Fluidized Bed Reactors

Subjects: Engineering, Chemical
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Fluidized gasification reactors can be used to produce hydrogen. They are operated in three modes including bubbling, circulating, and dual beds, as depicted inC. In a bubbling fluidized bed (BFB), the fuel is introduced from the bottom or side of the bed. The bed starts bubbling when the velocity of gasification agent is beyond the minimum fluidization velocity.

Keywords: hydrogen ; fluidized bed reactor ; supervised machine learning ; review

1. Introduction

The United Nations (UN) has promoted climate neutrality to produce no net greenhouse gas (GHG) emissions for years, as GHG emission has been considered one of the major causes of global warming [1]. GHG emissions in the atmosphere from fossil fuels, generated either by power plants or automobiles, have also risen and become a tremendous threat to environmental sustainability [2][3]. In recent years, a series of efforts shas been made, including using renewable resources or clean energy such as hydrogen fuels to mitigate the situation, reducing carbon dioxide emissions and in realizing sustainable development [4][5][6][7]. However, the conventional generation techniques of hydrogen are adopted from fossil fuels, including steam methane reforming (SMR) and derivations from natural gas, also known as “gray hydrogen” [8]. On a related note, hydrogen production using renewable resources is called “blue hydrogen” or biohydrogen (such as by the means of electrolysis, nuclear, solar photovoltaic-PV, wind, hydro or geothermal technologies), which is regarded as more environmentally friendly [3][5][6][9][10][11][12][13]. The current hydrogen generation technologies from different feedstocks are summarized in Figure 1. Apparently, the balance of feedstock between deploying fossil fuel and renewable resources for hydrogen generation has become lopsided, and this trend will become more prominent in the foreseeable future.

While a large number of techniques are available for hydrogen generation, the employment of those techniques faces great challenges when it comes to considering the more complex factors (e.g., cost-effectiveness, reliability and efficiency). For example, electrolysis is considered to be not cost-effective, and bioprocessing through dark fermentation using biomass as the feedstock is not efficient due to its intrinsic, slow biological processing feature [14]. Recently, biomass gasification by fluidized bed reactors (FBRs) has been found to significantly enhance the efficiency of hydrogen production, but its obvious drawbacks, such as complex reaction mechanisms and catalyst usage, somehow limit its application [15][16]. For fluidized bed operation, many operational parameters (such as the carbon content, residence time, lower heating values and particle size) play vital roles in determining the expected outcomes (e.g., conversions and yield) [17], and there are very few examples in the literature that try to systematically correlate these critical operational parameters with the corresponding performances. Therefore, this initiates our interest in using our developed artificial neural networks, coupled with a response surface methodology (ANNs-RSM) algorithm, to assess the statistical significance of the investigated operational parameters upon the performances of FBRs during hydrogen generation.

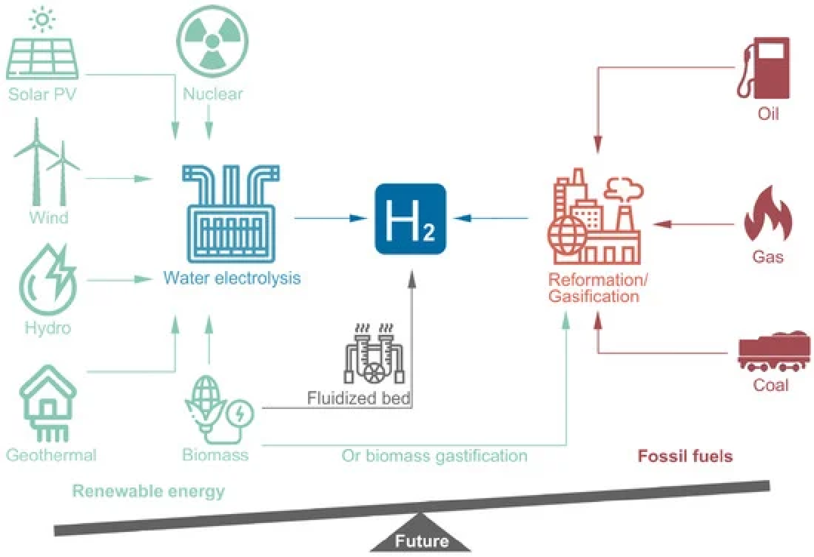

Figure 1. Hydrogen production from different resources via different technical routes. Left: blue hydrogen. Right: gray hydrogen.

