

Hydrodynamics of the Pilot Scale Wet Scrubber with Restricted Outlet Absorbent Flow Rate

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ABSTRACT

This paper presents the hydrodynamics of the wet scrubber coupled to a pilot CFB incineration facility. The scrubber was operated using tap water as a scrubbing liquid. The outlet liquid flow rate, Q_o , and accumulation rate, Q_a , strongly depend on the inlet liquid flow rate, Q_{in} , with different profiles. At higher Q_{in} values, Q_o stabilizes, leading to higher Q_a and finally flooding. The values of Q_a were higher than Q_o except for Q_{in} ranging between 0.53 and 0.72 L/s (safe operating range) in which $Q_a \cong Q_o$ and $Q_a = Q_{in}/2$. The outlet-to-inlet liquid flow rate ratio, Q_o/Q_{in} decreased for $Q_{in} > 0.53$ L/s. The increase in the accumulation-to-inlet liquid flow rate ratio, Q_a/Q_{in} , at higher Q_{in} indicates a change in flow regime towards flooding, accompanied by an abrupt increase in the height of accumulating liquid, H_a . The difference between Q_a/Q_{in} and Q_o/Q_{in} (denoted as, $\Delta Q_{ao}/Q_{in}$), shows a minimum close to zero in the safe operating range. The gas flow rate towards the wet scrubber had slight effect on Q_o and Q_a when Q_{in} was maintained constant. The ratio Q_o/Q_{in} decreased slightly with H_a/H_i irrespective of gas velocity. Changing the liquid-to-gas ratio, L/G and Q_{in} strongly affects the maximum and minimum values of Q_o/Q_{in} and Q_a/Q_{in} .

Keywords: Wet Scrubber; Liquid Accumulation Rate; Liquid Accumulation Level; Outlet Liquid Flow Rate; Liquid-to-Gas Ratio; Valve Opening Position; Incineration

1. Introduction

Wet scrubbers are wet collection devices for fumes, mists and suspended dusts used in air pollution control systems [1]. Other air pollution control devices for dusts control include electrostatic precipitators [2], cyclones [3], bag houses [2,4-6], etc. Wet scrubbers collect particles by direct contact with a liquid (usually water or lime water). Wet scrubbers have been used for air pollution control in incineration and waste-to-energy processes [7]. There are multitudes of scrubber designs grouped according to the liquid contacting mechanism used. In addition, scrubbers can be broadly classified as low-, moderate-, or high-energy units depending on how the liquid is introduced into the scrubber [8]. Energy requirements in wet scrubbers can be expressed as the pressure drop across the scrubber or by the level of contacting power, expressed as kWh/m³ gas treated [9]. The most common units of measurement for contacting power are kWh/1000m³ of gas, while the liquid circulation rates are given in liters per m³ of gas [10-12].

During wet scrubber operation, the liquid inlet flow rate corresponding to the existing gas flow rate is determined from mass balance equations. However, the outlet liquid flow rate is normally less than the inlet liquid flow

rate due to some of the liquid accumulating in the bottom of the scrubber. The advantages of the liquid accumulation include sealing effect provided which prevents the flue gas from short-circuiting to the scrubbing solution tank and also as a cooling agent for the incoming hot gases. However, the critical disadvantage of liquid accumulation is the possibility of flooding, which occurs when the liquid level in wet scrubber becomes excessively high leading to overflow of the liquid towards the gas inlet pipe and thus interfering with the combustion process.

This paper investigates the hydrodynamics of the wet scrubber based on inlet and outlet liquid flow rates, accumulation rate for the liquid in the wet scrubber bottom (expressed as the accumulation rate and accumulation height), gas flow rate, liquid outlet control valve opening position, liquid-to-gas ratio, etc.

2. Literature Review

Wet scrubbers rely on a liquid spray to remove gaseous emissions, with particulate control as a secondary function. The major types of wet scrubbers are venturi scrubbers, jet (fume) scrubbers, and spray towers or chambers. Venturi scrubber's consume large quantities of

scrubbing liquid and electric power and incur high pressure drops. Jet or fume scrubbers rely on the kinetic energy of the liquid stream. The typical removal efficiency of a jet or fume scrubber (for particles 10 μm or less) is lower than that of a venturi scrubber. Spray towers can handle larger gas flows with minimal pressure drop. Spray towers are also used as gas coolers where the hot gases are cooled prior to exiting the process to the environment.

Because wet scrubbers may contribute to corrosion, removal of water from the effluent gas from scrubbers may be necessary. Another consideration is that wet scrubbing results in a liquid effluent contaminated with solids present in the gas stream. Wet scrubbing technology is used where the contaminant cannot be removed easily in a dry form, for soluble gases and wettable particles, and if the contaminant will undergo some subsequent wet process (such as recovery, wet separation or settling, or neutralization). Gas flow rates range from 20 to 3000 m^3/min . Gas flow rates approximately 2000 m^3/min may have a corresponding pressure drop of 25 cm H_2O column [13]. **Figure 1** shows the typical wet scrubber designs.

Wet scrubbers capture relatively small dust particles with large liquid droplets. In most wet scrubbing systems, droplets produced are generally larger than 50 μm (in the 150 to 500 micrometer range). The size distribution of particles to be collected is source specific. For example, particles produced by mechanical means (crush or grind) tend to be large (above 10 μm); whereas, particles produced from combustion or a chemical reaction will have a substantial portion of small (*i.e.*, less than 5 μm) and submicrometer-sized particles. Several mechanisms for particle removal in a wet scrubbing system are summarized in **Table 1**.

The most critical sized particles are those in the 0.1 to 0.5 μm range because they are the most difficult for wet scrubbers to collect. A relationship between particle size and collection efficiency for typical wet scrubber exist, such that from 0.1 μm , the collection efficiency drops below 90% and increases again beyond 0.5 μm reaching about 100% at 2 μm and above.

