21st Australasian Fluid Mechanics Conference
Adelaide, Australia
10-13 December 2018

Heat and Mass Transfer Process in Exhaust Wet Scrubber

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Abstract

An exhaust wet scrubber was experimentally investigated based on the heat transfer analysis for gas-liquid two-phase flow. Different inlet operating conditions for gas phase such as temperature 24- 650 °C, 113.3 standard litre per minute flowrate and 5 mm orifice plate holes were tested. The purpose of the orifice plate is to break bubbles into smaller ones, leading to more heat transfer due to the increase of the bubble surface area. Moreover, bubble motion is recorded using a high-speed video system. An image processing software (*ImageJ*) is processed both images and videos effectively to track bubbles, remove image noise, and set image threshold. Bubble dynamic and thermal parameters and non-dimensional numbers were calculated using *MATLAB* program. The measured parameters will be used to develop a heat transfer model for the wet scrubber.

1. Introduction

The exhaust wet scrubber is a pollutant removal device for the diesel engines, especially for underground mines. Itis purpose is mainly as a liquid tank to scrub the pollutants from the engine exhaust gas passing through the liquid by generating bubbles and to reduce exhaust temperature, as shown in Figure 1. These bubbles may have a non-uniform shape and size due to turbulence.

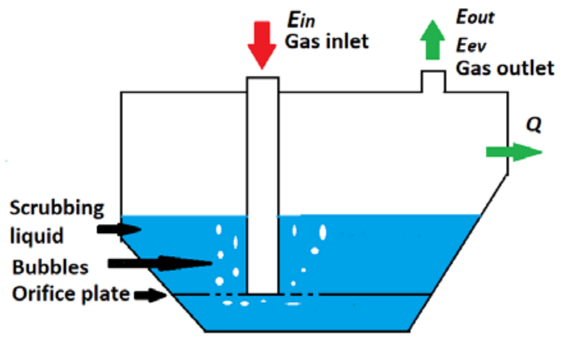


Figure 1. Exhaust wet scrubber schematic diagram.

Previous researchers attempted to improve the performance of exhaust wet scrubbers by reducing the humidity at the scrubber's exit leading to reduce the blockage of the particulate filter, hence to prolong its life and operating time. A steady-state thermodynamic analysis was performed to calculate the energy balance for the wet scrubber [1]. Their theoretical analysis showed that the liquid evaporation leads to enthalpy drop of diesel exhaust gas at the scrubber exit. Also, increasing the temperature at the scrubber exit is combined with decreasing of the relative humidity at the same location. In a further work a transient state using the same technique was used to analyse the scrubber [2]. Those results showed that the water leaves the scrubber in a liquid condition which can cause some operational negative effects. However, the non-steady-state method was adopted to investigate the air-water system bubble column at various liquid levels [3]. It was found that the heat transfer coefficient was strongly affected by changing the gas flow rate and it does not depend on the liquid height.

Although the wet scrubber has been analysed thermodynamically at the boundary and inlet/outlet, the local heat transfer process between bubbles and water was not studied directly. Hence, the aim of this work is to conduct heat transfer analysis of the wet scrubber to optimize its performance, which would lead to more reliable design in the future.

2. Experimental setup and analysis method

2.1. The apparatus setup

The experimental facility is shown in Figure 2. It is a 316 stainless steel tank except that the front and rear sides are made from transparent high-temperature resistant Perspex. It is also equipped with an industrial hot air blower. This blower is supplying a maximum temperature 650°C at 113.3 standard litre per minute (SLPM) inlet gas-phase flow rate. This flow rate is measured by a *Dwyer* rotameter. Filtered air from laboratory lines is used for the gaseous-phase inlet. This gas enters the scrubber via a 49 mm inlet diameter steel pipe. An orifice plate is a 3 mm thickness 316 stainless steel sheeting. This plate contains 100 holes to maintain the same cross-section area as the inlet pipe diameter to avoid back pressure generation. Gas phase leaves the experimental facility through the exit with higher relative humidity and lower temperature than the inlet condition. Several thermocouples are placed at different locations and connected to a *Picolog* data logger and to a laptop. A *Thermoworks* humidity probe measures the relative humidity effectively. The system has been cleaned previously to the experimentation to remove any possible contaminant, then it filled with fresh distilled water. Liquid phase (water) was maintained at constant volume and temperature to exclude their effect on the scrubber performance.

