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ANALYSIS ON MASS FLOW RATE OF FLUE GAS FOR A PULVERIZED COAL POWER PLANT AT INLET & OUTLET

Mehedi Hasan Tusar[1], **Abdullah Al Noman**[2] **and Muhammed Kamrul Islam**[3]

[1-3]Department of Mechanical Engineering, CUET, Chittagong-4349, Bangladesh
meheditusar95@gmail.com[1], aanoman926262@gmail.com[2], kamrul.cuetme@gmail.com[3*]

Abstract- *In this paper, mass flow rate of flue gas at inlet & outlet for pulverized coal power plant are analyzed with consecutive steps. For this required coal input for a specific power generation is determined with help of ultimate analysis of coal. It is observed that mass flow rate of flue gas depends mainly on the characteristics of the coal as it fixes the amount of coal required and imposes many condition on flue gas purification. Low sulfur content in coal rises electrical resistivity of flue gas so additional additives are added to lower its resistivity. Nature of flue gas, temperature, design, operating methods & conditions, excess air drawn for combustion effects electrostatic precipitator efficiency thus particulate materials removal. Purification methods also determines mass flow rate. Flue gas desulfurization unit has variable* SO_x *collection efficiency with respect to liquid to gas ratio. Addition of different types of chemicals such as Adipic Acid, Magnesium Oxide improves* SO_x *collection efficiency. After disposal of fly ash in electrostatic precipitator, removal of sulfur pollutants in flue gas desulfurization unit & liquid slurry in demister mass flow rate in outlet is found. After modeling inlet & outlet mass flow rate of flue gas this model is applied for determining the mass flow rate of flue gas for a 500 MW pulverized coal power plant*.

Keywords: Flue gas, electrostatic precipitator, flue gas desulfurization unit and flow measurement

1. INTRODUCTION

Mass flow is the measurement of flow rate without consideration of the process conditions. It is an ideal measurement of flow since it is not affected by variation in properties such as pressure, temperature of flow [1]. Flow rates are expressed in mass basis or volume basis. Large number of Industries use volumetric flow rate since it could be measured easily, a lot of direct numerical formulas available from USEPA or EN 12952-15 to calculate volumetric flow rate. To measure volumetric flow rate differential pressure, vortex shedding, turbine flow meters, averaging Pitot tube a lot of methods are available. But this measurement is effected by variation in pressure, temperature & need to measure a lot of parameters such as differential pressure, absolute pressure, absolute temperature etc. However, mass flow rate measuring devices such as thermal mass flow meter & Coriollis mass flow meter may remove these difficulties. Mass flow rate can be found from volumetric flow rate multiplied by density. Density of flue gas varies with temperature & pressure. Different power plants operate in different temperature & pressures. It creates a need for standard to compare different volumetric flow rates, to convert actual flow rate to STP flow rate. Measurement of volumetric flow rate needs a lot of instruments to measure different parameters which may be error-prone as velocity and pressure could be asymmetric across the cross section due to geometry. Calculation of mass flow rate is important for power plant designing. For calculation of mass flow rate it is necessary to know the flue gas flow process. Figure 1 describes the flow diagram of flue gas for a pulverized coal power plant using limestone slurry in FGD system.

2. DESCRIPTION

In electrical output method power output is given. For producing required amount of energy more heat energy need to be supplied in boiler as thermal efficiency, η_{th} of the cycle is less than unity. So required boiler heat supply is,

$$h_{boiler} = \frac{p_{output}}{\eta_{th}} \quad (1)$$

Boiler doesn't utilize the whole energy supplied by flue gas. In order to obtain high boiler efficiency it is necessary to grind the coal to a high degree of fineness [4]. If boiler has efficiency, η_{boiler} then energy required to be supplied by coal,