In order to properly design a particulate wet scrubber, one must obtain as much information as possible concerning the characteristics of the flue gas stream to be treated. This information must be obtained or estimated

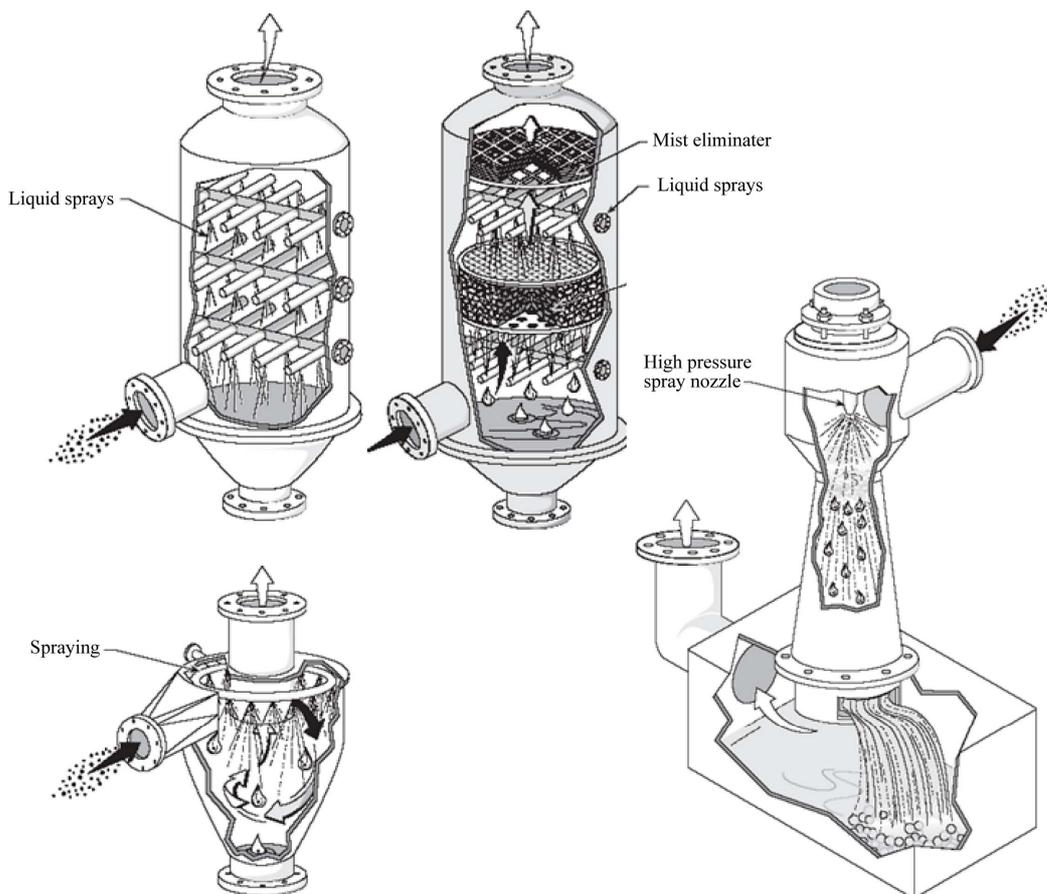


Figure 1. Typical designs for wet scrubber configurations (spray chamber, counter-current-flow packed tower, irrigated cyclone scrubber, and venturi scrubber).

Table 1. Particle collection mechanisms for wet scrubbing systems.

Mechanism	Explanation
Impaction	Particles too large to follow gas streamlines around a droplet collide with it.
Diffusion	Very tiny particles move randomly, colliding with droplets because they are confined in a limited space.
Direct interception	An extension of the impaction mechanism. The center of a particle follows the streamlines around the droplet, but a collision occurs if the distance between the particle and droplet is less than the radius of the particle.
Electrostatic attraction	Particles and droplets become oppositely charged and attract each other.
Condensation	When hot gas cools rapidly, particles in the gas stream can act as condensation nuclei and, as a result, become larger.
Centrifugal force	The shape or curvature of a collector causes the gas stream to rotate in a spiral motion, throwing larger particles toward the wall.
Gravity	Large particles moving slowly enough will fall from the gas stream and be collected.

for both the average and maximum ranges that will occur. During combustion, for instance, the gas flow rate always exceeds the blower capacity due to additional gases generated. Scrubbing systems must be able to operate effectively at both the normal day-to-day conditions as well as to accommodate any maximum ranges.

There are a number of parameters that affect particle and acid gas removal efficiency and must be considered in the design of a wet scrubbing system, that is, dust properties (particle size distribution being most important), exhaust gas characteristics, static pressure drop [13], scrubber liquid flow rate [12], required particle removal efficiencies, and removal of entrained liquid droplets.

Dust properties include particle size distribution, concentration and chemical composition. The particle size distribution is the most important factor that affects scrubber design and operation. However, particle size distribution data is rarely available for most sources and generally must be estimated from similar type sources. The average and maximum particle concentrations (or grain loading) must be obtained to properly size the scrubber and the solids removal system. For incinerators, grain loading depends on amount of fly ash escaping from the primary and secondary combustion chambers. The chemical composition of the dust particle is important as it determines if the material will cause any plugging problems or precipitate problems.

Liquid flow rate is based on the gas flow rate, temperature in the scrubber, compensation for evaporation rate and type of scrubbing system utilized. Values need to be identified for both normal and maximum operating conditions. Also, for the extended life of pumps, the recirculation rate and permissible levels of suspended solids in the recirculated liquid need to be identified. In this study, the scrubbing liquid is continuously pumped into the scrubber at a high rate with recirculation.

