Nuclear Engineering and Technology 52 (2020) 2230–2237

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

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

Original Article

Experimental investigation of aerosols removal efficiency through self-priming venturi scrubber

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ARTICLE INFO

Article history:
Received 8 May 2019
Received in revised form
20 February 2020
Accepted 18 March 2020
Available online 19 March 2020

Keywords:
Aerosols
Self-priming venturi scrubber
Filtered containment venting system
Particulate removal

ABSTRACT

Self-priming venturi scrubber is one of the most effective devices used to collect aerosols and soluble gas pollutants from gaseous stream during severe accident in a nuclear power plant. The present study focuses on investigation of dust particle removal efficiency of the venturi scrubber both experimentally and theoretically. Venturi scrubber captures the dust particles in tiny water droplets flowing into it. Inertial impaction is the main mechanism of particles collection in venturi scrubber. The water injected into venturi throat is in the form of jets through multiple holes present at venturi throat. In this study, aerosols removal efficiency of self-priming venturi scrubber was experimentally measured for different operating conditions. Alumina (Al_2O_3) particles with 0.4-μm diameter and 3950 kg/m^3 density were treated as aerosols. Removal efficiency was calculated for different gas flow rates i.e. 3-6 m^3/h and liquid flow rates i.e. 0.009–0.025 m^3/h. Experimental results depict that aerosols removal efficiency increases with the increase in throat velocity and liquid head. While at lower air flow rate of 3 m^3/h, removal efficiency decreases with the increase in liquid head. A theoretical model of venturi scrubber was also employed and experimental results were compared with mathematical model. Experimental results are found to be in good agreement with theoretical results.

1. Introduction

Nuclear power plant (NPP) containment is the last defensive barrier against the release of radioactivity in the environment. However, extreme severe event at nuclear power plant results in failure of all safety and vital equipment. This leads to the excruciating core damage and consequent core meltdown which produces enormous steam. This results in reactor containment over pressurization. Along with steam generation during core meltdown, a vast amount of highly volatile radioactive products are produced in the reactor containment [1]. In order to avert the release of these radioactive products into environment, the containment integrity must be sustained during severe accidents. It is achieved through filtered venting of gaseous stream present inside the containment. Filtered containment venting system (FCVS) is extensively used to ensure the containment integrity during severe accidents in NPPs. FCVS depressurizes the containment in a passive way by venting the gaseous stream into environment, while air borne particulates are restrained into containment atmosphere [2]. The FCVSs operating around the world typically are classified into two categories; wet type and dry type system. The wet type FCVSs uses venturi scrubber for elimination of aerosols and radioactive gases from polluted gaseous stream. In wet type scrubber system, venturi scrubbers are followed by dry metal fiber filter for filtration of very fine particles that are penetrated through venturi scrubber. Dry filtration system typically uses deep bed filters such as sand bed filters, ceramics and dry bed filters as main preservation stage for air borne particulates [3].

Nowadays, several kinds of wet scrubber devices are available in power plants and different industries. These devices may be venturi scrubber, packed bed scrubber, mechanically aided scrubber, fiber bed scrubber, moving bed scrubber, ionizing bed scrubber and condensation growth scrubbers. Wet type scrubbers are most efficient devices and generally used for gas cleaning, aerosol removal and elimination of polluted gases from gas stream by using liquid scrubbing techniques [4]. Among all these wet scrubbers,

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https://doi.org/10.1016/j.net.2020.03.019

venturi scrubbers are the most efficient cleaning devices that use scrubbing solution in form of fine droplets emerged in venturi throat and encapsulate the air borne particles. Whereas radioactive gases like SO_2, I_2 and CH_3I, etc., are absorbed by the liquid droplets. Venturi scrubber eliminates the aerosols of size range from 0.1 μm to 100 μm [5].

Venturi scrubber is a key component of wet type FCVS as it removes aerosols from gaseous stream during severe accidents in NPPs. Wet scrubber system removes fine dust particles more efficiently as compared to dry scrubber, because of internal recirculation developed inside the liquid drop [6]. Venturi scrubber envelops the aerosols in tiny water droplets flowing into the throat of venturi. Water enters the venturi throat in the form of a water film and is converted into fine droplets by gas stream flowing into venturi throat [7]. The venturi scrubber performance is improved by increasing throat gas velocity, and liquid injection rate in venturi throat [7,8]. Aerosols removal efficiency of venturi scrubber is enhanced by enlarging the venturi throat length as impaction phenomenon mainly takes place at the venturi throat. Venturi scrubbers are categorized into two types based upon liquid injection; self-priming and force feed venturi scrubber. In self-priming, liquid gets injected into throat by pressure difference between hydrodynamic head of liquid column and static pressure of gas in the throat. While pump is used in force feed mechanism to inject liquid in the venturi throat [8,9]. For particle size larger than 0.5-μm, venturi scrubber achieves 99%efficiency with throat gas velocity greater than 120 m/s, however efficiency gets worsen rapidly when particle diameter is decreased under 0.5 μm [8].

