

Gasification of Waste Tires

Isam Janajreh*, Syed Shabbar Raza

Department of Mechanical and Materials Engineering, Masdar Institute of Science and Technology
Abu Dhabi, United Arab Emirates
Email: ijanajreh@masdar.ac.ae

Abstract—Gasification is a thermochemical pathways used to convert carbonaceous feedstock into syngas (CO and H₂) in deprived oxygen environment. The process can accommodate conventional feedstock such as coal as well as discarded waste including plastics, rubber, and even MSW due to the high reactor temperature of 1000 to 1600°C. Pyrolysis is another conversion pathway yet it is more selective to the carbonaceous feedstock as it proceeds at relatively lower process temperature (350 to 550°C). Discarded tires can be subjected to pyrolysis, however the yield involves the formation of intermediates radicals that remaining in additional to unconverted char that require further distillation and upgrading. Also due to continuous Random Fission/Radical Recombination, β -Scission/Radical Addition, Depropagation/Propagation, Hydrogen Abstraction devlatilization and recombination, pyrolysis fails to follow equilibrium and is very complex to predict and thereby model. Gasification, however, due to their higher temperature and shorter residence time is more opted to follow quasi-equilibrium and predictive. In this work tire crumbs are subjected to two levels of gasification modelling, i.e. equilibrium zero dimension and high fidelity multi-dimensional computational reactive flow. The objective is to investigate the effect of the oxidizer amount on the conversion of tire granules and syngas composition in compute process metrics. The simulation is carried out in a small 20kw cylindrical gasifier of 19in height by 10.75in diameter. Initially the chemical composition of several tire samples are measured following Standard ASTM procedures for proximate, ultimate and heating value. The measured data are used to define the tire properties and carry out equilibrium based gasification subjected to different equivalence ratio. This followed with reactive flow analysis to gain more details of the species distribution and reaction kinetics as twelve reactions including combustion, reduction, and methanation additional gas and water shift reactions are considered with their appropriate kinematics. The result shows that both models are reasonably predictive averaging 68% gasification efficiency, the devolatilization is less sensitive than the char conversion to the equivalence ration as complete devolatilization is always achieved. In view of the plausibly attained efficiency, it is suggested that tire gasification system is economically viable.

Keywords: Gasification, biomass, syngs, cold efficiency

I. INTRODUCTION

Human development while sounds positive, unfortunately it comes at environmental and ecological hurdles; augmentation and stockpile of waste, raise in CO₂ and other GH gas emission, strain in energy-water-food resources are amongst these costs. *Recycling, reusing and reducing* is an early intellectual practice to lessen the societal trans-developments impact while paying more attention to the finiteness of resources. For example making of the wheel have carried civilization following the other, but less emphasis was put into its disposal until recently. Used tires besides being unsightly and taking up valuable land space, their illegal dumps and stockpiles raise many environmental concerns. It is estimated that annual worldwide generation of discarded tire is over 1.2 billion with only fraction is re-treaded, granulated or subjected to energy recovery while the majority being openly incinerated, dumped or stockpiled. In US it is estimated that one tire is generated per capita annually (i.e. over 300M) and the current stockpiles is estimated to be more than 1.5 billion. In Japan around 100M is generated annually and in Australia is about 18M with over one year of stockpile for both countries. In Europe, in a study by the European Union in 2002 an estimate of 250M tires were disposed and with over 3 billion were stockpiled. Tire is a composite mix of many chemical components including natural rubber, polypropylene, polyesterine, anti-oxidants, inorganic stabilizer, carbon black, silicate, fabric, nylon, aramid, and steel in addition to the vulcanizing sulphur. Pyrolysis, following shredding and metal stripping, into liquid oil, gas, and metal streams as well as a reasonable grade of active carbon still facing many technical challenges. It is due to the low temperature in which a mixed paraffin, aromatics, raisins, and asphaltine are coexist within the liquid cuts. Also similar impurities exist within the gaseous stream with presence of sulphur dioxins at large proportion beside the methane, ethane and propane side to syngas (CO and H₂). Further distillation and gas separation which are thermally driven processes which lowers the overall process metrics. Alternatively gasification at higher temperature to a single stream of syngas that ensures complete feedstock conversion and narrower syngas mix renders the process higher metrics.

