the results of this study, the concentration of CO₂ is still high, so it is necessary to improve the quality of the syngas. Applying in-situ CO₂ absorption in the gasification process will increase hydrogen production in syngas (Duan and Yu, 2018; Li et al., 2020). Gasification can be carried out using different gasifying agents, such as air, CO₂, oxygen, and steam (Meng et al.,

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2019; Islam, 2020b; Samimi et al., 2020). However, for CO₂ absorption in the gasification process, steam is more profitable because it increases the performance of the water gas shift (WGS) reaction (Salaudeen et al., 2020). Thus, in addition to CO₂ being absorbed, hydrogen, the target of gas products, also increases. With adsorbents, gasification can occur at relatively low temperatures, thereby reducing operating costs. This work is the first for fine coal.

Sorption-enhanced gasification integrates steam gasification of a feedstock with in-situ absorption of CO₂ to produce H₂-rich syngas. CaO has been used as a CO₂ absorber, and its effect on gasification using either steam or other gasifying agents has been extensively investigated. Besides being cheap, available, and adaptable to high temperatures, calcium oxide is suitable for use as an adsorbent at medium-to-low gasification temperatures (Shahbaz et al., 2017b; Wu et al., 2018; Zhang et al., 2020). Previous studies using CaO in the gasification process have shown an increase in H₂ and a reduction in tar (Aprianti et al., 2022).

Lazzarotto et al. (2020) investigated the steam gasification of plastic waste consisting of polypropylene, polystyrene, and polyethylene with CaO. Besides acting as an adsorbent, CaO also acts as a catalyst that increases gas and H₂ yield. In sewage sludge, absorption in the gasification process using CaO with support materials and metal additives has succeeded in increasing the yield and moles of H₂ (Chen et al., 2020). This is in line with the research of Yang et al. (2021), which obtained H₂ up to 72.2 vol% at 550 °C (first stage) with a ratio of sewage sludge to CaO of 7:3. Wang et al. (2020) compared the catalytic gasification of fir sawdust with and without in-situ absorption of CO₂. The results showed that Ni/CaO produced the highest H₂ concentration at low temperatures (19.32 vol%). According to Mbeugang et al. (2021), operating conditions above 750 °C caused CaO to no longer act as an adsorbent. Optimal conditions were achieved at 650 °C and CaO to Cellulose 4 with an H₂ concentration of up to 45 vol%. Dashtestani et al. (2020) investigated the efficiency of CO₂ uptake by adsorbents (70 wt% CaO, 30 wt% Fe₂O₃) in simulated biomass gasification. The results showed that the average efficiency of absorption cycles reached 90.4 % at 620 °C. The absorption process at high temperatures is less effective because the adsorbent is deactivated, and the reaction leads to the formation of CO from CO₂. Soomro et al. (2018) also stated that the increase in CaO loading increased the concentration of H₂ and decreased the concentration of CO₂. This was proven by the gasification of lignin and cellulose at 650 °C.

Research using coal in sorption-enhanced steam gasification using CaO has been conducted before. Kumabe et al. (2020) performed steam gasification of coal char using CaO. The results showed that the production of H₂ was influenced by the absorption of CO₂ by CaO. In addition, the concentration of H₂ was increased due to the catalytic effect of CaO, as found by Jiang et al. (2018). Zhou et al. (2019) employed calcium looping hydrogen generation coal using K₂CO₃ as a catalyst at 700 °C and 3.5 MPa. The research results revealed that, in addition to acting as an adsorbent, CaO worked as a heat carrier and reduced half of the total CO₂ concentration in syngas. Most gasification reactions are endothermic and thus require a heat supply. The CaO carbonation reaction releases heat, which is compensated for by the gasification process. The same thing was found by Zhou et al. (2018), where CO₂ decreased to 12.80 % from 25.61 % at a Ca/C ratio of 0.5 in coal gasification. In addition, H₂ also increased by 17.38 %. Sun et al. (2016) enhanced coal gasification using modified CaO and found that H₂ concentrations were successfully produced by up to 80 %. In the steam co-gasification of coal and switchgrass by Masnadi et al. (2015), H₂ increased by almost 22 % using CaO at <700 °C.

