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Modeling of Steam-Air-Blown Gasification for Biomass in a Dual Circulating Fluidized Bed (CFB) Gasifier

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session **Biorefinery – Thermochemical Conversion of Biomass II**

November 10th, 2010

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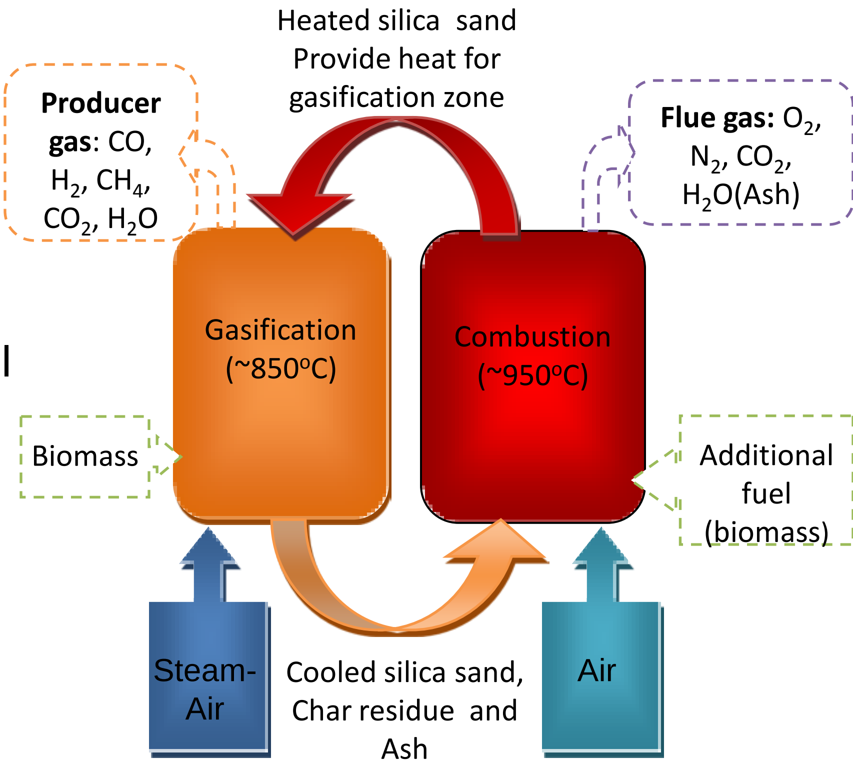
Contents

Introduction

- A three-stage-steady-state thermodynamic equilibrium model (TSM) including mass and energy balances was applied for steam-air-blown biomass gasification in a dual circulation fluidized bed (CFB) to calculate the gas product composition, the LHV, circulation ratio and the heat recovery of biomass.
- The heat required for gasification reaction was provided by the circulating bed material (silica sand)
- The final composition of the gas product is obtained from two-stage equilibrium model incorporated with biomass pyrolysis and combustion.
- The effects of reaction temperature, steam to fuel ratio and oxygen to fuel ratio on the gas product composition and overall performance of CFB gasifier were studied base on the final gas composition.



- In the comparison of the final gas composition with steam gasification (for same biomass and operating conditions), the objective of this study (increase LHV of gas product) was confirmed.

Three stage model (TSM)

Stage 1

Pyrolysis and combustion are divided into two steps:
(1) Biomass Pyrolysis:
- Decomposes into gas, tar and char
- Thermal cracking of tar
(2) CO and H_2 combustion reactions

Stage 2

Char-gas reactions include:
- Boudouard reaction
- Char-steam reactions

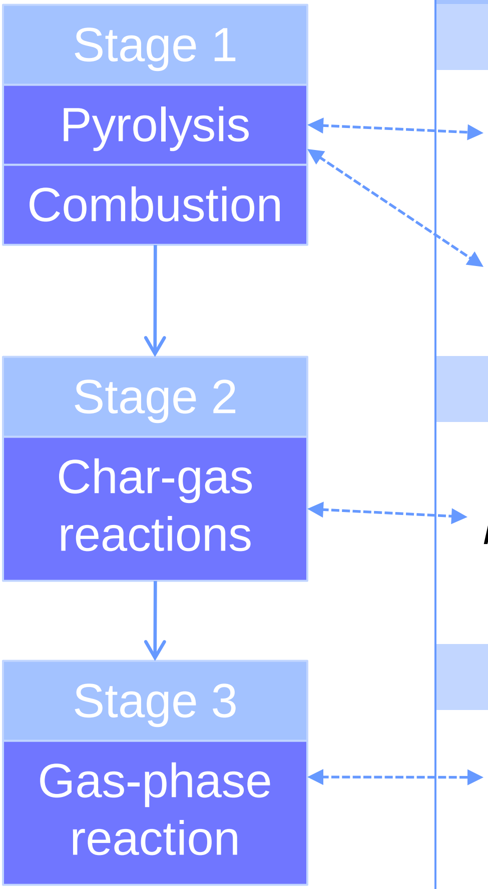
Stage 3

Gas-phase reaction is a Water-gas shift reaction

TSM/ Assumptions

Stage	***Reactions***	***Products proposed***	***Assumed***	***References***
Pyrolysis	First step: Thermal decomposition	CO, CO_2, CH_4, H_2 and H_2O	CO, CO_2, CH_4, H_2 and H_2O	Sadaka et al. (2002); Radmanesh et al. (2006); Wurzenberger et al. (2002); Rath et al. (2001) [3,12-14]
	Second step: Tar cracking	CO, CO_2, H_2, heavier hydrocarbon (e. g., C_2H_6, C_2H_4, and C_3H_6), and inert tar.		
	Combustion reactions in very short time: $CO(g) + O_2(g) \rightarrow CO_2(g)$ $H_2(g) + O_2(g) \rightarrow H_2O(g)$	After combustion, the solid is fixed carbon (that does not react), the gases include: CO_2, H_2O, CO, H_2, N_2, CH_4	The Oxygen reacted completely in very short time.	Smith et al. (2005) [15]
Solid–gas reactions	$C(s) + CO_2(g) \leftrightarrow 2CO(g)$ $C(s) + H_2O(g) \leftrightarrow CO(g) + H_2(g)$	(Char unreacted) CO, CO_2, H_2, (H_2O residue)	Char unreacted, CO, H_2, H_2O residue	Nguyen et al. (2010) ; Yoshida et al. (2008) [2,5]
Water–gas shift reactions	$CO(g) + H_2O(g) \leftrightarrow CO_2(g) + H_2(g)$	CO, CO_2, H_2, H_2O	CO, CO_2, H_2, H_2O	Wei et al. (2007); Walawender et al. (1985); Herguido et al. (1992) ;Sharma et al. (2008); Altafini et al. (2003) [4,6-9]

TSM/ Structure of TSM



Stage 1

Pyrolysis

Combustion

Stage 2

Char-gas reactions

Stage 3

Gas-phase reaction

Empirical models combined

CO formation and CH_4 formation

$$\varphi_{CO} = \frac{n_{CO}}{n_{CO_2}} = 4697 \times \exp(-\frac{7162.3}{T})$$

$$\varphi_{CH} = \frac{n_{CH_4}}{n_{H_2}} = 0.0013 \times exp(-\frac{-6064.8}{T})$$