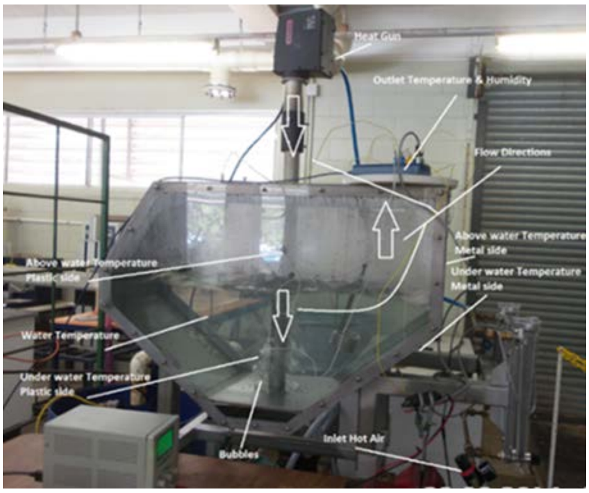


Figure 2. Experimental facility.

2.2. High-speed camera setup

Bubbles size, shapes and distribution are investigated using the image analysis technique. To clarify, both photos and movies were taken using a *Photron FASTCAM Viewer* camera (Model UX100, 1280x1024 pixels at 4,000fps, 12-bit monochrome, 36-bit colour). This camera is aligned horizontally to visualize the flow region and it was operated at 1,000 fps. A glass ball with a known diameter is used to calibrate from pixels to millimeters.

2.3. Experimental condition

This study investigates the effect of inlet gas-phase temperature on diesel exhaust wet scrubber performance. Table 1 explains the current three experimental conditions. Liquid volume, type and temperature were maintained constant to eliminate their possible effect on that performance. For the same reason, a size orifice plate with 5 mm holes was tested only. Indeed, this orifice plate breaks bigger bubbles into smaller ones and increases heat transfer as a result of increasing the contact surface areas between the two phases. Furthermore, tracking bubbles becomes simpler and more accurate using this orifice plate.

Test number	1	2	3
Inlet gas-phase temperature (°C)	24	300	650
Inlet gas-phase flow rate (SLPM)	113.3		
Gas phase	Pure air		
Liquid-phase temperature (°C)	60		
Liquid-phase volume (liter)	115		
Liquid phase	Distilled water		
Orifice size (mm)	5		

Table 1. Experimental condition.

2.4. Image analysis

A sequence of images has been analysed using *ImageJ* software as shown in Figure 3. Furthermore, choosing the suitable threshold from the process command for the binary images would increase the analysing efficiency of this software. After that, analysing these images provides all details about bubble movement such as their position, area and orientation. To clarify, *ImageJ* is outlining all bubbles by red numbers that appear in Figure 3 and their corresponding details can be found in separate sheet.

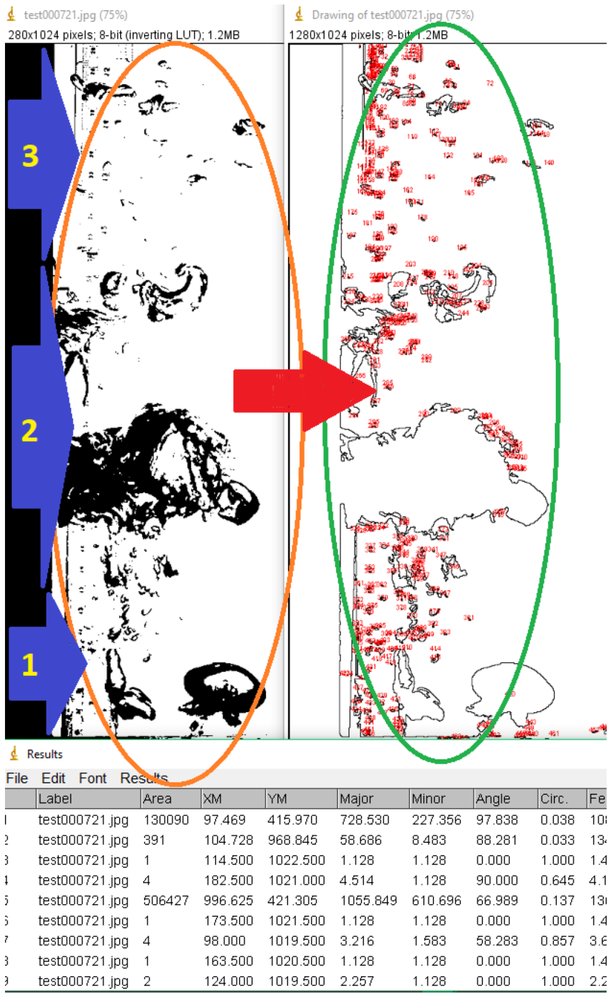


Figure 3. *Image J* software screenshot.