The absorption of CO₂ by CaO during the gasification process is more critical than the process separately. The reduced CO₂ from syngas will directly affect the formation of H₂ along with the increased absorption by CaO. Our previous research revealed that

CO₂ absorption in fine coal catalytic gasification separately could only produce 48.8 vol% H₂ (Faizal et al., 2021b). To the best of our knowledge, fine coal has never been evaluated in the steam gasification process using in-situ CO₂ absorption, let alone using bentonite as a catalyst. Previously, bentonite was used more in wastewater treatment than as a catalyst (Hamad, 2021). This study aims to produce hydrogen-rich syngas using the CO₂ absorption process in steam fine coal gasification. The results will be used as materials for evaluation and comparison to utilizing fine coal in sorption-enhanced gasification technology.

2. Materials and methods

2.1. Feedstocks

Fine coal was obtained from South Sumatra coal mining. The fine coal was sieved into a particle size of about <0.5 mm. The physical and chemical properties of the fine coal were determined by proximate and ultimate analysis. As the catalyst specified in previous works (Aprianti et al., 2021; Faizal et al., 2021a), bentonite with a particle size of around 100 μm was obtained from a local site in Jambi, Indonesia. While CaO with a particle size of 100 μm was purchased from Pudak Scientific, Bandung, Indonesia, it was used as a CO₂ adsorbent in the gasification process. The characteristics of CaO were revealed by several analyses. The crystal structure and phases of CaO were analyzed using X-ray diffraction using a Rigaku Miniflex 600 X-ray diffractometer, while the functional groups were determined using Fourier Transform Infra-Red (Thermo Scientific Nicolet iS10 FT-IR Spectrometer). The morphology and elemental composition of CaO were analyzed using a scanning electron microscope (SEM JEOL-JSM-6510 LA) and X-ray fluorescence spectroscopy (PANalytical Epsilon 3 XLE XRF). The physisorption analysis was conducted using Brunauer-Emmett-Teller (BET) surface area analysis and Barrett-Joyner-Halenda (BJH) pore size and volume analysis (Autosorb-iQ-MP/XR).

2.2. Experimental procedure

Fine coal (2 kg/h) was fed into the top of a fixed-bed gasifier. The catalyst and CaO were loaded into the gasifier. The ratio between the feedstock and the catalyst was 1:0.25. The steam-to-fine-coal ratio (S/F) varied by 0, 0.5, 1, 1.5, 2, and 2.5, and the ratio of CaO to fine coal (Ca/C) was 0.5, 1, 1.5, and 2. The temperature was set to 650 °C with a heating rate of 10 °C/min at atmospheric pressure to start the process. Water was pumped into a steam generator to produce steam. The heat in the gasifier was supplied from three nozzle electrical heaters. The gasifier was made of stainless steel (SUS316) with a length of 67 cm, a diameter of 23 cm, and a thickness of 1.5 cm. The syngas came out from the top gasifier and cooled in a heat exchanger. This process took place about three minutes after passing through the heat exchanger. After a constant temperature and steady state were achieved for about one hour, the sample was collected in a Tedlar bag. Each experiment was repeated three times, and the data were averaged. The gas was then analyzed using gas chromatography (Perkin Elmer Clarus 680). The main gases in this process consisted of H₂, CO, CO₂, and CH₄. The whole gasification process is described in Fig. 1.

3. Results and discussion

3.1. Material characteristics

Proximate and ultimate analysis of fine coal on a dry basis was carried out and is shown in Table 1. The XRD pattern of the CaO

