Design & Fabrication of a Venturi Scrubber system for Decontamination of Particulate Matter

By

Muhammad Umair Qazi

Moatasim Farooque

Ali Faizan Wattoo

Supervised By

Abdul Naeem Khan

School of Mechanical and Manufacturing Engineering

National University of Sciences & Technology

Islamabad, Pakistan

June 2017

Design & Fabrication of a Venturi Scrubber system for Decontamination of Particulate Matter

---

A final year project report

Presented to

SCHOOL OF MECHANICAL AND MANUFACTURING ENGINEERING

Department of Mechanical Engineering

NUST

ISLAMABAD, PAKISTAN

In Partial Fulfillment

of the Requirements for the Degree of

Bachelors of Mechanical Engineering

---

by

Muhammad Umair Qazi

Moatasim Farooque

Ali Faizan Wattoo

JUNE 2017

ABSTRACT

Design of a system aimed to purify industrial gases from particulate matter. A detailed analysis of the factors that determine and contribute towards the design of a typical venturi scrubber was performed. Incorporation of modern engineering software for performance enhancement and optimization of efficiency curves. The design techniques for the development of a scaled-down model of an industrial scale Venturi Scrubber were utilized specifically targeting cement industries. Extensive use of fluid mechanics and thermodynamics was involved in addition to the empirical studies carried out in the previous research work. The device is theoretically capable of 95% efficiency that is against particulate matter there is only 5% chance that particulate matter will be deposited in the atmosphere. Our design achieved an overall efficiency of 90.50%.

Our research and experimental findings will help extend the research in the field. These studies can be carried further into other areas targeting other pollutants and contaminants in other industries. Our data can serve as guidelines for the incorporation of these devices into the modern industries and provides for the quantification in reference to efficiency and particulate emissions. Furthermore, the results and trends in the form of empirical data, can be helpful for the industries in order to design a Venturi Scrubber of specific requirements. This will help industries tailor their emissions according to the safe-limits set by EPA, economically and efficiently.

PREFACE

We, as final year students at SMME, NUST are required to design & manufacture a project in order to complete our four-year degree program. The project must not only bring economical value to the industry but also has a wide scope in order to address problems faced by our society.

World today is facing environmental threats due to pollution and contamination mainly as a result of global industrialization. We three members, due to our common concern for the cause, decided to team up the skills and knowledge we have gained in these years in order to address the contamination of particulate matter in the Earth's atmosphere due to the industrial emissions.

The main focus of our work was to develop and study a scrubber system.

In spite of a narrower time window and limited financial resources, we still managed to design, manufacture and then derive the results through experimentations.

This project report aims to encompass all the aspects of our work on the project. At the end of the report we have tried to summarize our results through data tabulation and graphical plots too.

Nonetheless, there is a room for a lot of improvements which have also been proposed at the end. It was a great pleasure to work on such an impactful project.

ACKNOWLEDGMENTS

We are grateful to the faculty of SMME as a whole for providing us with the resources required for the completion of the project specifically Head of Department Mechanical Dr. Khalid Akhtar.

We and our project is highly indebted to the efforts put out by our Supervisor Dr. Abdul Naeem Khan and Co-supervisor Dr. Emad Uddin. They were present with us at every step for guidance and motivation. They advised us frequently about the different approaches and methods and offered honest remarks about improvement where ever it was necessary.

None of this would have been possible without the constant and timely efforts of our fabricator Mr. Shahid. His role extends beyond that of just manufacturing of the product. He recommended numerous design modifications keeping in view the practicalities involved in the actual manufacturing procedure.

We would like to highlight the welcoming environment of “Air Engineering” and “DG Cements” for providing us with the detailed specification of industrial scale scrubbers and sharing real-time pollution data in their industry.

ORIGINALITY REPORT

Design & Fabrication of a Venturi Scrubber system for Decontamination of Particulate Matter

ORIGINALITY REPORT

15%	13%	11%	6%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	www.scielo.br Internet Source	2%
2	Ali, Majid, Changqi Yan, Zhongning Sun, Haifeng Gu, and Khurram Mehboob. "Dust particle removal efficiency of a venturi scrubber", Annals of Nuclear Energy, 2013. Publication	1%
3	www.engr.sjsu.edu Internet Source	1%
4	www.esciencecentral.org Internet Source	1%
5	www.epa.gov Internet Source	1%
6	Cheremisinoff, . "Gas Cleanup Technologies", Chemical Industries, 2005. Publication	1%
7	Submitted to Universiti Teknologi Petronas Student Paper	1%

8	Submitted to University of Wolverhampton Student Paper	1%
9	Submitted to University of Central Oklahoma Student Paper	1%
10	etd.lsu.edu Internet Source	1%
11	www.krishisanskriti.org Internet Source	1%
12	Desai, R., and Omprakash Sahu. "Study of Venturi Scrubber Efficiency for Pesticide Industry", International Letters of Natural Sciences, 2014. Publication	<1%
13	"Venturi Scrubber", Pollution Control Handbook for Oil and Gas Engineering, 2016. Publication	<1%
14	gravel-machine.com Internet Source	<1%
15	www.pollutioncontrolequipments.com Internet Source	<1%
16	www.4cleanair.org Internet Source	<1%
17	Ali, Majid, Changqi Yan, Haifeng Gu, Khurram Mehboob, and Athar Rasool. "Removal	<1%

Efficiency of Iodine at Saturated Steam in Submerged Venturi Scrubber", Volume 3 Next Generation Reactors and Advanced Reactors Nuclear Safety and Security, 2014.
Publication

18	www.scribd.com Internet Source	<1%
19	Submitted to University Of Tasmania Student Paper	<1%
20	P SJOHOLM. "Gas-cleaning technology", Industrial Ventilation Design Guidebook, 2001 Publication	<1%
21	Submitted to EDMC Student Paper	<1%
22	doras.dcu.ie Internet Source	<1%
23	Zarei, S.. "PVC dust removal from the air by a new dynamical scrubber", Chemical Engineering & Processing: Process Intensification, 201011 Publication	<1%

EXCLUDE QUOTES ON
EXCLUDE BIBLIOGRAPHY ON
EXCLUDE MATCHES OFF

COPYRIGHT

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

FYP	**Final Year Project**
PM	**Particulate Matter**
EPA	**Environmental Protection Agency**
AC	**Alternating Current**
DC	**Direct Current**
RPM	**Revolutions Per Minute**
CAD	**Computer Aided Design**
QTY	**Quantity**
PKR	**Pakistani Rupee**
cmA	**Centimeter Area**

NOMENCLATURE

η	Efficiency
d_{ps}	Mass Median Particle size
ρ_p	Particle Density
μ_g	Gas Viscosity
ρ_g	Gas Density
Q_g	Gas Flow Rate
T_g	Temperature of the Gas
T_l	Water Temperature
ρ_l	Liquid Density
L/G	Liquid-to-Gas Ratio
D_{pg}	Particle Aerodynamic Geometric Mean Diameter
P_t	Penetration
K_{pg}	Inertial Impaction
D_d	Droplet Diameter
V_{gt}	Throat Velocity
L_t	Throat Length
A_t	Throat Area
C_c	Cunningham Slip Correction Factor

CHAPTER 1

INTRODUCTION

Keeping in view the prevalent environmental issues in the world we decided to based our project to solve the problems. We felt like no significant procedure has been adopted for the removal of particulate matter in Pakistan. We specifically targeted cement industry and developed a scale down model of the actual product that can then be properly scaled and implemented in any cement industry. A Scrubber is any device that is used to remove contaminants from a stream of flue gases.

Our area of concern is particulate matter so the best scrubber is venture scrubber in this domain. It uses a Converging-Diverging Nozzle setup. Flue gases containing dust (Cement Dust in our case) enter the converging section and are accelerated to a high velocity in the throat region. Water is sprinkled in this region. High velocity gases shear through the liquid along the walls of the section and cause atomization. The water is now present in a droplet form and captures the incoming particles by inertial impaction. The stream continues along the diverging section where pressure and velocity is regained. It is then transported to a cyclone separator where water droplets containing particles are removed by centrifugal principal and clean stream is discharged.

The designed product is theoretically capable of 95%.

Need

Ever since the dawn of industrial revolution the world is facing severe environmental deterioration. The $C0_2$ levels have risen well above the safe-limits set by environmental organizations and are enough to cause massive changes at global scale. Global warming and climate change have become an undisputed fact in scientific circles. According to a Report from the UN Office for the Coordination of Humanitarian Affairs (OCHA):

"Climate disasters are on the rise. Around 70 percent of disasters are now climate related – up from around 50 percent from two decades ago." [1]

In Pakistan too the situation is graver than ever. Industries are brazenly allowed to emit their hazardous waste into the air unchecked. Apart from the global changes environmental effects have begun to adversely harm our daily routine jobs. Visibility in big cities is getting lesser each year. Smog outbreaks are happening more frequently. Respiratory problems are on the rise. In short every sort of Flora and Fauna is being affected. We felt like no significant procedure has been adopted for the control of pollution activities in modern industries and no quantified emission database is available that can then be compared with the allowed values.

Major Cities of Pakistan have PM contamination above the safe standards set by EPA.

Table 1 -- WHO AAP Database (May 2016)

WHO AAP Database (May 2016)			
COUNTRY	**CITY/TOWN**	**ANNUAL MEAN µg/m³**	**YEAR**
Pakistan	Islamabad	217	2011
-	Karachi	290	2009
-	Lahore	198	2010
-	Peshawar	540	2010
-	Rawalpindi	448	2010

Keeping in view the prevalent environmental issues in the world we decided to based our project to solve these problems.

