MODELING OF A HYBRID MICROWAVE PLASMA GASIFICATION PROCESS: EXPERIMENTAL VERIFICATION AND CRITICISM

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Abstract. *Microwave plasma gasifier; MCw GASIFIER is a laboratory sized test system operated for the decomposition of solid granular materials -fuel into syngas to determine the overall plasma gasification performance. The system operation is assessed with different types of coal, sawdust and polyethylene used as sample solid fuel. Standard air is plasma gas at the rates of 50 sL/min, 75 sL/min and 100 sL/min for different input plasma power, P; 3 kW ≤ P ≤ 6 kW. Therefore, plasma gasification performance is based upon the monitoring of 108 different operational test cases.*

The solid fuel inside invisible reactor is decomposed into syngas with the solid ash leaving the cyclone filter at the end of the gasification process. The decomposition of fuel is under steady state steady flow of plasma gas at steady uniform – continuous uninterrupted microwave input power application. Furthermore, the operation is under standard atmospheric pressure conditions. However, fuel decomposition-syngas production is a transient process. Therefore, critical parameter of syngas production - material decomposition is the gasification time- duration t_g. Monitoring of gasification is through the local instantaneous temperature measurements along the reactor at 5 different stations and instantaneous syngas content analysis reflecting the nature of the process.

The emphasis herein is devoted to modeling of hybrid (steady-transient) plasma gasification process. The modeling which is verified by the extensive data set is independent of type of fuel, rate of air and magnitude of microwave power. Therefore, the major aim is to provide a criticism to a previously published study of the authors [1].

Keywords: *Hybrid Plasma Gasification Process, Material Decomposition Modeling, Syngas, Gasification Time, Time-Dependent Operational-Monitoring*

1. Introduction

The process of plasma gasification is introduced to overcome the environmental problems of conventional combustion as an emerging technology for waste to energy conversion [2]. Instead of the other techniques of plasma generation (direct current; DC, radio frequency; RF) microwave; MCw plasma is preferred due to the advantages it offers [3]. Waste to energy conversion is coupled with "syngas" generation which is at utmost importance for the state of art on alternative fuels [4-6]. The energy content of syngas makes it an alternative fuel besides its solution serving for the waste storage zones.

In fact; conversion of biomass by means of pyrolysis has an early start dating back to 1984 with the review paper of Grahamet al. 1984 [7]. Recent research articles likewise [8-15] can be cited as the sample references indicating the increasing interest of the community. However, besides the variety of applications with different biomass and plasma systems there is almost no consensus for the treatment of the thermochemical decomposition process and related definitions. In order to describe the state of art following basic questions can be referred.

1) Temperature: It is estimated that reactor temperature, is not significant on gasification performance in comparison with biomass/air ratio for a conventional gasification process. However thermochemical decomposition is a special process therefore determination of reactor temperature is a matter of fact. Furthermore temperature varies during decomposition process .Therefore syngas temperature reactor temperature or process temperature is the interrelated definitions

2) Syngas: Description of syngas is also a matter of fact since gasification necessitates use of a plasma medium commonly in gaseous form.

3) Efficiency: In terms of efficiency Janajrehet al. 2013 [10] deduced that plasma efficiency is 42% while conventional process efficiency is 72%. The relationship between available chemical energy of biomass and that of syngas produced by thermochemical decomposition is the major point of importance. However differences in applications different efficiency definitions are available.

In terms of the above-mentioned questions a brief is outlined below:

It is also known that an increase in temperature (T) results in an increase in CO/CO_2 and thereby heating value of syngas. Meanwhile temperature of syngas T_{syn} is another critical parameter which is also definitive on the heating value of the syngas. Hlinaet al. 2014 [9] used water-argon plasma and used wood pellets and determined low energy efficiency for plasma system. Tuet al. 2009 [13] denoted

