

Effect of Moisture Content on Composition Profiles of Producer Gas in Downdraft Biomass Gasifier

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Abstract

Biomass, mainly in the form of wood, is the oldest form of energy used by humans. Gasification is a process of conversion of solid carbonaceous fuel into combustible gas by partial combustion. In the present study, a model developed by us in our earlier study is used for predicting the steady-state composition and rate of reaction profiles for the reduction zone of the downdraft biomass gasifier are predicted. The effects of moisture content on the composition profiles and rate of reaction profiles are studied. Boudouard reaction rate and water gas reaction rate along the bed length and its correlation with gas compositions are analyzed.

Key words: Biomass Gasification; Pyrolysis; Modeling; Simulation.

Introduction

Biomass is recognized to be one of the major potential sources for energy production. There has been an increasing interest for thermochemical conversion of biomass and urban wastes for upgrading the energy in terms of more easily handled fuels, namely gases, liquids, and charcoal in the past decade. It is a renewable source of energy and has many advantages from an ecological point of view (Babu and Chaurasia, 2003a). Each of these products has commercial importance depending upon the type of application (Babu and Chaurasia, 2004a). The pyrolysis process consists of the thermal degradation of the biomass feedstock, in the absence of oxygen/air, leading to the formation of solid, liquid and gaseous products (Babu and Chaurasia, 2003b). Gasification is an important and efficient energy-conversion technology for a wide variety of biomass fuels. The large-scale deployment of efficient technology along with interventions to enhance the sustainable supply of biomass fuels can transform the energy supply situation in rural areas. It has the potential to become the growth engine for rural development in the country. The understanding of the interaction between chemical and physical mechanisms during gasification is of fundamental importance, for the optimal design of biomass gasifier (Babu and Chaurasia, 2004b). In view of the considerable interest in the gasification process worldwide, it is necessary to model and predict the performance of

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the gasifier *in priori*. Modeling of biomass gasification implies the representation of chemical and physical phenomena constituting pyrolysis, combustion, reduction, and drying in the mathematical form.

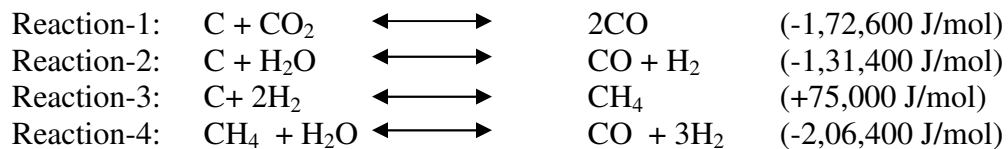
Many researchers have developed models for biomass gasification (Zainal et al., 2001; Mathieu and Dubuisson, 2002; Di Blasi, 2002; Giltrap et al., 2003; Jayah et al., 2003; Babu and Sheth, 2005a; Sheth and Babu; 2005b). Zainal et al. (2001) used the equilibrium model to predict the composition of producer gas. The effects of initial moisture content in the wood and the temperature in the gasification zone on the calorific value are investigated. Mathieu and Dubuisson (2002) have developed a model based on minimization of Gibbs free energy is performed in the ASPEN PLUS process simulator. The effects of the oxygen factor, the air temperature, operating pressure and the injection of steam are studied. Di Blasi (2002) developed a one-dimensional unsteady-state model for biomass gasification in a stratified concurrent (downdraft) reactor. Heat and mass transfer across the bed are coupled with moisture evaporation, biomass pyrolysis, char combustion and gasification, gas-phase combustion and thermal cracking of tars. Giltrap et al. (2003) developed a model for the reduction zone of downdraft biomass gasifier to predict the composition of producer gas under steady-state operation. Factors affecting the gas composition are pyrolysis fraction (fraction of pyrolysed gas in the initial gas entering the reduction zone of biomass gasifier), air to fuel ratio, moisture content of biomass, bed temperature, and reactivity of char. Molar balance, energy balance, pressure gradient equation and Arrhenius type of temperature dependence kinetic equation forms the set of first order differential equations, which are solved by finite difference method. The accuracy of the model is limited by the availability of data on the initial conditions at the top of the reduction zone. Moreover it is assumed that char reactivity factor (*CRF*), which represents the reactivity of char and the key variable in simulation, is constant throughout the reduction zone. Jayah et al. (2003) developed a model incorporating Milligan's (1994) flaming pyrolysis sub-model along with the gasification zone sub-model. The model does not include the effect of packed char particles in reduction zone as it is limited by considering only a single particle. Babu and Sheth (2005a) have modified the Giltrap's (2003) model by incorporating the variation of char reactivity factor (*CRF*) along the reduction zone of the downdraft biomass gasifier. The model is simulated with finite difference method to predict the temperature and composition profiles in the reduction zone. Finite difference technique has been successfully applied to solve such type of partial differential equations in other studies (Babu and Chaurasia, 2004a; 2004b). *CRF* value is increased linearly as well as exponentially along the reduction bed length in the model. The model predictions are compared with the experimental data reported by Jayah et al. (2003). The effects of pyrolysis fraction and bed temperature on gas compositions are studied by Sheth and Babu (2005b).