Flow region could be divided into three regions. The first one is located above the orifice plate and it contains bubbles defined as inlet bubbles. The second one is located downstream the previous one. It contains both big bubbles due to coalescence and small bubbles as the result of bubble break-up. Figure 3 also show a high percentage of bubble overlaping which cause difficulties for image analysis. The third region is near the surface. It contains small bubbles that shaped after breaking-up the previous region bubbles, and they are defined as outlet bubbles. Therefore, regions 1 and 3 were included in this study to eliminate the turbulence effect.

The number of bubbles can be obtained directly by analysing the *avi* video file from the high-speed camera using *ImageJ* software. Inlet bubble number and outlet bubble number were measured at regions 1 and 3, respectively. Hence, the inlet to outlet bubbles ratio (R_{io}), which is defined as the ratio of inlet bubbles number to outlet bubbles. The higher percentage of this ratio refers to high heat transfer between bubbles and their surrounding due to increasing the contact area.

Bubble vertical velocity (v_b) was obtained by tracking several bubbles in different image frames with error percentage ± 1%. Moreover, *ImageJ* software provides the projected area [6] of all bubbles (A_P), which has been used a *MATLAB* software input to find the Sauter Mean Diameter (SMD, d_{32} or $D[3,2]$) [4,7,8,9,10,11,12,13]. The diameter error percentage was estimated to be 2%.

2.5. Heat transfer calculations

Bubble characterisation factors such as velocity and diameter are obtained based on data provided by *ImageJ* and processed by *MATLAB* software. The heat energy carried by the gas phase can be calculated from:

$$Q = \dot{m}_g c_{pg}(T_{ginlet} - T_{gexit}), \quad (1)$$

where Q is the heat energy, $\dot{m}_g$ is the gas-phase mass flow rate, c_{pg} is the thermal heat capacity of gas phase.

Heat loss or gain from gas phase is totally transferred to the liquid phase based on no phase change assumption, therefore:

$$Q = h\sum_{i=1}^{N} A_b(T_b - T_l), \quad (2)$$

where h is the heat transfer coefficient between bubbles and their surrounding liquid, N is the total bubbles number, A_b is the bubble surface area, and T_l is the liquid temperature.

Heat transfer coefficient between gas bubbles and their surrounding liquid can be obtained by combining eqs. 1 and 2:

$$h = \frac{\dot{m}_g c_{pg}(T_{ginlet} - T_{gexit})}{\sum_{i=1}^{N} A_b(T_b - T_l)}. \quad (3)$$

Dimensionless numbers reduce the variables and simplify physics, data analysis and test modeling [14]. Therefore, developing new correlations and/ or revising the existing ones based on these dimensionless numbers that connect between various operating conditions might lead to optimising the scrubber performance. This optimisation would suggest a new, low cost and more reliable scrubber design. To simplify these numbers, bubbles are assumed to contain pure air at a constant temperature equal to the average temperature between the inlet and exit gas-phase temperature. Also, both phases are assumed as having constant physical properties