equal fractions of CO-H_2 at 600 ℃ and determined that amount of product gas during pyrolysis reaches 80 % of biomass. Zhaoet al. 2001 [15] used pyrolysis of wood and rice by argon-hydrogen plasma system and determined 79 % and 72 % conversion for carbon (C) and oxygen (O). The conversion of biomass into syngas and the amount of syngas is the critical parameter for the process. In the very recent study of Ibrahimoglu and Yilmazoglu 2019 [16], a 3D numerical simulation of a downdraft plasma gasifier is considered. They paid attention to the effects of the equivalence ratio (ER) on the syngas properties. They used boundary conditions for the air plasma inlet of the gasifier from the outlet of a 10 kW microwave plasma generator. A conventional gasification analysis was carried out to validate the model. In the second part of their study, plasma reactions were added to conventional gasification equations. Mole fractions of the constituents of the syngas and temperature contours were obtained for different ER values. According to their results, with the increase of ER from 0.20 to 0.45 the lower heating value of the produced syngas decreased from1536.6 kcal/m^3 to751.8 kcal/m^3.

In this paper the operational test cases of MCw GASIFIER are presented to introduce the modeling for the decomposition of solid granular fuel into syngas as a criticism on the previously published article of the authors [1]. The referred article is based upon an available theoretical study on literature timely . However, after the operational study of MCw GASIFIER the treatment of the process necessitates a correction and verification for plasma gasification process.

The analysis on the performance evaluation - syngas characteristics of different materials of plasma gasification is not discussed since the aim of the paper is to describe the gasification modeling through conducted operational study, independent of the type of fuel gasified and the gasification process characteristics. The provided modeling is a general one for a hybrid procedure of solid material decomposition into syngas. An experimental verification on modeling with definitions of the relevant parameters based upon operational monitoring is the basic contribution aimed.

2. Experimental system and methodology for operational study MCw gasifier system

Although the details of the constructed system set-up and methodology are available in [4,5, 17, 18] following description is necessary ;

MCw GASIFIER is an open cycle blower type atmospheric pressure set-up (Figure 1). The heart of the set-up is the commercial microwave plasma generation and control system of MUEGGE. The individual components-subsystems are MX6000D-110K model 0-6 kW power supplier, MH6000S-213BF model Magnetron for the generation of microwave signal at 2450 MHz frequency, MW1006A-210EC model isolator, MW2010A-260EF model 3-stub tuner, 500 mm length WR340 cross-section waveguide and a MA6000A-013BB model plasma applicator. Plasma applicator had a quartz glass tube located at the center of the reactor lid having a diameter of 30 mm and a length of 50 mm. Plasma applicator is placed in line with the centerline of reactor lid. MM1001B-110AB model power detector is used to vary the microwave power input, P. with a sensitivity of 1% variation in P. The utilized P range is between 3 kW and 6 kW.

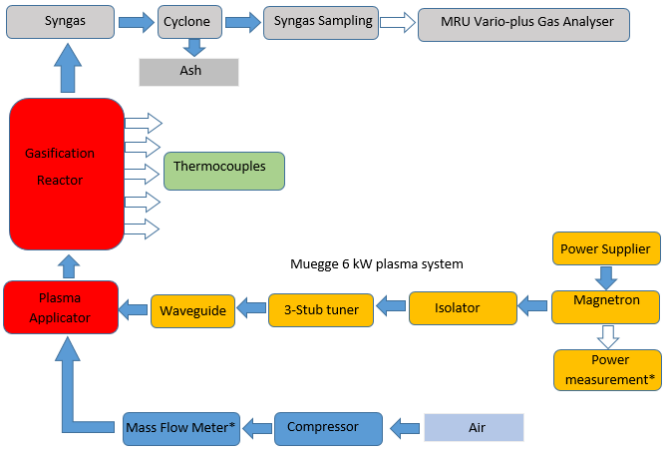

Fig. 1. Sketch of MCw Gasifier [18]

Air is the plasma environment gas. Air supply is under standard atmospheric conditions through a continuous steady state steady flow process. A screw compressor with a commercial name of LUPAMAT-LKV 30/8 model is used to supply air at 8 bar pressure and at ambient temperature. The pressure leaving the compressor is reduced to 4 bar pressure by using a pressure regulator. The required STP conditions air flow rate; sL/min is supplied to plasma applicator via a commercial ALICAT MCR-250SLPM-D model mass flow controller which has a capability range of 0-250 sL/min. The utilized range of air flow rate is 50 sL/min, 75 sL/min and 100 sL/min at an uncertainty of 0.7 sL/min for the conducted cases.