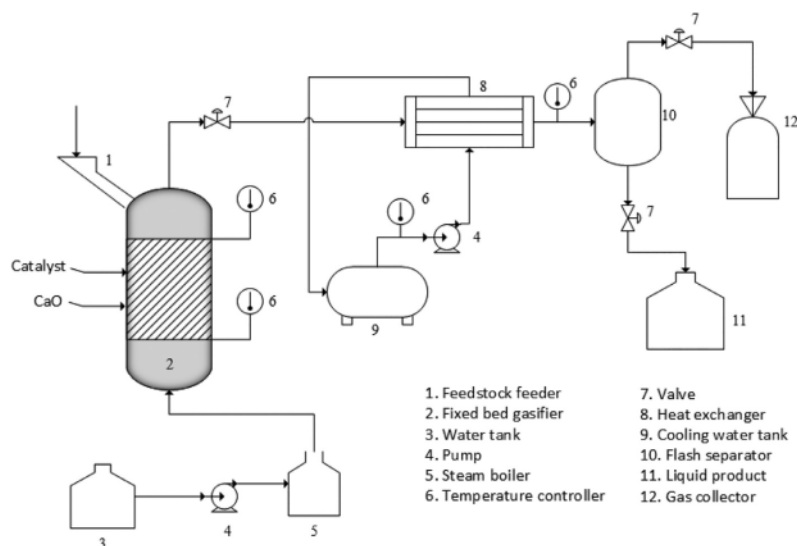


Fig. 1. Schematic diagram of the fine coal gasification process.

Table 1
Proximate and ultimate analysis results of fine coal.

Parameter	Result	Standard method
Ash content (%)	4.73	ASTM D 3174-12
Volatile matter (%)	47.59	ASTM D 3175-18
Fixed carbon (%)	47.67	ASTM D 3172-13
Total Sulphur (%)	0.48	ASTM D 4239-18
HHV MJ/kg	28.27	ASTM D 5865-13
Carbon (%)	74.03	ASTM D 5373-16
Hydrogen (%)	5.13	ASTM D 5373-16
Nitrogen (%)	1.04	ASTM D 5373-16
Oxygen (%)	14.60	ASTM D 3176-15

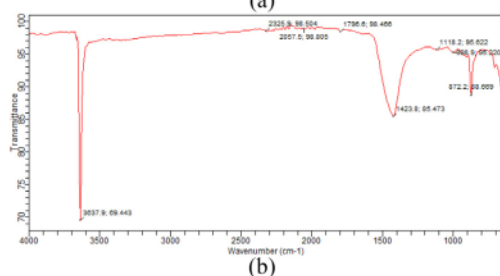
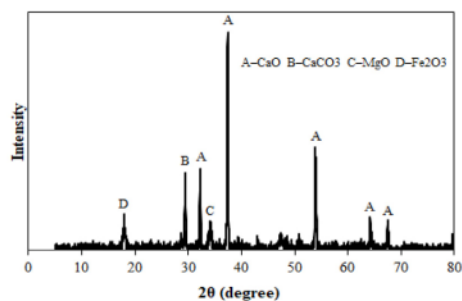


Fig. 2. XRD pattern (a) and FTIR spectra of CaO.

sorbent is shown in Fig. 2a. The peaks appear at around 17.98° for Fe_2O_3 , 29.44° , which is presumed to be carbonate diffraction, whereas at 34° , associated with MgO , the main peaks of CaO were recorded to appear at 32.22° , 37.4° , 53.88° , 64.18° , and 67.52° . The same peak CaO was found in other studies (Zhang et al., 2018; Dashtestani et al., 2020; Li et al., 2021). The FTIR spectra of the CaO are shown in Fig. 2b. The presence of the OH stretching band in the absorbent could be seen at $3,637.9\text{ cm}^{-1}$, and the broadband at $1,423.8\text{ cm}^{-1}$ indicates vinyl C–H. The characteristic absorption peaks, which also presented at 872.2 cm^{-1} , could be attributed to C–O and CaCO_3 bonds. The harmonic vibrations corresponding to the C=O could be seen at $1,796.6$ and $2,325.9\text{ cm}^{-1}$. The purchased CaO was analyzed to determine the composition of its chemical compounds, which are shown in Table 2. CaO has a purity of up to 96.23 %, which is acceptable for the absorption process. A small number of other components in CaO , such as MgO , SiO_2 , Al_2O_3 , and Fe_2O_3 , as well as others (Table 2), positively affect the gasification process (Shahbaz et al., 2017a). A physio-sorption test was performed to analyze the pore properties. The BET surface area was found to be $2.706\text{ m}^2/\text{g}$. Porosity qualities are linked to pore volume and size, which are crucial for carbonation reactions. The pore volume was $0.013\text{ cm}^3/\text{g}$, and the BJH pore size was 18 nm . Table 2 presents the particle and bulk densities. The morphology of CaO before and after absorption is shown through the SEM images in

Table 2
Characteristics of CaO .

