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A Thermo-Fluid Study of a Diesel Engine Wet Scrubber

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Abstract

In underground coal mining, wet scrubbers are used to remove diesel particulate matter and improve air quality, reduce equipment maintenance, and eliminate fire/explosion hazards by spark arresting and reduction of exhaust temperatures. Due to the difficulties of scrubber experimental investigations there is almost no published literature their thermo-fluid behaviour. This paper reports a study of a transient state mass and energy (thermodynamic first law) analysis on a scrubber. Quantitative data was obtained experimentally over 16 tests to investigate the energy balance of the scrubber. Energy contain within the exhaust gas is the lone source of energy input to the scrubber while Energy leaving from the scrubber comprises four portions namely exhaust energy, energy out due to change in control volume, heat lost from scrubber and heat flux in to the water. The average values of these output energies were 53.37%, 35.76%, 12.80% and 0.26% of input energy respectively. Energy balance errors of up to 50% of input energy were found in the data due to the difficulties associated with measuring radiant/convective heat loss and water content of high temperature exhaust gases. Never the less the analysis provides a benchmark for design of future investigations and highlighted some major issues associated with these devices. The major finding was that liquid water is ejected from the scrubber (*i.e.* Two-phase flow) due to excessive turbulence and high velocities at the exit which are highly undesirable for several operational reasons including damaged post-scrubber diesel particulate filters, and increased maintenance. The data analysis of this report can be used to provide a better understanding of the operating capacity of a scrubber. This will ultimately result in better advances in scrubber technology for the reduction of diesel emissions and improved humidity control strategies to prevent fire/explosion occurring in an underground mine and minimize adverse health effects on miners and associated staff.

Introduction

The diesel combustion process releases both gaseous pollutants and diesel particulate matter (DPM) in the environment that have primary and secondary impacts on air quality, human health, and climate [1]. As a result, government policy and regulations have become increasingly stricter on emissions. Coupled with the growing appreciation of the environmental damage our society is causing, it is necessary to develop emission reduction technologies. Furthermore, due to the combustible gases present in underground coal mining it is necessary to reduce emission temperatures to below the ignition point of these gases. Many authorities impose maximum exhaust temperatures and scrubbers are one of the most common technologies used for reducing the outlet temperature.

Wet scrubbers are an apparatus used for the physical separation and removal of particles, either solid or liquid, from the diesel engine exhaust gas stream. They clean the exhaust streams by bringing target particles into contact with a scrubbing solution, primarily water which may sometimes contain additives. Wet scrubbers are typically utilised to improve air quality by the removal of DPM, to reduce equipment maintenance (particulate filters), and to eliminate fire/explosion hazards by spark/flame arresting and reduction of exhaust temperature at tail pipe. While particulates are removed from the gas stream, water scrubbers have little effect on gaseous emissions [2]. Dry particulate filters (DPF) are commonly used in conjunction with wet scrubbers to assist in meeting these outcomes. A DPF is attached to the scrubber outlet with the aim of ensuring particles not absorbed by the scrubbing liquid are filtered. Efficiencies of DPFs are generally varies 85% to 99% depending upon the particle sizes, although numbers of ultrafine particles may still be high as they are beyond the capacity of the DPF [3]. Currently the filters require frequent replacement because the water vapour generated by the scrubber damages the filter material, reducing the DPF efficacy. According to Schnelle and Brown [4], wet scrubbers display unique characteristics useful for DPM control: (i) particles are captured in a liquid allowing for their easy removal from the scrubber; (ii) used with high temperature and potentially explosive gases; (iii) relatively inexpensive when the removal of fine particulates is not critical; and (iv) easily operated compared to alternative types of DPM removal equipment. Wet scrubbers have become ubiquitous in underground coal mines because of their spark arresting and exhaust treatment properties [5], yet these filters have to be replaced as often as every four hours in some cases despite the suppliers' advice that they have a 40-hour operating life. Operators have speculated that short filter life could be a consequence of scrubber water penetrating the filter, altering the structure of the fibre [3]. The major inconvenience this causes mining companies is not in the cost of replacing the filters (unit cost $400) but rather in the downtime (mid-shift) caused by the filters needing to be replaced for the vehicles equipped with the scrubbers and filters.