Steam participation

$$\beta = \frac{n_{H_2O,0}}{n_{H_2O,tot}} = 51.4 \times exp(-\frac{7542.8}{T})$$

Non-equilibrium factor

$$\kappa = 9 \times 10^{10} \times exp(-\frac{24400}{T})$$

References

Sakada et al. (2002) [3]

Fagbemi et al. (2001) [1]

Nguyen et al. (2010) [2]

Wei et al. (2007) [4]

TSM/ Empirical models (1/4)

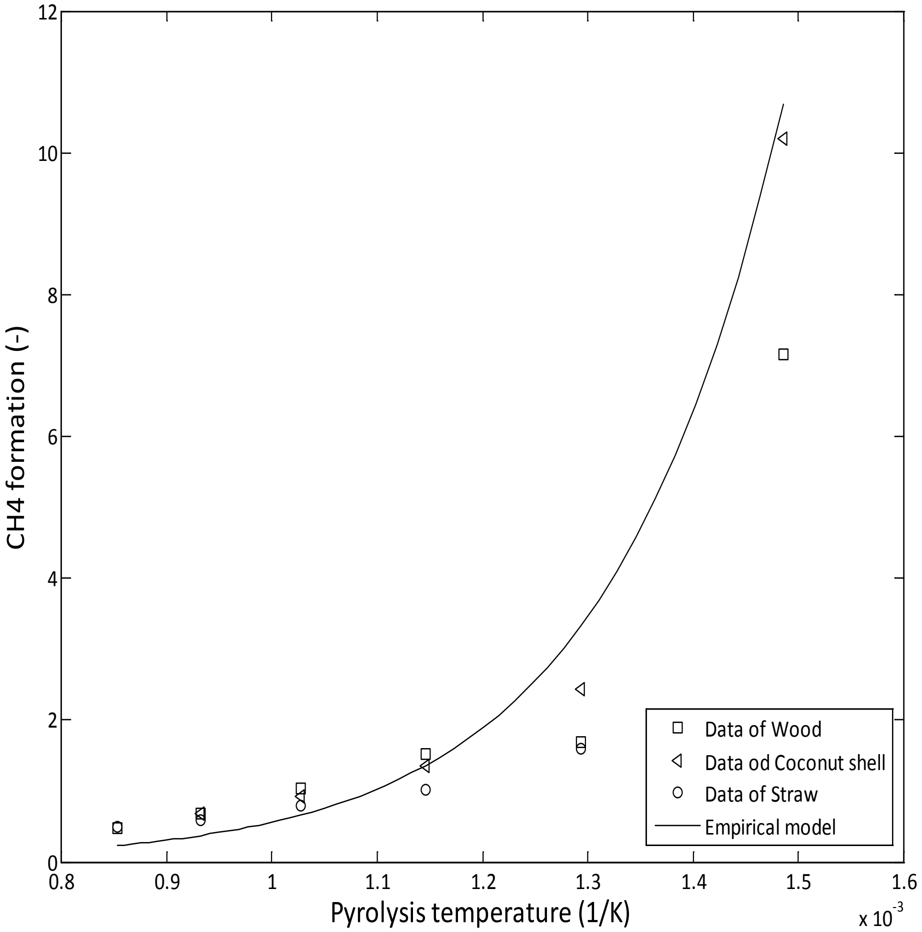


Fig. 1. Empirical model for CH_4 formation versus pyrolysis temperature. Experiment data were taken from Fagbemi [1]

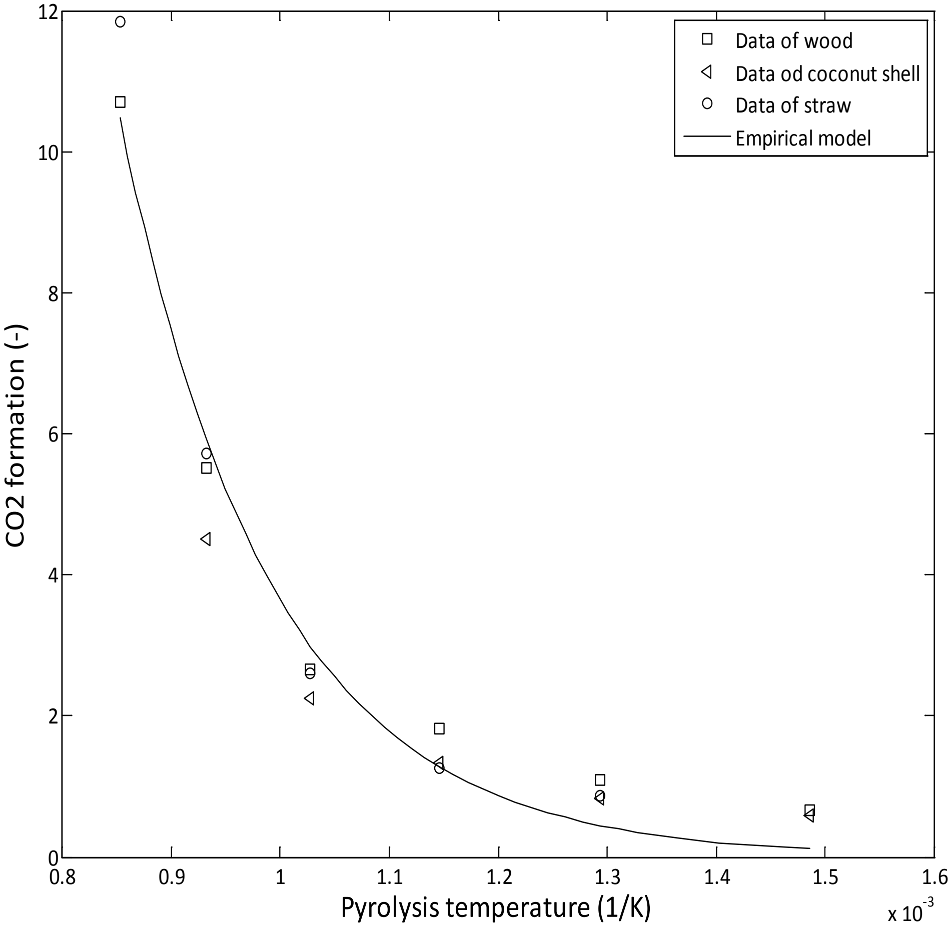


Fig. 2. Empirical model for CO_2 formation versus pyrolysis temperature. Experiment data were taken from Fagbemi [1]

TSM/ Empirical models (2/4)

- Steam participation is expressed as the steam amount involved in the char-gas equilibrium reactions. $\beta = (n_{H2O,involved}/n_{H2O,total})$

