Separation and Purification Technology 98 (2012) 221–229

Contents lists available at SciVerse ScienceDirect

Separation and Purification Technology

journal homepage: www.elsevier.com/locate/seppur

Removal of ammonia and particulate matter using a modified turbulent wet scrubbing system

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ARTICLE INFO

Article history:
Received 8 January 2011
Received in revised form 27 May 2011
Accepted 19 July 2012
Available online 27 July 2012

Keywords:
Wet scrubber
Particulate
Size
Turbulence
Toxic gases
Scrubbing efficiency

ABSTRACT

Conventional scrubbers are typically modified to serve the needs of modern industries that discharge effluents that cause synergetic, adverse effects on the environment. We designed and developed a modified turbulent wet scrubber (MTWS) to remove air pollutants as they emerge from a coal furnace. Experiments were conducted to estimate the pressure drop and the efficiencies of ammonia gas and particulate removal via the MTWS. The optimum water levels and gas flow rates for effective scrubbing of ammonia gas at different concentrations and particulate matter at different feed rates were estimated. For ammonia gas at a concentration of 45 ppm, a gas flow rate of 3.5 m^3/s and a water level of 58 cm in MTWS and position B (central position of the nozzle) in the water level of the nozzle yielded efficient ammonia gas removal for the given time. Similarly, for a fly ash feeding rate of 140 mg/min, the same gas flow rate and water level in the MTWS yielded high efficiencies even for particles at the submicron level.

1. Introduction

Industrial effluent gases contain a variety of air pollutants depending on the unit operations and types of processes that are carried out in a given industry [1–5]. These pollutants are usually in the form of particulates and toxic gases. Particles produced from chemical process industries may contain significant portion of small (i.e. less than 5 μm) and sub-micrometer-sized particles. The most critical sized particles are those in the range of 0.1–0.5 μm because they are the most difficult to removed from the effluent streams. Among the gaseous pollutants, such as SO_2, NH_3, H_2S, and NO_2, which are usually emitted from industries, ammonia gas is colorless, toxic, reactive, and corrosive when combined with sulfur dioxide and must be removed at the source [6]. Ammonia has adverse effects on human health and on the atmosphere. It can be converted into aerosol form. The conversion of NH_3, to NH_4^* aerosol depends on the concentration of acids in the atmosphere [7]. Anthropogenic sources of ammonia have increased substantially over time, and it is predicted that by 2010, ammonia will be the largest source of acidifying gas in Europe [8]. In most of the chemical process industries, such as petrochemical refining, agricultural processes, livestock farming, and composting facilities, ammonia is generated along with other toxic gases and particulate matters [9,10]. Since NH_3 is considered a toxic gas like SO_2 and is common in most effluent gases, researchers have declared the importance of designing and developing techniques to remove particulate-laden ammonia gas. In most wet scrubbing systems, droplets produced are generally larger than 50 μm (150–500 μm range). The size distributions of particles to be collected are source specific. Droplets collect particles by collection mechanisms like impaction, direct interception, diffusion, electrostatic attraction, condensation, centrifugal force, and gravity. Fine particles (<0.1 μm) experience Brownian movement in an exhaust stream. Bombardment of the inter-particles resulted in the movement of tiny particles in a random manner or to diffuse through the gas. The random motion of the particles may cause the particles to collide with droplets and get adhered on the surface. Diffusion is the primary collection mechanism in wet scrubbers for particles smaller than 0.1 μm. In the particle size range of approximately 0.1–1.0 μm, neither of these two collection mechanisms (impaction or diffusion) dominates. Fig. 1 represents the efficiency of wet scrubbers in particulate collection [11]. Laitinen et al. had reported that the efficiency of the conventional wet scrubbers with non-electrical forces in scrubbing particles of the size ranging from 0.01 to 1 μm almost zero [12]. Ammonia scrubbing under acidic conditions is considered the most cost-effective physicochemical technique for ammonia abatement [10,13–16]. Literature also indicates the generation of ammonia for flue gas conditioning and NOx reduction along with particulate matter in urea manufacturing processes [17]. A review of literature on the abatement of particulate-laden gaseous pollutants reveals that both sequential and simultaneous removal techniques have

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1383-5866/$ - see front matter
http://dx.doi.org/10.1016/j.seppur.2012.07.014

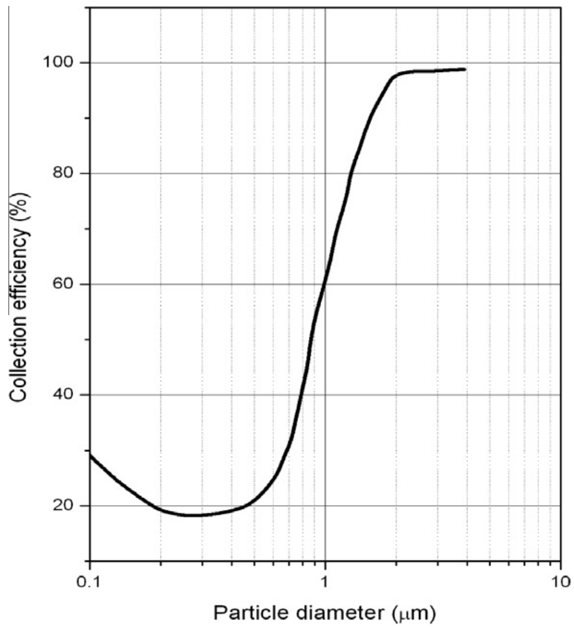

Fig. 1. Typical relationship between particle size and collection efficiency for wet scrubber.

