7TH INTERNATIONAL CONFERENCE ON SUSTAINABLE SOLID WASTE MANAGEMENT
26-29 June 2019, Heraklion, Crete Island, Greece
HERAKLION 2019

Effects of (Co-)Combustion Techniques and Operating Conditions on the Performance and NO Emission Reduction in a Biomass-Fueled Twin-Cyclone Fluidized-Bed Combustor

Vladimir I. Kuprianov[1], Pichet Ninduangdee[2], Chhaina Se[1]

[1] Sirindhorn International Institute of Technology, Thammasat University, Thailand
[2] Faculty of Engineering and Industrial Technology, Phetchaburi Rajabhat University, Thailand

Email: ivlaanov@siit.tu.ac.th

Rationale of the Study

- In Thailand, rice husk and sugar cane bagasse have been important bioenergy resources. The domestic annual energy potentials of these biomass residues account for 99 PJ and 210 PJ, respectively.

- Energy conversion from rice husk in direct combustion systems is generally accompanied by elevated NO_x emissions, while burning sugarcane bagasse may cause instabilities in fuel supply and flame quenching, mainly because of high moisture content in this fuel

- The fluidized bed-combustion technology is proven to be one of the most effective technologies for energy conversion from biomass.

- Co-firing is a least-cost method that can effectively reduce NO_x emissions.

- Air staging and flue gas recirculation (FGR) are effective tools widely used for minimizing NO_x emissions in various combustion systems.

- *However, limited information on the effects of air staging/FGR on combustion and emission performance of fluidized-bed combustors with a swirling fluidized bed have been reported*.

Objectives

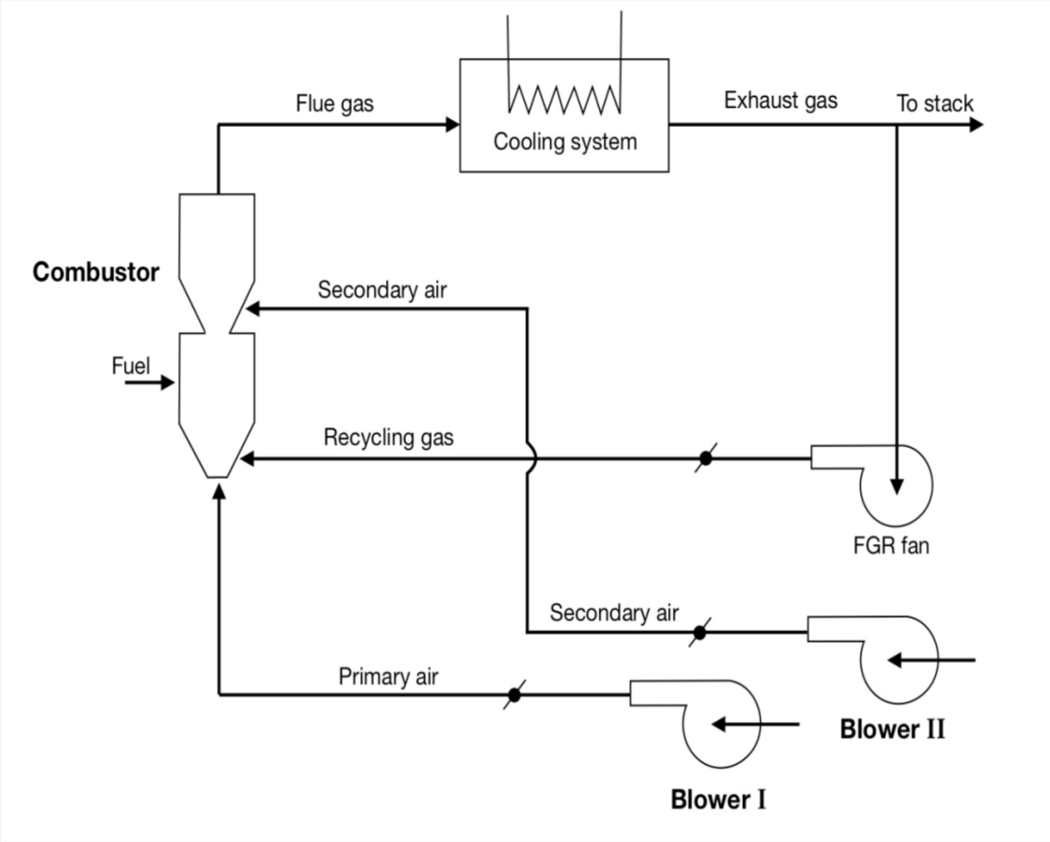
- This work was performed on a novel twin-cyclone fluidized-bed combustor (referred to as ‘twin-cyclone FBC’) with a swirling fluidized bed, to explore the potential of different (co-)combustion methods for reducing NO emission from this biomass-fueled combustor.

- The effects of operating parameters (excess air, secondary-to-total air ratio, and proportion of FGR) on the behavior of major gaseous pollutants (CO, C_xH_y, and NO) in different combustor regions, as well as on the combustion and emission performance of the proposed combustor, were compared between the selected techniques (methods).

- A special focus was an optimization of the operating parameters ensuring the minimal “external” (emission) costs of the techniques.