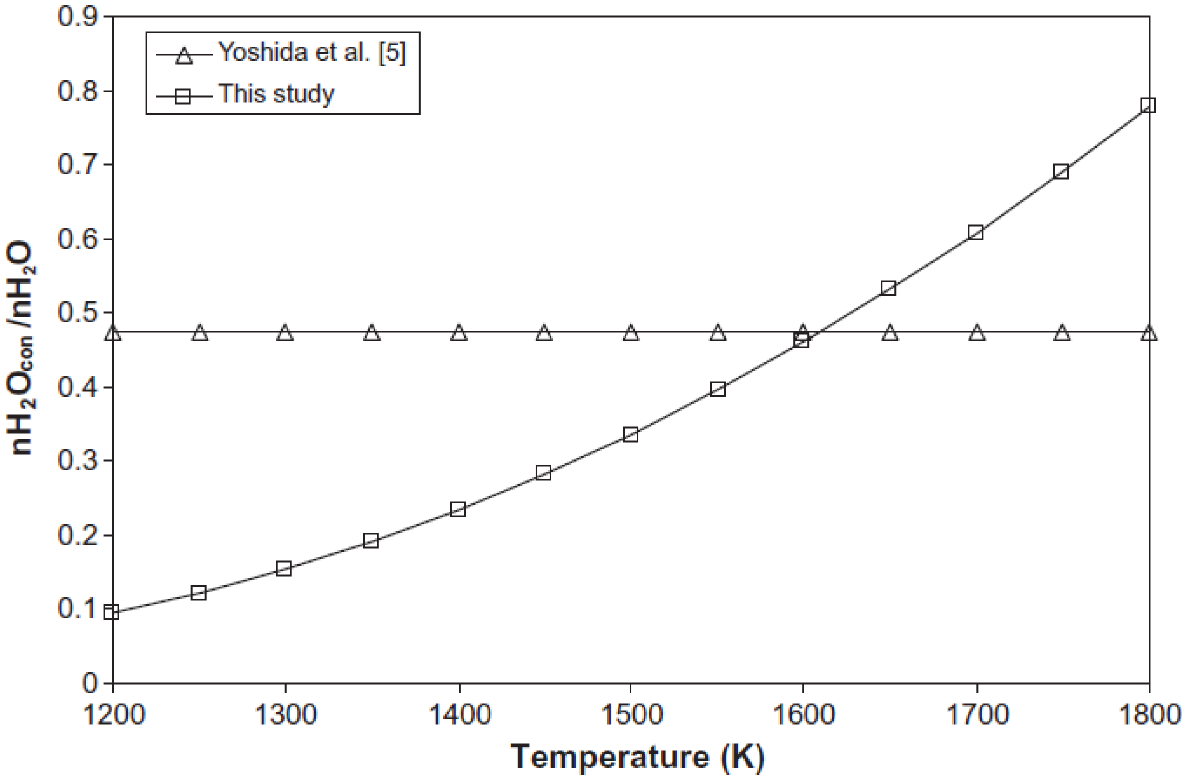


Fig. 3. Water amount contributing to the equilibrium reaction of the second stage (β), this function was taken from Nguyen et al. (2010) [2]

TSM/ Empirical models (3/4)

- The equilibrium constant of water-gas shift reaction is corrected by the non-equilibrium factor (κ)

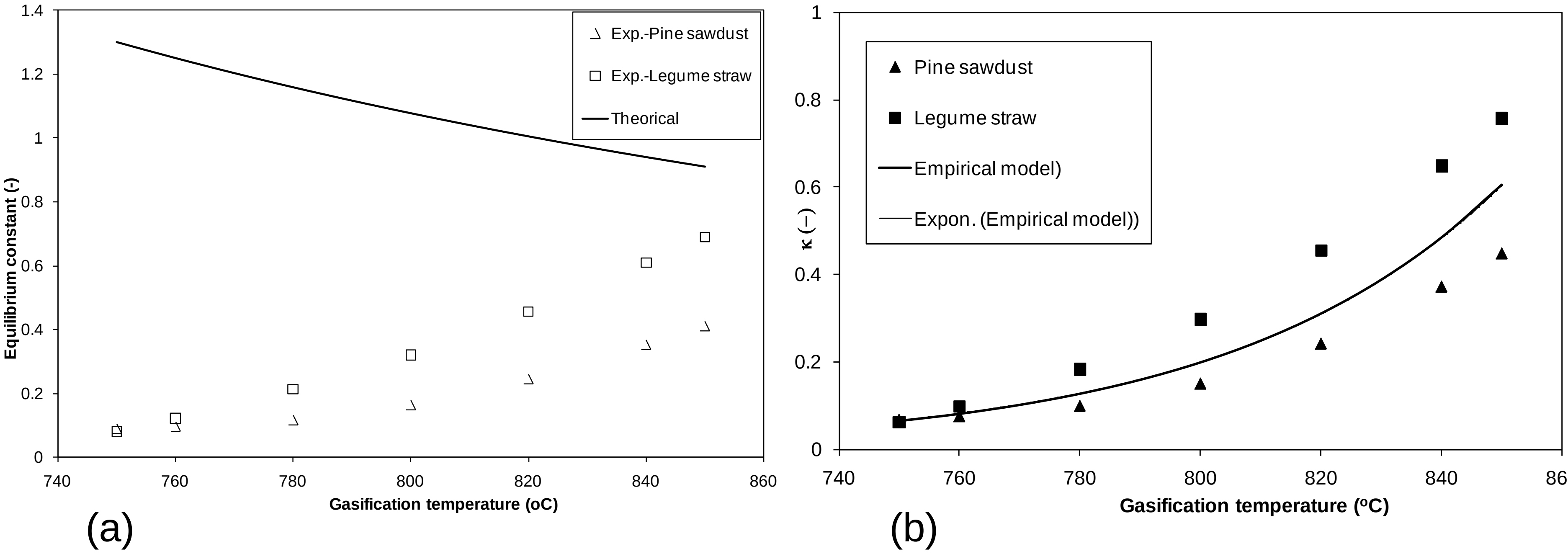
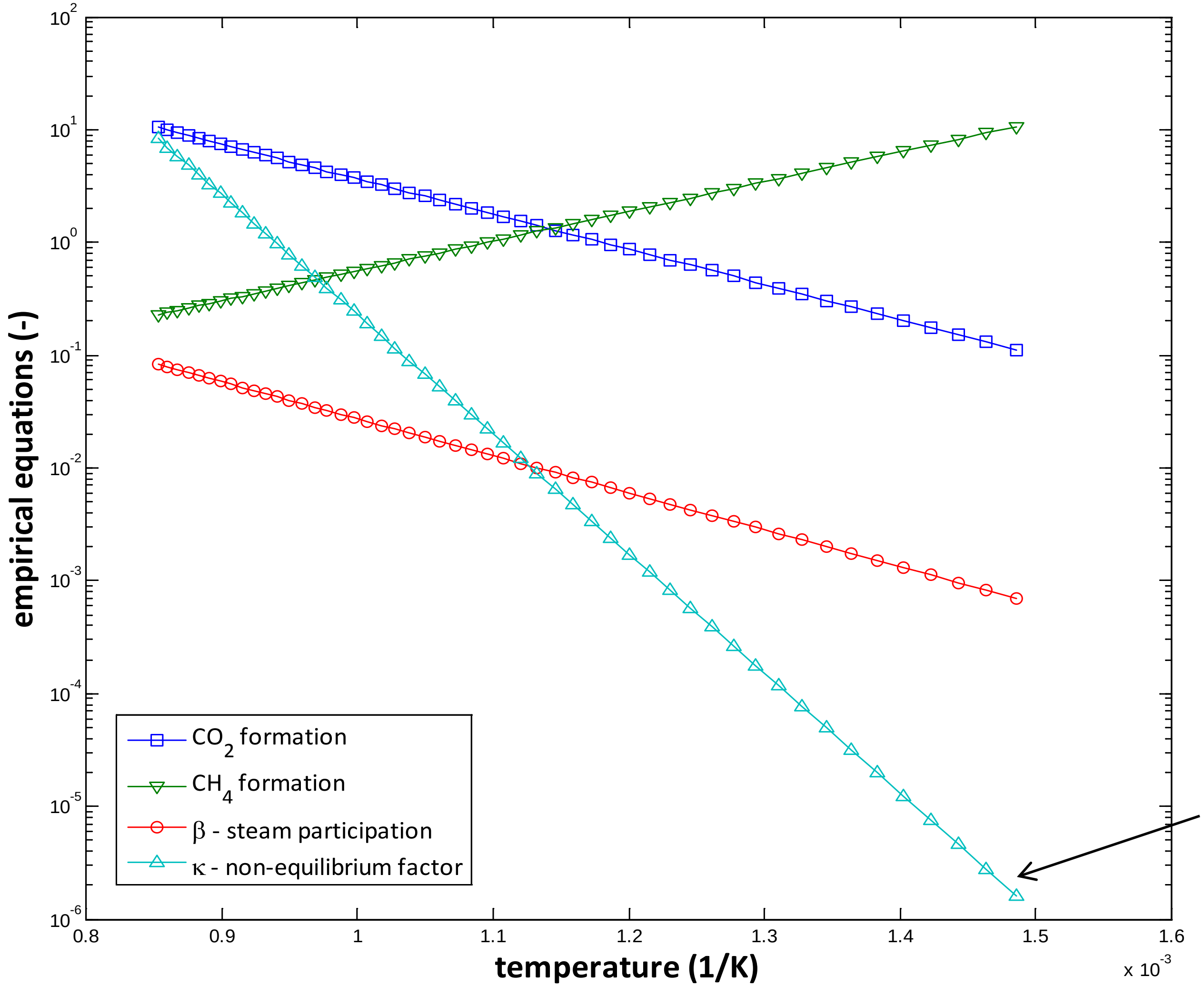


