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Performance of cyclone separator for syngas production in downdraft gasifier

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Abstract. The excess use of conventional sources of energy by the industries and power sector result in acute shortage of energy produced by fossil fuel. To overcome this energy crisis, biomass feedstock is used to produce syngas or producer gas. For cleaning the dust particle present in the producer gas cyclone separators are largely used. In this paper we investigate the performance parameters of cyclone separator mainly efficiency and pressure drop for different feedstock. Cyclone performance has been evaluated based on experimentation and empirical approach using Leith and Licht model. The same has also been calculated by using turbulent RSM in Ansys Fluent for Wood and Coconut shell feedstock. Experimental results show that using feed stock with 10 % Calcium oxide (CaO) by weight, the efficiency of cyclone got reduced from 71.87% to 70.75% for wood feed stock, whereas in case of coconut shell, the cyclone efficiency got reduced from 78% to 73.44%. It is also seen that Leith and Licht model and Reynolds stress model (RMS) predicts very close to the particle collection efficiency evaluated by using experimental data.

Keywords: cyclone separator; downdraft gasifier; Leith and Licht model; RSM (Reynolds Stress Model)

1. Introduction

Syngas is a fuel gas mixture consisting primarily of hydrogen, carbon monoxide, and very often some carbon dioxide. It is produced by gasification process. The gasification process is the conversion of solid fuel into the gaseous form followed by some process like Drying, pyrolysis, combustion and reduction. The producer gas produced during gasification process having contaminants like tar and dust particle etc. are removed using filtration process. For removing heavy particles present in producer gas, cyclone separator is used. Lim *et al*. (2004) found that the collection efficiency changes by varying the vortex finder diameter, length and the flow rate. Rongbiao *et al*. (2001) investigated that the reduction in cone bottom diameter results higher collection efficiency without increasing pressure drop. Zhu *et al*. (1999) found that the collection efficiency increases by varying the flow rate. Fine particle can be collected more as the cylinder height is increased with high flow rate. Shin *et al*. (2005) studied effects of high temperature and pressure environment on high efficiency cyclone separator. Higher Pressure increases collection

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efficiency of cyclone but higher temperature decreases collection efficiency of cyclone. Fassani and Jr. (2000) studied effect of higher solid loading on cyclone parameters. Pressure drop increases with increase in inlet velocity but with change in solid loading pressure drop doesn't change much. In numerical modeling of cyclone separator different turbulence models investigated by Hoekstra *et al*. (1999) for axial and tangential velocity K-E and RNG K-E model predict unrealistic velocity distribution but RSTM results are comparable with experimental results. Software has been developed by Altmeyer *et al*. (2004) to calculate cyclone performance parameters using different empirical models. They have compared different empirical model with experimental results. Cut size dia. is predicted well by Mothes and Loffler model above 5 m/s velocity. For smaller flow rate Barth model gives good result but for higher flow rate Mothes and Loffler model gives better results. Flow rate higher than 10m/s Mothes and Loffler and Lorenz gives better prediction of efficiency and pressure drop. Different empirical models are compared with experimental results by Gimbun *et al*. (2006) they have studied Iozia and leith, Li and Wang model, Koch and licht model, Lapple model. Li and Wang model predicts efficiency well at room temperature. For larger particles lapple and koch-licht models underestimate efficiency. Lapple model is suitable for high temperature and pressure. For higher pressure Koch-licht model is suitable. Dirgo and Leith (1985) found that the modified version of Leith- Licht and Barth’s theory was very closer to the experimental results then others for a particle sizes 1 to 7 μm.

Three different geometries of cyclones are studied by Senapati *et al*. (2014) to extract unburnt carbon particles. Highest collection efficiency is found in cyclone having longer cone than that of cylinder having vortex finder. Wang *et al*. (2003) studied numerically gas-powder flow in Lapple cyclone using Reynolds stress model and K-e model.They use isotropic stress model therefore, it is not used in cyclone having anisotropic turbulence. ASM-algebraic stress model can't predict recirculation zone. Rankine vortex is strongly swirl flow because it underestimates the effects of stress convection and hence RSM is used in numerical studies. Charisiou *et al*. (2011) proposed the Plimpton CS software to calculate the efficiency and pressure drop of a cyclone for known geometry. Also some of the most theoretical models are incorporated with this software for cyclone design.

Cyclone separator has been used for many years to separate particles from fluid. Many researchers including Tripathi and Shukla (2015) performed work on cyclone to study its performance and parametric studies but for gasification though it is important, very few research have been carried out. This paper investigates the performance parameters for cyclone separator mainly efficiency and pressure drop for different feed stocks.

