Experimental Study of Iodine Removal Efficiency in Self-Priming Venturi Scrubber

A.D.Landge

Department of Mechanical Engineering, SVERI's College of Engineering, Pandharpur Maharashtra, India.

Email id:amarnathlandge@gmail.com

Abstract:

The objective of present experimental study is to examine the iodine removal efficiency of a self-priming venturi scrubber for submerged operating condition. The venturi scrubber is used in Containment Filtered Venting System of Nuclear Power Plants to remove the gaseous pollutants from contaminated gas during severe accidents. The experiment consists of mixing the iodine vapours with the air using suction venturi and pressure cooker system. The purpose of iodine mixing with air is to examine scrubbing performance of the designed venturi scrubber with water as scrubbing liquid. The performance parameters of venturi scrubber are expressed mainly in terms of pressure drop and iodine removal efficiency. The iodine removal efficiency of venturi scrubber is estimated for a series of two experiments by measuring the quantity of iodine in water from iodometric titration with four distinct pH of water. It has been experimentally observed that iodine removal efficiency is improved by using higher pH value of scrubbing liquid since solubility of iodine gets improved at higher pH.

Keywords: Iodine removal efficiency, Iodometric titration, Nuclear Power Plant, Venturi Scrubber.

Introduction:

In the severe accident of nuclear power plant (NPP), the fission products are released from the molten core into the containment. Among many of the radioactive fission products released during an accident, the radioactive iodine I-131 is a major constituent that has significant impact on the environment and human health. Radioactive iodine I-131 has a short half-life of eight days. It accumulates in the thyroid gland of human body and increases the risk of thyroid cancer. Radioactive I-131 can enter human body via contaminated water, milk or air. To mitigate the level of contamination, Containment Filtered Venting System (CFVS) is installed in NPP. A venturi scrubber is one of the most competent devices to collect the particulate matter and gaseous pollutants from a gas stream simultaneously in CFVS. A venturi scrubber consists of three main parts: a converging section, a throat section and a diffuser section. The converging section is used to accelerate gas for atomizing the scrubbing liquid. The throat part is in between convergent and diffuser, which is used for interaction of liquid and gas. The diffuser is used for deceleration of gas to allow some pressure recovery. The goal of conducting this experimentation is to study the iodine removal efficiency in a self-priming venturi scrubber. For this purpose, venturi scrubber is designed and used to scrub the air stream (which contains iodine vapours) with water as the scrubbing liquid. The design of venturi scrubber used for the present study is as shown in Fig. 1 and the venturi scrubber which is machined from acrylic block is shown schematically in Fig. 2.

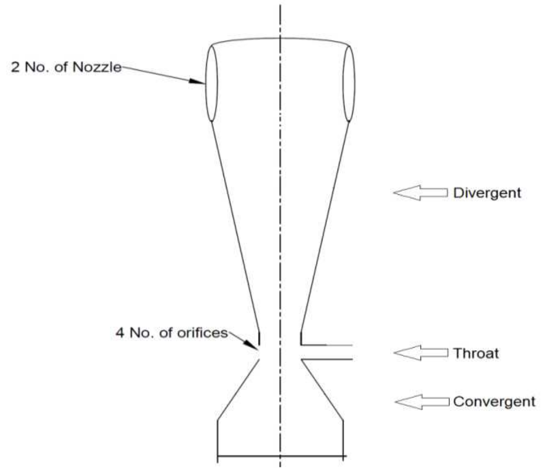

Fig. 1: Schematic of venturi scrubber

Fig. 2: Venturi Scrubber machined of acrylic material

Experimentation: Mechanism of Removal Phenomenon in Venturi Scrubber

The iodine removal phenomenon in venturi scrubber is affected by several mechanisms, viz.: an inertial impaction, interception, diffusion, electrostatics, condensation and the growth followed by nucleation. The iodine removal contribution of above mechanisms depends on size of particle, droplet and their relative velocity. The mechanism of inertial impaction is the governing mean of capturing the larger size particles while the other mechanisms are weak in comparison. Many investigators suggested that the inertial impaction is the most suitable mechanism for removal phenomenon. Therefore the present experimentation focuses on the approach of inertial impaction.

