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Original Article

Study of an improved and novel venturi scrubber configuration for removal of radioactive gases from NPP containment air during severe accident

Mujahid Farooq [a], Ammar Ahmed [a, *], Kamran Qureshi [a], Ajmal Shah [b], Khalid Waheed [c], Waseem Siddique [c], Naseem Irfan [c], Masroor Ahmad [c], Amjad Farooq [c]

[a] *Department of Mechanical Engineering, Pakistan Institute of Engineering and Applied Sciences, Islamabad, Pakistan*
[b] *Centre for Mathematical Sciences, Pakistan Institute of Engineering and Applied Sciences, Islamabad, Pakistan*
[c] *Department of Nuclear Engineering, Pakistan Institute of Engineering and Applied Sciences, Islamabad, Pakistan*

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ABSTRACT

Owing to the rising concerns about the safety of nuclear power plants (NPP), it is essential to study the venturi scrubber in detail, which is a key component of the filtered containment venting system (FCVS). FCVS alleviates the pressure in containment by filtering and venting out the contaminated air. The main objective of this research was to perform a CFD investigation of different configurations of a circular, non-submerged, self-priming venturi scrubber to estimate and improve the performance in the removal of elemental iodine from the air. For benchmarking, a mass transfer model which is based on two-film theory was selected and validated by experimental data where an alkaline solution was considered as the scrubbing solution. This mass transfer model was modified and implemented on a unique formation of two self-priming venturi scrubbers in series. Euler-Euler method was used for two-phase modeling and the realizable $K-\varepsilon$ model was used for capturing the turbulence. The obtained results showed a remarkable improvement in the removal of radioactive iodine from the air using a series combination of venturi scrubbers. The removal efficiency was improved at every single data point.

1. Introduction

The nuclear power plants (NPPs) provide cleaner power generation, sustainable and reliable energy. But due to accidents like the ones at NPPs of Three Mile Island, Chernobyl, and Fukushima Daiichi, there are some concerns regarding the safety of NPP. The most prominent concern regarding its safety is the release of radioactive products into the environment. In these radioactive products, iodine-131, due to its airborne properties and having a half-life of 8 years, is the most worrisome radioactive product. To prevent any exposure to radioactivity in the environment, the integrity of the containment building must never be jeopardized. A filtered containment venting system (FCVS) is used to protect the integrity of the containment building during severe accidents. In severe accidents, the pressure and temperature of the containment rise, which, in return, makes the integrity of containment to be vulnerable. FCVS reduces the pressure by filtering and then releasing a certain amount of containment air into the atmosphere. Venturi scrubber technology is the most effective option for the removal of gaseous pollutants as well as dust particles. It is used in the FCVS to filter contaminated air. In order to improve its performance, it is essential to study the flow physics of a venturi scrubber and the factors that influence the removal of contaminants. Venturi scrubber is a type of venturi tube having small orifices at its throat [1]. It has been the topic of research for a long time now, mainly due to its high removal efficiency.

Uchida-Wen [2] first presented a mathematical model regarding the removal of gaseous pollutants like sulfur dioxide (SO_2) using a venturi scrubber. The model predicted the pressure drop in the venturi scrubber as well as heat and mass transfer for SO_2 removal. First-order equations were used and droplets were assumed to be rigid, spherical, having no coalescence with the same size distribution and results were in good agreement with experimental data. Cooney [3] studied the removal efficiency of the venturi scrubber and improved the model presented by Uchida-Wen [2] by incorporating the pH and diffusion effects. Ravindram-Pyla [4] studied the removal of pollutants using a venturi scrubber and proposed a mathematical model that incorporated the diffusion effects as well as second-order irreversible reaction. Alonso et al. [5] studied the

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* Corresponding author.
E-mail address: ammarahmed@pieas.edu.pk (A. Ahmed).

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hydrodynamics of the venturi scrubber by performing several experiments having different types of injection methods. The main purpose was to measure the droplet size of the scrubbing solution for multiple gas flowrates using a laser diffraction method. The conclusion was that Sauter mean diameter obtained from Boll et al. correlation [6] instead of Nukiyama-Tanasawa correlation [7], gives more agreeable results with the experimental data.

Gamisans et al. [8] developed a two-film theory based model while considering the effects of both liquid droplets and film formation. Concentration difference was considered to be the major driving force and the scrubbing solution was considered to have interacted with air as droplets and as a film. It was concluded that the reaction is kinetically rapid, so the mass transfer phenomenon was diffusion-controlled and dominant near the liquid-gas interface. Pak and Chang [9] presented a three-phase (gas, liquid, and dust particles) model to predict the pressure drop and the collection efficiency of a venturi scrubber. The results were compared with the experimental data and were found to be in good agreement with them. Ali et al. [10] performed experiments to study the submerged and non-submerged venturi scrubber and noted that the efficiency of removal of iodine increased with an increase in the air mixture flowrate.