2. Statistical Analysis of Parameter upon Output

In this review, among the different operational parameters, we choose seven parameters (temperature, residence time, equivalent ratio, steam-to-biomass ratio, carbon content, lower heating value and particle size) due to availability in reported literatures. Taking the feedstock sources for an example, different sources of feedstock may own various calorific values, carbon content, or moisture content that can significantly affect the conversion rate to hydrogen. The results are summarized in **Table 1** and **Table 2** (**Table 1** for different types of FBGs and **Table 2** for general FBGs that the types were not specified in the literatures). Using the collected references as training data set via ANNs-RSM algorithm, the predictions were made against the actual reported values from references. The results are shown in **Figure 2**. Apart from some values possessing relative higher uncertainties over ±20%, the majority of calculated data fall into the reasonable range, indicating that our constructed network can generate reliable predictions.

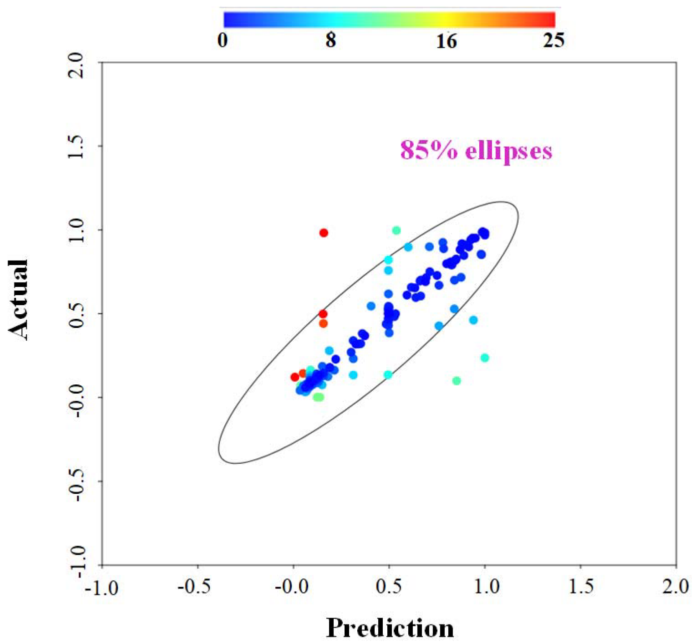

Figure 2. Analysis result—actual versus prediction from ANNs modeling, where color bar represents the uncertainties.

Table 1. Operational parameters versus corresponding hydrogen generation, where - represents the value that is not available from the literature (in this work, for easiness of data handling, the voids were replaced by the average reported value).

Bed Type	Feedstock	Feedstock Particle Size (μm)	Carbon Content (wt.%)	LHV (MJ/Nm^3)	T/°C	Process Time/min	ER	SBR	Yield (Nm^3/kg)	Yield H_2 Content/vol%	(CCE) %	Reference
Bubbling	Torrefied and raw pine	468	13.80	-	800	45	0.28	-	80.56	15.13	-	[18]
	Wood sawdust	1500	-	-	850	300	-	-	1.15	42.00	85.00	[19]
	Rice husk	7500	11.69	3.84	600	-	0.20	-	0.50	2.70	95.00	[20]
	Wood-PET pellets	6000	12.16	19.19	800	90	0.28	-	-	8.10	98.60	[21]
	Rice husk	-	36.00	9.30	800	60	0.30	-	-	12.50	-	[22]
	MSW	-	8.46	14.40	900	-	0.25	1.00	-	-	-	[23]
	Cocoa shells	461	21.70	-	900	60	0.23	1.20	1.49	49.10	50.00	[24]
	Rice husk and coal	1575	22.37	-	850	210	0.26	1.21	-	8.64	89.00	[25]
	Pine sawdust	-	12.60	-	600	120	-	0.20	1.03	38.60	71.20	[26]
	-	-	-	14.30	800	42	0.30	-	-	4.00	76.00	[27]
	Pine sawdust and brown coal	4000	13.20	-	900	-	0.20	0.50	-	50.60	84.20	[28]
	Torrefied woodchips	240	22.82	19.26	850	30	0.22	1.20	1.12	28.66	89.20	[29]
	Carbonaceous feedstock	15,000	11.50	20.53	785	30	0.21	-	2.10	7.10	84.10	[30]
	Rice husk	-	14.99	-	850	-	0.30	0.80	-	11.00	76.00	[31]
	Cypress wood chips	-	20.64	15.80	700	-	0.30	1.20	-	0.59	-	[32]
	Torrefied woodchips	-	20.18	3.00	800	30	0.24	-	1.77	14.31	78.00	[33]
	Poultry litter	525	22.82	19.26	850	90	-	1.40	1.41	43.00	87.52	[34]
	-	310	8.81	5.36	700	30	0.30	0.24	1.36	17.58	88.00	[35]
	Spruce slice	615	-	20.05	809	60	0.20	-	-	9.69	50.00	[36]
	Miscanthus	300	14.99	4.25	850	-	0.35	0.50	-	12.30	-	[37]
	Torrefied and raw pine	630	-	5.55	915	60	0.32	-	-	10.80	91.00	[38]
Circulating	Torrefied wood residues and mixed wood	5000	24.65	11.70	850	180	0.22	1.26	1.60	53.00	82.40	[39]
	Wood residue and Tabas coal	175	18.20	-	850	55	0.40	-	-	52.70	-	[40]
	Methane and biomass	-	-	-	1000	-	0.21	1.00	-	28.00	-	[41]
	Sub-bituminous coal and sawdust	3675	35.93	22.39	800	-	0.29	-	2.11	12.63	84.00	[42]
	-	1890	-	3.96	800	-	0.41	0.60	-	4.00	-	[43]