Fig. 3 shows the removal phenomenon in venturi scrubber due to atomization of scrubbing liquid. When the high speed air stream passes through the throat of venturi scrubber, air provides the suction of liquid water due to low pressure. The liquid water enters into the venturi scrubber due to pressure difference between inside and outside of venturi throat. The pressure difference is created as a result of static pressure of air and hydrostatic head of liquid water in scrubber unit. Due to impaction of high speed air, the liquid water is disintegrated into tiny droplets. These droplets travel along with the air stream and interact with the iodine particles present in it. During this interaction, the droplets pick up the iodine particles from air stream and further coalesce into larger droplets. The whole mixture then comes out from the venturi outlet nozzles (refer Fig. 3.) and mixes with the water present inside the bubbler tank. In this way the absorbed iodine in the form of droplets is collected in water, and clean air (scrubbed air) exits through vent stack.

Fig. 3: Removal phenomenon in Venturi Scrubber due to atomization of scrubbing liquid

Experimental Setup:

Fig. 4 depicts the experimental setup for experimentation of the self-priming venturi scrubber to analyze the removal efficiency of iodine. The arrow head pointing towards the enlarged view in Fig.4 shows the provision made in the experimental facility for mixing of iodine vapours with air stream.

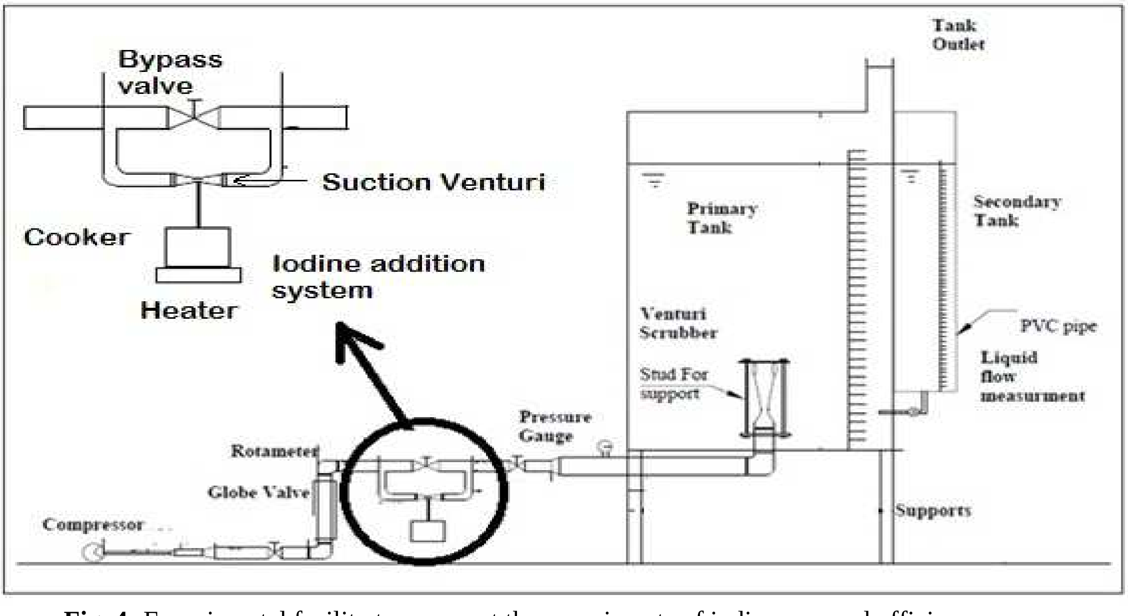

Fig. 4: Experimental facility to carry out the experiments of iodine removal efficiency

The experimental setup consists of several apparatus for effective functioning. The several components and their locations in experimental setup are mentioned in the Table 1. The primary bubbler tank of 3m heights is provided with the necessary sampling ports to collect the water samples. The overflow lines at four different locations of tank (1.0 m, 1.5 m, 2.0 m, 2.5 m) are also provided to collect the overflow of water. A venturi scrubber is kept submerged into the water present inside the bubbler tank. Compressed air from compressor is received at suitable pressure which is maintained at required starting system pressure using air pressure regulator. The regulator outlet pressure is observed within 0.7-1.25 kgf/cm2 and to maintain this pressure the flow rate is adjusted accordingly. The mixing of iodine vapours into the air stream is done by using suction venturi and bypass valve (as shown in enlarged view of Fig. 4).

