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Scale up and Assessment of Energy Production in a Microwave-Assisted Producer Gas Tar Conversion Reactor

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***Abstract*—The purpose of the present work is to assess the feasibility of scaling up of thermal treatment of tar conversion in a microwave reactor to improve the quality of the producer gas for power generation. The scale up process was analyzed based on microwave heating capacity and energy balance of material. The scale up analysis was conducted to obtain reactor performance with a capacity of 3.37 Nm3/h of producer gas based on the obtained experimental results in a small scale microwave reactor of 0.337 Nm3/h. The chemical and sensible energy contents of the input and output streams were considered for energy balance calculation. Energy supply from microwave power for heating process and heat losses from the wall of microwave reactor to the environment were also included. The results showed that the energy balance closure of the small scale microwave reactor was 75% only on average. In the mean time, scaling up analysis of the bigger reactor has better performance with average energy balance closure of more than 91%, showing that thermal treatment of tar process in a microwave reactor is very promising to enhance producer gas quality at relatively higher capacity.**

***Keywords*—scale up of microwave reactor, producer gas tar conversion, thermal treatment, biomass gasification**

I. INTRODUCTION

Fast depletion of the fossil-based energy reserves, increase in energy consumption and greater environmental awareness for global climate change due to CO_2 emissions have encouraged studies to look for greener sources of energy as alternatives to substitute the fossil fuels. In this case, generation of energy from renewable resources would be an option, making research activities on renewable energy sources particularly biomass have become more and more important. In principle, biomass including cellulose, hemicelluloses and lignin can be thermochemically converted into useful forms of energy through torrefaction, pyrolysis, gasification and combustion. In such cases, to produce high fuel gas content from biomass processing, gasification should be applied. Biomass gasification takes place at high temperature of more than 700°C, wherein, biomass wastes are converted into producer gas which is suitable for feeding gas engines and gas turbines as well as synthesis of biofuel [1]. However, producer gas is always accompanied by undesirable products such as tar and particulates. The presence of tar in the producer gas can cause serious operational problems in downstream pipeline and end user application. It also reduces the energy efficiency of the overall process [2]. Therefore, conversion of tar as well as particulates from producer gas into fuel gases is important. For this purpose, two generally methods of primary (gasifier design and optimization of operating conditions) and secondary methods (mechanical, thermal and catalytic treatments) have been applied [3; 4].

In spite of the different progresses and advancements made in the past decades, tar conversion still faces some technical and economical challenges in terms of improving tar conversion efficiency and reducing electrical energy consumption for heating process. It should be noted that the heating strategy plays an important role during tar conversion process as the reaction takes place at high enough temperature that requires a continuous supply of heat. In general, tar conversion reaction can be limited within a conventionally/electrically heated reactor due to the heat/mass transfer limitations as the heat is supplied from the external wall in most of the conventional heating reactors [5; 6]. It is believed that the heating strategy by means of microwave irradiation which offers various advantages can solve the limitations of conventional heating. The unique feature of volumetric heating of this technique can result in more rapid heating process of the reactor in the presence of absorber material [7], thereby saving energy significantly, reduce process time, improve process yield, and environmentally friendly [8; 9]. In this sense, the use of microwave energy for thermal treatment of tar from biomass producer gas has been investigated [2]. Their primary experimental results in a lab-scale facility showed that this strategy was found to be a very attractive technique for tar conversion which is not only effective but has also low energy consumption. Regarding gas phase reactions, microwave irradiation helps in triggering radicals formation making it possible to accelerate the reaction, save space and provide better energy utilization on reactants [10]. Nevertheless, by far, tar conversions under microwave irradiation have been mainly demonstrated in a small/lab scale reactor. Therefore, studies on the application of higher treatment capacity of microwave reactor to eliminate producer gas tar from biomass gasification are still the challenge.

This work was conducted to assess the feasibility of a higher microwave thermal treatment reactor in improving the quality and production of producer gas on the basis of our previous investigation. Scale up process was analyzed based on heating capacity of the microwave and energy balance of material before and after leaving microwave reactor.

