Study on physico-chemical treatment of effluents from biomass gasifier power generation system

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Abstract: The study aimed at a physico-chemical treatment of effluent/wastewater generated from the biomass gasification power generation system. A laboratory study determined the optimum dose of lime (CaOH2) as coagulant and alum ($Al_2(SO_4)_3 18H_2O$) as flocculants in the proportion of 1:1 g/l of effluent which later applied in the field experiment. The field results showed that freshwater used once could be used for two more recirculation by giving physical settling treatment. Thereafter, the chemical treatment with a predetermined dose of lime and alum was given due to increased load of tar and SPM which made possible to use the wastewater two more recirculation. After fifth-time use, the turbidity increased to 118.3 NTU which could not be brought down further with chemical treatment. The cost of chemical treatment for laboratory-grade chemicals was found ₹0.85 per litre of effluent and ₹0.10/litre of effluent for commercial grade chemicals.

Keywords: gasifier; syngas; effluent; tar; physico-chemical treatment.

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1 Introduction

Biomass is one of the important sources of energy for the world since the many decades and considered as a renewable energy source. Biomass conversion through the various thermochemical and biochemical process gives clean energy which can be utilised for thermal and power generation. Biomass gasification, thermochemical conversion technology is one of the promising renewable energy technologies for sustainable energy production which has the potential to decrease the dependence on fossil fuel (Berggren et al., 2008; Heidenreich and Foscolo, 2015). Gasification process is a thermo-chemical conversion of carbonaceous material into a gaseous fuel called as producer gas or syngas through its partial oxidation at an elevated temperature with air, oxygen, steam or their mixture (Caballero et al., 2000; Warnecke, 2000; Bridgwater, 2003; Brett et al., 2009; Basu, 2010). The process takes place in an oxygen-deficient environment which prevents complete combustion of the carbon and hydrogen present in the feedstock into CO_2 and H_2O respectively, and result in the formation of combustible components such as CO, H_2 and CH_4. In addition to these components, the producer gas also contains the typical product of combustion like CO_2, N_2, O_2 and H_2O (Martínez et al., 2012).

The major problem with the gasification process is the formation of the tar which requires great efforts to clean from the gas and creates operational issues in downstream equipment due to condensation and deposition of tar. Tar is an organic produced under thermal or partial-oxidation regimes (gasification) of any organic material and generally assumed to be aromatic (Milne et al., 1998). It is a complex mixture of condensable hydrocarbon which includes single to multiple ring aromatic compound along with other oxygen-containing hydrocarbon and complex polycyclic aromatic hydrocarbon (Devi et al., 2005) or hydrocarbons with a molecular weight higher than benzene (Maniatis and Beenackers, 2000). Raw syngas contains tar and other impurities like ash and char particles and has high exit temperature in the range of >400°C. It is necessary to ensure that the quality of the syngas is suitable in terms of tar and particulate content to use in an internal combustion engine (diesel and spark ignition engine) for electricity generation to maintain reliable engine operation, to provide adequate durability of major engine components and to avoid a high degree of engine maintenance (Hasler and Nussbaumer, 1999; Wu et al., 2002; Martínez et al., 2012). The permissible limit of solid particulate matter (SPM) and tar is <50 mg Nm^{-3} and <100 mg-Nm^{-3} respectively for satisfactory operation of the internal combustion engine (Hasler and Nussbaumer, 1999).

Producer gas cleaning can be done using several methods which include mechanical and physical methods for removal of both particulate and tar from the gases. Mechanical/physical methods are divided into two categories: dry and wet gas cleaning. Dry gas cleaning is usually used where the temperature is greater than 500°C and partly below 200°C and the types of equipment generally used are cyclone, bag filters, ceramic filters, sand filters, electrostatic precipitators (ESP), etc. While wet gas cleaning is used typically about at 20–60°C using devices like spray towers, packed bed columns scrubber, impingement scrubber, ventury scrubber, wet electrostatic precipitator, wet cyclone etc. (Reed and Das, 1988; Anis and Zainal, 2011; Asadullah, 2014).

