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INFLUENCE OF SYNGAS COMPOSITION ON CALCULATIONS OF FLOW RATE MEASURED BY USING ORIFICE PLATES

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Abstract

Biomass gasification is a thermochemical process that results in the generation of a flammable gas mixture called syngas. This gas is composed of five main components; CO, H_2, CH_4; CO_2 and N_2. Measured flow rate value of generated syngas is one of the most important parameters to evaluate the gasification performance. Orifice plates are very usable for biomass gasification systems. They have a very common usage in flow rate measuring together with differential pressure sensors. The limits of orifice plate usage and calculation methods are given with ISO5167-2. Syngas values used in flow calculations according to ISO5167-2 are density, dynamic viscosity, and isentropic exponent. In experimental studies carried out in the field of biomass gasification, changes in the composition of the measured gas require recalculation of these values. In this paper, the influence of the changes in density, dynamic viscosity, and the isentropic coefficient on the flow rate calculation for the varying compositions of the synthesis gas is investigated.

Keywords: syngas, orifice plates, flow rate, biomass, gasification, gas mixtures.

INTRODUCTION

Biomass gasification is one of the most important and popular subjects in the field of renewable energy research. Gasification is a thermochemical process and it results in a combustible gas mixture called synthesis gas, syngas or producer gas. The flow rate and composition of syngas are important parameters determining the performance of the gasification system.

The gas composition determines the heating value of syngas and the output energy of the gasification system. The gas flow rate is a parameter that must be measured in order to calculate the output power of the system.

There are many methods and instruments for flow measuring. Variable area flow meters, thermal mass flow meters, electromagnetic flow meters, turbine flow meters, ultrasonic flow meters etc. Flow measurement using orifice plates and differential pressure gauges is also an economical method widely used in biomass gasification systems.

Flow measurement with orifice plates is standardized with EN ISO 5167-2.

EXPOSITION

Due to some advantages of orifice plates, they are widely used in biomass gasification systems. They can be used in dirty and hot gas measurements. Their mounting and dismounting operations are easy to apply.

The principle of this method of measurement is based on the installation of an orifice plate into a pipeline in which a fluid is running full. The orifice plate is a plate that reduces the flow cross-section of the pipe. The presence of the orifice plate causes a static pressure difference between the upstream and downstream sides of the plate. The location of the pressure tappings characterizes the type of standard orifice meter [1]. Depending on the position of the pressure tappings, the orifice meter types are considered as three types, with corner tappings, flange tappings, and D-D/2 tappings.

Experimental setup:

In this study, the orifice plate made of 2 mm stainless steel is placed between the flanges and pipeline is 2’’. When the diameter of the orifice is 18 mm, it is possible to measure the required parameters for operation. **Fig1** shows the orifice plate used in this study. The high-pressure side of the orifice plate is machined to 1 mm flat and the low-pressure side to be 45° in accordance with EN ISO 5176-2. D-D/2 type orifice plate is discussed and it's shown schematically in **Fig2**.

Fig. 1. *The orifice plate*

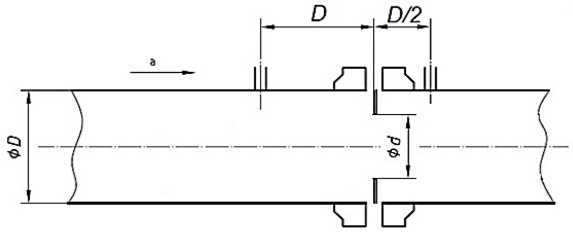

Fig. 2. *D-D/2 type tappings*

The orifice plate is assembled on the pipeline vertically as shown in **Fig3**. The pressure pipes are connected to the orifice section at a distance of D/2 at the high-pressure side and D (inner diameter of the pipe) at the low-pressure side. The difference between the orifice inlet and outlet pressures is detected by the differential pressure sensor and read in mbar on the HMI panel.

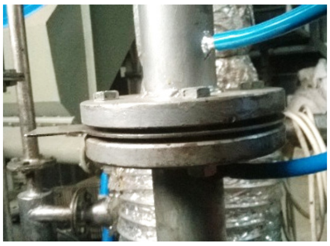

Fig. 3. *Orifice connection on the line*

A laboratory scale biomass gasification system was constructed and manufactured for syngas generation. The gasification system used to generate syngas is shown in **Fig4**. This is an open top throatless reactor which has 170 mm of reactor diameter. Measured data of temperature and pressure have been collected, viewed and stored by HMI control panel. The air was used as gasification agent in the process. The selected biomass feedstock was pelleted rice straw.

