EQUILIBRIUM MODELING OF HEMP HURD GASIFICATION

Simone Pedrazzi, Nicolò Morselli, Marco Puglia, Massimiliano Parenti, Filippo Ottani
BEELab (Bio Energy Efficiency Laboratory), Department of Engineering "Enzo Ferrari"
University of Modena and Reggio Emilia,
Via Vivarelli 10/1 – 41125 Modena, Italy.
Website: www.beelab.unimore.it; phone: +3905920565229; mail: simone.pedrazzi@unimore.it

INTRODUCTION

The aim of this work is modeling a gasification process where a non-conventional biomass is used as fuel. In particular, hemp hurd residues are considered. This biomass is usually left of the field of burned in wildfires in the context of hemp cultivation for seeds and flowers harvesting. The amount of this biomass is not negligible; literature reports an annual productivity in cold climate conditions of about 10 ton per hectare of dry matter including flowers and seeds that represent a small fraction of the whole plant. In this paper, an equilibrium model of the gasification reaction is implemented in the Phyton™ software environment. Syngas composition, syngas higher heating value, tar production and gasification cold gas efficiency are evaluated at different value of biomass moisture starting from biomass ultimate analysis and reaction equivalence ratio (ER) value.

The model is able to predict char and tar production as function of biomass composition, moisture and ER. Char will be used as soil admendant in the hemp cultivation itself increasing hemp productivity and storing carbon from the atmosphere. Tar is a pollutant of the syngas stream that can be dangerous for mechanical components of the gasification power plants. High is the tar amount high is the filtering effort needed to purify the syngas, however a low tar production below 1 g/Nm³ is difficult to reach with biomass residues because of high moisture and low higher heating content of the residue. A comparison with experimental data obtained from hemp hurd gasification was done in order to validate equilibrium model results. Gasification tests were performed using a low capacity lab-scale gasification reactor designed to use about 1 kg per hour of dry biomass fuel. Results show small errors between model results and experimental result. A cold gas efficiency of about 58% and a syngas heating value of about 4.4 MJ/Nm³ are obtained from the equilibrium model with 10% of biomass moisture and equivalence ratio ER = 0.3; these values are in line with literature data about fixed bed gasification. Model simulations varying ER in the range 0.2-0.4 and varying M in the range 0-20% show a good dependency of the gasifier with the ER value.

MATERIALS AND METHODS

Chemical analysis

Table 1: Chemical analysis

M (ar)	10.00	% wt			
ASH (dry)	7.38	% wt			
ASH (ar)	6.64	% wt			
Ultimate analysis (AR)			**Ultimate analysis (DB)**		
C	38.70	% wt	C	43.00	% wt
H	5.03	% wt	H	5.58	% wt
N	0.41	% wt	N	0.45	% wt
S	0.00	% wt	S	0.00	% wt
O	39.22	% wt	O	43.58	% wt
ASH	6.64	% wt	ASH	7.38	% wt
M	10.00	% wt	M	0	% wt
tot	100.00	% wt	tot	100	% wt
Heating values					
HHV_db =	16.94	MJ/kg	LHV_dry =	15.72	
HHV_ar =	15.24	MJ/kg	LHV_ar =	13.78	
m_da =	5.005611	kg_air/k_dry,bio			


Figure 1: Hemp hurd sample

Equilibrium modeling

Generalized gasification reaction [1,2]

$$CH_xO_yN_z + m(O_2 + 3.76N_2) = n_{H_2}H_2 + n_{CO}CO + n_{CO_2}CO_2 + n_{H_2O}H_2O + n_{CH_4}CH_4 + n_{tar}\,Tar + (1-\alpha_c)Char + \left(\frac{z}{2} + 3.76\,m0\right)N_2$$

$$x = \frac{HM_c}{CM_H},\quad y = \frac{OM_c}{CM_o},\quad z = \frac{NM_c}{CM_N}$$

$$w = \frac{MW_{bio}\cdot M(100+ASH)}{100\cdot[MW_{H_2O}(1-{}^{M}/_{100})}$$

$$m = ER\cdot\left(1+\frac{x}{4}-\frac{y}{2}\right)$$

Chemical balances

Carbon balance leads to

$$n_{CO} + n_{CO_2} + n_{CH_4} - 1 = 0$$

Hydrogen balance leads to

$$2n_{H_2} + 2n_{H_2O} + 4n_{CH_4} - x = 0$$

Oxygen balance leads to

$$n_{CO} + 2n_{CO_2} + n_{H_2O} - 2m - y = 0$$

Reactions equilibrium constant [3,4]