Among these methods, the water spray is widely used as a scrubbing device due to lower pressure drops and simple construction (Reed and Das, 1988). The wet scrubber is important equipment for cleaning of syngas/producer gas which uses water scrubbing method to condense tar from the syngas and simultaneously removing the particulates (Anis and Zainal, 2011). The water required for cleaning of syngas varies from

600–1,800 l/h, this, in turn, leads to the generation of tar, ash and contaminated water (Tripathi et al., 2013). The characteristics of wastewater and tar generated are dependent on the type of biomass, gasifier configuration, temperature of the gasifier and oxygen content in the gasifier (Devi et al., 2003). The large-scale gasifier systems require even much water however, for large-scale gasifier systems, it is neither feasible to get a large amount of neither freshwater nor it is economical. Due to the strict environmental regulations, disposal of dirty effluent must be done under strict norms. So, it is desirable to recycle and treat the wastewater generated from the gas scrubbing devices and reuse the same as long as tar and particles content in cleaned producer gas presents within the permissible limits (150 $mgNm^{-3}$) prescribed for the engine applications (Pathak et al., 2007). If the water used in wet scrubbing system is given a suitable chemical treatment to remove the impurities (tar and SPM) and maintain it within the permissible limit, i.e., below <150 mg Nm^{-3} and temperature below 50°C, it will reduce the freshwater requirement for cooling and cleaning of producer gas substantially and will also help in reducing environmental pollution caused due to disposal of large quantities of water containing a high amount of impurities. The physico-chemical treatment using coagulation, flocculation and adsorption on activated carbon is reported to yield good removal efficiency for impurities from biomass gasifier wastewater (Mehta and Chavan, 2009); also a biodegradation method with activated charcoal gave satisfactory cleaning with enhanced recycling ability (Jeswani and Mukherji, 2013).

The dispersed solids in the wastewater include non-sedimentary suspended particles or particles with very low sedimentation velocity. These particles are negatively charged which expel the similarly charged particles granting stability to suspension. When the coagulants are added to effluent, metal disintegrates and hydrolyse the metal ions and metal hydroxide ionic complex with high positive charges are formed. They are absorbed to surface of colloids and neutralise the negative charge and get condensed via van der Waals forces. This adsorption is used to strengthen by water turbulence, called flocculation (Sarparastzadeh et al., 2007). The chemicals were selected based on their sludge formation properties and cost-effectiveness (Aziz et al., 2007; Zazouli and Yousefi, 2008). The efficiency of treatment was measured in terms of pH and turbidity (removal of total suspended solids).

The purpose of this study was to find out the efficiency of chemical treatment using chemicals like alum ($Al_2(SO_4)_3 18H_2O$), lime $(CaOH)_2$ and ferrous sulphate ($FeSO_4.7H_2O$) on effluent generated from wet scrubber unit and reuse treated water to minimise the overall freshwater requirement in gasifier power generation system. The chemical treatment used in the experiment includes coagulation and flocculation phenomenon.

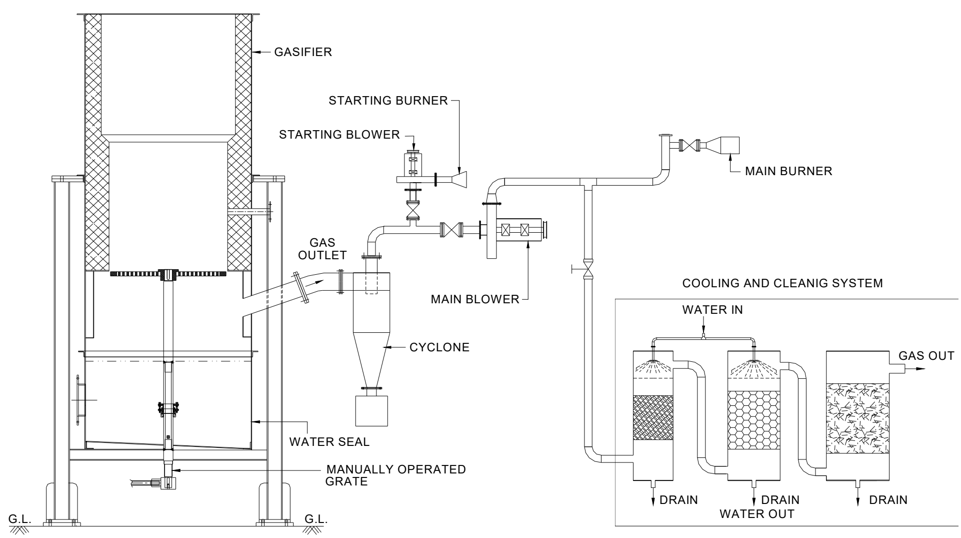
2 Materials and methods

The experimental setup included a biomass gasifier system, wet scrubber unit used for cooling and cleaning of the syngas and chemical treatment set up for treatment of the effluent.

