CHAPTER 5

SIMULATION RESULTS AND ANALYSIS

There are 5 simulation results sets in this study. Three sets of the simulation are compared with results taken from actual cyclone which is currently used for removal of fly ash from boiler flue gas and two sets of the simulation compared with case studies from other literature. Optimization method emphasizes Thailand real expense in both total fixed cost and total operating cost. Total fixed cost includes material and fabrication cost for cyclone body. Support structure and transportation costs are excluded. Total operating cost is calculated based on electricity cost from the Electricity Generating Authority of Thailand (EGAT). Maintenance cost for the cyclone is excluded.

5.1 Simulations of an Existing Cyclone

A cyclone, Shepherd and Lapple type 0.96 m in diameter and 2.0 mm thick, is used for collection of fly ash from boiler flue gas having capacity of 2 tons/hour of combustion exhaust. Tables 5.1 and 5.2 show detail configuration of the cyclone and details of fuel oil and recommended exhaust gas quality. Three different measurements of exhaust gas qualities were conducted on three different days by SGS (THAILAND) Co., Ltd. Cyclone operating conditions and measured exhaust gas qualities are shown in Table 5.3. Using the operating conditions in each measurement, cyclone simulation are conducted and the results are shown in Table 5.4 to 5.6 for comparison.

From the measured exhaust gas quality results, it is observed that air quality and air temperature are different each time (day) that the measurements are made. The different in air quality would result in quality of fuel oil and the different in air temperature also results in the difference in physical characteristic such as density and viscosity.

The main reason for the difference in these operating conditions is the steam consumption in each day. In normal operation of the process, amount of steam used in each day depends on types of products manufactured on that day. When the consumption of steam varies, fuel oil and air which are used for generation of heat required for steam generation also varies.

Table 5.1 Details of the experiment cyclone.

The experiment cyclone : Shepherd and Lapple			
Term	Description	Value	Unit
D	Body diameter	960	mm
a	Inlet height:	480	mm
b	Inlet width:	240	mm
S	Outlet length:	600	mm
D_e	Outlet diameter:	480	mm
h	Cylinder height:	1,920	mm
H	Overall height:	3,840	mm
B	Dust outlet diameter:	240	mm
K	Configuration parameter	402.9	-
N_H	Inlet velocity heads	8.0	-
$Surf$	Surface parameter	3.78	-

Table 5.2 Details of fuel oil and exhaust gas from fuel combustion.

Fuel data	Value	Unit
Particle size MMD	10.0	μm
Boiler capacity	2,000	kg/hr
Oil consumption	245	kg/hr
Sulfur content in fuel	3.0	%
Exhaust gas temperature	≈200	C^{o}
CO_2 in exhaust gas	13.5	%
Fuel gravity	20.0	API
Exhaust gas pressure	1.01×10^{5}	Pa
lb. of exhaust gas/lb. of fuel	17.2	-
lb. of exhaust gas	9,291.87	lb./hr
emission factor for TSP	0.033	lb. TSP/gal fuel
lb. TSP/hr	1.0372	kg TSP/hr

Table 5.3 Cyclone operating conditions and measured exhaust gas qualities.

Parameter	Experiment cyclone operating condition		
	Measurement No. 1	Measurement No. 2	Measurement No. 3
d_{cpr} ; m	3.20×10^{-6}	3.20×10^{-6}	3.20×10^{-6}
Q ; m^3/s	1.501	1.522	1.486
ρ_p ; kg/m^3	1500	1500	1500
ρ ; kg/m^3	0.73625	0.74573	0.74096
μ ; Pa.s	25.97×10^{-6}	25.746×10^{-6}	25.86×10^{-6}
DL ; kg/m^3	0.0001919	0.0001919	0.0001919
Temperature ; K^o	473	467	470
Humidity ; %	8.42	8.31	8.36
TSP_{in} ; mg/Nm^3	457.30	451.329	442.811
Cyclone Diameter ; m	0.96	0.96	0.96
Operating hours/year	6,000	6,000	6,000
Y ; year	5	5	5
c_e ; baht/unit	1.07	1.07	1.07
N	1	1	1
Particle diameter range			
0 - 5 µm , g	35.8	35.8	35.8
<5 -10 µm , g	22.3	22.3	22.3
<10 - 15 µm , g	14.9	14.9	14.9
<15 - 20 µm , g	6.4	6.4	6.4
<20 -30 µm , g	7.1	7.1	7.1
<30 -50 µm , g	7.0	7.0	7.0
<50 - 100 µm , g	6.5	6.5	6.5