Water-gas shift reaction: $CO+H_2O = CO_2+H_2$

$$K_1 = \frac{n_{CO_2}\times n_{H_2}}{n_{CO}\times n_{H_2O}}\qquad K_1 = e^{\frac{4276}{T}}-3.961$$

Methane reaction: $C+H_2 = CH_4$

$$K_2 = \frac{n_{CH_4}\times n_{total}}{n_{H_2}\times n_{H_2}}$$

$$\ln(K_2) = \frac{7082.842}{T} - 6.567\times\ln(T) + \frac{(7.467\times10^{-3})\times T}{2} - \frac{2.167\times10^{-6}}{6}\times T^2 + \frac{0.702\times10^5}{2\times T^2} + 32.541$$

Tar weight fraction [5]

$$W_{tar} = 35.98e^{-0.00298T}$$

Carbon conversion factor [6]

$$\alpha_c = 0.901 + 0.439\times\left(1-e^{-ER+0.0003T}\right)$$

Heat balance

$$H^0_{f,\,\mathrm{biomass}} + \left(mH^0_{f,O_2} + 3.76mH^0_{f,N_2} + Q_{air}\right) = \sum n_j\left(H^0_{f,j} + \int_{298}^{T} c_{p,j}dT\right) + (3.76m + z/2)\left(H^0_{f,N_2} + \int_{298}^{T} c_{p,N_2}dT\right)$$

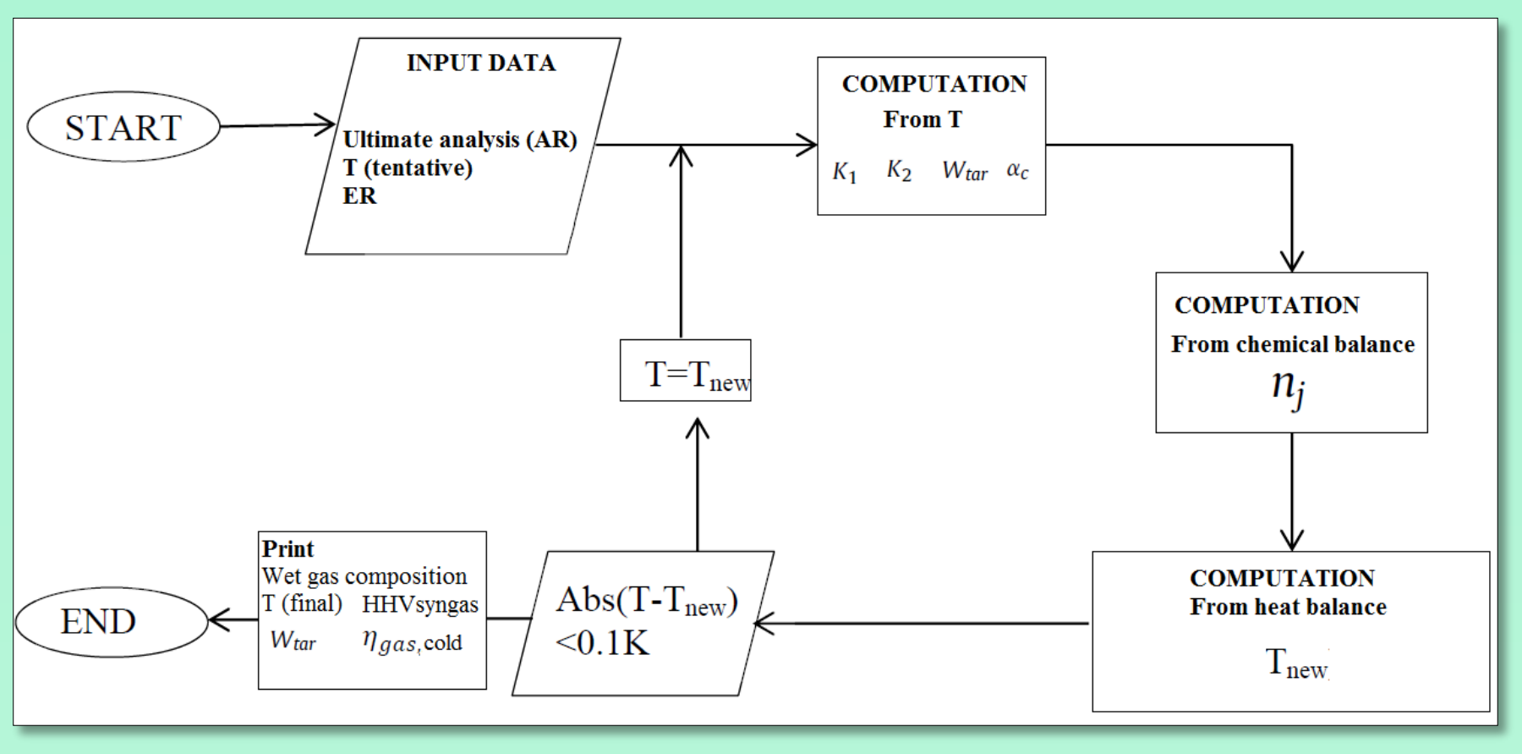
$$Q_{air} = m\int_{298}^{T_{air}} C_{p,O_2}dT + 3.76m\int_{298}^{T_{air}} C_{p,N_2}dT$$