Materials and Methods

Experimental Setup



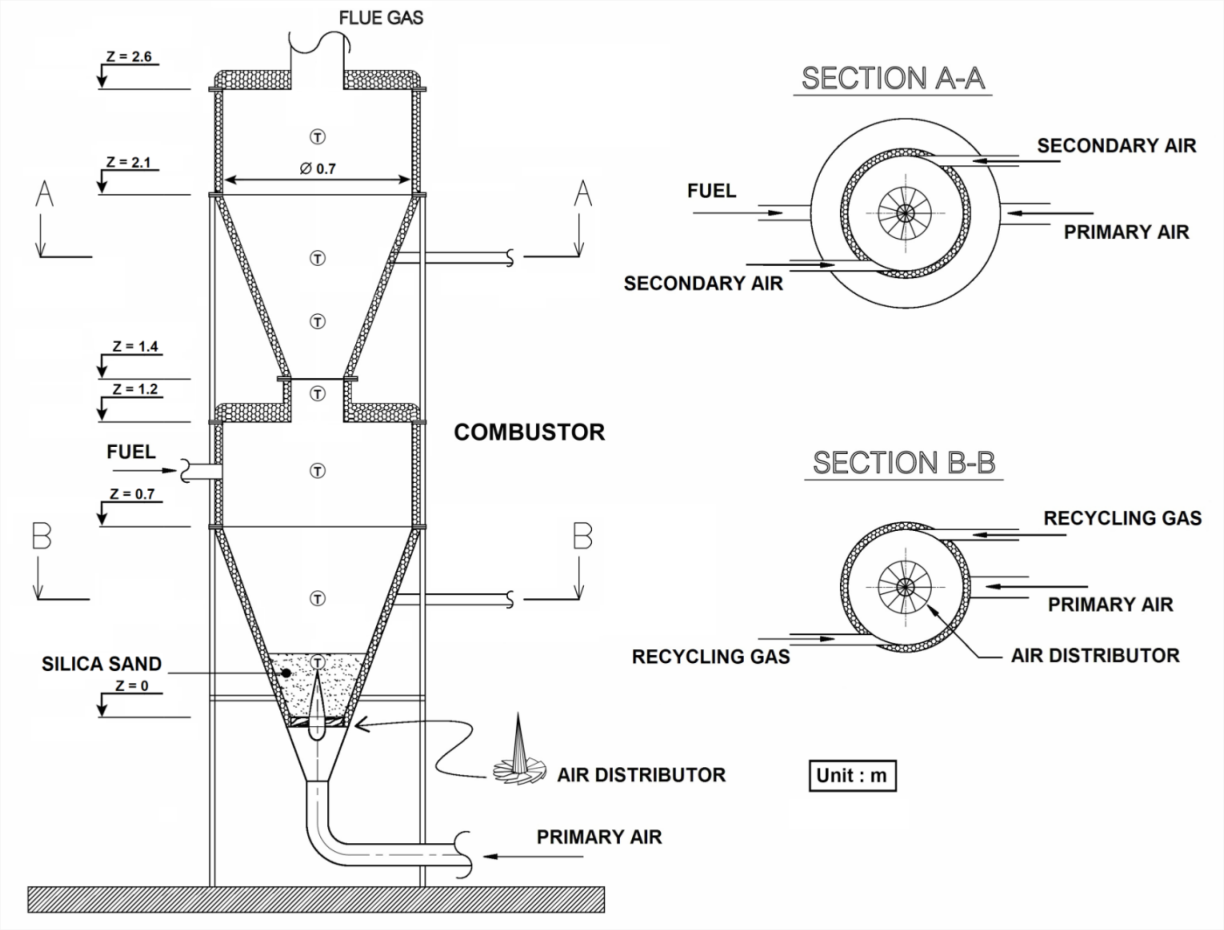
Experimental setup with a twin-cyclone fluidized-bed combustor with a swirling fluidized bed (twin-cyclone FBC)

The combustor is designed to achieve high combustion efficiency and mitigate NO emission using different techniques when (co-firing) biomass fuels.

The lower combustion chamber is principally aimed at the high-intensive burning of biomass (or fuel blend) delivered into this chamber by a fuel feeder, whereas the upper chamber is used to ensure complete combustion of the fuel burned.

Materials and Methods (cont'd)

Experimental Setup (cont'd)



Schematic diagram of the twin-cyclone FBC with dimensional characteristics

Silica sand with a solid density of 2500 kg/m^3 and particle sizes of 300–500 μm was used as the bed material in this combustor.

In all experiments, the bed material was maintained at 20 cm height (under static conditions)

The Fuels

Rice husk (RH)

Sugar cane bagasse (SB)

Properties of the selected fuels

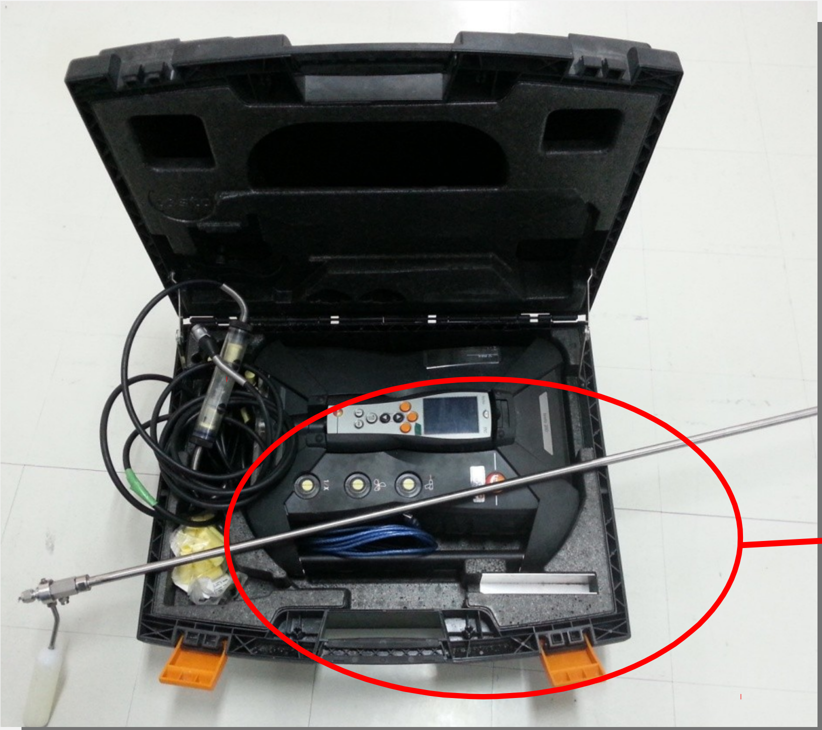
	VM	FC	A	W	C	H	N	O	S	
	59.75	14.72	15.07	10.46	47.84	6.23	0.40	45.10	0.43	13.26
	21.48	5.05	1.18	72.29	49.90	6.67	0.49	42.71	0.23	4.65

[a] *On an "as-received" basis.*

[b] *On a dry and ash-free basis.*

Materials and Methods (cont’d)

Gas Analyzer



A new model “Testo-350” gas analyzer was used to measure temperature and gas concentrations (O_2, CO, C_xH_y, and NO) at different locations in the conical FBC, as well as at stack.