Scope

The scope of our project can be summarized by the following points

- Our project encompasses the utilization of wide range of interdisciplinary core mechanical fields and their merger with environmental and energy engineering including Thermodynamics, Fluid, Materials, Manufacturing and Mechanical Design
- Scale Down Model of the system, demonstrating the experimental setup in order to verify the theoretical results, through empirical data collection and interpretation
- The main target Industries are – Coal Power Plants, Brick Kilns, Incinerators, Biomass Energy Plants, Cement and Metal Processing

Focus

We specifically targeted cement industry and developed a scale down model of the actual product that can then be properly scaled and implemented in any cement industry. A Scrubber is any device that is used to remove contaminants from a stream of flue gases. Our area of concern is particulate matter so the best scrubber is venturi scrubber in this domain. It uses a Converging-Diverging Nozzle setup.

What are scrubbers? [2]

Scrubber systems are a diverse group of air pollution control devices that can be used to remove some particulates and/or gases from industrial exhaust streams.

Types of Scrubbers

1- Wet Scrubbers

2- Dry Scrubbers

3- Absorbing Scrubbers

Why use scrubbers?

Industrial exhaust emissions consist of gases and particulate matter which if not removed and disposed properly may cause harmful effects to the organisms as well as to the environment. In order to regulate these emissions different regulatory bodies operate in order to ensure environmental protection by setting emission standards. All industries are bound to limit their emissions within the standards in order to keep operating. Scrubbers are one of the pollution control devices that help these industries to control their emissions.

Why Venturi Scrubbers?

Venturi scrubber is the most commonly used scrubber for particle collection and is capable of achieving the highest particle collection efficiency of any wet scrubbing system (upto ~99%)

• As we aim to collect particulate matter of size of around 10 micrometers (PM10) out of the industrial exhaust emissions efficiently, so venturi scrubber is the best option of all the scrubbers due to its highest PM collection efficiency

• Gas-atomization is required for removal of fine-sized particles which can only be achieved at very high speeds. Venturi scrubber is perfect for the case [3]

Aims and Objectives

The goal of the project is to design and implement a low-cost, scaled down model of a venturi scrubber system for effective and efficient removal of particulate matter from the industrial exhausts, in order to comply with the environmental emissions standards. The project aims to collect the empirical data through the testing and experimentation on this physical system model in order to study the factors affecting the efficiency of a Venturi Scrubber System.

Following are our main aims for this project:

- Scaling down an industrial scale venturi system
- Benchmarking with theoretical calculations

- Comparison of our product with benchmark values and those obtained through industrial data & Experimental validation
- Removal of Particulate matter ranging from *10-40µm*

Value to Industry

Ours is an industry oriented project. Our project complements the following benefits to the industry:

- The project aims to produce empirical data based upon the real industrial exhaust conditions that can prove valuable to the prospective industries, in the application of venturi scrubber.
- Our project provides an economical solution to the process industries especially cement, chemical industries.
- Industries can comply with environmental standards & regulations by reducing their PM emissions using this system

Value to the Society

We are addressing a real-life problem that affects the society as a whole from a global perspective. For the global community we bring the following to the table:

- Reduction in the emissions from industries thus avoiding the contamination of public air space within safe limits
- Reduction in Respiratory problems often caused by PM contaminants

Basic Principle

Flue gases containing dust (Cement Dust in our case) enter the converging section and are accelerated to a high velocity in the throat region. Water is sprinkled in this region. High velocity gases shear through the liquid along the walls of the section and cause atomization.

The water is now present in a droplet form and captures the incoming particles by inertial impaction.

The stream continues along the diverging section where pressure and velocity is regained.

It is then transported to a cyclone separator where water droplets containing particles are removed by centrifugal principal and clean stream is discharged.

The designed product is theoretically capable of 95%.

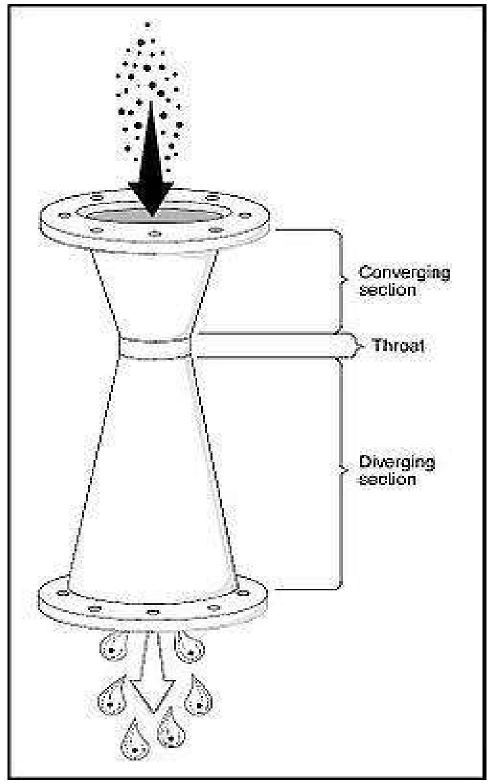


Figure 1 -- Venturi Scrubber -- Sections

CHAPTER 2

LITERATURE REVIEW

We started our research by studying research papers, thesis and taking into account empirical data available from industries and the standards issued by EPA.

Following is a comparison between the constituents of Pure Air and a Polluted Atmosphere. [4]

Table 2 -- Comparison of Pure Air & Atmosphere

A Comparison of Pure Air and a Polluted Atmosphere

Component	Considered to Be Pure Air	Typical Polluted Atmosphere
Particulate matter	10–20 μg/m³	260–3200 μg/m³
Sulfur dioxide	0.001–0.01 ppm	0.02–3.2 ppm
Carbon dioxide	300–330 ppm	350–700 ppm
Carbon monoxide	1 ppm	2–300 ppm
Oxides of nitrogen	0.001–0.01 ppm	0.30–3.5 ppm
Total hydrocarbons	1 ppm	1–20 ppm
Total oxidant	0.01 ppm	0.01–1.0 ppm

In our project, the particulate matter is the object of concern. According to the recent studies our cities that house major industries have particulate matter well above that considered safe for atmosphere. PM_{10} particles are shown in comparison to the pollution caused by other pollutants and contaminants.

The U.S. EPA defines PM 10 as particulate matter with a diameter of 10 micrometers collected with 50% efficiency by a sampling collection device. Although other elements are present in large amounts too but their removal process involves usage of chemical and material domain.

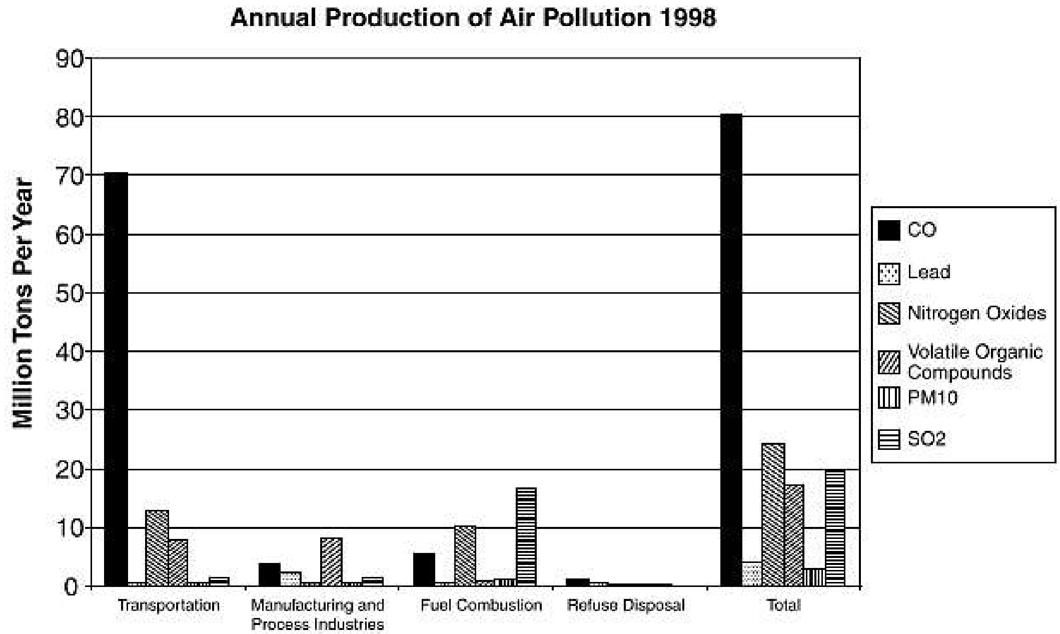


Figure 2 -- Annual Production of Air Pollution (1998)

Emission Stream Characteristics:

Air Flow: Normally the gas flow rates for venturi-scrubbers with non-variable throat area and length are 0.2 to 478 standard cubic meters per second (sm3/sec). Flows higher then this range use either multiple venturi scrubbers in parallel or a multiple throated venturi (EPA, 2001).

Temperature:

Inlet gas temperatures normally range from 4 to 400/C (40 to 750/F) (EPA 2002).

Pollutant Loading:

Waste gas pollutant loadings have a domain ranging from 1 to 115 grams per standard cubic meter (g/sm3) [5]

Other Considerations:

In situations where waste gas contains both particulates and gases to be controlled, venturi scrubbers are sometimes used as a pretreatment device, removing PM to prevent clogging of a downstream device, such as a packed bed scrubber, which is designed to collect primarily gaseous pollutants

Flow analysis along a Venturi Duct:

We first studied the variation of flow properties of air along a venturi duct and its interaction with water droplets.

Most simplest model was the one we came across in the paper "Analysis of Pressure and Velocity at the Throat of Self-Priming Venturi Scrubber" by N. P. Gulhane , H. S. Kadam and S. S. Kale" [6]

In this approach Ansys Fluent was used to study the two phase (liquid-gas) flow across the tube. There are two ways to model this: the Euler–Euler approach and the Euler–Lagrangian approach. As this research requires to deal in determining the pressure and the velocity parameters at the throat, the Euler–Euler approach was preferred over Euler–Lagrangian approach, which deals with the continuous and the dispersed phase separately that requires a huge memory and much time. Turbulence k–ε model for air and a dispersed phase zero equation model for water was used. For the mathematical modeling continuity and momentum equations were used. Steady state conditions were assumed.

