Gasification And Combustion Of Waste Tires For Process Heat And Power Generation

Peter Mtui

ABSTRACT: Numerical modeling technique based on computational fluid dynamics (CFD) has been used to study the gasification and combustion of chipped scrape tire in a two-stage system for recycling scrape tire for heat recovery. Effect of equivalence ratio on the syngas composition and combustion behavior was investigated. Results indicated that it is possible to recover energy from recycled waste tire through this two-stage system. Optimal gasification of chipped tires was achieved in the primary chamber at equivalence ratio around 0.3 in which the average syngas composition constituted of 0.22 and 0.17 for of CO and H2, respectively. Further, the high velocity staged air injection to the secondary chamber created "turbulent jet mixing" effect thereby uniform temperature distribution is achieved and is contained in the upper half of the secondary chamber. The uniform temperature distribution and the increased wall heat flux at optimal equivalence ratio, clearly indicates better heating rate of the water tubes located in the secondary chamber for steam generation. This study contributes additional understanding of the complex phenomena occurring in a two-stage gasification and combustion system of scrape tires in addressing the environmental challenge of recycling scrap tires.

Keywords: CFD, modeling, reactor, turbulence, modeling, scrap tire, gasification, combustion

————————————————◆————————————————

1. INTRODUCTION

The disposal of plastic solid waste such as scrap tires has become a major environmental challenge worldwide. Traditionally, these non-biodegradable wastes have been dumped off through land-filling, consequently remain a lasting environmental burden. For example, the USA, Europe and Japan together generate about 55 million tons of post consumer plastic waste [1]. In recent years, thermal treatment techniques such as pyrolysis and gasification have gained an increased interest particularly to recover energy from the wastes. Gasification and combustion of large fuel particles furnaces is limited in the literature. Therefore, systematic investigation of chipped waste tires as fuel for steam generation furnaces is of interest. Understanding the phenomena in furnaces by experiments is not a trivial task because of complex heat, mass transfer and chemical reaction mechanism during the process. The purpose of this work is therefore to study the gasification and combustion of scrap on the particles transport and heat and mass transfer within the furnace which was carried out using computational fluid dynamics modeling. Gasification of carboneous materials such as coal and biomass have been extensively studied and reported elsewhere in literature. Gasification is commonly operated at high temperatures (600° C to 800°C) in an oxygen-deficient environment, generally between 20% and 40% of oxygen that would have been required for combustion. The product of gasification is syngas, is mainly composed of CO and H2. During gasification process, devolatilization takes place prior to gasification.

Larsen and Schultz [11] studied devolatilization of rubber and reported that the devolatilization times of cylindrical tire rubber particles with diameters from 7 to 22 mm at 840 °C in an inert atmosphere is 30−100 sec. Further, Chinyama and Lockwood [4] reported that devolatilization time of large tire particles increases with increasing particle size and decrease with increasing temperature. Previous work [1] about the combustion of char from pyrolysis of tire has been made with a few mg of tire char particles in the 100−500 μm size in thermogravimetric analyzers (TGA). Char conversion times are reported to be well below 1 s in air and at 1200 °C for tire char with particle size of around 500 micrometer [1]

2. MATERIALS AND METHOD

The geometry shown in Figure 1 represents a two-stage prototype equipment for the gasification and combustion of scrap tires at a rate of 1 ton/hr. Chipped tires are fed into cylindrical gasification chamber where limited amount of primary air is introduced. The syngas produced in the gasification chamber is directed into the vertical secondary combustion chamber (furnace) and mixed with excess air from secondary and tertiary air supply through high velocity air nozzles. The high air velocity creates turbulent mixing so that the syngas and char undergo combustion in the vertical secondary combustion chamber. The secondary chamber contains a bundle of water tubes heated for steam generation. The exhaust flue gases are discharged out through the down-comer for stack cleaning. Scrap tire materials fed to the primary chamber have similar properties of proximate and ultimate analyses as reported by reported by Juma [10] and shown in Table 1.