Table 1: Details of apparatus in the experimental setup

Sr. No.	**Apparatus**	**Functions**	**Position in the experimental setup**
1.	Compressor	To compress the air.	-
2.	Pressure regulator	To adjust the required system pressure.	Next to compressor.
3.	Globe valve	To control the volumetric flow rate of air.	Prior to rotameter.
4.	Rotameter	To meter the volumetric flow rate of air.	After the globe valve.
5.	Suction Venturi	To suck the iodine vapours.	Between the bypass line.
6.	Pressure cooker	To store the iodine flakes.	Connected to suction venturi via connection lines.
7.	Pressure gauge	To read the pressure at the inlet of venturi scrubber.	Prior to Venturi scrubber.
8.	Bypass valve	To divert the flow of air stream through suction venturi.	Parallel to suction venturi.
9.	Needle valve	To control the quantity of iodine.	In the connection line.
10.	Venturi Scrubber	To scrub or clean the air.	Inside the primary tank.

The experimental setup is divided into two different configurations for carrying out two different experimental studies.

Configuration I

Fig.5 shown below depicts layout of the configuration I of experimental setup in which interconnecting plate is mounted inside the tank at 700 mm distance from bottom of primary tank. The interconnecting plate separates the primary tank into two parts such that outlet of venturi scrubber is connected to upper part of tank and secondary tank is connected to lower part of primary tank at throat. Following parameters are determined from the Configuration I.

i. L/G ratio: The rate of liquid flow is an important parameter in wet scrubbing systems. It is common in wet scrubber terminology to express the liquid flow as a function of the gas flow rate. For particulate removal, the L/G ratio is a function of the mechanical design of the system; however for gas absorption this L/G ratio gives an indication of the difficulty of removing a pollutant. In this experiment, liquid flow rate is estimated by collecting and measuring the quantity of water coming out from overflow line for a specific time period. The flow rate of the air in the main system is controlled through the globe valve and is measured by rotameter.

ii. Pressure drop across venturi scrubber: Bourdon pressure gauge is used to measure the inlet pressure to the venturi scrubber. The hydrostatic pressure is developed due to the presence of water level above diffuser outlet in the tank. Outlet of the tank is open to atmospheric pressure. The pressure drop across venturi scrubber is obtained using the formula given below.

    Pressure drop across venturi scrubber = Inlet pressure to venturi scrubber - pressure due to water level in tank above venturi outlet.

Configuration II

Both interconnecting plate and secondary tank are removed from Fig. 5. Following parameters are determined from Configuration II

i. Iodine removal efficiency: By measuring concentration of iodine in air stream at inlet and outlet, iodine removal efficiency of venturi scrubber can be calculated.
ii. Pressure drop across venturi scrubber: It is same as explained earlier in Configuration I.
iii. Pool swelling: It is the study of swelling of water pool inside the bubbler tank because of increase of diameter of bubble of air. The Fig. 6 depicts the pictorial view of pool swelling during the experimentation.

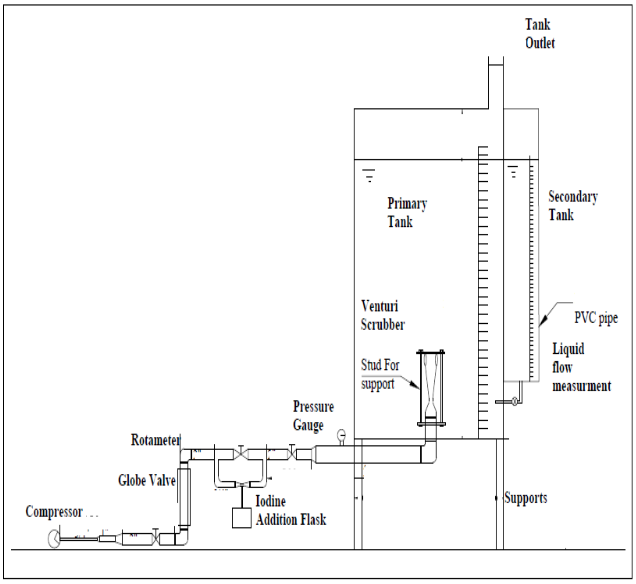

Fig. 5: Experimental setup prototype (Configuration I) **Fig. 6:** Pool swelling Effect