In the present study, modified model developed by Babu and Sheth (2005a) is used to calculate the calorific values and composition profiles along the bed of reduction. The pyrolysis fraction variable (f_p) value of 0.3 and exponentially varying char reactivity factor is considered in the simulations. The effect of moisture content on composition profiles of various components is studied. Composition profiles and rates of various

reactions are carefully observed to find the temperature value at which the rate of Boudouard reaction (reaction-1, which is described in the following section).

Model Formulation

Giltrap et al. (2003) proposed a phenomenological model of downdraft gasification under steady-state operation for reduction zone of the biomass gasifier. The pyrolysis and cracking reactions were not considered in this model as the number of possible pyrolysis products along with all the possible reactions and intermediate products would make the model very complex. It is assumed that the entire amount of oxygen supplied from the air inlet is being combusted to CO₂ and that the pyrolysis products are completely cracked. Solid carbon in the form of char was assumed to be present throughout the reduction zone. Model uses the reaction kinetic parameters developed by Wang and Kinoshita (1993) and the adopted reaction scheme is as follows:



Nomenclature

A	Cylindrical bed area (m^2)
A_i	Frequency Factor for reaction i (sec^{-1})
c_x	Molar heat capacity ($J/mol K$)
CRF	Char reactivity factor
E_i	Activation Energy of reaction i ($Joules /mol K$)
f_p	Fraction of pyrolysis
K_i	Equilibrium constant of reaction I
L_n	Normalized Length
L_{in}	Initial normalized length at which 85 % of the total composition change
n_x	Molar density of species x (mol/m^3)
n	Summation of n_x of all species
P_x	Partial pressure of gaseous species x (Pa)
r_i	Rate of reaction i (mol/m^3sec)
R_x	Rate of formation of species x (mol/m^3sec)
R	Gas constant ($J/mol K$)
T	Temperature (K)
v	Superficial gas velocity (m/sec)
z	Axial distance (m)

Greek Letters

ρ Density (kg/m^3)

Subscript

x Species $N_2, CO_2, CO, CH_4, H_2O, H_2$
 i Reaction number

This model assumes a cylindrical gasifier bed of uniform cross-sectional area A with negligible radial variation in the properties of both the bed and gas. Molar balance and Energy balance result in a set of following equations (Eqns.1-3). Species considered here are nitrogen, carbon dioxide, carbon monoxide, methane, steam and hydrogen.

$$\frac{dn_x}{dz} = \frac{1}{v} \left(R_x - n_x \frac{dv}{dz} \right) \quad (1)$$

$$\frac{dT}{dz} = \frac{1}{v \sum_x n_x c_x} \left(- \sum_i r_i \Delta H_i - v \frac{dP}{dz} - P \frac{dv}{dz} - \sum_x R_x c_x T \right) \quad (2)$$

$$\frac{dv}{dz} = \frac{1}{\sum_x n_x c_x + nR} \left(\frac{\sum_x n_x c_x \sum_x R_x}{n} - \frac{\sum_i r_i \Delta H_i}{T} - \frac{dP}{dz} \left(\frac{v}{T} + \frac{v \sum_x n_x c_x}{P} \right) - \sum_x R_x c_x \right) \quad (3)$$

The empirical formula as given by Eqn. 4 is used to find the pressure gradient of a fluid flowing through a bed of solid char particles, (Supplied by Dr. Donna Giltrap on request which was used, but not reported in their article (Giltrap et al., 2003)).

$$\frac{dP}{dz} = 1183 \left(\rho_{\text{gas}} \frac{v^2}{\rho_{\text{air}}} \right) + 388.19 v - 79.896 \quad (4)$$