3. Materials and Methods

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3.1. Process Description

The test series consisted of runs with gas flow rates ranging from 0 to 14 m/s and liquid flow rates ranging from 0.15 to 0.95 L/s. Different combinations of gas and liquid flow rates were used. Experiments were designed to study the hydrodynamics of the scrubber Stage 1, which is similar to Stage 2. The gas flow rate was controlled by using a flap on the blower suction side (connected to the wind box), while the inlet liquid flow rate from the pump was controlled using a gate valve connected to a flow meter. The flue gas from the combustion chamber exits the riser and passes through a series of cyclones for removing solid particles, heat exchanger for reducing temperature and finally passes through the multistage wet scrubbers. **Figure 2** shows the experimental setup, incorporating a circulating fluidized bed incineration facility with multistage wet scrubbers used in this study.

3.2. Varying the Outlet Valve Opening Position

The outlet liquid flow rate from the wet scrubber was controlled using the valve connected to the outlet pipe at the bottom of the scrubber Stage 1. Three opening positions, V_{op} , were studied, that is full-open, 3/4-open, and 1/2-open positions, as a means of controlling the outlet flow rate, Q_o , thus, the assumed values of V_{op} were 1.0, 0.75, and 0.5, respectively. Lower values of V_{op} were not tested because below 1/2-open position, the accumulation rate was exceedingly high leading to flooding of the scrubber. The outlet liquid flow rate was determined by

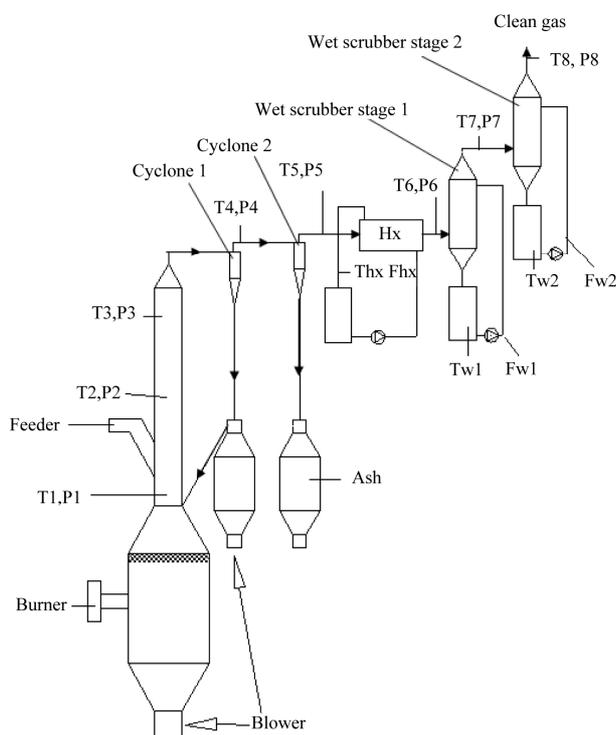


Figure 2. The experimental set up.

noting the time required to collect a known volume of liquid using a stopwatch. The average of three measurements was used to establish the outlet flow rate.

3.3. Determination of Liquid Accumulation Rate in the Wet Scrubber

A known flow rate of scrubbing liquid was introduced into the scrubber in the form of a spray directed downwards. The optimum operation of the wet scrubber was measured by using the scrubbing liquid level that remains within the scrubber, defined as liquid accumulation rate, Q_a . If the liquid accumulation rate is too high, the scrubbing liquid flows back to the heat exchanger, through the gas duct, and finally to the cyclones and combustion chamber. An accumulation liquid level was necessary in order to provide sealing effect to prevent the gas from short-circuiting to the scrubbing solution tank. This reason necessitated studying the water level within the scrubber bottom. The liquid accumulation rate was determined using Equation (1):

$$Q_a = d_Q = Q_{in} - Q_o \quad (1)$$

The liquid accumulation data was collected at different gas flow rates. The level of scrubbing liquid within the scrubber, H_a , was determined by reading the level of liquid in the level indicator tube. The data was collected by varying the inlet liquid flow rate from 0.15 to 0.95 L/s. There are three terms used for accumulation, these are:

Accumulation rate (dQ or Q_a) is the amount of scrubbing liquid retained in the wet scrubber per unit time; liquid accumulation height (H_a) is the height occupied by scrubbing liquid retained in the wet scrubber; and, effective height ($H_e = H_t - H_a$), which is the height of wet scrubber used for scrubbing processes between the liquid level and top of the scrubber. Thus, accumulation reduces the available space for mass and heat transfer in the wet scrubber.

The difference between Q_a and Q_o was determined from Equation (2):

$$Q_{ao} = Q_a - Q_o \quad (2)$$

3.4. Liquid Flow Rate Ratios

Two ratios were defined in order to normalize the wet scrubber data, so that it can be used in any scale of operation. The outlet-to-inlet liquid flow rate ratio, Q_o/Q_{in} , is the ratio between outlet flow rate and inlet flow rate, data of which eliminates the scale dependency of the results. Another useful quantity is the accumulation-to-inlet liquid flow rate ratio, Q_a/Q_{in} , which is the ratio between liquid accumulation rate and the inlet flow rate. The difference between the two quantities was estimated as per Equation (3):

$$\frac{\Delta Q_{ao}}{Q_{in}} = \frac{Q_a - Q_o}{Q_{in}} \quad (3)$$

3.5. Determination of the Liquid-to-Gas Ratio

The liquid to gas ratio was calculated by dividing the liquid flow rate (L/s) by the flow rate of the gas in the wet scrubber (m^3/s) giving Q/G in litres of liquid per m^3 of gas (L/m^3), as shown in Equation (4):

$$\frac{L}{G} \left(\frac{L}{m^3} \right) = \frac{Q \left(\frac{L}{s} \right)}{G \left(\frac{m^3}{s} \right)} \quad (4)$$

Each velocity of the gas applied was multiplied by the cross-sectional area of the duct of the blower to get volumetric flow rate of gas in m^3/s .