Fig. 4. *Gasification system*

The calculation of the output power of gasification system needs the lower heating value and gas flow rate. **Eq1** is used for this.

$$P_G = (LHV_G \cdot GFR)/3600 \qquad (1)$$

P_G : *Output power (kW)*
LHV_G : *Lower heating value of gas (kJ Nm^{-3})*
GFR : *Gas flow rate (Nm^3 h^{-1})*

Syngas samples that taken from the line were analyzed by Agilent 7890B GC model gas chromatography device shown in **Fig5**. The gas composition values obtained from analysis are used for determining the lower heating value of the gas (LHV_G).

Fig. 5. *GC device for syngas analysis*

In case of using air as gasification agent, syngas has five main components: H_2, CO, CH_4, CO_2, and N_2. This gas mixture is flammable. The syngas flame generated during the gasification process is shown in **Fig6**. The lower heating value of syngas can be calculated as (MJ Nm^3) by the **Eq2** if the volumetric percentages are known [2].

$$LHV_G = 10.8\ \%H_2 + 12.63\ \%C + 35.8\ \%CH_4 \qquad (2)$$

Fig. 6. *Syngas flame*

Standard calculation acc. To ISO5761-2:

In calculations made according to EN ISO 5761-2, the **Eq3** (mass flow relation) is used [1].

$$q_m = \frac{C}{\sqrt{1-\beta^4}}\varepsilon\frac{\pi}{4}d^2\sqrt{2\Delta P\rho} \qquad (3)$$

q_m : *Mass flow rate (kg s^{-1})*
C : *Coefficient of discharge*
ε : *Expansion factor*
ΔP : *Differential pressure (Pa)*
β : *Diameter ratio*
d : *Diameter of orifice (m)*
ρ : *Density of gas (kg m^{-3})*

The diameter ratio is taken as $\beta = d/D$ and the coefficient of discharge (C) is calculated by using the Reader-Harris/Gallagher equations (**Eq4**, **5**, **6**, **7**, and **8**). Coefficient of discharge can be handled as three parts. C_1 is the data of orifice media, C_2 is the data of D tapping, and C_3 is the data of D/2 tapping. C_4 should be added when the diameter of the pipe was less than 71.12 mm [1].

$$C = C_1 + C_2 + C_3 + C_4 \qquad (4)$$

$$C_1 = 0.5961 + 0.0261\beta^2 - 0.216\beta^8 + 0.000521\cdot\left[10^6\frac{\beta}{Re}\right]^{0.7} + (0.0188 + 0.0063A)\beta^{3.5}\left(\frac{10^6}{Re}\right)^{0.3} \qquad (5)$$

$$C_2 = [0.043 + 0.08e^{-10L_1} - 0.123e^{-7L_1}]\cdot(1 - 0.11A)\cdot\frac{\beta^4}{1-\beta^4} \qquad (6)$$

$$C_3 = -0.031\cdot(M_2 - 0.8M_2^{1.1})\cdot\beta^{1.3} \qquad (7)$$

$$C_4 = 0.011\cdot(0.75-\beta)\cdot(2.8 - \frac{D}{25.4}) \qquad (8)$$

In accordance with EN ISO 5761-2; values of L_1 and L_2 is taken as 1 and 0.47 respectively and the following expressions are taken as basis for M_2 and A in **Eq9** and **10**:

$$M_2 = \frac{2L_2}{1-\beta} \qquad (9)$$

$$A = \left(\frac{19000\beta}{Re}\right)^{0,8} \qquad (10)$$

The number of Reynolds is found by **Eq11**. The flow rate calculation is valid if this number was greater than 5000.

$$Re = \frac{\rho V d}{\mu} \qquad (11)$$

Here $V\ (m\ s^{-1})$ is the velocity of the fluid in the cross section and $\mu\ (Pa\cdot s)$ is the dynamic (absolute) viscosity. $d\ (m)$ is the orifice diameter and $\rho\ (kg\ m^{-3})$ is the density of syngas in actual conditions.