The gasification of solid granular material is inside a cylindrical home-made reactor (Fig. 2). Reactor is made up of stainless steel of diameter 81 mm total height of 625 mm including the plasma applicator in combination with the lid of the reactor. (Fig. 1) The vertically placed reactor is in combination with a home-made Stairmand model of [19]cyclone filter at the top of the reactor.

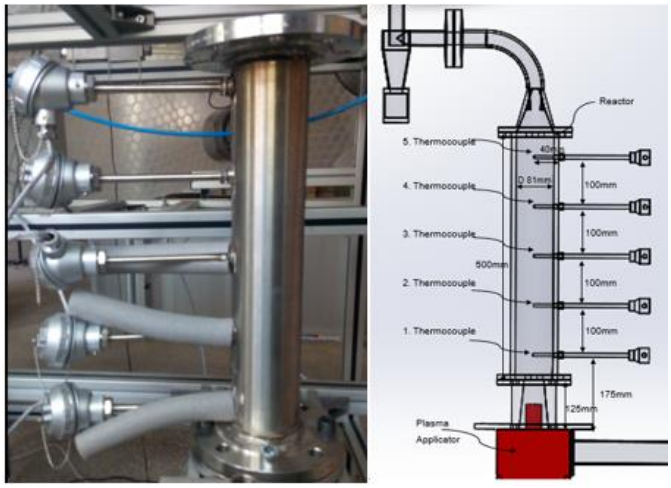

Fig. 2. Reactor -Cyclone Filter Assembly with Thermocouple Locations

Syngas is passed through a Semi-Continous Syngas Monitoring System with a commercial name of MRU VARIO PLUS at the top of the filter and ash is collected at the bottom of the filter. (Figure 2) MRU-VARIO PLUS measure the syngas content of CO, CO2, CH4, H2, and N2 up to 100 % and O2 up to 25 % in volumetric base. It uses nondispersive infrared sensors (to measure CO, CO2 and CH4) while thermal conductive detector is used to measure H2 and electrically conductive sensor is used to measure O2. System has 1 % linearity and repeatability error It has also 2 % span drift and 0.05 % detection limit. The syngas content is measured with a 2 seconds sampling frequency.

The local instantaneous temperature measurements are taken by B type (Pt18 Rh- Pt) thermocouples located along the reactor at specified 5 locations. The thermocouples are submerged at 40 mm depth from the reactor. The first thermocouple is at 175 mm above the plasma applicator edge and the remaining 4 are located 100 mm apart. Thermocouples have a sensitivity of ± 4 C.

The solid granular material – fuel sample (for different materials of three types of coal, two types of sawdust and polyethylene) is forming a stationary bed in the bottom of the reactor. The height of the material bed for the covered cases at the start of the gasification is varying between 64.5 mm to 228.7 mm having the diameter of the reactor. Air supply is as a swirling jet inlet from the bottom of the reactor to form MCw plasma flame. The gasification is possible in an up- draft application of MCw plasma as a result of several trials. During the gasification application of MCw plasma flame and thereby input power, P is steady and continuous without any interruption.

The reactor was filled with the fuel of 250 g and closed. A stabilizing time at a supplied amount of air at a specified MCw power input P application is necessary for a continuous plasma flame. At the start of the operation the recording of MRU VARIO PLUS of the gas output from cyclone filter is of pure standard air content. The time for the observed departure of gas content from that of pure standard air indicates the start of the material decomposition. The gas output is called as "syngas "including the amount of gasified fuel and the amount of air supply. The end of the gasification, tg is determined whenever the "syngas content" returns to that of standard pure air. The local instantaneous temperature measurements are recorded during the process.

At the end of gasification ash leaving the cyclone filter is collected and measured by using TP 214 model mass balance device. At the end of the process when the reactor is opened (for the covered 108 test cases) nothing is left inside the reactor. Therefore, the ash leaving the cyclone filter is the amount of fuel which is not gasified. The ash is considered to be generated at the starting phase of the process.