The results are discussed as follows:

Gas Velocity

The simulation results for the velocity-field show the increase in the velocity up till the throat, where the velocity is maximum, and then it decelerated up to the end. Furthermore, velocity distributions for different mass flow-rated of the gas are also plotted.

Gas Mixture Pressure

The simulation results show a decrease across the length of the nozzle, with minimum pressure at the throat where a vacuum is created, whereas the pressure increases across the length of the diffuser section. Furthermore, gas pressure across the length of the system for different mass flow rates show that as the mass flow rate of the gas increases the throat pressure decreases.

Pressure drop across the Duct

Pressure drop across the venturi scrubber was plotted for different mass flow rates and it shows that pressure drop increases with increasing mass flow-rates

This study helped us in gaining valuable insights pertaining to the flow properties and the trends of velocity, pressure and pressure drop as air-liquid interact with each other and flow through the converging and diverging sections.

In another cited paper [7] we found an experimental setup designed to remove the fine powder from a confined gas stream by using a Venturi Scrubber. The paper analyzed the efficiencies in particle collection using different gas velocities, throat lengths and liquid flow rates. The experimental setup was simple and we derived useful information regarding its practicalities.

Following results were obtained:

Liquid Flow rate

Increasing the amount of liquid increases the efficiency. However, a combination of high liquid usage with small orifices can lead to excessive jet penetration. In this situation, the jet will atomize near the opposite wall facilitating droplet deposition and thus decreasing the amount of liquid available as droplets.

Throat Length

An increase in gas velocity is normally accompanied by an increase in collection efficiency. However, this increase is not linear, and beyond a certain gas velocity the gain in efficiency is small and not justified in view of the higher pressure drop and higher energy required for the operation.

Gas Velocity

Collection efficiency increases with throat gas velocity. Grade efficiency curves exhibit a minimum for particles of about 0.3 μm, indicating that two collection mechanisms may be operating, one predominant for greater particles, and another for smaller particles;

The use of venturi scrubbers in nuclear reactors was proposed in the paper [8] . This paper discusses the benefits of these scrubbers for the removal of contaminated particles from gaseous streams in case on accidents in nuclear facilities. The paper highlights the importance of venturi scrubber for this purpose:

- ✓ It is relatively simple.
- ✓ It occupies less space.
- ✓ It has no rotating part

It includes both the numerical simulations and proposes an experimental setup for its practical validations.

The following results were derived from the research:

Liquid flow rate increases in throat with the increase in hydro-static head in the tank and decreases with the increase in throat gas velocity.

The dust particle removal efficiency increases with the increase of throat gas velocity and liquid flow rate.

The maximum dust particle removal efficiency of venturi scrubber is 99.5%, which is measured for gas velocity 200 m/s at throat.

Cyclone Separator

Cyclone Separator is the part that removes mist containing particulate matter from the final emissions. After Venturi Scrubber Cyclone Separator is present and complements it.

The cyclone separator is discussed by Shah Nikhil [9] in which he describes the vortex flow and separation mechanism. In this review he has discussed new technology used in mechanical separation. A reverse flow mechanism has been implemented to study the centrifugal flow. CFD was used to understand the flow properties.

Following is a detailed set of advantages and disadvantages of a typical Venturi Scrubber system it will give us a better idea about the applications and limitations of the system.

Advantages

Advantages of venturi scrubbers include:

- ✓ Can handle flammable and explosive dusts with little risk;
- ✓ Can handle mists;
- ✓ Relatively low maintenance;
- ✓ Simple in design and easy to install;
- ✓ Collection efficiency can be varied;
- ✓ Provides cooling for hot gases; and
- ✓ Corrosive gases and dusts can be neutralized

Disadvantages:

- ✓ Effluent liquid can create water pollution problems;
- ✓ Waste product collected wet;
- ✓ High potential for corrosion problems;
- ✓ Protection against freezing required;
- ✓ Off gas may require reheating to avoid visible plume;
- ✓ Collected PM may be contaminated, and may not be recyclable; and
- ✓ Disposal of waste sludge may be very expensive

Operational Details:

Venturi scrubber utilizes the scheme of scrubbing liquid atomization by the acceleration of waste gas stream this also helps in improving the contact surface between the two phases. The acceleration is achieved by the introduction of throat section in the duct that forces the gas stream to increase its velocity as it flows along a CD Nozzle. In the throat region turbulence and gas velocity are both increased. Depending upon the scrubber design, the scrubbing liquid is sprayed into the gas stream before the gas encounters the venturi throat, or in the throat, or upwards against the gas flow in the throat. Turbulence causes the liquid to atomize into small droplets in the throat and this causes an interaction between the droplet and particle [10]

Further down the duct as the Nozzle expands the mixture begins to lose the velocity and further impaction causes the droplets to absorb. Once the particles have been captured by the liquid, the wetted PM and excess liquid droplets are separated from the gas stream by an entrainment section which usually consists of a cyclonic separator and/or a mist eliminator.

Current designs for venturi scrubbers generally use the vertical down-flow of gas through the venturi throat and incorporate three features:

(1) Wet-approach or flooded-wall: Entry section to avoid a dust buildup at a wet-dry junction

(2) Adjustable throat: The presence of an adjustable throat allows for modifying gas velocities which is beneficial if a diverse amount of particle sizes are present.

(3) Flooded elbow located below the venturi and ahead of the entrainment separator, to reduce wear by abrasive particles. The venturi throat is sometimes fitted with a refractory lining to resistabrasion by dust particles

CHAPTER 3

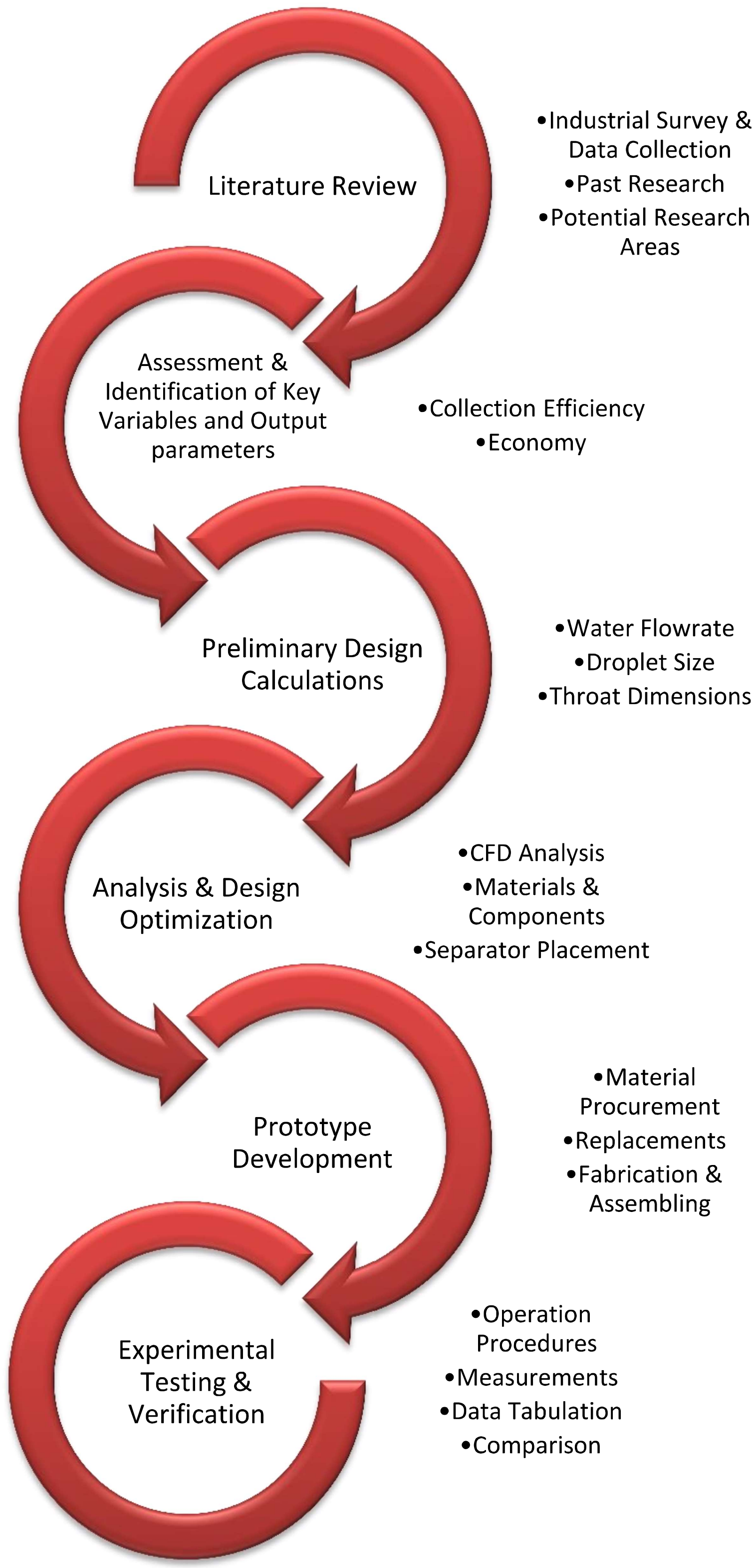
METHODOLOGY

Our methodology constitutes the standard procedure towards the development of a system for experimental and data collection purposes. Literature review along with the industrial data combined has enabled us to go about the project. We are focusing on particulate matter and aiming at a 95% efficiency because of its performance in these conditions. Based on the available data first, we selected the scrubber type suitable to our needs. The data that we utilized is the standard data available on cement industries data-sheets and that obtained by our visits to the industry. After that scaling was done , a suitable scaling factor was obtained after a thorough dimensional analysis keeping in view the mobility and the experimental nature of the project. A number of design parameters were discussed along with the justification of the parameters that were used. Design calculations were done by starting with the theoretical model in which conceptual design points were taken into account. Mathematical calculations were then incorporated by following the model that was deemed perfect for our project.

The Calculations are based on both established engineering numerical formulations and empirical equations used in industries. Our main components are Venturi Duct and Cyclone Separator.