Various mathematical models are available for prediction of venturi scrubber performance. Inertial impaction is the main mechanism through which particles are collected in venturi scrubber [10]. [11] Predicted venturi performance by assuming venturi's infinite throat length. They validated model by performing experiments on particle size range 0.5–4.6 μm, Calvert introduced designed factor (f) for different particles and recommends $f = 0.2$ for hydrophobic particles [11]. Young et al. modified the Calvert model and assumed that collection is only performed in venturi throat. They eliminated empirical constant and developed a relation for maximum throat length required by venturi [12]. Boll predicted venturi performance by solving drop motion, momentum exchange and inertial impaction equations simultaneously and concluded that performance of venturi is mainly dependent on particle size distribution and concentration [13]. The aerosols in the reactor containment generally exist in normal distribution, and the particulates size vary from 0.1 to some hundred microns. Thus, the venturi scrubber requires more outstanding collection enactment, especially for the particles of diameter less than 0.5 mm [7].

This study focuses on investigation of aerosols removal efficiency in self-priming venturi scrubber. Water was used as scrubbing liquid in both cases. Mathematical model based upon inertial impaction was employed for venturi scrubbers' experimental results validation. This study is the first of its kind for validation of a mathematical model with experimentation at low throat velocities (42-85 ms^{-1}). Alumina (Al_2O_3) particles used in this research which are hydrophobic in nature. However, these hydrophobic Al_2O_3 particles are taken as dust particles to simulate insoluble aerosols produced within the containment due to interaction of corium and concrete after a core-meltdown accident. Additionally, the hydrophilic CsI has significantly more decontamination factor as compared to the hydrophobic MnO [14]. So, it may be assumed that in case of CsI the removal efficiency is for more than that of hydrophobic Al_2O_3. In this research, Alumina (Al_2O_3) powder of mean particle diameter 0.4 μm was used as simulants of the aerosols, and the collection efficiency was examined rationally under different operational conditions i.e., throat velocity and liquid injection rate.

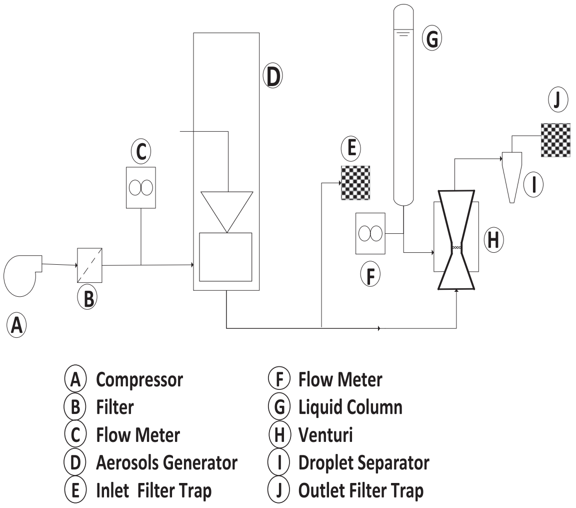

Fig. 1. Schematic diagram of experimental setup.

2. Experimental setup

Schematic diagram of experimental setup is shown in Fig. 1. The compressed air from compressor is passed through air filter and moisture separator to remove moisture contents from incoming air. Rotameter is used to measure the air flow rate and air flow rate is controlled by a valve. Aerosols are uniformly mixed into inlet air by aerosol generator and air containing aerosols are injected at venturi inlet. Column G injects the liquid at venturi throat H while liquid is injected via pressure difference between hydrodynamic head of liquid column and static head of air in venturi throat. Water level in liquid column is maintained during experiment to establish the required hydrostatic head in liquid column. Air flow direction is against the gravity in venturi scrubber. After scrubbing action takes place in venturi, air and droplets exit at venturi outlet. To remove droplets from exit stream, droplet separator is installed after the venturi exit. In droplet separator, liquid settles down in bottom and air stream comes out of vortex finder.