_____

- Peter Mtui
- College of Engineering and Technology, University of Dar es Salaam, P. O. Box 35131, Dar es Salaam, Tanzania, Email: plmtui@yahoo.com
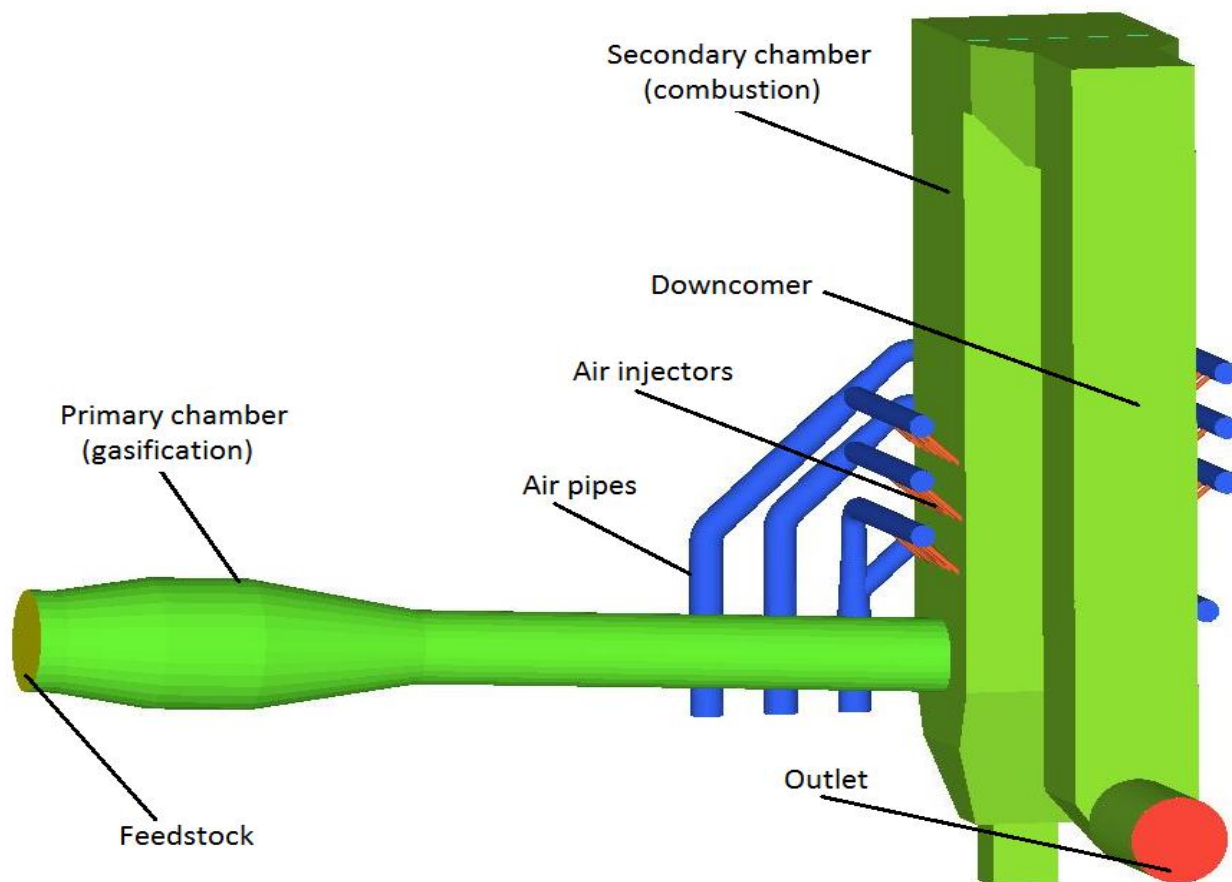
Figure 1: Scrap tire gasification and combustion system

Table 1: Scrap tire fuels data [10]

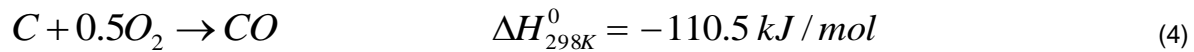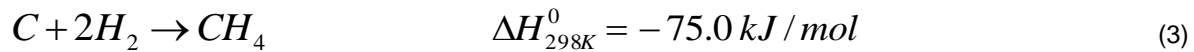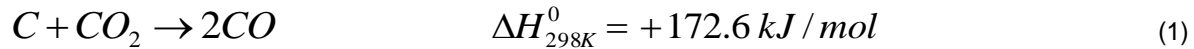| Proximate analysis (dry basis)	Scrap tire
Fixed carbon (%wt)	22.66
Volatiles (%wt)	61.61
Moisture (%wt)	1.72
Ash (%wt)	14.01
LHV (MJ/kg)	34.2
Proximate analysis (dry basis)	
C	81.24
H	7.36
O	8.92
N	0.3
S	2.18

2.1 The Model
This section seeks to develop mathematical models for devolatilization and char oxidation and combustion of carboneous fuels. The models account for the thermochemical processes of the reactive flow in the gasification and combustion of waste tire system.

2.2 Chemical Kinetics and Equilibrium
This section seeks to develop mathematical models for devolatilization and char oxidation of carboneous fuels. The models account for the thermochemical processes of the reactive flow in the gasification and combustion of waste tire system. Modeling of gasification involves the evolution of volatile, gasification and char particles burnout, and coupling the homogeneous chemistry occurring in the gas phase also the heterogeneous in the solid phase. The whole process is the most challenging aspects of calculations of reactive flows, particularly when turbulent. The four commonly sited char reactions [8] and other six gaseous phase reactions that are represented as follows.

Heterogeneous reactions

$$C + CO_2 \rightarrow 2CO \qquad \Delta H^0_{298K} = +172.6 \, kJ/mol \tag{1}$$

$$C + H_2O \rightarrow CO + H_2 \qquad \Delta H^0_{298K} = +131.4 \, kJ/mol \tag{2}$$

$$C + 2H_2 \rightarrow CH_4 \qquad \Delta H^0_{298K} = -75.0 \, kJ/mol \tag{3}$$

$$C + 0.5O_2 \rightarrow CO \qquad \Delta H^0_{298K} = -110.5 \, kJ/mol \tag{4}$$

Homogeneous reactions

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad \Delta H^0_{298K} = +206.4 \, kJ/mol \tag{5}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad \Delta H^0_{298K} = -41.7 \, kJ/mol \tag{6}$$

$$CH_4 + 2O_2 \leftrightarrow CO_2 + H_2O \qquad \Delta H^0_{298K} = -802.3 \, kJ/mol \tag{7}$$

$$CO + 0.5O_2 \rightarrow CO_2 \qquad \Delta H^0_{298K} = -283.0 \, kJ/mol \tag{8}$$