Components	Wt%
CaO	96.23
MgO	1.75
Fe_2O_3	0.15
SiO_2	0.86
K_2O_3	0.06
Al_2O_3	0.17
Other metal oxides	0.78
BET surface area (m^2/g)	2.706
Pore Volume (cm^3/g)	0.013
Pore Size (nm)	18
Bulk density (kg/m^3)	1100
Particle density (kg/m^3)	3065

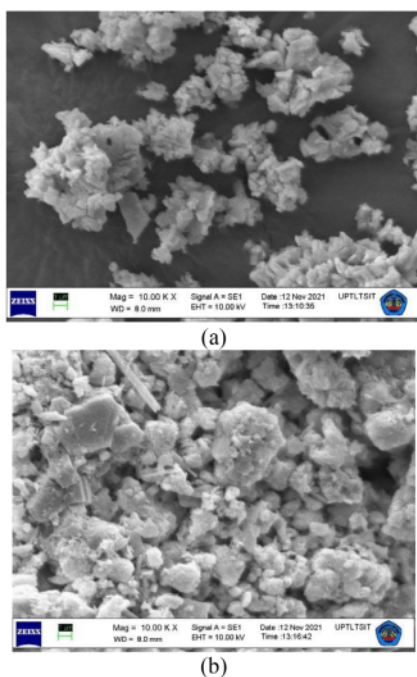


Fig. 3. SEM image of CaO (a) before and (b) after absorption.

Fig. 3. The surface of fresh CaO appears loose, porous, and rough, which is suitable for the diffusion and carbonation of CO_2 . After absorption, the surface of CaO turns into a tight fit and accumulates into larger particles, and small cracks can also be seen on the surface of the particles.

3.2. The effect of the steam-to-feedstock ratio on gas composition

The gasification process of fine coal using steam increased the hydrogen concentration through the water gas shift reaction. Fig. 4 illustrates the effect of steam on the gas composition of the catalytic gasification process of fine coal with a steam-to-feedstock (fine coal) (S/F) ratio. At a constant reaction temperature of 650 °C and a fine coal feeding rate of 2 kg/h, the steam flow rate varied from 0 to 5 kg/h to cover the S/F from 0 to 2.5. The reactions involved in sorption-enhanced gasification (R1–R11) are listed in Table 3.

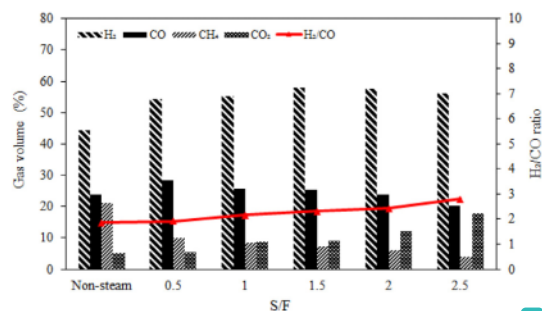


Fig. 4. The effect of variations in the S/F ratio on the volume of syngas in the catalytic gasification of fine coal.

Table 3

Reactions in gasification.