Flow properties and two phase interaction is studied by the use of ANSYS Simulations. The trends obtained gives useful information about the velocity variation and pressure drop. Dimensions were obtained through these techniques and the final product was modeled on Solid Works. The components in accordance with the design were checked and final modifications made.

Later manufacturing plan and layout is discussed. After the fabrication experimental setup and result validation is achieved. Later we have discussed the comparison of the theoretical calculations with the experimental results and explored the reasons for some of discrepancies involved.


Literature Review
•Industrial Survey & Data Collection
•Past Research
•Potential Research Areas
Assessment & Identification of Key Variables and Output parameters
•Collection Efficiency
•Economy
Preliminary Design Calculations
•Water Flowrate
•Droplet Size
•Throat Dimensions
Analysis & Design Optimization
•CFD Analysis
•Materials & Components
•Separator Placement
Prototype Development
•Material Procurement
•Replacements
•Fabrication & Assembling
Experimental Testing & Verification
•Operation Procedures
•Measurements
•Data Tabulation
•Comparison

TECHNICAL DETAILS

Efficiency: 95%

Targeted Particulate Size: *10μm-40 μm*

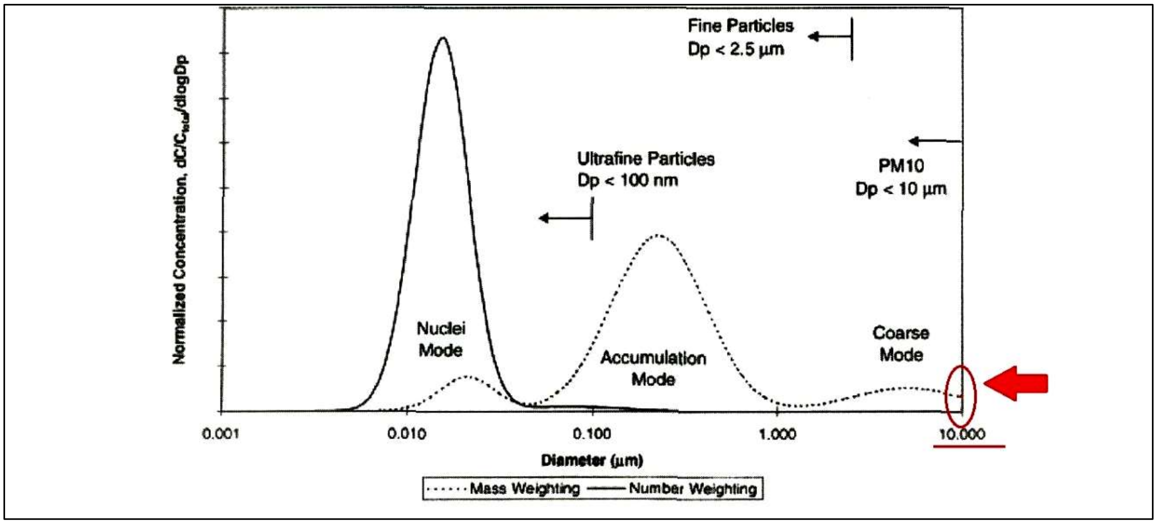


Figure 3 -- PM number and mass size distribution in the atmosphere [11]

Coal Power Plants, Brick Kilns, Incinerators, Biomass Energy Plants, Cement and Metal Processing industries produce this PM of this size and can benefit from this project

OPERATING CONDITIONS

Table 3-- Operating Conditions

Efficiency =	**η**	**0.95**
Mass Median Particle size	d_{ps}	10 μm
Particle Density	ρ_p	1.9 g/cm^3 (0.5-2.5 g/cm^3)
Gas Viscosity	μ_g	1.983 × 10^{-4} g/cm^2
Gas Density	ρ_g	1 kg/m^3
Gas Flow Rate	Q_g	15m^3/s
Temperature of the Gas	T_g	80°C
Water Temperature	T_L	30°C
Liquid Density	ρ_L	1000 kg/m^3
Liquid-to-Gas Ratio	L/G	0.0009 Litre/m^3
Scrubbing Fluid		Water (Effective, cheap, easily available, nontoxic, low viscosity)

DESIGN [12]

We have developed a model of venturi scrubber which theoretically gives 95% efficiency when used to remove particulate matter of size 10um from a stream of gases.

Design Aspects

- *Scaling of the system Model*

Venturi scrubbers are large systems with industrial implications. Our design involves scaling it down to a laboratory scale model where its results can be experimentally tested and compared against those obtained through theoretical calculations.

In this project the scalability concerned about the geometry and the fluid mechanics aspects:

Two important quantities in fluid mechanics in flows in capillary conduits:

A.Volumetric Flow

From Hagen-Poiseuille's equation

$$Q = \frac{\pi a^4 \Delta P}{8\mu L}$$

Leads to: $Q \propto a^4$

Meaning a reduction of 10 in conduit radius → 10^4 = 10000 times reduction in volumetric flow!

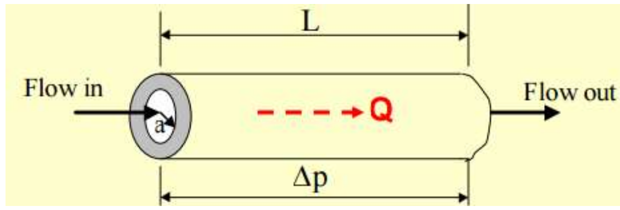
B. Pressure Drop:

From the same Hagen-Poiseuille's equation, we can derive:

$$\Delta P = \frac{8\mu V_{avg} L}{a^3}$$

Leads to: $\Delta P/L \propto a^{-3}$

A reduction of 10 times in conduit radius → 10^3 = 1000 times increase in pressure drop per unit length!



Scalability in the Geometry follow the following rule:

If we let L = linear dimension of a solid, we will have:

Volume (V) $\propto L^3$

Surface (S) $\propto L^2$

A 10 times reduction in length induces a 10^3 = 1000 time reduction in volume BUT a 10^2 = 100 time reduction in surface area.

Since volume, V relates to mass and surface area, S relates to buoyancy force.

- *Circular Vs Squared Cross Section*

We chose squared cross-section for our venturi scrubber as we aim to target PM10 particles which require higher flow rates as well as higher pressure drop. Square cross sectional duct will provide these suitable conditions when compared with the circular cross-section. Furthermore, since squared cross-section ducts are easier and cheaper to fabricate, therefore in order to control the project cost within the budget Squared Cross-Section was chosen.

- *Wetted vs. Dry Scrubbing*

The difference lies in the position of the fluid injector (water sprinkler) along the Converging-Diverging Nozzle.

In wetted scrubbing the sprinkler is present behind the throat in the converging section while in dry scrubbing it is present in the throat. We are using the Dry-Scrubbing approach as it helps in making the structure Leak-proof easily as compared to the wet scrubbing approach

- *Vertical Vs. Horizontal arrangement*

A vertical arrangement is selected so that we can easily use counter flow water sprinkler method. In horizontal method there was a chance that the particulates or droplets get stuck along the pipe. In vertical arrangement, the force of gravity adds in to the local force vectors, thereby assisting in the whole process. Therefore, the vertical arrangement has been preferred

- *Sampling & Measuring Technique for analyzing efficiency*

Due to the non-availability of a precise and accurate particle sampling and measuring device, we were left to use the conventional devices like sieves & filter paper. As we were aiming at particle size of around 10µm, therefore sieves were not preferable instead we used filter paper for isolating the removed particles and estimate the particle collection efficiency.

- *Cross Flow Vs. Counter Flow Scrubbing*

The cross-flow Scrubbing was arranged as the cross flow method of injecting fluid is more efficient as it comes in contact with a larger area of the incoming gases and thus it can capture dust more efficiently.

- *Mist Eliminator Selection*

A cyclone separator will be used to remove the mist containing dust particles from the gases so that water is removed and gases come out with their original composition. A cyclone separator will be deployed for this purpose. It uses the principle of vortex separation in which inlet gases are coerced to move about in the vessel in cyclones thus removing heavy droplets, gases can then be discharged out.

- *Droplet Size selection*

Droplet size will depend on the particle size and the throat velocity. Its calculation is done based on Nukiyama Tanasawa equations.

DESIGN CALCULATIONS

Table 4 Design Calculations – Operating Conditions

Operating Conditions		
Efficiency =	η	0.95
Mass Median Particle size	dps	10 µm
Particle Density	ρ_p	1.9 g/cm^3 (0.5-2.5 g/cm^3)
Gas Viscosity	μ_g	1.983×10^{-4} g/cm^2
Gas Density	ρ_g	1 kg/m^3
Gas Flow Rate	Q_g	15m^3/s
Temperature of the Gas	T_g	80°C
Water Temperature	T_L	30°C
Liquid Density	ρ_L	1000 kg/m^3
Liquid-to-Gas Ratio	L/G	0.0009 Litre/m^3
Scrubbing Fluid		Water (Effective, cheap, easily available, nontoxic, low viscosity)

Design Equations

1-Nukiyama Tanasawa equation

2-Infinite throat Model

3-Cunninghum Correction equation

Summarizing the design calculations in the *APPENDIX-II* :

Table 5 -- Design Parameters

Design Calculations		
Inertial Impaction	$\mathbf{K_{pg}}$	K_{pg} =1394
Water Flowrate	$\mathbf{Q_L}$	382.32 liter/hr
Droplet Diameter	$\mathbf{d_d}$	0.0122 cm
Throat velocity	$\mathbf{V_{gt}}$	1493 cm/s
Throat length	$\mathbf{L_t}$	0.07 m
Throat area	$\mathbf{A_t}$	0.008 m^2

EXPERIMENTAL SETUP

In order to develop the project, required materials and components were identified and their specifications were determined based upon the data in the theoretical design.

