Situ, Rong, Brown, Richard J., Wang, Hao, Surawski, Nicholas C., & Ristovski, Zoran (2012) Exit humidity of wet scrubbers for underground coal mines. In *18th Australasian Fluid Mechanics Conference*, 3-7 December 2012, Launceston, TAS.

18th Australasian Fluid Mechanics Conference
Launceston, Australia
3-7 December 2012

Exit Humidity of Wet Scrubbers for Underground Coal Mines

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Abstract

A wet scrubber is a device used in underground coal mines for the exhaust treatment system of various internal combustion engines (generally diesel) primarily as a spark arrestor with a secondary function to remove pollutants from the exhaust gas. A pool of scrubbing liquid (generally water based) is used in conjunction with a Diesel Particulate Filter (DPF). Scrubbers are widely used in underground applications of diesel engines as their exhaust contains high concentration of harmful diesel particulate matter (DPM) and other pollutant gases. Currently the DPFs have to be replaced frequently because moisture output from the wet scrubber blocks the filter media and causes reduced capacity. This paper presents experimental and theoretical studies on the heat and mass transfer mechanisms of the exhaust flow both under and above the water surface, aiming at finding the cause and effects of the moisture reaching the filters and employing a solution to reduce the humidity and DPM output, and to prolong the change-out period of the DPF. By assuming a steady flow condition, heat transfer from the inlet exhaust gas balances energy required for the water evaporation. Hence the exit humidity will decrease with the increase of exit temperature. Experiments on a real scrubber are underway.

Introduction

Combustion processes in diesel engines have inherent characteristics that lead to the release of both gaseous and particulate pollutants in the environment that have primary and secondary impacts on air quality, human health, and climate [1]. To meet with the criteria of emission standards, mines employ several methods such as promotion of use of low sulphur fuels, liquid filled scrubber tanks (wet scrubbers), chemical decoking of engines, non-flammable disposable dry exhaust filters, increased ventilation and more sophisticated, elaborate versions of the above methods [2].

More than 90% of underground mine vehicles use a wet scrubber to lower diesel exhaust (DE) temperature, then use a dry particulate filter (DPF) to reduce DPM. The wet scrubber contains a scrubbing liquid (e.g. water) in a vessel which conducts wet cleaning on the air from the exhaust. The diesel exhaust (DE) from the engine passes through the column of liquid, which scrubs out larger particles and some pollutant gases. A DPF is attached to the outlet of the wet scrubber to ensure any particle not absorbed by the liquid bed is filtered. DPFs can reduce up to 95% of particle mass emitted, though numbers of ultra fine particles may still be very high because they are beyond the range of the DPF. This technology is widely accepted in the mining industry [3]. However, ultra fine particles in the nanometre range with a mass fraction of only 0.01 may still represent the vast majority of particle numbers.

Wet scrubbers have become ubiquitous in underground coal mines because of their spark arresting and exhaust treatment properties[4], yet these filter have to be replaced every four hours 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[5]. 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.

This 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.

Literature Review

Diesel exhaust gases

Gases present in the exhaust stream of a diesel engine can be either soluble or insoluble in the scrubbing liquid used. As the research concentrates on using water or any water based liquid as the scrubbing liquor, water soluble gases will be dissolved, in effect removing them from the exhaust gas. The common water soluble components of the exhaust are chemicals like Nitrogen Oxide (NO_2), ammonia (NH_3), and some Hydro Carbons (HC). The dissolution of such components can be accelerated by the addition of a neutralizing agent such as an acidic washing liquid, which keeps the pH value of the liquid stable as well. To improve the absorption of acidic components, basic scrubbing liquid can be used [7]. It was found that Nitrogen Oxide (NO) being insoluble in water had to be removed using a reagent like $NaClO_2$, $FeSO_4$, or $KMnO_4$, making the process expensive to be carried out. Urea ($(NH_2)_2CO$) was found to be an effective alkaline reagent acting positively in the removal of both Sulphur dioxide (SO_2) and NO (accounting for more than 90% of the NO_x in the exhaust gas), producing recyclable and controllable products [8]. The denitration and desulphurization using urea solution produces ammonium sulphate (which can be recycled) and gases like carbon dioxide (CO_2) and nitrogen (N_2) (which can be released to the ambient through a filter after purification, if required). However as both the reaction mechanisms are exothermic and increased reaction temperature is not desirable from a thermodynamic point of view. It is also unfavourable to the mechanism of the wet scrubber, in relation to controlling the temperature of the exhaust. So the option discussed can be considered under special needs in controlling the NO_x and SO_2 emissions.