$$h_{coal} = h_{boiler}/\eta_{boiler} \quad (2)$$

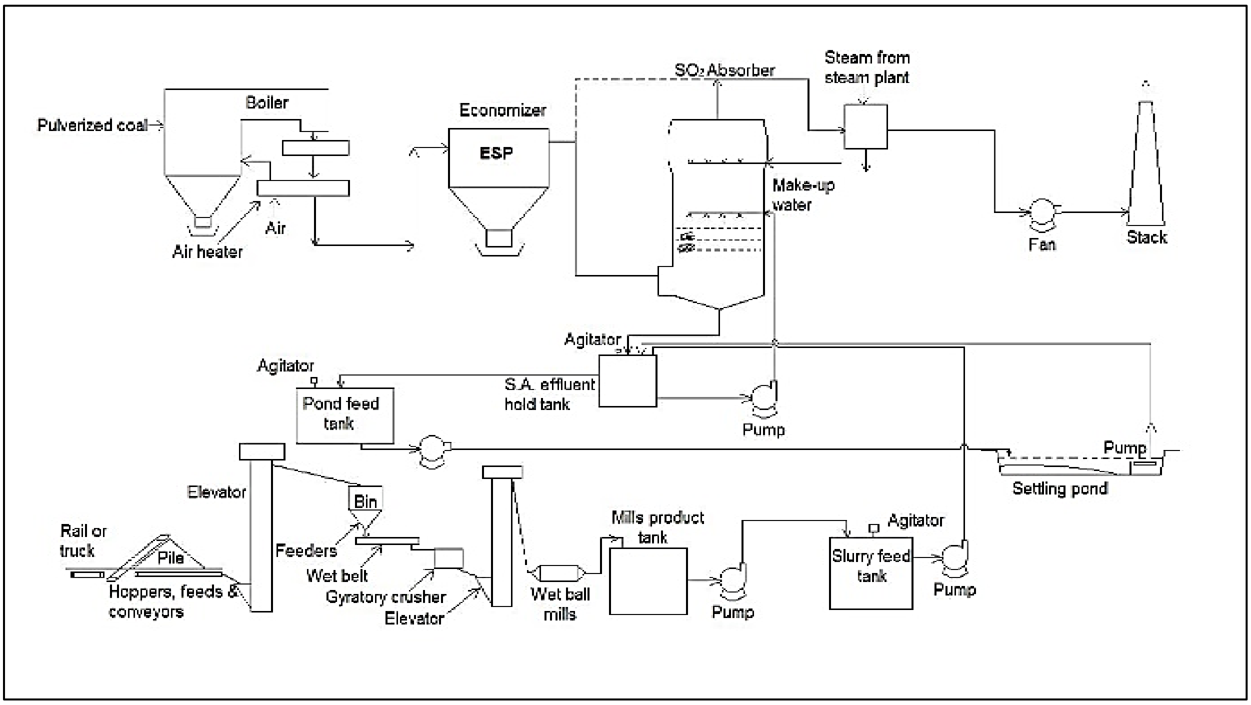

Figure 1: flue gas with limestone slurry process flow diagram [2,3]

Amount of coal required per second depends on the calorific value which is an internal property of coal. Higher calorific value coal minimizes the amount of coal & air required. Coal power plant is a source of environmental pollution as it emits fly ash, SO_x, mercury in air, it also contains arsenic, bismuth, antimony, phosphorus and lot of potentially hazardous elements in the sludge [5] that causes water & soil pollution. High calorific value coals are preferred for use in power plants as it reduces emission per power generation, reduces machinery size & cost. It also reduces erosion, servicing of machinery due to less slagging than low-grade coals. The amount of coal required per second,

$$m_{coal} = \frac{h_{coal}}{calorific\ value\ of\ coal} \quad (3)$$

At least stoichiometric amount of air is required to burn this coal perfectly. Stoichiometric air is the theoretically minimum amount of air to burn the fuel where no fuel particle remains unburned. But in case of solid fuels some particles always remain unburned which is harmful, reduces efficiency, increases fuel cost. So, excess air is supplied for proper burning of fuel. One major disadvantage is the heat loss for heating the excess air. Therefore, optimized amount of excess air need to be selected for coal burning. Individual component masses of coal are essential to calculate the stoichiometric air. Analysis of coal is carried out by following methods.