The simulation can be used both as an analysis tool for prediction of the effect of changes on systems and as a design tool for prediction of the performance of new systems under varying sets of variables or circumstances. To optimize the design of parallel cyclone having a tangential gas inlet, the behaving of the system is studied by developing a simulation model. This model usually takes the form of a set of following assumptions concerning the operation of the system.

A differential equation describing this particle motion may be set up by making a force balance on the particle with the following assumptions:

(1) The particle is spherical in shape.

(2) The motion of a particle is not influenced by the presence of neighboring particles.

(3) The drag force radically on the particle is given by Stokes'Law

(4) The radial velocity of the gas is zero.

(5) The tangential velocity component of the particle is the same as that of the gas stream, that is, there is no slip in the tangential direction between the particle and the gas.

(6) The tangential velocity component is related to the radial position by a modified form of the Equation for a free vortex in an ideal fluid:

$$u_T . R^n = const.$$

In the ideal free vortex law $n=1$, but experimental observation by Shepherd, C.B., and C.E., Lapple (1939) show that in a cyclone n may range between 0.5 and 0.9 according to the size of the cyclone and the inlet air temperature.

Table 5.4 Comparison of simulation results and measured results of cyclone operated on conditions based on measurement No. 1.

Parameter	Results	
	Measured values	Simulation values
d_{cp50} ; m	-	3.05×10^{-6}
d_{cpr} ; m	3.20×10^{-6}	3.20×10^{-6}
Q ; m^3/s	1.501	1.501
Temperature ; K^o	473	473
Cyclone Diameter ; m	0.96	0.96
Operating hours/year	6,000	6,000
Y ; year	5	5
c_e ; baht/unit	1.07	1.07
N	1	1
ΔP ; N/m^2	510.60	500.10
TSP_{out} ; mg/Nm^3	149.38	-
c_{fixed} ; baht	19,500.00	17,126.54
c_{oper} ; baht	24,601.78	24,095.76
c_t ; baht	44,101.78	41,222.30
Objective eq^n value	.00099908	0.00102006
Overall Collecting Eff. ; %	65.61	69.49

Table 5.5 Comparison of simulation results and measured results of cyclone operated on conditions based on measurement No. 2.

Parameter	Results	
	Measured value	Simulation value
d_{cp50} ; m	-	3.01×10^{-6}
d_{cpr} ; m	3.20×10^{-6}	3.20×10^{-6}
Q ; m^3/s	1.522	1.522
Temperature ; K^o	467	467
Cyclone Diameter ; m	0.96	0.96
Operating hours/year	6,000	6,000
Y ; year	5	5
c_e ; baht/unit	1.07	1.07
N	1	1
ΔP ; N/m^2	533.45	520.81
TSP_{out} ; mg/Nm^3	154.41	-
c_{fixed} ; baht	19,500.00	17,126.54
c_{oper} ; baht	26,062.34	25,444.70
c_t ; baht	45,562.34	42,571.24
Objective eq^n value	0.00096172	0.00098506
Overall Collecting Eff. ; %	65.80	69.71

Table 5.6 Comparison of simulation results and measured results of cyclone operated on conditions based on measurement No. 3.