2. Materials and methods

The fuel used for gasification contains mineral compositions which are oxidized during combustion and pyrolysis. This results into ash and along with ash there are tar and char particles mixed with Syngas. Therefore, it is desirable that before using it for different purposes, it should be cleaned. Dust particle size and concentration depend on feed stroke, operating conditions, gasifier type etc. Syngas is used in electricity generation and as a fuel of IC engine. According to Hasler and Nussbaumer (1999) acceptable particle size for IC engine should be less than 10 micron and for gas turbines it is less than 5 microns. Hence, particles more than these must be removed from syngas.

Fig. 1 shows the part schematic of down draft gasifier set up. The main parts of the system have also

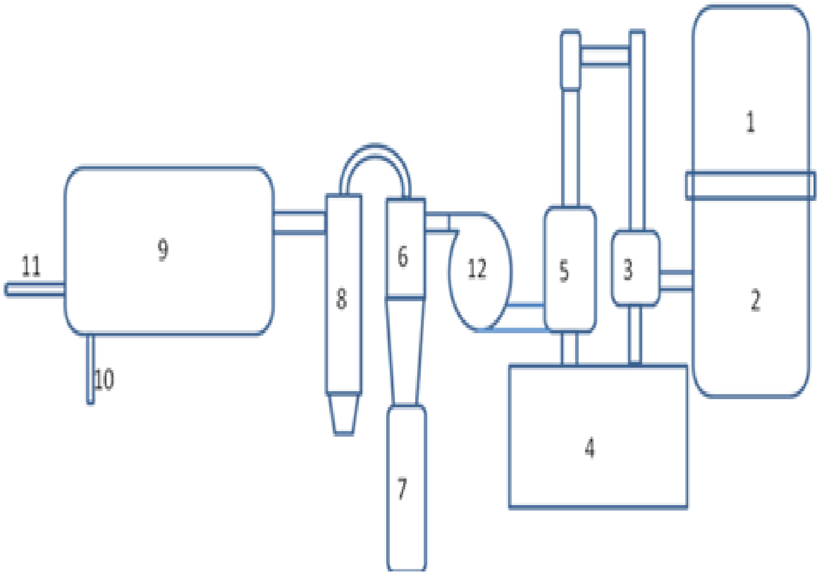

Fig. 1 Schematic of gasifier setup

Table 1 Names of the parts of the gasifier unit

Part number	Part name	Part number	Part name
1	Reactor first	7	Dust collector
2	Reactor second	8	Catch pot
3	Up draft/ Pack column	9	Three way gas filter
4	Tar collecting pot	10	Moisture drain valve
5	Drain box	11	Producer gas outlet
6	Cyclone separator	12	Blower

been indicated in the figure itself. First of all wood is fed from the top of the gasifier through the hopper in the first reactor where solid feedstock is partially converted into gaseous form followed by pyrolysis process. After pyrolysis the next processes take place in second reactor where feedstock completely converted into the form of producer gas which contains the significant amount of tar, particulate matter and other impurities. The producer gas comes out of reduction chamber and it passes through the pack column where the gas is showered by water to remove initial amount of tar and other impurities. It is stored in the tar collecting pot. Due to high temperature of gas, water turns into steam and passes along with the gas. The mixture of steam and producer gas is then separated and condensed down in drain box. The blower sucks the gas from the drain box and pushes it into the cyclone separator. In the cyclone separator the particulate matters are settled down. Even if some of the impurities are left in the producer gas, they are eliminated through the use of catch pot. Remaining impurities like dust, particulates etc. are separated by passing the gas through the three way filter. The three way gas filter is a filter which has three chambers in which the first is filled with rice husk, second one is filled with woody waste and the third chamber is filled with cotton. If the moisture still remains in the producer gas then it will be removed by the moisture drain valve, which is attached to the three way filter. Now the pure producer gas is supplied to the diesel engine through air filter to run the engine.