Eq12 is used for the expansion factor (ε). Here, κ refers to the isentropic exponent, P_1 refers to the high pressure at the entrance of the orifice, and P_2 refers to the low pressure at the exit of the orifice.

$$\varepsilon = 1 - (0{,}351 + 0{,}256\beta^4 + 0{,}93\beta^8)\left[1 - \left(\frac{P_2}{P_1}\right)^{1/\kappa}\right] \qquad (12)$$

Calculation of density:

Eq13 is used for the calculation of density of syngas in standard conditions ($T = 0$°C $P = 1\ atm$). v_i is the volumetric ratio and ρ_i is the density of each component in standard conditions.

$$\rho_0 = \sum \rho_i\cdot v_i \qquad (13)$$

Volumetric percentages that obtained from GC analysis were used to calculate volumetric ratio by the **Eq14**.

$$\%v_i = 100\cdot v_i \qquad (14)$$

Densities of syngas components in standard conditions are given in **Table1**.

Table 1. *Densities of syngas components in standard conditions*

	ρ_0 **(kg m^{-3})**
H_2	0. 0889
CO	1. 25
CH_4	0. 717
CO_2	1. 977
N_2	1. 2506

The density of syngas in actual temperature (T°C) can easily be determined according to the ideal gas laws by the **Eq15**.

$$\rho = \rho_0 \cdot \frac{273.15}{(273.15 + T)} \tag{15}$$

Calculation of dynamic viscosity:

Dynamic viscosity value is needed to determine the Reynolds number. Herning-Zipperer equation [3] is used to calculate this value (**Eq16**). M_{mi} is the molar mass (g/mol), x_i is mol fraction, and μ_i is the dynamic viscosity (Pas) of each syngas component.

$$\mu = \frac{\sum(\mu_i \cdot x_i \cdot \sqrt{M_{mi}})}{\sum(x_i \cdot \sqrt{M_{mi}})} \tag{16}$$

Dynamic viscosities of syngas components in different temperatures are given in **Table2** [4].

Table 2. *Dynamic viscosities of syngas components in different temperatures*

		0 °C	**20 °C**	**50 °C**	**100 °C**
Dynamic viscosity (10^{-5} Pas)	H_2	0.84	0.88	0.94	1.04
	CO	1.66	1.74	1.88	2.10
	CH_4	1.03	1.10	1.19	1.35
	CO_2	1.37	1.47	1.61	1.85
	N_2	1.66	1.76	1.89	2.12

Mol fraction is found by the **Eq17**. Here M_i is mol number of each component.

$$x_i = \frac{M_i}{\sum M_i} \tag{17}$$

Mol number of each component is found by the **Eq18**. In this equation, T is the temperature of syngas (°C), ρ_i is the density of each component in standard conditions (kg/m^3), M_{mi} is the molar mass of the component (g/mol), and v_i is the volumetric fraction of the component determined by GC analysis.

$$M_i = \frac{v_i \cdot \rho_i \cdot 273.15}{\frac{M_{mi}}{1000} \cdot (273.15 + T)} \tag{18}$$

Calculation of isentropic exponent:

For the gas mixtures, the isentropic exponent can be calculated by **Eq19**. Here w_i is mass fraction, c_{pi} is the specific heat at constant pressure (kJ/kgK), and c_{vi} is the specific heat at constant volume (kJ/kgK) for each component of syngas.

$$k = \frac{\sum(w_i \cdot c_{pi})}{\sum(w_i \cdot c_{vi})} \tag{19}$$

The specific heat values change with the temperature. The **Eq20** is used to calculate the specific heat values at constant pressure [5]. In this equation, T is the temperature in °C and c_{pi} is in kJ/(kmol·K). Unit of c_{pi} should be converted from kJ/(kmol·K) to kJ/(kg·K) by dividing it to molar mass of the component before using the value in **Eq19**.

$$\begin{aligned} c_{pi} = A + (B \cdot 10^{-2}) \cdot T + (C \\ \cdot 10^{-5}) \cdot T^2 + (D \\ \cdot 10^{-9}) \cdot T^3 \end{aligned} \tag{20}$$

The coefficients A, B, C, and D are given with the **Table3** [5] for syngas components to be used in **Eq20**.