Ali et al. [11] proposed a mathematical model based on the two-film theory similar to a model proposed by Gamisans et al. [8], to study the non-submerged venturi scrubber. It was considered that reaction rates are kinetically rapid while the mass transfer was diffusion-controlled and dominant at the gas-liquid interface as proposed by Gamisans et al. [8]. It was concluded that the efficiency of iodine removal increases with an increase in the flowrate of air mixture and the amount of inlet concentration of iodine in it. Zhou et al. [12] conducted experiments and proposed a mathematical model to estimate the efficiency of iodine removal of the self-priming venturi scrubber. Ashfaq et al. [13] studied the effect of variation in diameter of the droplet on removal efficiency of iodine in a non-submerged, self-priming, venturi scrubber using CFD, for various flowrates of liquid and gas. Extending the work of Ashfaq et al., Ahmed et al. [1] studied the phenomenon of mass transfer in a venturi scrubber using ANSYS FLUENT. The mass transfer model which was based on the two-film theory was developed and validated with experimental results. The proposed model was implemented in CFD software by using a user-defined function (UDF). Ahmed et al. tuned the distribution parameter by calculating its value for different gas flowrates and inlet iodine concentration.

The present research is an extension of the work presented by Ahmed et al. [1]. This research aims to improve the removal efficiency of the venturi scrubber using the methodology presented by Ahmed et al. [1]. For this purpose, a novel arrangement of venturi scrubbers has been proposed. The unique formation of two circular, self-priming, non-submerged venturi scrubbers in series (vertically stacked upon each other) is presented. After validating the methodology for a single venturi scrubber, the removal efficiency is improved by using a unique formation of two venturi scrubbers in series. Moreover, two variations of the mass transfer model based on droplet diameter in both venturi scrubbers have been used. The same droplet size on both venturi scrubbers in series, as well as different droplet sizes for each of them, were implemented on this unique formation and results have been compared. This novel configuration of venturi scrubbers as well as the variation of mass transfer model for this arrangement are being presented here for the first time in the light of open literature. The effect of different flowrates, water head, and inlet concentration on removal efficiency, iodine mass fraction, velocities, and pressure inside the venturi scrubbers are also presented in this work. The results show that at lower gas flowrates (5–6.5 m^3h^{-1}), the maximum removal efficiency is predicted to be around 98%, which is very high considering the lower gas flowrates.

2. Methods and procedure

In this study, CFD investigation has been carried out to study and improve the removal efficiency of two self-priming, circular, non-submerged venturi scrubbers in series. A mathematical model developed by Ahmed et al. [1] was implemented in the ANSYS FLUENT module using a user-defined function (UDF). The performance of the venturi scrubber was judged based on its efficiency to remove iodine from the air. The difference in concentration of iodine between inlet and outlet of the venturi scrubber was used to calculate the removal efficiency.

2.1. Mathematical model for flow

The Eulerian model has been used for two-phase modeling as suggested by Ahmed et al. [1]. The following are the equations used by the Eulerian model to solve for each phase. Continuity equation [14]:

$$\frac{\partial}{\partial t}(\alpha_q\rho_q) + \nabla\cdot\left(\alpha_q\rho_q\vec{v}_q\right) = \sum_{p=1}^{n}(\dot{m}_{pq} - \dot{m}_{qp}) + S_q$$

Equation (1) is for phase q having $\vec{v}_q$ velocity for phase q, where $\dot{m}_{pq}$ represents the mass transfer from $p\ to\ q$ and S_q represents source term.

Momentum equation [14]:

$$\frac{\partial}{\partial t}\left(\alpha_q\rho_q\vec{v}_q\right)+\nabla\cdot\left(\alpha_q\rho_q\vec{v}_q\vec{v}_q\right)=-\alpha_q\nabla p+\nabla\cdot\bar{\bar{\tau}}_q+\alpha_q\rho_q\vec{g}$$
$$+\sum_{p=1}^{n}\left(\vec{R}_{pq}+\dot{m}_{pq}\vec{v}_{pq}-\dot{m}_{qp}\vec{v}_{qp}\right)$$
$$+\left(\vec{F}_q+\vec{F}_{lift,q}+\vec{F}_{wl,q}+\vec{F}_{vm,q}+\vec{F}_{td,q}\right)$$

where the above-mentioned momentum equation is also for phase q and $\bar{\bar{\tau}}_q$ is stress tensor of q^{th} phase.