Gasification is a core technology that can be utilized broadly to generate energy without polluting the environment. Because of its many applications, it is currently enjoying a considerable renaissance [1]. Gasification is one of a thermo-chemical conversion

process which can be used to produce clean fuels. Gasification is compatible with new applications in the area of biomass conversion (when used with biomass, is carbon neutral); coal-to-liquid; superior environmental performance especially with regard to CO₂ capture and sulfur removal; and the prospect for substantial efficiency improvement when incorporated in Integrated Gasification Combined Cycle plants (IGCC) for electricity generation.

Using the gasification process, a wide range of carbonaceous material can be converted into high value fuel. The range covers from coal, biomass and municipal/agricultural/industrial waste including discarded tires. The product of gasification is normally composed of syngas that is a mixture of hydrogen and carbon monoxide. The production of syngas using gasification is a complex process that is based on several factors including the composition of feedstock, the gasifier temperature/pressure and the amount of oxidizer and moderator [2]. The process of gasification utilizes the partial combustion of feedstock by carefully controlling the amount of oxidizer. The amount of oxidizer also controls the temperature of the gasification process that is the most important parameter of gasifier, as reported by Walawender [3]. Details of the process cannot be captured by zero dimensional equilibrium model.

The chemical and physical phenomena that occur during gasification of tire crumbs are essentially similar to a typical carbonaceous material subjected to thermal decomposition. This includes drying, devolatilization (which includes release of volatile flammable gases, flaming combustion of the volatiles, and glowing combustion of fixed carbon), heat conduction, fissioning, shrinkage, and fragmentation of solid particles [6]. The chemical reactors used in the gasification process are distinguished by the concurrent flow of feedstock and gasifying agent.

Previous research using the systematic analysis, numerical simulation and experimental studies were conducted at the Waste to Energy lab at Masdar Institute and are available in the literature [11-15]. In this research a small scale gasifier will be utilized to demonstrate the bench scale conversion metrics of tire crumbs. The main aim of this study is to perform two levels of simulations systematic zero dimensional and a reactive coupled numerical simulation using CFD to investigate the system conversion of tire crumbs into syngas and with evaluation of the process metrics. In order to perform the desire simulation an experimental study is conducted to measure the chemical composition of the tire. These values are used to define the tire particle in both the system approach model and CFD simulation. Results of the simulations are presented in the form tire conversion by mean of volatile and char conversion. The behavior of CO and H₂ formation is also studied.

II. TIRE COMPOSITION

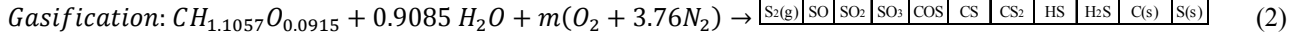
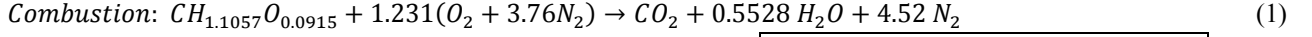
To establish the theoretical framework for gasification of the tire, both the thermal properties and chemical composition are determined. The thermogravimetric Q600SDT is used to determine the proximate composition of tire in terms of its moisture, volatile, fixed carbon, and ash fractions. The analysis is based upon measurements of the mass change of the sample as a function of a controlled/specified temperature profile. Thermo scientific Flash 2000 Organic Analyzer is used to evaluate the elemental composition of tire by analyzing the combusted stream while passed thog appropriate thermally conductive detection column. Also, the Bomb calorimeter is used to find out the heating value of tire. The result of proximate, ultimate and heating value analysis are given in **Error! Reference source not found.** The composition are normalized for one mole of Carbon on dry basis which lead to the unit composition formula for the tire of $CH_{1.1057}O_{0.0915}N_{0.0035}S_{0.0066}$. This is an essential data to be used for the low fidelity analysis.

Table 1: Tire proximate and ultimate analysis

Composition	Tire
Proximate (Wt.%)	
<i>Moisture</i>	1.0
<i>Volatile Matter</i>	68.0
<i>Fixed Carbon</i>	23.2
<i>Ash (dry)</i>	8.8
Ultimate (Wt.%) (dry)	
<i>C</i>	73.8
<i>H</i>	6.8
<i>N</i>	0.3
<i>S</i>	1.3
<i>O</i>	9.0
<i>Ash</i>	8.8
HHV (MJ/kg)	36.0
MW (kg/kmole)	14.83
$CH_{1.1057}O_{0.0915}N_{0.0035}S_{0.0066}$	

III. LOW FIDELITY SYSTEM MODEL APPROACH AND ANTICIPATED PROCEEDS METRICS

Equation 1 below shows the overall stoichiometric reaction such that 1.231 mole of the oxidizer is required to completely burn off one unit mole of tire. This unit mole is inferred from the proximate analysis such that the tire elemental composition is described as moisture ash free, then each is converted into molar value and finally normalized on the basis of unit carbon mole.