Fig. 4. Effect of gasification on the equilibrium constant of the water-gas shift reaction: (a) equilibrium constant vs. gasification temperature; (b) non-equilibrium factor (κ) vs. gasification temperature

TSM/ Empirical models (4/4)



Non-equilibrium factor (in water-gas shift stage) has the most effect when temperature changes

Fig.5. The temperature effect comparison between empirical sub-models

Operating conditions (1/2)

Table 1: Analysis properties of Korean wood chips, that used in this study.

Biomass properties			
Proximate analysis (wt%)		Ultimate analysis (wt%)	
H_2O	6.40	C	50.80
Volatile	75.90	H	5.37
Fixed carbon	17.40	O	43.6
Ash	0.30	N	0.00
		S	0.00
		Cl	0.00

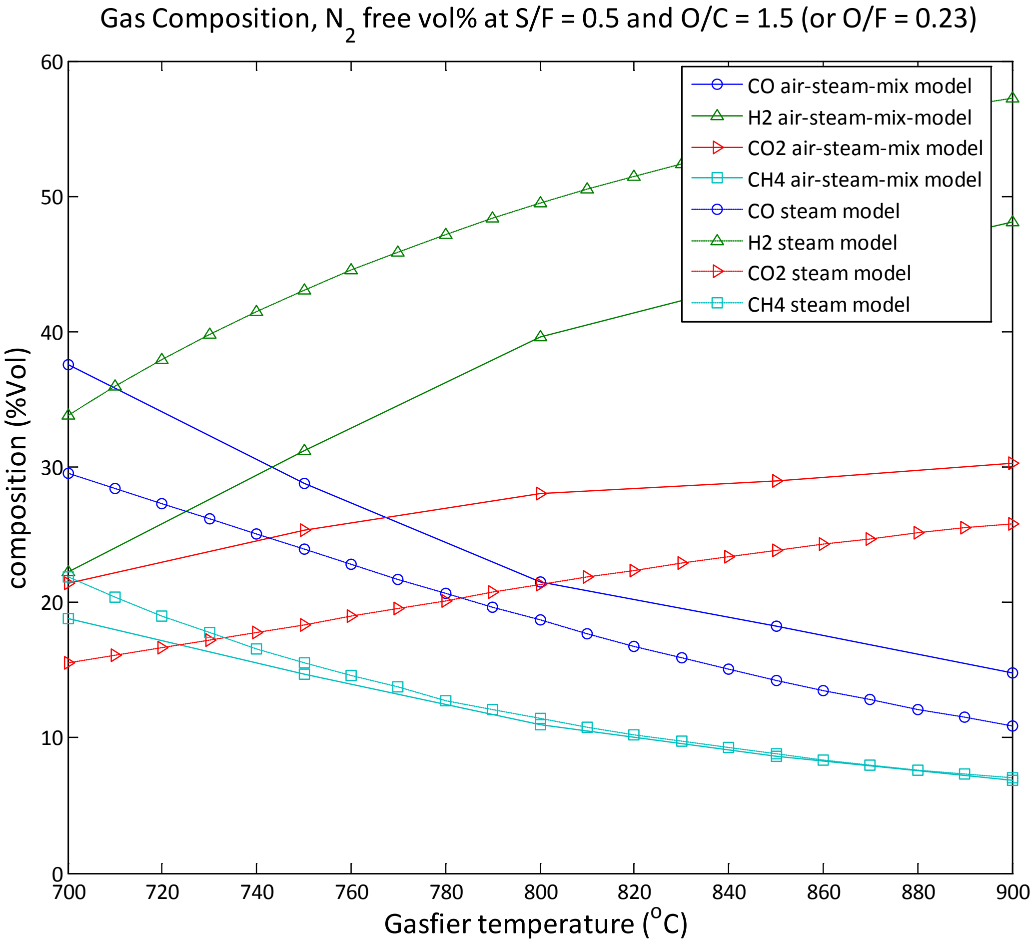
Operating conditions (2/2)

Table 2: Operating conditions of each case study.

Case study	Operating conditions Effects of S/F ratio	Effects of gasification temperature	Effects of Oxygen to Fuel ratio
Temperature of steam inlet (*K*)	673	673	673
Temperature of fuel (biomass) inlet (*K*)	598	598	598
Required heat capacity (*MW*)	100	100	100
Gasifier temperature (*K*)	1173	900-1173	1173
Steam to fuel ratio(*kg/kg*)	1.0-2.0	1.0	1.0
O/C ratio (-)	2	2	1.0 - 2.0
(Oxygen to fuel ratio (*kg/kg*))	(0.46)	(0.46)	(0.0 - 4.6)

Results and Discussion (1/7)

Effect of Temperature on the final gas product composition



-The water-gas shift reaction is known to proceed forward at the temperatures above 700°C in the presence of steam [6,17]. ➔ Increase of H_2 and CO_2 formations and a decrease of CO formation when temperature increase.