In previous work, Situ et al [6] has developed a model for the exit humidity of wet scrubbers. This model shows the relative humidity at the scrubber outlet against the outlet temperature for varying inlet temperatures. Only one data point was displayed on the exit humidity model, which was obtained from an experimental analysis conducted in the QUT Biofuel Engine Research Facility (BERF) for a 4.5L naturally aspirated diesel Perkins engine coupled to a scrubber. This continuing research aims at improving the life of the wet scrubbers, by reducing the steam content exiting the liquid surface because moisture reaching the filter is found to be the major concern in their durability. It also aims to reduce the DPM output from the water surface and reduce water consumption. The aim of this project is to develop an energy balance model for the exit humidity of wet scrubbers, and obtain data points to improve the model and its validity. The data analysis of this report will assist in providing a better understanding of the operating capacity of a scrubber, which will ultimately result in better advances in scrubber technology for the reduction of diesel emissions. It will further advance the fundamental understanding of heat and mass transfer in the process, and result in better emission and humidity control strategies. These aims will be achieved by conducting a transient state thermodynamic first law analysis on the scrubber.

Experimental Setup and Procedure

The experiment was conducted over 16 tests at Peak3 P/L, a specialist Diesel Emissions Management company based in Brisbane, Australia in mid-2013. The wet scrubber used to collect data was an EIMCO Australia wet scrubber, model number A2U913-291154. DPFs were used in the outlet of the wet scrubber. This exhaust cleaning equipment was coupled to a commercial Caterpillar 7.2L turbo-diesel engine which provided the exhaust to be cleaned by the scrubber. Although this engine was of a capacity above the rating of the scrubber, it was run at a reduced engine rpm and load so that the exhaust gas flow did not exceed that of the rated capacity of the scrubber. Several sensors were set up to record the following engine data: oil pressure (kPa),, coolant temperature (°C), percentage engine load (%), turbo boost (kPa), RPM, throttle pedal position (%), intake manifold temperature (°C), barometric pressure (kPa), exhaust gas temperature (°C), exhaust O_2 percentage (by mass) (%), and instantaneous fuel usage rate (l/h). The values of each of these data streams are automatically recorded by a custom data logging system with a sampling frequency of 1 Hz and can be downloaded into an Excel spreadsheet for post-processing. This engine data was used to calculate volumetric and mass flow rates of exhaust from the engine all of which goes into the scrubber. Thermocouples were used to collect the temperature data which can conveniently be used in conjunction with the custom data logging system above to record temperature at 1 Hz. Temperature and engine data can both be downloaded into an Excel spreadsheet for post-processing. The position of these thermocouples and the data logger in relation to the scrubber is displayed in Figure 1. Additionally a Digitech QM7221 InfraRed Thermometer was used to measure the surface temperatures of the scrubber from which to calculate the heat loss gradients.

The engine was turned on for approximately 10 to 15 minutes before data collection to warm up both the engine and the testing equipment. To begin data collection the sensors and data loggers are activated with the engine switched on immediately after. This data collection equipment records the temperatures and the engine conditions. Additional data including the scrubber weight and scrubber wall temperature was taken manually across the entire test from before the engine was started to after it was switched off. After a period of approximately 20 minutes when conditions begin to approach steady-state, the DPFs would be added (two were used in every test except test 9). This was not done before the test started to prevent an excessive build-up of DPM on the filters which would block them, and to reduce the back pressure so the equipment measuring the diesel particles was not overwhelmed as significantly more DPM left the engine during this time period than at any other time. The test was ended with the engine being switched off when the outlet temperature increased significantly. Data was still collected after this time for up to an hour.