$$\bar{\bar{\tau}}_q=\alpha_q\mu_q\left(\nabla\vec{v}_q+\nabla\vec{v}_q^{T}\right)+\alpha_q\left(\lambda_q-\frac{2}{3}\mu_q\right)\nabla\cdot\vec{v}_q\bar{\bar{I}}$$

where α_q is the volume fraction, μ_q is shear viscosity while λ_q represents the bulk viscosity of the q^{th} phase. $\vec{F}_q$, $\vec{F}_{lift,q}$, $\vec{F}_{wl,q}$, $\vec{F}_{vm,q}$, $\vec{F}_{td,q}$ represent the external body force, lift force, wall lubrication force, virtual mass force, and turbulent dispersion force respectively. $\vec{R}_{pq}$ represents the phase interaction between all phases and depends upon the cohesion forces, pressure, and frictional forces between phases. $\vec{v}_q$ denotes velocity of qth phase and $\vec{v}_{pq}$ denotes the interphase velocity. $\bar{\bar{I}}$ represents the unit tensor.

Energy equation [14]:

$$\frac{\partial}{\partial t}(\alpha_q\rho_q h_q)+\nabla\cdot\left(\alpha_q\rho_q\vec{u}_q h_q\right) = \alpha_q\frac{\partial p_q}{\partial t}+\bar{\bar{\tau}}_q : \nabla\vec{u}_q-\nabla\cdot\vec{q}_q$$
$$+S_q+\sum_{p=1}^{n}(Q_{pq}+\dot{m}_{pq}h_{pq}-\dot{m}_{qp}h_{qp})$$

where h_q represents the enthalpy of q^{th} phase, S_q represents the source term, Q_{pq} represents the heat intensity between p^{th} and q^{th} phases and $\vec{q}_q$ denotes heat flux of q^{th} phase while h_{pq} shows the interphase enthalpy.

2.2. Mass transfer model

A two-film theory based mathematical model, as suggested by Ahmed et al. [1] has been presented below. Mass transfer in venturi scrubber is diffusion-controlled and concentration difference is the only driving force [8]. A user-defined function was built based on the schematic (shown in Fig. 1) of the model proposed by Ahmed et al. [1].

In Fig. 1, d_d represents the droplet diameter calculated using Boll et al. correlation [6], Q_l represents volume flowrate of liquid into the venturi scrubber, Q_g is the volume flowrate of gas mixture, v_r is the relative velocity between liquid and gas at throat of venturi scrubber. Sc represents Schmidt number calculated using dynamic viscosity (μ_g) and density (ρ_g) of the gas mixture, and diffusion coefficient of iodine in gas (D_g). Re is the Reynolds number calculated using density and viscosity of the gas mixture, droplet diameter, and velocity of the gas mixture (v_g) at the throat of the venturi scrubber. Sh represents the Sherwood number which has been calculated utilizing Steinberger and Treybal correlation [15]. k_G is the diffusion coefficient calculated using the definition of Sherwood number. $\dot{M}$ is the mass transfer rate of iodine per unit volume for a single computational domain calculated using the formula developed by Ahmed et al. [1]. α_l is the volume fraction of liquid in a computational domain, C_{in} is the inlet concentration of iodine in gas mixture, and r_d is the radius of droplet. m represents the mass distribution parameter defined as follows

$$m = \frac{Equilibrium\ concentration\ of\ iodine\ in\ mixture\ of\ water}{Equilibrium\ concentration\ of\ iodine\ in\ mixture\ of\ air}$$

2.3. CFD simulations

CFD simulations were performed on the FLUENT module of ANSYS. Geometry details for a single venturi and dimensions were obtained from Ahmed et al. [1] as shown in Fig. 2. For this study, simulations were performed on two venturi scrubbers in series, where each venturi scrubber had the same dimensions as shown in Fig. 2. Geometry was modeled in ANSYS Design Modeler, whereas meshing was performed in the ANSYS Meshing module. The meshed geometry has been shown in Fig. 3.

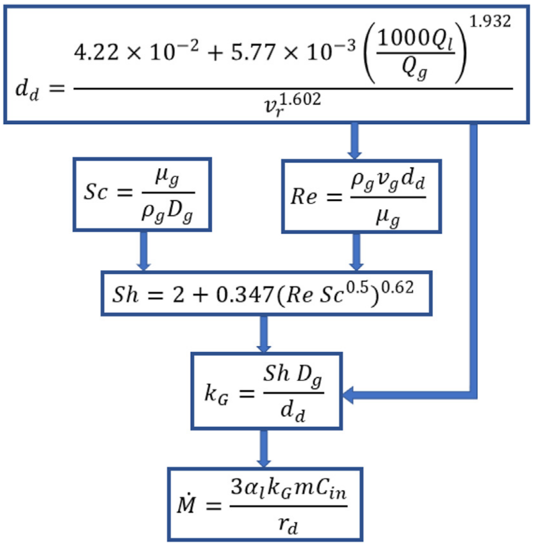


Fig. 1. Mass transfer model schematic [1].