Diesel Particulate Matter (DPM)

In DPM, one of the most dangerous contents is the Polycyclic Aromatic Hydrocarbons (PAHs), because of its carcinogenic and mutagenic properties [9]. Nitro-PAHs and oxygenated PAHs have also been linked with increases in mutagenicity [10]. There are more than 100 different PAHs found in PM [3]. Diesel particulate matter consists of highly agglomerated solid carbonaceous material and ash, as well as organic and sulphur compounds. Carbon in the fuel is mostly oxidized during combustion with the residue exhausted in the form of amorphous particulate. A small fraction of the fuel and evaporated lubricant oil escape oxidation and appear as soluble organic fraction (SOF). The resolvable portion of SOF contains alkanes, PAHs, organic acids, and can also contain some hetero-atoms such as oxygen, nitrogen, and sulphur. In the particulate diesel emissions, PAHs and alkylated PAHs were the major proportion (44%) [3].

Wet scrubbers

Wet scrubbers possess numerous advantages over other devices used in the post treatment of exhaust gas. It is highly temperature and moisture resistant. They are comparatively small in size, increasing the ease of placement in an engine. Most importantly, the wet scrubbers can handle both gaseous pollutants and PM in the diesel exhaust [4].

The fluid dynamic characteristic in the scrubber is similar to that in a bubble column, which is a cylindrical vessel with a bubble generator at the bottom [11]. The flow regimes in the bubble column are generally classified as homogeneous (bubbly flow) regime and heterogeneous (churn-turbulent) regime [12]. The heat transfer mechanism in the bubble column, however, is quite different from that in the scrubber, where heat is transferred to liquid from high-temperature bubbles, rather than from the boundary or some immersed body.

Mass transfer inside the scrubber is far more complex than a bubble column. There are three main mass transfers occurring during the movement of the bubbles through the water. They are:

- **Soluble Gas:** the gaseous elements present in exhaust stream which are soluble in water break down and thus get removed from the bubble.
- **Water vapour:** if the scrubbing liquid is at a temperature less than 100^{o}C, the water vapour present in the diesel exhaust will condense into the water.
- **Particulate Matter:** due to the scrubbing action of the liquid, a portion of PM present (particularly larger particles) in the exhaust is transferred into the water.

Experimental studies have been conducted by Agranovski [13] on wet scrubbers by immersing a porous media in the scrubbing liquid using the Nuclear Magnetic Resonance (NMR) imaging. Agranovski demonstrated that wet filtration was considerably more efficient than dry filtration. A venturi scrubber, which is another cleaning device in the wet scrubber family, has high efficiencies of cleaning over the packed scrubbers [14].

It was found that there was scant literature on the studies of bubbles and the heat and mass transfer in the wet scrubber. Modelling becomes more difficult if heat transfer between bubble and water is coupled with condensation/deposition of soluble gas, water steam, and DPM.

Theoretical Analysis

The heat and mass transfer mechanisms inside the wet scrubber are very complex. High temperature diesel exhaust is pushed into the liquid pool, and divided into a number of bubbles with variable size. When bubbles rise up in the water pool, some water vapour and soluble gas condense in the liquid, and the bubble temperature is decreasing because of the heat transfer from bubble to liquid. Bubble breakup and/or coalescence may occur in this period. If the flow regime is churn-turbulent, bubble movement under the liquid surface can be quite violent. When bubbles burst out from the liquid surface, they may carry some liquid into the air. The liquid surface might not be flat if the flow regime is turbulent. Evaporation and condensation would both occur at the surface. As time goes on, water pool will get heated up, and water level decrease. So it is not a steady flow process in reality. Many industrial scrubbers have automatic water replacement by a float valve.