$$H_2 + O_2 \rightarrow H_2O \qquad \Delta H^0_{298K} = -241.8 \, kJ/mol \tag{9}$$
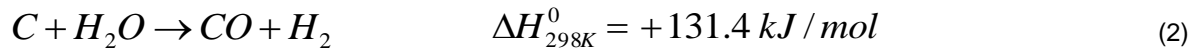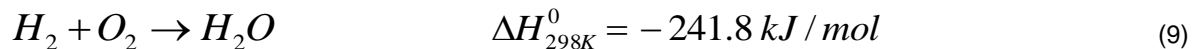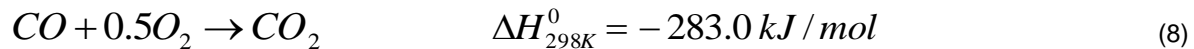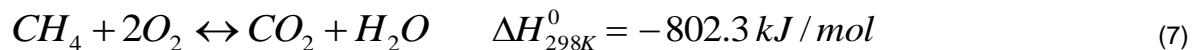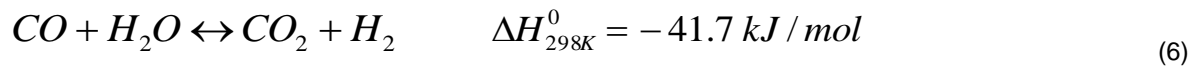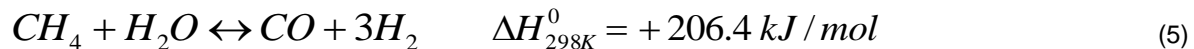
For the above equations, the rate of production of species due to chemical reaction can be written as a function of molar concentration of the species using the law of mass-action as follows [5].

$$\sum_{j=1}^{N} v'_{ji}[X]_j \Leftrightarrow \sum_{j=1}^{N} v''_{ji}[X]_j \tag{10}$$

where v'_{ji} and v''_{ji} are the stoichiometric coefficients for the reactants and products, respectively, for the jth species in the reaction i^{th} equation. The square bracket [ ] represents molar concentration of species j^{th}. The net production rate of each species in a multi-step mechanism is given as:

$$R_i = \left(v''_{ji} - v'_{ji}\right)\left(k_{fi} \prod_{j=1}^{N}[X_j]^{v'_{ji}} - k_{bi} \prod_{j=1}^{N}[X_j]^{v''_{ji}} \right) \tag{11}$$

where k_{fi} and k_{bi} are rate constants for forward and backward the ith reaction that involve species j^{th}. The term R_i becomes a source term in transport equation for the conservation of species in equation (16). Under equilibrium conditions, the above equations can be generalized to reversible reactions associated with equilibrium equation in terms of either their molar concentration or partial pressure as follow:

$$K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b} \text{ or } K_p = \frac{p_C^c p_D^d}{p_A^a p_B^b} \tag{12}$$

and $\quad K_c = K_p (RT)^{c+d-a-b}$

The superscripts are the forward and backward stoichiometric coefficients, i.e. $v'_i = a, b, ...$ and $v''_i = c, d, ...$, respectively.

and $\quad \dfrac{k_f}{k_b} = K_c$

where $[X]$ represents molar concentration of species X while and the rate parameter K_c is expressed in Arrhenius form as:

$$k_c(T) = e^{-\frac{\Delta G^0}{RT}}$$

(13)

where ΔG^0 is the change in Gibbs free energy.

$$k_c(T) = A * T^\alpha \exp(E/RT)$$

where A is the pre-exponent constant, α is temperature exponent, E is the activation energy, T is temperature and R is the universal gas constant. The value of equilibrium constant k_c is evaluated at constant temperature and pressure using the standard state Gibbs energy of change [12].

2.3 Char Combustion Model

Surface char combustion is accounted for using the kinetic/diffusion reaction rate model which assumes that the surface reaction rate is determined either by kinetics or a diffusion rate. In this work, the model of Braum et al [3] and Field [4] is used such that the diffusion rate,

$$R_1 = C_1 \frac{\left(\frac{(T_P + T_\infty)}{2}\right)^{3/4}}{D_p}$$

(14)

and the kinetic rate

$$R_2 = C_2 \exp(-E/RT_p)$$

(15)

$$\frac{dm_p}{dt} = \pi D_p^2 P_0 \frac{R_1 R_2}{R_1 + R_2}$$

(16)

where P_0 is the partial pressure of oxidant species in the gas surrounding the combusting particle and the kinetic rate R_2 incorporates the effects of chemical reaction on the internal surface of the char particle and pore diffusion. The particle size is assumed to remain constant in this model while the density is allowed to decrease.

2.3 Transport Equations

Modeling of gasification involves the application of conservation laws, and accounting for volatile evolution, char particles burnout, and coupling the flow field with the homogeneous chemistry occurring in the gas phase as well as the heterogeneous in the solid phase. Transport equation for each species is solved numerically with control volume method. Char is treated as discrete particle and solved by Lagrangian model while the continuous phase was solved by Eulerian model and the standard k-ε model is utilized for turbulence generation and description. The trajectory of particles (solid phase) are tracked from continuous phase. The three-dimensional conservation equations of mass, momentum, energy and species can generally be written in the integral form shown in equation (17). These equations are discretized in control volumes and solved iteratively using CFD technique.

$$\int_{CV} \frac{\partial(\rho\varphi)}{\partial t}dV + \int_{CV} div\,(\rho\varphi u)\,dV = \int_{CV} div\,(\Gamma\,grad\,\varphi)\,dV + \int_{CV} S_{\varphi}\,dV \qquad (17)$$

where φ is a general variable such as velocity components, temperature, mass fraction, etc. ρ is the fluid density, and u is the fluid velocity vector. The variable Γ_{φ} represents the transport coefficient and S_{φ} is a source term. These equations are discretized and solved iteratively so that the CFD technique enforces the conservation of mass, momentum, energy and species concentrations over the entire computational domain. The computational procedure includes setting the boundary conditions. Each inflow boundary is fully specified by the mass flow rate and the corresponding ambient temperature. The gasifier outlet was modeled as pressure outlet boundary. Wall boundaries are specified appropriately. The transient solution was initialized and the model was run to convergence [7]