Conceptualizing Thermodynamic Model

The wet scrubber is to be conceptualized as an open system with an imaginary boundary so exhaust gas flowing through the scrubber, as shown in Figure 2. The energy balance of the scrubber is described by the following equation

$$\dot{E}_{in} - \dot{E}_{out} - \dot{E}_{\Delta v} - \dot{Q}_L - \dot{E}_w = 0 \quad (1)$$

where $\dot{E}_{in}$ is the diesel exhaust energy entering the scrubber from the engine in kW, $\dot{E}_{out}$ is the diesel exhaust energy leaving the scrubber in kW, $\dot{E}_{\Delta v}$ is the energy loss due to the change in water volume in kW, $\dot{Q}_L$ is the heat energy lost from the scrubber to the ambient and $\dot{E}_w$ is the heat flux into the water. To improve the $\dot{E}_{in}$ and $\dot{E}_{out}$ calculations, the mass flow rate of the exhaust gas through the scrubber and the specific heats, c_p, are proportionally divided between the four major combustion products on a percentage mass basis. These combustion products are carbon dioxide (CO_2), water vapour (H_2O), oxygen (O_2), and nitrogen (N_2)

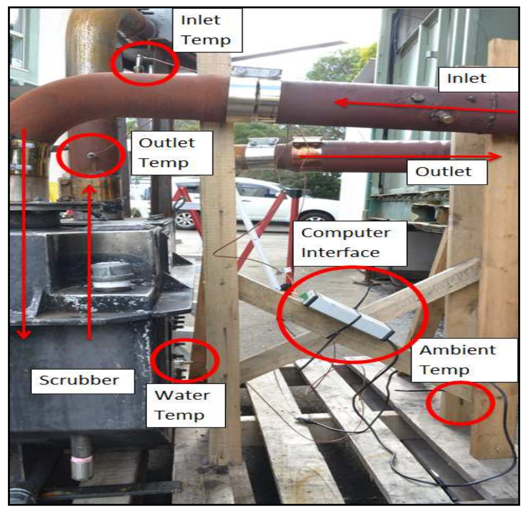

Figure 1. Experimental Setup.

$$\dot{E}_{in} = \dot{m}_{CO_2} T_{in} c_{p,CO_2,in} + \dot{m}_{H_2O} T_{in} c_{p,H_2O,in} + \dot{m}_{O_2} T_{in} c_{p,O_2,in} + \dot{m}_{N_2} T_{in} c_{p,N_2,in} \quad (2)$$

$$\dot{E}_{out} = \dot{m}_{CO_2} T_{out} c_{p,CO_2,out} + \dot{m}_{H_2O} T_{out} c_{p,H_2O,out} + \dot{m}_{O_2} T_{out} c_{p,O_2,out} + \dot{m}_{N_2} T_{out} c_{p,N_2,out} \quad (3)$$

Where, $\dot{m}$ is the mass flow rate, T_{in} is the scrubber inlet temperature, and T_{out} is the outlet temperature. As total mas loss rate from scrubber (dW/dt) split into two parts to account for the water that is evaporated and the water that exits the scrubber as liquid hence the energy loss due to the change in water volume $\dot{E}_{\Delta v}$ is subdivided into two parts: (i) the energy of the evaporated vapour; (ii) the energy of the water that exits as liquid form.

$$\dot{E}_{\Delta v} = \left(\dot{m}_{w,out} - \dot{m}_{w,in}\right)\left(h_{fg} + c_{pw}\left(T_{out} - T_{water}\right)\right) + \left(\frac{dW}{dt} - \dot{m}_{w,out} + \dot{m}_{w,in}\right) c_{pw}\left(T_{out} - T_w\right) \quad (4)$$

Where, $\dot{m}_w$ is the water vapour mass flow rate, h_{fg} is the latent heat, c_{pw} is the specific heat for water, and T_w is the water temperature inside the scrubber tank. The heat loss from the scrubber can be deemed as from three clearly definable areas: (i) the upper scrubber walls not in contact with the water; (ii) the scrubber walls in contact with the water; and (iii) the water. The heat loss $\dot{Q}_L$ can be calculated by finding the gradient of cooling curves taken when the engine was turned off (scrubber not operating) as there was no transfer of energy at this time. Heat loss by conduction to the inlet and outlet pipes was neglected.