The Eulerian model has been used for the multiphase modeling, the realizable $K - \varepsilon$ model for turbulence modeling, and the mass transfer model was coupled with ANSYS FLUENT using a user-defined function (UDF). For species transport, the air-iodine mixture has been selected as the primary phase, while, instead of 0.2% $Na_2S_2O_3$ and 0.5% NaOH solution, water has been selected as the secondary phase, because the flow physics of water and alkaline solution is similar.

The summary of the CFD settings has been mentioned in Table 1.

2.4. CFD model validation

The CFD model used for the study has been validated by comparison of the simulation results of a single venturi scrubber with the results published by Ahmed et al. [1]. The experiments were performed on a lab-scale setup where filtered air was passed through iodine sublimation chamber and the concentration of iodine in air was determined using iodine trap (containing 0.1 M KOH solution) just before inlet of venturi scrubber. A similar iodine trap was used at exit of venturi scrubber. The trap solutions were analyzed using UV–visible spectrophotometer to determine the concentration of iodine [1]. Fig. 4 shows that the simulated results are in good agreement with the experimental data and the maximum error is about 9.4%. Thus, it validates the model used in this work and shows that the simulated model is credible and reliable in representing the physics of the removal of iodine from the air mixture using a venturi scrubber.

2.5. Mesh independence study

Furthermore, to validate the CFD model of two venturi scrubbers in series, mesh independence study, has been performed by plotting iodine mass fraction along the length of two venturi scrubbers in series for different number of mesh elements. From Fig. 5, it can be inferred that simulations become mesh independent after 143168 elements. So, further results have been obtained at 143168 number of mesh elements. Convergence criteria of absolute residuals less than 10^{-5} has been used in these simulations.

3. Results and discussion

In this study, the removal efficiency of the venturi scrubber at lower gas flowrates has been improved by implementing a unique formation of two venturi scrubbers in series. The model was validated by benchmarking with experimental data and mesh independence study was performed which have been described in detail. To justify the improvement in removal efficiency of iodine from the air, a comparison has been made between the results of single venturi scrubber with the ones of two venturi scrubbers in series. Moreover, the comparison of two unique mass transfer models: (1) using the same droplet diameter at both venturi scrubbers in series, (2) different droplet diameter at each venturi scrubber, has been performed. The effect of different parameters such as gas flowrate and iodine inlet concentration on the removal efficiency, mass transfer rate, velocity, and pressure along the length of two venturi scrubbers have also been plotted and contours are presented to further elaborate the scrubbing phenomenon especially when two venturi scrubbers are stacked upon each other vertically.

3.1. Removal efficiency

Fig. 6 is a testimonial to the claim that using the unique formation of two venturi scrubbers in series (vertically stacked upon each other) has improved the removal efficiency by a margin of

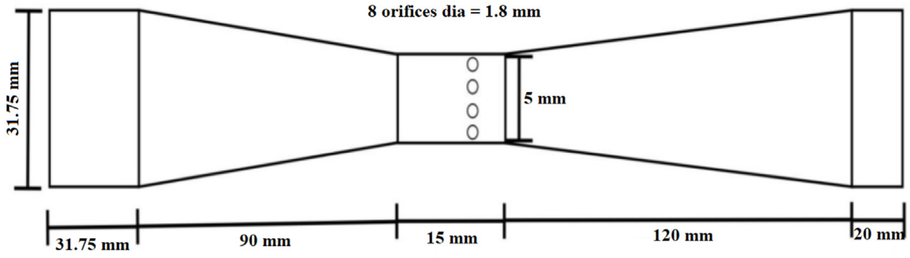


Fig. 2. *Geometric details of a single venturi* [1].