3. RESULTS AND DISCUSSIONS

This section provides discussions on the distribution of temperature and concentration of species in the primary and secondary chambers depicted in geometry shown in Figure 1. Illustrated in Figures 2 and 3 is the concentration of syngas (CO and H2) in the system. It is observed that most of the CO and H2 are generated in the horizontal chamber whose primary function is gasification of the chipped tires. The syngas is convected horizontally to the vertical chamber where is mixed with excess secondary air jets (Figure 4) so that turbulent combustion takes place in this secondary chamber. It is observed that all O2 is instantly consumed as it enters the secondary chamber. Figure 5 shows high combustion near uniform temperature occupying about half top of the secondary chamber. Temperature profile shown in Figure 6 illustrates the influence of equivalence ratio on the combustion characteristic in the secondary chamber. The trends illustrate consistent higher temperature near equivalence ratio of 0.3 and. The first temperature peak shown at about 1 meter along the height of the secondary chamber coincides with the lower level of combustion air intake to the secondary chamber. The second temperature peak at 2 meter high coincides with the upper level of tertiary combustion air to the secondary chamber. For all values of equivalence ratio studied, it is seen that temperature is nearly uniform along the chamber heights from 2 to 5 meter high. This behavior is also reflected in Figure 5 where the top half of the secondary chamber is engulfed with near uniform temperature which provides heating of the steam tubes that are located in the secondary chamber. The axial concentration of CO and H2 in the primary chamber are respectively depicted in Figures 7 and 8. Results indicate that for all equivalence ratios, the concentrations of CO and H2 are nearly constant along the horizontal length of the primary. This trend of concentrations reflects the existence of uniform temperature in the primary chamber together with enough residence time for gasification to take place. Figure 9 depict mean concentrations of CO and H2 in the primary chamber. Both the concentrations of CO and H2 indicate similar trend with maximum values at equivalence

ratio near 0.3. The combustion performance results are shown in Figure 10 that depicts the wall heat flux that provides heating of water tubes in the secondary chamber for steam generation. Results indicate optimal heat flux corresponds with equivalence ratio near 0.3.

5. CONCLUSION

This paper shows a successful method of recycling crap tires for energy recovery through thermal gasification and combustion in a two-stage process. Computational results indicate that the temperature in the primary chamber is uniformly distributed and consequently the concentration (mol fraction) of sygas is nearly uniform along the radial and axial direction of the primary chamber. At optimal equivalence ratio, the corresponding average concentrations of CO and H2 are about 0.22 and 0.17, respectively. Further, the top half of the secondary chamber is found to be occupied with uniform temperature averaging 1950 K. This temperature uniformity may be attributed by the "jet-mixing" effect due to high velocity air inlet nozzle that creates turbulent mixing and combusting regime. The effect of equivalence ratio on the reactor operation was investigated, and the optimal value was found to be around 0.3. This optimal value coincides with maximum heat flux in the secondary chamber where the water tubes are located for steam generation. Although the results presented here look promising, further work may be required on experimental investigation in conjunction with additional CFD modeling to assist the equipment troubleshoot and optimize the design and process condition. In addition, it can be concluded that the use of different feedstock in the proposed two-stage gasification and combustion system is possible provided the process condition are matched with individual type of feedstock.
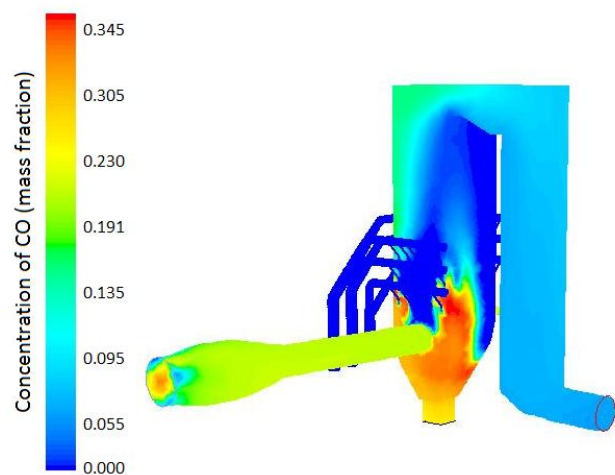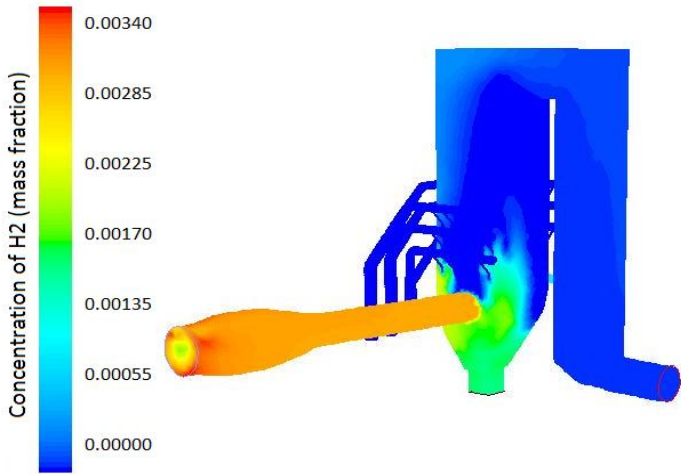