Bed Type	Feedstock	Feedstock Particle Size (μm)	Carbon Content (wt.%)	LHV (MJ/Nm^3)	T/°C	Process Time/min	ER	SBR	Yield (Nm^3/kg)	Yield H_2 Content/vol%	(CCE) %	Reference
	PP plastic pellets, wood chips and plant capsules	660	8.01	26.00	900	10.67	0.30	-	2.53	29.70	82.00	[44]
	Rice straw	1250	18.74	-	800	120	0.24	-	1.20	5.38	84.77	[45]
	PE plastic bags, sawdust and PP plastic particles	780	5.00	-	900	-	0.30	0.50	-	53.10	-	[46]
Dual	PE plastic bags, sawdust and PP plastic particles	700	5.00	-	700	35	0.30	0.60	-	39.38	-	[47]
	Volatile, fixed carbon and ash	-	17.16	9.90	800	-	0.19	1.56	1.72	22.34	91.50	[48]
	Pine sawdust	200	12.73	11.40	850	120	0.30	0.30	10.51	47.30	98.00	[49]
	Biomass briquette	-	18.71	11.00	670	300	0.19	-	1.20	24.00	98.82	[50]
	PE plastic bags, wood chips and PP particles	660	-	-	900	35	0.30	0.60	-	50.96	92.59	[51]

Table 2. Operational parameters of general fluidized bed (types not specified in literatures) versus corresponding hydrogen generation, where - represents the value that is not available from the literature (in this work, for easiness of data handling, the voids were replaced by the average reported value).

Catalyst	Feedstock	Feedstock Particle Size (μm)	Carbon Content (wt.%)	LHV (MJ/Nm^3)	T/°C	Process Time/min	ER	SBR	Yield (Nm^3/kg)	Yield H_2 Content/vol%	CCE %	References
ZSM-5 zeolite	Beech-wood and poly	-	-	-	954	20	-	0.63	-	-	84.20	[52]
-	Palm kernel shell and sub-bituminous coal	160	40.00	21.13	800	1440	0.60	0.20	-	12.00	82.80	[53]
NiO/modified dolomite	Coffee husk	-	-	-	900	-	0.15	1.50	1.75	27.00	-	[54]
-	Carbonaceous feedstock	275	0.80	-	820	-	0.19	1.00	2.00	40.00	-	[55]
-	Citrus peel	500	40.31	4.65	750	20	0.30	1.25	0.69	26.00	87.00	[56]
$Ni/CeO_2/Al_2CO_3$	Wood residue	-	49.18	-	823	44	0.17	0.71	1.66	42.52	93.56	[57]
-	Straw	7500	17.15	14.96	850	60	0.16	-	0.90	17.00	75.00	[58]
Commercial Ni-catalyst *[1]	Almond shells	-	11.00	-	815	60	-	0.49	1.70	55.30	-	[59]
Ternary molten carbonates	Forestry biomass waste	-	3.89	-	750	60	-	1.00	-	55.00	-	[60]
-	Pine sawdust and MSW	2000	18.82	-	850	-	0.21	-	13.40	9.80	-	[61]
High-alumina bauxite	Straw	7500	17.50	9.35	726	60	0.16	-	-	14.90	70.99	[62]
Calcium (Ca)	Rice husk and bamboo dust	670	-	5.05	800	30	0.35	0.41	1.72	-	98.00	[63]
Commercial Zeolite *[2]	Empty fruit bunch	3000	8.60	-	973	30	-	2.00	-	75.00	-	[64]
Industrial sludge derived catalysts	-	320	10.35	4.84	800	50	0.30	1.00	-	12.46	100.00	[65]
SCG ash	-	1400	20.00	12.20	900	30	-	0.53	-	6.00	-	[66]
Coal bottom ash	Palm kernel shell	750	14.25	12.50	692	60	-	1.50	-	79.77	59.90	[67]
Calcined dolomite	-	5000	35.20	-	1000	50	0.14	1.00	-	49.10	60.80	[68]