Reaction	Reaction name	Reaction code
$\text{C} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}$	Partial oxydation	R1
$\text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O}$	Hydrogen oxydation	R2
$\text{CO} + \frac{1}{2} \text{O}_2 \rightarrow \text{CO}_2$	CO oxydation	R3
$\text{C} + \text{CO}_2 \leftrightarrow 2\text{CO}$	Boudouard reaction	R4
$\text{C} + \text{H}_2\text{O} \leftrightarrow \text{CO} + \text{H}_2$	Water gas reaction	R5
$\text{CO} + \text{H}_2\text{O} \leftrightarrow \text{CO}_2 + \text{H}_2$	Water gas shift reaction	R6
$\text{C} + 2\text{H}_2 \leftrightarrow \text{CH}_4$	Methanation reaction	R7
$\text{CO} + 3\text{H}_2 \leftrightarrow \text{CH}_4 + \text{H}_2\text{O}$		R8
$\text{CH}_4 + \text{H}_2\text{O} \leftrightarrow \text{CO} + 3\text{H}_2$	Steam methane reforming	R9
$\text{CaO} + \text{CO}_2 \rightarrow \text{CaCO}_3$	Carbonation reaction	R10
$\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$	Calcination reaction	R11

As S/F increases within that range, the percentage of H_2 volume is up to 58 % at S/F 1.5, which was previously 44.30 % in gasification without steam. As more steam is supplied, more CH_4 is converted into synthesis gas (H_2 and CO). However, the CO percentage drops considerably as the water–gas shift equilibrium reaction shifts forward when using more steam (Shen et al., 2018; Chein and Hsu, 2020; Xiao et al., 2020). There was a continuous increase in the H_2 content as the S/F increased to 1.5 wt/wt. Based on Le Chatelier's principle, increasing the ratio of steam to fine coal made the H_2O consumption reaction dominant due to the increase in the partial pressure of steam. This is what was expected to happen, according to R6. On the other hand, the CO concentration decreased as the steam ratio increased, with a final concentration at S/F 2.5 of 20.10 %. Although there is a Boudouard reaction (R4), this reaction is very endothermic and requires high temperatures to reach the reaction. After S/F increased to 2 and 2.5, the H_2 concentration slowly decreased. Increasing S/F strongly affects H_2 production, but there is a limit at which increasing S/F (more steam) requires additional energy (Jin et al., 2019; Kumari and Mohanty, 2020; Upadhyay et al., 2020; Yu et al., 2020). To produce more steam, additional energy is needed. When injecting excess steam, the operating temperature of the gasifier drops quite dramatically. To overcome this, additional energy is required to increase the temperature back. From the results obtained, S/B 1.5 indicates optimal H_2 production, following the results obtained by Fremaux et al. (2015), who concluded that S/F had a marginal effect on hydrogen concentration.

The CH_4 concentration dropped drastically when 0.5 S/F was applied and consistently continued to decline until S/F 2.5. Methane is formed during the pyrolysis step of gasification, which vaporizes the material (R7–R9). The S/F ratio has a less significant effect on the methane formation process. The methane formed is consumed again in the steam methane reforming reaction to produce more hydrogen. Meanwhile, compared to the gasification of fine coal instead of steam, CO_2 continues to increase as the supply of steam into the gasifier increases. The CO_2 concentration rises to 12.60 % at S/F 2.5. The increased steam ratio not only encourages the WGS reaction to produce but also produces more CO_2 . CO that has been formed can also be converted into CO_2 through CO oxidation (R3), which is very exothermic. The steam-to-fine-coal ratio, which increases to a certain extent, shows an increasing trend in the H_2/CO ratio, as shown in Fig. 4. The continuous increase in the H_2/CO ratio is due to steam promoting the water gas shift reaction. The highest H_2/CO ratio was found at an S/F 2.5 of 2.79, which was initially only 1.85.

3.3. The effect of Ca/C

The gasification process of fine coal using absorbent is carried out at atmospheric pressure to suppress the formation of CO_2 and encourage more optimal steam methane reforming and WGS