$$Re_b = \frac{v_b d_{32} \rho_b}{\mu_b}, \quad (4)$$

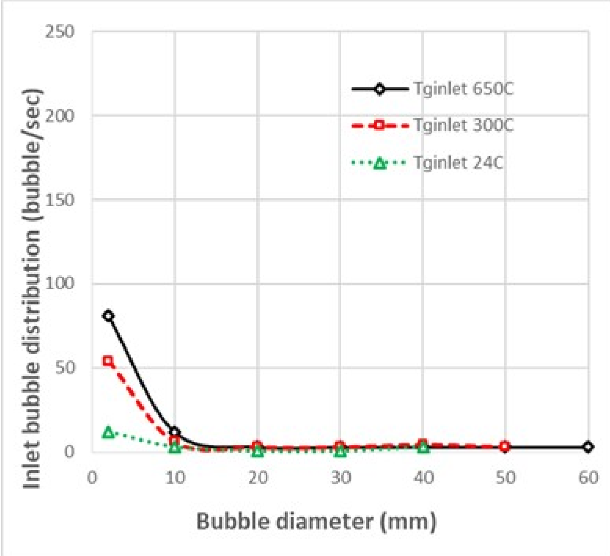
$$Nu = \frac{h d_{32}}{k}, \quad (5)$$

$$We = \frac{\rho_b v_b^2 d_{32}}{\sigma}, \quad (6)$$

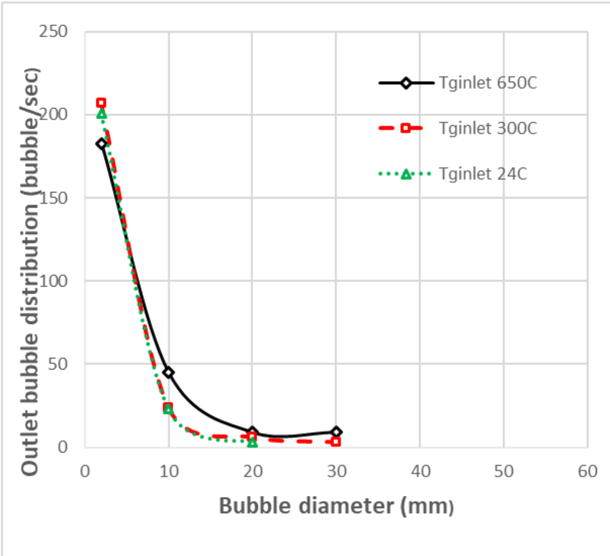
where, Re_b, Nu and We are Reynolds, Nusselt and Weber number respectively, v_b is the average bubble vertical velocity, ρ is the density, μ is the dynamic velocity, σ is the surface tension and k is the thermal conductivity of the bubble.

3. Results and discussions

In the scrubber, bubbles are changing shape and size by breaking-up and/or coalescing due to flow turbulence. In test 1, Bubbles gained heat from the surrounding liquid because their temperature is less than the liquid temperature. However, the liquid gain heat from gas bubbles for the other two tests. This increases liquid temperature until it reaches the steady-state condition. Figure 4 shows the (a) inlet and (b) outlet bubble distribution for the three inlet temperature 24, 300 and 650°C conditions respectively. It clearly shows that the bubble distribution profile curve move left due to the decrease of bubble size decrease and increase of the small bubble number. This is mainly because flow turbulence breaks bubbles into small ones.



(a). Inlet



(b). Outlet

Figure 4 Bubbles distribution profile at inlet and outlet.

Table 2 shows the results of dimensional and dimensionless parameter based on image analysis. The bubble ratio between inlet and outlet is approximately constant for the 3 tests. This indicates that the inlet-bubble breaking-up rate is not affected by gas temperature change. The slight difference might be due to flow turbulence.

Test number	1	2	3
Bubble ratio, R_{io}	0.77	0.82	0.78
d_{32} @ Region 1(mm)	31.9	38.3	35.6
v_b @ Region 1 (cm/sec)	3.8	12.2	15.4
Total A_b (m^2)	0.12	0.19	0.22
Q (Watt)	75.0	608	1520
h ($W/m^2.K$)	17.0	18.1	19.2
Re_b	790	969	511
Nu	21.0	18.4	13.8
We	0.8×10^{-2}	5.3×10^{-2}	4.9×10^{-2}
Bubbles roundness	0.515	0.495	0.519

Table 2. The experimental results.

Inlet bubble diameter (d_{32}) has a small variation with the change of inlet gas temperature. Theoretically, bubble departure diameter is dependent on orifice size and volume flow rate. In the experiment, the orifice diameter is fixed, same with the volume flow rate at the rotameter, which is located upstream of the heater. Hence the volume flow rate is higher for high inlet gas temperature due to the decrease of gas density. This can be justified by the finding that both bubble velocity and area increase as the gas temperature increases. Leifer *et al.* [15] also found that the bubble rising velocity depends on air-water temperature difference for different bubble size. De Vries [16] claimed that the temperature gradient has a strong effect on bubble rising velocity. To explain that, this temperature increment reduces gas density and increases the buoyancy effect [17].

The heat transfer, Q, increases with the increase of the temperature differences between the two phases. As a result of that the heat transfer coefficient between bubbles and their surrounding was also increased. However, the Nusselt number decreases because of the increase of the thermal conductivity.

Table 2 also shows that the change of the bubble Reynolds number is not linear due to effect of bubble diameter and gas viscosity. Nevertheless, Weber number increase with the increase of temperature due to its high dependence on bubble velocity.