Materials and Methods (cont'd)

Experimental Methods

Experimental planning

Test series	Parameters	Specified value or range
Case Study 1: Conventional fluidized-bed combustion of RH	Total heat input to the combustor	100 kW_{th}
	Excess air (EA)	30%, 40%, 50%, and 60%
Case Study 2: Co-firing RH premixed with SB using air staging	Total heat input to the combustor	100 kW_{th}
	Energy fraction (EF_2) of SB in the fuel blend	0.15
	Excess air (EA)	40%, 50%, and 60%
	Secondary-to-total air ratio (SA/TA)	0.1, 0.2, and 0.3
Case Study 3: Firing RH using flue gas recirculation	Total heat input to the combustor	100 kW_{th}
	Excess air (EA)	30%, 40%, 50%, and 60%

Determining Excess Air and Combustion Efficiency

- **The (total) excess air coefficient:**

$$\alpha = \frac{21}{21-(O_2-0.5CO-2CH_4)}$$

- **Excess air:**

$$EA=(\alpha-1)\times 100\%$$

- **The combustion-related heat losses**

The heat loss due to unburned carbon:

$$q_{uc,cf} = \frac{32,866}{LHV_{cf}}\left(\frac{C_{fa}}{100-C_{fa}}\right)A_{cf}$$

The heat loss due to incomplete combustion:

$$q_{ic,cf} = (126.4\ CO + 358.2\ CH_4)_{@6\%O_2}10^{-4}\times V_{dg,cf@6\%O_2}\frac{(100-q_{uc,cf})}{LHV_{cf}}$$

- **The combustion efficiency:**

$$\eta_{c,cf} = 100-(q_{uc,cf}+q_{ic,cf})$$

Optimization of the Operating Parameters

- **A cost-based approach** was used to determine the optimal values of EA, SA/TA, and FGR fraction ensuring the minimum emission (or "external") costs of the combustor operated with the proposed (co-)combustion techniques

The objective function represented as:

$$J_{\mathrm{ec}} = \mathrm{Min}\left(P_{\mathrm{NO_x}}\dot{m}_{\mathrm{NO_x}} + P_{\mathrm{CO}}\dot{m}_{\mathrm{CO}} + P_{\mathrm{C_xH_y}}\dot{m}_{\mathrm{C_xH_y}}\right)$$

where the specific emission costs of NO_x (as NO_2), CO, and C_xH_y (as CH_4) were assumed to be: ***P_{NOx}* = 2400 US$/t**, ***$P_{CH4}$* = 330 US$/t**, and ***P_{CO}* = 400 US$/t.**

- The emission rates of NO_x (as NO_2), CO, and C_xH_y (as CH_4) were determined by taking into account the fuel feed rate (kg/s) and the actual pollutant concentration (ppm) at the cyclone exit as:

$$\dot{m}_{\mathrm{NO_x}} = 2.05 \times 10^{-6}(\dot{m}_{\mathrm{f1}} + \dot{m}_{\mathrm{f2}})\mathrm{NO_x}V_{\mathrm{dg,cf}}$$

$$\dot{m}_{\mathrm{CO}} = 1.25 \times 10^{-6}(\dot{m}_{\mathrm{f1}} + \dot{m}_{\mathrm{f2}})\mathrm{CO}V_{\mathrm{dg,cf}}$$

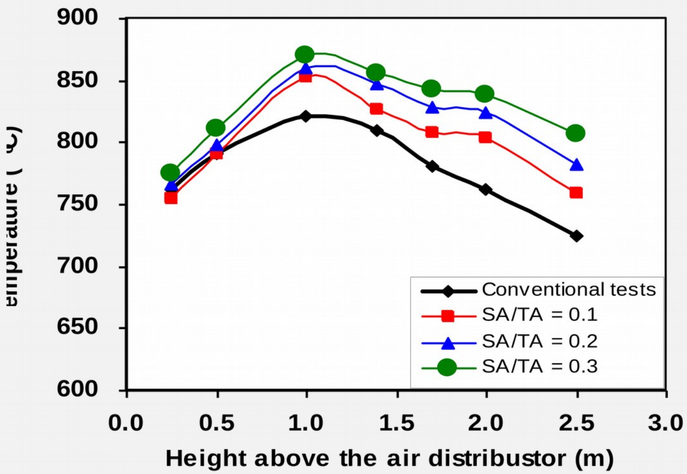
$$\dot{m}_{\mathrm{C_xH_y}} = 0.71 \times 10^{-6}(\dot{m}_{\mathrm{f1}} + \dot{m}_{\mathrm{f2}})\mathrm{C_xH_y}V_{\mathrm{dg,cf}}$$