$$\dot{Q}_L = m_{UpperWall} c_{p,wall} \frac{dT_{UpperWall}}{dt} + m_{LowerWall} c_{p,wall} \frac{dT_{LowerWall}}{dt} + m_{water} c_{p,water} \frac{dT_{water}}{dt} \quad (5)$$

Finally, heat flux to the water can be calculated by multiplying mass of water with specific heat of water and temperature difference as follows where T_{w1} is the water temperature at the beginning and T_{w2} is the same at the end.

$$\dot{E}_w = m_w C_p (T_{w1} - T_{w2}) \quad (6)$$

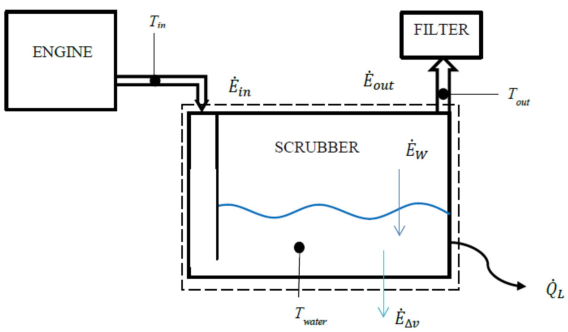

Figure 2. Schematic diagram of a wet scrubber

Data analysis

Volumetric Flow Rate of Exhaust Gas

By assuming the average diesel compound is $C_{12}H_{23}$ [7], and that diesel is fully combusted with 150% theoretical air, so the combustion reaction becomes

$$C_{12}H_{23} + 26.625(O_2 + 3.76N_2) = 12CO_2 + 11.5H_2O + 8.875O_2 + 100.11N_2 \quad (7)$$

where the molar volume increases by 3.72% from reactants to products. The volumetric flow rate was calculated as follows:

$$\dot{V} = 1.0372 \frac{C_{engine}}{1000} \frac{RPM}{60} \frac{1}{2} R_B \eta_{Volumetric} \quad (8)$$

where, C_{engine} is the engine capacity in litres which is 7.2L for the test engine, RPM is the revolution per minute of the drive shaft, R_B is the ratio between the boost gauge pressure and atmospheric pressure for the engine boost, and $\eta_{Volumetric}$ is the volumetric efficiency of the engine assumed to be 85%. The mean value of measured rpm and calculated volumetric flow rate for the 16 data sets were 1215.92 and 0.074 m^3/sec respectively. While, average boost ratio ($R_{B)}$ was found to be 1.155.

Water Mass Loss from Scrubber

The engine exhaust gas entering the scrubber causes the water to evaporate into water vapour which exits the scrubber along with water droplets. As a result, a certain amount of water in the scrubber was lost over the course of the tests. To measure this change in constant water volume (water loss) of the scrubber (dW/dt). A scale was used and manually calibrated by adding known masse of water the scrubber. As introduced above, the change in control volume of the water was split in two parts, evaporated water, and liquid exiting the scrubber. This is necessary because it was observed during testing that the exhaust gas exiting the scrubber also contains liquid. If the exhaust gas at scrubber outlet is assumed to be 100% relative humidity, the mass flow rate of the evaporated water vapour can be calculated from the following equation.

$$\omega \equiv \frac{\dot{m}_{w,out}}{\dot{m}_a} = \frac{R_a}{R_v} \frac{\phi P_g}{P - \phi P_g}, \quad (9)$$

where ω is the specific humidity, R_a is the gas constant of dry air, R_v is the gas constant of water vapor, ϕ is the relative humidity, P_g is the saturation pressure of water, and P is the atmospheric pressure. Average humidity ratio for the data set and their corresponding temperatures and water losses are shown in Table 1.