Bubble roundness measures how the bubble shape is close to a perfect sphere. Table 2 also shows that the average inlet bubble roundness is around 0.5, because bubble size more than 3 cm is more like a cap bubble instead of spherical bubble. The bubble roundness has an effect on heat transfer calculation.

Conclusions and Future works

This paper investigate the heat transfer process in a wet scrubber using pure air injecting though water. The inlet gas-phase temperature changed from 24 °C to 650°C. The gas volume flow rate was set as 113.3 SLPM and the liquid temperature is maintained at 60°C. It was found in the experiment that the increase of the inlet gas temperature increases bubble vertical velocity, bubble surface area, heat transfer coefficient and the Weber number. However, the bubble Reynolds number does not increase with temperature because it is also dependent on gas properties. This change of gas property also lead to the reduction of the Nusselt number.

Future work will investigate the effect of other parameters such as gas flow rate and orifice size on heat transfer rate of the scrubber. Furthermore, experimental data will be compared with the existing correlations, and new model which better describes the process will be developed. This will hopefully lead to optimum scrubber design.

References

[1] Situ R., *et al.,* Exit humidity of wet scrubbers for underground coal mines. *18th Australasian Fluid Mech. Conf. 3rd-7th Dec., Australia*, 2012.

[2] Hoque N., *et al.,* A thermo-fluid study of a diesel engine wet scrubber. *19th Australasian Fluid Mech. Conf. 8th-11th Dec., Australia*, 2014.

[3] Zizka M., *et al.,* Heat transfer between gas and liquid in a bubble column. *Chem. Eng. Trans.*, 2017, 57, pp. 1261-1266.

[4] Besagni G. & Inzoli F., The effect of liquid phase properties on bubble column fluid dynamics: Gas holdup, flow regime transition, bubble size distributions and shapes, interfacial areas and foaming phenomena. *Chem. Eng. Sci.*, 2017, 170, pp. 270-296.

[5] Azevedo M. *et al*., Characterization of velocity and shape of rising bubbles in a stagnant liquid vertical column by ultrasonic and visualization techniques. *14th Brazilian Congress of Thermal Sci. Eng., 18th-22th Nov. 2012, Rio de Janeiro, RJ, Brazil*, 2012, pp. 1-8.

[6] Ziegenhein T., Fluid dynamics of bubbly flows. *Technischen Universität, Berlin, Germany*, 2016.

[7] Vinnett L. *et al.,* Bubble Size Analysis and Boundary Conditions for Automatic Control of Industrial Flotation Cells. *IFAC Proceedings*, 2009, 42, pp. 161-166.

[8] Kowalczuk P. & Drzymala J., Physical meaning of the Sauter mean diameter of spherical particulate matter. *Particulate Sci. Tech.,* 2015, 34, pp. 645-647.

[9] Filippa L. *et al.,* Sauter mean diameter determination for the fine fraction of suspended sediments using a LISST-25X diffractometer. *Measurement*, 2012, 45, pp. 364-368.

[10] Pacek A. *et al.* On the Sauter mean diameter and size distributions in turbulent liquid/liquid dispersions in a stirred vessel. *Chem. Eng. Sci.,* 1998, 53, pp. 2005-2011.

[11] Loth E. *et al.,* Effective diameter for group motion of polydisperse particle mixtures. *Powder Tech.,* 2004, 142, pp. 209-218.

[12] Asar M. & Hormozi F., Experimental Determination of Bubble Size in Solution of Surfactants of the Bubble Column. *J. Adv. Chem. Eng.,* 2014, 4, pp. 1-5.

[13] Tang H. *et al.,* Calculation method for particle mean diameter and particle size distribution function under dependent model algorithm. *Chinese optics letters,* 2007, 5, pp. 31-33.

[14] Stern F., Mechanics of fluid and transport processes, 2013, 7, pp. 1-20.

[15] Leifer I. *et al.,* A study on the temperature variation of rise velocity for large clean bubbles, *J. Atmospheric Oceanic Tech*., 2000, *17,* pp. 1392-1402.

[16] De Vries A., Path and wake of a rising bubble, *Twente University, Enschede, The Netherlands*, 2001.

[17] Zhang Y. *et al.,* Temperature effect on single bubble velocity profile in water and surfactant solution. *Colloids & Surfaces A: Physicochem. Eng. Aspects,* 2003, 223, pp. 45-54.