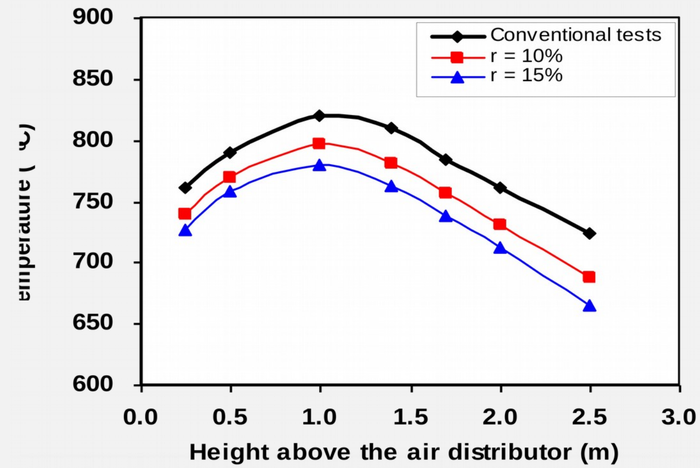
Results and Discussion

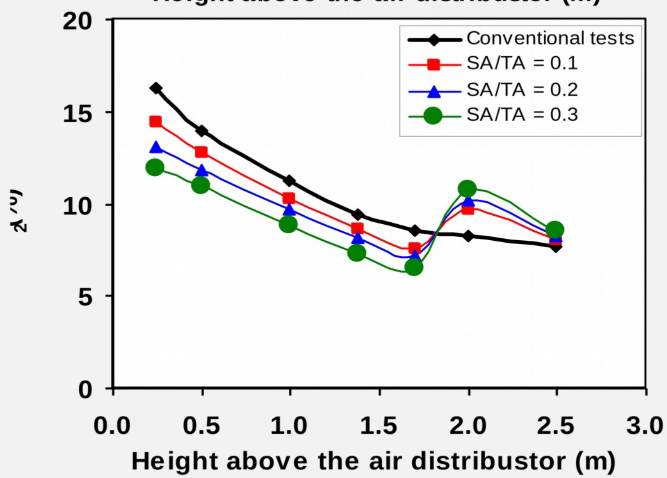
Distribution of Temperature and O_2 in the Twin-Cyclone FBC

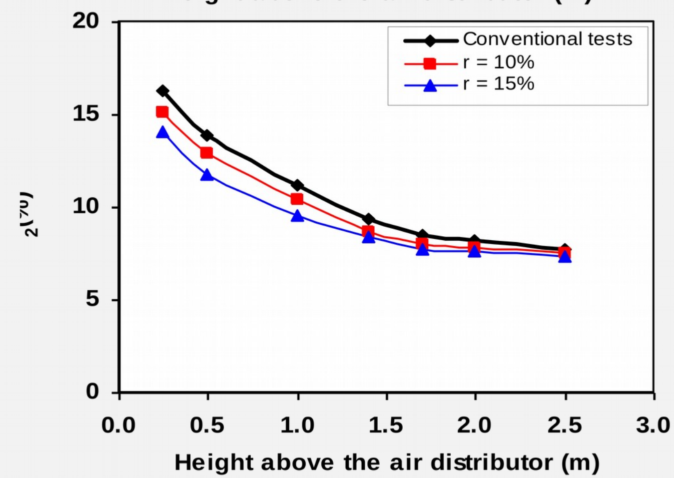
Co-firing premixed RH and SB using air staging

Firing pure RH using FGR





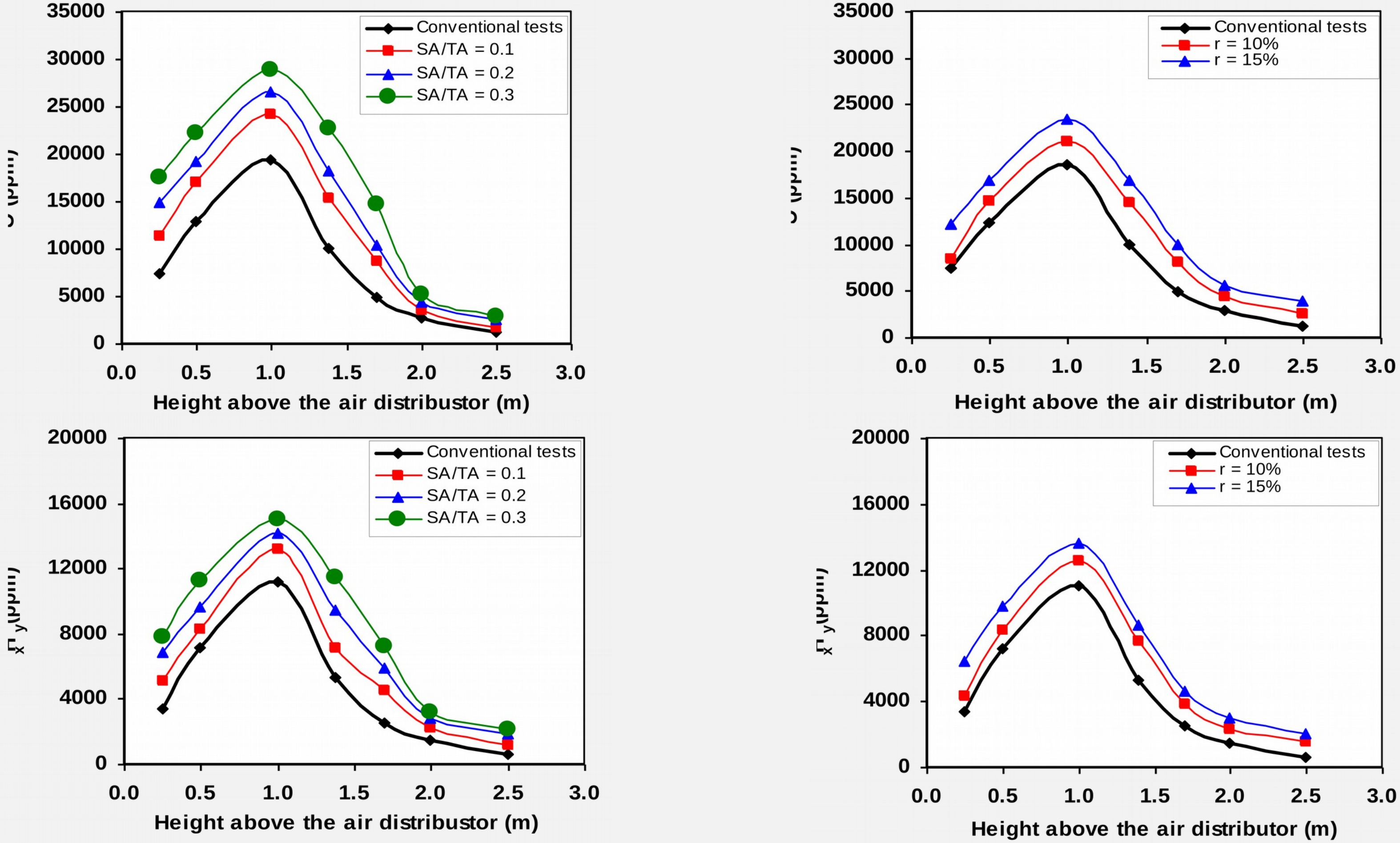




Axial profiles of temperature (upper graphs) and O_2 (lower graphs) in the twin-cyclone FBC operated at EA ≈ 50% when co-firing pre-mixed RH and SB (at EF_2 = 0.15) using air staging and firing