- Proximate analysis
- Ultimate analysis
- Calorific value

Ultimate analysis of coal consists in the determination of percentage of carbon, hydrogen, nitrogen, oxygen, sulfur, phosphorus in the coal. This analysis is done in dry basis. So, the percentage of components of coal found in this process is different from actual percentage of coal as moisture is present at firing condition

$$\%\ of\ component\ of\ coal_{firing\ condition} = \frac{100 - \%\ of\ moisture}{100} \times \%\ of\ component_{dry\ basis} \quad (4)$$

Individual component masses can be found from equation (5).

$$m_{components} = \%\ of\ component_{firing\ condition} \times m_{coal} \quad (5)$$

In pulverized coal power plant some sulfur and ash are deposited in the furnace which varies with nature of coal. Ash deposition, y is normally 20% for this type of power plant. So mass of sulfur and ash remaining in flue gas,

$$m_{s.f.g} = (1 - x) \times m_s \quad (6)$$

$$m_{ash.f.g} = (1 - y) \times m_{ash} \quad (7)$$

Oxygen required to burning this component is given by equation (8).

$$m_{oxygen} = \frac{m_{components} \times (atomic\ mass\ of\ oxygen \times no.of\ atoms)}{atomic\ mass\ of\ component \times no.of\ atoms} \quad (8)$$

Small amount of oxygen, s_{oxygen} is supplied by coal itself. Total amount of oxygen, T_{oxygen} required from air,

$$T_{oxygen} = \sum m_{oxygen} - s_{oxygen} \quad (9)$$

Oxygen has 23.14% mass of air. Total air supplied for combustion, m_{air}

$$m_{air} = \frac{(1 + fraction\ of\ access\ air) \times (\sum m_{oxygen} - s_{oxygen})}{0.2314} \quad (10)$$

After deposition remaining components of coal and air drawn forms up the flue gas at inlet.

$$m_{inlet} = m_c + m_h + m_o + m_n + m_{s.f.g} + m_{ash.f.g} + m_{air} \quad (11)$$

As coal power plants are source of pollutes, flue gas goes through several cleaning stages.

- Electrostatic precipitator for dust particle collection
- Flue gas desulfurization unit for so_x removal
- Demisters to prevent wash away of scrubber liquids

All electrostatic precipitator operates in efficiency greater than 99% to reduce emission. Electrostatic precipitator efficiency depends on dust resistivity, gas temperature, chemical composition (of dust and gas) and particle size distribution. Temperature and chemical composition of the dust and gas stream are factor which can influence dust resistivity. Conduction through dust particles occurs in two ways: surface conduction, volume conduction. Volume conduction occurs through material and a property of material. Surface conduction occurs through liquid or gases adsorbed by particles [6]. Electrical resistivity is also an important parameter that determines ESP efficiency. If the dust electrical resistivity exceeds 10^{11}-10^{13}Ω.cm it is called high electrical resistivity. If resistivity lies between 10^{10}-10^{11}Ω.cm it is in optimal range for collection [7]. Particle charge dissipates slowly in collection plate which creates difficulty in dislodge when particle have higher electrical resistivity. Low resistivity particles rapidly lose their charge and pick up the charge of the plate and repels back to the gas stream. Both type of resistivity reduces collection efficiency of ESP. One process to reduce electrical resistivity is adding conductive components such as Steam, Ammonia (NH_3), Sulfur Dioxide (SO_2), Sodium Carbonate (Na_2CO_3). If conductive components are added then,

$$m_{esp(inlet)} = m_{inlet} + m_{added} \quad (12)$$

Where, $m_{esp(inlet)}$ = mass of flue gas entering ESP, m_{added} = mass of components added for particle conditioning.