reactions so that the hydrogen concentration increases. Fig. 5 illustrates the gas composition as a function of the Ca/C ratio with bentonite loading as a catalyst, a ratio of 0.25 to fine coal, and S/F 1.5 at 650 °C. Compared to the process using S/F 1.5 with the highest H₂ yield, the addition of CaO without a doubt increased the H₂ concentration at Ca/C 1.5 to 75.80 vol% from 58 vol%. Although at Ca/C 0.5, the increase in H₂ was not significant, when Ca/C was increased, it was seen that H₂ increased rapidly. The increased concentration of H₂ is caused by the carbonation reaction (R10), which drives the water–gas shift reaction (R6) to produce H₂ (Martínez et al., 2020). The CO₂ absorbed by CaO weakens the Boudouard reaction because CO₂ as a reactant has been reduced (Wu et al., 2018). This was also accompanied by a decrease in CO₂ concentration to 2.6 vol%. The concentration of CO in the syngas decreased by 16.90 vol% at Ca/C 2, while methane consistently fell. A similar trend was also found by Zhou et al. (2018). The reduced CO concentration is possible due to the restriction of ether bond cracking by CaO in the pyrolysis step (Bunma and Kuchonthara, 2018). The Ca/C ratio is increased to promote the carbonation reaction if the partial pressure of CO₂ in the system is high. The decrease in methane concentration is not very significant. This proves that the R7 reaction is not very significant, and CaO produces a small effect. By varying the Ca/C ratio, the H₂/CO ratio also increased from 2.79 at the S/F 2.5 ratio to 9.11 at the Ca/C ratio of 2. The increase in the H₂/CO ratio reinforces the statement that R6 is (Zhou et al., 2018) the most influential reaction in improving the quality of syngas in steam gasification using CaO absorbent. The resulting syngas also meets the standards for Fischer–Tropsch synthesis.

The reaction to the right is favored if the pressure of one of the products is reduced when applied to the equilibrium reaction according to Le Chatelier's principle. The reduction in CO₂ concentration in the syngas with increasing Ca/C was due to the enhanced R11 reaction. As the partial pressure of CO₂ decreases, the reactions leading to the formation of CO₂ are reduced. Therefore, it suffices to say that the reduction in carbon monoxide concentration with increasing Ca/C is the result of the conversion in reactions R3, R6, and R8. The increase in hydrogen concentration was due to the preference for reaction R6 and increased tar cracking and hydrocarbon reforming.

CaO showed good tar cracking activity for in-situ tar removal during the gasification process of fine coal. The mechanism of tar cracking by CaO begins with the absorption of tar molecules and H₂O/CO₂ on the active site of CaO. CaO base sites can promote dehydrogenation, dealkylation, and ring-opening of tar molecules to form activated carbon deposits and gases. Activated carbon can be further condensed to form coke or react with H₂O/CO₂ to form H₂ and CO/CO₂ (Islam, 2020a; Li et al., 2022).

The cold gas efficiency (CGE), initially 57.09 % at gasification without steam, dropped drastically after steam was used (Fig. 6). CGE describes the energy of raw materials that are converted into

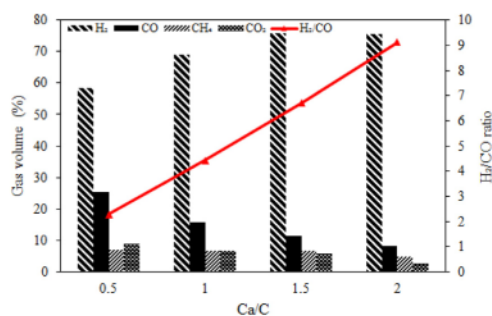


Fig. 5. Gas composition on variation of Ca/C ratio.

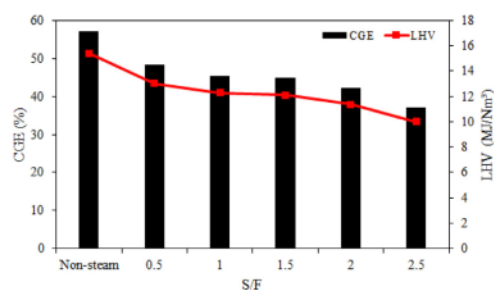


Fig. 6. Cold gas efficiency and LHV of syngas under variation of Ca/F ratio.

syngas energy, representing energy or system efficiency. This is related to the low heating value (LHV), which is the basis for calculating the CGE. LHV is the syngas lower heating value in MJ/Nm³ calculated by comparing the low heating value from all gas components of the syngas with the low heating value of feedstocks. Because the concentrations of CO and CH₄, which are the main points for calculating LHV, continue to fall while H₂ increases, this will also impact CGE. This trend was also found in several previous studies (Shahbaz et al., 2017b; Zaman et al., 2020) but differs from the finding of Hu et al. (2020) that CGE increases with an increase in the ratio of steam to theraw materials used. The highest CGE and LHV values in fine coal catalytic gasification using steam were found at S/F 0.5 of 48.30 % and 13 MJ/Nm³ and then decreased to 37.16 % and 10 MJ/Nm³.