2.1 Biomass gasifier system

An open core downdraft gasifier (Fig. 2) with fuel consumption rate (FCR) of 50 kg h^{-1} designed and developed by Sardar Patel Renewable Energy Research Institute (SPRERI) was used in the experiment. The fuel used for the operation of gasifier was wood and agro-residue briquettes to generate the syngas to be further used for power generation. The outlet temperature of the syngas ranged between 400–450°C. A cyclone separator was used as a primary device to remove course solid particles from the syngas while wet scrubber unit was used for cooling and cleaning i.e conditioning of the syngas. A wet scrubber unit consisted of three cylindrical columns connected in series – first two wet scrubbers provided with water spray and third dry filter provided with filter media. The first scrubber was filled with Raschig rings made of stainless steel (diameter = 15 mm, length = 15 mm). The Raschig rings helped to increase the contact surface area between syngas and spray water increasing the cleaning and cooling efficiency. The high outlet temperature (400–450°C) of the syngas was reduced to 42–44°C after passing though wet scrubber as most of the sensible heat was removed by direct contact of syngas with the water. The impurities like tar and solid particulate matter (SPM) consisting of ash and carbon particles got removed in the wet scrubber unit. The tar vapor in the syngas comes in direct contact with the water, get condensed and separated from the gas phase. The second filter was filled with wood charcoal pieces (size: ~15–20 mm) helps in absorbing the moisture as well as tar from the gas and further enhances the gas purity. The third filter contains coconut coir as filter media.

Figure 1 Setup of the gasifier and producer gas wet scrubber unit



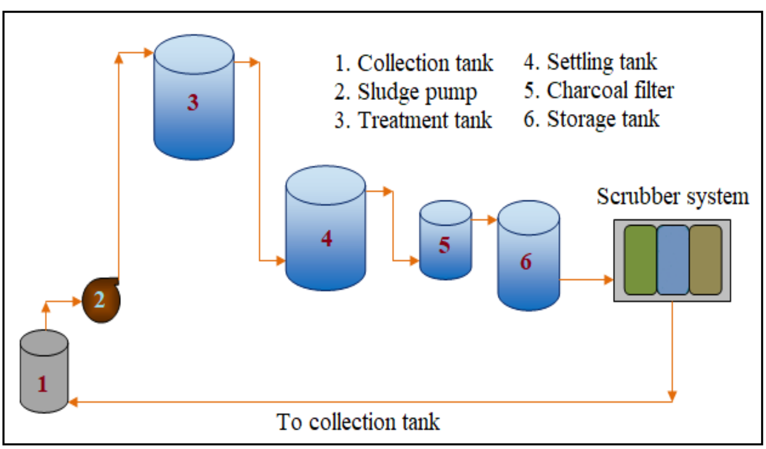
2.2 Laboratory study

A preliminary physico-chemical treatment consisting of a coagulation and flocculation process was performed at the laboratory level in 'Imhoff' cone to determine the optimum dose and concentration of the selected chemicals to treat the effluent to reduce the concentration of tar and particles. Lime, alum and ferrous sulphate at varying concentration and combination (0.8–2.0 g/l) were selected for the study based on the literature available. The pH and turbidity of freshwater and the effluent from wet scrubber were measured using pH meter and turbidity meter (Chemiline make). Mehta and Chavan (2009) have reported satisfactory treatment efficiency without pH adjustment of the effluents from producer gas scrubber. Therefore, all the experiments were performed without altering pH. The effluent was first stirred thoroughly and then 250 ml sample was drawn in Imhoff cone. Different doses of selected coagulants and flocculent were added to the effluents and mixed thoroughly by manual stirring. The flocs formed after the coagulations-flocculation process was allowed to settle down for 25 minutes. The value of pH, turbidity and sludge volume were measured. The concentrations were selected to minimise the quantity of chemical used and maximise settlement of the tar and particles.