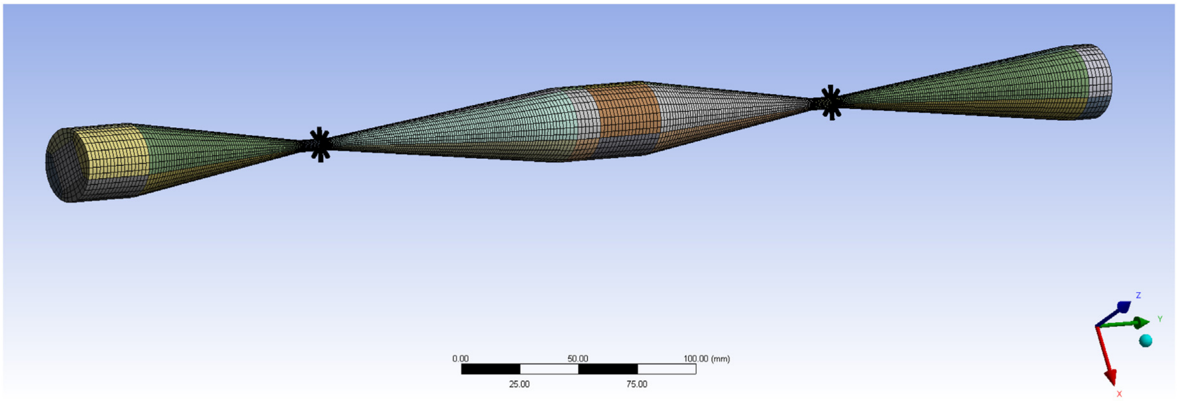


Fig. 3. Meshed domain of two-venturi scrubbers in series.

Table 1
Summary of CFD settings.

Multiphase Model	Eulerian-Eulerian Model
Mass Transfer Model	Iodine from Phase-1 to Phase-2 using UDF
Turbulence Model	Realizable $K-\varepsilon$ model
Primary Phase	Air-Iodine
Secondary Phase	Water-Iodine
Droplet Diameter of secondary phase	Boll et al. Correlation using UDF

The details of the boundary conditions are mentioned in Table 2.

approximately 8%–10%. When two venturi scrubbers are in series, the efficiency of the first and second venturi scrubbers combined is greater than single venturi scrubber at lower flowrates (5–6.5 m^{3}h^{-1}). In a submerged self-priming venturi scrubber, a water pool of a certain length is stacked above the venturi scrubber which results in more interaction between air and water when air is bubbling through the water column. Thus, it enhances the removal efficiency. Two non-submerged venturi scrubbers in series perform better at lower flowrates and provide an outstanding efficiency. As reported by multiple studies, with the increase in gas flowrates, the removal efficiency increases. So, at the lower gas flowrates, it is expected to obtain lower removal efficiency. Ali et al. performed submerged venturi scrubber experiments and reported the maximum efficiency of 99.5% but at a very high gas flowrate of 360 m^{3}h^{-1}. Goel et al. [16] also performed experiments for submerged venturi scrubber and reported the removal efficiency to be 95% but at a very high gas flowrate of around 204 m^{3}h^{-1}. Thus, at lower gas flowrates, obtaining 98.5% efficiency for the non-submerged venturi scrubbers is a remarkable achievement in itself. So, this work provides sufficient evidence to claim that the two-venturi scrubbers in series perform better at lower flowrates.

Table 2
Summary of boundary conditions in ANSYS FLUENT.

Venturi Scrubber Inlet	Mass flowrate of the air-iodine mixture
Venturi Scrubber Outlet	Outlet pressure
Orifices Inlet at first Venturi Scrubber	Inlet pressure
Orifices Inlet at second Venturi Scrubber	Inlet pressure
Walls of the Domain	No-slip condition

From Fig. 6, it can be seen that with two venturi scrubbers in series, with the same inlet concentration of iodine, the removal efficiency has been increased considerably. The reason may be that when two venturi scrubbers are stacked upon each other, the interaction between air and liquid droplets increases. Furthermore, in this model, the removal efficiency is very much dependent on the size of the liquid droplet formed, due to the introduction of water through orifices of the venturi scrubbers.

3.2. Droplet diameter

The diameter of a droplet is one of the most important parameters in the mass transfer model because smaller droplets will provide more total surface area for mass transfer and vice versa. It is considered that the secondary phase interacts with the primary phase both as a film and as droplets. The droplet diameter was represented by Sauter mean diameter as suggested by Alonso et al. and was calculated using Boll et al. correlation, as suggested by Ahmed et al. When the scrubbing solution enters through orifices at throat of venturi scrubber, high velocity air comes in contact with the liquid and disintegrates it into fine droplets. With the increase in the gas flowrate, the droplet size will decrease and with the increase in the water head, more amount of liquid flows through the orifices of the venturi scrubbers [5]. Thus, the liquid droplet size will decrease with flowrate of air and increase with an increase in the scrubbing solution pressure head [5,6].