Venturi Duct

Following design conditions were determined for the venturi duct in order to meet the theoretical design requirements:

- ✓ Inlet area: 7.5”x7.5”
- ✓ Outlet area: 7.5”x7.5”
- ✓ Throat area: 3.5”x3.5”
- ✓ Throat length: 3”
- ✓ Material : Stainless Steel Grade 304
- ✓ Sheet Metal Gauge : 20 SWG

Cyclone Separator

In order to create a swirl in this chamber, the inlet port was connected tangentially over the outermost circumference of the Separator body in order to aid in the elimination of mist coming from the venturi section.

- ✓ Inlet cross-section: 3”x1.5”
- ✓ Cyclone diameter: 8”
- ✓ Gas exhaust diameter: 4”
- ✓ Waste disposal diameter: 2.5”
- ✓ Material : Stainless Steel Grade 304
- ✓ Sheet Metal Gauge : 20 SWG

Blower

In order to simulate the industrial exhaust conditions we decided to employ a blower of such specifications so as to get the calculated flowrate and velocity in the venturi scrubber, at the throat sections.

- ✓ Discharge Cross-Section : 3”x 3” = 0.0058 m2
- ✓ Impeller Radius = 4” = 0.1016 m
- ✓ RPM : 2200 RPM
- ✓ Discharge Velocity = 23.41 m/s

- ✓ Discharge Flowrate = Qg = 8.15 m3/min
- ✓ Voltage = DC 48V

Water Pump

In order to produce the mist of the droplet size calculated in the theoretical design, highly sophisticated nozzles were used. The nozzles require a high pressure for operation. To meet this criteria a high pressure water pump was required. Pump of following specifications was used :

- ✓ High Pressure Water Pump
- ✓ Max. Pressure = 1740 psi
- ✓ Operating Pressure = 1180 psi
- ✓ Flow Rate = 6 L/min = 360 L/hr
- ✓ Voltage = AC 220V
- ✓ Power= 1500W

Development Plan

In order to fabricate and assemble the project according to the developed design it was not possible for us to fabricate the whole system ourselves.

It was suitable for us to hire the services of a professional fabricator, who would help us in realizing our design.

After a comprehensive search around the twin cities we were able to find an appropriate person for the job, in the Gawalmandi, City Saddar Area, Rawalpindi

We were visiting him daily for around two weeks, looking over the progress and guiding him over the whole design, throughout the stages. Procurement of materials and parts were done by us in different regions of Rawalpindi like College Road, Jinnah Road, Saddar etc.

Our manufacturing plan comprised of following several stages:

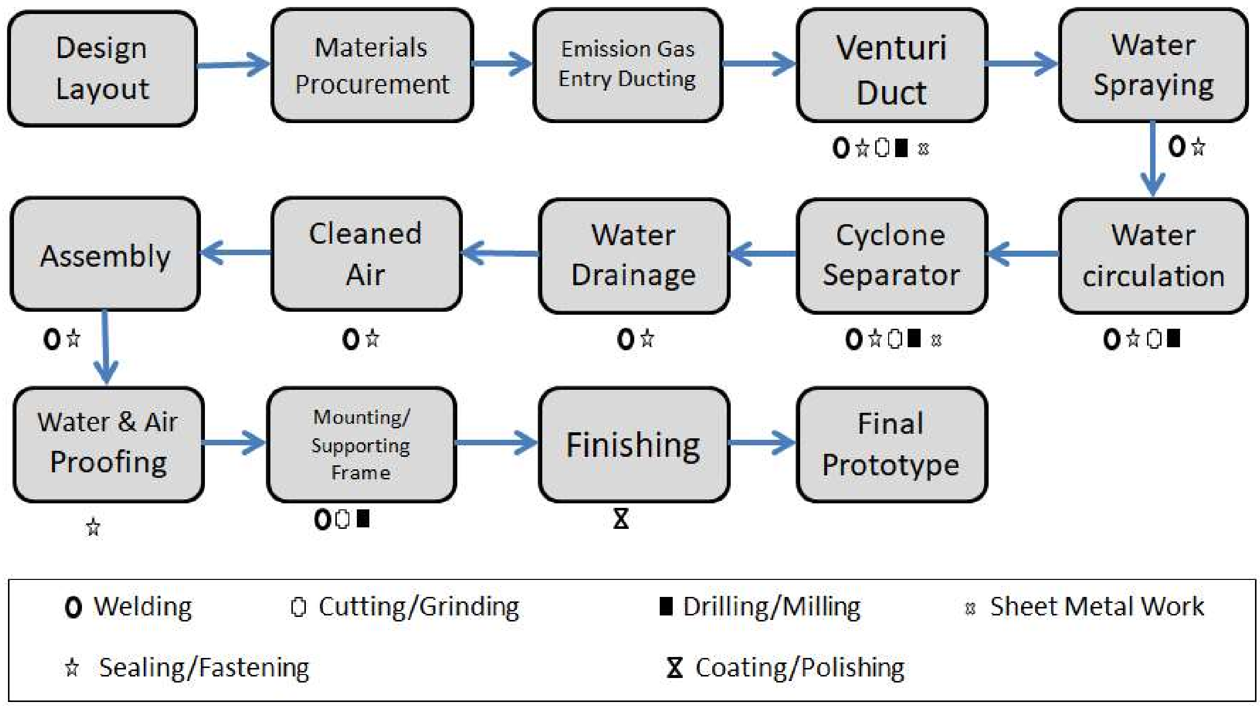


Figure 4 -- Manufacturing Plan

Figure 5 -- The Manufactured prototype

CHAPTER 4

RESULTS

The prototype was tested under the operating conditions in order to verify and tabulate the results with the theoretical design. This series of experimentations, which were done under controlled variables, produced results which not only tabulated but also plotted to get a general view of trends.

Following procedure was followed in order to get the system working:

- The high pressure pump was connected to the water source at normal pressure and connected to the electrical power source
- The piping circuit was completed by using high pressure rubber pipes with press fit non return valves. Furthermore, every time it was made sure that there is no leakage
- The blower along with its 48V power supply was fixed at the top of the venturi duct, in order to provide the required flow rate
- Before running the system, all connection were checked twice for leakages
- In order to run the system, power supply to blower and then to the pump was closed, which made the system start working at the operating conditions

Following procedure was followed in order to get the experimental results:

- Lime dust introduced at the blower suction, gets absorbed by the mist droplets at the throat due to shearing and separated as a sludge at the outlet of the cyclone separator
- In order to calculate the efficiency, there were several methods:
    1. Particulate Emissions Analyzer (Gas Analyzer)
    2. Filter Paper Test

Due to non-availability of the emissions gas analyzer, we were left with filter paper test in order to get our results. Though, simple, it was a quite slow process to get multiple readings through this test.

- Lime dust of known mass $\mathbf{m_i}$ at the blower suction, and mass of lime stone $\mathbf{m_f}$ in the sludge as separated by the ultra-fine filter paper gave pretty accurate readings for the collection efficiency
- Difference of the two masses was used to calculate the the experimental collection efficiency
- The experiment was performed under the same operating conditions 3 times to get three sets of data

$$\textbf{Collection Efficiency} = \frac{\textbf{mf}}{\textbf{mi}} \textbf{ x 100}$$

The experimental results are tabulated as follows:

Table 6 -- Collection Efficiency

TEST #	Inlet Mass (g)	Mass Extracted from sludge (g)	Collection Efficiency (%)
1	10	9.23	92.3%
2	15	13.71	91.45%
3	25	22.48	89.92%
4	35	30.9190	88.34%

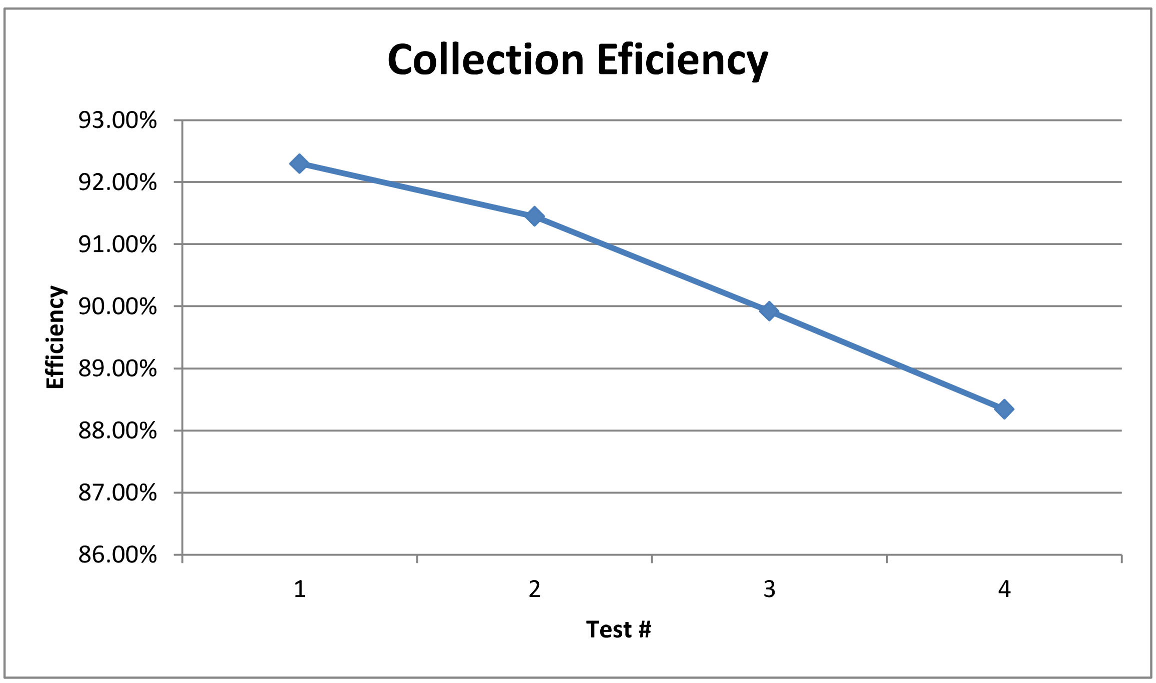


Figure 6 -- Experimental Results for Collection Efficiency

Average Collection Efficiency = $\frac{92.3\% + 91.45\% + 89.92\% + 88.34\%}{4}$

$$= 90.50\%$$

Table 7-- Comparison of Results for Collection Efficiency

	Theoretical	Experimental
Collection Efficiency	95%	90.50%

It can be seen that the experimental results are well in accordance with the predicted theoretical design. The error of around 4.73% was observed in the results due to the fact that the leakage was not completely removed due to the high pressure pump and ultra-fine misting nozzles and every time the experiment was performed, a small amount of leakage always prevailed.