Low sulfur coals have high electrical resistivity due to less conductive gases in flue gas. Adding additives are costly, increases instrument sizes and they also need separation from flue gas due to pollute emission regulation. Another method is to lower its temperature. Resistivity of flue gas for low sulfur coals sharply decreases if the flue gas temperature at the ESP inlet is reduced to100˚c [8]. ESP collection efficiency is given by [9],

$$\eta(d) = 1 - \exp\{-\omega_t(d).\frac{L}{h.v}\} \quad (13)$$

Where, ŋ(d) = precipitation efficiency for a particle with diameter, $\omega_t(d)$= theoretical migration velocity,L = length of electric field, h = wire plate distance, υ = kinematic viscosity coefficient.

Total precipitation efficiency, $\eta_c(d)$ can be calculated by,

$$\eta_c(d) = \sum_{d_{min}}^{d_{max}} q_3(d).\eta(d) \quad (14)$$

Dust removal in ESP,

$$m_{ash(removed)} = \eta_c(d).m_{ash.f.g} \quad (15)$$

So, mass at ESP outlet,

$$m_{esp(outlet)} = m_{esp(inlet)} - m_{ash(removed)} \quad (16)$$

Table 1: input parameters for mass flow rate determination of a 500 MW power plant

Characteristics	**Case values**
Gross power generation	500MW
Gross cycle heat rate	9496 KJ/Kwh
Thermal efficiency of the cycle	44%
Boiler thermal efficiency	9496KJ/KWh
Percent excess air	33%
Sulfur in gas stream	95%
Fly ash in gas stream	80%
Electrostatic precipitator efficiency	99.5%
Hot gas temperature	149◦C
Coal moisture content (as fired)	9.80%
Coal analysis (dry basis)	
Carbon	65.41%
Hydrogen	1.18%
Oxygen	7.34%
Sulfur	3.50%
Ash	17.74%
Coal heating value (as fired)	24428 KJ/Kg
Environmental regulatory constraint	
Sulfur dioxide emission limit	520 ng/J
Scrubber system characteristics (TCA)	
Scrubbing pH	5.65
Liquor Mg and cl	0 ppm
Number of beds	3
Number of grids	4
Heights of spheres per bed	5 in. (127mm)
Scrubber gas velocity	12 ft. /sec (3.0 m/s)
SO2 removal efficiency	86% (assume)
99.3% (assume)	99.3% (assume)
Water entrainment at demister gas	0.1% wt. of flue

SO_2 removal efficiency of a FGD system is a function of scrubber module design, as well as gas conditions and process conditions including inlet SO_2 concentration, flue gas velocity, slurry composition, liquid to gas ratio and slurry pH. Although scrubber chemistry is not fully predictable semi empirical models can adequately predict the performance of current limestone system [2] [3]. Scrubber performance for SO_2 removal is found based on the semi empirical formula developed by Bechtel Corporation with Tennessee Valley Authority Shawnee Test Program using packed bed and spray tower absorbers. For a turbulent contact absorber (TCA), the sulfur dioxide removal efficiency is given by [10],

$$\eta_{so_2} = 1 - \exp\{-2.05\times10^{-4}\left(\frac{L}{G}\right)^{0.81} v^{0.36} \times \exp[4.3\times 10^{-3} v\left(\frac{h}{d}+N\right) + 0.81pH - 1.7\times10^{-4}SO_2 + 7.9\times 10^{-5}Mg + 1.3\times10^{-5}cl]\} \quad (17)$$

Where, η_{so_2}=fraction of SO_2 removed from flue gas, L/G =liquid to gas ratio (gal/1000acfm at scrubber outlet conditions), V =flue gas velocity at contactor conditions (ft. /sec), h = Static packing height (in.), d =packing diameter (in), N =number of TCA grids, pH =inlet slurry pH, SO_2=inlet SO_2 concentration (ppm), Mg =effective Mg^{++} concentration (ppm), cl =liquor cl concentration (ppm)