Figure 2: Concentration of CO
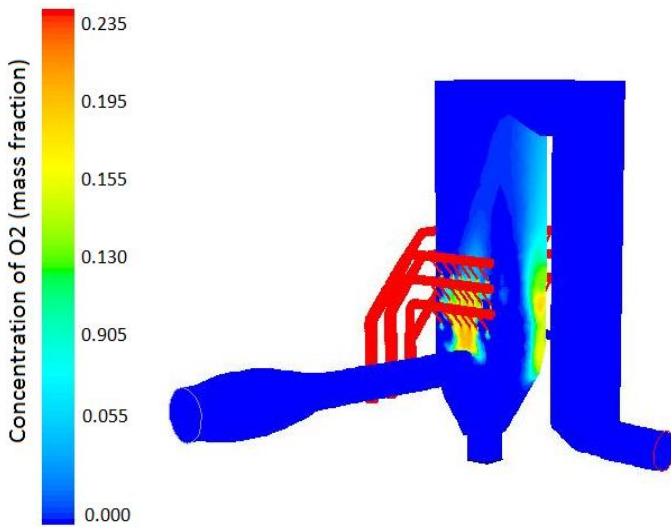
Figure 3: Concentration of H2

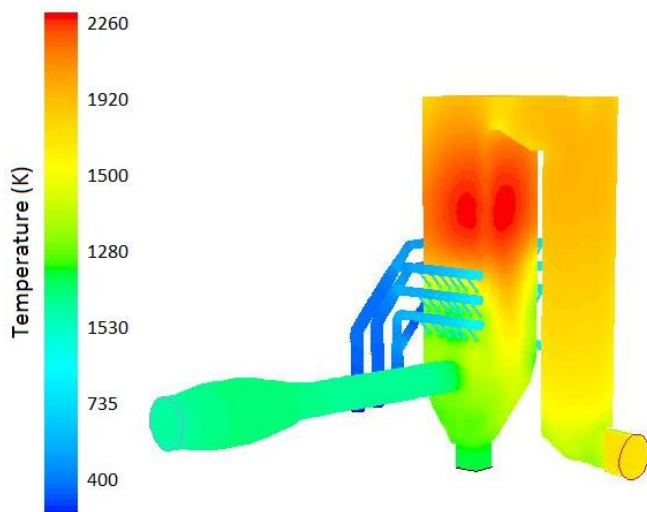**Figure 4: Concentration of O2**