Species											
C(g)	CH	CH ₂	CH ₃	CH ₄	C ₂ H ₂	C ₂ H ₄	C ₂ H ₆	C ₃ H ₈	H	H ₂	
O	O ₂	CO	CO ₂	OH	H ₂ O	H ₂ O ₂	HCO	HO ₂	N	N ₂	
NCO	NH	NH ₂	NH ₃	N ₂ O	NO	NO ₂	CN	HCN	HCNO	S(g)	
S ₂ (g)	SO	SO ₂	SO ₃	COS	CS	CS ₂	HS	H ₂ S	C(s)	S(s)	

Equation 2 shows nearly a comprehensive list of the possible gasification product and hence Gibbs energy minimization is utilized to determine their molar fraction [12]. Nevertheless, the details of the gasification process is very complex inside the reactor with chemically intrinsic, unsteady flow of multiple-phase, highly turbulent, and multiple species of chemically reacting flow. Despite this, the process can be steered under equilibrium steady conditions given that the process is operating at high temperature, utilizing small feedstock particle size (few tens of micron), and with short but sufficient residence time. These conditions are only operable within the entrained flow gasifier technology. It should be noted that both of N and S traces are ignored from the unit molar formula of the tire as they have negligible influence on the conversion process metrics. Also 0.9 moles of water steam is utilized to moderate the gasifier temperature and enhance the production of hydrogen. This addition is recommended by previous work of the author and his coworkers to reach to optimal metrics at reasonable and practical temperature.

Results of the main species under H₂O moderation are shown in figure 1. The process efficiency also is computed which represents the sum of heating values of the product syngas (CO, H₂ and CH₄) each multiplies by its stoichiometric coefficient divided by the heating value of the tire unit mole. This is written as:

$$GE = \frac{a(283800)+b(283237.12)+c(889000)}{HHV_{feedstock}} \quad (3)$$

Where a, b and c are mole fractions of hydrogen, carbon monoxide and methane, respectively. A gasification efficiency of 77.14 at 1,136k was obtained. The high efficiency is mainly due to the consideration of an insulation system with zero heat loss. Generally speaking the sensible heat from the product as well as the process is used within the IGCC plant for cogeneration or simply for preheating the feedstock.

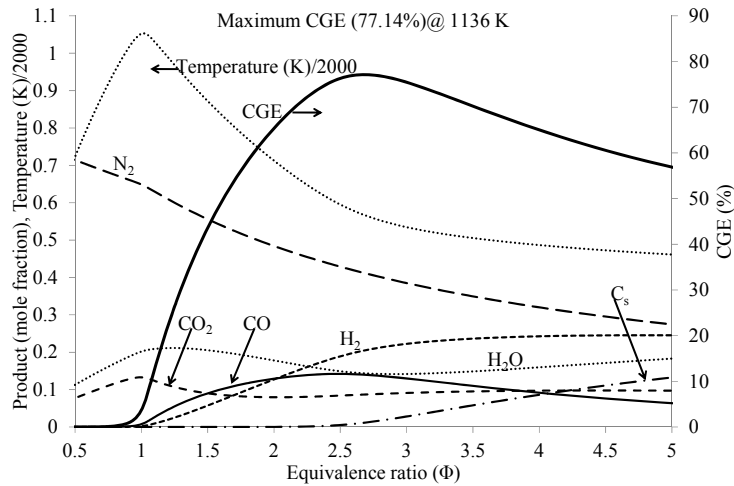


Fig. 1: Results of tire gasification following equilibrium based model

IV. HIGH FIDELITY REACTIVE CFD FLOW ANALYSIS

The downdraft gasifier is modeled using the finite volume code coupled with a conjugate heat transfer with the bulk metal separators and insulation. The computation is carried out on a two dimensional axi-symmetric geometry of the gasifier. The segregated implicit solver was used to solve the transport equations. The flow is assumed to be two dimensional axi-symmetric with steady state. No-slip boundary condition is applies on reactor walls and separator/insulation bulk material.

The particles modeled have a uniform distribution and are spherical in shape but with a much smaller size. Second order discretization scheme was implemented for all calculated variables. The SIMPLE algorithm is used for velocity – pressure coupling. Turbulence is modeled by the $k - \epsilon$ with standard wall function. An axi-symmetric model is built for the downdraft gasifier with the dimensions and generated mesh displayed in figure 2. It is fitted with a baseline structural multi-blocking mesh consisting of 53,155 rectangular cells. Refinement near the air nozzle outlet and in the combustion and reduction zones at the gasifier bell was emphasized to allow for better capturing of the steep flow gradients in these highly turbulent regions.