Aerosols are collected at inlet port E and outlet port J. Filtration technique was used for collection and measurement of aerosols in air stream. Aerosols are collected in filter paper. Digital weight balance was used for aerosols measurement in sample. The weight of the filter paper was measured before and after the experiment. Weight difference of filter paper indicates the aerosols concentration accumulated in filter paper. The concentration of aerosols is measured at venturi inlet and exit and aerosols removal efficiency of venturi scrubber is calculated from the following equation:

$$\eta = 1 - \frac{\boldsymbol{Co}}{\boldsymbol{Ci}} \tag{1}$$

Where $\boldsymbol{Co}$ is aerosols concentration at venturi outlet and $\boldsymbol{Ci}$ is aerosols concentration at venturi inlet.

2.1. Venturi scrubber

Non-submerged venturi scrubber was used in this research. In non-submerged case, there is no scrubbing solution head above the venturi. Scrubbing action only takes place inside the venturi and liquid is injected into venturi throat through multiple fine holes provided at the periphery of venturi throat. Liquid is injected through hydrodynamic head of liquid in the scrubbing column. This configuration is called as self-priming venturi scrubber because there is no external pump used for liquid injection in the throat. Fig. 2 shows different sections of venturi scrubber used in the experimental setup.

Table 1 shows the dimensions of venturi scrubber used. It can be seen that throat of venturi has four equidistant holes for liquid injection.

2.2. Droplet separator

Droplet separator is always integrated with venturi scrubber either as an integral part or separate device. There are two important parameters required for effective design of droplet separators:

1. Liquid drops size distribution
2. Gas stream inlet loading

The droplet size distribution depends upon method by which droplets are formed. For venturi scrubber system, droplet diameter was estimated using Boll's model [15] and assumed that all droplets are of same diameter. It is given by Eq. (2).

$$D_d = \frac{4.22 \times 10^{-2} + 5.77 \times 10^{-3}\left(1000\frac{Q_l}{Q_g}\right)^{1.932}}{v_r{}^{1.602}} \tag{2}$$

Where D_d is drop diameter, Q_l is liquid loading at venturi throat, Q_g is gas loading and v_r is relative velocity of gas and droplets. All units in SI system.

Cyclone separators are most commonly used with venturi scrubbers and various mathematical models are available in literature for performance/efficiency prediction of cyclone separators [16]. Derived mathematical model for cyclone separator for performance prediction and this model works well at low temperature conditions. Using this mathematical model, cyclone separator predicts collection efficiency of 99.57% for 30 μm droplet size. Design diagram of cyclone separator used in this research is shown in Fig. 3.

2.3. Aerosols generator

The schematic of aerosols generator used in this research is shown in Fig. 4. Closed type fluidized bed dust generator used in this research. Because of very sticky nature of alumina powder used in this research the isolation of dust bed from outside environment is necessary to prevent the powder agglomeration. Closed type aerosols generator completely insulate the fluidized bed from external atmosphere. Aerosols generator fluidization bed area is gradually increased in the direction of gas flow to avoid the channeling effect. Aerosols generator is covered in Perspex glass in order to insulate from outside environment. Hopper used in Aerosols generator is made of galvanized iron. Particles efflux tube is made of stainless steel with 4 mm internal diameter and flexible to move in axial direction. Particles flow is also controlled by particles efflux tube movement.

Table 1
Dimensions for different sections of venturi scrubber.

Inlet Diameter, D_i	36.25 mm	Throat inner Diameter, D_{th}	5 mm
Inlet Length, L_i	12 mm	Injection Hole Diameter, D_h	1.5 mm (x4)
Convergent Length, L_c	82 mm	Exit Length, L_e	12 mm
Throat Length, L_{th}	15 mm	Outlet Diameter, D_o	36.25
Divergent Length, L_D	100 mm	Material	Brass

2.4. Measurements

Rotameter is used for measurement of flow rate. The maximum capacity of rotameter used in experimental rig is 16 m^3/h with a uncertainty of ±0.5 m^3/h. The ball valve is incorporated with rotameter for precise flow measurement. Mass of the filters was measured by a digital balance Shimadzu AX200 with uncertainty of ±0.1 mg.

3. Mathematical model

Following assumptions were adopted to develop the mathematical model:

- Liquid and air in co flow direction
- Air and drops flow against the gravity
- Frictional losses are negligible
- Air flow is incompressible
- Air velocity is constant in throat
- Liquid drops distribute uniformly and having same diameter.
- Liquid drops are spherical in shape
- There is no condensation and evaporation in venturi
- Buoyant forces are negligible
- Relative velocity between particles and air is zero i.e., $v_p = v_g$
- No coalescence of fine droplets.