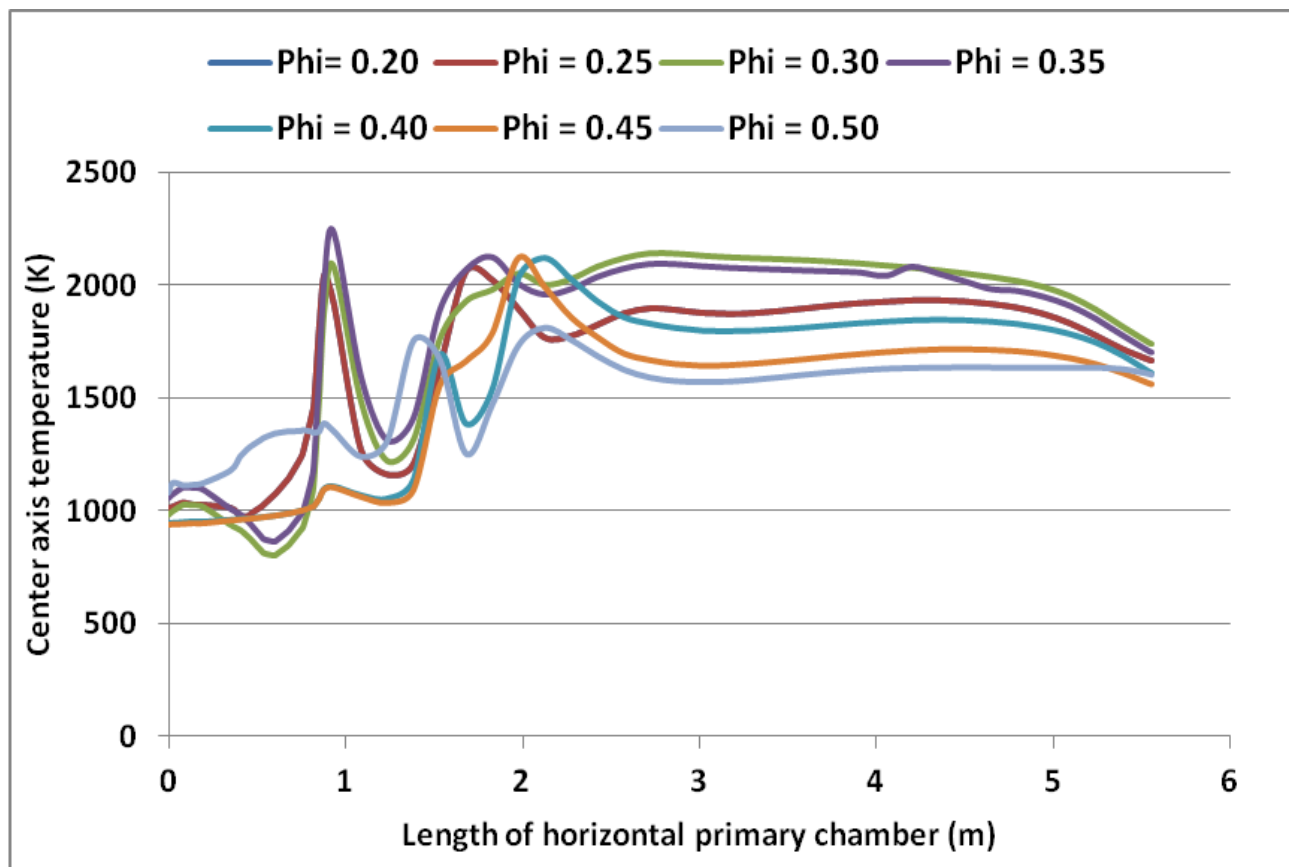**Figure 5: Temperature distribution**

Figure 6: Temperature profile along the vertical centerline of the secondary chamber
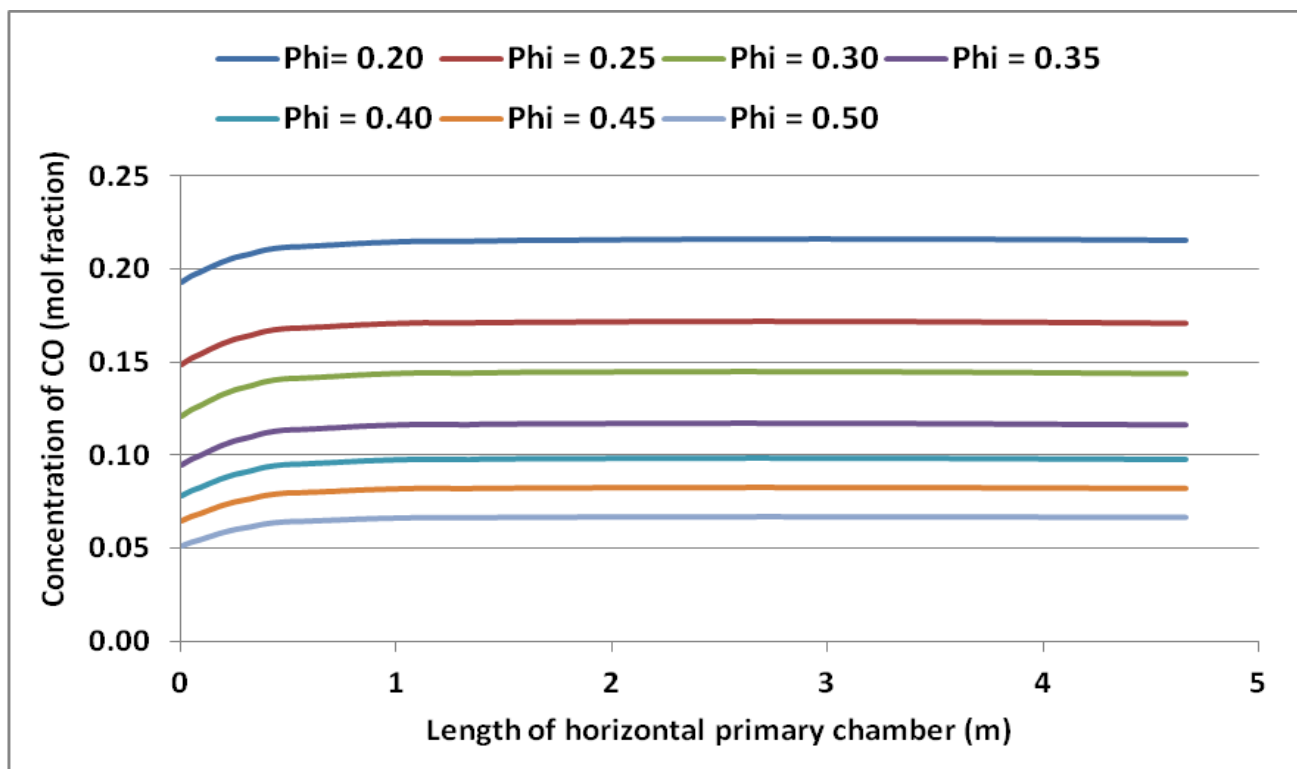