We were able to reduce the leakage by sealing through different chemicals like Adhesives, Silicone Gel etc. Before this the error in the results was 6.5%

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Air pollution problems can be ameliorated by a variety of ways and the best method can be obtained by exploring and comparing a number of alternatives. After establishing that a scrubbing system is the most technically feasible method in terms of both, its efficiency and reliability, research would then be focused towards the types of scrubbers. The scrubbers are then evaluated on the basis of desired efficiency and economics, and the best scrubber is selected.

KEY-POINTS:

Following conclusions can be drawn from the experimentations:

- The dust particle removal efficiency increases with the increase of throat gas velocity and liquid flow rate.
- Increase in temperature reduces the efficiency.
- A trend between the pressure and efficiency can be obtained only if the Cunningham factor is constant. If that is the case then increase in pressure will increase the efficiency.
- The maximum dust particle removal efficiency of this venturi scrubber is 95%, which is calculated using theoretical calculations. Experimental values come out to be nearly 90%.
- The theoretical model of removal efficiency based on inertial Impaction fits well with experimental result.

DISCREPANCY EXPLANATION:

An error of about **4.73%** was observed between the experimental results and theoretical predictions. This error can be attributed to the following reasons:

1) Leakage: This was one of the biggest challenges encountered during the project. High pressure brass nozzles were inserted into the misting bracket. Welding was not possible as the material of these nozzles is brass. So leakage problem was faced. We managed to reduce the leakage by about *85%* by the use of insulation and water-proofing using O-rings, adhesives like depoxy and silicone gel sealant.

2) Fluid Friction: Flow of fluid through the whole ducting system required it to move through more than 4ft. This resulted in in friction along the walls of the system and between the fluid layers themselves. Also the different types of bends were present. These frictional effects resulted in loss of pressure head and consequently the particle-collection efficiency due to both major and minor losses along the duct.

EFFECT OF VARIATION IN OPERATING CONDITIONS:

1) Temperature

Physical properties of dust particles change as a result of any variation in temperature or pressure. The droplet formation and their collection capability is also affected consequently. The collection efficiency at higher air temperatures is less since viscosity of gas increases with temperature, due to which the inertial impaction parameter also decreases in its value, thereby reducing collection efficiency.

In our case temperature was already low but on industrial scale we have to deal with heated gases so some mechanism can be introduced for pre-cooling.

2) Pressure:

Air pressure affects the Reynolds number and Inertial Impaction factor as consequence of the change in gas density. With the increase in inlet pressure, the collection efficiency increases in the case of constant Cunningham factor. Cunningham factor depends on the particle diameter so for a specific industry with one type of emissions we can use constant Cunningham factor as a reasonable assumption. Pressure is already high in industrial gases, care should be taken to avoid pressure and head losses to maintain efficiency.

ALTERNATE POLLUTION CONTROL METHODS:

Following methods should also be explored

Alternate methods of solving the pollution emissions problem are available, and possibilities which should be considered are:

- Modify the operation of the present process
- Select non-polluting raw materials or fuel
- Change the process or equipment
- Eliminate the process
- Apply a control device

A combination of the said devices might serve the job in certain applications. Selection of the appropriate device depends on the following factors: economics, space required, availability, delivery time, maintenance required, past experience, additional facilities, etc. Following categories are recommended for consideration:

- Centrifugal collector (cyclone or multi-cyclone)
- Gravity Settler
- Electrostatic Precipitator
- Fabric Filter
- Wet Scrubber
- Incineration
- Adsorption Bed

RECOMMENDED AUGMENTATIONS:

Many improvements and extensions could have been made to the final product if we were not constrained by limited time and resources. We propose the following enhancements:

Corrosion:

A commonly occurring cause of failure is corrosion and precipitation. In our project we used Stainless Steel to get rid of the corrosion problem but it extensively adds to the cost. In industrial level the use of Stainless Steel cannot be justified economically so we have to settle for some other metal. Such materials can be selected which allow more durable functionality of Venturi scrubbers. Several properties of materials are considered for scrubber construction. Proper selection of materials can prevent or solve a reliability problem. Plugging with solids either from mechanical causes or from scale precipitation is another common problem. Empirical data on the materials of construction should be studied and an evaluation should be carried out as of how well they have held up under the moist conditions and pressure.

Noise Pollution:

It should be made sure that the noise from the device does not affect the lives of the people. The presence of a plant where it is installed in a metropolitan area or if the technicians working on it are in the vicinity of the equipment then noise problem could be a problem. The use of scrubber should be properly justified. One large Midwestern company located in a city received complaints from citizens up to a mile away about dust emissions. The company solved the dust problem with a large, efficient scrubber. However, the scrubber used a large fan, and the fan made so much noise that the residents around the plant could not sleep at night. The complaints about the noisy scrubber system were much more severe than the previous complaints about dust. A proper vibration analysis should be done of the various components involved and unwanted noises should be minimized to the lowest.

SIGNIFICANCE OF OUR PROJECT:

Our project in its raw form cannot be used in an industry but the research involved and the fabrication of the model provides framework necessary for its industrial incorporation. It helped us understand the primary pollution control methods and their limitations in specific circumstances.

Our design parameters can be utilized for the extension of the research into other domains of pollutants too. The tabulation of the results provides a vivid comparison between theoretical and practical values.

FUTURE WORK / RECOMMENDATIONS

In this project we mainly focused on designing and fabrication of the venturi scrubber, but having done that we aim to carry on the research further as:

- To design a *Variable Throat area*, so that we can study the change in the operating efficiency by changing the hydraulic diameter of the throat
- To make a *Design Software*, for commercial use, this will take the user input and accordingly display the design parameters of a venturi scrubber system as an output
- To design & compare the *efficiency and other output variables* of venturi scrubber with other types of scrubbers
- To compare the overall *economic aspects* of a venturi scrubber with other types of scrubbers
- To design a *full scale* venturi scrubber for the cement limestone kiln for an industrial application, with improved and better features

WORKS CITED

[1] Website: http://www.unocha.org/what-we-do/advocacy/thematic-campaigns/climate-change/threats-solutions

[2] Topic : *"Types of Scrubbers"* Source : http:// www.globalspec.com/learnmore/manufacturing_process_equipment/air_quality/scrubbers

[3] Calvert, S. 1977*. "3.1.6 : Gas Atomized Spray Scrubbers". Chapter 3 Pg# 3-2. Calvert, S., J. Goldschmid, D. Leith, D. Mehta. 1972, August.* Wet Scrubber System Study. Vol. 1, Scrubber Handbook. EPA-R2-72-118a. U.S. Environmental Protection Agency

[4] Source : https://www.epa.gov/air-trends

[5] EPA-CICA Fact Sheet Packed Bed Packed Tower Scrubber ; (Turner, 1999 ; Dixit, 1999)

[6] *"Analysis of Pressure and Velocity at the Throat of Self-Priming Venturi Scrubber"* by N. P. Gulhane, H. S. Kadam and S. S. Kale

[7] *"Performance of a Venturi scrubber in the removal of fine powder from a confined gas stream"* by Maria A.Martins Costa; Ana P. Rodrigues; Érica R. Tognetti; Mônica L. Aguiar; José A. Silveira; José R. Coury

[8] "*Dust particle removal efficiency of a venturi scrubber*" by Majid Ali, Changqi Yan, Zhongning Sun, Haifeng Gu, Khurram Mehboob

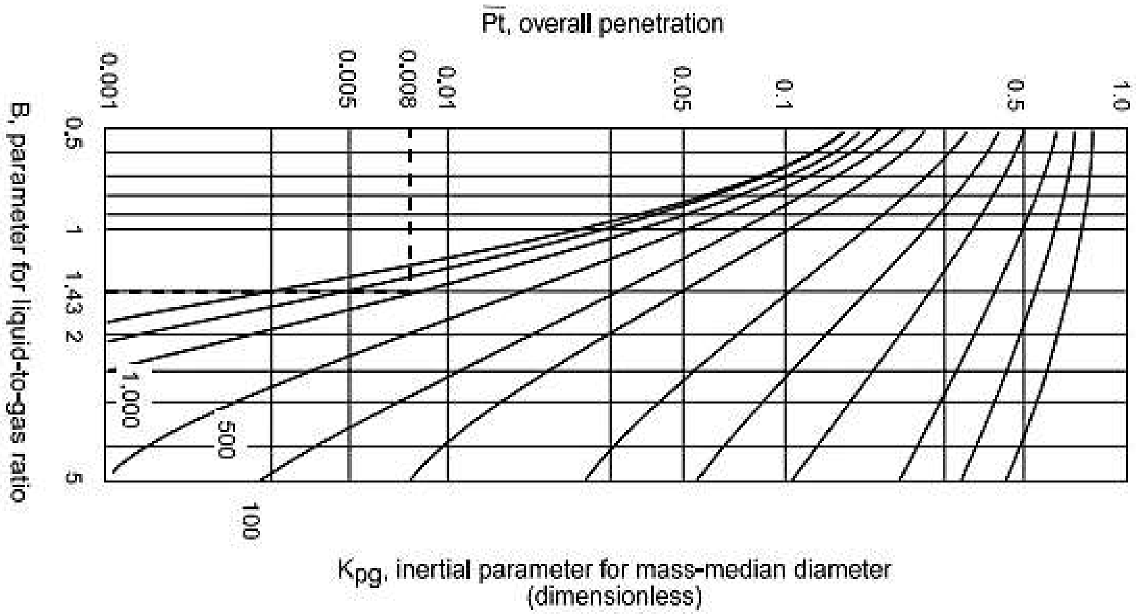
[9] *"A Review on Gas Solid Cyclone Separator Parametric Analysis"* by Shah Nikhil