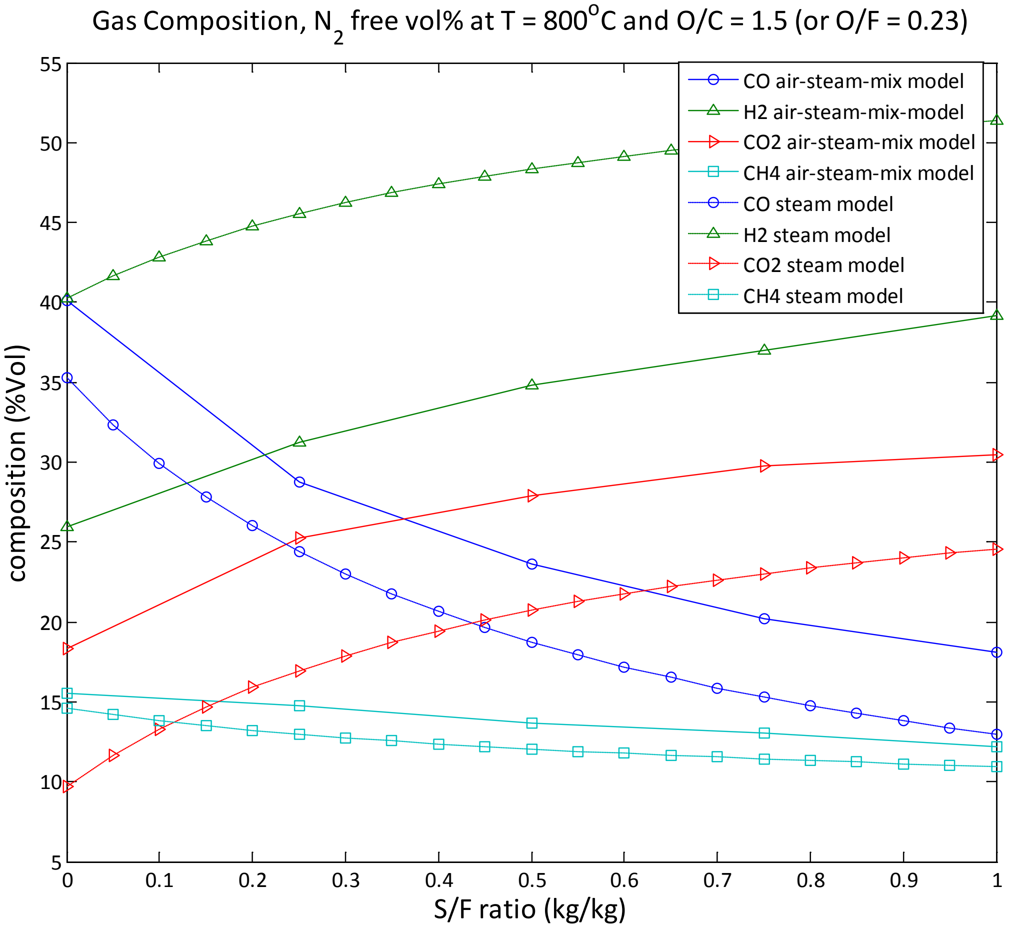
-In air blown system, combustion reactions lead to produce CO_2 and steal CO (as initial contents of stage 2 and 3) ➔ reduce influence of water-gas shift reaction ➔ CO content ↑ and H_2 content ↓ in the final gas product

➔ Increase LHV of gas product

Fig. 6. The comparison of final gas composition between TSM of Steam-air-blown gasification and Steam gasification (fixed Steam to fuel ratio = 0.5 and Oxygen to Fuel ratio = 0.23) with the variety of gasification temperature.

Results and Discussion (2/7)

Effect of S/F ratio on the final gas product composition



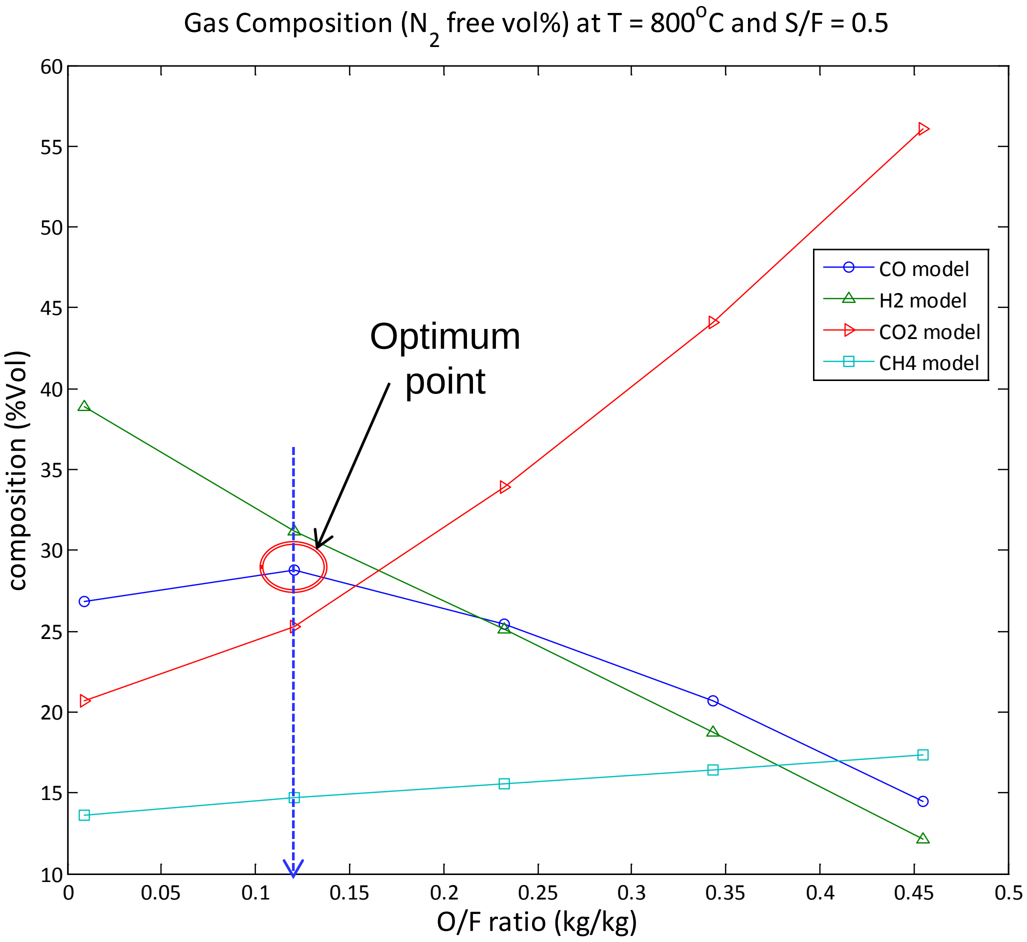
-The forward water-gas shift reaction rate increases with the increase of steam to fuel ratio [17,18]. ➔leads to increase of H_2 and CO_2, while CO and CH_4 decrease.

- In overall, the variation of the syngas composition in biomass gasification with respect to the steam to fuel ratio is mainly influenced by the water-gas shift reaction [6,7,19,20]

Fig. 7. The comparison of final gas composition between TSM of Steam-air-blown gasification and Steam gasification (fixed Temperature = 800°C and Oxygen to Fuel ratio = 0.23) with the variety of Steam to Fuel ratio (S/F).