II. METHODS

Published experimental data [2] on thermal treatment of producer gas tar were acquired in a small scale microwave tar treatment reactor. Producer gas tar with a flow rate of 0.337 Nm^3/h was converted by means of thermal treatment operated at temperatures in the range of 900-1200^{o}C and at a fixed residence time of 0.5 s. Details of the experiments are given in the previous paper [2].

Scale up analysis of microwave reactor was done based on the obtained experimental data. This bigger reactor is assumed to have a capacity of 3.37 Nm^3/h. The feasibility of the reactor performance was evaluated based on microwave heating capacity and energy balance of material. The calculation of energy balance was performed according to previous studies [11; 12]. Energy balances are evaluated based on the input and output streams across the microwave reactor as given in Fig. 1. Total energy input *(H_i)* is assumed to contain five components of producer gas (H_2, O_2, N_2, CO, CH_4, and CO_2), tar, fine particles, moisture and energy supply from microwave power. While the total energy output *(H_o)* is also assumed to contain five components that are producer gas, tar, fine particles, moisture and heat losses from microwave reactor.

The chemical and sensible energy contents of the input and output streams were considered for energy balance calculation. The chemical energy is determined based on heating value of the constituent whilst the sensible energy is measured by assuming the temperature and pressure references of the dead state are 32.7^{o}C and 1 atm, respectively [12]. Energy balance closure *(H)* is then evaluated using the below equation and the complete calculation can be found elsewhere [13]:

$$H = \frac{H_o}{H_i} * 100 \tag{1}$$

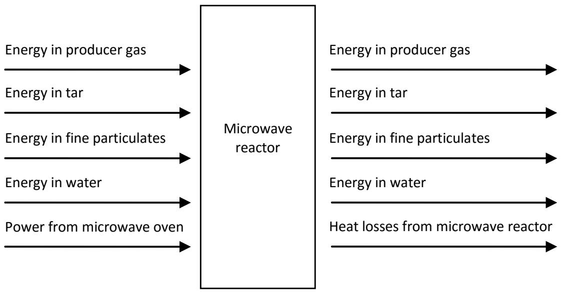

Figure 1. Energy balance flow diagram across the microwave reactor

III. RESULTS AND DISCUSSION

A. *Energy Balance of the Small Scale Microwave Reactor*

Energy balance closures across the microwave reactor from thermal treatment of producer gas tar experiments [2] were evaluated to assess the capability of the small scale system. Energy balance was evaluated for each reaction temperatures applied ranging from 900^{o}C to1200^{o}C. The results of energy balance calculation are presented in Table 1.

TABLE I. ENERGY BALANCE OF THERMAL TREATMENT OF TAR FROM PRODUCER GAS IN A SMALL MICROWAVE REACTOR

Component	**Energy Input (MJ/h)**	**Energy Output (MJ/h)**			
		900^{o}C	***1000^{o}C***	***1100^{o}C***	***1200^{o}C***
Dry producer gas	1.6797	1.7502	1.7807	1.8602	2.0361
Tar	0.0187	0.0093	0.0053	0.0027	0.0018
Fine particulates	0.0027	0.0004	0.0001	0.0001	0.0000
Water	0.0552	0.0171	0.0154	0.0111	0.0101
Microwave power	1.0080	-	-	-	-
Heat losses	-	0.1493	0.1768	0.2073	0.2385
Total (MJ/h)	2.7642	1.9264	1.9783	2.0815	2.2865
Energy balance closure, H (%)		69.69	71.57	75.30	82.72
Average, H (%)	74.82				

It can be observed from the table above that the energy balance closure increased with the increase of reaction temperature. This result is possible due to producer gas contains much more combustible gases of hydrogen and carbon monoxide that contributes in enhancement of energy content of the producer gas. Nevertheless, the average energy balance closure is below 80%, except for thermal treatment at temperature of 1200^{o}C. The main possible reason for this result should be attributed to the inadequate volume of producer gas treated within the reactor compared to the need of energy for heating process. This is also due to the limitation of reactor capacity that is highly related to the desired gas residence time for tar conversion, thus impeding the conversion of tar at higher producer gas flow rate.