The presence of CaO in gasification steam increases CGE more with a reasonably stable trend to Ca/C 1.5 (Fig. 7) but then decreases when Ca/C rises to 2. At Ca/C 1.5, the CGE and LHV produced were 44.53 % and 12 MJ/Nm³.

When the Ca/C mass ratio increased from 0 to 2, the carbon conversion decreased from 64.95 % to 24.45 %. CO and CH₄ were consumed to produce H₂. The increased CO₂ absorption by CaO with the increased amount of CaO also causes the carbon conversion rate to decrease. This trend follows previous work by Mbeugang et al. (2021). In this research, the tar content detected by GC–MS mainly consisted of benzene, toluene, ethylbenzene, (p + m)xylene, o-xylene, and naphthalene.

3.4. Effect of CO₂ absorption

The quantity of CO₂ absorbed by CaO during the enhanced sorption gasification process serves as a direct measure of CaO's ability to absorb CO₂. To our knowledge, this is rarely reported, and the function of CaO is also strongly influenced by the gasification temperature. Moreover, it is reasonable to understand that the yield of CO₂ almost did not change, as the absorption activity of CaO was

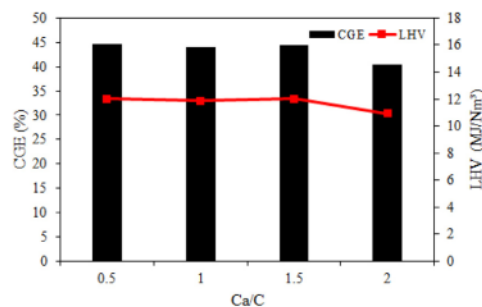


Fig. 7. Cold gas efficiency and LHV of syngas under variation of Ca/C ratio.

reduced when the temperature was raised over 650 °C. Another reason is that steam prohibits a strong inhibitory effect on CO₂ absorption, especially at high temperatures. The absorbed CO₂ increases with the increase in the variation of Ca/C (Fig. 8). The highest success rate of CO₂ absorption occurred in Ca/C 2, which was 78.33 %, with an increase in H₂ of 70.74 %. Overall, it can be seen that CO₂ absorption by CaO at Ca/C 1.5 runs optimally in line with high H₂ production.

The presence of CaO only absorbed CO₂ in the syngas, which further increased H₂ and did not act as a catalyst characterized by a decrease in CO. Some of the CO₂ formed from WGS was fixed into solid-phase CaCO₃. According to previous literature, CaO generally plays the role of a CO₂ absorbent when the reaction temperature is low enough, not more than 700 °C (Li et al., 2017; Chen et al., 2018), which fits well with this work, where the experiment took place at 650 °C. Through the carbonation reaction (R10), CaO reacted with CO₂ to create CaCO₃, lowering CO₂ concentration. On the other hand, high temperatures are unfavorable for CO₂ absorption because the exothermic process of CaO carbonation diminishes over time (Hu et al., 2015). It should also be mentioned that the concentration of CH₄ and CO changes with variations in the Ca/C ratio. It was found that the trend of CH₄ was slightly reduced, and CO production was reduced but still active, indicating the catalytic effect of the catalyst used. Gas continued to be produced through the steam reforming of hydrocarbon by bentonite. The catalytic effect did not come from CaO but from bentonite as the catalyst. This is indicated by the CO and CH₄ content, which are still around 5 % and 10 %. CaO acts only as an absorbent rather than as a catalyst. This was indicated by a significant increase in H₂ after CaO was applied.