2.3 *Effluent treatment system*

The effluent treatment system (Figure 2) was designed for 1,000 litre capacity and was consisted of a treatment tank, settling tank, storage tank and charcoal filter. The effluent from the syngas wet scrubber unit was allowed to flow into the collection tank and pumped to the treatment tank with the help of a sludge pump. A pre-determined dose of alum and lime was mixed into the treatment tank for coagulation and flocculation process and then it was transferred to the settling tank without disturbing the sludge layer formed at the bottom of the treatment tank. The treated water was passed into the storage tank through the charcoal filter for further reuse in the syngas wet scrubber unit. The sludge left in the treatment tank was decanted through the drain provided at the bottom before the next cycle of water recirculation.

Figure 2 Setup plan for treatment of effluent (see online version for colours)



2.4 *Field experiment*

The field experiments were first carried without chemical treatment and monitored for the pH and turbidity of effluent to determine its suitability for recirculation in the wet scrubber unit after giving it sufficient settling time. When pH and turbidity showed non-reversal sign, chemical treatment was applied. A pre-determined dose of the selected chemicals was added to the effluents in the treatment tank, mixed thoroughly and left undisturbed for 20 hours. After 20 hours of settling time, decanted water was passed through a charcoal filter to the storage tank and reused in the wet scrubber unit. The same practice was followed for every recirculation and decided the number of time the treated effluent could be reused in the wet scrubber unit. The pH, turbidity and temperature of the effluent were measured before and after every use i.e. at inlet and outlet of the wet scrubber unit. The producer gas samples were taken and analysed for tar and SPM content at inlet and outlet of the wet scrubber unit for every time. The experimental setup used for the experiment is shown in Figure 3.

Figure 3 Field setup for chemical treatment of effluent water (see online version for colours)

3 Results and discussions

3.1 Laboratory experiment

The samples of effluent water coming from the wet scrubber unit had a typical greyish black colour as it contained char and ash particles as well as tar in a liquid state. The pH and turbidity of the freshwater and the effluents, after first-time use in wet scrubber unit, were measured. The data (Table 1) shows that the turbidity of the water was increased by around eightfold while pH lowered down slightly. The reason being the suspended solid particles in the gas were captured in the water effluents while the acidic nature of the tar reduced the pH value.

Table 1 pH and turbidity

Sample	*pH*	*Turbidity, NTU*	*Colour*
Fresh water	8.75	6.30	-
Effluents water	8.30	58.60	Greyish black

The samples of the effluent water from the wet scrubber system were treated in the laboratory with alum and lime and observations on pH, turbidity and sludge volume were measured for each treatment given and presented in Table 2. It was found that the dose of alum and lime by weight of 1.0 g/l of effluent respectively, i.e., in 1:1 ratio gave the best results for the reduction in turbidity, pH and increased ability for settling of the sludge.

Table 2 Parameters of laboratory study of effluent chemical treatment

Sample, ml	*Dose, g/l*			*Retention time , min*	*pH*	*Turbidity, NTU*	*Sludge vol., cm^3*	*Remarks*
	Alum	*Lime*	*Ferrous sulphate*					
250	2.0	--	--	25	------ Light flocs -----			-
250	--	2.0	--	25	10.44	906	2	Light flocs
250	0.8	1.2	--	25	9.19	143	12	Light flocs
250	0.8	0.8	--	25	8.8	757	10	Light flocs
250	1.2	0.8	--	25	8.49	54.2	21	-
250	1.2	1.2	--	25	8.85	576	13	Light flocs
250	1.0	1.0	1	25	8.56	235	11	Water turns greenish
250	2.0	2.0	--	25	9.48	748	20	Light flocs
250	1.0	1.0	-	25	8.86	40.8	18	-
1,000	1.0	1.0	--	20*	8.57	8	20	-

Note: *stands for hours.

3.2 Field experiment

3.2.1 Treatment without chemicals

Initially, freshwater was used in the wet scrubber unit for conditioning of the raw producer gas. The effluent water was collected in the collection tank, pumped it to the settling tank and allowed to settle for 20 h every time and then reused in the wet scrubber unit without any chemical treatment. The parameters like pH, turbidity and temperature of the freshwater, effluents after second and third-time use were measured at the inlet and outlet of the wet scrubber unit and are depicted in Table 3.