The reaction rates are assumed to have an Arrhenius-type temperature dependence and to be proportional to the difference between the actual reactant / product ratio and the corresponding equilibrium ratio. The reaction rates for the reactions-1 to 4 are shown in Eqns.5-8.

$$r_1 = n CRF A_1 \exp\left(\frac{-E_1}{RT}\right) \cdot \left(P_{\text{CO}_2} - \frac{P_{\text{CO}}^2}{K_1} \right) \quad (5)$$

$$r_2 = n CRF A_2 \exp\left(\frac{-E_2}{RT}\right) \cdot \left(P_{\text{H}_2\text{O}} - \frac{P_{\text{CO}} \cdot P_{\text{H}_2}}{K_2} \right) \quad (6)$$

$$r_3 = n CRF A_3 \exp\left(\frac{-E_3}{RT}\right) \cdot \left(P_{\text{H}_2}^2 - \frac{P_{\text{CH}_4}}{K_3} \right) \quad (7)$$

$$r_4 = n CRF A_4 \exp\left(\frac{-E_4}{RT}\right) \cdot \left(P_{\text{CH}_4} \cdot P_{\text{H}_2\text{O}} - \frac{P_{\text{CO}} \cdot P_{\text{H}_2}^3}{K_4} \right) \quad (8)$$

The values of the frequency factor and Activation energy used in our simulations are shown in Table-1.

Method of solution and simulation of model equations

Eqns.1 to 4 give a set of nine first order differential equations in the system variables n_x (where x denotes the six different gas species considered), P , v , and T . These eqns are solved by explicit finite difference method (Ghoshdastidar, P.S., 1998, Babu, B.V., 2004).

Initial Conditions

The initial position in this model is the top of reduction zone and the end of oxidation zone. Gases coming from the oxidation zone are a mixture of pyrolysed gas, incombustible CO₂ and inert N₂. The exact proportion of each of these components depends upon the rate of air flowing into the gasifier relative to the rates of combustion, pyrolysis and cracking reactions. Babu and Sheth (2005a) modified Giltrap's model (2003), which is in very good agreement with the experimental data of Jayah et al. (2003), in comparison with the mathematical model of Jayah et al. (2003). Table-2 shows the parameters used in the simulation and initial conditions (Babu and Sheth, 2005a). The value of char reactivity factor (*CRF*), which represents the reactivity of char must be varied along the reduction zone of the down draft biomass gasifier. Exponentially varying *CRF* values are considered in the present study. The equation used for exponential increment is $CRF = A e^{Bz}$ where $A = 1$ and $B = 0.0037$ (Babu and Sheth, 2005a).

Results and Discussion

The effect of moisture content (dry basis) on composition profiles of various components is studied. Composition profiles and rates of various reactions are carefully observed. It is found that after certain height of the gasifier from top, composition of carbon monoxide starts decreasing and that of carbon dioxide increasing as the rate of reaction-1 becomes negative.

Fig.1 shows the effect of moisture content on the molar compositions of outgoing gas from gasifier. Mole fraction of hydrogen is increasing from 0.163 to 0.194 with moisture content increment from 5 wt % to 20 wt% linearly. Mole fraction of carbon monoxide is decreasing and of carbon dioxide is increasing with moisture increment. Methane concentration is not changing significantly with moisture content.

According to reaction-2 and reaction-4, amount of carbon monoxide should increase with moisture content whereas Fig. 1 shows contradictory results. To identify the cause, composition profiles of carbon monoxide and carbon dioxide are simulated using the model equations. Fig. 2 shows the composition of carbon monoxide and carbon dioxide with bed length for moisture content varying from 5 wt% to 20 wt%. It is clearly indicating that the compositions of carbon monoxide are increasing along the reduction bed upto a certain height and after that they start decreasing. For carbon dioxide the mole fraction values are decreasing along the reduction bed upto the same height when CO starts decreasing, and later on CO₂ starts increasing. For 20 wt% moisture content, the mole fraction of carbon monoxide is highest upto the bed length of 0.2 m. After that maximum reduction in carbon monoxide mole fraction is observed for the moisture content of 20 wt% and least reduction in carbon monoxide mole fraction for the moisture content of 5 wt% is observed. Due to this behavior of the system, carbon monoxide mole fraction at outlet is decreasing with moisture content increment.