4. Results and Discussion

4.1. Variation of Q_o with Q_{in}

Figure 3 shows the variation of Q_o (L/s) with Q_{in} (L/s) at variation gas velocities in the combustion chamber, U_g (m/s), when the scrubbing solution outlet valve is full open, 3/4-open and 1/2-open. The curves have similar shapes for all valve opening positions, that is, increasing initially and stabilizing for $Q_{in} > 0.8$ L/s as reported also by Said *et al.* (2010). Stabilizing curves indicate that Q_o

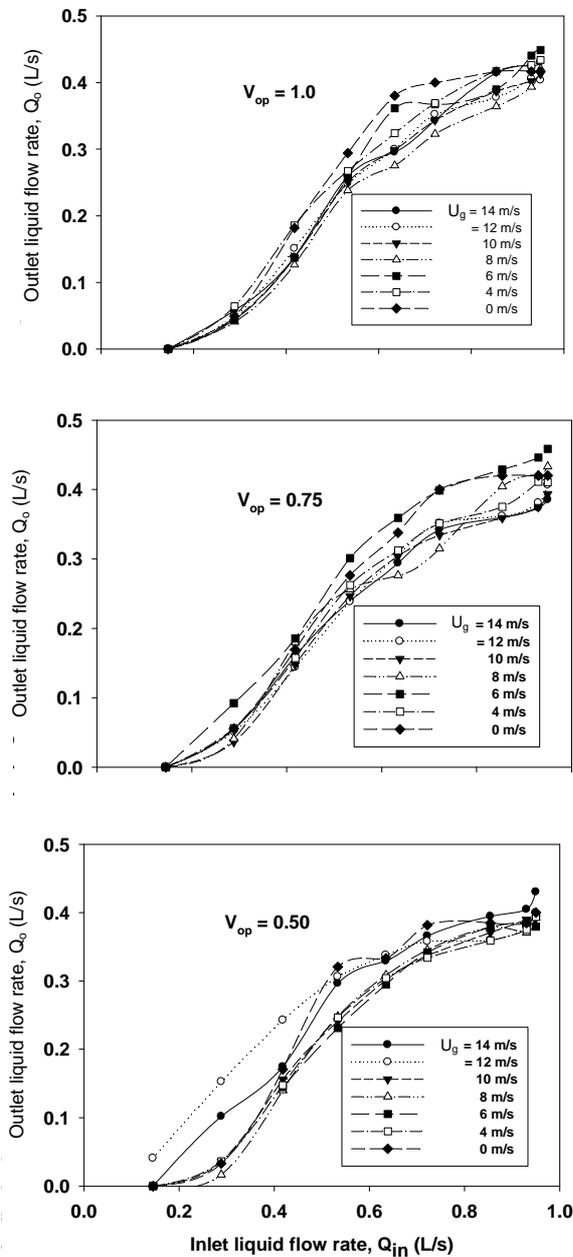


Figure 3. Variation of the outlet liquid flow rate with the inlet liquid flow rate at different valve opening position and flue gas velocities.

ceases to increase, implying that also that Q_a increases further (based on Equation (1)) which can lead to flooding. Thus, $Q_{in} = 0.8$ L/s is assumed to be the maximum inlet liquid flow rate. In all combinations of operating conditions of U_g , Q_{in} , and V_{op} , Q_o is less than Q_{in} indicating that there is always liquid accumulating in the wet scrubber. There is a delay in the appearance of Q_o , which signifies that there is also a minimum inlet flow rate at which the scrubbing solution flows outside the scrubber, that is when $Q_{in} > 0.2$ L/s, as shown in Figure 3. The minimum liquid flow rate into the scrubber depends on

gas velocity and valve opening position.

4.2. Dependency of Q_a on Q_{in}

The variation of Q_a with Q_{in} (Figure 4) shows different profiles compared to those of Q_o . Despite the general increase in Q_a with increasing Q_{in} , Q_a stabilizes for Q_{in} ranging between 0.4 and 0.7 L/s even when the outlet valve is open ($V_{op} = 1.0, 0.75$ and 0.5). This behaviour was also reported by Said *et al.* (2010). The initial increase in Q_a at very low values of Q_{in} was not reported by former researchers because the range of Q_{in} was shorter,

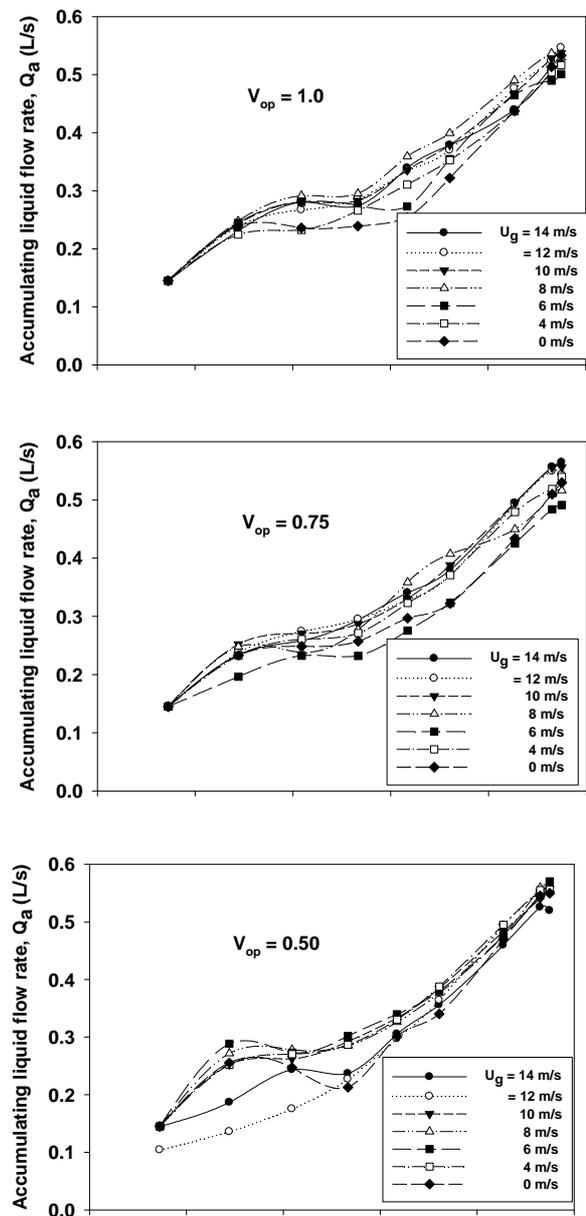


Figure 4. Variation of Q_a with Q_{in} in the scrubber at different outlet valve opening positions and the flue gas velocities.