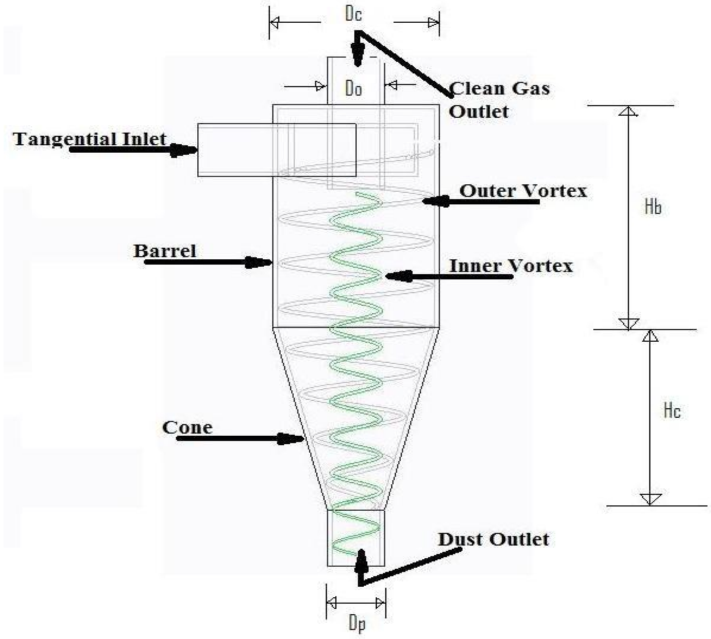

Fig. 2 Schematic of cyclone separator

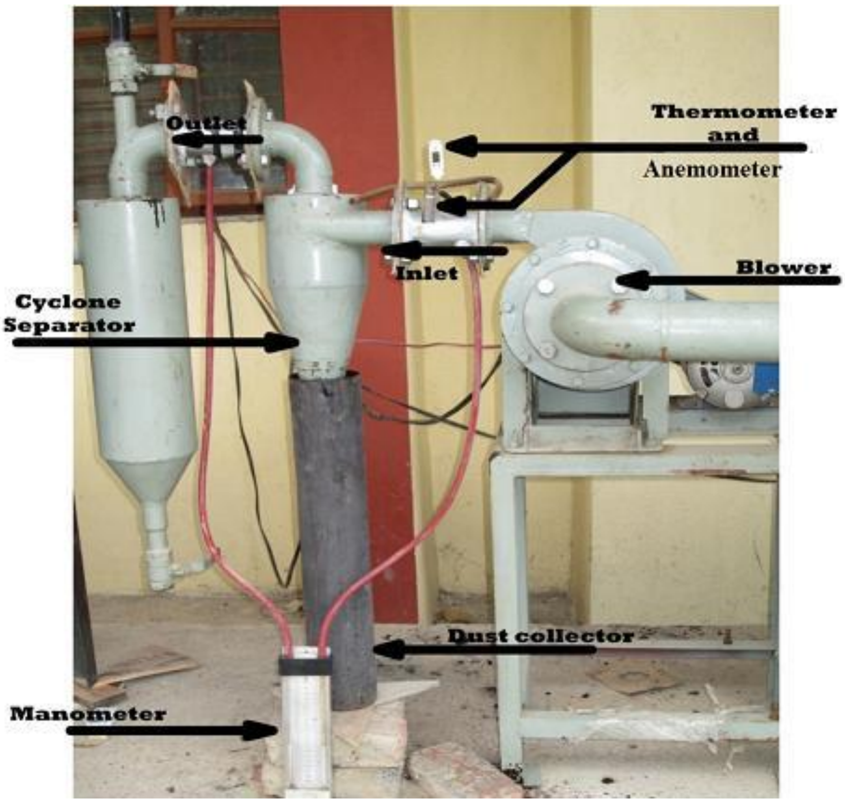

Fig. 3 Experimental setup at IIT (BHU)

Fig. 2 represents the cyclone separator working on the principle of separation of particles due to centrifugal action and gravity force. At high inlet velocity, mixture of fluid and particles enter through tangential inlet. Due to shape of cyclone separator; this mixture rotates and form a vortex. The particles having higher density than that of fluid can't follow curve vortex path and due to more inertia, it strikes with outer wall of cyclone. As a result, it losses it's tangential velocity and fall down due to gravity. Further it is collected in dust collector at bottom of cyclone (*Air Pollution Control Technology Fact Sheet*).

The experimental setup of cyclone separator is attached with the downdraft gasifier system. The producer gas was supplied by the blower in inlet port of cyclone where the velocity, temperature and pressure have been measured by using anemometer (range 0.1 to 99.9 km/h), digital thermometer (range -30 to 3000℃), and U tube manometer respectively. Now the heavy particles are separated by the centrifugal action of cyclone separator. The efficiency of cyclone separator is measured by the use of filter papers with one at the inlet of blower and other at the outlet of cyclone as shown in Fig. 3.