Experimental Procedure and Methodology:

The major issue in the experiment was how to mix the iodine into air stream. As only iodine vapours can mix with air, so to sublimate iodine, a provision is made for heating it to its sublimation point and then to suck the formed vapours through proper channel. For the same purpose pressure cooker with heater is used and two different extension lines are provided for pressure cooker: pressurization line and suction line (refer Fig. 7). Pressurization line is provided for the necessary pressure requirements to suck the vapours through suction venturi. In the suction line a needle valve is used to control the quantity of iodine vapours during suction process. The lines are made transparent to view the status of online suction process. The bypass valve, in parallel with the suction venturi diverts the flow path of air stream through suction venturi (refer Fig. 8).

Fig. 7: Pressure cooker with heater **Fig. 8**: Bypass valve in parallel with suction venturi

A known amount of iodine flakes is taken into the pressure cooker and heated to its sublimation point to form iodine vapours. These vapours are sucked into air stream by using bypass valve and suction venturi. The time span kept for this process is 30 minutes to ensure all the sublimated iodine is transferred into air stream. Fig. 9 shows the residual of iodine at the end of 30 minutes

Fig. 9: Residual of iodine in Cooker (After 30 minutes) **Fig. 10:** Samples of water collected for testing

Two experiments are performed using distinct pH of water and the quantity of trapped iodine in water is measured through iodometric titration. To standardize sodium thiosulphate ($Na_2S_2O_3$) solution, a solution of potassium dichromate ($K_2Cr_2O_7$) of normality 10 N (Normal) is used. This standardization is an example of iodometric titration in which the normality of unknown solution like $Na_2S_2O_3$ is determined by titrating it with the standard solution like $K_2Cr_2O_7$. When $K_2Cr_2O_7$ is treated with dil. H_2SO_4 (Sulphuric acid), nascent oxygen is liberated with the formation of potassium sulphate (K_2SO_4) and chromic sulphate ($Cr_2(SO_4)_3$). This reacts with KI solution and liberates the iodine which is then treated with $Na_2S_2O_3$ solution. Starch is used as an indicator. The following chemical reactions occur at the time of standardization.

Chemical Reactions:

$$K_2Cr_2O_7 + 4H_2SO_4 \longrightarrow K_2SO_4 + Cr_2(SO_4)_3 + 4H_2O + 3[O]$$
$$6KI + 3H_2SO_4 \longrightarrow 3K_2SO_4 + 6HI$$
$$6HI + 3[O] \longrightarrow 3I_2 + 3H_2O$$
$$2Na_2S_2O_3 + I_2 \longrightarrow Na_2S_4O_6 + 2NaI$$

In the experiment, some part of iodine is transferred from air stream into the water and its presence is observed with water colour changing to reddish. Solubility of iodine is very less (0.34 gm/L) in neutral water. To increase its solubility, around 10 to 12 gms of KOH are used to increase pH of water. The iodine mixing is carried out for two different cases: i) with the neutral water of pH 7 ii) with basic water of pH 8, 9, and 10. Therefore, two different samples of water containing iodine are collected in the sampling bottles from sampling ports as shown in Fig. 10. The result of starch test (which produces blue colour solution with the water samples without KI and produces black colour solution with KI) is as shown in Fig. 11. To examine the presence of iodine in both the samples is the main objective of starch test.