3.5. Comparative study on H₂ concentration

A comparison of H₂ produced from the steam gasification process with absorption using CaO is presented in Table 4. In the present work, the hydrogen concentration achieved was 75.80 vol% at 650 °C with an S/F ratio of 1.5 and a Ca/C ratio of 1.5 using a bentonite catalyst. Mostafavi et al. (2016) produced 85 mol% H₂ from ash-free coal gasification using 20 % calcium carbonate as the catalyst with a sorbent-to-carbon ratio of 2 in a fixed bed reactor at 675 °C. Zhou et al. (2018) reported an 82.99 vol% mixture of H₂ and CH₄ produced from steam gasification (50 %) of catalytic sub-bituminous coal using K₂CO₃ as a catalyst and CaO as an absorbent (Ca/C = 0.5) in a fixed bed gasifier. A hydrogen yield of more than 80 % with only a small amount of CH₄ in the gas mixture was produced under reaction conditions of 700 °C and 3.5 MPa. Meanwhile, under the same operating conditions, the H₂ concentration was successfully achieved at 77 vol% in pressurized coal catalytic gasification using K₂CO₃ as a catalyst and CaO as an absorbent for six cycles (Zhou et al., 2019). Furthermore, at the same steam gasification temperature as in the present study, H₂ with a purity

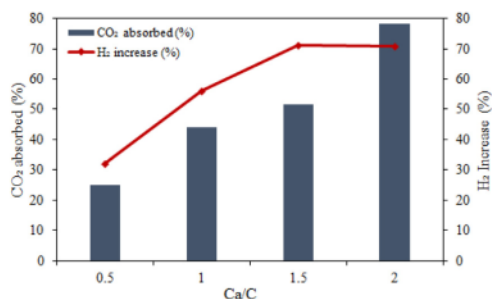


Fig. 8. CO₂ absorbed and H₂ increased at different Ca/C ratios.

Table 4
Comparative study of H₂ concentration.

Feedstock	H ₂ (%)	Conditions	References
Fine coal	75.80	T = 650 °C S/F = 1.5 Ca/C = 1.5	Present study
Coal	77	T = 700 °C Ca/C = 1	(Zhou et al., 2019)
Sub-bituminous coal	82.99 H ₂ + CH ₄	T = 700 °C Ca/C = 0.5	(Zhou et al., 2018)
Coal	around 84	T = 650 °C Ca/C = 0.5	(Sun et al., 2016)
Bituminous coal	82.66	T = 930 °C Ca/C = 2	(Han et al., 2016)
High sulfur coal	77.41	T = 930 °C Ca/C = 0.25	
Ash-free coal	85	T = 675 °C Ca/C = 2	(Mostafavi et al., 2016)

of about 84 vol% was produced using modified CaO-MgO as an absorbent with a smaller Ca-to-coal ratio of 0.5 (Sun et al., 2016). Han et al. (2016) reported the gasification processes of two different types of coal at high temperatures (930 °C). In bituminous coal, the concentration of H₂ reached 82.66 vol% at a Ca/C 2 ratio, while in high sulfur coal, H₂ was produced at 77.41 vol% at a lower Ca/C ratio (0.5). Different types of coal produced different concentrations of H₂ due to different volatile matter and carbon content. A higher steam input leads to more energy input. The temperatures in other studies were also much higher. Nevertheless, the quality of syngas produced from fine coal can compete with coal types from other studies regarding the H₂ concentration achieved.

4. Conclusion

The sorption-enhanced gasification of fine coal with CaO as an adsorbent was investigated in a fixed-bed gasifier under different conditions. The steam raised H₂ at the right temperature and catalyst. The increase in S/F ratio and CO₂ absorption showed a good synergy effect, with significant results in increasing H₂ and decreasing CO₂. The H₂ content in the syngas reached about 75.80 % using steam (S/F = 1.5) at 650 °C and Ca/C 1.2. The increase in CaO significantly reduced CO₂, with almost 80 % absorption. Excess CaO does not substantially affect H₂ production, although it still lowers CO₂ concentration. CaO acted as an adsorbent at a medium gasification temperature in this study.

2 Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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