starting from 0.3 L/s onwards different from minimum value used in this study, *i.e.*, $Q_{in} = 0.1$ L/s. Similar to results reported in literature [12], the effect of U_g on Q_a diminishes at higher Q_{in} higher than 0.7 L/s, below which, Q_a increases sharply with Q_{in} for all valve opening positions. The accumulation rate can also be regarded as a cause of deviation of Q_o from Q_{in} . This deviation is important for safe operation of wet scrubbers connected to combustion systems which receive hot gases.

4.3. Comparison between Q_o and Q_a at Different Valve Opening Position

Based on the results presented in Figures 3 and 4, it is evident that a difference exists between Q_a and Q_o not only in actual values, but also in the way these parameters change with Q_{in} . Figure 5 presents the variation the average values of Q_o and Q_a values (averaged over all gas velocities) for the three valve positions (full-open, 3/4-open and half-open) with inlet scrubbing liquid flow rate, Q_{in} . For $Q_{in} < 0.5$ L/s, and $Q_{in} > 0.7$, Q_a values are higher than Q_o . The values Q_o and Q_a are equal in the Q_{in} range between 0.5 and 0.7 L/s. Above half-open outlet valve position ($V_{op} > 0.5$), the valve opening position was observed to have a small effect on the outlet flow rate such that the averaged values for all gas flow rates fall almost on the same curve as shown in the Figure 5. Similarly, the average values of Q_a for different air flow rates fall on the same curve, regardless of changes in valve opening positions for $V_{op} > 0.5$. It is evident from Figure 5 that the Q_o and Q_a become equal for Q_{in} values ranging between 0.53 and 0.72 L/s, while before and after this range, Q_a values are higher than Q_o . Superimposed in Figure 5, is the plot of the quantity ΔQ_{ao} , that is, the difference between Q_a and Q_o against Q_{in} . This difference shows a minimum turning point equal to zero for

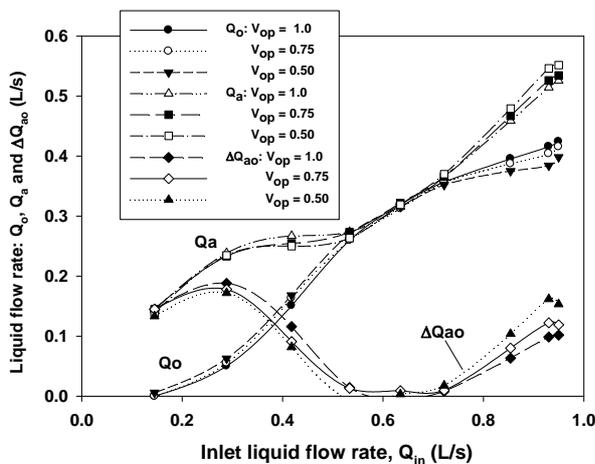


Figure 5. Comparison of the averaged outlet liquid flowrate and liquid accumulation rate in the wet scrubber at different valve opening positions.

Q_{in} between 0.533 and 0.722 L/s.

4.4. Dependency of Q_o/Q_{in} and Q_a/Q_{in} Ratios on Q_{in}

Figure 6 shows the variation of the ratio (Q_o/Q_{in}) with Q_{in} at different conditions of gas flow rate and valve opening positions. Initially, at low values of Q_{in} , the ratio Q_o/Q_{in} increases faster, reaching a maximum value, location of which depends slightly on gas velocity, U_g and valve opening position, V_{op} . The values of Q_o/Q_{in} , however, decreases slightly after a maximum. An observation

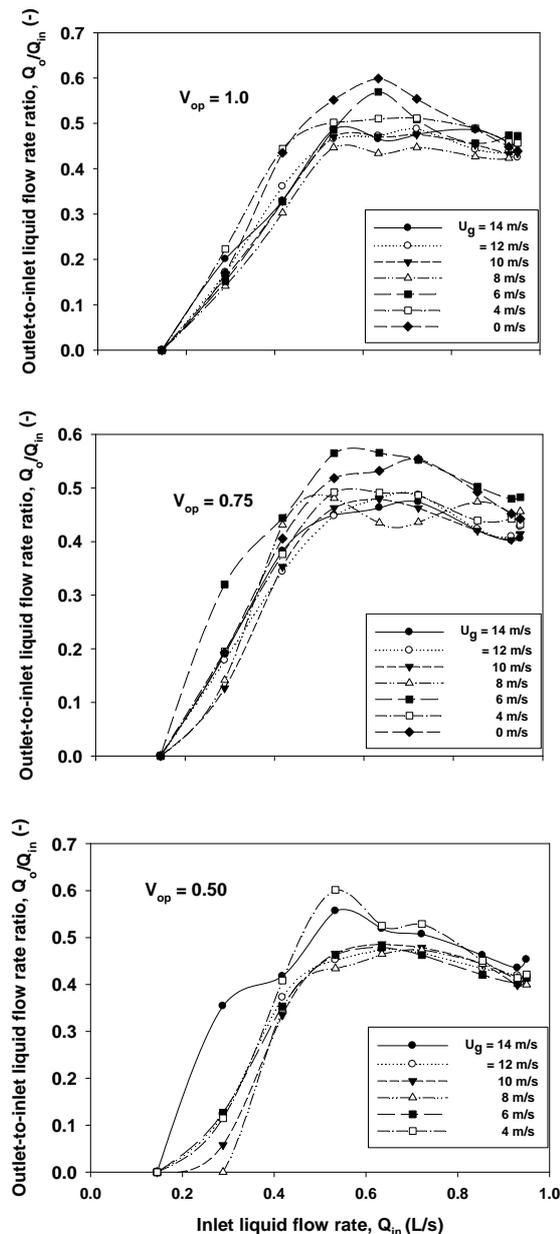


Figure 6. Variation of outlet-to-inlet liquid flow rate ratio with inlet liquid flow rate under different outlet valve opening position and gas velocities.

which can be attributed to the fact that Q_o ceases to increase as Q_{in} is increased from 0.5 to 0.95 L/s such that the ratio Q_o/Q_{in} decreases also, as reported also in **Figure 3**. It should be noted that Q_o/Q_{in} do not exist for $Q_{in} < 0.2$ L/s because no outlet liquid flow is observed at very low values of Q_{in} .