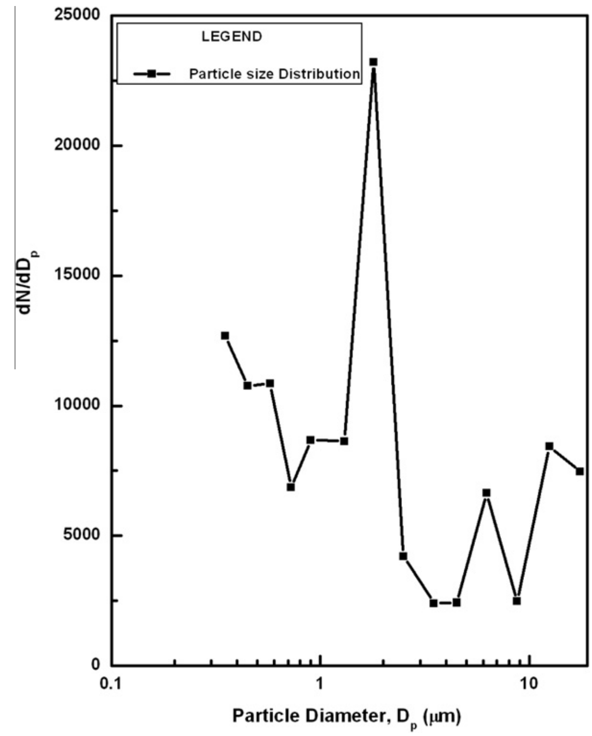

Fig. 2. Particle size distribution in the effluent gas stream fed to Turbulent Wet Scrubber (MTWS).

been practiced for the abatement of particulate-laden toxic gases [18–22].

Various wet scrubbers used in practice offer a choice between liquid-dispersed and gas-dispersed systems [23–28]. However, turbulent scrubbers offer the possibility for both phases to mix almost completely and aid the scrubbing process effectively [29]. Despite some of the inherent shortcomings of wet scrubbers [30–32], they are the only equipment available in today's marketplace that can effectively combat particulate-laden SO_2 pollution [33]. Furthermore, where a liquid phase is used to remove particulate matters, wet scrubbers are unique in their ability to remove both particulate and gaseous pollutants [19–22,33]. Conventional wet scrubbers like bubble columns or single stage or multi-stage packed columns use sparger disks [29,33–38]. The installation of sparger disks or packings (as column internals) poses a significant cleaning problem for particulate collection and high pressure drop in packed columns in practical situations. Critical survey of the literature reveals that there is a need to develop and design wet scrubbers that can combat the narrow range of particles having size around 1 μm. However, high efficiencies in these systems can be achieved only with high energy dissipation and mechanical complications [33]. Operation of such systems thus becomes very complicated, expensive, and difficult due to sticky particles, clogging problems from salt formation, and frequent maintenance [32–34].

The present study aims to assess the removal of particulate matter and ammonia gas from an effluent gas stream by a newly designed modified wet scrubber. The details of the modified turbulent wet scrubber are discussed in the following section.

2. Materials and methods

Fig. 2 shows the particle size distribution of the particulate matter present in the effluent gas stream that is fed into the modified turbulent wet scrubber (MTWS). Fig. 3 shows the schematic diagram of the MTWS system used to analyze the removal efficiency of ammonia gas and particles. The MTWS system consists mainly of a wet scrubber, an aerosol spectrometer, two flow meters, and a fly ash (particles) feeding device or ammonia gas injector. A vertical cylindrical column, packed with granular activated carbon (ECOPRO Inc., Korea) and connected to the outlet of the MTWS, is employed to remove 100% of the uncontrolled ammonia gas and particles from the MTWS in the system. The MTWS has the simple design shown in Fig. 4. This design consists of a polycarbonate column with inlet and outlet diameters of 100 mm and 120 mm, respectively. The column has a length of 600 mm, width of 220 mm, and height of 1 m. The MTWS has a 20 × 200 mm rectangular nozzle, through which the fly-ash–air or ammonia–air mixture passes, with the combination of a deflector and two baffles in the inner compartment of the scrubber. The baffle/deflector is semicircular to create turbulence by passing the gas at relatively high velocities through the rectangular nozzle. The horizontal ammonia flow or dusty gas stream scoops the water and throws it against the baffles. The curved baffle causes the water to fall back like waves, leading to turbulence in the water column within the inner compartment. Furthermore, the continuous flow of the gas stream causes it to mix well with the water and raises the gas–water up through the baffle/deflector, where it overflows into the water in the outer compartment after hitting the first baffle/deflector. The overflow creates disturbance, splashing, and entrainment in the outer compartment. The gas leaving the outer compartment passes through the second baffle/deflector and a de-mister to avoid entrainment of the liquid.

The efficiencies of ammonia removal are calculated by measuring the difference between ammonia concentrations at the inlet and outlet using ammonia detector tubes (Gastec No. 3L, GASTEC Co., Japan) [41,42]. The Gastec gas sampling pump that aspirates the ammonia from the MTWS is used together with the detector tube. Particle collection efficiencies are computed by measuring the difference between particle mass concentrations at the inlet and outlet using the portable aerosol spectrometer (Portable Dust Monitor with 15 Particle Size Channels, Model No. 1.108, GRIMM Inc.). The dust feeder (Solid Aerosol Particle Generator, Model No. 7.870, GRIMM Inc.) generates fly ash collected from a coal-fired power plant with aerodynamic diameters ranging from 0.23 μm

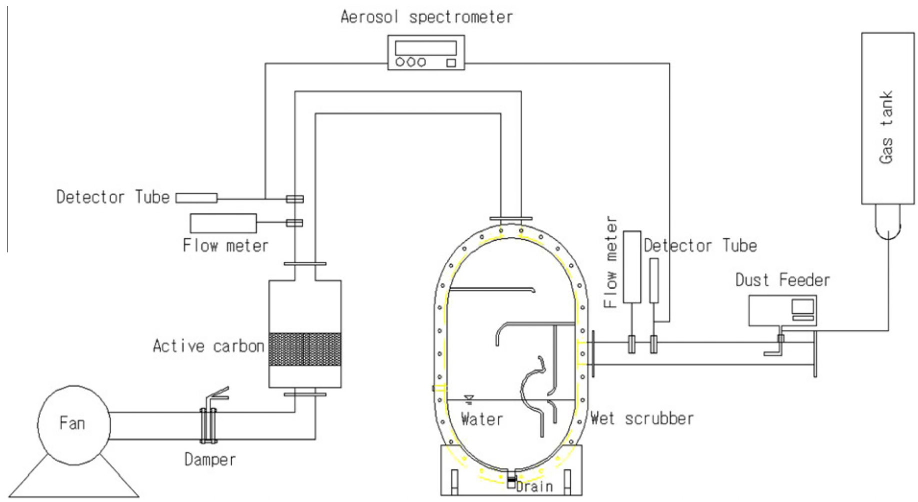

Fig. 3. A schematic diagram of the modified turbulent wet scrubber (MTWS).

