Nitrogen Gas Adsorption Filter (NgAF) to enhance producer gas quality

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Abstract. Biomass gasification is a thermochemical conversion process of solid biomass into a gaseous fuel called producer gas that can be used to generate power and electricity. The producer gas consists of around 47% of Nitrogen (N₂), 24% Carbon Monoxide (CO), 16% Carbon Dioxide (CO₂), 12% Hydrogen (H₂), and 1% Methane (CH₄). However, Nitrogen (N₂) content in the producer gas reduces its heating values as N₂ acts as a diluent because of the low calorific value (LCV) of gas. This study aims to design a Nitrogen gas filter for capturing nitrogen gas from producer gas to increase the heating value of producer gas as fuel in combustion. The method to increase the heating value of producer gas will increase the number of combustible gases or reduce the composition of non-combustible gases in producer gas. The use of material name zeolite with its microporous structures able to adsorb nitrogen molecules and act as catalysts to chemical reactions. Zeolites 5A have a small pore highly efficient to adsorb nitrogen gas because pore diameter is relatively similar to the size of nitrogen molecules. The quality of the producer gas depends on the design and operating parameters of the zeolite catalyst. Nitrogen Gas Adsorption Filter is a new method that has to be designed to improve the previous producer gas quality. Nitrogen Gas Adsorption Filter consists of a cylindrical shape body packed with crushed zeolites 5A. When this method of adsorption process is applied, the heating value of the producer gas is increased by observing the quantity of blue flame colour produced by NgAF.

1. Introduction
In 2017, the world primary energy consumption increased by 2.2%. This growth was driven by natural gas consumption which has increased by 3.39 trillion cubic feet since 2010 [1]. Biomass gasification is a thermochemical conversion process of solid biomass into a gaseous fuel called producer gas that can be used to generate power and electricity. Producer gas is a mixture of gases typically composed of 24% of Carbon Monoxide (CO), 12% Hydrogen (H₂), 1% Methane (CH₄), 16% Carbon Dioxide (CO₂), and 47% Nitrogen (N₂) [2]. CO, H₂, and CH₄ are combustible gases [3], whereas N₂ and CO₂ are non-combustible gases [4]. These two non-combustible gases act as a diluent. High concentrations of CO₂
and N₂ reduce the heating value of the gas and may cause other technical problems and are thus removed to meet pipeline and transport specifications [5]. In this paper, the study is only focused on N₂ gas. Improving the quality of the producer gas with the adsorption process of CO₂ has been studied and done by Mahadzir et al. [6,7].

Nitrogen gas has the highest composition in producer gas compared to carbon dioxide. The known method to increase the heating value of producer gas was by manipulating the gasification conditions, which will increase the number of combustible gases or reduce the composition of non-combustible gases in producer gas [8,9]. N₂ gas can be reduced by the process of adsorption. Adsorption is a major process for the separation and purification of gases in different industries. Moreover, the selection of appropriate adsorbents in this procedure is an important factor, where the ideal adsorbent should have some specifications including high adsorption capacity, selectivity, hydrothermal stability, and facile regeneration [10].

Zeolites are the most famous adsorbents that are generally used for N₂ separation. The N₂ adsorption properties of different zeolites have been investigated in [11,12,13] including “Zeolite X”, “Zeolite A”, “Clinoptilolite”, “Chabazite”, “mordenite”, etc. Zeolites have been discovered to have the ability in adsorbing gases into their microporous structure. It can adsorb organic and mineral molecules in the gas phase without any modification of their structure. This adsorption is due to their high specific surface (40 to 800 m²/g) to some hydrophobic-hydrophilic surface effects and their structure. In industry, zeolites have been used widely for medical applications and the separation of gases. There are commercial units of zeolites that can provide oxygen of 95% purity to be used in hospitals for medical purposes. The gas separation process using zeolites enables oxygen to be separated from the air almost in a state of purity because zeolites preferentially adsorb N₂ which is 80% of the air due to it has a much larger quadrupole moment [14].

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This paper presents a new approach is to design a Nitrogen gas filter that can reduce the composition of N₂ gas from producer gas in order to increase the heating value of producer gas as fuel in combustion. The producer gas has been produced by the gasification process using a downdraft gasifier [15]. According to the best knowledge of authors, Zeolites 5A as adsorbents in N₂ adsorption. Zeolites 5A as adsorbents are designed to be used in NgAF, in which nitrogen adsorption with high capacity is the main challenge. The conclusion has been determined where the NgAF has been presented. Other researchers so far have not used zeolites as bed material for the adsorption process in the gasification process. Therefore, there is still room for the author to study in this area.