Next part in this experiment is the estimation of amount of iodine present in water samples. To estimate iodine in water samples the iodometric titration is performed at the chemical laboratory. The first sample (neutral) of water is titrated against 0.001N sodium thiosulphate solutions using freshly prepared starch as an indicator to get the end point reading. Similarly, the second sample of water (pH 10) is titrated against 0.005N silver nitrate solution using potassium chromate (5%) as an indicator to get the end point reading. The obtained readings and data are further used to calculate iodine removal efficiency of designed venturi scrubber.

Fig. 11: Starch test of the water sample

Results:

From the experimentation it is found that the present venturi scrubber is able to remove only 41-66% of the iodine particles from the air. The results presented herein shows much less efficiency could be reached, the reason behind this is explained as below:

The efficiency is low because of extremely low solubility of iodine in water and to some extent it is observed that the un-necessary deposition of iodine within the system which is responsible for reducing the quantity and hence the measurement. The requirement for the iodine removal efficiency of Containment Filtered Venting System in nuclear power plant is not less than 99%. The lower efficiency in the present work may be due to several possible uncertainties, such as limited solubility of iodine into water, accuracy of methods used for the measurement and incomplete mixing of vapours due to surface deposition of iodine particle inside the pipelines. The Table 2 given below illustrates the results of the experimental study on iodine removal efficiency. Increasing the pH level of water takes it far away from the neutral behavior, because of which solubility of iodine gets improved to some extent that leads to improve increase in iodine removal efficiency.

Table 2: Iodine removal efficiency of venturi scrubber

Sr. No.	pH of water inside the tank	Quantity of iodine in the cooker before starting of experiment (gm)	Quantity of iodine in the cooker after experiment is over	Quantity of iodine found in 10 ml of water sample by iodometric titration (gm)	Total volume of water in the tank (litre)	Total quantity of iodine in tank water (gm)	Iodine Removal Efficiency (%)
1	7.0	20	Nil	0.0002538	325	8.2485	41.24
2	8.0	20	Nil	0.0002918	325	9.4857	47.42
3	9.0	20	Nil	0.0003299	325	10.7030	53.61
2	10.0	10	Nil	0.0004415	150	6.6623	66.62

The pressure drop across the venturi scrubber is analyzed with respect to three different mathematical models: Boll's model, Volgin's model and Hesketh's model. As inertial impaction plays a key role in the success of venturi scrubber, experiments performed with high pressure drop across venturi scrubber can provide better optimization of its performance. The Table.3 gives the comparative experimental and theoretical results of pressure drop.

Table 3: Comparison of experimental and theoretical results of pressure drop across the venturi scrubber

Experimental Pressure Drop (kgf/cm2)	**Theoretical Pressure Drop (kgf/cm2)**		
	Volgin's model	Boll's model	Hesketh's model
0.08 - 0.14	0.04 – 0.19	0.02 – 0.05	0.03 – 0.32

The pressure drop study reveals that, the theoretical models shows agreement within the range of experimental pressure drop but with deviations. In case of Boll's model and Hesketh's model, the pressure drop across the venturi scrubber is rather different from the models prediction due to assumptions in theoretical model and several uncertainties in the experimentation. Therefore, Volgin's model is preferred to validate the results for present work.

Conclusions:

An experimental study of iodine removal efficiency in self priming venturi scrubber has been carried out successfully. This study holds many advantages for the demonstration work on predicting solubility of iodine in water and its pH dependency. The results of this study present the practical situation of containment removal phenomenon and it can be extended for simulation work based on various scrubber geometries. Although this work is limited to titration method, other methods such as High Performance Liquid Chromatography (HPLC), Ultraviolet (UV) chromatography can also be used for the measurement of iodine concentration. The results are obtained for four different pH levels of water, i.e. neutral water of pH 7 and basic water of pH 8, 9 10. The maximum iodine removal efficiency is obtained for water of pH 10. Therefore, it can be concluded that venturi scrubber removes iodine more efficiently when scrubbing liquid has a high pH value since solubility of iodine improves at higher pH value. The pressure drop study reveals that, the theoretical models shows agreement within the range of experimental pressure drop with deviations. These deviations may be due to instrumental error and measurement technique. However, results of pressure drop obtained using Volgin's model are more accurate towards the experimental value. Thus, Volgin's model is preferred to validate the results for present work.

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