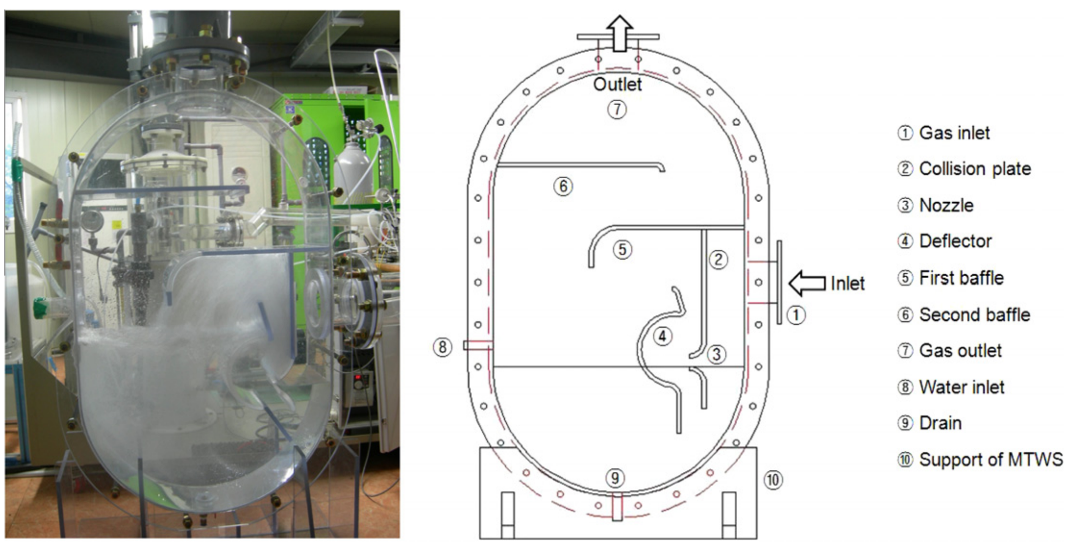

Fig. 4. Pictorial and schematic view of the modified turbulent wet scrubber (MTWS).

to larger than 20.0 μm. The pressure drop is also monitored by an instrument for measuring pressure (TESTO 350-S/XL, TESTO Inc.). The MTWS contains water as a scrubbing medium to capture particles and absorb ammonia gas.

Experiments on the removal efficiency of ammonia gas and particles were conducted for the operating conditions presented in Table 1. The removal efficiency of ammonia gas for concentrations between 40 and 60 ppm is measured as a function of water level (56, 58, 60 cm), flow rate of gas stream (3.5, 4.5 m^3/min) and different water levels at the nozzle at constant temperature and pH. The particle collection efficiency of the MTWS is measured as a function of particle feeding rates (140, 345, 824 mg/min), water levels in the MTWS (56, 58, 60 cm), volumetric flow rate of the gas stream (3.5, 4.5 m^3/min) and water levels at the nozzle. The water levels at the nozzle can be classified into four stages as A–B, B, B–C and C, as shown in Fig. 5. The removal efficiencies of ammonia gas and particles were estimated and expressed as percentages for the variables mentioned above to study the performance of the MTWS.

3. Results and discussion

Experiments were conducted to investigate the performance of MTWS in terms of the scrubbing efficiency of ammonia gas and particulate matter (fly ash) individually. This was done by manipulating

Table 1
Experimental conditions of the MTWS system.

Gas removal		Particle collection	
Temperature of water	15 °C	Temperature of water	15 °C
pH of water	7–7.5	Water level	56, 58, and 60 cm
Water level	56, 58, and 60 cm	Flow rate of gas stream	3.5, 4.5 m^3/min
Flow rate of gas stream	3.5, 4.5 m^3/min	Fly ash feeding rate	140, 345, 824 mg/min
Input NH_3 conc.	Constant		
Water level at the nozzle	A–B, B, B–C, C	Water level at the nozzle	A–B, B, B–C, C

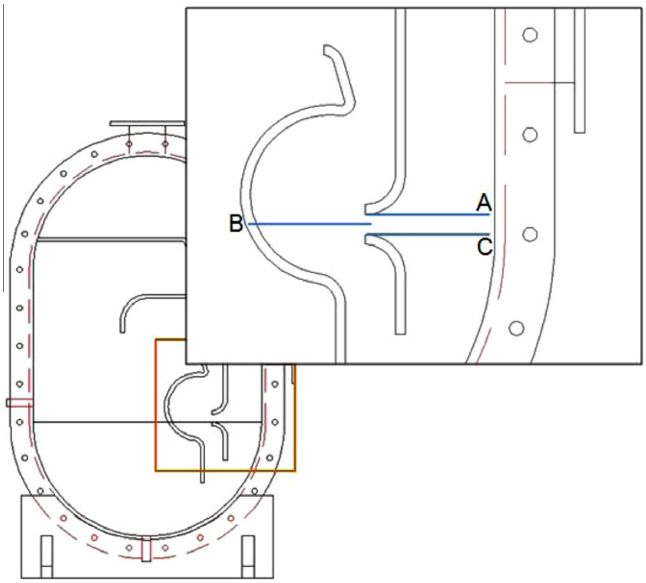

Fig. 5. Schematic representation of water level in the nozzle of the MTWS.

operating variables like gas flow rate, water level in the MTWS, water level in the nozzle, concentration of ammonia gas, particulate matter, and particle size distribution.