Table 3 Parameters of effluent without chemicals treatment

Parameter	*Treatment without chemicals*								
	Fresh water			*First reuse*			*Second reuse*		
	WS_{in}	*WS_{out}*	*After 20 h*	*WS_{in}*	*WS_{out}*	*After 20 h*	*WS_{in}*	*WS_{out}*	*After 20 h*
pH	8.52	8.03	8.40	8.38	7.98	8.23	8.23	8.17	8.20
Turbidity, NTU	2.20	42.80	32.30	30.20	51.20	43.30	40.70	80.30	72.50
Temp., °C	24	33	31	31	39	33	33	41	40

Note: WS_{in} – wet scrubber inlet; WS_{out} – wet scrubber outlet.

It could be seen that change in the pH and temperature of the water after the first reuse and second reuse was marginal; however, there was a substantial increment in the turbidity. Initially, freshwater had turbidity and pH at 2.20 NTU and 8.20 respectively. When it was used in the wet scrubber unit, turbidity increased to 42.80 NTU while pH reduced to 8.03. After 20 h of settling period, the turbidity reduced to 32.30 NTU while pH increased nearly to its original value. The effluent was then recirculated for the first time reuse where the same trend in change in turbidity and pH was observed. After the second reuse, the turbidity of effluent increased up to 80.3 NTU and the pH reduced to 8.17. After 20 h settling, the turbidity improved marginally to 72.5 NTU which made water unsuitable for next use. The increase in turbidity was due to more accumulation of tar and solid particles in the effluent while a fall in pH was due to the acidic nature of the tar. Every time, after giving 20 h of settling time, the pH was normalised to nearly its original level. It was observed that the turbidity of effluent had lowered down marginally every time as the effluent passed through the charcoal filter where some tar and suspended particles get trapped. Table 4 shows the cumulative tar and solid particles content in the producer gas at the inlet and outlet of the wet scrubber system which shows that it was well below 150 mg Nm^{-3}, permissible for IC engine application. The tar and solid particle content in raw producer gas varied in all the readings which in general depend on the real-time operation of the gasifier.

Table 4 Tar and solid particulate matter content in the producer gas

Parameter	*Fresh water*		*First reuse*		*Second reuse*	
	WS_{in}	*WS_{out}*	*WS_{in}*	*WS_{out}*	*WS_{in}*	*WS_{out}*
Tar + SPM, mg m^{-3}	298.3	120.1	165.4	63.72	181.4	78.05

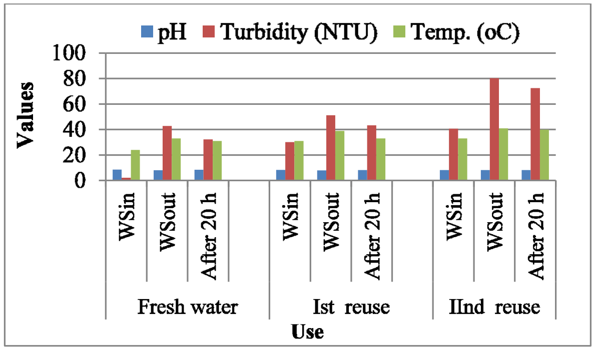
3.2.2 Treatment with chemicals

The same effluent water used earlier in the wet scrubber unit without chemical treatment was used in the next phase of chemical treatment. It was observed that the pH and turbidity of the effluent used in the first stage without chemical treatment increased significantly after third-time use. Therefore, alum and lime in the proportion of 1:1 were thoroughly mixed with the effluent in the treatment tank. The mass was stirred manually to allow coagulations-flocculation and left undisturbed for 20 h. the turbidity of the effluent which was used earlier for the third time without chemical treatment was of 72.50 NTU reduced to 14.6 NTU after chemical treatment, while pH increased to 8.59 from 8.20.

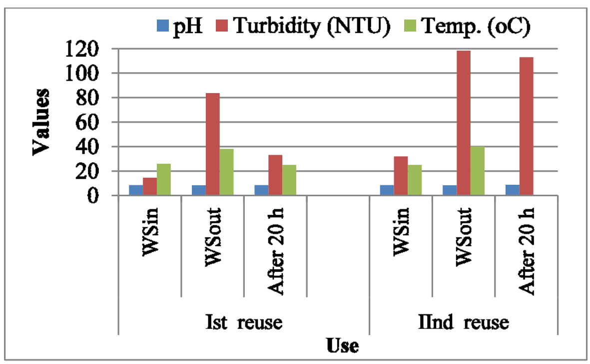
Table 5 pH, turbidity and temperature of effluent after chemical treatment