2. Methodology

2.1. Data Collections: Nitrogen Gas Adsorption by Zeolites
Zeolites have small pores that can adsorb small polar molecules. Its internal microporosity gives rise to the high surface area and provides sites for the adsorption of molecules [8,16]. Zeolites have a higher tendency to adsorb N₂ over O₂ because of the permanent quadrupole moment which interacts with cations in zeolite structure [10]. Generally, the common adsorption processes of air separation are divided into two categories [17]. The first category is consisting of processes that make use of zeolites as N₂ adsorbents under the equilibrium conditions and O₂ is a processed product. The second one contains processes that utilize Carbon Molecular Sieves (CMSs) as O₂ adsorbents. Based on kinetic separation in this kind of category, O₂ is adsorbed owing to its faster permeation and higher selectivity. Moreover, N₂ is produced as a product in such processes. In the past, numerous studies of gas adsorption by zeolites have been done using various types of zeolites. Some that are closely related to nitrogen adsorption is simplified in table 1:
In a study of separation of O₂ using zeolite 5A, the air is allowed to pass at 10 to 30 cm³/(STP)/min through a sample of about 18g of zeolite 5A. The equilibration was reached in the 10 minutes allowed for each adsorption point. For air passing at 20 cm³/min into the bed of 5A zeolite beads, from a time of 2 min to about 12 min, pure O₂ was recovered at the outflow, showing the essential of N₂ adsorption, equivalent to 2.4 cm³/g of zeolites. According to this study, the amount of O₂ recovered from the air is independent of the flow rate range 15 to 30 cm³/min, indicating that the gas transport to the surface of zeolite particles was not the limiting step in adsorbent utilization [24]. Furthermore, in this study, following the adsorption run, desorption takes place at 25°C results in outflow gas had a composition close to that of air. This means that zeolites are reusable for another N₂ adsorption process once the gas has been desorbed from its microspores.

The adsorption capacity in the adsorption bed depends on the factors such as pressure, temperature, and flow rate. The adsorption and desorption cycle of a Pressure Swing Adsorption (PSA) system operates by pressure increasing and decreasing. As pressure increases, the adsorption rate of more strongly adsorbed components increases [11]. On the other hand, at near room temperature and atmospheric pressure, N₂ adsorption from the air is 2.4 cm³/g in zeolites 5A bed in 12 minutes duration. The adsorbing capacity of zeolites is expected to be the same in the N2 adsorption process from producer gas. If so, 1kg of zeolites 5A will be able to absorb up to 2400 cm³ of N₂ gas. On average, the gasification of 1 kg of biomass produces about 2.5 m³ of producer gas of which 47% of the volume is the composition of nitrogen gas [25]. This is equivalent to 1.18 m³ of nitrogen produced from 1 kg of gasified biomass. Taking this data, about 50kg of zeolites is needed to entirely absorb nitrogen in producer gas from 1 kg of biomass.

### 2.2. Design of Nitrogen Gas Adsorption Device

The dimension of NgAF is restricted in a lab scale to compromise and to ensure it is compatible with the designs of existing downdraft gasifier, heat exchanger and cooling cum cleaning systems in this project [15].

The flow of producer gas in this study is the high-temperature producer gas from gasifier will flow through a heat exchanger to bring down its temperature to ambient temperature (60 – 30°C). The producer gas is then will pass through a cleaning cum cooling system where tar and moisture content will be removed from the gas. After the cleaning and cooling process takes place, this is the section where producer gas will be going through NgAF to capture N₂ gas content and increase the heating value of producer gas.

In industry, there are commercial units of N₂ absorber using zeolites that carry out air separation process mostly to produce oxygen in an almost pure state. This commercial unit is known as an oxygen concentrator. The concentrator consists of two adsorption zeolite columns, a dual-head air compressor, five three-way solenoid valves, a back-pressure regulator, an oxygen sensor a surge tank, a pressure sensor, and a cooling fan to avoid the temperature rise of the air compressor [26]. Figure 1 shows the

| Researchers | Gas pair | Zeolites Adsorbent | Adsorption Selectivity |
|-------------|----------|-------------------|-----------------------|
| 18 Ocean C et. al | CO₂/N₂ | NaK-ZK-4 Zeolites | CO₂ over N₂ |
| 19 Yangguo F et. al | N₂/O₂ | Faujasite (FAU) zeolites | N₂ over O₂ |
| 20 Hamida P et. al | N₂/O₂ | M₃Na₉₆₋ₓ LSX zeolites | N₂ over O₂ |
| 21 Samira S et. al | CO₂/N₂ | FAU- and LTA-type zeolite nanocomposites | CO₂ over N₂ |
| 22 Jiangfeng Y et. al | CH₄/N₂ | ZK-5 zeolite | CH₄ over N₂ |
| 23 Patricia A P M et. al | CO₂/N₂ | 5A zeolite | CO₂ over N₂ |

Table 1. Previous studies of gas adsorption selectivity.
schematic of the oxygen concentrator using a two-column PSA cycle. The working principle of the oxygen generator is that it adopts air as raw materials with pressure swing adsorption (PSA) technology and the N₂ from the air can be selectively adsorbed by the zeolite molecular sieves.