To understand the phenomena of carbon monoxide reduction and carbon dioxide increment, rates of all four reactions are studied and profiles of reaction rates are obtained. Fig. 3 shows the rate of reaction-1 variation with temperature for moisture content varying from 5 wt% to 20 wt%. It shows the temperatures of 961 K and 951 K at which the rate of reaction-1 becomes negative for the moisture content of 10 wt% and 20 wt% respectively. It clearly indicates that for the moisture content value of 5 wt%, the rate of reaction is higher than for the higher values of moisture content. This is because the initial concentrations of CO, CH₄ and H₂O in gas are less at lower values of moisture content compared to those corresponding to higher values of moisture content. It also shows that the maximum reduction in the rate of reaction is for 20 wt% moisture content. Due to maximum reduction in rate of reaction for 20 wt% moisture content, carbon monoxide decrement for 20 wt% moisture content is maximum, which is shown in Fig. 2.

Fig. 4 shows the variation of rate of reaction-2 with temperature for moisture content ranging from 5 wt% to 20 wt%. Rate of reaction-2 is increasing upto a certain height from top of the bed and after that it starts decreasing due to reduction in H₂O mole fraction, which is consumed by reaction itself. For 20 wt% moisture content the rate of reaction is higher than for the lower values of moisture content. It is also evident from Fig. 4 that for the moisture content of 5 wt% and 10 wt%, the rate of reaction-2 becomes negative. Due to less amount of H₂O for 5 wt% moisture content, rate of reaction-2 becomes more negative compared to 10 wt% moisture content. For the moisture content of 20 wt% the rate of reaction-2 is started increasing at a temperature of 936 K, this phenomena is not understood completely.

Fig. 5 shows the rate of reaction-3 for moisture content changing from 5 wt% to 20 wt%. Rate of reaction-3 is negative and decreases with moisture content increment. The initial value of CH₄ is less due to higher value of moisture content and rate of reaction-3 is decreasing. Rate of reaction-3 is increasing upto some extent and then it start decreasing and again increasing.

Fig. 6 shows the rate of reaction-4 for moisture content changing from 5 wt% to 20 wt%. Rate of reaction-4 is not changing significantly for the low value of moisture content. It is increasing rapidly for the moisture content value of 20 wt%.

Conclusions

The steady-state model discussed here predicts the composition and rate of reaction profiles across the length of the reduction zone. Moisture content of biomass is one of the key variables in modeling of downdraft gasifier. Simulations are carried out by varying the moisture content (dry basis) ranging from 5wt% to 20 wt%. Based on the results obtained and the discussions carried out in the earlier section, the following conclusions are drawn:

- Mole fraction of hydrogen in outgoing gas from the gasifier is increasing with moisture content increment linearly.

- Mole fraction of carbon monoxide in outgoing gas from the gasifier is decreasing and carbon dioxide is increasing with moisture increment.
- Methane concentration in outgoing gas from the gasifier is not changing significantly with moisture content.
- The compositions of carbon monoxide are increasing along the reduction bed upto a certain height and after that they start decreasing.
- For carbon dioxide, the composition is decreasing along the reduction bed upto the same height when CO starts decreasing and later on CO₂ starts increasing.
- For 20 wt% moisture content, the mole fraction of carbon monoxide is highest upto the bed length of 0.2 m. After that maximum reduction in carbon monoxide mole fraction is observed for the moisture content of 20 wt%, and least reduction in carbon monoxide mole fraction for the moisture content of 5 wt% is observed.
- At the temperatures of 961 K and 951 K, the rate of reaction-1 becomes negative for the moisture content of 10 wt% and 20 wt% respectively.
- Rate of reaction-2 is increasing upto a certain height from top of the bed and after that it starts decreasing due to reduction in H₂O mole fraction, which is consumed by reaction itself.

These results are very useful to the designers, as the bed temperature should not fall below a value, which may lead to negative rate of reaction –1. Moisture content in biomass should be such that rate of reaction-2 has to positive.