Figure 7 shows the variation of Q_a/Q_{in} ratio with Q_{in}

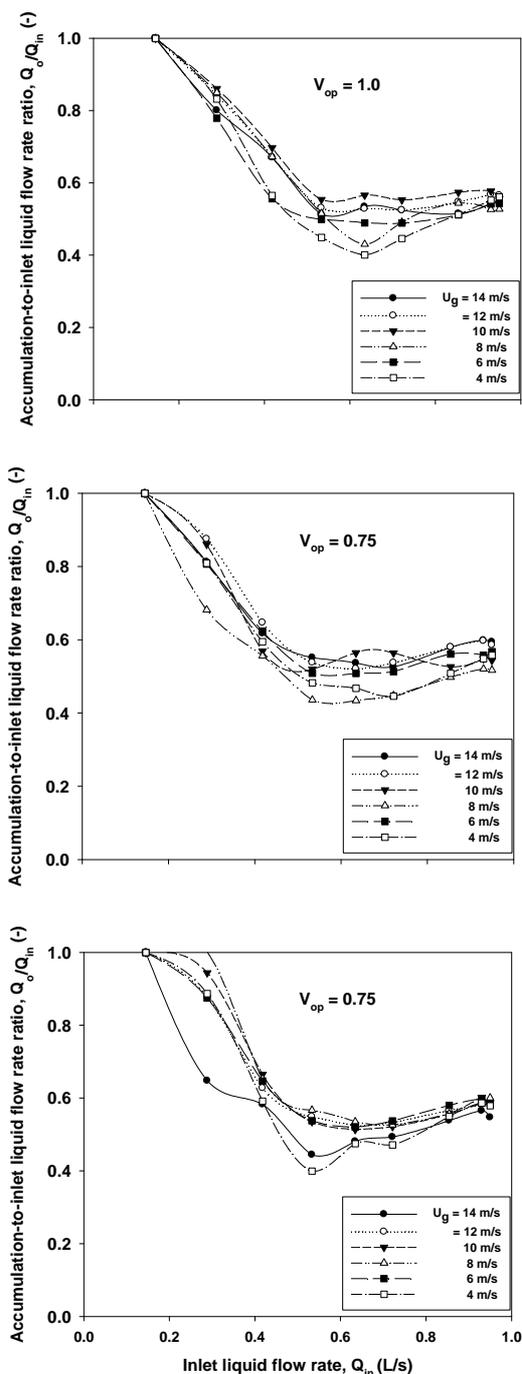


Figure 7. Variation of accumulation-to-inlet liquid flow rates with Q_{in} under different outlet valve opening positions and gas velocities.

for different valve opening positions and gas flow rates. Different from Q_o/Q_{in} , Q_a/Q_{in} decreases with increasing Q_{in} until a minimum point is reached beyond which Q_a/Q_{in} increases slightly.

However, both ratios show turning points so that a quadratic relationship is depicted between these parameters. This shows that as Q_{in} is increased beyond 0.5 L/s the accumulation rate is low compared to Q_{in} , but beyond the minimum point Q_a is still lower than Q_{in} but higher compared to the original values. The fact Q_a/Q_{in} starts at 1.0 is because initially all the liquid entering the scrubber do not flow out ($Q_o = 0$) at lower Q_{in} values and $Q_a = Q_{in}$. For $Q_{in} < 0.2$ L/s, $Q_a/Q_{in} = 1.0$ indicating that all the liquid entering the wet scrubber accumulates with $Q_o = 0$. This is because, at low inlet liquid flow rate, the accumulating liquid is filling the wet scrubber bottom and no outlet flow is observed.

Figure 8 compares the ratios Q_a/Q_{in} and Q_o/Q_{in} at various Q_{in} values and valve opening positions. The two ratios are equal when $Q_{in} = 0.5$ to 0.7 where they are equal to 0.5. The curves are opposite in nature because $Q_{in} = Q_a + Q_o$. In general, Q_a is higher than Q_o , except for the Q_{in} values from 0.5 to 0.7 L/s. Superimposed in **Figure 8** is the variation of the ratio $\Delta Q_{ao}/Q_{in}$ with Q_{in} . Initially, the difference between Q_a/Q_{in} and Q_o/Q_{in} is very high but drops to zero when Q_{in} reaches 0.53 to 0.75 L/s. Beyond this range, $\Delta Q_{ao}/Q_{in}$ increases again due to abrupt increase in Q_a as flow regime approaches flooding. The re-surfacing of the ratio $\Delta Q_{ao}/Q_{in}$ is an indication that the flow regime in the wet scrubber is changing towards flooding regime.

4.5. Effect of Gas Flow Rate on Q_o and Q_a

The flow of hot gases into the wet scrubber and evaporating water increases the pressure in the scrubber shell.