Table 3. *The coefficients to be used for Eq20.*

	A	**B**	**C**	**D**
H_2	29.11	-0.1916	0.4003	-0.8704
CO	28.16	0.1675	0.5372	-2.2220
CH_4	19.89	5.0240	1.2690	-0.1101
CO_2	22.26	5.9810	-3.5010	7.4690
N_2	28.90	-0.1571	0.8081	-2.8730

Universal gas constant R_u is well known value as 8.3144598 kJ/(kmol·K) for ideal gasses. Specific gas constant and specific heat values at constant volume can be found easily with **Eq21**.

$$R_i = \frac{R_u}{M_{mi}} = c_{pi} - c_{vi} \tag{21}$$

Mass fraction is found by the **Eq22**.

$$w_i = \frac{m_i}{\sum m_i} = \frac{v_i \cdot \rho_i}{\sum(v_i \cdot \rho_i)} \tag{22}$$

Calculation results:

The composition of syngas sample which obtained from GC analysis is given in the **Table4** that used in the calculations.

Table 4. *The composition of syngas sample*

	H_2	**CO**	**CH_4**	**CO_2**	**N_2**
%v_i	15.188	16.452	2.203	12.910	53.247

The lower heating value of this composition is found 4,584 MJ Nm^{-3} by using the **Eq2**.

Known and measured parameters before calculations are shown in the **Table5.**

Table 5*. Known and measured parameters before calculations*

Flow diameter	D	[m]	0.052
Orifice diameter	d	[m]	0.018
Gas temperature	T	[°C]	50
High-pressure	P_1	[mbar]	1005
Differential pressure	dP	[mbar]	4

The parameters which belong to syngas composition (density, dynamic viscosity, and isentropic coefficient) are calculated and the results are given in the **Table6**.

Table 6. *Calculated parameters belong to syngas composition*

Density	ρ	[kg m^{-3}]	0.977
Dynamic viscosity	μ	[10^{-5}·Pa·s]	1.78484
Isentropic exponent	k		1.375

Table7 shows the values of molar masses, and the results of the calculations of dynamic viscosities, mole fractions, and the mol numbers for each component.

Table. *7. Dynamic viscosity calculation results*

	M_{mi}	**μ_i**	**x_i**	**M_i**
	g/mol	10^{-5} Pas		
H_2	2.0159	0.940	0.15163	5.72523
CO	28.0101	1.879	0.16436	6.20600
CH_4	16.0425	1.194	0.02203	0.83207
CO_2	44.0095	1.615	0.12983	4.90214
N_2	28.0134	1.891	0.53215	20.0931

For 50°C of temperature, the calculated specific heat coefficients and mass fractions are given in the **Table8**.

Table 8. *Specific heat coefficients for 50°C and mass fractions*

	w_i	**c_{pi}**	**c_{vi}**
		kJ/(kg·K)	kJ/(kg·K)
H_2	0.012	14.326	10.202
CO	0.178	1.042	0.745
CH_4	0.014	2.311	1.793
CO_2	0.220	0.868	0.679
N_2	0.576	1.040	0.743

The results of the standard orifice calculations which were done acc. to ISO5167-2 are shown in **Table9**.

Table 9. *Standard orifice calculation results acc. to ISO5167-2.*

Coefficient of discharge	C		0.6129
Reynolds number	Re		6020
Expansion factor	ε		0.9989
Mass flow rate	q_m	[kg s^{-1}]	0.0044
Mass flow rate	q_m	[kg h^{-1}]	15.798
Volumetric flow rate	q_v	[Nm^3 h^{-1}]	13.667

CONCLUSION

Orifice plates are widely used in biomass gasification systems as an economic measurement instrument. This method is simply based on the differential pressure measuring in the pipeline that created by the narrow cross-section of an orifice plate. The calculation methods are already standardized by ISO 5167-2. In biomass gasification systems, the syngas composition is generally not constant. Different biomass materials and different gasification conditions cause some changes of syngas properties like density, dynamic viscosity, and isentropic exponent.

In order to do the accurate calculation of flow rate of syngas which measured by using orifice plates, density, dynamic viscosity, and isentropic exponent of syngas are the parameters that should be known or should be calculated.

The gasifier was designed by the project NKUBAP.00MBAR1403 and the data control and measurement system was designed by the project NKUBAP.00.24.AR.14.28 in Namık Kemal University.

The sample of syngas which was generated by our biomass gasification system was analyzed and the lower heating value was found 4,584 MJ Nm^{-3}. Flow measurement was done by orifice plate and differential pressure transmitters acc. to ISO 5167-2. Since the syngas was a gas mixture, the density, the dynamic viscosity, and the isentropic exponent were calculated by including the effect of the gas composition.

The volumetric volume was found as 13.667 Nm^{3}h^{-1}. The output power of gasification system is determined as 17.4 kW.

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