Results and Discussion (3/7)

Effect of O/F ratio on the final gas product composition

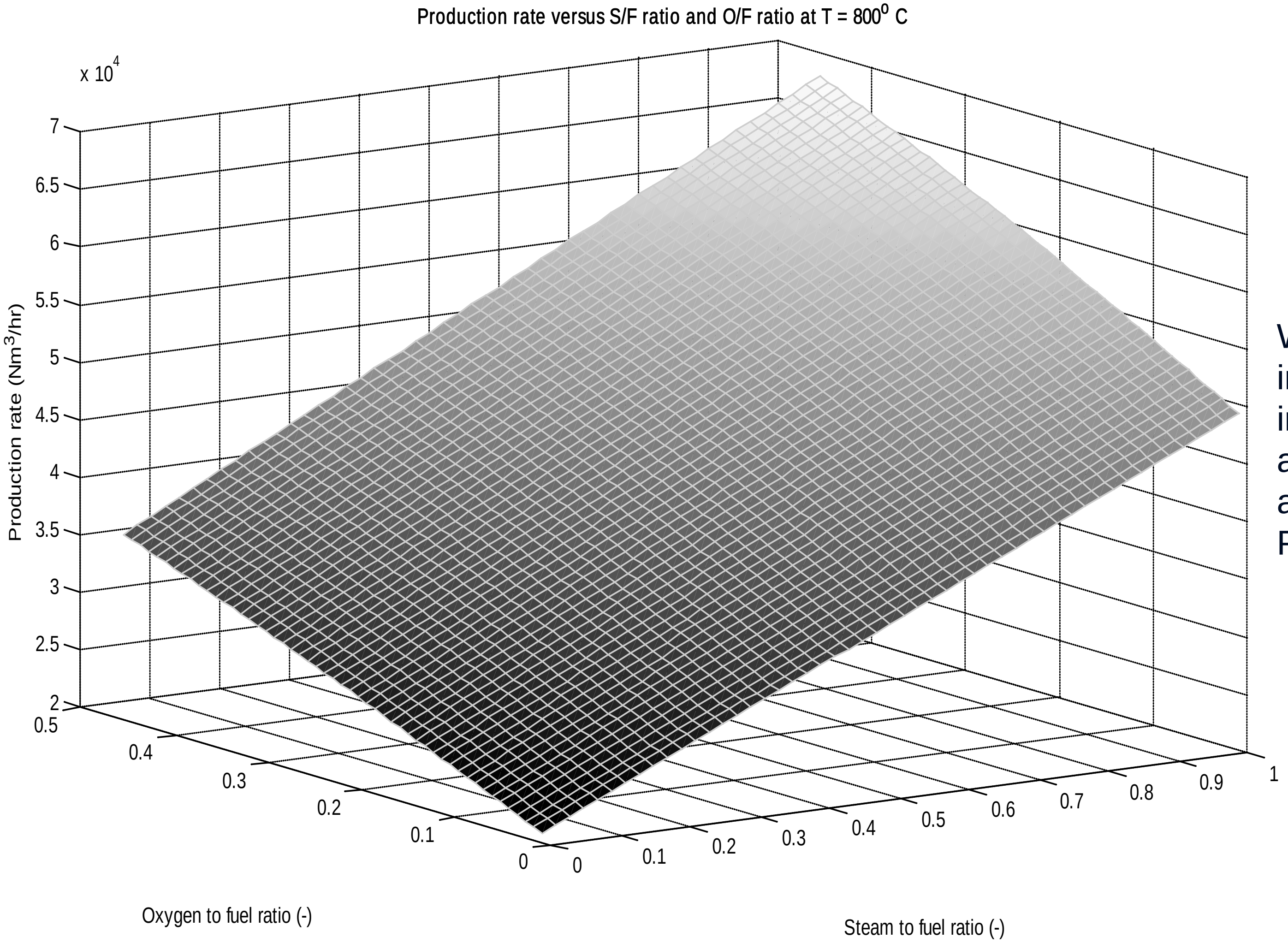


-The oxygen content lead to violent combust of CO and H_2 ➔ makes higher CO_2 content in final gas product.

-In this study, we found an optimum point is O/F = 0.12 (for the highest CO content in the final gas composition→ highest LHV of final gas product).

Fig. 8. The effect of Oxygen to fuel ratios on the final gas compositions (fixed Temperature =800°C and Steam to Fuel ratio = 0.5) in TSM of Steam-air-blown gasification.

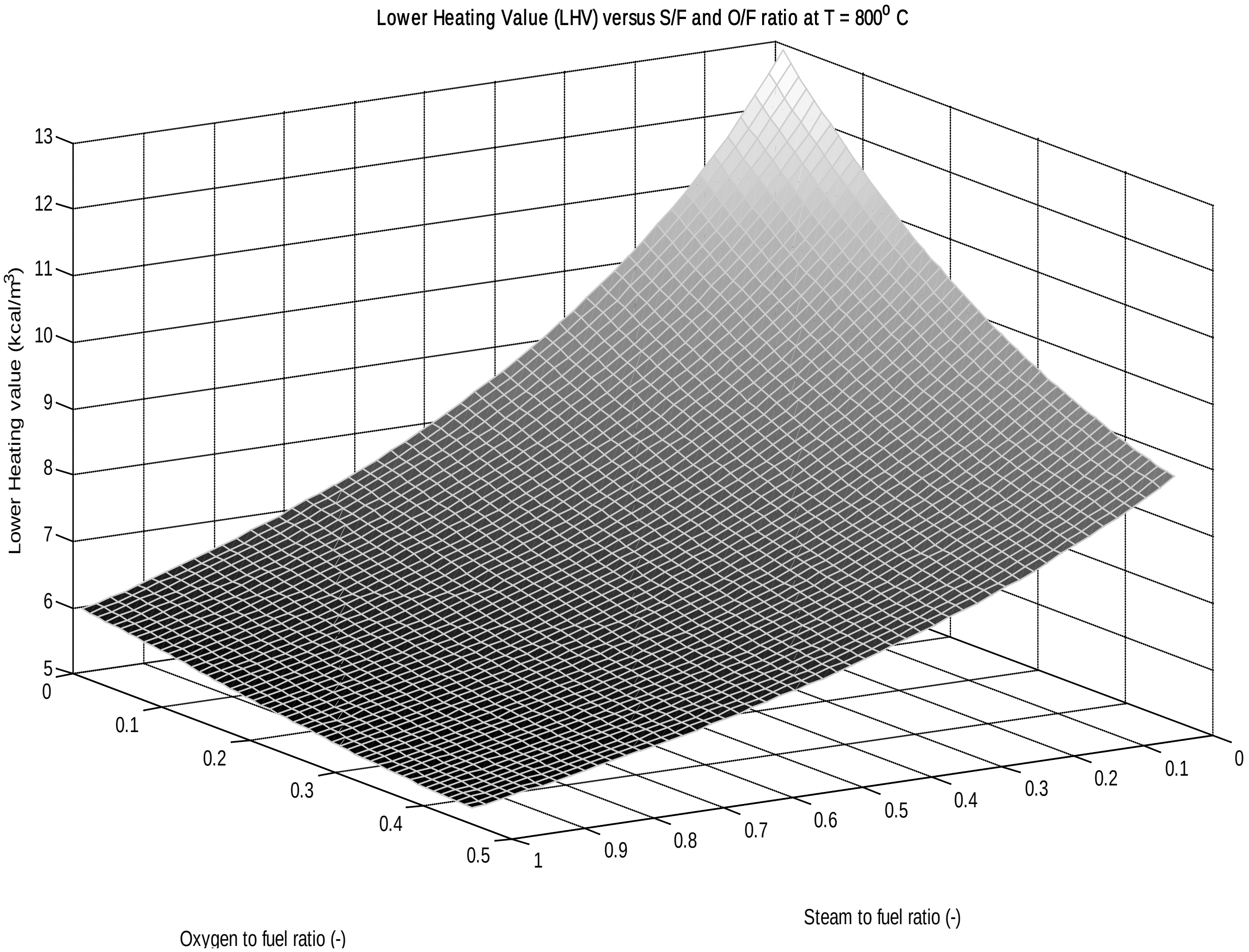
Results and Discussion (4/7)