3.1. Effects of gas flow rate on pressure drop

The modified turbulent wet scrubber was subjected to pressure drop studies in order to estimate the energy spent in scrubbing the air pollutants. For three different water levels, viz. 56, 58, and 60 cm in the MTWS, the gas flow rates through the nozzle were varied and the pressure drop across the scrubber was measured using a measuring instrument from TESTO 350-S/XL, TESTO Inc. Fig. 6 represents the effects of the gas flow rate on the pressure drop. As the gas flow rate increases, the pressure drop increases steeply and has an almost linear relationship for higher gas flow rates. Higher gas flow rates lead to high turbulence in the MTWS, which results in greater pressure drops due to high frictional losses. Thus, an increase in the pressure drop due to an increase in the gas flow rate was observed in the MTWS. As the water level increases, the pressure drop also increases due to the increase in the hydrostatic head above the nozzle. A maximum pressure drop of 150 mm H_2O is observed in the MTWS for a gas flow rate of 4.5 m^3/min at a water level of 60 cm.

3.2. Removal of ammonia gas

Ammonia is very much soluble in water. It forms ammonium hydroxide, which is a weak base that is partially ionized in water according to the equilibrium given below. The solubility of ammonia in water will increase with decreasing pH. Hence the particles (fly ash) present in the scrubbing liquid (water) of the MTWS that can cause a reduction in the pH of the liquid can increase the absorption of the ammonia gas.

$$NH_3 + H_2O \rightarrow [NH_4OH] \rightarrow NH_4^+ + OH^-$$

3.2.1. Effects of scrubbing time

Fig. 7 shows that an increase in the scrubbing time decreases the efficiency of ammonia gas absorption by the MTWS. Initially, the water in the MTWS is fresh (zero concentration of ammonia) and there exists a large driving force for ammonia gas molecules to diffuse into the water. As the scrubbing time of the ammonia gas increases, the concentration of ammonia in the water increases. Thus, the driving force between the concentration of ammonia in the liquid phase (water) and gas phase starts to decrease as the liquid in the MTWS is not refreshed by fresh water.

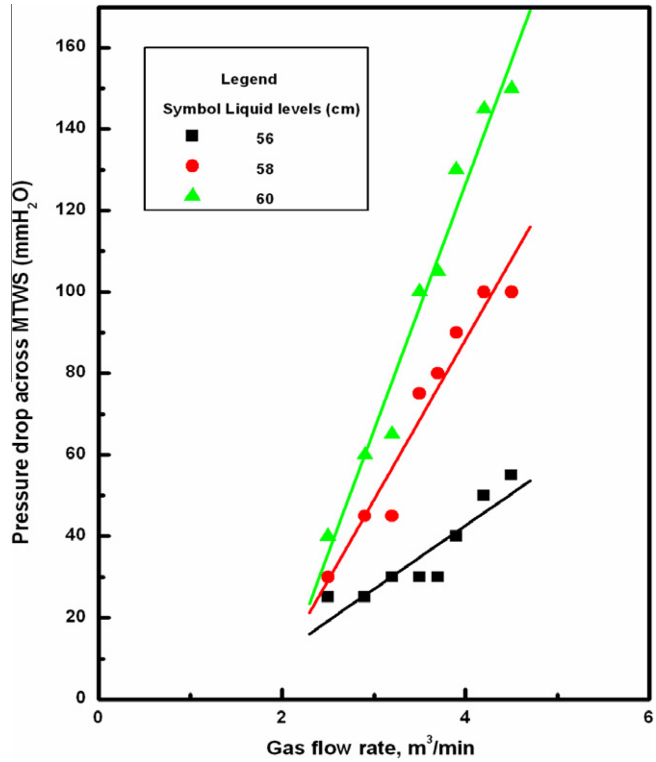

Fig. 6. Effect of gas flow rate on pressure drop.

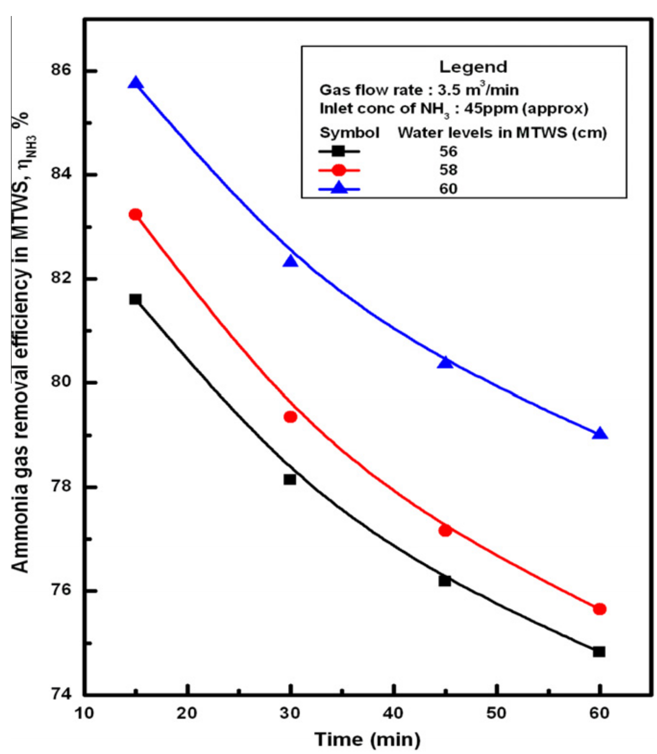

Fig. 7. Effect of scrubbing time on ammonia removal efficiency of MTWS.

The decrease in the driving force for the absorption of ammonia gas in the scrubbing medium leads to a decrease in the ammonia removal efficiency of the MTWS with respect to scrubbing time. Fig. 7 also shows that as the volume of liquid increases, the amount of ammonia absorbed increases. The increase in the ammonia removal efficiency with respect to the increase in volume of water in the MTWS is also due to an increase in the saturation concentration (solubility power). A maximum ammonia removal efficiency of 85.75% was observed for an inlet concentration of 45 ppm and water level of 60 cm in the MTWS with a gas flow rate of 3.5 m^3/min.