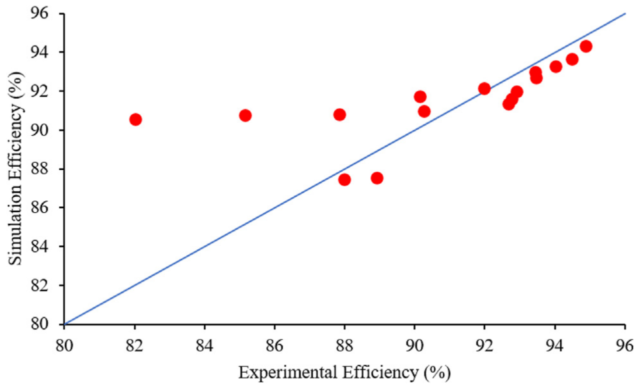


Fig. 4. Simulated data validation.

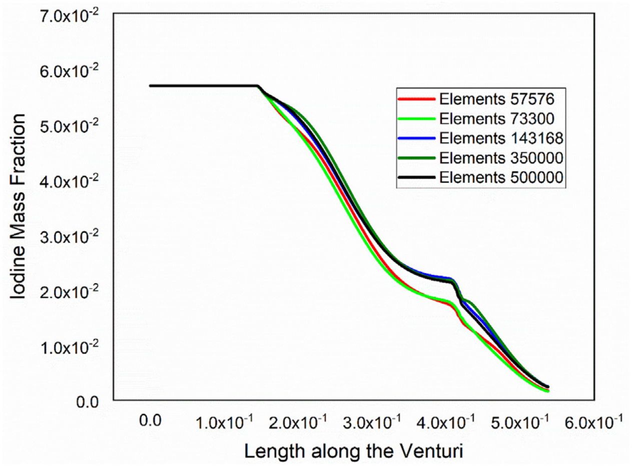


Fig. 5. Mesh independence study.

Droplet diameter depends upon the gas flowrate and the water head. So, when two self-priming venturi scrubbers are stacked upon each other vertically, there will be different droplet diameters at each venturi scrubber. Because of the difference between air velocities and water head at each venturi scrubber, the water flowrate will be different. In consequence, the size of the droplets at throat of each venturi scrubber will be different. In this work, the droplet diameters for different cases lie between 30 μm to 75 μm.

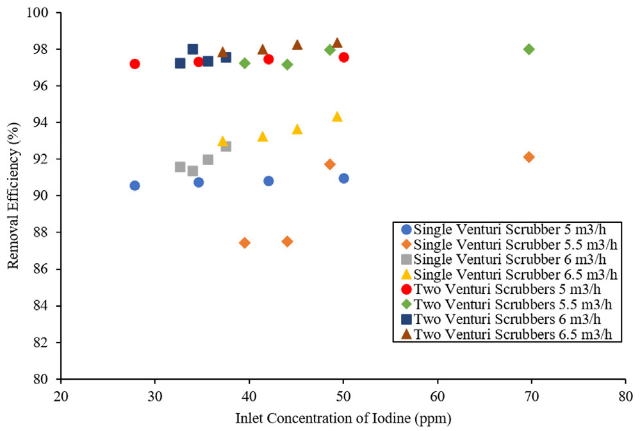


Fig. 6. Effect of concentration of iodine at inlet on removal efficiency of single and two-venturi scrubbers in series for multiple flowrates.

Two approaches have been opted to simulate the removal of iodine from the air using series configuration of self-priming venturi scrubbers; same size droplets at both venturi scrubbers and different size droplets at each venturi scrubber.

If same size of the droplets is considered at both venturi scrubbers, it will neglect the dependency of the droplet diameter on the gas flowrates and water heads for the second venturi scrubber. From Fig. 7, it can be seen that the iodine mass fraction is lesser along the length of the second venturi scrubber for different size droplets approach. And it shows that the removal efficiency will be higher if different droplet diameters are considered at each venturi scrubber. So, it is established that the different droplet diameter approach is better for simulating the removal efficiency of two self-priming venturi scrubbers in series. All the following results have been obtained by using the different-droplet diameter approach.

3.3. vol fraction of phases

Mass transfer between two phases also depends upon the volume fraction of phases in the region. From Fig. 8, it can be seen that water enters through the orifices of both venturi scrubbers and quickly disintegrates into droplets. Film formation can also be seen in the figure immediately downstream to orifices of the first and second venturi scrubbers. When high-speed air enters the throat section, some amount of incoming liquid is forced towards the inner wall section of the venturi scrubber. Film formation enhances the mass transfer because in this small region liquid phase is dominant and the difference of iodine concentration is very high, that's why, it is important to incorporate the effects of the film as well as droplets, as mentioned by Gamisans et al. [8].