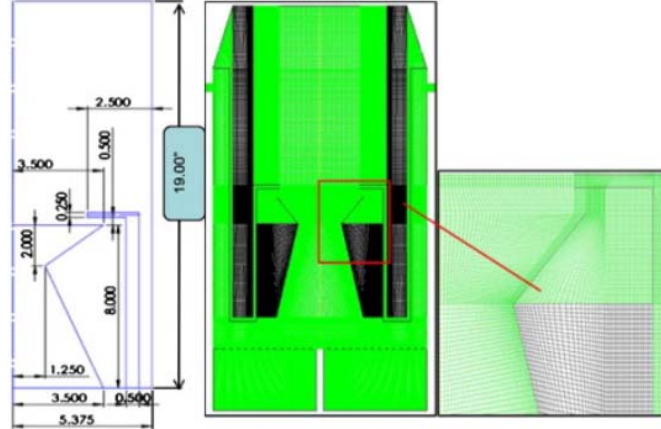


Fig. 2: Model dimensions and the grid generation

V. GOVERNING EQUATIONS

A reactive Navier-Stokes flow is pursued in the following analysis. Due to the presence of the solid feedstock, two phase flow comprises of the Lagrangian/discrete solid and the Eulerian/continuous fluid. The discrete flow formulation is best suited to model the incoming solid feedstock particles while the continuous flow formulation governs all gaseous species including incoming oxidizer, moderator and all other transported species. This formulation accounts for multiple reacting species both homogeneously (volume reaction) and heterogeneous (surface reaction) reaction. The continuous phase is governed by the following equation:

$$\frac{\partial}{\partial t}(\phi) + \frac{\partial}{\partial x_i}(u_i \phi) = - \frac{\partial}{\partial x_i} \left(\Gamma_\phi \frac{\partial \phi}{\partial x_i} \right) + S_\phi \quad (3)$$

Time rate advective diffusion source

where ρ is the density and S_ϕ is the source terms due to the dispersed/discrete phase interaction. ϕ is the dependent variable corresponding to density (ρ), the density velocity multiple (ρ, u_i), and the temperature (T), representing the conservation of mass, momentum, and energy, respectively. It also represents turbulent scalars, i.e. turbulent kinetic energy (k) and turbulent dissipation rate (ϵ). Similarly, the transportation of species m_i is written as:

$$\frac{\partial}{\partial t}(\rho m_i) + \frac{\partial}{\partial x_i}(\rho u_i m_i) = \frac{\partial}{\partial x_i}(\rho D_{i,m} + \mu_t / Sc_t) \frac{\partial m_i}{\partial x_i} + R_i + S_i \quad (4)$$

where $D_{i,m}$ is the diffusion coefficient. Sc_t is the turbulent Schmidt number which is a ratio of the eddy viscosity μ_t to the eddy diffusivity $D_{i,m}$. These transport equations incorporate a homogenous reaction source term R_i in addition to the discrete phase interaction source S_i .

The R_i term is governed by the stoichiometric reaction below for all the reaction listed in table 2:



Because of the wide gap between the gas-phase and the solid particle reactions in terms of their kinetics, the finite rate/eddy dissipation is used to model the interaction between the chemistry and turbulence so that chemically controlled and eddy (mixing) controlled reactions are accurately modeled. Global reactions representing CO combustion, H₂ combustion, and water-gas shift are considered. A multiple surface reactions model is used to model the wood particles combustion and gasification reactions. These reactions involved char combustion and reduction of CO₂, H₂, and H₂O.

Table 1: Reaction mechanism

Reaction (#)	Stoichiometry of the reaction	Reference
R1	$2 CO + O_2 \rightarrow 2 CO_2$	[17, 18]
R2	$2 H_2 + O_2 \rightarrow 2 H_2O$	[17, 18]
R3	$CO + H_2O \leftrightarrow CO_2 + H_2$	[18]
R4	$C_{(s)} + O_2 \rightarrow CO_2$	[18]
R5	$C_{(s)} + CO_2 \rightarrow 2 CO$	[18]
R6	$C_{(s)} + 2 H_2 \rightarrow CH_4$	[18]
R7	$C_{(s)} + H_2O \rightarrow CO + H_2$	[18]
R8	$vol + 0.4 O_2 \rightarrow 1.317 CO + 2.09 H_2 + 0.064 N_2$	[19]