Applying Newton's second law on liquid droplet in venturi,

$$ma = F_D + \rho_g\left(\frac{\pi}{6}\right)D_d^3 g - \rho_d\left(\frac{\pi}{6}\right)D_d^3 g \tag{3}$$

Where m = mass of liquid droplet $\left(m = \rho_d\left(\frac{\pi}{6}\right)D_d^3\right)$

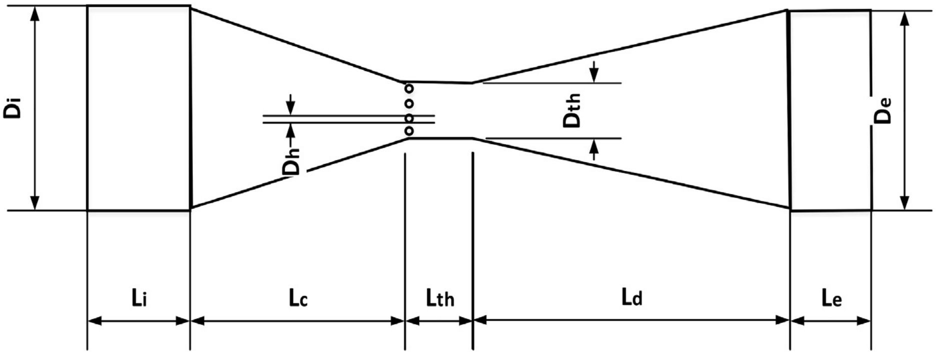

Fig. 2. Different sections of venturi scrubber.

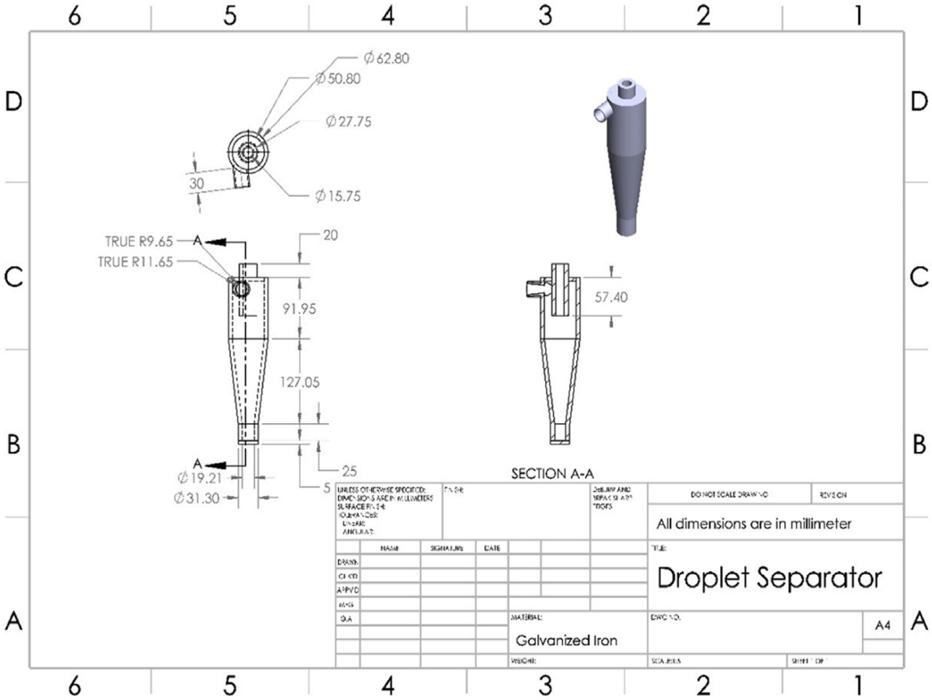

Fig. 3. Design diagram of cyclone separator.