Mass of sulfur content removed in FGD system,

$$m_{s(removed)} = \eta_{so_2} . m_{s.f.g.} \quad (18)$$

Some ash or dust particles escaped from ESP are also entrained in the liquid. Mass flow rate at FGD outlet,

$$m_{FGD(outlet)} = m_{esp(outlet)} - m_{s(removed)} \quad (19)$$

Flue gas desulfurization causes entrainment of scrubber liquor droplets in flue gas which is a source of potential chemical pollutants. Although the quantitative determination of entrained liquid levels in gases leaving scrubber demisters has long been recognized as an important goal, no satisfactory and convenient methods are available [11]. Carnahan et al [12] [3] taken water entrainment as 0.1% mass of flue gas.

$$m_{outlet} = (1 + 0.001) m_{FGD(outlet)} \quad (20)$$

For case study a 500MW power plant is selected with input parameters shown in Table 1from Carnahan, et al in [12], [3]

Here the output is 500MW. The efficiency of the overall system can be found by multiplying η_{th} and η_{boiler} or from equation (21).

$$\eta_{overall} = \frac{3600}{gross\ cycle\ heat\ rate(kj/kwh)} \quad (21)$$

To generate 500MW power, 1351.35MJ energy is required per second that is supplied from 55.32 kg of coal at firing condition (equation 3). Percentage of components of coal at firing condition from ultimate analysis (dry basis) are C=59%, H=4.24%, N=1.06%, O=6.62%, S=3.16%, Ash=16%. So, mass of each components are C=32.64kg, H=2.35kg, N=0.59kg, O=3.66kg, S=1.75kg, Ash=8.85kg, Moisture=5.42kg (using equation 4, 5). Mass of Sulfur and Ash in flue gas are 1.66kg, 7.08kg (equation 6, 7). Neglecting Nitrogen oxidation C, H, S components of coal are burnt in the presence of Oxygen. Oxygen required for burning C, H and S is 87.04kg, 18.8kg, and 1.75kg. Coal itself supplies 3.66kg of Oxygen and it has 23.14% mass of air. Total Oxygen required from air is 103.93kg that comes from 449.14 kg of air. So, mass flow rate of flue gas at inlet is 502.54kg (equation 8, 9, 10, 11).

If Sulfur content in flue gas is high it lowers electrical resistivity of flue gas so it doesn't require addition of conductive gases for particle conditioning. Then inlet mass at furnace is equal to mass of flue gas at ESP inlet. ESP's removes dust, grit from flue gas. Its collection efficiency depends on particle size, electric potential, plate length and increases if this parameters increases [13] [14]. Mass flow rate at ESP outlet for efficiency of 99.3% is 495.5kg. FGD system efficiency depends on liquid to gas ratio, SO_2 concentration etc. As liquid to gas ratio increases efficiency of FGD system increases, but it also increases pressure drop of flue gas which requires more energy for reheating. Its efficiency ranges from 50% to 98%. The highest removal efficiency achieved by wet scrubbers, greater than 90% and the lowest for dry scrubber's less than 80% [15].It is also observed that addition of different types of ions such as Magnesium, Adipic acid may increase FGD system efficiency from 85% to 95-97% [16]. For 86% efficiency mass of flue gas reduces to 494.07 kg. In this process small amount of scrubbing liquid are carried away which may also cause chemical pollution. To prevent this demisters are used which causes water entrainment of 0.1% weight of flue gas approximately. So mass flow rate at outlet becomes 494.57kg. SO_2 emission limit can be calculated using this formula,

$$m_{so_2(emitted)/J} = \frac{m_{s.f.g(kg)} - m_{s.removed(kg)}}{power(MW)} \times 10^6 \quad (22)$$

From which it is visible that SO_2 emission from this power plant is 464.8ng/J. That is below regulatory standards. Another expression of SO_2 emission is grain/ ft.^{3}.