When steam and oxygen increase ➔ The reactions in both combustion stage and water-gas shift stage are promoted strongly ➔ Produce more gas product.

Fig. 9. The 3D-plot of gas production rate versus Steam to Fuel ratio and Oxygen to Fuel ratio at gasifier temperature is 800°C

Results and Discussion (5/7)

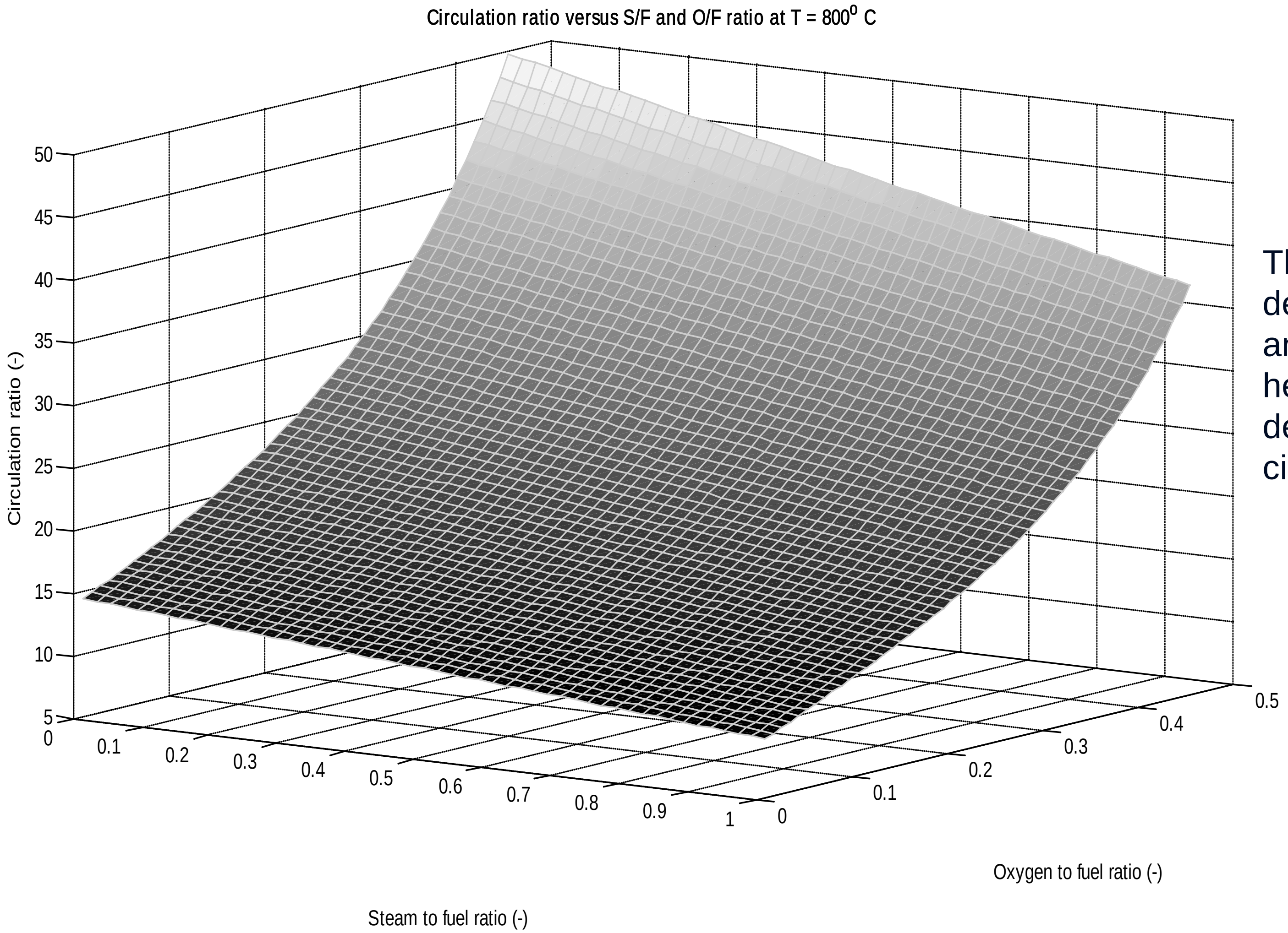


- The concentration of CO and CH_4 decreases with an increase of steam to fuel ratio ➔ the lower heating value of gas product decreases.

- The increasing of Oxygen to Fuel ratio ➔ concentration of CO and H_2 decrease ➔ heating value of gas product decrease .

Fig. 10. The effect of Steam to Fuel ratios and Oxygen to Fuel ratios on the Lower heating Value of gas product (at T = 800°C).