3.4. Mass transfer of iodine

The process of mass transfer is considered to be diffusion-controlled, so, the only driving force is the concentration difference between iodine in two phases. So, the inlet concentration plays an important role in dictating the mass transfer between two phases. So, when the concentration difference is higher, more mass transfer will happen. Furthermore, it can be seen from Fig. 9, that the concentration difference between the two phases is large immediately downstream of the orifice region. That's why the mass transfer is dominant in that region. It can also be seen that the iodine mass fraction decreases drastically downstream of the orifices of the second venturi scrubber. There might be several reasons behind this phenomenon. The first one might be that the pressure differential at the orifice of second venturi scrubber is greater than the first one. So, more volume of water will pass through the second venturi scrubber's orifices, which will increase the interaction between phases, and hence mass transfer is increased. Also, the velocities are much higher at the second venturi scrubber's throat than that of the first one. So, the higher-velocity air will create finer droplets of water, which will also benefit the mass transfer.

The secondary phase is considered to interact with the primary phase both as film and as droplets. Film formation will further enhance the mass transfer, as described by Gamisans et al. [8]. Fig. 9 (b, c, d and e) show the zoomed sectional view of contours of mass fraction of iodine in air. From Fig. 9 (b and d), film formation and mass fraction contours show that amount of iodine is very small at the walls of the venturi scrubber immediately downstream of the throat section, a phenomenon discussed in detail by Ahmed et al. [1].

Mass transfer between two phases is dominant at the interface of phases interacting with each other. As the interfacial area increases, mass transfer increases. It has been established that finer atomization of the liquid phase will result in higher mass transfer. Also, according to the mass transfer model summarized in Fig. 1, the

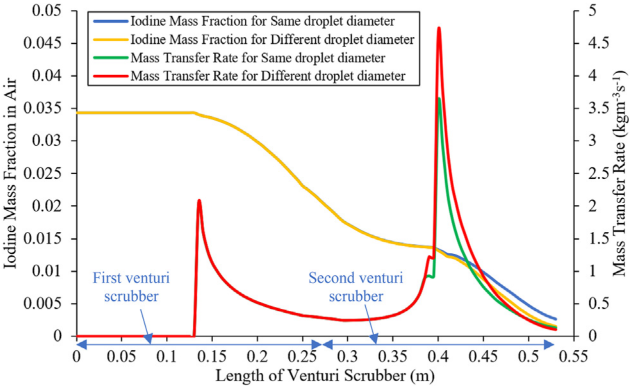


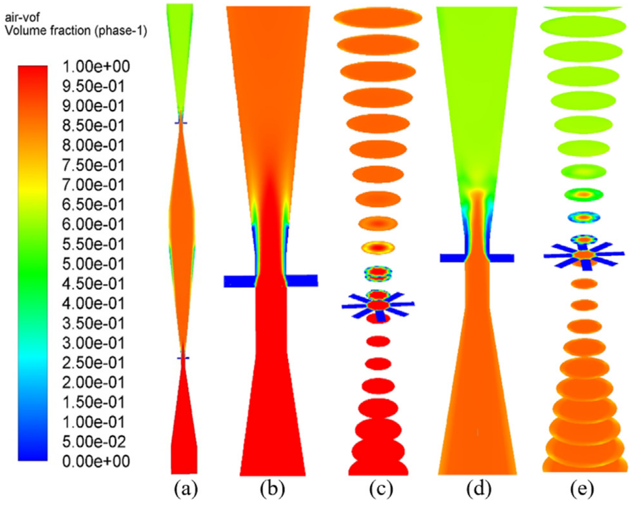
Fig. 7. Comparison between same droplet diameter approach and different droplet diameter approach for mass fraction of iodine in air and the mass transfer rate plotted along the axis of venturi scrubber.

mass transfer rate is inversely proportional to the diameter of the liquid droplets. Thus, by increasing gas flowrate, finer droplets are obtained and mass transfer is increased.

Fig. 7 shows that the mass transfer rate is higher downstream of the orifice of second venturi scrubber as compared to the orifice of first one. The reason for the higher mass transfer rate at the second orifice can be explained using the equation for mass transfer used in the model shown in Fig. 1. The mass transfer rate is inversely proportional to the size of the liquid droplets. Due to the much larger pressure differential observed at the orifice of the second venturi scrubber, the water flowrate is higher in the second venturi scrubber. Furthermore, at the second venturi scrubber, liquid droplets are smaller in size, that's why the mass transfer rate is more near the orifice of the second venturi.