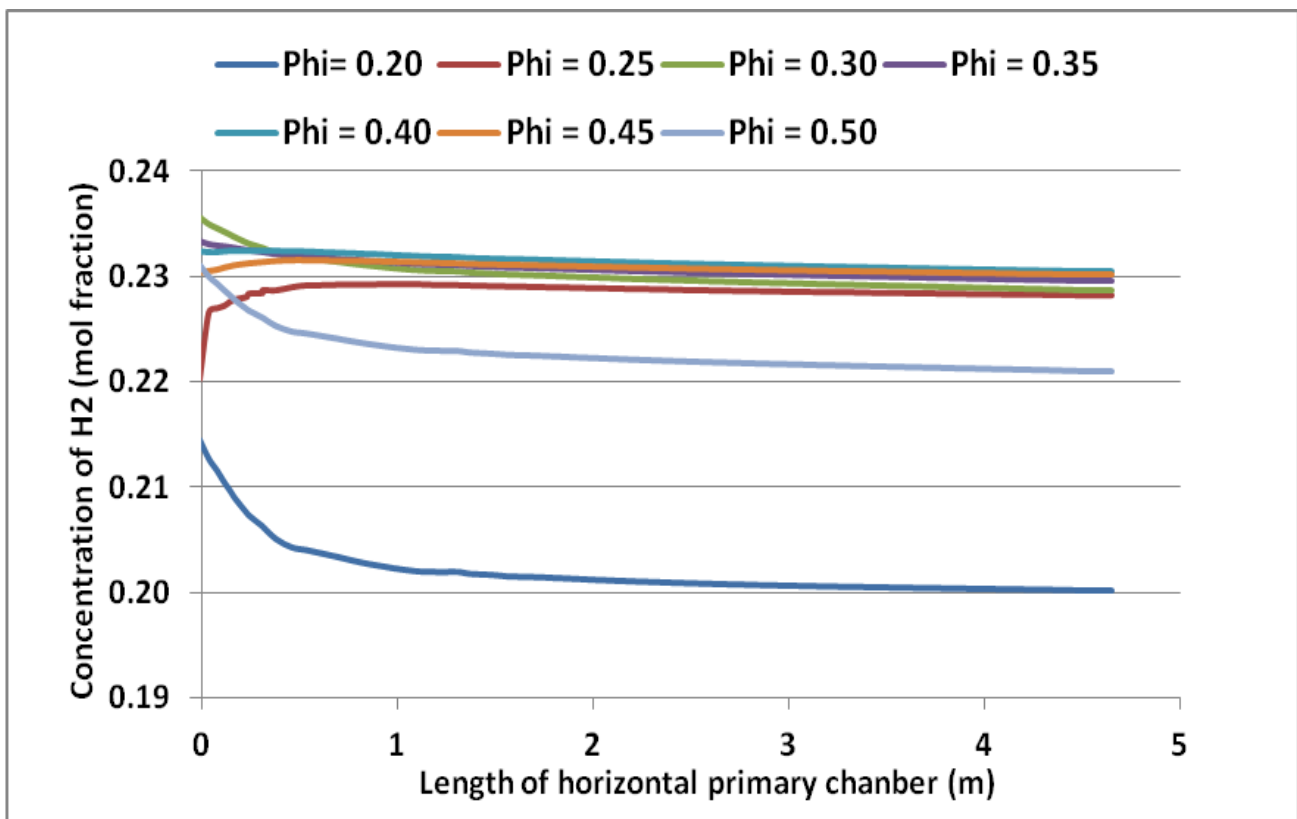**Figure 7: Concentration of CO along the axial centerline of the primary chamber**

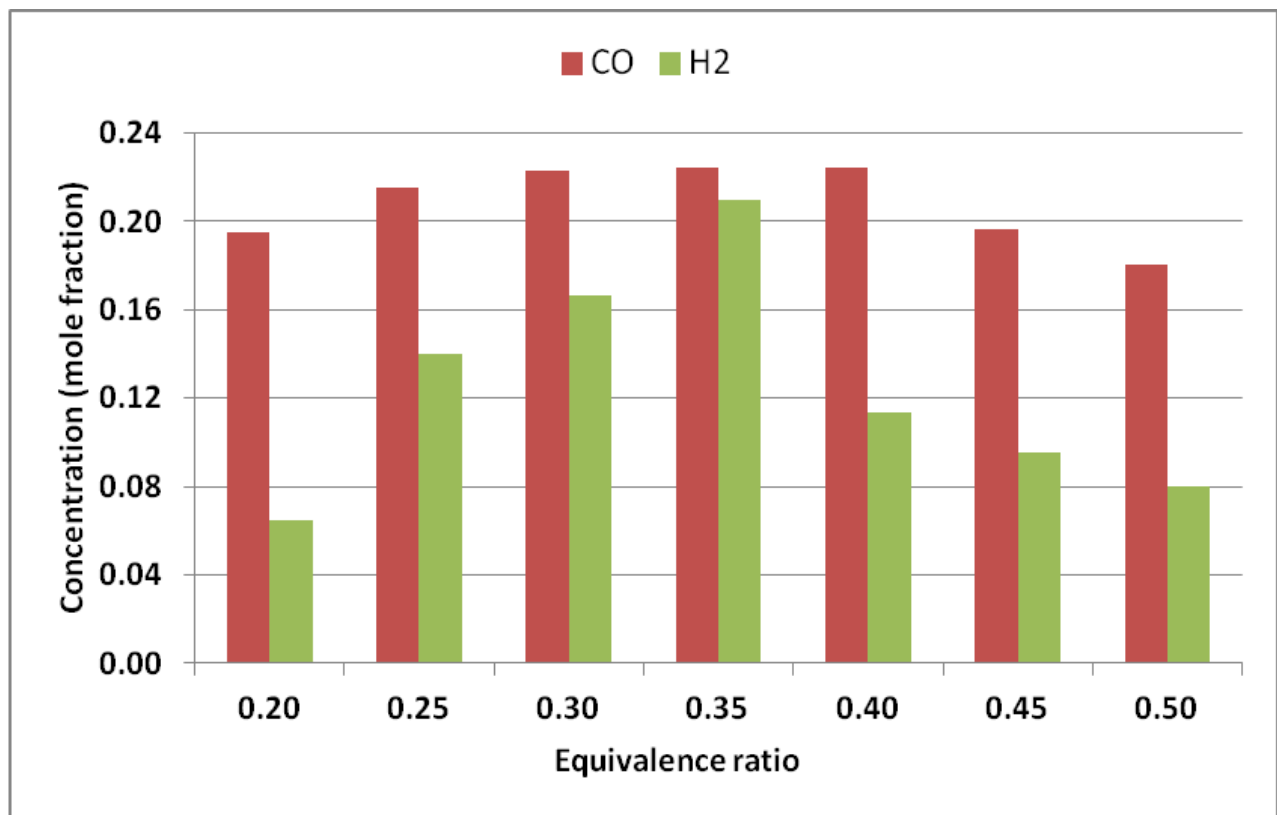**Figure 8: Concentration of H2 along the axial centerline of the primary chamber**