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List of Tables

1. Frequency factor and Activation Energies values (Wang and Kinoshita, 1993)
2. Parameters used in the model simulation and Initial conditions

Table 1. Frequency factor and Activation Energies values (Wang and Kinoshita, 1993)

Reaction i	A_i (1/s)	E_i (kJ/mol)
1	3.616×10^1	77.39
2	1.517×10^4	121.62
3	4.189×10^{-3}	19.21
4	7.301×10^{-2}	36.15

Table 2. Parameters used in the model simulation and initial conditions (Babu and Sheth, 2005a)

Parameters	Values
Bed Length	24.5 cm
v initial	1.175 m/sec
T initial	1400 K
Moisture Content	5%, 10%, 15%, 20% (dry basis)
CRF	Exponentially varying
f_p	0.3
P	1.005 atm

Figure Captions

1. Mole fraction vs. Moisture content (wt% Dry Basis)
2. Composition (mole fraction) versus Length (m)
3. Rate of reaction-1 ($\text{mol/m}^3\text{s}$) versus Temperature (K)
4. Rate of reaction-2 ($\text{mol/m}^3\text{s}$) versus Temperature (K)
5. Rate of reaction-3 ($\text{mol/m}^3\text{s}$) versus Temperature (K)
6. Rate of reaction-4 ($\text{mol/m}^3\text{s}$) versus Temperature (K)

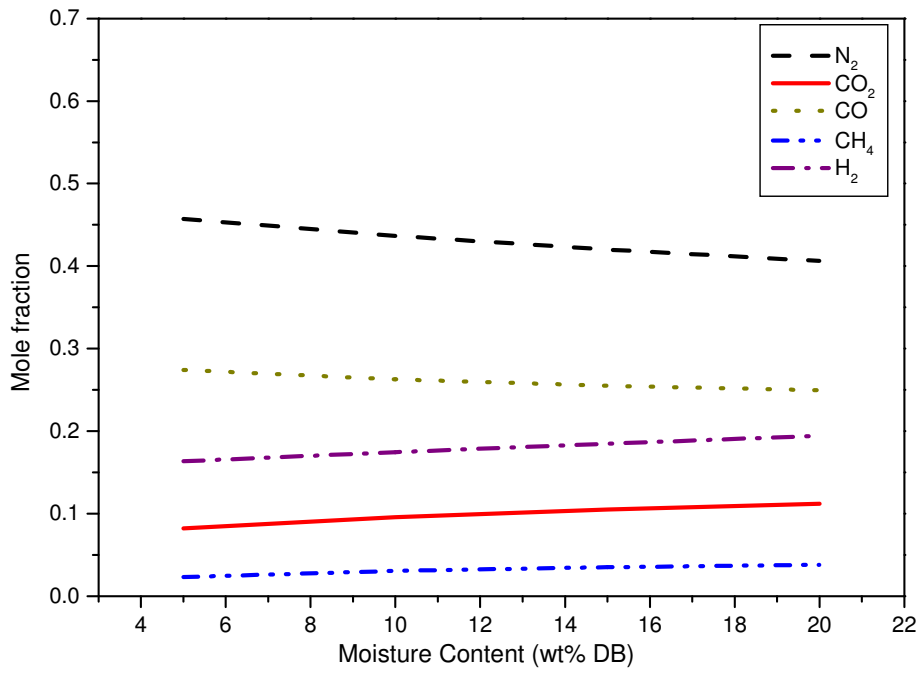


Fig. 1 Mole fraction vs. Moisture content (wt% Dry Basis)