Coupling of momentum, heat, and mass transfer between the solid and gas phases is accounted for by the two-way coupling Cloud model in [19]. In this model the Lagrangian-based particle trajectory is tracked as a cloud of particles about a mean trajectory. The mean trajectory is then calculated by solving the ensemble-averaged equations of motion for all particles represented by the cloud. The i^{th} species production/destruction due to the reaction r follows either:

1) The instantaneous eddy-dissipation model that assumes the chemical reaction proceeds as the reactants meet and is faster than the time scale of the turbulence eddies and is expressed as:

$$R_{i,r} = \nu'_{i,r} M_i A \rho \frac{\epsilon}{\kappa} \min_R (Y_R / \nu_{R,r} M_R) \quad (6)$$

where A is constant and Y is the mass fraction of reaction specie.

2) or the finite rate model written as:

$$\hat{R}_{i,r} = \Gamma(\nu''_{i,r} - \nu'_{i,r}) \left(k_f \prod_{j=1}^N C_{j,r}^{\nu_{j,r}^*} - k_b \prod_{j=1}^N C_{j,r}^{\nu_{j,r}^*} \right) \quad (7)$$

$$\text{and } R_i = M_i \sum_{r=1}^n \hat{R}_{i,r}$$

Where Γ is the net effect of third bodies on the reaction rate, k here is the Arrhenius reaction constant, $[C]_j$ is the molar concentration of j^{th} specie raised to stoichiometric coefficients ν and reaction order η , and M_j is the molecular weight of species i . When the solid char particle and the oxidizer react they form either CO or CO₂. Hence additional heterogeneous (or surface) reaction for the discrete particles occurs and is expressed as:

$$\bar{R}_{i,r} = A \eta_r Y_r R_{j,r} \quad (8)$$

$$\text{with } R_{i,r} = K_{kin,rc} [p_j - R_{i,r} / D_{o,r}]^{Nr}$$

where A here is the particle surface area, η is the effective factor, Y_i is the mass fraction of species i , R is the rate of reaction, k is the kinetic rate of reaction, and p is the bulk partial pressure of the species i , D is the diffusion rate coefficient for reaction r and N is apparent order of the reaction r .

The discrete solid particle phase is solved in a Lagrangian frame of reference. This phase consists of spherical particles of 1 cm diameter dispersed in the continuous phase. Their trajectory is predicted by integrating the force balance on the particle. This force balance equates the particle inertia with the forces acting on the particle and can be described as:

$$\frac{d\vec{u}_p}{dt} = F_D(\vec{u} - \vec{u}_p) + \vec{g}(\rho_p - \rho)/\rho_p \quad (9)$$

where $F_D(u - u_p)$ is the drag force per unit particle mass; u is the fluid phase velocity; u_p is the particle velocity; ρ is the fluid density, and ρ_p is the density of the particle. The trajectory equations are solved by stepwise integration over discrete time steps. Integration of Eq. (9) yields the velocity of the particle at each point along the trajectory, with the trajectory itself predicted by

$$\frac{dx}{dt} = u_p \quad (10)$$

Equations similar to (9) and (10) are solved for each coordinate direction to predict the trajectories of the discrete phase. The trajectories of the discrete phase particles are computed as well as the heat and mass transfer to and from them. Solid particles are subjected to stepwise conversion laws. Inert heating law is applied while the particle temperature is less than the vaporization temperature. Devolatilization law is applied to the combusting particle mass (m_p) when the temperature of the particle reaches the vaporization temperature, T_{vap} . It is written as:

$$-\frac{dm_p}{dt} = Ae^{-(E/RT)}[m_p - (1 - f_v^0)m_p^0] \quad (11)$$

Where f_v and m_p^0 are the volatile fraction and initial mass, respectively. It remains in effect while the mass of the particle, m_p , exceeds the mass of the non-volatiles in the particle. The heat transfer to the particle during devolatilization process governs the contributions from convection, radiation, and the heat consumed during devolatilization. It is written as:

$$m_p c_p \frac{dT_p}{dt} = hA_p(T_\infty - T_p) + \frac{dm_p}{dt} h_{fg} + \epsilon_p A_p \sigma (T_R^4 - T_p^4) \quad (12)$$

where c_p , h_{fg} , A , and σ are specific heat, latent heat of evaporation, particle surface area and Stefan constant, respectively. After the volatile component of the particle is completely evolved, a surface reaction begins, which consumes the combustible fraction of the particle until the combustible fraction is consumed. Heat, momentum, and mass transfer between the solid fuel particles and the gas will be included by alternately computing the discrete phase trajectories and the continuous phase equations