2.1 Methodology

The data obtained on downdraft gasifier during experimentation, the following relations have been used for

Efficiency

$$\eta = 1 - \frac{M_0}{M_i} \tag{1}$$

Pressure drop

$$\Delta P = (\rho_w - \rho_g) \times g \times h \tag{2}$$

Table 2 Particle size efficiency for wood practically

Particle diameter (m)	Efficiency (η) %
Below 5.00×10^{-06}	0
5.00×10^{-06}	12.88
10.00×10^{-06}	56.00
15.00×10^{-06}	88.91
20.00×10^{-06}	98.50
Above20.00×10^{-06}	100

Table 3 Particle size efficiency for Wood + CaO (10% Wt.) practically

Particle diameter (m)	Efficiency (η) %
Below 5.00×10^{-06}	0
5.00×10^{-06}	18.91
10.00×10^{-06}	60.36
15.00×10^{-06}	89.71
20.00×10^{-06}	98.45
Above20.00×10^{-06}	100

Table 4 Particle size efficiency for Coconut shell practically

Particle diameter (m)	Efficiency (η) %
Below 5.00×10^{-06}	0
5.00×10^{-06}	31.55
10.00×10^{-06}	68.93
15.00×10^{-06}	92.65
20.00×10^{-06}	98.57
Above20.00×10^{-06}	100

Table 5 Particle size efficiency for Coconut shell +CaO (10%Wt.) practically

Particle diameter (m)	Efficiency (η) %
Below 2.00×10^{-06}	0
2.00×10^{-06}	1.81
5.00×10^{-06}	19.27
10.00×10^{-06}	66.30
15.00×10^{-06}	95.20
20.00×10^{-06}	99.65
Above20.00×10^{-06}	100

Data of Feed stock 1- Wood

M_i=0.4620 g, M_o=0.1300 g, T= 47℃

Q= 0.028 m^3/s, η=71.87 %, ΔP=68.4 Pa.

Data of Feed stock 2- Wood + CaO (10% by Wt.)

M_i=0.2393 g, M_o=0.070 g, T= 47.4℃

Q=0.016 m^3/s, η=70.75 %, ΔP=81 Pa

Data of Feed stock 3- Coconut shell

M_i=0.3752 g, M_o=0.0823 g, T= 47.7℃

Q=0.013 m^3/s, η=78 %, ΔP=89.1 Pa.

Data of Feed stock 4- Coconut shell + CaO (10% by Wt.)

M_i=0.3502 g, M_o=0.093 g, T=39℃

Q=0.00989 m^3/s, η=73.44 %, ΔP=72.9 Pa

2.1.1 Cyclone performance evaluation by EMPIRICAL equations

Leith and Licht model By Charisiou *et al*. (2011)

Efficiency

$$\eta = 1 - \exp\left[-2\times\left(\left[\frac{G\times\tau\times V_0}{D^3{}_c}\times(n+1)\right]^{\frac{0.5}{n+1}}\right)\right] \tag{3}$$

$$G = \frac{4 \times D_c \times (2 \times V_S + V)}{\frac{\pi}{4} \times D^2{}_i} \tag{4}$$

$$V = I + II + III \tag{5}$$

Where

$$I = \frac{\pi}{4} \times D_c{}^2 \times (H_b - L)$$

$$II = \frac{\pi}{4} \times D_C{}^2 \times \left(\frac{Z_c + L - H_b}{3}\right) \times \left(1 + \frac{d_c}{D_C} + \frac{d_C{}^2}{D_C{}^2}\right)$$

$$III = -\frac{\pi}{4} \times D_0{}^2 \times Z_C$$

$$V_S = \pi \times \left(L - \frac{D_i}{2}\right) \times \left(D_C{}^2 - D_0{}^2\right) \tag{6}$$

$$Z_c = 2.3 \times D_0 \times \left(\frac{D^2{}_c}{\frac{\pi}{4} \times D^2{}_i}\right)^{\frac{1}{3}} \tag{7}$$

$$n = 1 - \left[1 - 0.67 \times \left(D_c{}^{0.14}\right)\right] \times \left(\frac{T}{283}\right)^{0.3} \tag{8}$$

$$\tau = \frac{\rho_p \times d_p{}^2}{18 \times \mu} \tag{9}$$

Pressure drop

$$\Delta P = \frac{1}{2} \times V_i{}^2 \times \rho_g \times k \times \left(\frac{\pi \times D_i{}^2}{4 \times D_0{}^2}\right) \tag{10}$$

Data of Feed stock 1- Wood

Table 6 Particle size efficiency for Wood

Particle diameter (m)	Efficiency (η) %	Pressure drop ΔP, (Pa)
1.00×10^{-06}	0.353386	
2.00×10^{-06}	1.405998	
5.00×10^{-06}	8.46955	
10.00×10^{-06}	29.81208	
15.00×10^{-06}	54.90895	152.16
20.00×10^{-06}	75.73113	
30.00×10^{-06}	95.86608	
40.00×10^{-06}	99.6531	
50.00×10^{-06}	99.98566	