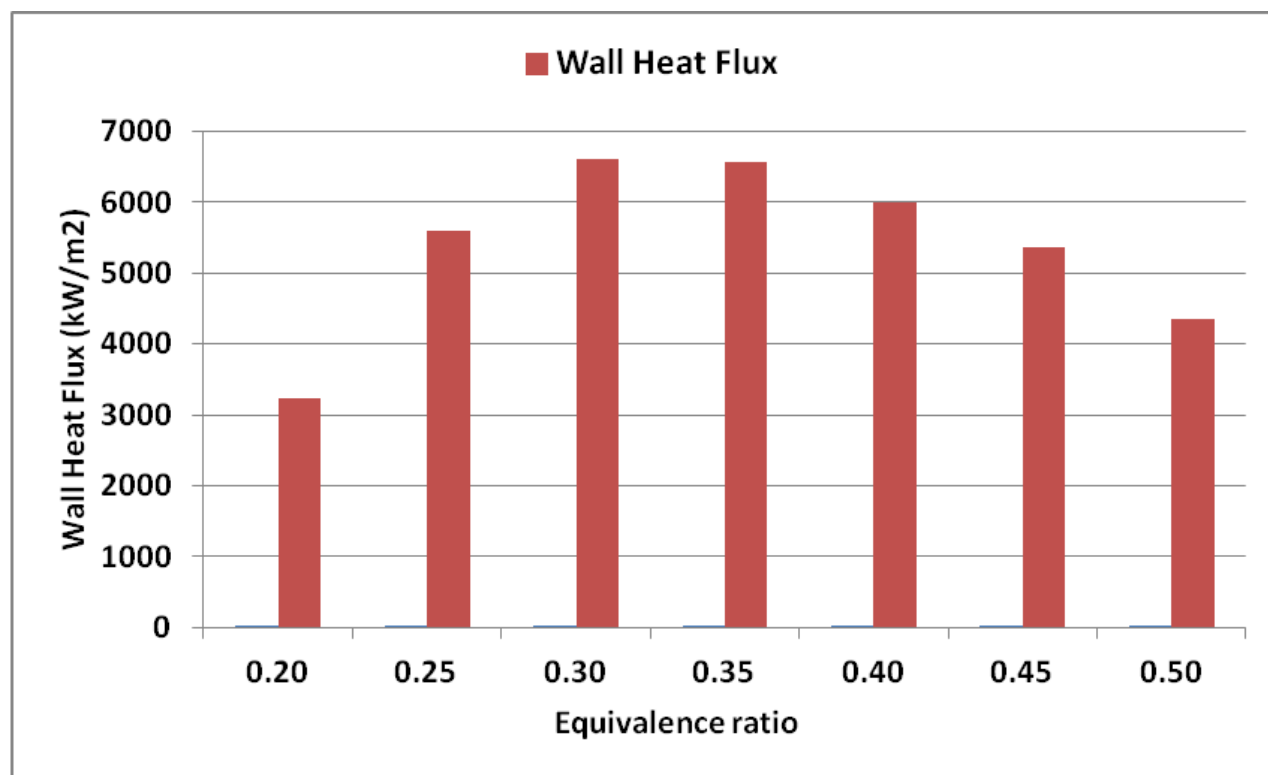**Figure 9: Average concentration of CO and H2 in the primary chamber**

Figure 10: Variation of wall heat flux in the secondary chamber

REFERENCES

[1]. Atal, A.; Levendis, Y. A. Fuel 1995, 74 (11), 1570−1581.

[2]. Baeyens, J., Brems, A. and Dewil, R., (2010) Recovery and recycling of post-consumer waste materials—Part 2. Target wastes (glass beverage bottles, plastics, scrap me- tal and steel cans, end-of-life tyres, batteries and house- hold hazardous waste). International Journal of Sustain- able Engineering, 3, 232-245. *doi:10.1080/19397038.2010.507885*

[3]. Braum M. M. and P. J. Street. Predicting the Combustion Behaviour of Coal Particles. *Combustion Science and Technology, 3*(5), 231-243. (1971)

[4]. Chinyama, M. P. M; Lockwood, F. C. J. Energy Inst. 2007, 80 (3), 162−167.

[5]. Coltrin, M., Kee, R.J., and Rupley, F. (1991), "Surface Chemkin: A General Formalism and Software for Analyzing Heterogeneous Chemical Kinetics at Gas-Solid Interfaces" International Journal of Chemical Kinetics, Vol. 23, pp. 1111-1128.

[6]. Field M. A. Rate of Combustion of Size-Graded Fractions of Char from a Low Rank Coal between 1200K - 2000K. *Combustion and Flame, 13*, 237-252. (1969)

[7]. Fluent 12 User Guide Copyright @2009 by ANSYS, Inc.

[8]. Giltrap, D., McKibbin, R., and Barnes, G., "A steady state model of gas-char reactions in a downdraft biomass gasifier," *Solar Energy*, vol. 74, pp. 85-91, 2003.

[9]. Huang H, Tang L. Treatment of organic waste using thermal plasma pyrolysis technology. Energ Convers Manage 2007;48(4):1331–7.

[10]. Juma, M., Z. Koreňová, J. Marks, J. Annus, L. Jelemensky Pyrolysis and Combustion of Scrap Tires Petroleum & Coal 48 (1), 15-26, 2006

[11]. Larsen, M. B.; Schultz, L.; Glarborg, P.; Skaarup-Jensen, L.; Dam-Johansen, K.; Frandsen, F.; Henriksen, U. Fuel 2006, 85, 1335−1345.

[12]. Sharma, A., Equilibrium modeling of global reduction reactions for a downdraft (biomass) gasifier. Energy Conversion and Management, 2008. 49(4): p. 832-842. doi:10.1016/j.enconman.2007.06.025