VI. FLOW CONDITIONS

The study is performed to simulate the conversion behavior of tire crumbs into syngas using the stoichiometry of a tire for an ideal gasification process in which the tire particles are completely converted into syngas without forming CO_2 , H_2O and without any other energy losses. The chemical equation of such case is given as under,



The first term on left hand side of the above equation represents the unit molar formula of the tire crumbs. It is calculated using the ultimate analysis presented in **Error! Reference source not found.**, for single tire atom. The number of mole of oxygen is calculated for only CO on the product side instead of CO_2 . Ideally, for any operating condition of gasifier if the above calculated amount of O_2 is injected, it should result only in CO and H_2 . But due to the contribution physical and chemical properties of tire and air this desired ideal condition is not guaranteed. The overall gasification process is a highly exothermic process due to the formation of CO_2 and conversion of hydrogen present in the tire into vapors (H_2O). The formation of both CO_2 and H_2O is desirable and at the same time inevitable. The decomposition of tire into volatile and char required a large sum of energy that cannot be achieved if only ideal gasification cycle is considered. Therefore, the conversion of some char into CO_2 is necessary to provide the energy to overall gasification system, similarly it holds for the conversion of H_2 into H_2O . The inlet condition for tire and air is given in

Table 2 for the stoichiometric condition that is chosen as the base line case.

Table 2: Inlet condition of gasifier

Tire inlet condition	
Inlet temperature (K)	300
Inlet velocity (m/s)	1.70E-04
Diameter (mm)	0.1
Air inlet condition	
Inlet temperature (K)	300
Inlet velocity (m/s)	0.195

VII. RESULTS AND DISCUSSION

The CFD simulations are performed according to the stoichiometric conditions presented in

Table 2. The parametric study is performed taking 0.195 m/s as the baseline velocity of the air Fig. 1 shows the temperature inside the gasifier for the baseline condition of velocity. Two points are emphasis for the primary importance from the counters of Fig. 1. First, the heat of the syngas leaving the gasifier is transferred to the inlet air duct through conduction, which eventually raise the temperature of the air. Secondly, As soon as the air injected throught the inlet nozzle it starts reacting with the tire particles falling down from the gasifier auger on the top. The maximum temperature inside the gasifier reaches around 2,500°K and the outlet temperature of the syngas is 1,120°K. The gasification effecinecy in the basis of syngas production is 63% at the optimal velocity. As this value is lower than than the systematic analysis it is attributed to fomation of other reaction components such as CO₂ and H₂O instead of CO and H₂.