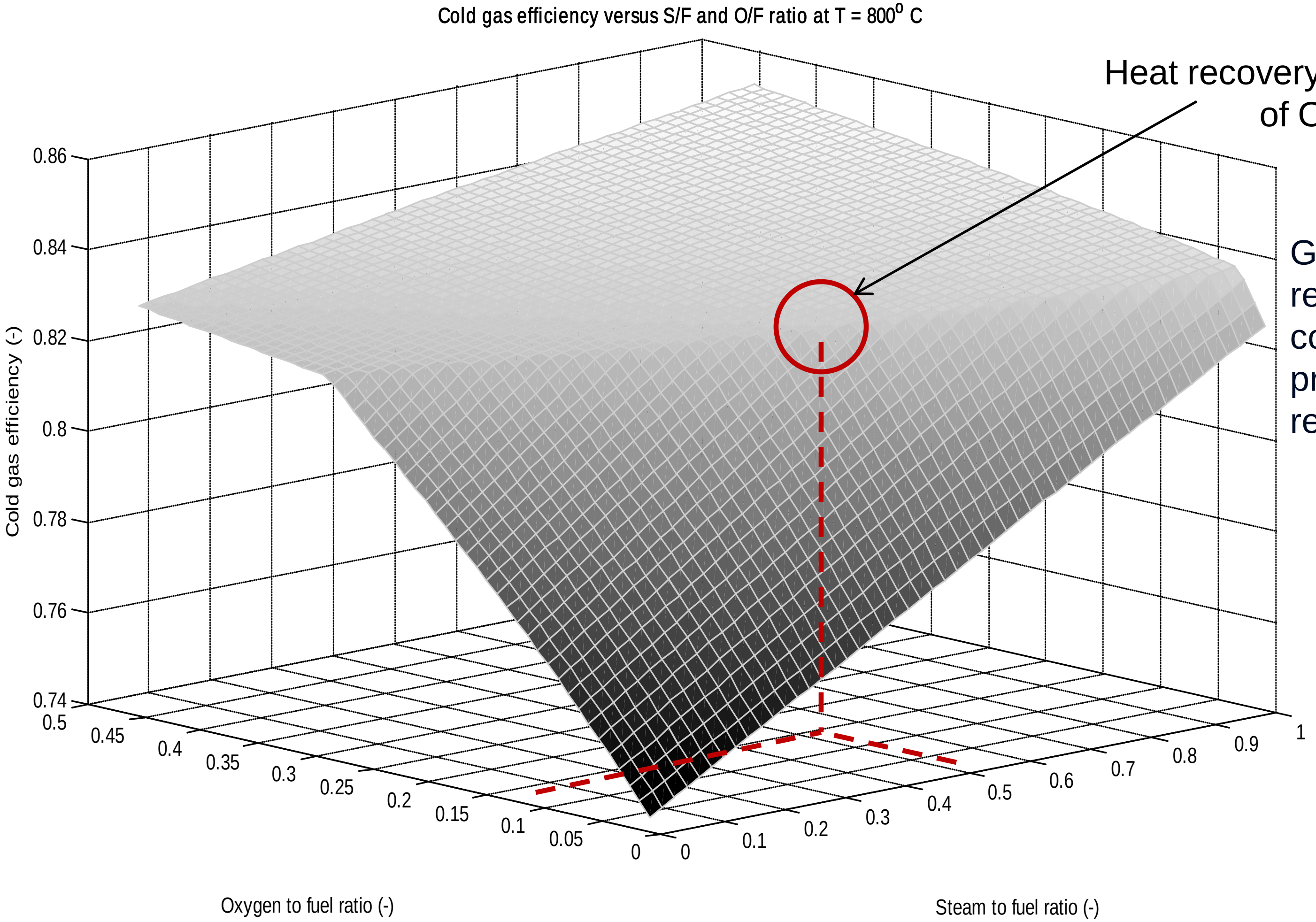
Results and Discussion (6/7)



The LHV of gas product decrease much when steam and oxygen increase ➔ (Total heat out – total heat in) decreases ➔ amount of circulation sand increase.

Fig. 11. The circulation ratio inside a CFB gasifier versus Steam to Fuel ratio and Oxygen to Fuel ratio (at T = 800^{o}C)

Results and Discussion (7/7)



Heat recovery at optimum point of O/F ratio

Gas yield (the amount of reacted biomass, and converted to another products) increases ➔ heat recovery increases.

Fig. 12. The 3D-plot of cold gas efficiency in a CFB gasifier versus Steam to Fuel ratios and Oxygen to Fuel (at T = 800°C)

Conclusions

- The TSM is developed to calculate the final gas composition, lower heating value, circulation ratio and heat recovery in a CFB gasifier.
- Due to the presence of oxygen in the gasifier, both biomass pyrolysis and gas combustion were taken into account in the first stage of model.
- With the comparison between two studies (steam gasification and steam-air-blown gasification), we conclude that, the biomass gasification process with steam-air-blown produced the higher LHV of gas product than the steam gasification and suitable for IGCC power generation system.
- In this study, we also found the optimum Oxygen/Fuel ratio is 0.12 when the gasifier temperature is 800ºC and Steam/Fuel ratio is 0.5; at this point the heat recovery is higher than 82%.

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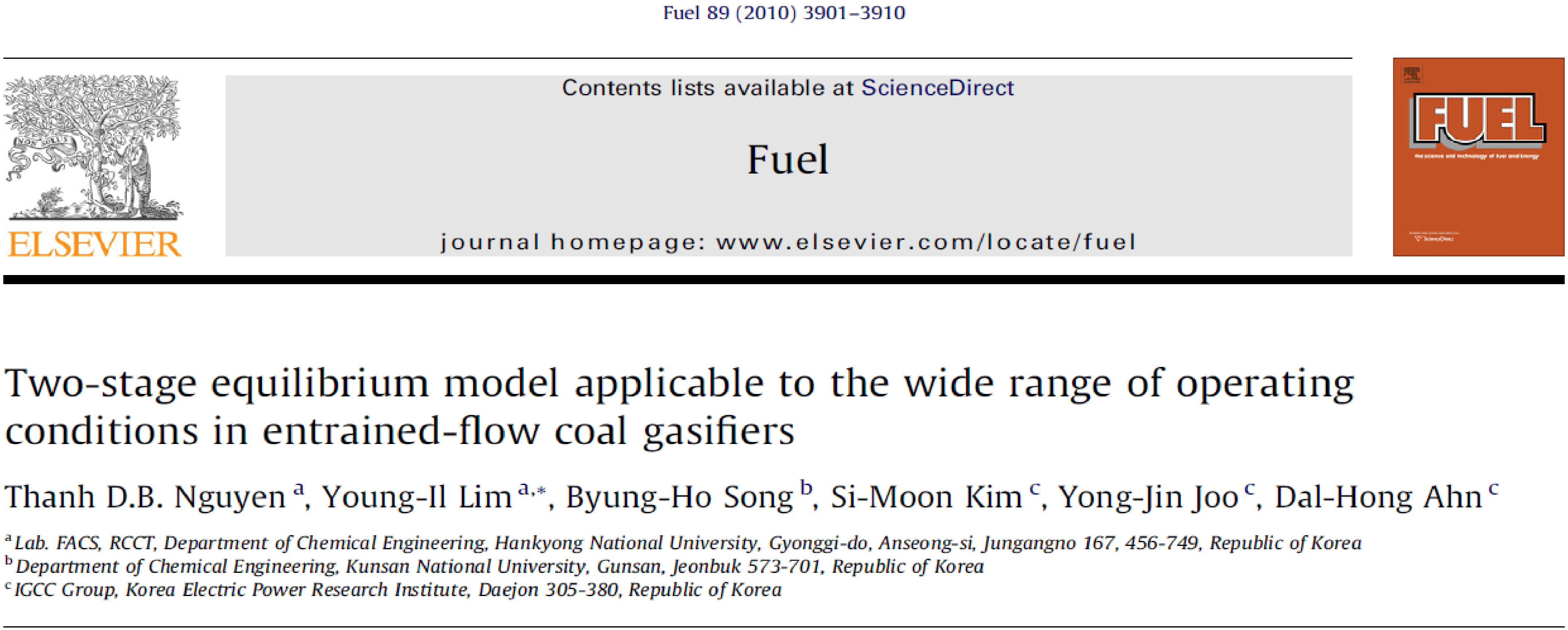

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Two-stage equilibrium model applicable to the wide range of operating conditions in entrained-flow coal gasifiers

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