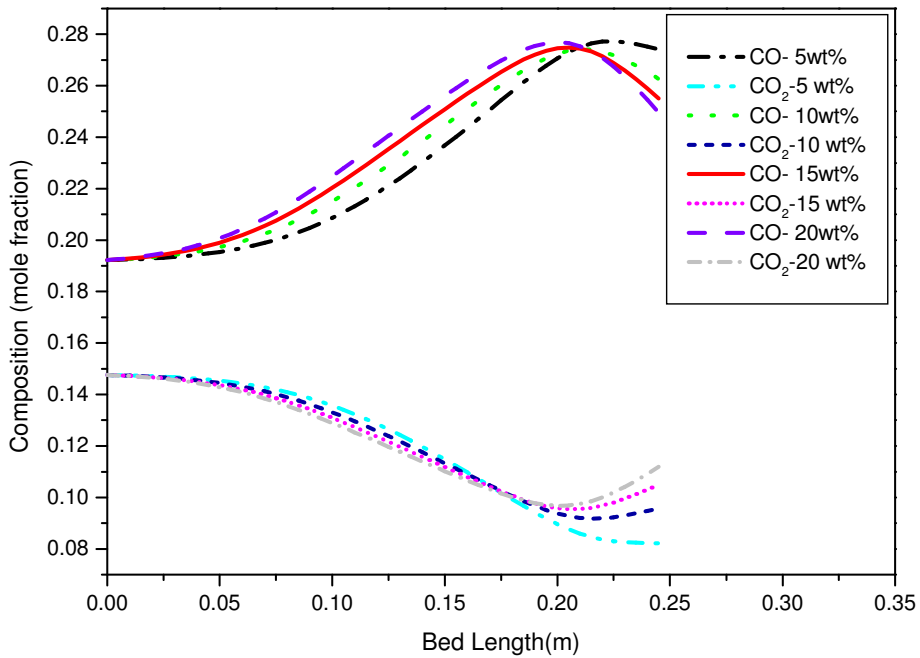


Fig. 2 Composition (mole fraction) versus Length (m)

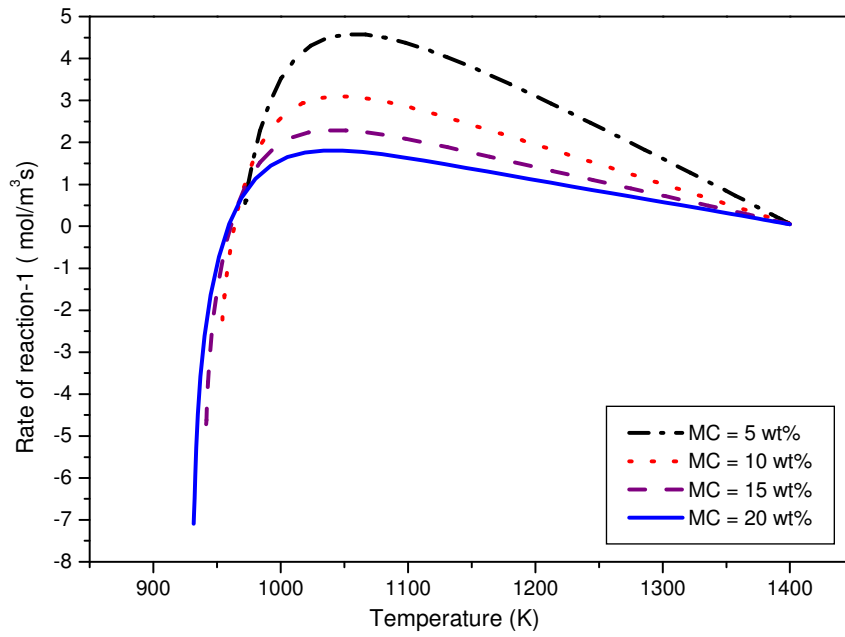


Fig. 3 Rate of reaction-1 (mol/m³s) versus Temperature (K)

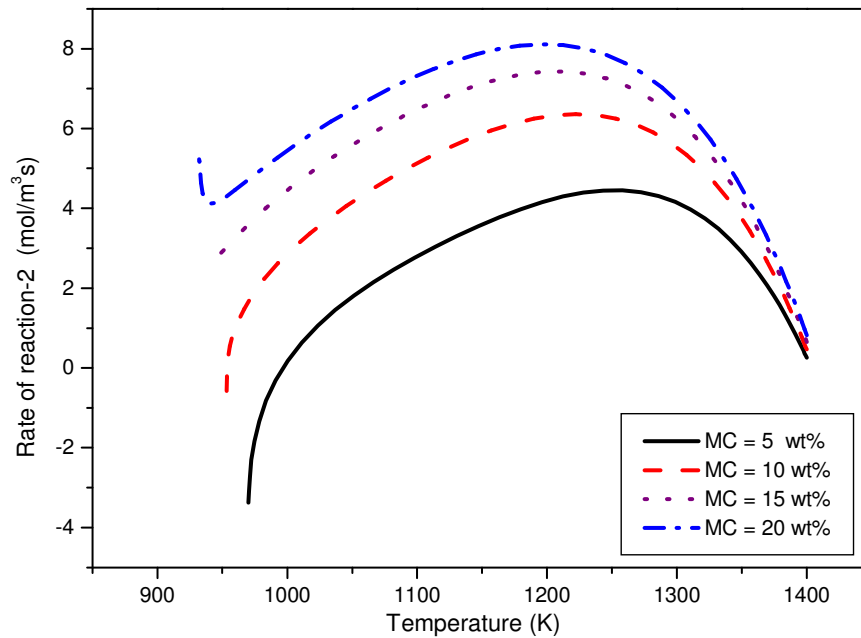


Fig.4 Rate of reaction-2 (mol/m³s) vs. Temperature (K)