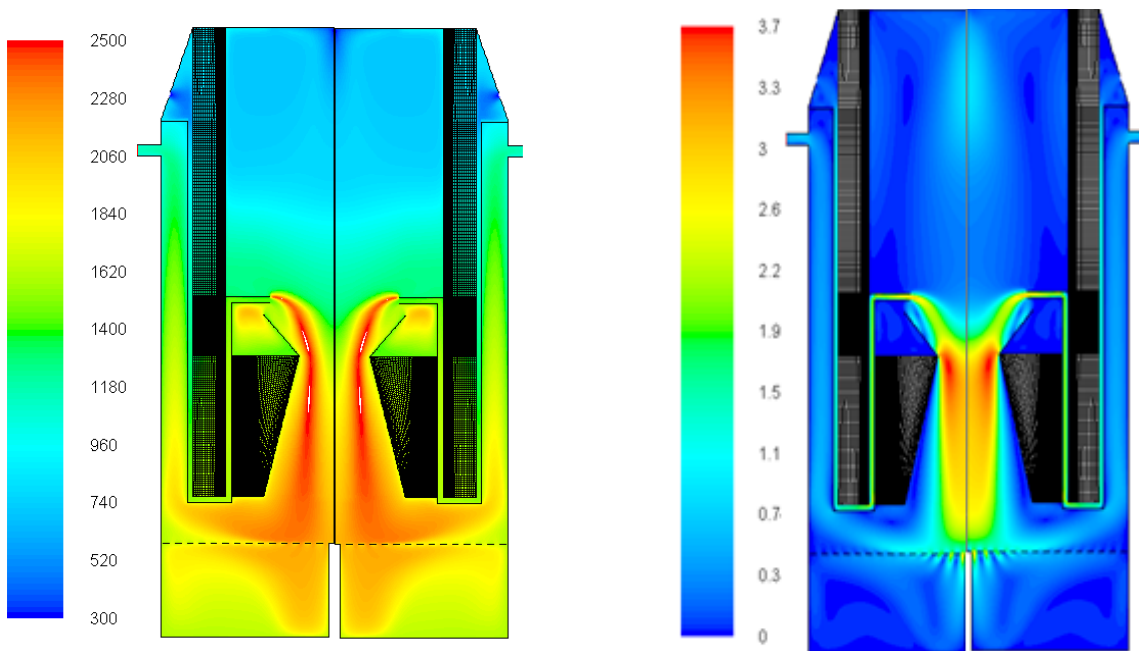


Fig. 1: Temperature (K) and velocity (m/s) distribution inside the gasifier

Similarly, Figure 2 shows the velocity distribution inside the gasifier for the baseline case. The overall velocity inside the gasifier is low and the higher velocities are only present near the air inlet going toward the syngas outlet due to pressure gradient. This high velocity area is also the high temperature zone. This area can be concluded as the reaction zone where all the chemical reactions, as defined in **Error! Reference source not found.**, are taking place. The total path of the flow in this area represents the actual resident time of the reactants and product in the gasifier. Any increase and decrease in the velocity of the incoming air can eventually effect the resident time proportionally. The the distribution of mole fraction of CO and H₂ are also shown in Figure 2.

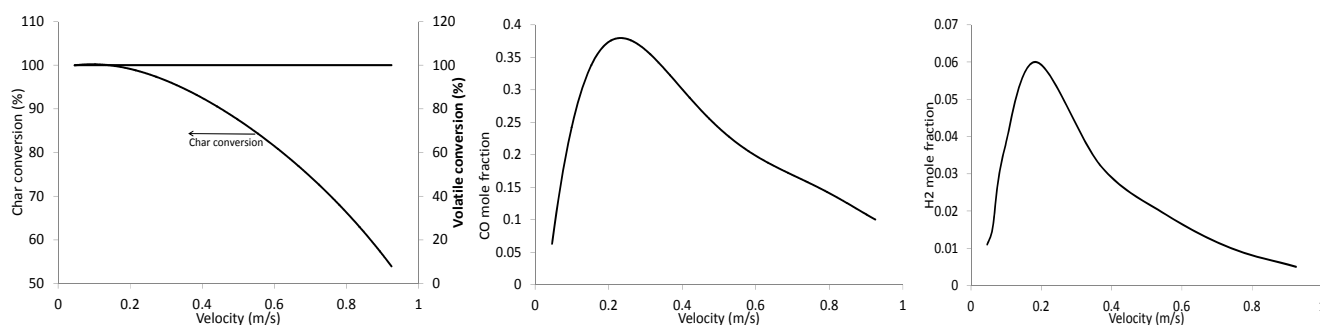


Fig. 3: Conversion of the char, volatile, CO and H₂ correspond to different velocity under same stoichiometric

Figure 3 also shows the effect of inlet air velocity on the mole fraction of devolatilization, char conversion and CO and H₂ molar fraction. Both figures show the maximum mole fraction of CO and H₂ corresponds to the inlet velocity magnitude of 0.195 m/s. At lower velocity the char present in the tire is converted into CO₂ and hydrogen into H₂O. Figure 3 shows the 100% of char and volatile conversion at lower velocities that directly support the claim of the formation of CO₂ and H₂O. It is due to high resident time and temperature inside the reaction that CO and H₂ is converted into CO₂ and H₂O respectively. The result presented in this research shows the similar kind of trend that is given in the literature [16-18]. It is due to the fact the change in the velocity of the inlet air directly affect the resident time of the reactants and products in the gasifier. The residence time directly affect the heat transfer amount the species with eventually give rise to the reaction rates based on Arrhenius equation.