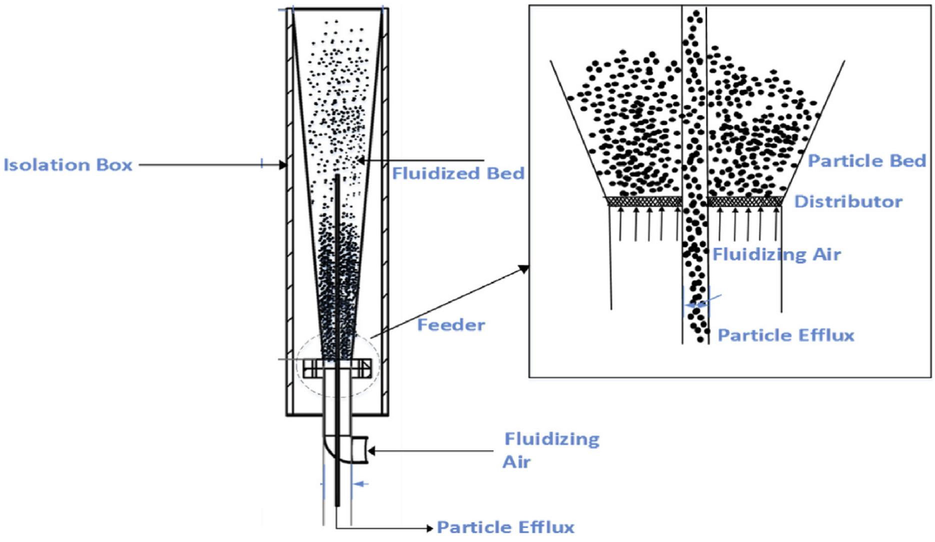

Fig. 4. The schematic of aerosols generator.

a = acceleration of liquid droplet ($a = \frac{dv_d}{dt}$)

$\rho_g \ll \rho_d$; $\rho_d - \rho_g \tilde{} \rho_d$

The drag force (on droplet) relation with velocity difference between gas and droplet has been developed by using non-dimensional drag coefficient,

$$C_D = \frac{F_D}{\left(\frac{\pi D_d{}^2}{4}\right)\rho_g\left(v_g - v_d\right)^2/2} \tag{4}$$

Putting Eq. (4) in Eq. (3) and by rearranging, we get

$$\frac{dv_d}{dt} = \frac{3}{4}\frac{\rho_g}{\rho_d}\frac{\left(v_g - v_d\right)^2 C_D}{D_d} - g \tag{5}$$

$$v_d = v_{di} + \int_{t_i}^{t} \frac{dv_d}{dt}\, dt \tag{6}$$

$$x = x_i + \int_{t_i}^{t} v_d \, dt \tag{7}$$

Where

x = Length of venturi (m)
x_i = x_i + Δx (x:0→X); X = Total length of venturi scrubber
X = L_{th} + L_d + L_e (as shown in Fig. 2)
t_i = t_i+Δt (t:0→T); T = Liquid droplet's journey in venturi scrubber
t = 0; When Liquid enter at venturi throat

In order to calculate the drag force experienced by liquid droplet due to relative motion of gas and liquid drops we first calculate the drag coefficient. Furthermore, from drag force used in force balance equation (Eq. (1)) kinematic properties of liquid droplets were calculated (acceleration, velocity, and time taken by droplet to complete its journey in venturi). Holland and Goel relationship was used to calculate the drag force experienced by liquid drop during its journey in the venturi. Holland and Goel relationship is adequate for Reynold number ranging from 10 to 500. In our case Reynold number of droplets is lying in the range in which Holland and Goel relationship is valid or best estimate the drag coefficient standard curve. Therefore, Drag Coefficient was calculated from Hollands and Goel [17] relationship,

$$C_D = C_{Di}\sqrt{\frac{v_g}{v_g - v_d}} \tag{8}$$

Where C_D is the Drag coefficient (Relates the force on a drop to velocity difference between droplet and gas), and C_Di is the Drag coefficient at throat entrance.

In this research Dickinson and Marshall correlation best estimate the drag coefficient standard curve for given Reynold number of droplets at throat entrance. Therefore, Drag Coefficient at throat entrance was calculated from Dickinson and Marshall [18] correlation,

$$C_{Di} = 0.22 + \frac{24}{Re_i}\left(1 + 0.15Re_i^{06}\right) \tag{9}$$

Where Re_i is the Reynold number at the beginning of throat.

$Re_i = \frac{(V_{gth} - V_{d0}\ )D_d}{v_g}$ calculated based on relative velocity of gas and drop at the beginning of throat.
V_{d0} = drop velocity at throat entrance (ms^{-1}) = 0, because liquid injected radially. Therefore, axial velocity component is zero.