$$C_p = a + bT + cT^2 + dT^3$$

$$H^0_{f,\,\mathrm{biomass}} = HHV_{\mathrm{biomass}} + \Sigma n_k H^0_{f,k}$$

$$HHV = 0.3491C + 1.1783H + 0.1005S - 0.1034O - 0.0151N$$

Solution algorithm


START
INPUT DATA
Ultimate analysis (AR)
T (tentative)
ER
COMPUTATION
From T
K_1 K_2 W_{tar} α_c
COMPUTATION
From chemical balance
n_j
COMPUTATION
From heat balance
T_{new}
Abs(T-T_{new}) <0.1K
T=T_{new}
Print
Wet gas composition
T (final) HHVsyngas
W_{tar} $\eta_{gas,cold}$
END

Experimentns

Lab scale gasifier prototype [7]

$$\eta_{gas,cold} = \frac{HHV_{Syngas}\cdot Volume\ of\ Syngas}{HHV_{bio,AR}\cdot Mass\ of\ biomass}$$

HHV_{Syngas} → *Estimated after* ***Gas – Chromatografic Analysis***

Volume of Syngas → ***Indirectly Measured*** [7]

Mass of biomass → ***Measured***

$HHV_{bio,AR}$ → *Estimated from* ***Ultimate Analysis***

EXPERIMENTAL AND SIMULATION RESULTS

Model Vs. Experiment

Table 2: Model Vs. Experimental results comparison

Syngas composition (dry basis) from the experimental test				Syngas composition (dry basis) from the equilibrium model (ER =0.3)	
	Sample 1	**Sample 2**	**Average**		
H2 % vol.	13.1	11.9	12.5	H2 % vol.	20.8
N2 % vol.	49.1	50.1	49.6	N2 % vol.	46.2
CH4 % vol.	2.3	2.2	2.25	CH4 % vol.	2.1
CO % vol.	20.1	18.1	19.1	CO % vol.	12.3
CO2 % vol.	11.9	13.4	12.65	CO2 % vol.	18.5
HHV [MJ/Nm^3]	5.1	4.7	4.9	HHV [MJ/Nm^3]	4.4
Cold gas efficiency				**Cold gas efficiency**	
eta_gas,cold [%]		65.81		eta_gas,cold [%]	58.10