3.2.2. Effects of reservoir water levels in the MTWS

The absorption of gases by liquids mainly depends on mass transfer aspects like interfacial area, film resistance from gas and liquid sides, residence time, and temperature leading to the extent of solubility in liquid [37]. The solubility of gases like NH_3 and CO_2 in water is usually low. Hence, they become saturated at low concentrations. Higher agitation or turbulence and a longer contact period lead to saturation of the gas in the liquid. In Fig. 8, the ammonia removal efficiency of the MTWS decreases with respect to scrubbing time for a gas flow rate of 4.5 m^3/min and an inlet concentration of approximately 45 ppm. This may be due to a reduction in contact time between the gas and liquid. Low residence time decreases the gas removal efficiency of the scrubber [38].

The efficiency of the MTWS drops from 83.7% to 77.42% as the water level increases from 58 cm to 60 cm for a gas flow rate of 4.5 m^3/min, which contradicts the previous Fig. 7. for a gas flow rate of 3.5 m^3/min. Higher gas flow rates and larger volumes usually lead to increases in efficiency due to high turbulence and greater volume for liquid absorption, which takes longer to reach saturation. However, the increases in the gas flow rate and the volume of scrubbing medium decrease the efficiency of the MTWS. This might be due to channeling in the MTWS. The gas escapes from the liquid without homogenizing or thorough mixing with the liquid. Thus, gas residence time decreases with the liquid at the specific conditions (water level of 60 cm and gas flow rate of 4.5 m^3/min), and the gas escapes lead to the decrease in the efficiency.

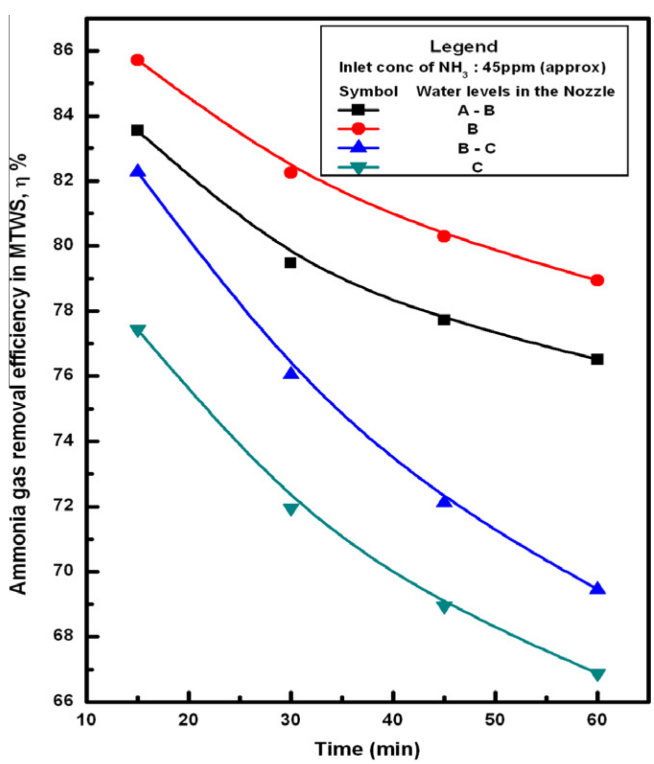

Fig. 8. Effect of water levels in nozzle on the ammonia removal efficiency of MTWS.

3.2.3. Effects of nozzle water levels

The water level in the nozzle during operation was varied with respect to the gas flow rates and the initial water levels in the MTWS. The water level in the nozzle determines the opening of the nozzle for the gas to enter, and thereby the velocity of the gas also becomes fixed. Hence, an optimum level in the water is estimated based on the efficiency of the MTWS. Fig. 8 clearly shows that a water level kept at position B of the nozzle yields the highest efficiency for the MTWS. Fig. 5 shows that water level B is almost the middle of the nozzle, and yields the optimum opening for the gas to flow and create better turbulence in the MTWS than positions A–B, B–C, and C. In position A–B, the gas may be unable to scour the liquid and mix completely, and may also undergo channeling with less residence time due to the increased gas flow rate that is caused by narrowing the nozzle opening. In cases where the water level is kept at B–C or C, the amount of scouring of water layers that occurs to form the homogenous medium may be less than cases where the water level is kept at position B. Thus, the efficiency of MTWS is low at positions B–C and C compared to position B in the nozzle. In particular, the large increase in the nozzle opening that occurs when the water level is kept at C may lead to the weakest turbulence, due to less scouring of the liquid layers from the surface of the liquid level in the MTWS which results in substantial decreases in the effective contact between the gas and the liquid and in the efficiency.

3.3. Removal of particulate matter

In order to design a wet scrubber for practical application, the fractional separating efficiency and the particle size distribution of the dust to be separated and shown for better understanding. In the present study the particulate removal efficiency of the MTWS is analyzed with respect water levels in the MTWS, gas flow rates, feed rate of the fly ash and water levels at the Nozzle against the particle size (aerodynamic size of the particle).

3.3.1. Effects of reservoir water levels

The particle removal efficiency of wet scrubbers mainly depends on the filtering effect of the droplets or blanketing effect of the thin liquid films, and on the extent to which the particles are wet, so that they agglomerate and become trapped easily. Fig. 9 represents the fly ash scrubbing efficiency of the MTWS with respect to particle size distribution and water level in the MTWS at a gas flow rate of 3.5 m^3/min. As the particle size increases, the scrubbing efficiency increases. Fine particles can move along with the gas more easily than coarse particles due to differences in their inertia. Thus, very fine particles (submicron size) tend to escape along with the gas [29,36–40]. Fig. 10 clearly shows that particles size falling below 1.0 μm (lesser than 0.5 μm) is removed with efficiencies around 55% and a maximum of 62% based on the liquid level in the MTWS at 4.5 m^3/min gas flow rate. Holzer in his studies on wet separation of fine dusts and aerosols had listed the efficiencies of the basic five wet scrubbers from packed bed scrubbing tower to high pressure venturi scrubber, where the maximum efficiencies of these scrubbers fall between 42% and 95.6% for a mean particle size of 1.5 μm [43]. Thus the present novel wet scrubber (MTWS) shows better efficiencies for the given particle size distribution at agreeable range of pressure drops.