[10] EPA, 1998; AWMA, 1992; Corbitt, 1990

[11] *Seigneur, Christian. "Current Understanding of Ultrafine Particulate Matter Emitted from Mobile Sources." Journal of the Air & Waste Management Association, vol. 59, no. 1, 2009, p. 3+*

[12] *Calvert, S. 1977. How to choose a particulate scrubber. Chemical Engineering. 84:133-140. Calvert, S., J. Goldschmid, D. Leith, D. Mehta. 1972, August. Wet Scrubber System Study. Vol. 1, Scrubber Handbook. EPA-R2-72-118a. U.S. Environmental Protection Agency*

APPENDIX I: GRAPH FOR INERTIAL PARAMETER



APPENDIX II: Design calculations

- Cunningham Slip Correction Factor

$$\mathbf{C_c} = 1 + \frac{(6.21\times 10^{-4})\ \mathrm{x}\ \mathrm{T}}{d_{ps}} = 1.022$$

- Particle Aerodynamic Geometric Mean Diameter

$\mathbf{d_{pg}}$ = dps ($C_c \times \rho_p$) 0.5 = 13.93 $\times 10^{-4}$ cmA

- Penetration

Pt = 1 – η = 0.05

For the given overall penetration, a number of liquid-gas parameters (B) are available which'll depend upon the exact geometric shape of the throat.

Value of Liquid-gas parameter *B = 1.4* is assumed because of proximity to our geometrical design

The *Graph 1-1* in the appendix-1 can be referred to calculate the value of Inertial Impaction (K_{pg}) , corresponding to the Liquid-gas parameter B = 1.4 & Penetration value of *0.05*

- <u>Inertial Impaction K_{pg}</u>

$$\mathbf{K_{pg}} = \frac{{d_{pg}}^2 \times v_{gt}}{9\mu_g \times d_d}$$

From the above equation the throat velocity can be calculated in terms of droplet diameter d_d

$\mathbf{V_{gt}}$ = 459867.79 x d_d -- (1)

Calculating K_{pg} for particle cut diameter d_{pa50} = 1.2 µm

⇨ K_{pg} =1394

- Water Flowrate

$\mathbf{Q_L} = \frac{L}{G} \times Qg = 6.372 \times 10^{-3}\ m^3/min = 382.32$ liter/hr

- Droplet Diameter

Calculated using Nukiyama Tanasawa equation:

$\mathbf{d_d} = \frac{50}{V\_gt} + 91.8 \text{ x } \frac{L}{G} \text{ x } 1.5$ ------------------------------------(2)

After solving:

$\mathbf{d_d} = 0.0122$ cm

- Throat velocity

By comparing eq (1) & eq (2) , Throat velocity comes out to be

$\mathbf{V_{gt}} = 1493$ cm/s

- Throat length

Now Throat length is related to throat velocity by:

$$\mathbf{L_t} = \frac{369.567 \times \frac{L}{G}^2}{(V_{gt})^{1.127}}$$

= 0.07 m

- Throat area

$$\mathbf{A_t} = \frac{Qg}{Vt}$$

$= 0.008\ m^2$

APPENDIX III: CAD MODELS

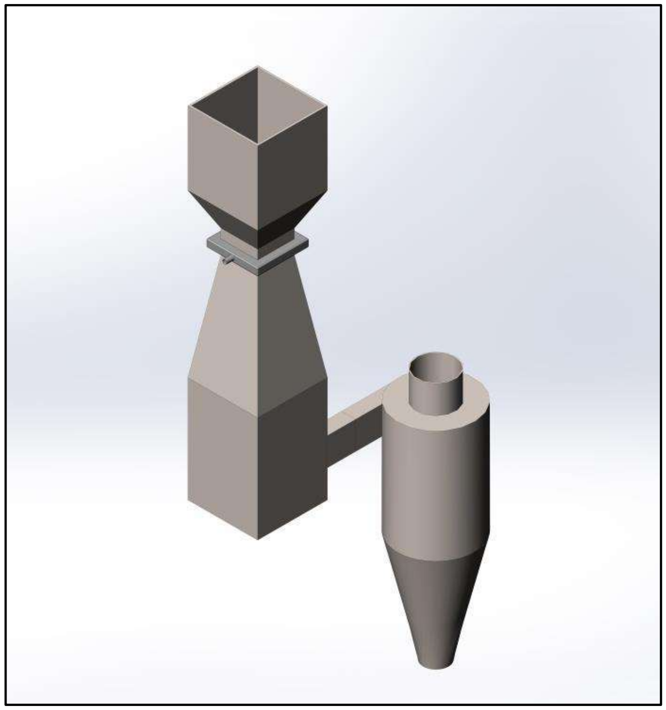


Figure 7-- Venturi Scrubber Assembly (Isometric View)

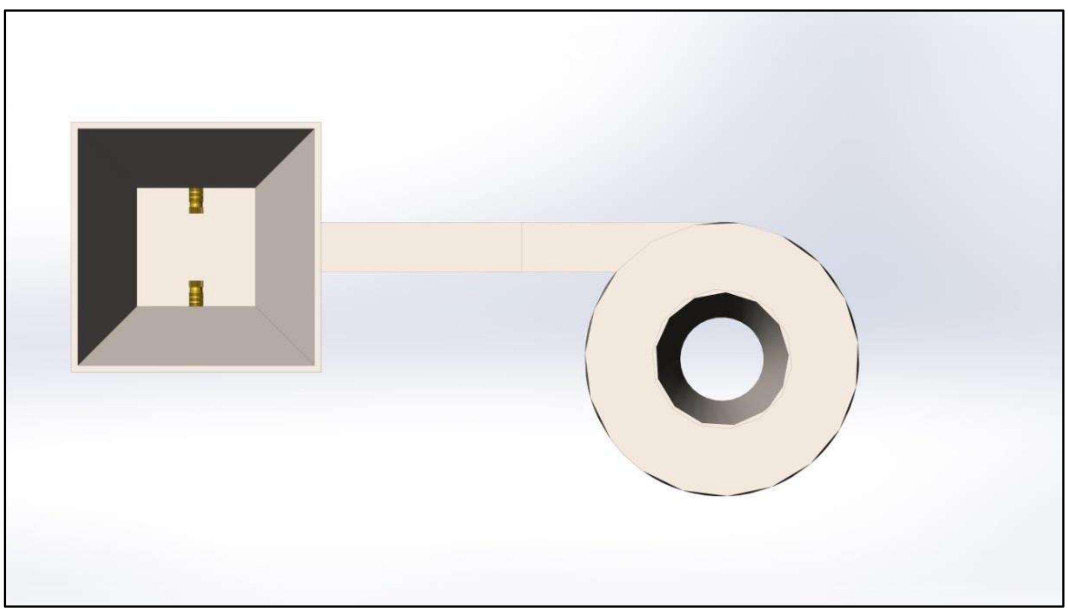


Figure 8 -- Venturi Scrubber Assembly (Top View)