However, in order to better understand this process, a theoretical analysis is developed by introducing the steady flow assumption. In this case, the liquid phase inside the wet scrubber has infinite volume, and its temperature has reached equilibrium. Heat loss from the scrubber to ambient is ignored by assuming good heat insulation at the scrubber wall. Hence the heat transfer from bubbles to liquid will be only used to evaporate liquid into the top air space above liquid surface. It is also assumed that condensation of water vapour and soluble gases are neglected. So the enthalpy difference of DE between inlet and outlet is equal to the enthalpy of evaporated water liquid.

$$\Sigma \dot{m}_{in} h_{in} - \Sigma \dot{m}_{out} h_{out} = \dot{m}_{ev} h_{fg} \, , \tag{1}$$

where $\Sigma \dot{m}_{in} h_{in}$, $\Sigma \dot{m}_{out} h_{out}$, $\dot{m}_{ev}$ are the total DE enthalpies at inlet and outlet, and the water evaporating mass rate, respectively.

By assuming the averaged diesel compound is $C_{12}H_{23}$ [15], and that diesel is fully combusted with 100% theoretical air, so the combustion reaction becomes

$$4C_{12}H_{23} + 71(O_2 + 3.76N_2) = 48CO_2 + 46H_2O + 267N_2 \tag{2}$$

Hence if the inlet temperature and outlet temperature are known, the water evaporating mass $\dot{m}_{ev}$ can be obtained from equation (1). The outlet relative humidity, ϕ_{out}, can also be calculated.

Figure 1 shows the relative humidity at the scrubber outlet, ϕ_{out}, against outlet temperature, T_{out} with different inlet temperatures T_{in}. It can be seen that as exit temperature increases, the enthalpy difference between inlet and outlet decreases. Hence less water is evaporated, and the humidity decreases. In addition, if the inlet temperature increases, more energy from the exhaust gas will be used for evaporation, so the relative humidity also increases.

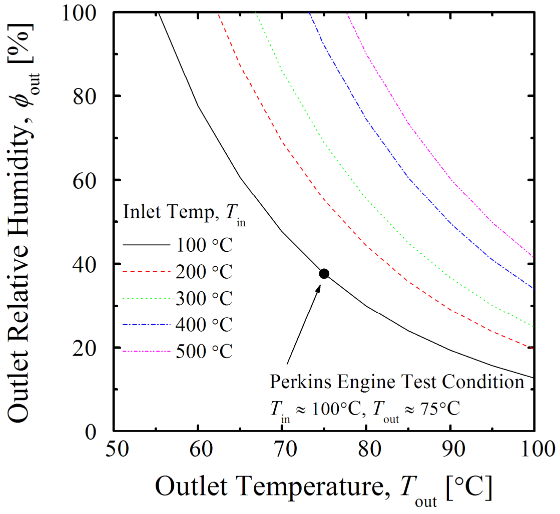

Figure 1. Exit humidity for Diesel exhaust under steady flow condition.

Preliminary Experimental Investigation Results

The results from the steady flow analysis help the estimation of humidity in a wet scrubber. To better understanding these heat and mass transfer mechanisms of the wet scrubber, two types of experiments are under progress.

Toyota LandCruiser transient test

A 10-mm stainless steel tube is connected from the muffler of a Toyota LandCruiser Ute to the top inlet of a 100-litre drum, as shown in figure 2. Exhaust gases is pushed through the down-coming pipe into the water pool, and then comes out in a horizontal outlet pipe. Thermocouples were installed at various locations to measure temperature at inlet, outlet, scrubber water, and the region above water level. Humidity at the outlet was also measured manually with dual wet/dry bulb thermometers.