Diameter of droplet was calculated from Boll et al. [15] correlation because this model works very well for gas throat velocity of 30–90 m/s,

$$D_d = \frac{4.22 \times 10^{-3} \ + 5.77 \times 10^{-3}\left(1000\frac{Q_l}{Q_g}\right)^{1.932}}{{v_r}^{1.602}} \tag{10}$$

Particles in venturi experience drag force and inertia force. By equating these forces, impaction parameter or inertial impaction is calculated for single droplet,

$$N_s = \frac{C\rho_p {D_p}^2 (v_g - v_d)}{18\mu_g D_d} \tag{11}$$

N_s represents separation number. It is also termed as impaction parameter or inertia parameter. C in equation (11) is Cunningham correction factor for (D_p<1 μm).

Target efficiency calculated from correlation developed by Mohebbi et al. [19] is given in equation (12).

$$\eta_t = \left(\frac{N_s}{N_s + 1}\right)^{0.759N_s^{-0.245}} \tag{12}$$

Aerosols removal efficiency was calculated using material balance equation for co-flow venturi scrubber [20] which is given in equation (13).

$$\text{Particles transferred to Liquid per unit time per unit volume} = -\frac{(\text{mass transferred to each droplet})\left(\frac{\text{Number of drops}}{\text{time}}\right)}{\text{volume of region}} \tag{13}$$

By rearranging, we get

$$\frac{dc}{c} = -\frac{3}{2D_d}\left(\frac{Q_L}{Q_g}.\eta_t\right)(v_g - v_d)dt \tag{14}$$

$$\boldsymbol{\eta} = 1 - \boldsymbol{exp}\left(-\frac{3}{2\,\boldsymbol{D_d}} \cdot \frac{\boldsymbol{Q_L}}{\boldsymbol{Q_g}} \cdot \int_0^{\boldsymbol{t}} \boldsymbol{\eta_t}|\boldsymbol{v_g} - \boldsymbol{v_d}|\,\boldsymbol{dt}\right) \tag{15}$$

4. Results and discussion

4.1. Liquid injection in the venturi throat for different air flow rates

Venturi scrubber used in this research was working in self-priming mode. There was no external pump required to inject liquid in the venturi throat. Liquid was injected by pressure difference developed between the venturi throat and scrubbing column head. Therefore, in self-priming mode, liquid flow rate is controlled by air flow rate. Whereas in force feed mode, liquid flow is independent of gas flow rate. As air moves through venturi in convergent section, velocity of air increases and its pressure decreases. Maximum velocity was achieved at throat while pressure of air reached minimum value. Therefore, pressure head was developed between throat and scrubbing column and liquid flowed from scrubbing column to venturi throat through multiple fine holes. Injected liquid was disintegrated into fine droplets by fine multiple holes present on the periphery of venturi throat [8]. Fig. 5 illustrates that liquid injection rate in the throat decreases with increasing the gas throat velocity. For same throat velocity, liquid injection rate is increased by increasing the hydrostatic head of liquid column. These trends are similar to the results of Lehner [8] and Majid et al. [21] in which liquid was injected in throat in the form of jet. Liquid jet is further disintegrated into fine droplets by air flow rate. By increasing the gas flow rate, static pressure of gas in the throat increases and pressure head between the throat and liquid column decreases. Therefore, liquid injection rate is decreased by increasing the gas velocity in the throat due to decrease in liquid driving head. For same throat velocity, liquid injection rate increases by increasing the liquid head in the scrubbing column.

4.2. Aerosols removal efficiency

Aerosols removal efficiency of venturi scrubber was measured

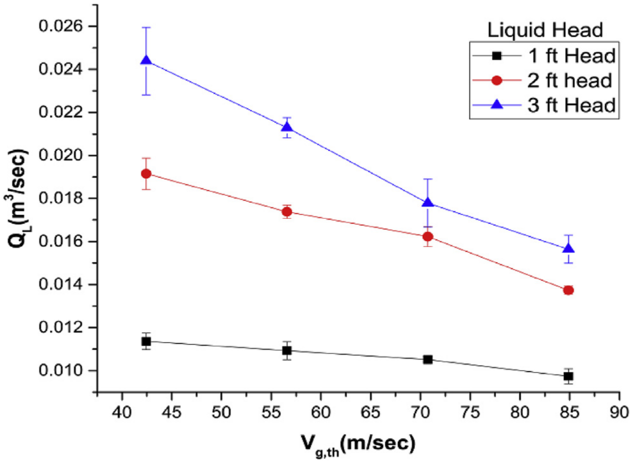

Fig. 5. Liquid injection rate for different operating conditions.