The exact collection mechanism in turbulent or fluidized wet scrubbers is difficult to predict. The problem in predicting the particulate removal mechanism in these scrubbers is under homogeneous

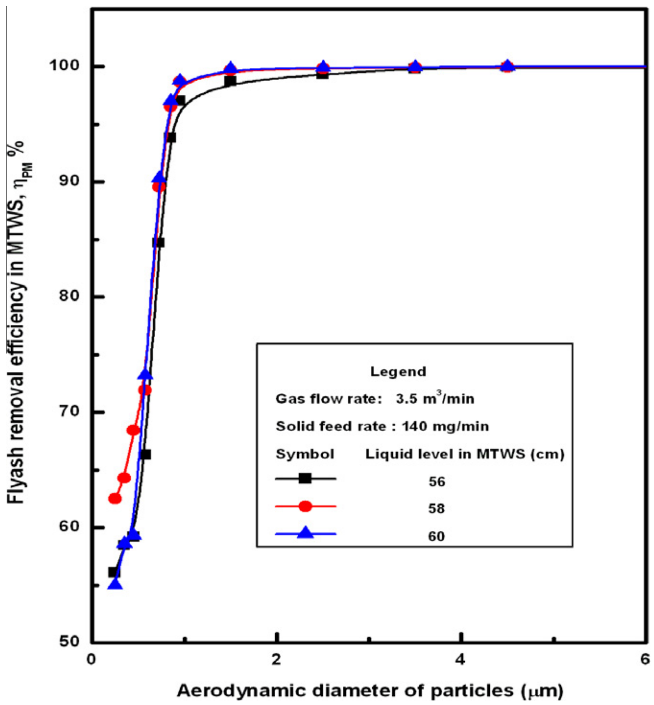

Fig. 9. Effect of water levels on the fly ash removal efficiency of MTWS at a gas flow rate 3.5 m^3/min.

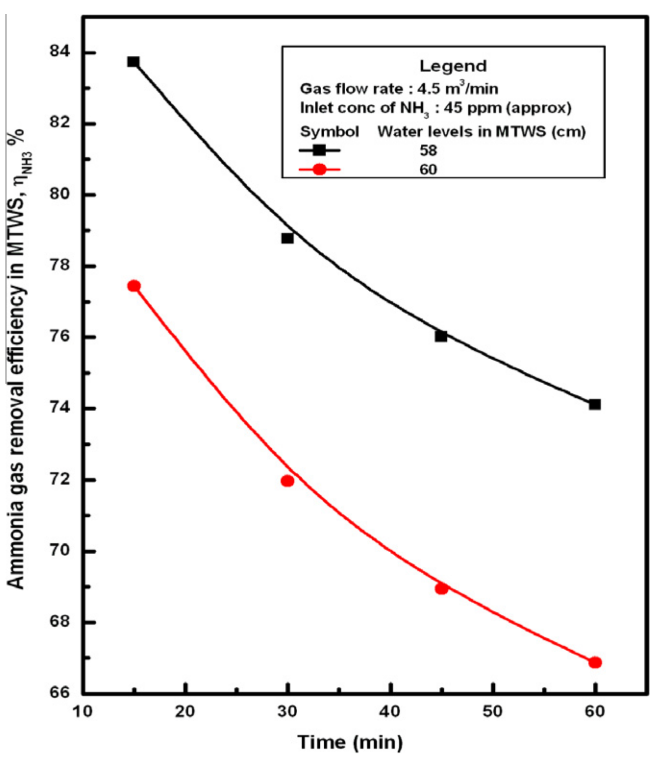

Fig. 10. Effect of water levels on the fly ash removal efficiency of MTWS at a gas flow rate of 4.5 m^3/min.

condition of three-phase [solid (submicron level), liquid, and gas] system, the parameters for particle scrubbing are highly dynamic and complicated nature. Similar problems were encountered by Peters et al. in their study on simulation of particulate removal in gas–solid fluidized beds [44]. The amount of liquid in the MTWS and the gas velocity decide the turbulence. High turbulence in the MTWS influences the collection mechanisms like to better impingement, wettability, and agglomeration of the particles. Hence, the optimum liquid level in the MTWS is found to be 58 cm. The fly ash scrubbing efficiency is found to be a little bit low, particularly in the submicron range for a water level of 60 cm as compared to 58 cm in the MTWS at a gas flow rate of 3.5 m^3/min. This may be due to the higher hydrostatic head, where the gas flow rate (velocity-kinetic energy) is not enough to create dispersion with the liquid that aids particle scrubbing.

3.3.2. Effects of feed loading rate

The overall efficiency of fly ash removal in the MTWS system increases with an increase in the solid loading. Fig. 11 shows the fly ash removal efficiency of the MTWS with respect to particle size distribution at different feed loading rates. As the feed rate increases, the fly ash removal efficiency of the MTWS decreases for submicron particles. The increase in the feed rate causes a proportional increase in the amount of fine particles in the feed; hence, the efficiency of the MTWS decreases moderately for the submicron particles with the feed rate for the given operating conditions. The particle removal efficiency of the MTWS is almost the same for the feed rate of 824 mg/min as for the feed rate of 324 mg/min. This may be due to the particle – particle interaction in a high population density of particles (concentration of particles) in the gas stream. Due to this hindering effect, the resultant efficiency of the MTWS is the same as that of the feed rate of 345 mg/min in the dusty gas.