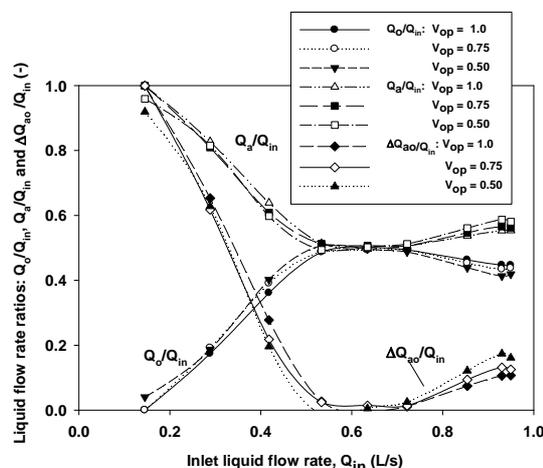


Figure 8. Comparison of outlet-to-inlet and accumulation-to-inlet flow rate ratios in the wet scrubber under different outlet valve opening positions.

As a result, the pressure at the top of the accumulating liquid surface is expected to increase the outlet liquid flow rate. However, the trend was observed to be strongly dependent on Q_{in} than on U_g . **Figure 9** shows the variation of Q_o and Q_a with gas velocity U_g at different inlet liquid flow rates. Results show that both Q_a and Q_o are independent of U_g but rather depend strongly on Q_{in} . The higher the inlet liquid flow rate, Q_{in} , the higher the outlet liquid flow rate, Q_o , and the liquid accumulation rate, Q_a . Under incineration conditions, U_g will increase beyond gas flow forced by blower, but will not strongly affect Q_a and Q_{in} as shown in **Figure 9**. Moreover, the increase in Q_{in} due to generation of the flue gas is shown to have no effect on the hydrodynamics of the wet scrubber.

4.6. Effect of Q_a and H_a on Outlet Liquid Flow Rate

Both H_a and Q_a affects the outlet liquid flow rate from the scrubber. Increasing H_a adds hydrostatic head which pushes the accumulated liquid downward, hence increasing the outlet flow rate. **Figure 10** shows the effect of H_a on the outlet liquid flow rate, Q_o (at 1/2 open valve position). In general, Q_o increases with H_a showing that

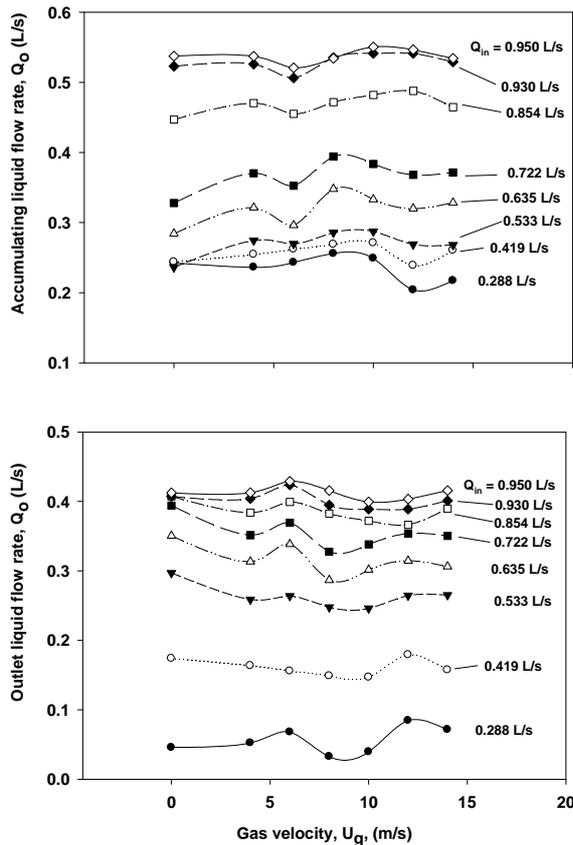


Figure 9. Variation of the outlet liquid flow rate and accumulation rate in the liquid scrubber with gas velocity at different inlet liquid flow rate.

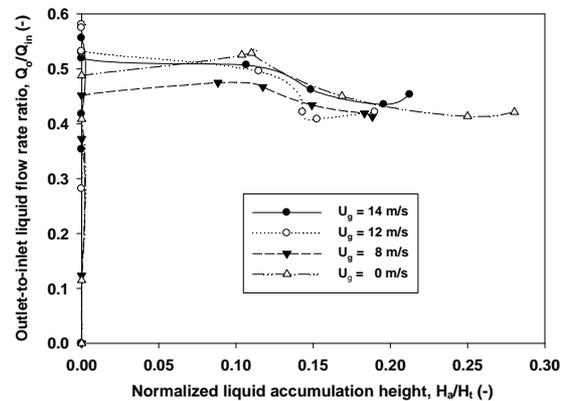
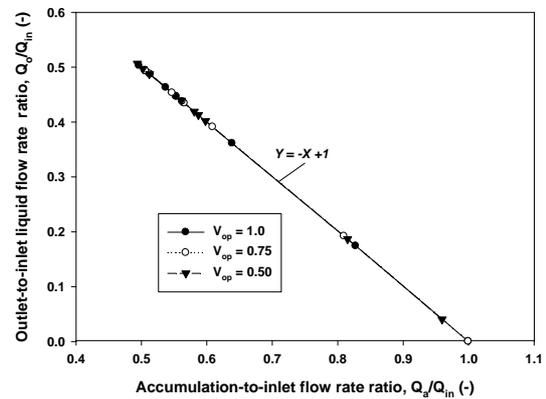


Figure 10. Dependence of Q_o on Q_a and H_a in the wet scrubber at different gas velocities (when the valve is half-open).

the hydrostatic head created by the accumulating liquid increases the scrubbing liquid outlet flow rate. However, Q_o depends also on the gas flow rate, which creates high pressure in the effective height of the scrubber, hence increasing Q_o and minimizing H_a and Q_a .

At lower Q_a values, Q_o is very low, and remains constant until Q_a is higher than 0.2 L/s, where the former increases abruptly. For $Q_a > 0.4$ L/s, Q_o stabilizes at about 0.4 L/s, which corresponds to Q_{in} in the range of 0.533 to 0.722 L/s as observed in **Figures 3** and **5**. The behaviour shown in **Figure 10** can be attributed to the balance between gas pressure in the equivalent scrubber height and the hydrostatic head of the accumulated liquid corresponding to H_a .