Table 7 Particle size efficiency for Wood + CaO (10% Wt.) empirically

Particle diameter (m)	Efficiency (η) %	Pressure drop ΔP, (Pa)
1.00×10^{-06}	0.476488	
2.00×10^{-06}	1.888429	
5.00×10^{-06}	11.23302	
10.00×10^{-06}	37.91227	
15.00×10^{-06}	65.78135	225.70
20.00×10^{-06}	85.13986	
30.00×10^{-06}	98.62895	
40.00×10^{-06}	99.95124	
50.00×10^{-06}	99.99933	

Table 8 Particle size efficiency for Coconut

Particle diameter (m)	Efficiency (η) %	Pressure drop ΔP, (Pa)
1.00×10^{-06}	0.361132	
2.00×10^{-06}	1.436732	
5.00×10^{-06}	8.647679	
10.00×10^{-06}	30.35686	
15.00×10^{-06}	55.6926	114.06
20.00×10^{-06}	76.47588	
30.00×10^{-06}	96.14606	
40.00×10^{-06}	99.69377	
50.00×10^{-06}	99.9882	

Inlet flow rate V_0=0.014
Viscosity μ=1.84×10^{-05}
Temperature T=320
Density of gas ρ_g=1.325
Density of particles ρ_p=2200

Data of Feed stock: 2- Wood+ CaO (10 % by Wt)
Inlet flow rate V_0=0.016
Viscosity μ=1.56×10^{-05}
Temperature T=313.4
Density of gas ρ_g=1.5

Data of Feed stock 3- Coconut shell
Inlet flow rate V_0=0.013
Viscosity μ=1.67x10^{-05}
Temperature T=314
Density of gas ρ_g=1.45
Density of particles ρ_p=2200

Table 9 Particle size efficiency for Coconut shell + CaO (10%Wt.) empirically

Particle diameter (m)	Efficiency (η) %	Pressure drop ΔP, (Pa)
1.00×10^{-06}	0.266783	
2.00×10^{-06}	1.06287	
5.00×10^{-06}	6.460364	
10.00×10^{-06}	23.44339	
15.00×10^{-06}	45.17722	80.50
20.00×10^{-06}	65.64968	
30.00×10^{-06}	90.96674	
40.00×10^{-06}	98.60773	
50.00×10^{-06}	99.87423	

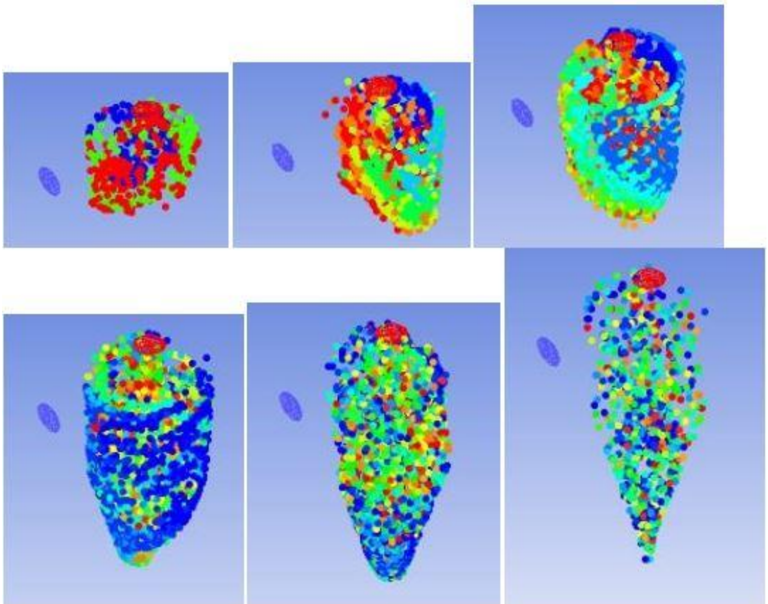

Fig. 4 Particle distribution at different time (Ansys fluent simulation)

Data of Feed stock 4- Coconut shell + CaO (10 % by Wt.)
Inlet flow rate V_0=0.0098
Viscosity μ=1.72×10^{-05}
Temperature T=312
Density of gas ρ_g=1.4