3.3.3. Effects of gas flow rate

Fig. 12 shows the fly ash removal efficiency of the MTWS with respect to particle size and gas flow rate at a water level of 58 cm and a feed rate of 140 mg/min. As the particle size increases, the efficiency increases. The efficiency is slightly greater for a gas

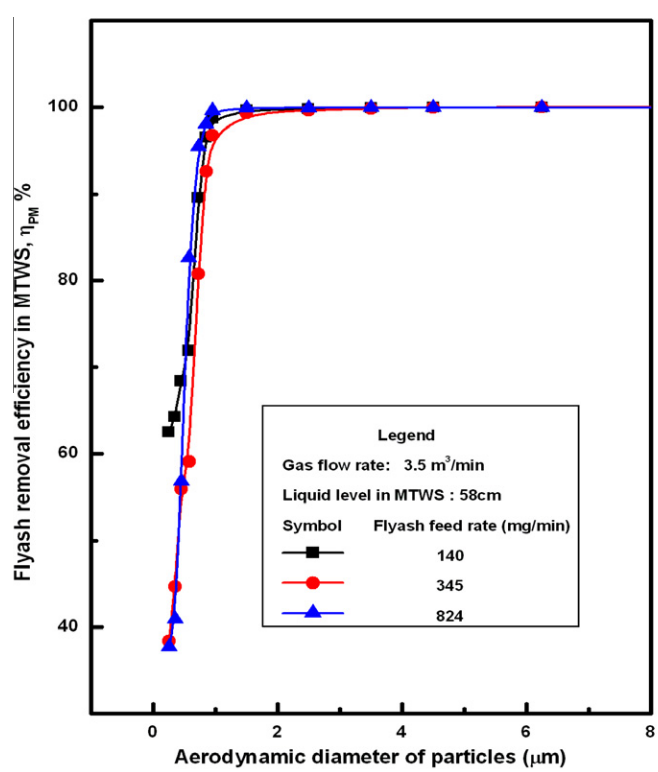

Fig. 11. Effect of feed rate on the fly ash removal efficiency of MTWS at a gas flow rate of 3.5 m^3/min.

flow rate of 4.5 m^3/min than for a gas flow rate of 3.5 m^3/min for the same water level (58 cm). This may be due to high turbulence created at the higher gas flow rate. High turbulence might have increased the gas–liquid contact to a greater extent, thereby increasing the wettability of the particles leading to agglomeration of further more fine particles so that fine particles get scrubbed. Moreover, the dilution in particle concentration (140 mg/min) and the increase in inertial force of the particles due to increase in the gas flow rate (4.5 m^3/min) result in higher filtration of the particles caught in the fluidized gas–liquid (homogenized) phase thrown against the baffles leading to significant increase in the efficiencies of the MTWS.

Fig. 13 shows the fly ash removal efficiency of the MTWS with respect to particle size, gas flow rate and a fly ash feed rate of 140 mg/min with a water level of 60 cm. The Fig. 13 shows that there is a decrease in fly ash removal efficiency with respect to gas flow rate at a water level of 60 cm compared to a water level of 58 cm. Due to the higher liquid level in the MTWS, the kinetic energy of the gas may not be sufficient to have enough mixing within the gas–liquid mixture. This might have resulted in formation of larger bubbles and droplets (spouts) that would have offered comparatively lesser wettability and impaction/interception of the particles thus reducing the filtering effect. Also, the fly ash removal efficiency for submicron particles at a gas flow rate of 4.5 m^3/min is low in comparison to 3.5 m^3/min at a water level of 60 cm. This may be due to channeling, where the gas bypasses the liquid medium through large bubble bursts at pressure created by higher gas flow rates at the higher hydrostatic heads.

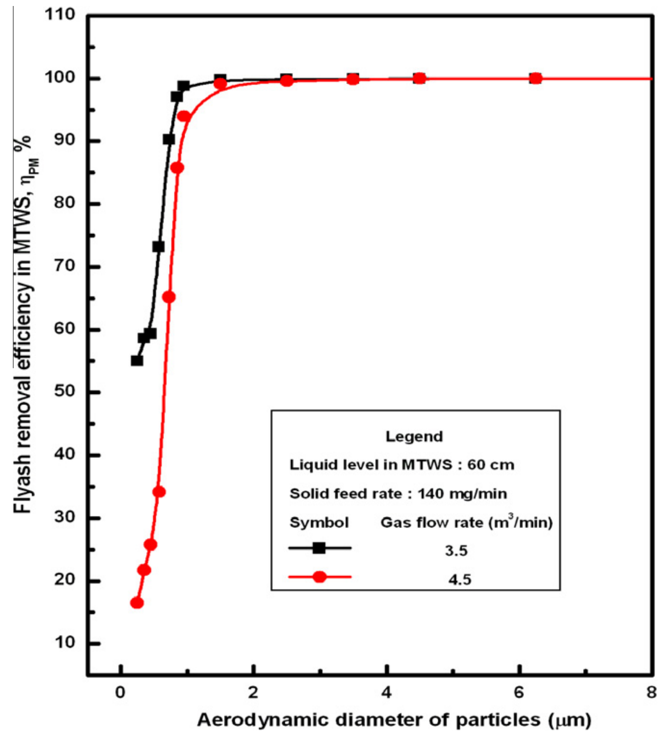

Fig. 13. Effect of gas flow rate on the fly ash removal efficiency of MTWS at 60 cm water level.