![Figure 1. Schematic of the Oxygen Concentrator [20].](image)

2.3. Experimental Set-Up
The NgAF was installed as in figure 2 and ready to be operated to test its efficiency in improving the heating value of the producer gas.

![Figure 2. Devices Installed According to Their Stages](image)

The NgAF was properly connected to the Cleaning Cum Cooling System (CCCS) to ensure gas from CCCS’s outlet flow into NgAF inlet. 1 kg of Zeolite sample was placed into the NgAF filter body. The top end cap of the filter body was closed tightly to ensure no leakage. The valve at the inlet was opened to allow producer gas to enter the filter body while the valve at the outlet was fully closed to allow
adsorption to take place. The outlet valve was opened every 30 minutes. The outlet producer gas was ignited to observe the combustion efficiency. The zeolite sample was weighted after the gas filtration was finished. The results mainly focused on the combustion efficiency in terms of the colour of flame produced during ignition. The flame produced before and after the gas pass through NgAF were compared to analyze the intensity of blue flame produced.

3. Result and Discussion

3.1. Nitrogen gas adsorption filter (NgAF)

The designation of NgAF in this paper is partially inspired by the design of an oxygen concentrator in Figure 1. The NgAF as illustrated in figure 3 used different working principles and approaches to capture nitrogen gas from producer gas. Just like the oxygen concentrator, NgAF is designed with two cylindrical filter columns containing zeolites.

![Figure 3. Schematic Diagram of NgAF.](image)

However, the NgAF does not use the PSA technology but the adsorption process will take place at 25-35°C temperature and 100kPa pressure by allowing producer gas to pass through the zeolites bed for a certain period. The NgAF is in a lab-scale dimension to make it compatible with the existing downdraft gasifier [15]. Polyvinyl chloride, PVC pipe is selected to be used as the body column because it has a smooth surface which causes frictional resistance. Other than that, it starts to decompose when the temperature reaches 140 °C, with melting temperature starting around 160 °C. figure 4a and 4b show the detailed views of NgAF.
The NgAF consists of two cylindrical columns and valves at each column inlet and outlet. Compared to the industrial oxygen concentrator, the NgAF takes producer gas as raw material to pass through the zeolite bed. Zeolite 5A is used in this study. It has a higher tendency to adsorb nitrogen gas molecules into its microspore is due to the relative similarity between its pore size (0.5 nm) and the size of nitrogen molecules (0.364 nm) that allows nitrogen molecules to be captured. Zeolite 5A molecular sieve has a surface area of 571 m²/g and a density of 1.16 g/cm³. To adsorb 0.59 m³ of nitrogen gas from producer gas produced by gasification of 0.5 kg biomass residue, 25 kg of Zeolites 5A is required with 12.5 kg separated in each NgAF column. 12.5 kg of zeolites is equivalent to 10775 cm³. Thus, a cylindrical body with a volume of 11000 cm³ is to be produced for the NgAF. The difference in zeolite volume and column volume is considering the air space in the zeolite bed. For the column body, PVC pipe with a large diameter is to be used. Thus, a PVP pipe of diameter D = 18 cm is selected.

3.2. Quality of producer gas, before and after NgAF

The producer gas was ignited with fire to test the presence of combustible gases that are methane (CH₄), carbon monoxide (CO) and hydrogen (H₂). The flames produced by the producer gas before and after passing through NgAF are compared in Table 2. The flames produced after passing through zeolite bed in NgAF contain blue flame even though it is hard to be seen. Referring to table 2, the observation of blue flame can be seen most clearly in the result of Experiment 3.
| Experiment | Before NgAF | After NgAF |
|------------|-------------|------------|
| 1          | ![Image 1]   | ![Image 2]  |
| 2          | ![Image 3]   | ![Image 4]  |
| 3          | ![Image 5]   | ![Image 6]  |

Table 2. Flames of producer gas before and after NgAF.

The production of blue flame means that the combustion of producer gas is more complete compared to the combustion before the gas passing through NgAF. More complete combustion was produced because the producer gas out from the NgAF has high density and concentration compared to the gas before pass through the system. This is because before the gas enters NgAF, it contains a high weight percentage of non-combustible nitrogen gas that acts as a diluent to the producer gas. Zeolite bed in NgAF captured the nitrogen molecules into its micropores help in increasing the heating value of producer gas thus lead to the appearance of blue flame at the outlet of NgAF.

4. Conclusion
The design of Nitrogen gas Adsorption Filter (NgAF) has been designed. This is an alternative method to increase the heating value of the producer gas where the N₂ gas can be reduced using zeolites. The NgAF is designed based on the analysis and results obtained by other researchers. When this method of adsorption process is applied, the heating value of the producer gas is expected to increase the heating value by observing the colour of blue flame produced. The proposed design is the outcome of this writing, and it is referring to the paper reviewing and studies.
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