2.1.2 Cyclone performance evaluation using Reynolds Stress Model (RSM) simulated in Ansys Fluent

The formula for Efficiency has been given by equation by Dirgo and Leith (1985)

$$\eta = \frac{N_i}{N_i + N_0} \tag{11}$$

Table 10 Overall efficiency of cyclone separator by simulation

Feed stock	N_i	N_o	Efficiency, η %
Wood	515	317	61.89
Wood+CaO	450	370	54.87
Coconut shell	545	257	67.95
Coconut shell+CaO	495	283	63.62

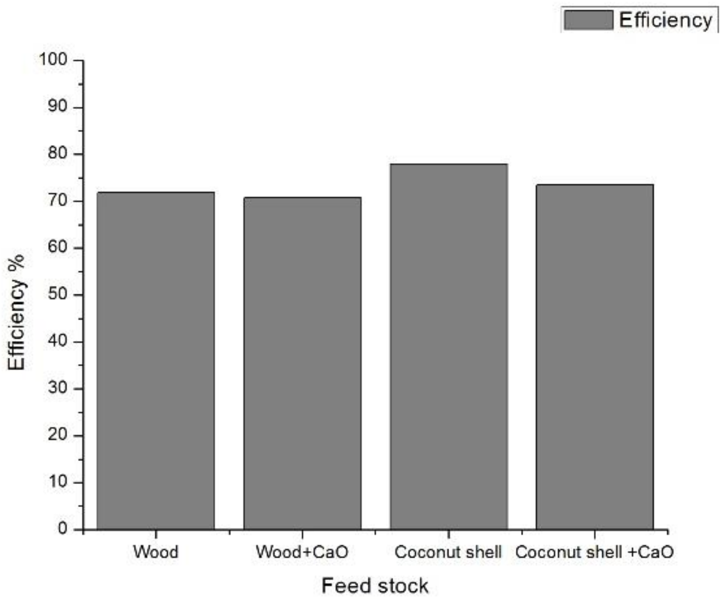

Fig. 5 Efficiency of cyclone for different feedstock (practically)

Fig. 4 shows particle distribution at different time after particle injected.
Followings are dimensions as,
Red particles has diameter of 14 micron
Green particles has diameter of 6-8 micron
Blue particles has diameter of 1-2.5 micron

3. Results and discussion

The efficiency obtained for different feed stock using the experimental data on this gasifier has been shown in Fig. 5. It is clear from the figure that using coconut shell as feed stock the efficiency is higher than other feed stock used in experimentation. The reason may be difference in density and viscosity of each feed stock and in turn their flow rate into the system. Using CaO with feed stock the efficiency decreases due to reduction in inlet loading and heavy particles.

Fig. 6 shows the variation in pressure drop with feed stock. It is clear that pressure drop varies with inlet flow rate and cyclone dimensions. Keeping dimensions constant when flow rate varies due to quality of gas, variation in pressure drop is seen. It also varies with type of feed stock.

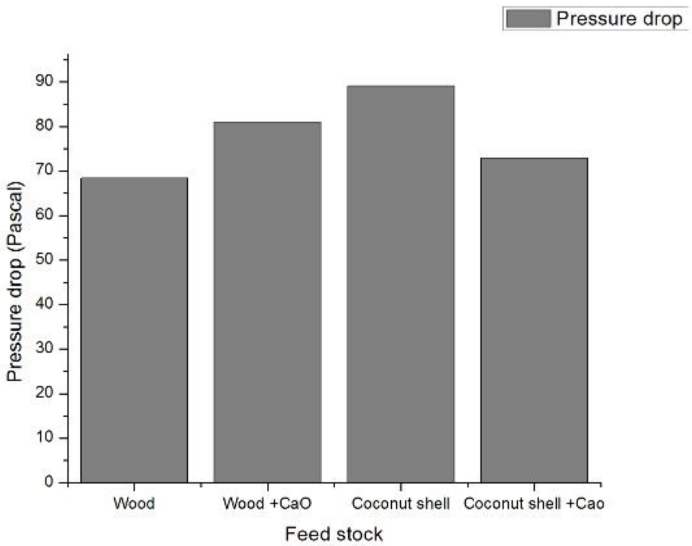

Fig. 6 Pressure drop V/s Feed stock (ΔP)