Parameter	*With chemical treatment*					
	First reuse			*Second reuse*		
	WS_{in}	*WS_{out}*	*After 20 h*	*WS_{in}*	*WS_{out}*	*After 20 h*
pH	8.59	8.36	8.58	8.58	8.48	8.71
Turbidity, NTU	14.6	83.75	33.1	31.9	118.3	112.9
Temp. °C	26	38	25	25	40	--

Figure 4 Change in parameters, (a) without chemical treatment (b) with chemical treatment (see online version for colours)



(a)



(b)

This chemically treated effluent used for the first time in the wet scrubber unit and observed that the turbidity increased to 83.75 NTU while the pH reached nearly to its initial level as shown in Table 5. The effluent was again treated with the same chemicals dose (1:1 ratio) with giving 20 h settling period which reduced the turbidity to 33.1 NTU. The treated effluent was reused for the second recirculation which increased the turbidity again to 118.3 NTU from 31.9 NTU. The effluent was again treated with a predetermined dose of chemicals but the turbidity reduced marginally to 112.9 NTU (Figure 4) which made it unfit for the further use in wet scrubber unit. The values of tar and particulates were measured which was below 150 mg Nm^{-3} given in Table 6, however, it could not reduce less than 120 mg Nm^{-3} in either trial.

Table 6 Tar and solid particulate matter content in the producer gas

Parameter	*First reuse*		*Second reuse*	
	WS_{in}	*WS_{out}*	*WS_{in}*	*WS_{out}*
Tar + SPM, mg m^{-3}	173.4	126.2	180	120

5 Conclusions

The study conducted on recycling of the waste effluent generated from wet scrubber system used for producer gas demonstrates that physicochemical treatment with and without chemical treatment could be one good option to treat the effluent containing tar and particulate matter. These benefits in saving a high amount of water required for conditioning of the producer gas as well as reduce the environmental pollution. The key conclusions that can be drawn from the study are:

- Physico-chemical treatment of gasifier wastewater consisting of coagulation and flocculation process was studied and a process has been proposed to reuse of the recycled wastewater.
- The effluent from the wet scrubber unit had a typical greyish black colour due to contamination of tar, char and ash particles.
- Good ability for the settling of sludge and removal of impurities was found in the laboratory study at the optimum dose of lime: alum ratio of 1:1 g/l of effluent.
- In the first stage, the effluent was given only physical settling treatment for 20 h without the addition of chemicals which allowed wastewater to be used for two more times. However, turbidity increased substantially to 80.3 NTU after second reuse.
- In the second stage, same wastewater was treated with a predetermined dose of lime and alum as a coagulant and flocculent providing 20 h settling period, which reduced turbidity of effluent from 72.50 NTU reduced to 14.6 NTU in the first treatment and from 118.3 NTU from 31.9 NTU in the second treatment. pH remained nearly in the same range during all recirculation.
- The values of tar and particulates were below 150 mg Nm^{-3}, however, it could not reduce less than 120 mg Nm^{-3} in chemical treatment.
- During the chemical treatment, neither pH adjustment was required for enhancing the coagulation-flocculation process nor for neutralisation of pH of the wastewater after treatment.
- The physico-chemical treatment results in enhancing the recycling ability of the wastewater lowering the overall water requirement for biomass-based power generation system.
- The process is simple, low-cost and efficient for the removal of contaminant, can be easily adopted for gasifier wastewater treatment.
- The cost of chemical treatment for laboratory-grade chemicals was found ₹ 0.85 per litre of effluent and ₹ 0.10 per litre of effluent for commercial grade chemicals.
- The study revealed the recycling ability of wastewater, however further study may focus on recycling and reuse of the wastewater from large capacity gasifier power plant with a different coagulant and flocculent considering more parameters like colour removal, total dissolved solids (TDS), alkalinity, phenols and COD.

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Abbreviations

FCR	Fuel consumption rate.
IC	Internal combustion.
mg Nm^{-3}	Milligram per normal cubic metre.
MJ Nm^{-3}	Megajoule per normal cubic metre.
NTU	Nephelometric turbidity unit.
SPM	Tar and solid particulate matter.
WS_{in}	Wet scrubber inlet.
WS_{out}	Wet scrubber outlet.