3. Measurement chain - data acquisition and uncertainty of measurements

The gasification monitoring is through instantaneous local temperature measurements and the syngas recording detailed above. The uncertainty of MRU VARIO PLUS is found as 3.16% for the covered operations. The standard deviation is found as 1.84 C with an individual uncertainty of 0.212 C. The data recording is done at each second from the thermocouples during gasification time. The instantaneous temperature data from 5 thermocouples are recorded at ELIMKO E-PR-110 model data acquisition card. The amount of uncertainty in temperature measurement is 12.02 C considering the data acquisition card compilation. The uncertainty in the weight measurement of ash is 0.24 mg. In the operational case number of data compilation is dependent on the gasification time of the process. The minimum and maximum gasification time is determined as 420 seconds and 1020 seconds respectively. Therefore, the number of temperature data at each station is varying between 420 and 1020 meanwhile gas analysis is based upon the number of data between 210 and 510.

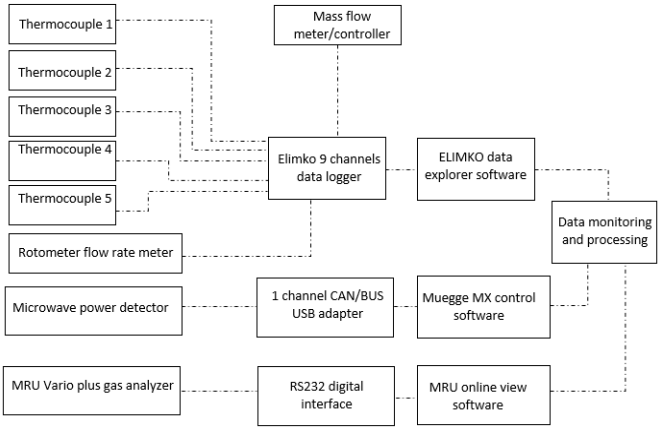

Fig. 3. Informative sketch on data acquisition system with measurement chain of MCw GASIFIER

4. Results and Discussion

4.1 Operational study and system characteristics

System is operating under STP conditions. The reactor is under standard atmospheric pressure and atmospheric temperature. The plasma environment gas is standard atmospheric air which is sensed by the amounts of volumetric flow rate standard liters per minute (sL/min).

Table 1. Operational Range of MCw GASIFIER

CASE	SPECIFICATION					
FUEL - 6 SAMPLE MATERIALS	2 TYPES OF SAWDUST; HSD, PSD					
	3 TYPES OF COAL; CTR, SA, CR					
	POLYETHYELENE; PP					
MCw POWER 6 RATES	3 kW	3.6 kW	4.2 kW	4.8 kW	5.4 kW	6 kW
AIR FLOW RATE AT STP CONDITIONS - 3 RATES	50 sL/min		75 sL/min		100 sL/min	
TOTAL NUMBER OF OPERATIONAL CASES	108					

The air supply and plasma application are from bottom to top of the reactor. Therefore, system is an up- draft type. The top of the reactor is connected to cyclone filter separating syngas from the ash. Air flow and microwave plasma power – flame is steady state steady flow (continuous and uniform) However material decomposition therefore syngas formation is not a steady state steady flow process. The covered test cases indicate 108 different operations (Table 1).

4.2 Criticism on previous approach

The paper of the authors [1] outlines the thermodynamic analysis and performance assessment of the process prior to the operational study of MCw GASIFIER. However, at the end of the operational study the picture is realized with the listed critical points below:

1) The decomposition of the fuel into syngas is a transient time dependent process. However, application of plasma power carried by introduction of standard conditions atmospheric air is a steady state steady flow process. Therefore, the overall process is a hybrid one.

2) The critical parameter is the gasification time for which all of the fuel inside the reactor is converted into syngas and ash. Meanwhile the so-called syngas is the total gaseous output of the process. Therefore, syngas is the amount of steady state steady flow amount of air m air and the gasified amount of fuel which is the initial amount of fuel minus ash collected (m_{fuel}-m_{ash}).

3) The hybrid nature of the process necessitates the mass balance in terms of total quantities instead of flow rates. Therefore, the amount of air, m_{air} used is determined based upon the gasification time t_g, for each case.

4.3 Hybrid modeling - gasification parameters

The gasification process is called as a hybrid one (Figure 4). Since the application of power and air flow rate are steady state steady flow processes. However, material-fuel decomposition is a transient process.