3.3.4. Effects of nozzle water levels

Fig. 14 represents the effect of the liquid level in the nozzle. The liquid level in the nozzle determines the height of the nozzle opening based on the gas flow rates and the liquid level in the MTWS. The liquid level in the A–B nozzle position for a solid feed rate of 140 mg/min results in high efficiencies for even the submicron range of particles in the MTWS. Position B is also found to have efficiencies closer to that of position A–B for particles 1 μm and above. The other two positions of water levels in the nozzle, B–C and C, exhibit a significant difference in the fly ash removal efficiencies

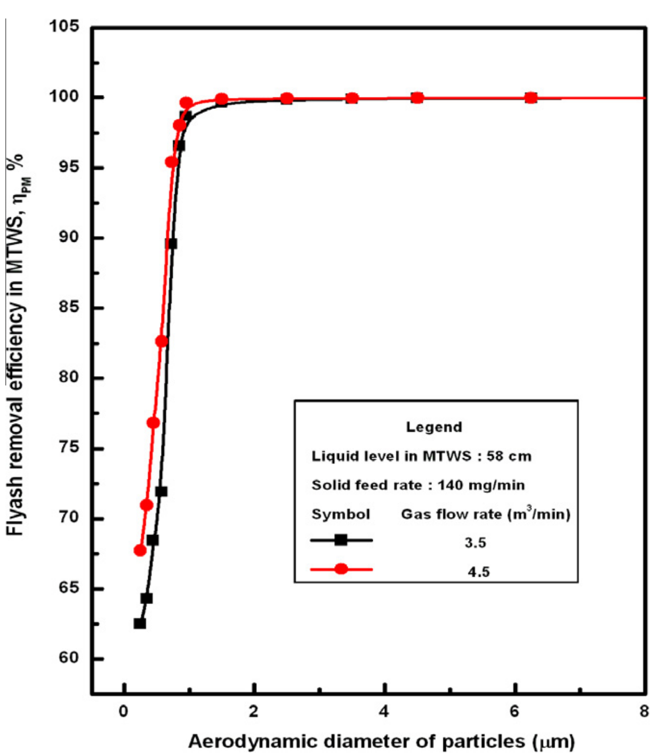

Fig. 12. Effect of gas flow rate on the fly ash removal efficiency of MTWS at 58 cm water level.

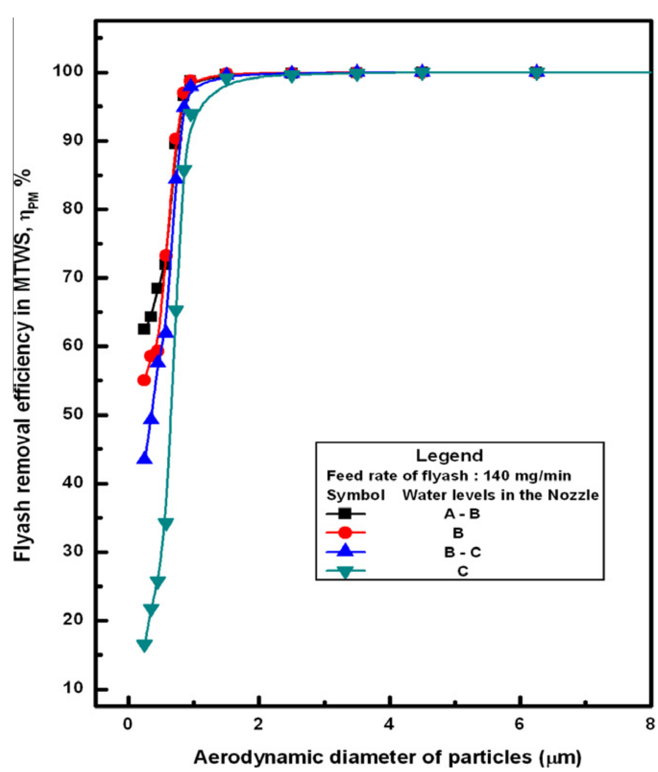

Fig. 14. Effect of liquid levels in the nozzle on the fly ash removal efficiency of MTWS.

with respect to position A–B. Fig. 9 shows that the scrubbing efficiency of ammonia gas in the MTWS with the water level at position B is greater than at position A–B in the case of particle scrubbing, as indicated by Fig. 14. The particles are removed at different hydrodynamics where impingement onto fine droplets and a blanketing effect by thin films of the scrubbing liquid are necessary. For gases, large contact area, high residence time, and greater turbulence between the gas and scrubbing medium favor the scrubbing process. Hence, particles are scrubbed at higher liquid levels than gas, where the filtering effect is more important than contact time.

3.4. Simultaneous scrubbing

The presence of particulate matter (fly ash) in the simultaneous scrubbing process of both gaseous pollutant and particulate matter is advantages, especially in case of gaseous pollutants like SO_2, NH_3, etc. [45,46]. Certain salts of chlorides, fluorides, sulfates and nitrates present in the particulate form might have reacted with ammonia, converting them into the respective ammonia salts. Thus the presence of the particles would have significantly enhanced the efficiency of the gaseous ammonia absorption in the MTWS. Further investigations have to be made to study the effect of particles concentration on the absorption potential of ammonia by MTWS.

4. Conclusions

Removal efficiency is a function of the inlet concentration of the pollutants. The concentration of ammonia is maintained almost constant to investigate the performance of the system. A high efficiency is achieved under the optimal operating conditions for both ammonia gas and particulate in the modified turbulent wet scrubber.

(1) A maximum efficiency of 79% is achieved from 45 ppmw of gas flowing at a rate of 3.5 m^3/min and with a liquid level of 60 cm in the MTWS.
(2) Similarly, a maximum efficiency of 62.48% is achieved for 0.25 μm-sized particles with a feed rate of 140 mg/min in a gas flow of 3.5 m^3/min with a water level of 58 cm in the MTWS which is unique to the present wet scrubber compared to scrubbers of its kind.
(3) With respect to the nozzle opening, position B is the most favorable level for ammonia gas and position A–B is the most favorable level for particle scrubbing. In the case of ammonia gas, the turbulence and residence time have strong influences on the removal efficiency of the MTWS. In the case of particle scrubbing, however, the wettability and filtering effect by the droplets and liquid films are vital in achieving higher efficiencies.
(4) Experiments conducted on a hydrodynamic study of the MTWS show that the maximum energy losses in terms of pressure drop are 150 mm H_2O for a maximum gas flow rate of 4.5 m^3/min operated in the system, which is considered to be nominal for the efficiency achieved in this compact system.

Thus, the MTWS can be employed in almost all industries that handle similar kinds of gaseous and particulate pollutants, as it is very economical and is the simplest and most efficient means of sustaining a cleaner and safer environment.

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