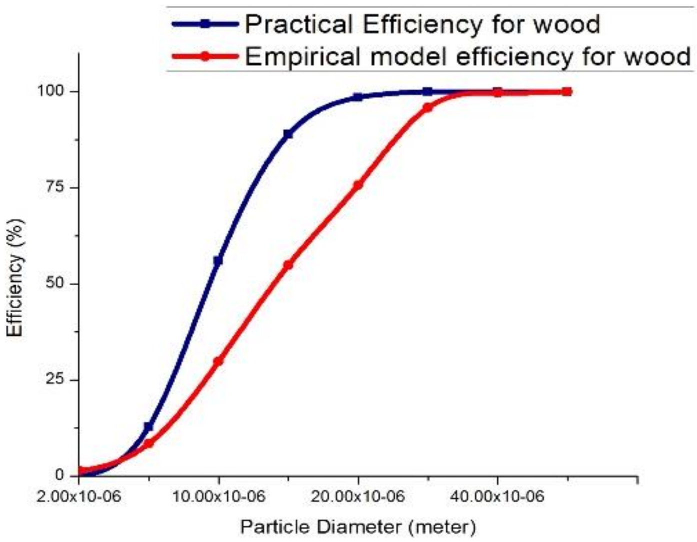

Fig. 7 Efficiency comparisons experimentally v/s Empirical model for feed stock Wood (Particle size efficiency for Wood Particle dia. in (m))

Fig. 7 shows the comparison of particle collection efficiency evaluated by using conventional and Leith and Licht model. It is clear from the figure that experimental values are much closer to predicted value.

Fig. 8 shows the variation in particle size efficiency with wood particle for wood and coconut shell feed stock without CaO and with CaO. It has been seen that particle size efficiency decreases after mixing the 10% CaO by weight in both feed stock. It is due to the reasons that during

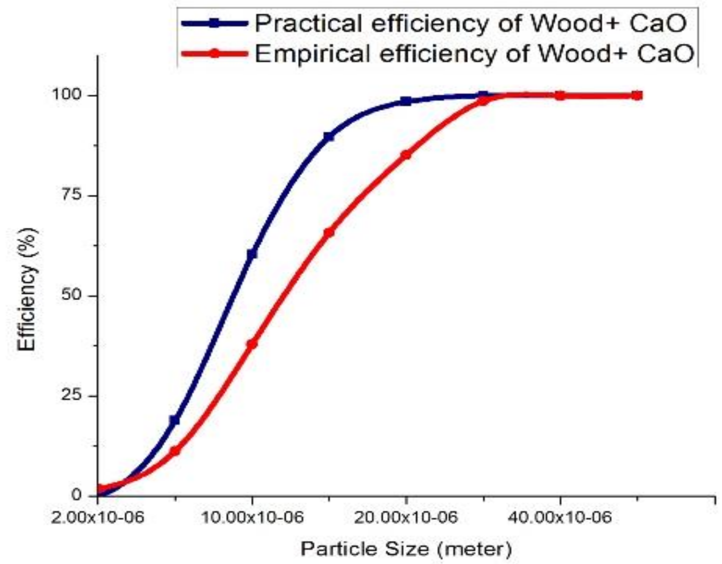

Fig. 8 Efficiency comparisons experimentally v/s Empirical model for feed stock Wood+CaO

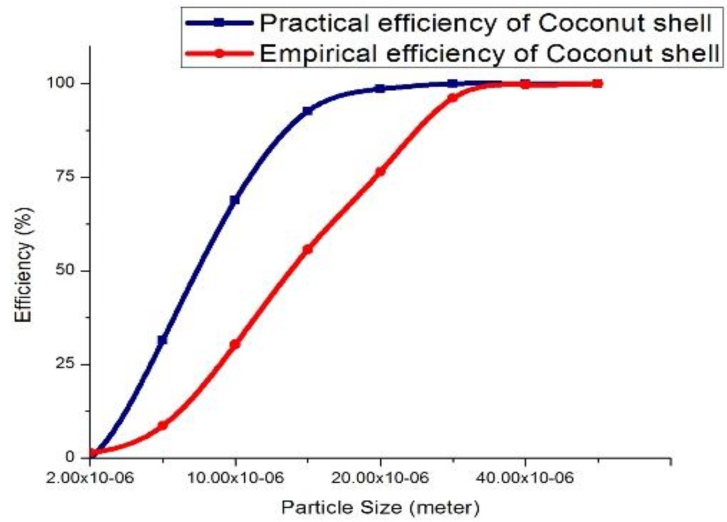

Fig. 9 Efficiency comparisons experimentally v/s Empirical model for feed stock Coconut shell

combustion of feed stock Cao reacts with gas and settle down the heavier particle. The particle size has the effect on the performance of the system. It means the lighter particle accounts for higher efficiency in both cases conventional and Leith and Licht model.