VIII. CONCLUSION

Two levels of thermoconversion of tire waste were carried out. Starting from the proximate and ultimate analysis of the feedstock, the molar unit formal of the tire crumbs was determined. This followed with stoichiometric equilibrium analysis that based on Gibbs energy minimization of nearly 44 species. Results of the air tire gasification lead to considerable high efficiency of 77.14% and at near 1,134°K. The low temperature is due to the addition the steam moderator to seek optimal condition at more practice temperature. High fidelity analysis also carried out inside a small size down draft gasifier. Parametric study of gasification process is performed at various inlet velocity of the oxidizer (air). The idea behind varying velocity is to establish the understanding of the behavior of tire conversion and effect on syngas production when the coal resident time is changed inside the gasifier. The result of CFD study shows that 100% conversion of tire is achieved at low velocity. Tire conversion is defined by both char and volatiles conversion. The result shows that a complete conversion of the volatile fraction is achieved at all velocity values. It is attributed to the high reaction zone temperature that is fairly higher than the devolatilization temperature of tire. On the other hand the conversion of char is highly depending upon the resident time of the feedstock particle inside the gasifier. At lower velocity the char conversion is fully achieved, however as the velocity increase the char conversion commence to decrease. It is also noticed that higher resident time favors the production of CO₂ and H₂O instead of CO and H₂. The optimum value of syngas is achieved at the inlet velocity of 0.195 m/s and any increase of velocity further decrease the quality of syngas. At this condition the achieved gasification effecinecy is 63%, this inferior value compared to the systematic analysis is due to the tendency of CO₂ and H₂O formation rather than syngas by the process reaction and in part to the effect of the surface boundary condition.

References:

- [1] DOE, Gasification World Database 2007 (Current Industry Status Report)", Office of Fossil Energy National Energy Technology Laboratory (NETL) 2007.
- [2] Abuadala, A., I. Dincer, and G. Naterer, Exergy analysis of hydrogen production from biomass gasification. International Journal of Hydrogen Energy, 2010. 35(10): p. 4981-4990.
- [3] Walawender, W., D. Hoveland, and L. Fan, Steam gasification of pure cellulose. 1. Uniform temperature profile. Industrial & Engineering Chemistry Process Design and Development, 1985. 24(3): p. 813-817.
- [4] Hsi C, Wang T, Tsai C, Chang C, Liu C, Chang Y, et al. Characteristics of an air-blown fixed-bed downdraft biomass gasifier. Energy Fuels 2008;22(6): 4196–205.
- [5] Zainal ZA, Rifau A, Quadir GA, Seetharamu KN. Experimental investigation of a downdraft biomass gasifier. Biomass Bioenergy 2002;23(4):283–9.
- [6] Kumar R, Kolar A, Leckner B. Effect of fuel particle shape and size on devolatilization time of Casuarina wood; 2004.
- [7] Blasi CD. Dynamic behaviour of stratified downdraft gasifiers. Chem Eng Sci 2000;55(15):2931–44.

- [8] Dogru M, Howarth CR, Akay G, Keskinler B, Malik AA. Gasification of hazelnut shells in a downdraft gasifier. *Energy* 2002;27(5):415–27.
- [9] McKendry P. Review paper: energy production from biomass (part 3): gasification technologies. *Bioresource Technol* 2002;83:55–63.
- [10] Syed Shabbar, Isam Janajreh, Thermodynamic equilibrium analysis of coal gasification using Gibbs energy minimization method, *Energy Conversion and Management*, Volume 65, January 2013, Pages 755-763,
- [11] Syed Shabbar, Isam Janajreh, and Chaouki Ghenai. "Thermodynamics Equilibrium Analysis within the Entrained Flow Gasifier Environment." *Int. J. of Thermal & Environmental Engineering* 4, no. 1 (2012): 47-54.
- [12] Isam Janajreh, Syed Shabbar, Rana Qudaih, Ilham Talab, (2010). Solar Assisted Gasification: Systematic Analysis and Numerical Simulation. *Int. J. of Thermal & Environmental Engineering*, 1(2), 81-90.
- [13] Syed, Shabbar, et al. "Kinetics of pyrolysis and combustion of oil shale sample from thermogravimetric data." *Fuel* 90.4 (2011): 1631-1637.
- [14] Janajreh, Isam, Syed Shabbar Raza, and Arnar Snaer Valmundsson. "Plasma gasification process: Modeling, simulation and comparison with conventional air gasification." *Energy Conversion and Management* (2012).
- [15] Janajreh, I., and M. Al Shrah. "Numerical and experimental investigation of downdraft gasification of wood chips." *Energy Conversion and Management* (2012).
- [16] Silaen, A. and T. Wang, Effect of turbulence and devolatilization models on coal gasification simulation in an entrained-flow gasifier. *International Journal of Heat and Mass Transfer*, 2010. 53(9): p. 2074-2091.
- [17] Hernández, J.J., G. Aranda-Almansa, and A. Bula, Gasification of biomass wastes in an entrained flow gasifier: Effect of the particle size and the residence time. *Fuel Processing Technology*, 2010. 91(6): p. 681-692.
- [18] Tremel, A., et al., Experimental investigation of high temperature and high pressure coal gasification. *Applied Energy*, 2012. 92: p. 279-285.