3. CONCLUSIONS

Environmental agencies and different organizations such as EU explicitly require the annual mass emissions of SO_2, NO_X and dust for large combustion plants with assured quality of the report. Conversion of volumetric flow rate to mass flow rate by ideal gas laws assumes a density of overall gas for different temperature and pressure. But gas density and volumetric flow rate varies within the system so it's become difficult to find the mass flow rate and mass of individual components. Determination of pollutant emissions may provide desired accuracy using above method cause it is done using material balance sheet. Though it is a lengthy process it is useful in software designing for flue gas monitoring and calculation method is cheaper sometimes better than measurement. Empirical formulas may vary with system, but material balance formulas are unique to all system.

4. REFERENCES

[1] Thermal Dispersion Mass Flow Material Handbook, Thermatel, Magnetrol International, Incorporated http://us.magnetrol.com/Literature/1/54-621.4%20Mass%20Flow%20Handbook.pdf

[2] G. G. McGlamery, R. L. Torstrick, W. J. Broadfoot, J. P. Simpson, L. J. Henson, S. V. Tomlinson, and J. F. Young, "Detailed Cost Estimates for Advanced Effluent Desulfurization Processes,"EPA-600/2-75-.006, U.S. EPA, Washington, DC, Jan. 1975.

[3] Rubin, Edward S., and Due G. Nguyen. "Energy requirements of a limestone FGD system." Journal of the Air Pollution Control Association 28.12 (1978): 1207-1212.

[4] Central Electricity Generating Board, Modern Power Station Practice vol 2, 2nd edition, PERGAMON PRESS, London, 1963

[5] Klein, David H., et al. "Pathways of thirty-seven trace elements through coal-fired power plant." Environmental Science & Technology 9.10 (1975): 973-979.

[6] Electrostatic Precipitators, Environmental Protection Agency, https://www3.epa.gov/ttn/caaa/t1/reports/sect5-2.pdf
[7] Maria Jędrusik and Arkadiusz Świerczok (2012). Design Efficiency of ESP, Air Pollution - Monitoring, Modelling, Health and Control, Dr. Mukesh Khare (Ed.), ISBN: 978-953-51-0381-3, InTech, Available from:
[8] http://www.intechopen.com/books/air-pollution-monitoring-modelling-health-and-control/design-efficiency-ofesp
[9] Bäck, Andreas. "Enhancing ESP efficiency for high resistivity fly ash by reducing the flue gas temperature." Electrostatic Precipitation. Springer Berlin Heidelberg, 2009. 406-411.
[10] White, Harry J. "Industrial electrostatic precipitation." Industrial electrostatic precipitation. Addison-Wesley, 1963.
[11] "EPA Alkali Scrubbing Test Facility: Advanced Program, Third Progress Report," EPA 600/7-77-105, Prepared by Bechtel Corporation for U.S. EPA, Sept. 1977.
[12] L.D. Jhonson, R.M. Statnick, " Measurement Of Entrained Liquid Levels In Effluent Gases From Scrubber Demisters, EPA-650/2-74-050, U.S. EPA Research Triangle Park, NC, June 1974
[13] E. S. Rubin, editor, "Comparative Environmental Assessments of Coal Utilization Systems. Volume II: Details of Model Development," Center for Energy and Environment Studies, Carnegie-Mellon University, Pittsburgh, PA, March 1978.
[14] Zhuang, Ye, et al. "Experimental and theoretical studies of ultra-fine particle behavior in electrostatic precipitators." Journal of electrostatics 48.3 (2000): 245-260.
[15] Gajbhiye, Narendra, et al. "Numerical calculation of particle collection efficiency in an electrostatic precipitator." Sadhana 40.3 (2015): 863-873.
[16] Pollutants, Applicable. "Air Pollution Control Technology Fact Sheet." Wang, Lawrence K., Clint Williford, and Wei-Yin Chen. "Desulfurization and emissions control." Advanced Air and Noise Pollution Control. Humana Press, 2005. 35-95.
[17] David Graham, H. Harnevie, R. V. Beek, F. Blank, “Validated methods for flue gas flow rate calculation with reference to EN 12952-15” Arnhem, January 31, 2012.