4.7. Effect of L/G Ratio on the Outlet Liquid Flow Rate

The L/G ratio is a combination of two parameters: liquid inlet flow rate, Q_{in} and gas flow rate Q_g . The effect of changing L/G ratio on the wet scrubber hydrodynamics was studied in order to establish the proper operating conditions for the wet scrubber. **Figure 11** shows the effect of increasing L/G ratio on the outlet liquid flow rate, Q_o , at different values of Q_{in} . The range of values of

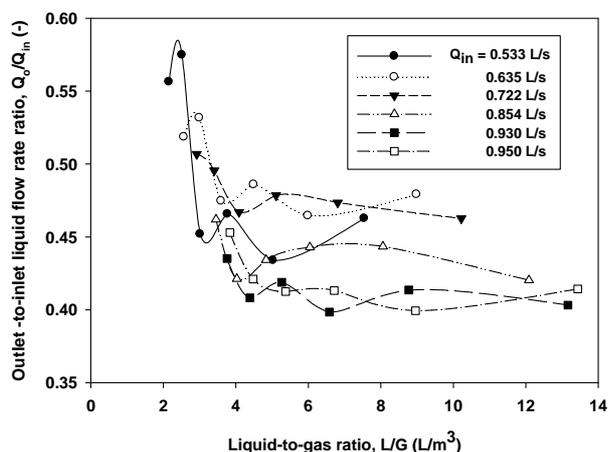


Figure 11. Mapping of Q_o values at different liquid-to-gas ratios and specific inlet liquid flow rates in the wet scrubber.

L/G observed in the wet scrubber increases with increasing value of Q_{in} , such that very narrow range exit at lower values of Q_{in} (for instance, 0.288 L/s) and very wide range of L/G at higher values of Q_{in} (that is, 0.95 L/s). The curves at different values of Q_{in} are similar, except that the range of values of Q_o (vertical position of the curves) depends solely on Q_{in} . While increasing Q_{in} causes the curves to shift upwards, the latter widens in the L/G range, and the troughs become wider as well.

4.8. Effect of L/G Ratio on Liquid Accumulation Rate

Figure 12 shows the variation of Q_a/Q_{in} with the liquid-to-gas ratio, L/G . As L/G is increased, the Q_a/Q_{in} values shows a peak, which migrates to the right as the inlet liquid flow rate is increased. Horizontally, Q_a curves increases as Q_{in} increases. The turning point indicates that at higher L/G ratio, that is higher liquid inlet flow rate at constant gas flow rate, the Q_a/Q_{in} decreases as a result of higher Q_{in} . Similarly, increasing Q_{in} raises the vertical position of the turning points. Moreover, higher Q_{in} leads to higher Q_a as stated before.

5. Conclusions

It can be concluded from the above findings that:

1) The outlet liquid flow rate from the scrubber depends strongly on the inlet liquid flow rate. However, at a very high inlet liquid flow rate the outlet liquid flow rate do not increase further, indicating possibility of flooding.

2) Despite the fact that the rate of accumulation increases with Q_{in} , the profiles of Q_a versus Q_{in} are different from those of Q_o .

3) The accumulation rate is always higher than the liquid outlet flow rate except for Q_{in} ranging between

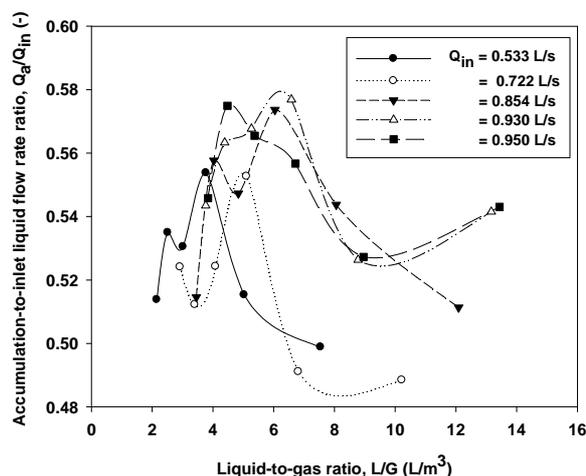


Figure 12. Values of Q_a at different liquid-to-gas ratios and specific inlet liquid flow rates in the wet scrubber.

0.53 and 0.75 L/s, in which $Q_a = Q_o$, and $Q_a = Q_{in}/2$. This range defines the safe operating range without regime change towards flooding.

4) The slight decrease in the outlet-to inlet liquid flow rate ratio, Q_o/Q_{in} for $Q_{in} > 0.5$ L/s signifies that Q_o remains constant even when Q_{in} is increased further. This observation is important to the operation of the wet scrubber as flooding can be avoided by limiting Q_{in} .

5) The initial decrease in Q_a/Q_{in} indicates that Q_a is always lower than Q_{in} . However, the slight increase in Q_a/Q_{in} at higher inlet liquid flow rate is an indication of a change in flow regime towards flooding, which can be avoided by observing the liquid accumulation height, H_a .

6) When compared, the difference between Q_a/Q_{in} and Q_o/Q_{in} decreases to zero as Q_{in} is increased between 0.53 and 0.72 L/s, beyond which the difference increases again.

7) The gas flow rate towards the wet scrubber has slight effect on Q_o and Q_a if the inlet liquid flow rate is maintained constant. This implies that since the incineration cycle is always carried out at constant liquid flow rate, below the flooding point, then the scrubber hydrodynamics is not affected even when the changes in flue gas flow rate due to combustion and blower action are extremely high.

8) The liquid-to-gas ratio, L/G , strongly affects both Q_o and Q_a and hence Q_o/Q_{in} and Q_a/Q_{in} . The relationship between L/G and the liquid flow rate ratios shows maximum turning points in different zones along the L/G axis.

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