The varying nature of syngas content as sensed by sample Figure 5 for the case of hornbeam sawdust HSD gasification at 100 sL/min air with the application of P = 6 kW. Syngas content monitoring indicates varying volumetric amounts of sensed gases of CO, CO_2, CH_4, H_2, O_2 and N_2 during gasification. The recorded gasification time t_g is 420 seconds and the amount of each gas component has shown a time –dependent behavior.

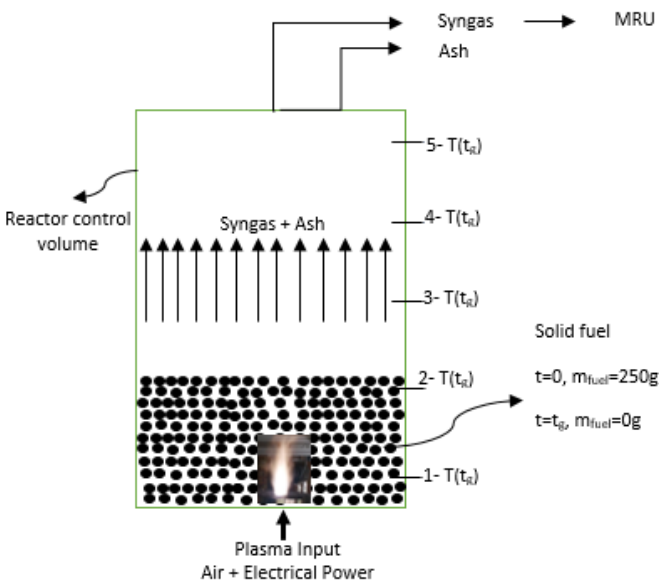

Fig. 4. Sketch for modeling of hybrid process of gasification

As can be seen from Figure 5a;

O_2 amount in syngas reduces from 5 % in the first 25 seconds and retains almost at a constant magnitude in the order of 1 % up to 300 seconds. Towards the end of gasification its magnitude increases to its starting magnitude of 5 %.

CO_2 amount in syngas increases from 14% to 18% in the first 50 seconds and retains the magnitude up to 250 seconds. Towards the end of gasification its magnitude decreases to 8 %.

CO amount in syngas has a drastical variation during gasification. It is in the order of 17 % at the start decreasing as stepwise fluctuations to 8% at 100 seconds. Its magnitude has fluctuating in the order of 8% up to 300 seconds and increases up to 12% during the end of gasification with a further drastical reduction to 6% at 420 seconds

H_2 amount in syngas decreases from 10% to 6% in the first 100 seconds and retains the magnitude towards the end of gasification.

CH_4 amount in syngas is almost constant during the gasification having slight variation between 3% and 2%.

As can be seen from Figure 5b N_2 amount in syngas increases from 55% to 60 % in the first 50 seconds and retains the magnitude in the order of 65% in the remaining period up to 350 seconds. Towards the end of gasification its magnitude increases towards 70 %.

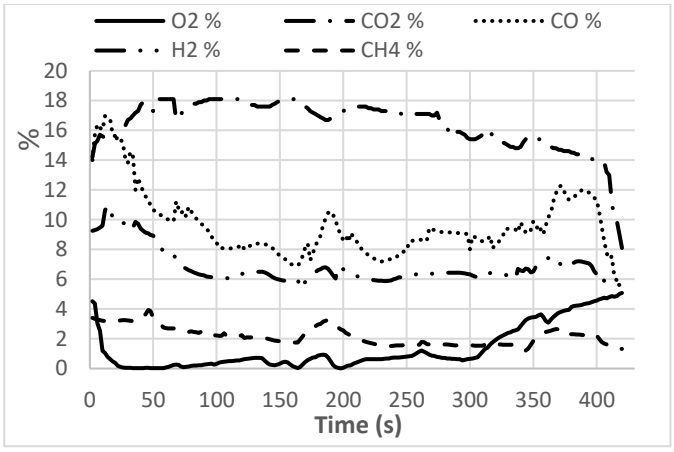

Fig. 5a. Instantaneous volumetric variation of O_2 %, CO_2 %, CO %, H_2 %, CH_4 % in syngas during gasification of HSD at P= 6 kW for 100 sL/min air