Similarly Figs. 9-10 explain the variation in efficiency using wood and coconut shell feed stock with and without CaO. This supports Fig. 8 as the efficiency decreases using CaO in both the cases. Comparison of overall efficiency using Ansys fluent simulated RSM model and the experimental data has been in Fig.11 for different feed stock with CaO and without CaO. It is clear that simulated results obtained using RSM model and experimental value are closed to each other.

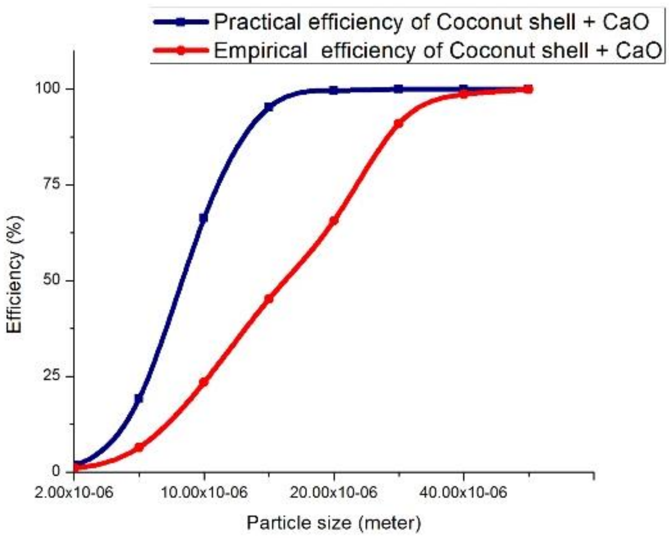

Fig. 10 Efficiency comparisons experimentally v/s Empirical model for feed stock Coconut shell+CaO

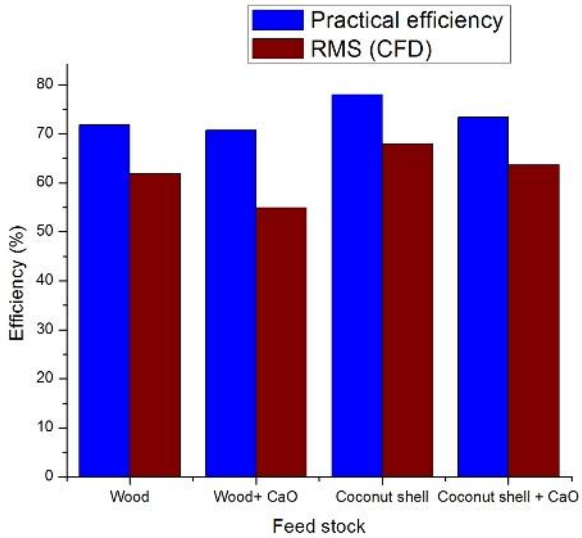

Fig. 11 Comparison of values of efficiency using RSM and conventional methods

4. Conclusions

From the above studies, the performance of downdraft gasifier was experimentally investigated for different feed stocks using cyclone separator to remove ash particles in Syngas.

- It is inferred that the efficiency of cyclone separator decreases after adding the CaO from 71.87% to 70.75% for wood feed stock and in case of coconut shell.
- The cyclone efficiency got reduced from 78% to 73.44% due to the quality of inlet gas, which has lighter particle in it. Leith and Licht model gives comparable results with practical results.

• It is also seen that by using Reynolds Stress Model (RSM), the overall collection efficiency can be predicted well.

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Nomenclature

D_c : Cyclone body diameter, (m)
D_i : Tangential inlet diameter, (m)
D_o : Gas outlet diameter (m)
D_p : Particles outlet diameter, (m)
d_p : Particle diameter, (m)
g : gravitational acceleration, (m/s^2)
G : It depends on dimensions of cyclone
h : manometric height, (m)
H : Total height, (m)
H_b : Barrel height, (m)
H_c : Cylinder height, (m)
K : Constant, lies between 12-18
L : Vortex finder length, (m)
M_i : weight of Ash collected at inlet, (gm)
M_o : weight of Ash collected at gas outlet, (gm)
n : It is term related to vortex
N_i : Number of Ash particles collected at dust collector
N_o : Number of Ash particles collected at gas outlet
Q : Inlet flow rate, (m^3/s)
T :Temperature, (K)
V_i : Inlet velocity, (m/s)
V_0 : Inlet flow rate, (m^3/s)
Zc : Natural length, (m)
ρ_p : Density of particles, (kg/m^3)
ρ_g : Density of gas, (kg/m^3)
ρ_w : density of kerosene, (kg/m^3)
η : Efficiency
τ : It shows relaxation term
μ : Viscosity of fluid, (Pa s)
ΔP : Pressure Drop, (Pa)