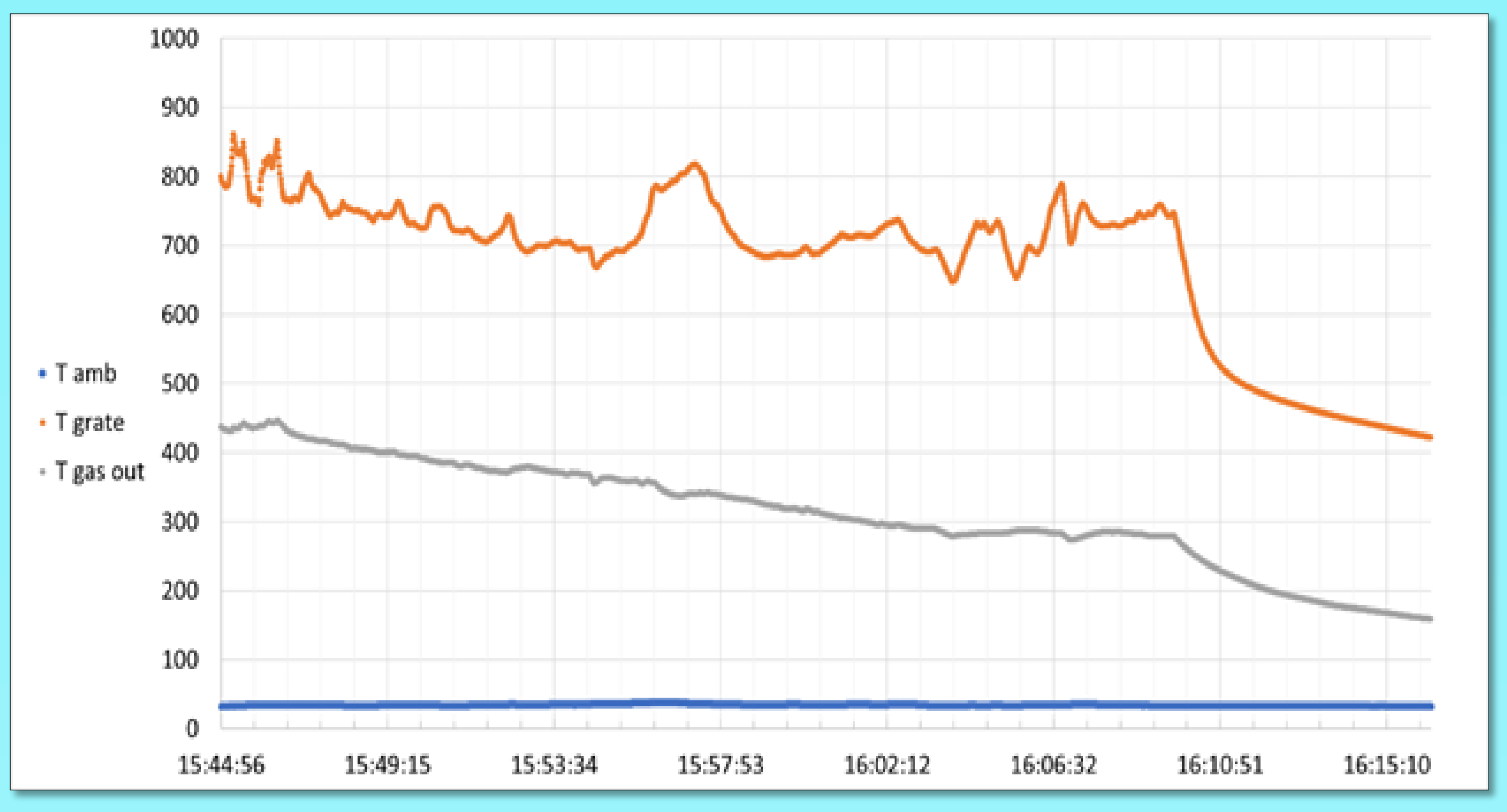


Figure 2: Gasifier temperature trends during the experimental test

Simulation results

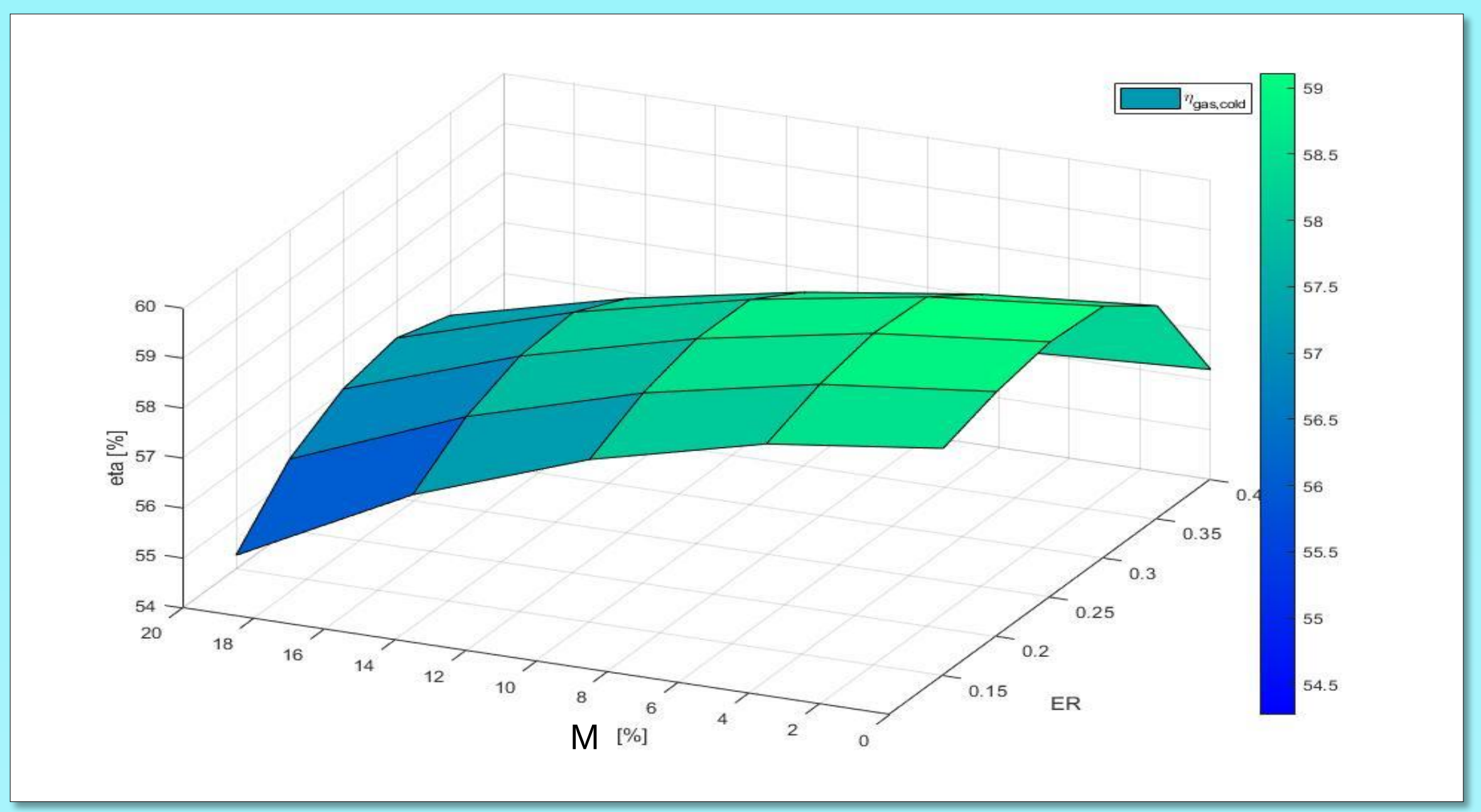


Figure 3: Gasifier cold gas efficiency Vs. moisture and ER

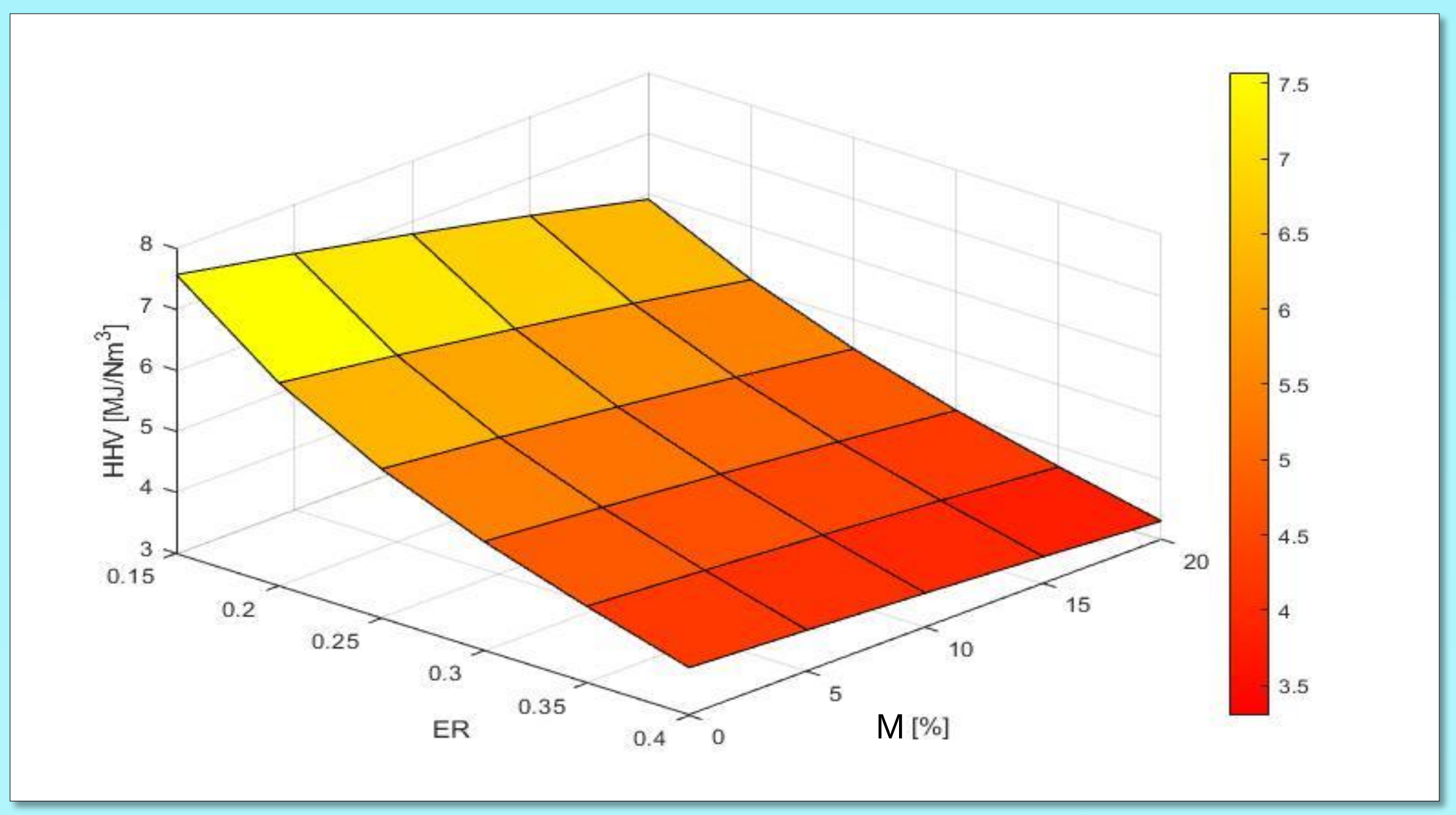


Figure 4: Wet syngas HHV Vs. moisture and ER

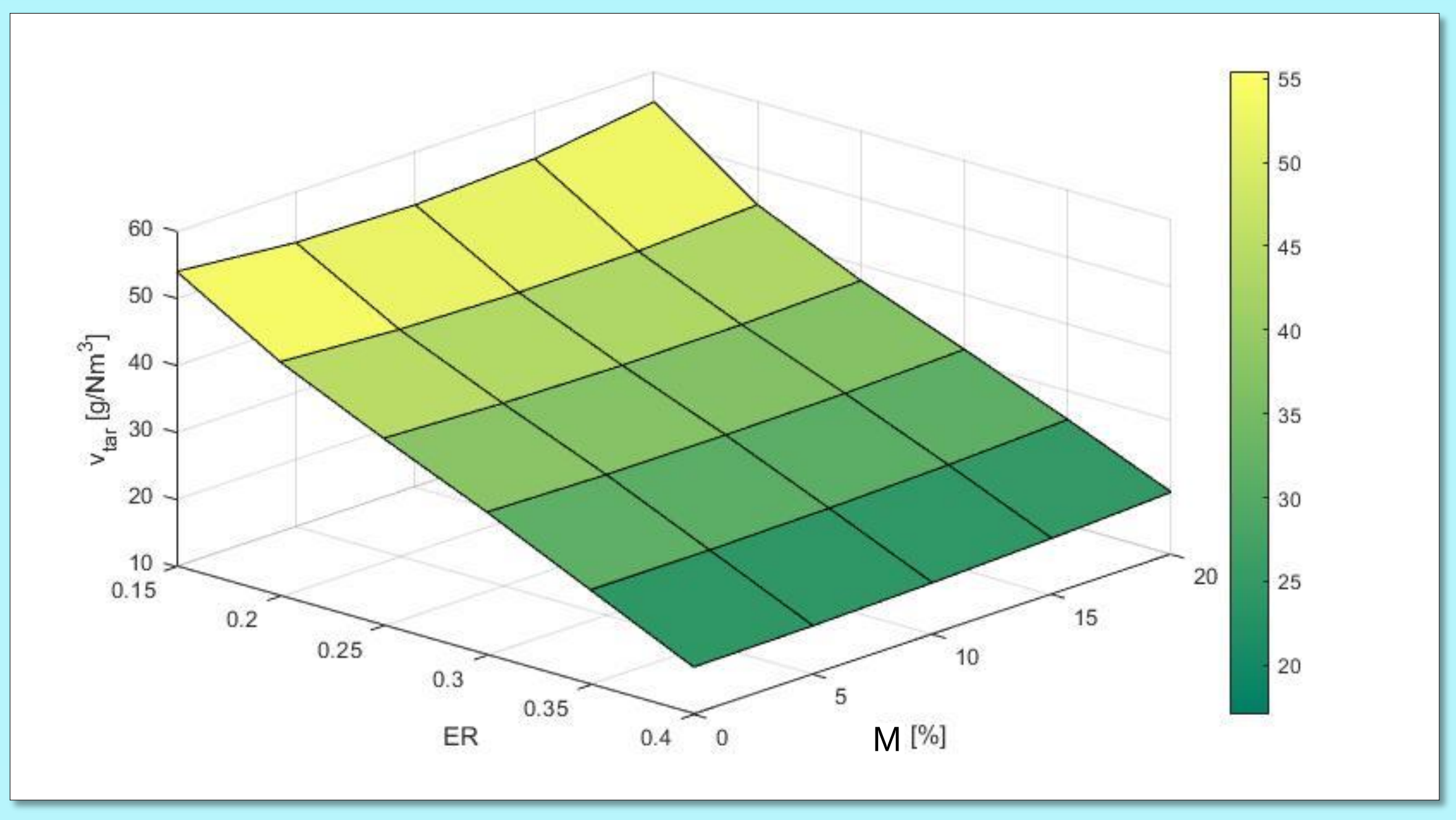


Figure 5: Volume percentage of tar in the syngas Vs. moisture and ER

RESULTS DISCUSSION AND CONCLUSIONS