Test	T_{in}	T_{out}	T_w	ω	dW/dt
	°C	°C	°C	-	g/s
1	291	59.0	61.0	0.16	10.6
2	349	61.7	64.5	0.19	10.6
3	349	62.7	65.5	0.20	9.3
4	342	61.5	64.0	0.19	12.8
5	343	65.3	67.5	0.23	10.9
6	336	64.2	66.0	0.21	8.3
7	357	66.5	68.5	0.25	13.4
8	356	66.5	68.2	0.24	12.4
9	272	59.7	61.0	0.16	8.7
10	321	64.0	65.7	0.21	10.2
11	301	61.2	63.5	0.18	8.2
12	365	66.5	68.0	0.24	12.0
13	364	66.5	68.5	0.25	10.2
14	372	66.3	68.5	0.25	10.6
15	355	65.0	67.0	0.22	11.9
16	364	66.0	67.7	0.24	11.9

Table 1: Measured scrubber parameters.

Heat Loss from Scrubber

A Digitech QM7221 InfraRed Thermometer was used to measure the temperature on the scrubber's surface. Laser targeting was used by the thermometer to ensure it was held the correct distance away from the object. A total of eleven dots were drawn on three sides of the scrubber to evenly measure the cooling temperature gradients across the scrubber and also to ensure the temperature was taken in the same position every time to avoid errors. The data from these points was then plotted on a time vs. temperature scale where an exponential trend line was fitted only to the data taken after the engine was turned off and the temperature was decreasing, to determine the gradients $\frac{dT_{UpperWall}}{dt}$ and $\frac{dT_{LowerWall}}{dt}$. This was done because there was no transfer of mass or energy after the engine was turned off. To ensure accurate results the exponential trend-line was only fitted to the temperature data from when the temperature decrease reached similar temperatures to those experienced during the test because a temperature spike occurs just before the engine was switched off. To calculate the heat loss from the water inside the scrubber, the change in temperature with respect to change in time, $\frac{dT_{water}}{dt}$, was found by fitting an exponential trend-line to the water temperature data for the time after the engine was switched off as there was no transfer of energy occurring under these conditions. It is important to note that the temperature of the water continued to gradually rise for a few minutes after the engine had been turned off before it began decreasing. This small increase in temperature immediately after the engine was switched off was ignored and assumed to be non-influential on the heat loss calculations. The exponential trend-line is therefore only fitted to the water temperature data from when the temperature begins to decrease (after the engine has been switched off) to when the temperature decrease levels out and becomes constant. The calculated energy values are depicted in table 2 and a sample calculation using data from Test 1 is given in Figure 3.

Test	$\dot{E}_{in}$	$\dot{E}_{out}$	$\dot{E}_{\Delta v}$	$\dot{Q}_L$	$\dot{E}_w$	$\Delta\dot{E}$
	kW	kW	kW	kW	kW	kW
1	26.6	15.3	12.8	2.7	0.03	4.2
2	28.5	14.8	18.1	4.7	0.02	9.2
3	28.1	14.6	19.1	3.8	0.05	9.6
4	28.2	14.8	16.9	3.7	0.0	7.2
5	28.3	15.0	21.7	3.9	0.09	12.5
6	28.2	15.1	19.4	4.5	0.05	10.9
7	28.5	14.8	24.3	4.3	0.12	15.1
8	28.4	14.8	23.6	3.7	0.09	13.7
9	26.6	15.8	9.2	3.5	0.05	2.1
10	27.1	14.9	19.5	3.8	0.02	11.2
11	27.3	15.4	15.9	3.2	0.09	7.3
12	28.7	14.7	23.8	2.9	0.08	12.9
13	28.2	14.5	24.4	2.7	0.08	13.5
14	28.2	14.3	24.7	2.8	0.06	13.7
15	28.2	14.7	21.7	3.3	0.14	11.6
16	28.1	14.4	23.3	3.2	0.20	13.1

Table 2: Calculated parameters assuming 100% exit humidity.