B. *Scale up of Microwave Reactor*

As mentioned before that the experimental reactor size installed in the microwave chamber is not enough for closing the heating energy requirement. Hence, scaling up of the reactor need to be assessed the reactor minimum capacity for producer gas treatment. However, bigger reactor capacity in general is accompanied by the increase of energy supply for heating process especially in the case of electrically conventional heating mechanisms.

Unlike conventional heating that is principally surface heating process, the microwave heating is volumetric heating that instantaneously occurs through molecular interaction with the electromagnetic field [14]. The volumetric heating of materials using microwave can result in significant energy savings, reduce process time, increase process yield, and compatible for environmental issues [15; 16]. With the unique features of microwave heating, the reactor can be scaled up to a certain size at a fixed microwave power depending on the frequency applied. For instance, the microwave system used in this work has a frequency of 2.45 GHz that can produce a wavelength of around 12.23 cm. So that, to obtain the best heating process inside the reactor, the reactor size or reactor diameter in particular should be less than the wavelength of the microwave. Additionally, the heating process is also highly related to the penetration depth of microwave power (D_p) into the material as expressed in (2) [17]. For instance, the penetration depth of microwave power into Silicon Carbide (SiC) as an absorber material used in this work is 6.25 cm that is about half the microwave wavelength. Since the reactor is installed at the center of microwave chamber, the reactor diameter can be then set along the microwave wavelength.

$$D_p = \frac{\lambda_0}{2\pi\sqrt{2\varepsilon'}}\left[\sqrt{1+\left(\frac{\varepsilon''}{\varepsilon'}\right)^2}-1\right]^{-1/2} \qquad (2)$$

where λ_0 is free space wavelength of the RF radiation, ε' and ε'' are the relative values of the dielectric constant and loss factor, respectively.

TABLE II. ENERGY BALANCE OF THERMAL TREATMENT OF TAR FROM PRODUCER GAS IN A BIGGER MICROWAVE REACTOR

Component	**Energy Input (MJ/h)**	**Energy Output (MJ/h)**			
		900°C	***1000°C***	***1100°C***	***1200°C***
Dry producer gas	15.989	16.317	16.703	17.568	18.315
Tar	0.187	0.092	0.052	0.027	0.017
Fine particulates	0.027	0.004	0.001	0.001	0.000
Water	0.552	0.168	0.151	0.110	0.095
Microwave power	2.520	-	-	-	-
Heat losses	-	0.149	0.177	0.207	0.238
Total (MJ/h)	19.275	16.729	17.085	17.913	18.665
Energy balance closure, H (%)		86.79	88.64	92.94	96.84
Average, H (%)	91.30				

Based on the above considerations, scaling up of the microwave reactor can be performed well without increasing the energy supply for heating process. For an example, taking into account the operating conditions, to obtain the performance of the reactor with a capacity of about 3.37 Nm^3/h of producer gas close to the experimental results; the appropriate minimum reactor diameter is about 6.3 cm. This capacity is equivalent to biomass consumption of 1.5 kg/h producing 4.6 kW$_T$ gasifier thermal power with 1.2 kW$_e$ engine power. Assuming that this approach is valid, the energy balance across the microwave reactor can be evaluated in the same way as given in the previous section. The results from this evaluation are presented in Table II. As can be seen, the energy balance closures in general are around 90% showing that the thermal treatment of tar process under microwave energy is very promising for producer gas tar conversion at relatively higher capacity.

IV. CONCLUSIONS

Scale up analysis of microwave reactor for tar conversion via thermal treatment was performed. Emphasis was made on energy balance and microwave heating capacity for considering thermal treatment of producer gas tar feasibility in a pilot scale microwave reactor. The results showed that the small scale experimental microwave reactor was not able to fulfill the need of energy for heating process due to the limitation of producer gas capacity that can be treated within the reactor. Related to the reactor size evaluation, scaling up of microwave reactor was analyzed and assumed to have a producer gas volumetric capacity of ten times bigger than the experimental reactor. It appeared feasible to consider that the thermal tar conversion process carried out in a bigger microwave reactor capacity is very promising without increasing the energy supply for heating process to enhance producer gas quality for power generation.

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