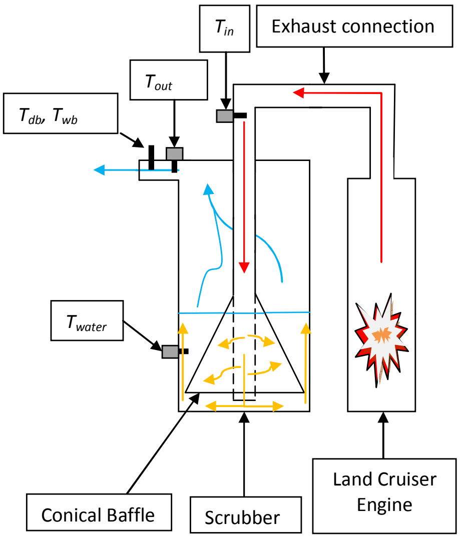

Figure 2. Schematic diagram of the transient test.

A transient test has been conducted with a Toyota LandCruiser engine at idling condition (zero load), from 750 rpm to 1000 rpm and then to 1200 rpm. The total time was about 160 minutes. Results of temperature at inlet, outlet, and scrubber water are plotted in figure 3. The humidity results, measured manually at 5-minute intervals, are also shown. Figure 3 shows that the inlet temperature increased sharply from 65°C to 120°C at the sudden increase of engine speed from 750 rpm to 1000 rpm at 60 minutes, and to 1200 rpm at 100 minutes, but it did not keep constant at any steady engine speed. The outlet temperature was very close to the temperature of the water, and both gradually rose from 23°C to 43°C. The outlet humidity, which was measured at 5-minute intervals, varied between 85% and 100%.

If Figure 1 is used to estimate the relative humidity in this test, with inlet temperature above 100°C after 100 minutes, the humidity at the outlet should be 100% because the outlet temperature is less than 55°C, which is indicated in Figure 1. In the transient test, nevertheless, it is far from the steady flow assumption and other assumptions used in the theoretical analysis. Firstly, the water temperature kept increasing, which means a certain amount of exhaust energy was used to heat up the water tank. Secondly, the drum was not heat-insulated. The estimated heat loss was 6% of the total inlet energy. And thirdly, during the experiment it was found that some amount of water spattered out from outlet of the drum, so the scrubber was losing more water than just water loss due to water evaporation.

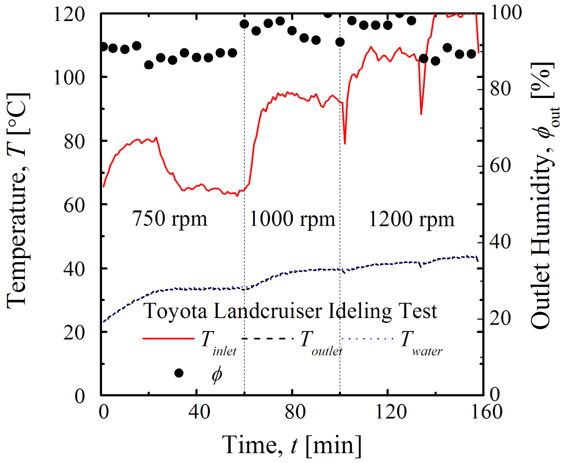

Figure 3. Transient test results for the Toyota LandCruiser engine at idling condition.

Perkins dynamometer steady state test

The results from the Ute test showed that a steady state condition is difficult to achieve when the engine is idling. Hence a Pekings engine with a dynamometer was used for a steady state experiment. A preliminary test was performed at the Biofuel Engine Research Facility (BERF) of the Queensland University of Technology. The Perkins Engine is a 4-cylinder 4.4-litre displacement diesel engine with rated power 62 kW at 2400 rpm. The engine load was absorbed by a DPX3 Froude dynamometer with maximum power rating of 168 kW. The exhaust gas from the engine passed through a catalytic converter then entered a wet scrubber manufactured by P.J. Berriman & CO. After the gas came out of the scrubber, it went through a water trap to have water vapour condensed before going through the exhaust extraction system and venting to ambient. A photo and schematic diagram of the test facility is shown in figures 4 and 5, respectively.