Formation and Oxidation of CO and C_xH_y in the Twin-Cyclone FBC

Co-firing premixed RH and SB using air staging | Firing pure RH using FGR

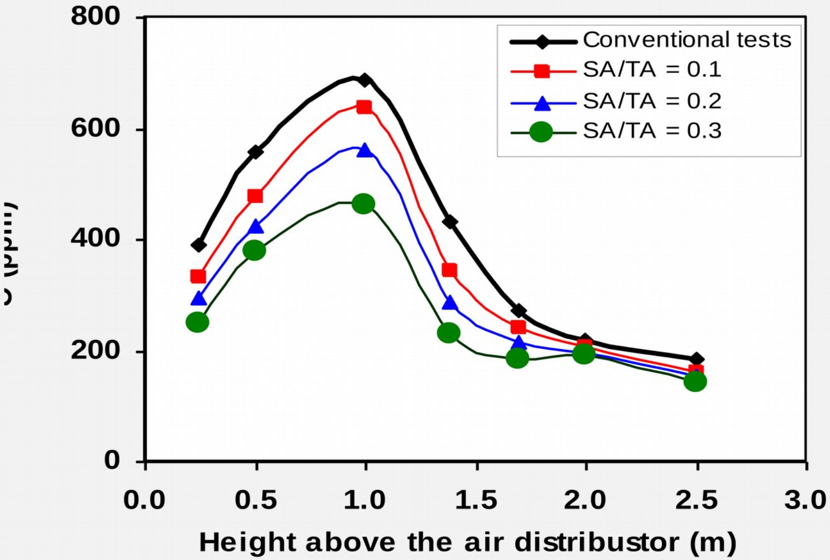


Axial profiles of CO, C_xH_y as CH_4, and NO in the twin-cyclone FBC operated at EA ≈ 50% when co-firing pre-mixed RH and SB (at EF_2 = 0.15) using air staging and firing pure RH using flue gas recirculation, as compared to conventional combustion of RH.

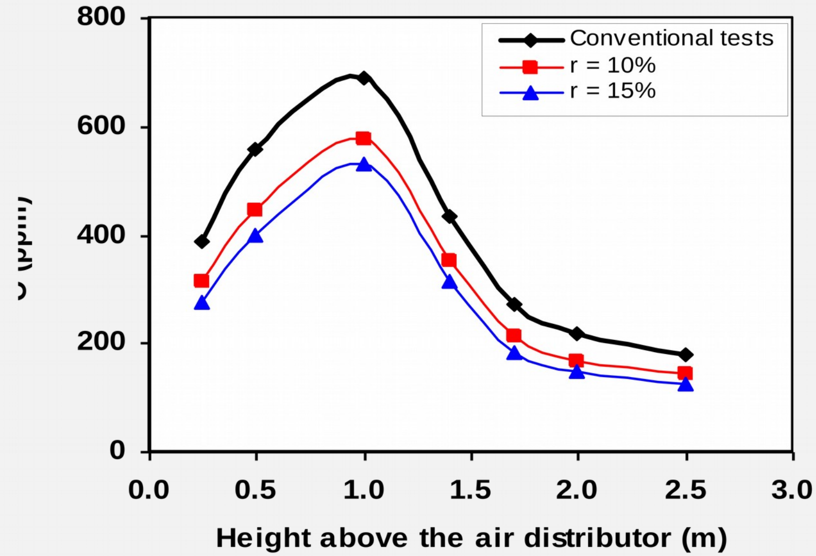
Results and Discussion (cont'd)

Formation and Reduction of NO in the Twin-Cyclone FBC

Co-firing premixed RH and SB using air staging



Firing pure RH using FGR

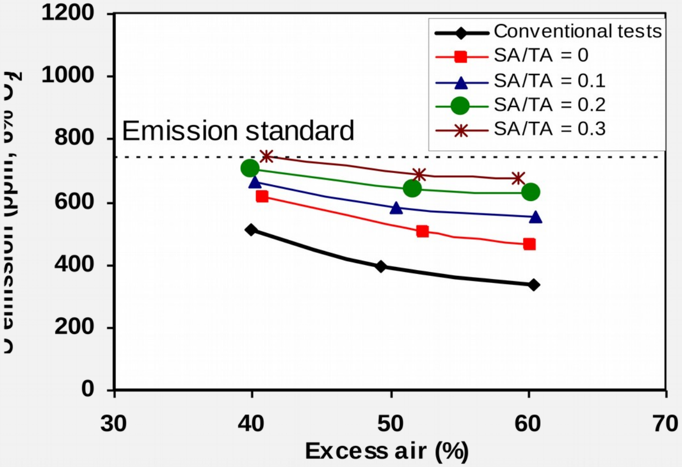


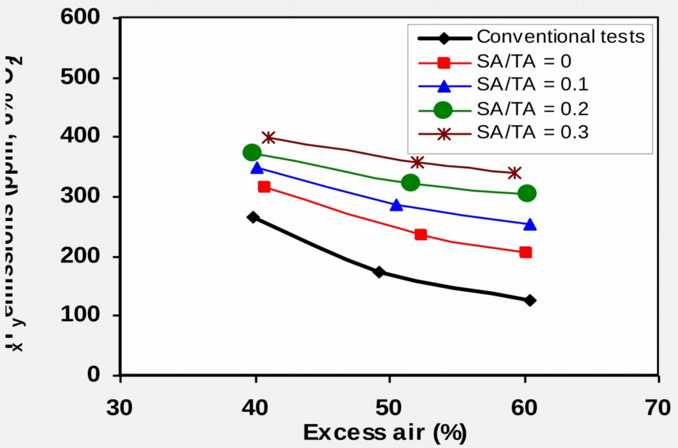
Axial profiles of CO, C_xH_y as CH_4, and NO in the twin-cyclone FBC operated at EA ≈ 50% when (a) co-firing pre-mixed RH and SB (at EF_2 = 0.15) using air staging and (b) firing pure RH using flue gas recirculation, as compared to conventional combustion of RH.