- The comparison between syngas composition evualuated through the equilibrium model and through gas cromatograph shows small differences probably given by the strong hyphotesis adopted in the equilibrium model and the unstable temperatures measured during the gasification test (Fig. 2). Further tests are needed to propely validate the model.
- 3D plots reported in the result section shows a strong dependency of the gasifier output with the biomass moisture and the equivalence ratio (ER). Lower is the moisture better is the gasifier behaviour in term of efficiency, syngas HHV and tar production. However, a moisture value lower than 10% is accettable in industrial application and do not create sensible inefficiencies. ER value is crucial to have a good cold gas efficiency, infact for ER = 0.3 the best efficiency of about 59.5 % was estimated. This value is quite common for fixed bed gasifier that are design to work in this precise conditions. In practice, ER is very hard to set during gasification operation, infact it depends on several factor such as biomass composition, particle dimensions and shape, moisture and syngas flow rate. A good control system should be able to recognise this value during operation and adjust the working parameter in order to achieve ER = 0.3.
- As show in Figure 5, tar production is almost constant in the moisture range 0-20%, however tar strongly depends on ER value. A high ER value (i.e. 0.4) descreases tar production, a low ER value (i.e. 0.2) increases tar production. Again a good compromise is ER = 0.3 where maximum efficiency is reached.