Parameter	Result	
	Measured value	Simulation value
d_{cp50} ; m	-	3.06×10^{-6}
d_{cpr} ; m	3.20×10^{-6}	3.20×10^{-6}
Q ; m^3/s	1.486	1.486
Temperature , K^o	470	470
Cyclone Diameter ; m	0.96	0.96
Operating hours/year	6,000	6,000
Y ; year	5	5
c_e ; baht/unit	1.07	1.07
N	1	1
ΔP ; N/m^2	504.20	493.29
TSP_{out} ; mg/Nm^3	154.01	-
c_{fixed} ; baht	19,500.00	17,126.54
c_{oper} ; baht	24,050.65	23,530.10
c_t ; baht	43,550.65	40,656.63
Objective eq^n value	0.00101097	0.00103334
Overall Collecting Eff. ; %	65.22	69.44

Table 5.7 Summary of the deviation of the measured values and the simulated values in each measurement.

Parameter	Measured value	Simulation value	Deviation ; %
Q_1 ; m^3/s	1.501	1.501	-
Q_2 ; m^3/s	1.522	1.522	-
Q_3 ; m^3/s	1.486	1.486	-
ΔP_1 ; N/m^2	510.60	500.10	- 2.10
ΔP_2 ; N/m^2	533.45	520.81	- 2.43
ΔP_3 ; N/m^2	504.20	493.29	- 2.21
η_1 ; %	65.61	69.49	+ 5.58
η_2 ; %	65.80	69.71	+ 5.61
η_3 ; %	65.22	69.44	+ 6.08

Comparison of the simulated results and the measured results of measurement No. 1, as shown in Table 5.4, shows that predicted pressure drop of the cyclone is lower than the measured value. The reasons for higher measured value of pressure drop are: (i) humidity of hydrocarbon combustion products which contain in gas stream approximately 8.35%, causes both fluid and particle density to be higher than the simulated condition and (ii) the cyclone wall is rusted and causes the wall friction to be higher than usual.

From Table 5.4, above comparison of cyclone overall efficiency, total fixed cost, total operating cost and total cost between measured value and simulation value show that overall efficiency of simulated value is higher than measured value. In actual operation, the cyclone wall surface is not as smooth as the simulated cyclone wall surface. The collected particles in actual cyclone can not easily slide down to the bottom collector and sometimes they would flow back into the gas stream. Total fixed cost of measured value is higher than simulation value because the structure and transportation costs are excluded in the simulation. Total operating cost of the simulation is less than the measured value because the pressure drop of the simulated value is less than the measured value. The difference in pressure drop would result in power consumption of the attached blower which in turns would result in difference in electricity costs.

Comparisons of results of other two measurements and simulations, shown in Table 5.5 and 5.6, also show the same behavior as observed in Table 5.4.

Table 5.7 summarizes the deviations observed in this study. It is clearly seen that the predicted pressure drop value is approximately 2.25% lower than the measured value and the predicted overall efficiency is approximately 5.6% higher than the measured value.

5.2 Cyclone optimization analysis.

Optimizations of the cyclones were conducted on 5 standard cyclone types and one User Type. The objective equation and constrains are as follow:

Objective Equation $\eta / \Delta P$ Maximize

Constraints

1) 15 m/s $\leq u_{T_2} \leq (u_{T_2 \max}$, 30 m/s, 1.35 $v_s)$

2) $N_{\min} \leq N_o \leq N_{\max}$;Integer

3) $0.5 \leq n \leq 0.9$

4) $\Delta P \leq 2500$ N/m^2

5) $d_{cp_{50}} \leq d_{cpr}$

6) Minimum total cost ; c_t

5.2.1 Cyclone optimization analysis

Optimization cyclone simulation of the actual value and 5 standard cyclones are calculated at minimum inlet velocity. Simulation results are shown in Tables 5.8 to 5.10.

Table 5.8 Optimization of the actual cyclone and other standard cyclones for measurement No. 1.