Results and Discussion (cont'd)

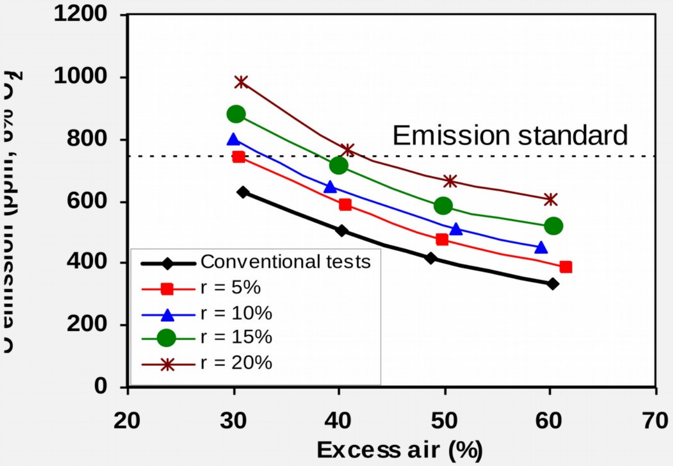
CO and C_xH_y Emissions

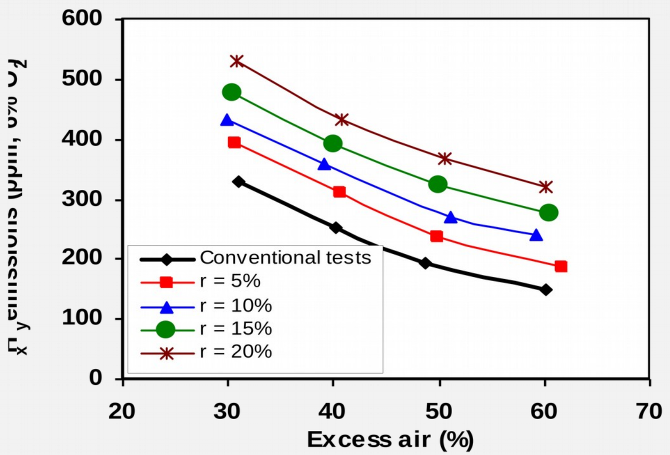
Co-firing premixed RH and SB using air staging





Firing pure RH using FGR



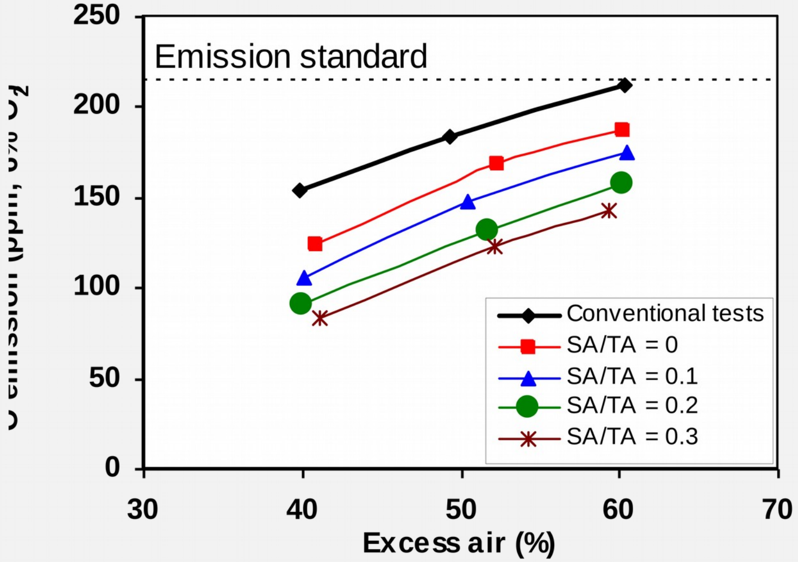


Effects of the (co-)combustion techniques and operating parameters on the CO and C_xH_y emissions.

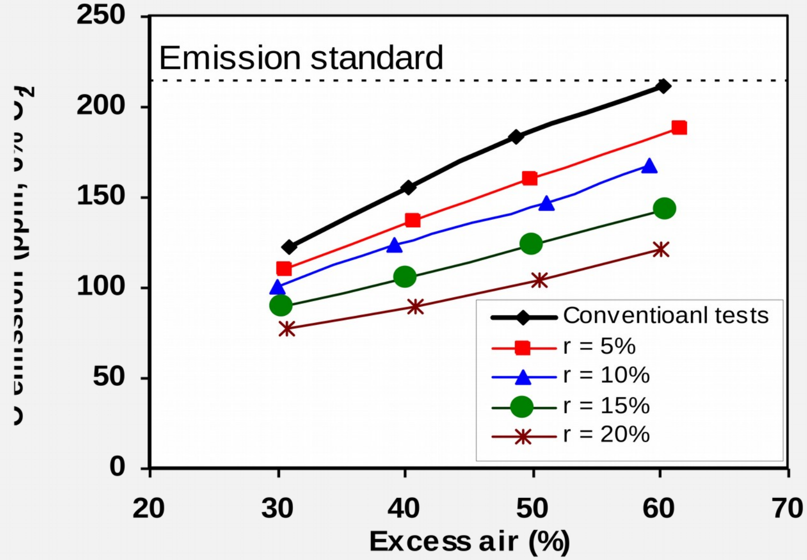
Results and Discussion (cont'd)