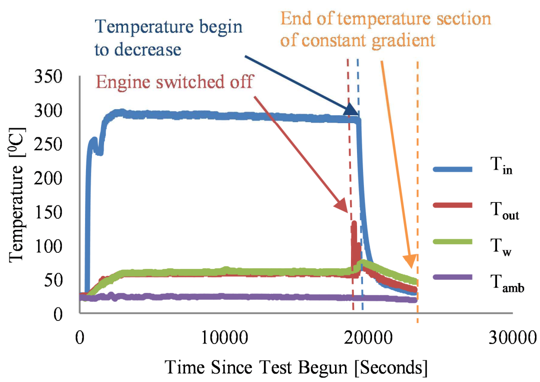

Figure 3. Temperature log for Test 1.

Heat Balance Analysis and Discussions

Based on the measured parameters and the above equations, the entire energy rate terms in Equation 1 were calculated and listed in Table 2. The energy rate balance ($\Delta\dot{E}$) are also shown in the table 2, which are defined as

$$\Delta\dot{E} = \dot{E}_{out} + \dot{E}_{\Delta v} + \dot{Q}_L + \dot{E}_w - \dot{E}_{in}\,, \tag{10}$$

$$\varepsilon_{\Delta\dot{E}} = \frac{\Delta\dot{E}}{\dot{E}_{in}} \times 100\%\,, \tag{11}$$

where, $\varepsilon_{\Delta\dot{E}}$ is the percentage of error and other parameters stand the same meaning as it was in equation 1. In an attempt to minimize the error introduced by the internal scrubber humidity, an additional test was conducted to determine this humidity with the deployment of wet and dry bulb thermometers. It was revealed that the data for both thermometers fluctuates erratically. Conducting an initial analysis of this data by smoothing it with the surrounding ten data points the temperature depression was found to be approximately 1.5°C, with the dry-bulb temperature approximately 65°C and the wet-bulb temperature approximately 63.5°C. The corresponding humidity was found to be 93%. Changing the scrubber exit humidity in the model to 93%, the first law analysis energy balance found the percentage error between 4~43% of input energy, an improvement on the original results but still a significant error. It is important to remember that the 93% humidity assumption was based on a separate test which is not shown in table 2; hence many of the other parameters that the energy balance is based on could have changed significantly. An alternative approach to addressing the large energy balance error is to use the humidity needed to minimise the error. A scrubber outlet humidity of 65%, gives the first law analysis percentage errors shown in Figure 4. This yields a maximum error of 12% with a difference in error of 23%, approximately half the error difference for the assumption of 100% humidity. Subsequently it can be seen that the humidity assumption contributes to approximately half of the error in the energy balance and hence needs to be the major focus in future works to best build upon the foundations laid by this paper.

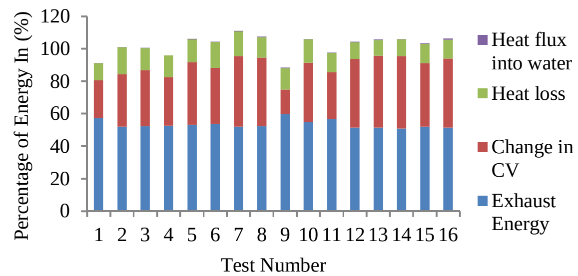

Figure 4. Thermodynamic first law analysis of scrubber energy as percentages with 65% exit humidity.

Conclusions

This paper aimed to provide a better understanding of the operating capacity of a scrubber, which would ultimately result in better advances in scrubber technology for the reduction of diesel emissions. This has been successfully achieved by conducting a steady state thermodynamic first-law analysis on the scrubber. Despite the error present in the heat balance calculations, an improved understanding of the heat and mass transfer through the scrubber has been resulted from the quantitative data. The major finding was that liquid water which leaves the scrubber results in several negative operation effects. By building on this work with further testing to better approximate the exit humidity of the scrubber it will be possible to develop improved emission and humidity control strategies for scrubbers use in underground coal mines.

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