A preliminary test was conducted with the engine running at 1400 rpm and 100% load. The measured inlet and outlet temperatures are shown in figure 6. It is shown that after 40 minutes from starting the inlet temperature reached steady state 97°C, and the outlet temperature varied around 75°C. According to the 100°C inlet-temperature curve in figure 1, the outlet humidity should be about 37.6%. Due to the difficulty in the modification of the wet scrubber, humidity has not been measured in the preliminary test. It is planned in the near future to insert a humidity sensor at the scrubber outlet and perform more tests to validate the theoretical analysis.

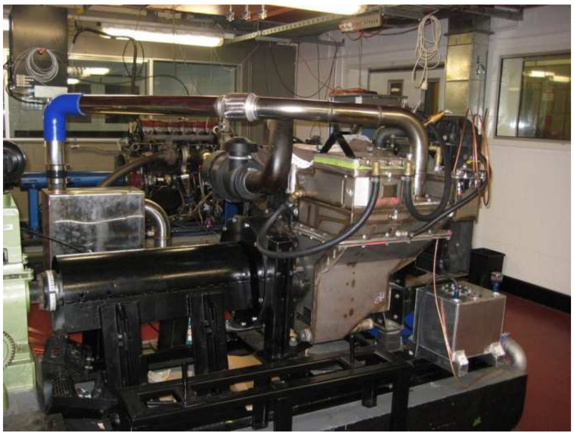

Figure 4. Engine dynamometer facility at BERF of QUT.

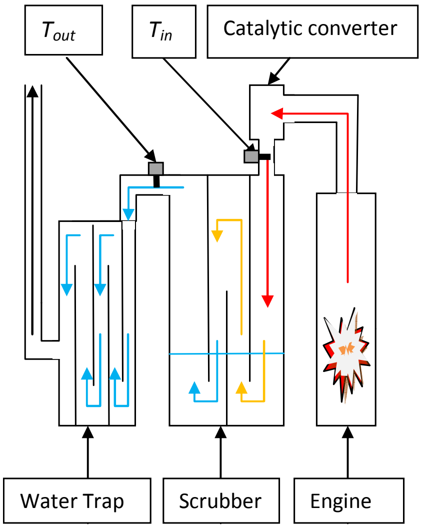

Figure 5. Schematic diagram of the steady state test of Perkins Engine.

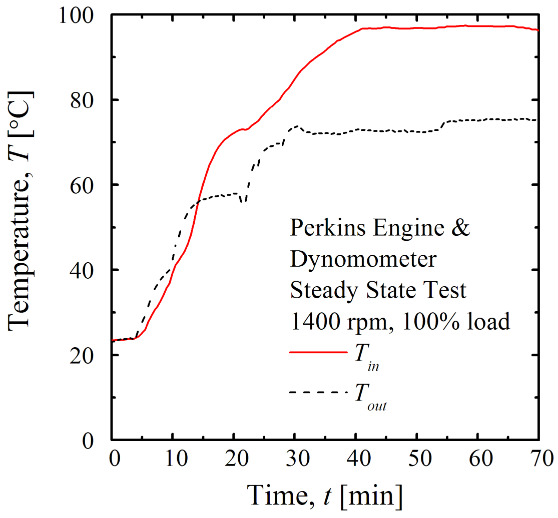

Figure 6. Preliminary steady state test with a Perkins Engine.

Conclusions

A wet scrubber for an underground coal mine diesel engine was under investigation to control the outlet humidity. Theoretical analysis with steady state assumptions found that the enthalpy drop of diesel exhaust due to the temperature difference between inlet and outlet is caused only by water evaporation. Hence the relative humidity at the outlet will decrease with the increase of outlet temperature. Preliminary test performed on an idling Ute showed that the inlet temperature could not be kept constant. While a Perkins engine running at full load with a dynamometer can achieve the steady state condition.

Acknowledgments

The authors would like to thank the following QUT students Dean Smith, Lukas Meiforth, Owen Chapman, and the following JCU students Harold Davies and Devassy Vellanikaran for their tremendous efforts in experimental and theoretical investigations. Assistance from technical staff from QUT and Peak 3 are also appreciated. The provision of the Perkins engine by Skillpro and ACARP (under Grant number C20036 DPM Risk Factor) is also acknowledged.

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