NO Emission

Co-firing premixed RH and SB using air staging



Firing pure RH using FGR

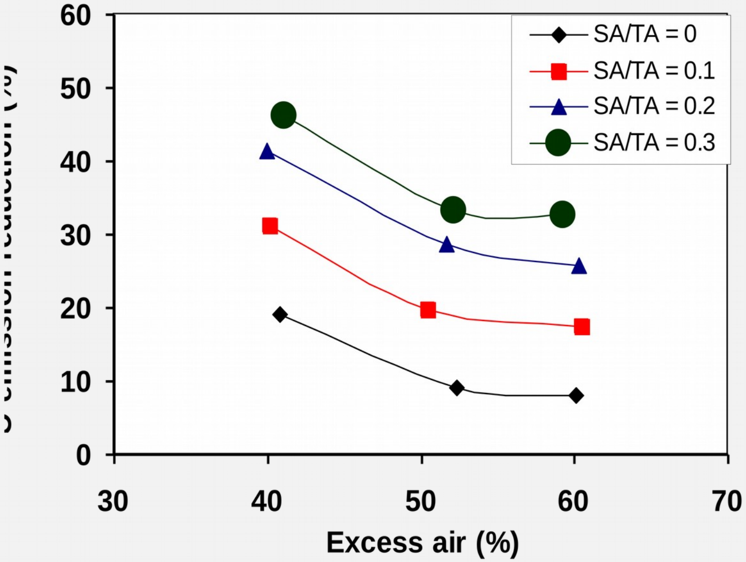


Effects of the (co-)combustion techniques and operating parameters on the NO emission.

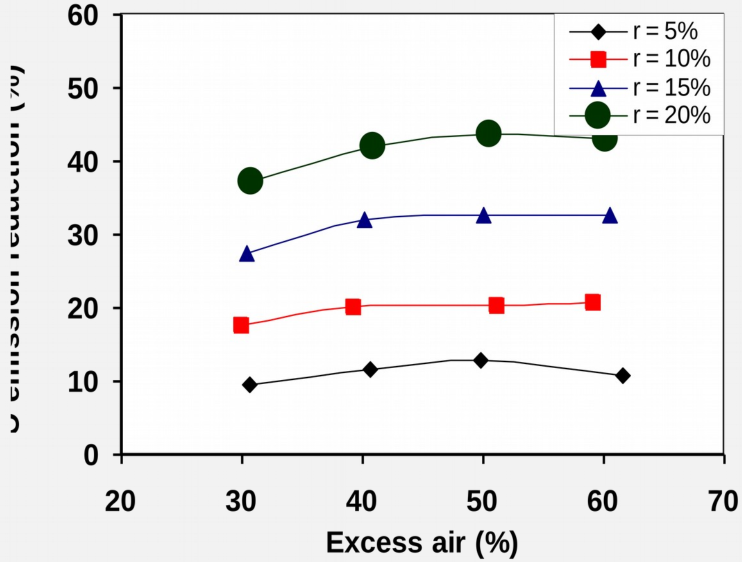
Results and Discussion (cont'd)

NO Emission Reduction

Co-firing premixed RH and SB using air staging



Firing pure RH using FGR



- When co-firing of RH and SB with no air staging (EA/TA = 0), up to 20% NO emission reduction can be achieved by lowing the amount of EA.
- However, via co-firing with air staging, a substantial (up to 46%) NO emission reduction can be achieved at the lowest EA with EA/TA = 0.3.
- The use of FRG during combustion of pure rice husk may result in 37–43% reduction of NO emission with the 20% FGR fraction, for the range of excess air.

Results and Discussion (cont'd)

Heat Losses and Combustion Efficiency

Combustion-related heat losses and combustion efficiency of the twin-cyclone fluidized-bed combustor using different combustion methods at actual operating parameters

EF_2	EA (%)	O_2 at stack (%)	SA/TA	FGR (%)	CO at stack (ppm)	C_xH_y at stack (ppm)	Unburned carbon in PM (wt.%)	Heat loss (%) due to:		Combustion efficiency (%)
								unburned carbon	incomplete combustion	
Conventional combustion of RH										
0	31	4.97	0	0	670	350	1.42	0.54	0.68	98.8
	40	6.03			520	260	1.04	0.39	0.55	99.1
	49	6.89			390	180	0.96	0.36	0.42	99.2
	60	7.90			280	130	0.94	0.35	0.32	99.3
Co-combustion of premixed RH and SB using air staging										
0.15	41	6.09	0	0	615	315	2.29	1.19	0.72	98.1
	52	7.22			465	217	1.75	0.91	0.56	98.5
	60	7.89			445	195	0.94	0.48	0.55	99.0
	40	6.02	0.1		660	345	1.80	0.93	0.78	98.3
	51	7.05			540	265	1.38	0.71	0.66	98.6
	61	7.92			480	220	1.02	0.52	0.61	98.9
	40	6.00	0.2		705	370	2.05	1.07	0.83	98.1
	52	7.16			590	300	1.47	0.76	0.74	98.5
	60	7.90			545	265	0.85	0.44	0.71	98.9
	41	7.12	0.3		730	390	2.18	1.13	0.88	98.0
	52	7.20			630	330	1.56	0.81	0.81	98.4

Results and Discussion (cont’d)