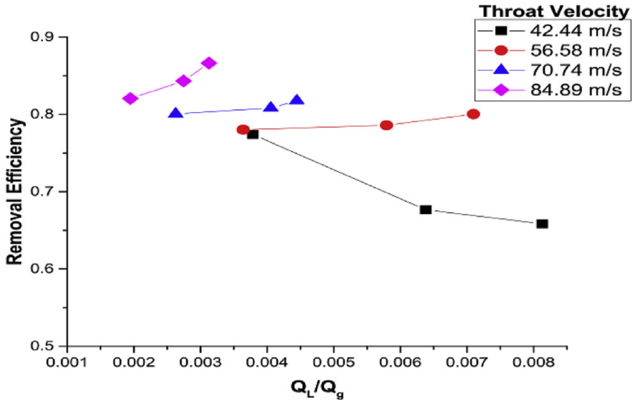

Fig. 7. Venturi scrubber removal efficiency for different liquid to gas ratios.

for different gas throat velocity and liquid head. Aerosols removal efficiency is the ratio of aerosols concentration removed to the aerosols concentration at venturi inlet.

In this research, alumina (Al_2O_3) particles of 0.4-μm size having 3950 kg/m^3 density were used as stimulus of aerosols. Alumina powder is hydrophobic in nature and it does not dissolve in water. Fig. 6 shows aerosols removal efficiency of venturi scrubber for different air throat velocity and scrubbing liquid head.

Fig. 6 illustrates that aerosols removal efficiency increases with increasing air velocity at throat. Also, for same throat velocity, removal efficiency increases with increasing the liquid head. Removal efficiency of venturi scrubber is a strong function of air velocity at throat as compared to liquid head. For low throat velocity of 42.44 m/s, removal efficiency decreases with the increase in liquid head.

In order to interpret the removal efficiency results at lower air velocity of 42.44 m/s, it is necessary to observe the effect of air velocity on droplet diameter and number of droplets formed per second under different operating conditions. Number of droplets was calculated by applying material balance equation on liquid injection in the throat. Assuming that all droplets have same diameter and are spherical in shape:

$$Q_L = N_D \times V_D \tag{16}$$

V_D is volume of droplet calculated using Boll Model [15].

Droplet diameter decreases with increasing velocity of air at throat and opposite effect is observed for droplet numbers. At lower air velocity at throat (42.44 m/s), almost same number of droplets were formed for different liquid heads while droplet diameter was increased. Therefore, at lower velocity of 42.44 m/s, surface area of droplets decreases by increasing the liquid head. Due to this effect, at lower throat velocity of 42.44 m/s, removal efficiency decreases with increasing the liquid flow rate. Maximum efficiency was obtained at higher air velocity at throat. At higher velocity of air, the relative velocity of air and droplets in the throat is high.

Venturi scrubber's performance is mainly dependent on gas throat velocity, liquid injection rate, aerosols particles size and aerosols concentration [8,21]. Aerosols removal efficiency for different liquid to gas ratio (QL/Qg) and throat velocity is shown in Fig. 7. By increasing the liquid to gas ratio removal efficiency increases but reverse situation is observed for lower throat velocity of 42.44 m/s.

In this study the effect of pressure drop is not evaluated only the aerosol removal efficiency of venturi scrubber is considered. Mean

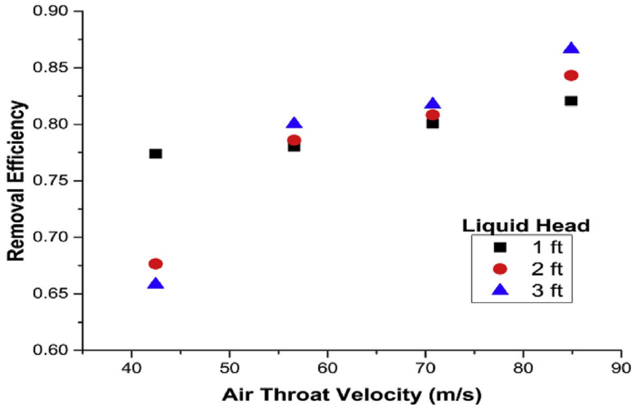

Fig. 6. Aerosols removal efficiency of venturi for different air throat velocity and liquid head.