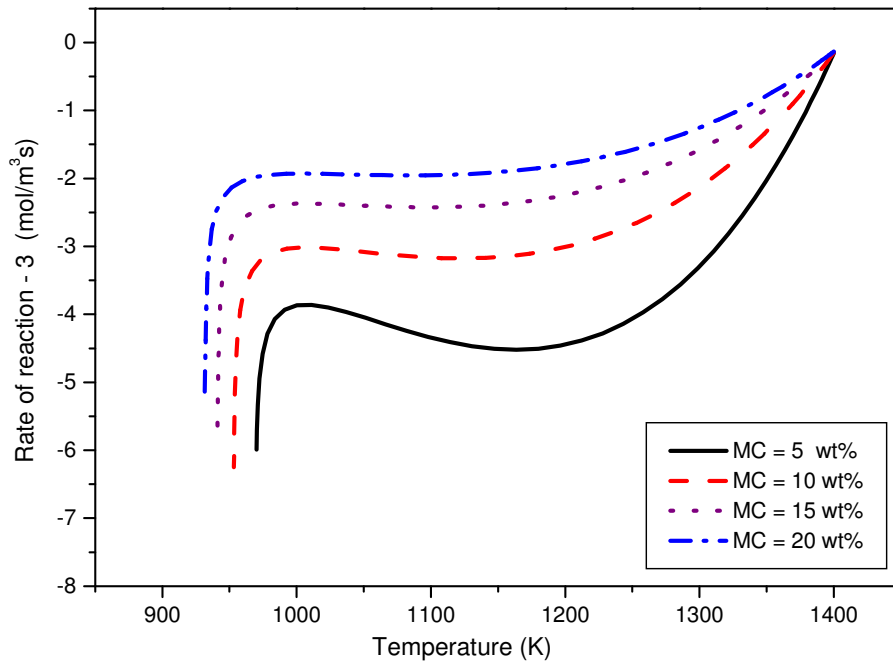


Fig. 5 Rate of reaction-3 (mol/m³s) vs. Temperature (K)

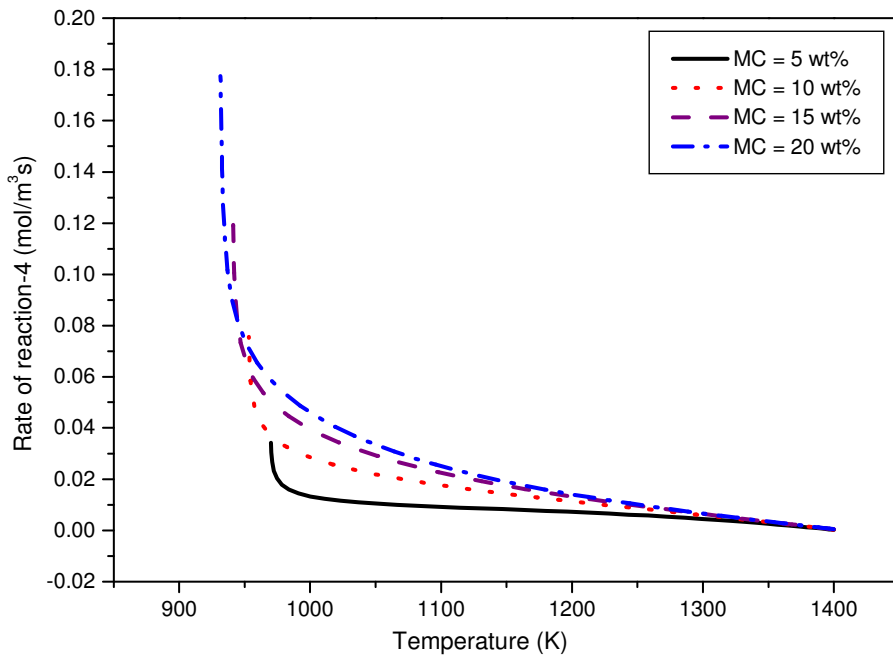


Fig. 6 Rate of reaction-4 (mol/m³s) vs. temperature (K)