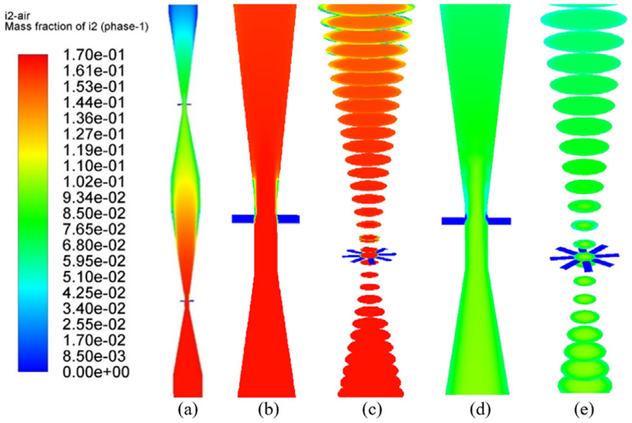
3.5. Variation of pressure and velocity

The plots of pressure and velocity provide the information to understand physics of the flow inside the venturi scrubbers and the effect of first venturi scrubber on the flow of second one. Fig. 10 shows pressure and velocity variation along the axis of venturi scrubber. The air-iodine mixture passing through the converging section the mixture is accelerated till the throat section. The pressure lost in the converging section is recovered in the diverging section. This mixture then enters the second venturi scrubber where same trend of pressure can be seen as in first one. It can be seen that at throats of both venturi scrubbers, there is reduced pressure which is driving force behind injection of water. But it can also be seen that there is lower pressure differential at throat of the second venturi scrubber which results in further increment in the flowrate of water through the orifices of the second venturi scrubber, and hence more mass transfer rate as seen in Fig. 7.



(a) (b) (c) (d) (e)

Fig. 8. Contours of volume fraction of air at (a) complete domain (b) zoomed view of first venturi scrubber (c) zoomed view of different cross-sections along first venturi scrubber (d) zoomed view of second venturi scrubber (d) zoomed view of different cross-sections along second venturi scrubber.



(a) (b) (c) (d) (e)

Fig. 9. Contours of iodine mass fraction in air at (a) complete domain (b) zoomed view of first venturi scrubber (c) zoomed view of different cross-sections along first venturi scrubber (d) zoomed view of second venturi scrubber (e) zoomed view of different cross-sections along second venturi scrubber.

It can be seen that at the throat region of both venturi scrubbers, there is a slight decrease in the slope and a sharp increase in the slope of the pressure curves. The reason is that after the converging section, a straight portion of the throat reduces the slope of the pressure curves. But a sharp increase in the slope and the peak is witnessed due to the introduction of water through the orifices of the venturi scrubbers, which results in a smaller area available for the mixture to pass through, as reported by Ahmed et al. [1]. So, an increase in the velocity will further reduce the pressure downstream of the throat. Also, it can be seen that velocity is higher at the second venturi scrubber. The behavior of velocity variation is opposite to that of pressure variation.

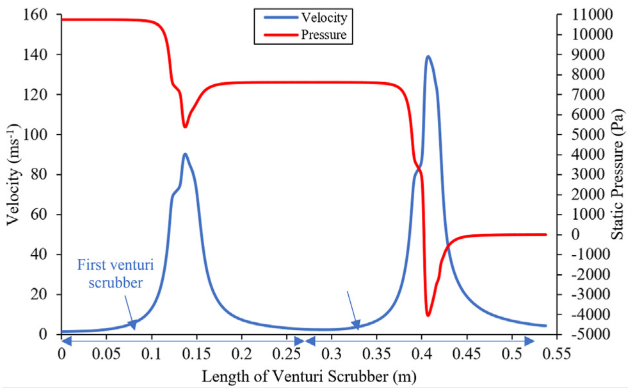


Fig. 10. Velocity and pressure variation along the length of venturi scrubbers.

4. Conclusions

This work extends the scope of the research about the removal efficiency of circular, non-submerged, self-priming venturi scrubbers, by introducing a unique formation of two venturi scrubbers in series (vertically stacked upon each other) to improve the removal efficiency. After validation of the model, it was implemented on the novel design of venturi scrubbers in series configuration, and removal efficiency has been reported. The effect of multiple gas flowrates on the mass fraction of iodine in air, mass transfer rate has also been reported. The effect of different gas flowrates and water heads, on pressure and velocities of two-venturi scrubbers in series, has also been plotted and explained. The following conclusions can be made based on this work:

- Two different approaches regarding the size of droplets have been opted and compared. From the comparison, it was established that a different droplet diameter at each venturi scrubber is a better and realistic approach for removal efficiency than the same size of droplets at both venturi scrubbers;
- Removal efficiency has been found to be improved by a margin of 10%, using two venturi scrubbers in series;
- The maximum removal efficiency found for the presented novel configuration is 98% at lower flowrates of 5–6.5 m^3h^{-1};
- Removal efficiency and mass transfer rate increases with the increase in the gas flowrates for two venturi scrubbers in series;
- A decrease in the droplet size of the liquid phase will increase the removal efficiency of the two venturi scrubbers in series.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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