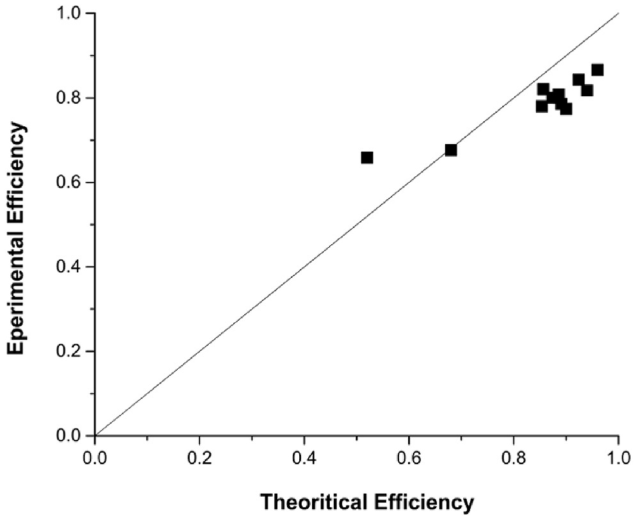

Fig. 8. Graph between theoretical and experimental results.

droplet diameter is not very sensitive to overall pressure drop of venturi scrubber. Aerosols removal efficiency of venturi scrubber is much more sensitive to the droplet size. Therefore, aerosols removal efficiency is very less sensitive to the pressure drop [13].

4.3. Results validation

A mathematical model was employed for validation of experimental results. Mechanism involved in capturing the aerosols particles depends upon the particles size, droplet size and gas velocity. Mathematical model employed in this study was only based on impaction phenomenon. Due to lower pressure of gas in the throat, vacuum is created in the throat and liquid drives into the venturi's throat in the form of jet. Liquid jet disintegrates into droplets by incoming gas flow. Droplet diameter was estimated using Boll model [15] given by Eq. (10) and impaction efficiency for a single droplet was calculated from Mohebbi et al. correlation [19] given by Eq. (12).

When particles laden air passes through venturi throat in the presence of liquid droplets then these tiny particles do not follow the stream line rather these particles stuck on the liquid drops present in the venturi. Fig. 8 shows the comparison between theoretical and experimental removal efficiency of venturi scrubber. In order to find the amount of aerosols in the air stream captured by droplet separator some experiments were performed without venturi scrubber. Air containing aerosols from aerosols generator was directly injected at droplet separator inlet and aerosols were measured at inlet and exit of droplet separator using filtration technique. However, at inlet and outlet of droplet separator the amount of aerosols was almost same and very small amount of aerosol was captured in the droplet separator. Therefore, it was concluded that aerosols removal efficiency was slightly overestimated by using of droplet separator.

5. Conclusion

Following conclusions can be drawn from the results obtained from experiments performed on experimental rig:

- Liquid injection in venturi throat decreases with increasing air throat velocity. For same throat velocity liquid injection rate increases with increasing liquid head.
- Aerosols removal efficiency of venturi scrubber increases with increasing the gas velocity and liquid head.
- For venturi scrubber removal efficiency is more dependent on air flow rates as compared to liquid head. For same air flow rates, there is a smaller increment in removal efficiency with increasing the liquid head.
- For throat velocity of 42.44 m/s, aerosols removal efficiency of venturi scrubber decreases with increasing the liquid head.
- Maximum removal efficiency of venturi is 87.5% which is obtained at 6 m^3/h air flow rate and 3 ft liquid head.
- Experimental results were found to be in good agreement with theoretical results.

Declaration of competing interest

It is hereby declared by the authors that this manuscript has no conflict of interest.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.net.2020.03.019.

Nomenclature

C	Cunningham correction factor
C_D	Drag Coefficient
D_d	Droplet Diameter/m
D_p	Particle diameter/m
F_D	Drag Force/N
N_s	Stokes number or impaction factor
L	Length/m
P	Pressure/Pa
Q_g	Gas Flow rate/m^3s^{-1}
Q_l	Liquid flow rate/m^3s^{-1}
Re	Reynold number
a	Acceleration/ms^{-2}
c	Aerosols concentration/Kgm^{-3}
f	Venturi design factor
g	Gravitational acceleration/ms^{-2}
m	Mass of liquid droplet/Kg
t	Time/sec
x	Length/m
a_d	Acceleration of liquid droplet/ms^{-2}
t_i	Initial time/sec
v_d	Droplet velocity/ms^{-1}
v_{di}	Initial velocity of Droplet/ms^{-1}
v_g	Gas velocity/ms^{-1}
v_r	Relative velocity of gas and droplet/ms^{-1}
ρ_g	Gas density/kgm^{-3}
ρ_D	Droplet Density/kgm^{-3}
μ_g	Gas dynamic viscosity/$kgm^{-1}s^{-1}$
η_t	Target efficiency
η	Removal efficiency

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