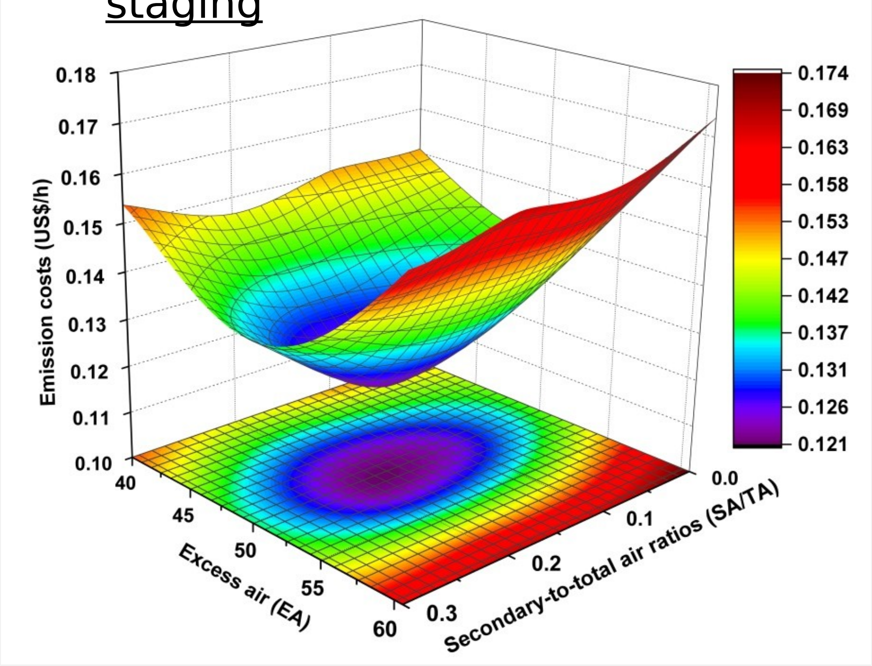
Heat Losses and Combustion Efficiency (cont’d)

Combustion-related heat losses and combustion efficiency of the twin-cyclone fluidized-bed combustor using different combustion methods at actual operating parameters

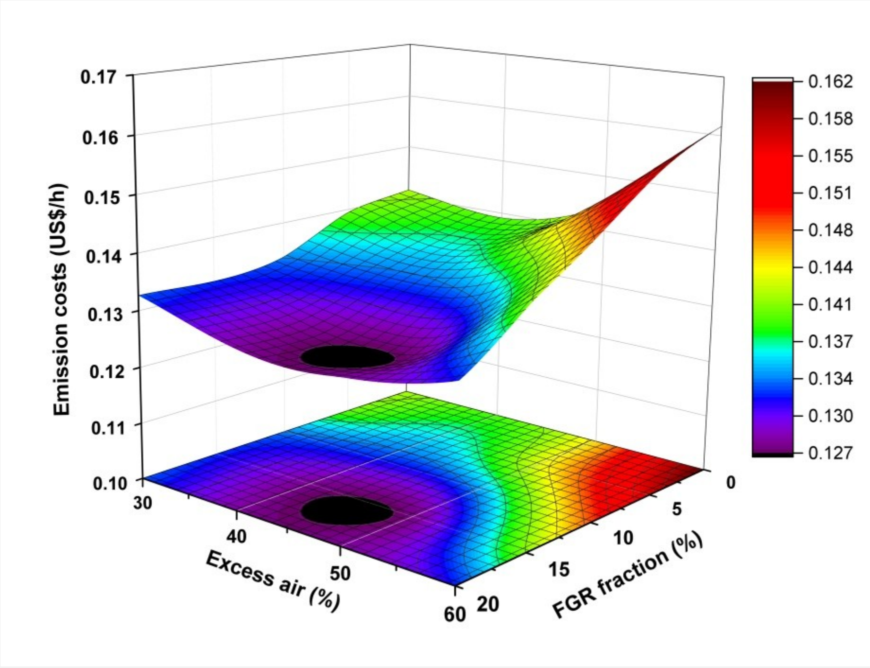
EF_2	**EA (%)**	**O_2 at stack (%)**	**SA/TA**	**FGR (%)**	**CO at stack (ppm)**	**C_xH_y at stack (ppm)**	**Unburned carbon in PM (wt.%)**	**Heat loss (%) due to:**		**Combustion efficiency (%)**
								unburned carbon	incomplete combustion	
Combustion of pure RH using flue gas recirculation										
0	31	4.93	0	5	790	420	1.33	0.50	0.80	98.7
	41	6.07			590	310	0.98	0.37	0.64	99.0
	50	6.99			440	220	0.82	0.31	0.50	99.2
	62	8.01			330	160	0.85	0.32	0.39	99.3
	30	4.85		10	850	470	1.29	0.49	0.88	98.6
	39	5.92			650	370	1.27	0.48	0.73	98.8
	51	7.11			470	255	0.93	0.35	0.56	99.1
	59	7.81			385	195	0.89	0.34	0.46	99.2
	30	4.9		15	940	510	0.95	0.36	0.97	98.7
	40	6.02			710	410	1.06	0.40	0.82	98.8
	50	7.01			540	305	1.05	0.40	0.66	98.9
	61	7.92			450	230	0.95	0.36	0.55	99.1
	31	4.95		20	1050	564	0.95	0.36	1.08	98.6
	41	6.10			760	760	1.16	0.44	0.91	98.7

Optimization of Operating Parameters for (Co-)Combustion Methods

Co-firing premixed RH and SB using air staging



Firing pure RH using FGR



Optimal operating parameters :
EA = 50% and SA/TA = 0.2
NO emission reduction: ~30%

Optimal operating parameters :
EA = 45% and FGR = 17%
NO emission reduction: 38%

Conclusions

- A novel twin-cyclone combustor with a swirling fluidized bed has been successfully tested with different NO reducing techniques: (i) co-firing rice husk with high-moisture sugarcane bagasse using air staging and (ii) burning rice husk alone using flue gas recirculation, for the ranges of operating parameters (excess air, secondary-to-total air ratio, and flue gas recirculation fraction).

- The (co-)combustion techniques and operating parameters have noticeable effects on the major gaseous (CO, C_xH_y as CH_4, and NO) emissions and combustion efficiency of the twin-cyclone combustor.

- Both techniques create NO reducing conditions, mainly due to the lowered O_2 and elevated CO and C_xH_y (primarily, in the lower combustion chamber), resulting in the reduction of NO emission from the combustor.

- With the optimal operating parameters, a noticeable NO emission reduction can be achieved: about 30% when co-firing rice husk premixed with sugar can bagasse using air staging, and 38% during combustion of pure rice husk using flue gas recirculation, while ensuring high (~99%) combustion efficiency of the proposed twin-

Acknowledgements

The authors wish to acknowledge sincerely the financial support from the Thailand Research Fund and Thammasat University (Contract no. BRG 5980005).

Thank You !