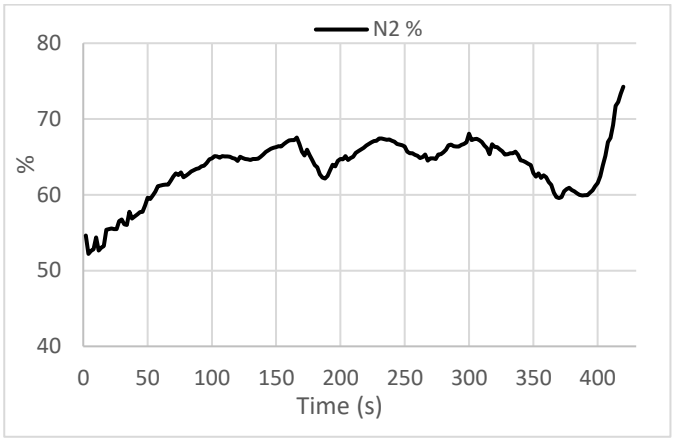

Fig. 5b. Instantaneous volumetric variation of N_2 % during gasification of HSD at P= 6 kW for 100 sL/min air

The modeling is based upon the first level parameters derived from the monitoring of the decomposition as follows:

Gasification time (t_g). Gasification time is the time from the start of the process to its end defined and measured experimentally. The start and end of the process is determined by the instantaneous measurements – monitoring of MRU VARIO PLUS syngas analyzer. The start of material-fuel decomposition is the deviation of the analyzer output from that of a pure standard air and the end of the process is the detection of pure air content secondly. The opening of the reactor and checking the material left inside the reactor is the justification of the time t_g.

The fuel bed inside the reactor is defined as control volume mass; $m = m_{fuel}$. The gasification process through gasification time t_g is expressed referring to control volume mass balance by equation 1.

$$m_{input} - m_{output} = (m_2 - m_1)_{CV} \quad (1)$$

Right hand side of equation 1 describes gasification time, t_g as follows:

The fuel bed inside the reactor $(m_2 - m_1)_{CV}$ is time -dependent. State 1 is the start of gasification while state 2 is end of the gasification

$$t = t_g \quad \text{for } m_2 = m_{fuel} = 0 \quad kg \quad (1a)$$

Since $m_1 = m_{fuel} = 0.25$ kg at t= 0

Left hand side of equation 1 describes the generation of gasification process in terms of steady and time-dependent transient mass balances where

$$m_{input} = m_{air}(kg) \quad (1b)$$

A steady state steady flow use of m_{air} is the case (equation 1.b). However instead of steady rate amount of air mass m_{air} in kg during t_g is referred for a transient fuel decomposition.

The supplied standard amount of air flow rate ($\dot{\forall}$) in units of sL/min is converted into kg following the conceptual equation of 1c.

$$m_{air}(kg) = \left(\dot{\forall}\left({}^{sL}/_{min}\right) . \frac{P_{atm(s)}(kPa)}{R_{air}\left(\frac{kPa.\,m^3}{kg.\,K}\right) . T_0(K)} \right) . t_g\,(s) \quad (1c)$$

In equation 1c, $P_{atm(s)}$, R_{air} and T_0 are 101.3 kPa, 0.287 kJ/kg.K and 25℃ respectively. t_g is the duration of gasification process.

$$m_{output} = m_{syn} + m_{ash} \quad (kg) \quad (1d)$$

A gasification time dependent definition is referred in equation 1d.

Syngas amount (m_{syngas}). Syngas is defined as the total gas output. It includes gasified amount of solid fuel determined by the collected ash amount (m_{ash}) and supplied air amount (m_{air}) during t_g

Syngas amount is derived from equation 1a. It is defined as equation 2.

$$m_{syngas}(kg) = m_{air}(kg) + m_{fuel}(kg) - m_{ash}(kg) \quad (2)$$

Since it is a hybrid process gasification time dependent solution necessitates mass quantities instead of rates for m_{syngas}.