Cyclone Type	High Efficiency Stairmand	High Efficiency Swift	Shepherd and Lapple
Amount Cyclone	1	1	1
Cyclone diameter ; m	1.000	1.0407	0.895
Pressure drop ; N/m^2	530.2451	765.5304	662.7837
50% cut size particle diameter ; m	2.76×10^{-6}	2.58×10^{-6}	2.78×10^{-6}
50% cut size particle diameter requirement ; m	3.20×10^{-6}	3.20×10^{-6}	3.20×10^{-6}
Objective Equation value	10.037×10^{-4}	7.1394×10^{-4}	8.0132×10^{-4}
Total fixed cost ; baht	20,044.77	21,327.71	14,876.85
Total operating cost ; baht	25,548.32	36,884.86	31,934.31
Total cost ; baht	45,593.09	58,212.58	46,811.17
Overall Efficiency ; %	71.23	72.34	71.23

Cyclone Type	General Purpose Swift	General Purpose Pet & Whitby	User type
Amount Cyclone	1	1	1
Cyclone diameter ; m	0.895	0.908	0.96
Pressure drop ; N/m^2	662.7837	642.9235	500.0978
50% cut size particle diameter ; m	2.85×10^{-6}	3.07×10^{-6}	3.05×10^{-6}
50% cut size particle diameter requirement ; m	3.20×10^{-6}	3.20×10^{-6}	3.20×10^{-6}
Objective Equation value	7.9235×10^{-4}	7.9120×10^{-4}	10.2006×10^{-4}
Total fixed cost ; baht	14,992.78	13,956.76	17,126.54
Total operating cost ; baht	31,934.31	30,977.41	24,095.76
Total cost ; baht	46,927.09	44,934.17	41,222.30
Overall Efficiency ; %	70.75	69.40	69.48

Table 5.9 Optimization of the actual cyclone and other standard cyclones for measurement No. 2.

Cyclone Type	High Efficiency Stairmand	High Efficiency Swift	Shepherd and Lapple
Amount Cyclone	1	1	1
Cyclone diameter ; m	1.007	1.0479	0.901
Pressure drop ; N/m^2	537.0566	775.3685	671.3370
50% cut size particle diameter ; m	2.75×10^{-6}	2.57×10^{-6}	2.76×10^{-6}
50% cut size particle diameter requirement ; m	3.20×10^{-6}	3.20×10^{-6}	3.20×10^{-6}
Objective Equation value	9.9249×10^{4}	7.0593×10^{-6}	7.9238×10^{-6}
Total fixed cost ; baht	20,325.48	21,626.33	15,084.75
Total operating cost ; baht	26,238.54	37,881.56	32,798.97
Total cost ; baht	46,564.02	59,507.89	47,883.73
Overall Efficiency ; %	71.28	72.38	71.28

Cyclone Type	General Purpose Swift	General Purpose Pet & Whitby	User type
Amount Cyclone	1	1	1
Cyclone diameter ; m	0.901	0.915	0.96
Pressure drop ; N/m^2	671.3370	651.1783	520.8081
50% cut size particle diameter ; m	2.84×10^{-6}	3.06×10^{-6}	3.01×10^{-6}
50% cut size particle diameter requirement ; m	3.20×10^{-6}	3.20×10^{-6}	3.20×10^{-6}
Objective Equation value	7.8353×10^{4}	8.2539×10^{4}	9.8506×10^{4}
Total fixed cost ; baht	15,202.29	14,152.26	17,126.54
Total operating cost ; baht	32,798.97	31,814.10	25,444.70
Total cost ; baht	48,001.27	45,966.36	42,571.24
Overall Efficiency ; %	70.80	69.46	69.71

Table 5.10 Optimization of the actual cyclone and other standard cyclones for measurement No. 3.