The types of fluidized bed reactors and their corresponding reported hydrogen contents from **Table 1** and **Table 2** were summarized and plotted in **Figure 3**. Obviously, different types of fluidized bed reactors from different reported sources tend to yield different reported values of hydrogen contents. In **Figure 3**, the top three reported hydrogen contents were annotated. For example, the hydrogen content could reach nearly 80% when almond shell was fed into fluidized bed gasifier using commercial nickel as catalyst. The bubbling fluidized bed reactor also generated hydrogen content reaching around 70% when empty fruit bunch was used as feedstock.

Company information: *[1] Johnson Matthey. *[2] Zeolyst, Malaysia Sdn. Bhd., Malaysia.

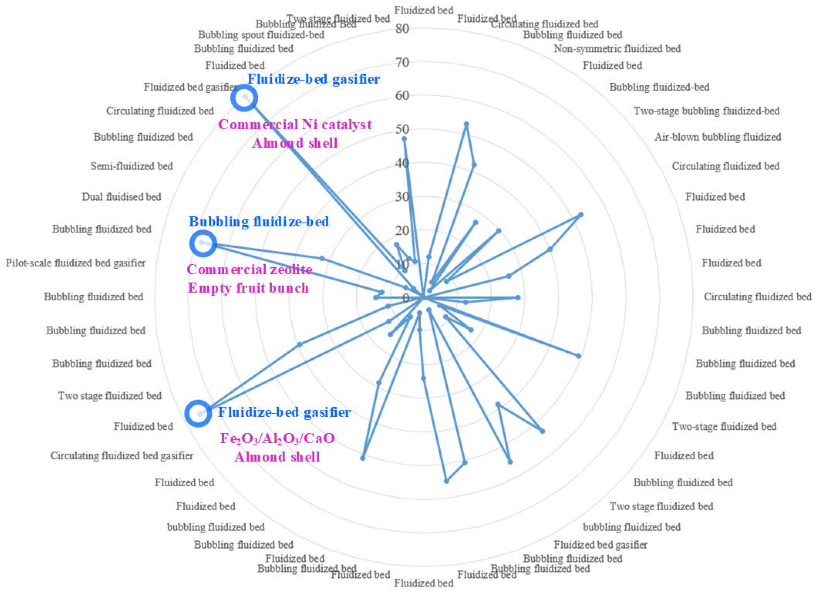

Figure 3. Types of fluidized bed versus hydrogen yield (vol-%), the circles with number labelled represent hydrogen yield (%) and the top three hydrogen yield case are displayed in blue and purple.

3. Conclusions

We compared the commonly used hydrogen production technologies including steam methane reforming, electrolysis, and biomass gasification. Among the technologies, biomass gasification using fluidized bed reactor was thoroughly reviewed, including the types and operating conditions. Biomass gasification can be considered as a promising alternative technology for hydrogen production owing to the renewable, abundant, carbon neutral, and cost-effective nature of the feedstock. Subsequently, biomass gasifiers including entrained flow gasifier, fixed bed and fluidized bed reactor (FBR) were compared. Due to the inherent advantage of enhanced mass and heat transfer, the FBR was identified as the most promising biomass gasification technique for hydrogen production. In addition, to quantitatively assess the pivotal operational parameters of FBR, seven key inputs and three outputs were extracted from the reported literatures as a training data set. These inputs are SBR, ER, temperature, PS of feedstock, residence time, LHV, and CC. The three outputs are HY, HC, and CCE. The results of the statistical analysis indicate that six binary parameters are statistically significant to the outputs. In terms of high HY, SBR, and ER, relatively low values were suggested for efficient reaction and economic considerations. A high HC was proposed based on a shorter reaction time within 180 min under 850 °C for biomass that contained high LHV and fine particle sizes. The optimal CCE values could be obtained within an ER range of 0.15 to 0.35, operating temperature of 700 to 850 °C, reaction time within 180 min, and with CC values beyond 8%, as inputs. This analysis may provide a revealing insight for users who wish to realize high working efficiency using biomass gasification technology for hydrogen production.

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