Local gasification time –averaged temperature. The local gasification time- The local temperature $T_{(y,t)}$ is measured with 1 seconds time intervals (Δt). Averaged temperature at each station ($T_{y/h}$) is calculated by using equation 3.

$$T_{y/h} = \frac{\Delta t}{t_g} \sum_{t=1}^{t_g} T_{(y,t)} \quad (3)$$

Syngas temperature. The gasification time averaged reactor overall temperature is defined as syngas temperature (T_{syn}).

It is determined by equation 4.

$$T_{syn}(℃) = {}^{\left(T_{y/h=0.28} + T_{y/h=0.44} + T_{y/h=0.6} + T_{y/h=0.76} + T_{y/h=0.92}\right)}/_{5} \quad (4)$$

Syngas Gravimetric Composition - Syngas Molecular Weight. The syngas content is measured with 2 seconds time intervals (Δt). The average of each gas component percentage in the syngas is determined by using equation 5 in the volumetric base.

$$\text{Syngas component (V \%)} = \frac{\Delta t}{t_g} \sum \text{Syngas component}_{(t)} \quad (5)$$

The syngas content percentages in volumetric base are identical with the molar based percentages of syngas mixture from Dalton/Amagat model. The syngas content percentages in volumetric base are converted to mass base by using equation 5a. The syngas molecular weight is calculated by equation 5b.

$$\text{Syngas component (m \%)} = \frac{(\text{Syngas component(n \%)}.\,M_{\text{Syngas component}})}{(\sum \text{Syngas(n \%)}.\,M_{\text{syngas}})}.100 \quad (5a)$$

$$\sum \text{Syngas(n \%)}.\,M_{\text{syngas}} = CO(\text{n \%}).M_{CO} + CO_2\,(\text{n \%}).M_{CO_2} + H_2(\text{n \%}).M_{H_2} + CH_4(\text{n \%}).M_{CH_4} + O_2\,(\text{n \%}).M_{O_2} + N_2\,(\text{n \%}).M_{N_2} \quad (5b)$$

Thermodynamic analysis of the fuel decomposition is defined through the calculated major performance parameters of plasma energy, fuel energy and syngas energy defined below:

Plasma Energy (E_{plasma}). A steady state continuous energy supply through Microwave power input (P) is essential. However for each case gasification time is used to determine the plasma energy used

$$E_{plasma} = P\,(kW).t_g(s) \quad (6)$$

Fuel Energy (E_{fuel}). Energy content of fuel is defined as Equation 7. Fuel energy is not related to gasification time.

$$E_{fuel}(kJ) = m_{fuel}(kg).HHV_{fuel}\left({}^{kJ}/_{kg}\right) \quad (7)$$

Syngas Energy (E_{syngas}). Syngas is a mixture of gases. The volumetric content of syngas is converted into mass and the syngas temperature is referred for the calculation of energy. In terms of m_{syngas}, gasification time governs the calculation through equation 2 therefore E_{syngas} is a function of t_g.

$$E_{syngas}(kJ) = m_{syngas}(kg).HHV_{syngas}\left({}^{kJ}/_{kg}\right) \quad (8)$$

Table 2. MCw GASIFIER operational results in terms of range of the parameters

t_g (s)	T_{syn} (°C)	m_{syngas} (kg)	M_{syngas} (kg/kmol)	m_{ash} (g)	E_{plasma} (kJ)	E_{fuel} (kJ)	E_{syngas} (kJ)
420 - 1020	621 - 1276	0.66 - 1.2	26.37-33.52	1.16-91.77	18000-4560	4485 - 8658	1644 - 6170

The details of calculation methodology for E_{fuel} E_{syngas} are available in [1,4,5] Table 2 outlines the measured ranges of t_g, T_{syn}, M_{syngas} , m_{syngas}, m_{ash}, and energy parameters of the operational study

5. Conclusions

Hybrid nature of microwave gasification process is resulted in a modeling described by the operational test cases of MCw GASIFIER. The decomposition of solid fuel into syngas is a transient process. Meanwhile air supply and microwave power supply are steady. Therefore, the critical parameter of process is gasification time which is determined by a continuous monitoring of the operation through local temperature and syngas content measurements. The basic criticism on the previous article [1] is the description of steady rate form of parameters. These parameters are meaningful if they are expressed as rate forms based upon the gasification time.

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