Cyclone Type	High Efficiency Stairmand	High Efficiency Swift	Shepherd and Lapple
Amount Cyclone	1	1	1
Cyclone diameter ; m	0.9950	1.0355	0.8900
Pressure drop ; N/m^2	533.6345	770.4179	667.0469
50% cut size particle diameter ; m	2.75×10^{-6}	2.57×10^{-6}	2.76×10^{-6}
50% cut size particle diameter requirement ; m	3.20×10^{-6}	3.20×10^{-6}	3.20×10^{-6}
Objective Equation value	9.9934×10^{4}	7.1083×10^{-6}	7.9786×10^{-6}
Total fixed cost ; baht	19,844.49	21,114.69	14,727.92
Total operating cost ; baht	25,454.69	36,749.39	31,817.54
Total cost ; baht	45,299.18	57,864.09	46,546.46
Overall Efficiency ; %	71.32	72.42	71.31

Cyclone Type	General Purpose Swift	General Purpose Pet & Whitby	User type
Amount Cyclone	1	1	1
Cyclone diameter ; m	0.890	0.904	0.96
Pressure drop ; N/m^2	667.0469	647.0281	493.2872
50% cut size particle diameter ; m	2.84×10^{-6}	3.06×10^{-6}	3.06×10^{-6}
50% cut size particle diameter requirement ; m	3.20×10^{-6}	3.20×10^{-6}	3.20×10^{-6}
Objective Equation value	7.8894×10^{4}	7.8785×10^{4}	10.3334×10^{4}
Total fixed cost ; baht	14,842.68	13,817.30	17,126.54
Total operating cost ; baht	31,818.54	30,863.93	23,530.10
Total cost ; baht	46,661.22	44,681.23	40,656.63
Overall Efficiency ; %	70.84	69.49	69.44

From Table 5.8, comparisons of pressure drop, cyclone overall efficiency, objective value and cyclone expense of user type cyclone with other five standard cyclones shows that :

1. Pressure drop and operating cost of user type cyclone are the lowest because air inlet velocity of user type cyclone equal to 13.03 m/s which is lower than minimum inlet velocity 15 m/s so the lowest pressure drop and operating cost are predicted. Two parameter which effect the pressure drop are: (i) air inlet velocity and (ii) inlet velocity head as shown in Equation (3.1).

$$\Delta P = \frac{1}{2}\rho_g u_{T_2}^2 N_H \quad \text{or} \quad \frac{1}{2}\rho_g\left(\frac{Q}{K_a K_b N}\right)^2 N_H \qquad (3.1)$$

where

$$N_H = \frac{16 K_a K_b}{K_{D_c}^2}$$

High Efficiency Swift cyclone give the highest pressure drop and operating cost because High Efficiency Swift cyclone has the highest inlet velocity head N_H.

Operating cost is a function of pressure drop, volume flow rate of inlet air, electricity cost and operating periods as shown in Equation (2.29). Variation in pressure drop value would also affect the operating cost.

2. Objective equation value of user type cyclone gives the highest objective equation value $\eta / \Delta P$ because user type cyclone having the lowest pressure drop. High Efficiency Swift cyclone give the lowest objective value because High Efficiency Swift cyclone has the largest pressure drop.

3. Cyclone overall efficiency of the High Efficiency Swift cyclone has the highest overall efficiency because cyclone configuration parameter of High Efficiency Swift is the largest.

For other two measurements, as shown is Table 5.9 and 5.10, comparisons of pressure drop, cyclone overall efficiency, objective value and cyclone expense of user type cyclone with other five standard cyclones show that :

1. Pressure drop and operating cost of user type cyclone are still the lowest because air inlet velocity of user type cyclone is lower than minimum inlet velocity 15 m/s while gas inlet velocity of other five standard cyclone is equal to 15 m/s.

2. Objective equation value of user type cyclone gives the highest objective equation value in measurement No. 3 which is similar to measurement No. 1 but in measurement No. 2 High Efficiency Stairmand is the highest objective equation value because rapidly increase in pressure drop in user type cyclone. In measurement No. 2 at higher flow rate of inlet gas, pressure drop increases with the square of the inlet velocity. Cyclone overall efficiency also increase, but not as rapidly as pressure drop.

3. Cyclone overall efficiency of the High Efficiency Swift cyclone is still the largest cyclone overall efficiency which is similar to measurement No. 1.