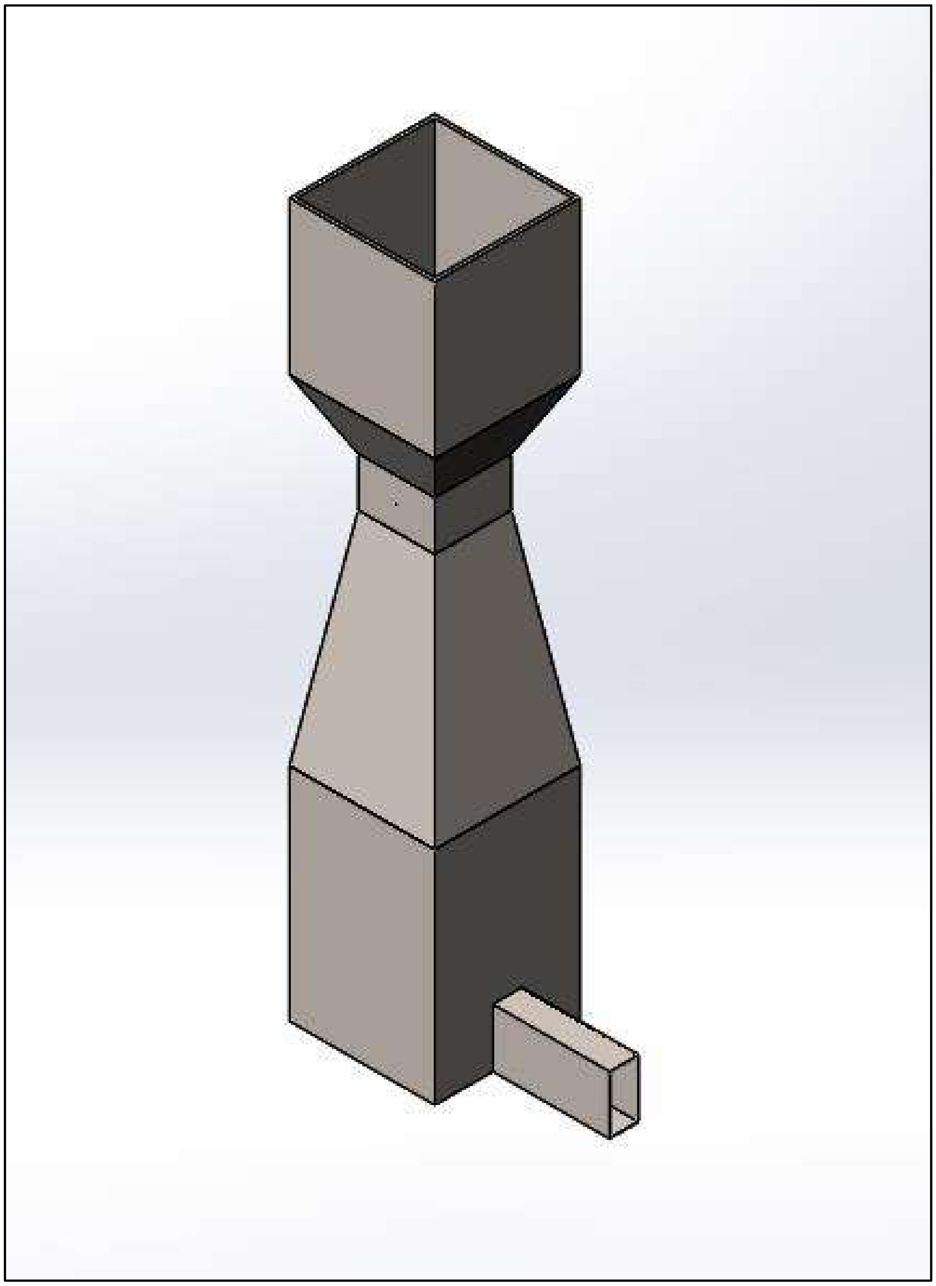


Figure 9 – Venturi Duct

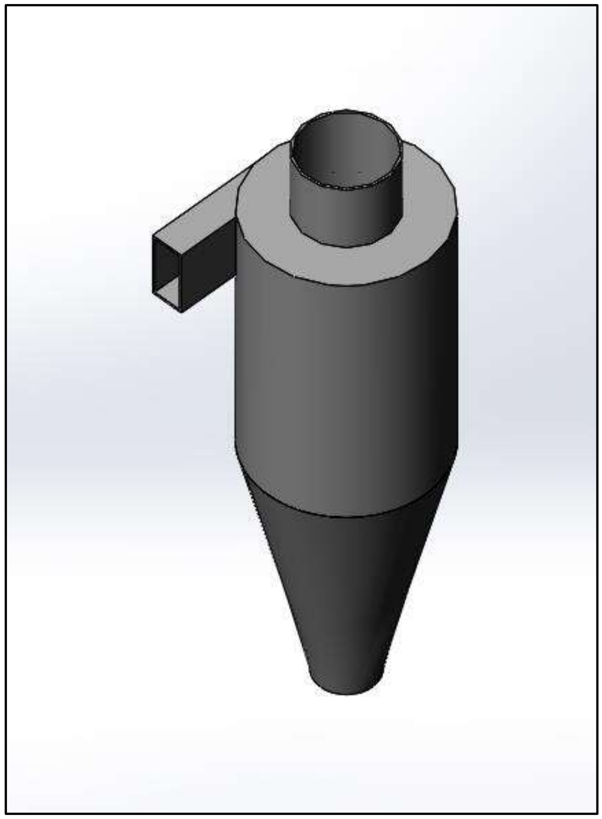


Figure 10 – Cyclone Separator

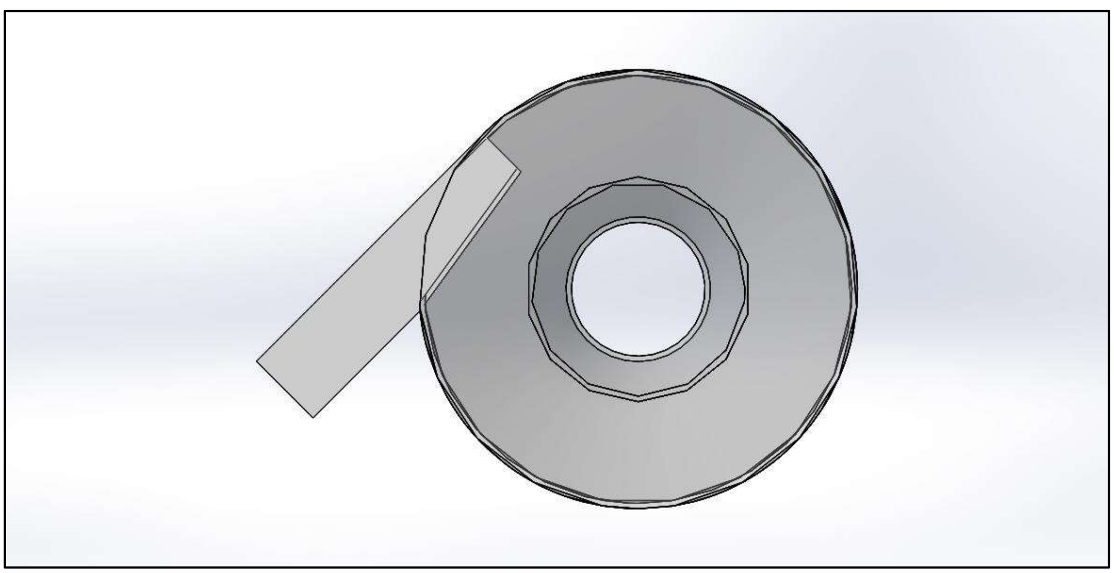


Figure 11 – Cyclone Separator (Top View)

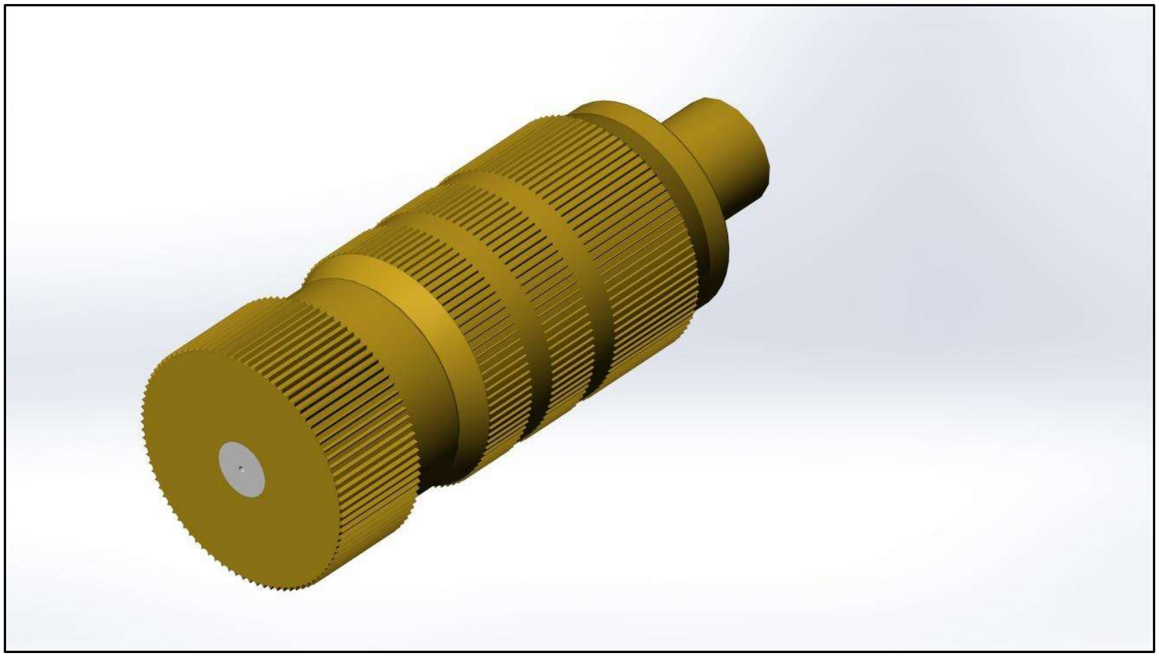


Figure 12 – Misting Nozzle

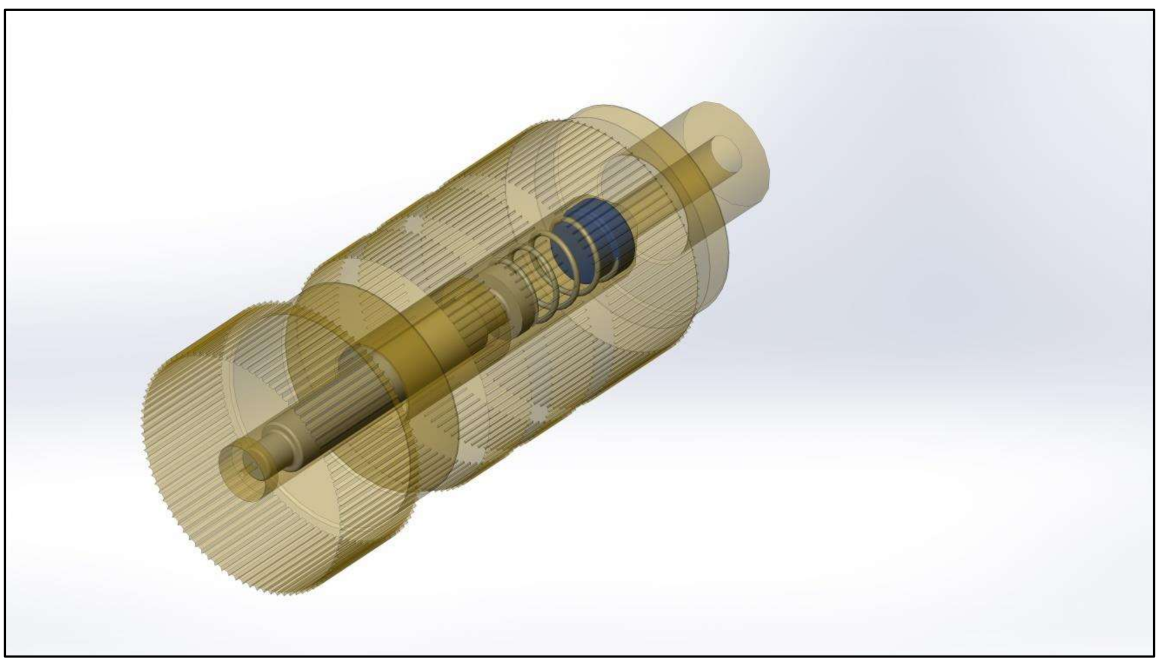


Figure 13 -- Misting Nozzle (Cross-Section)

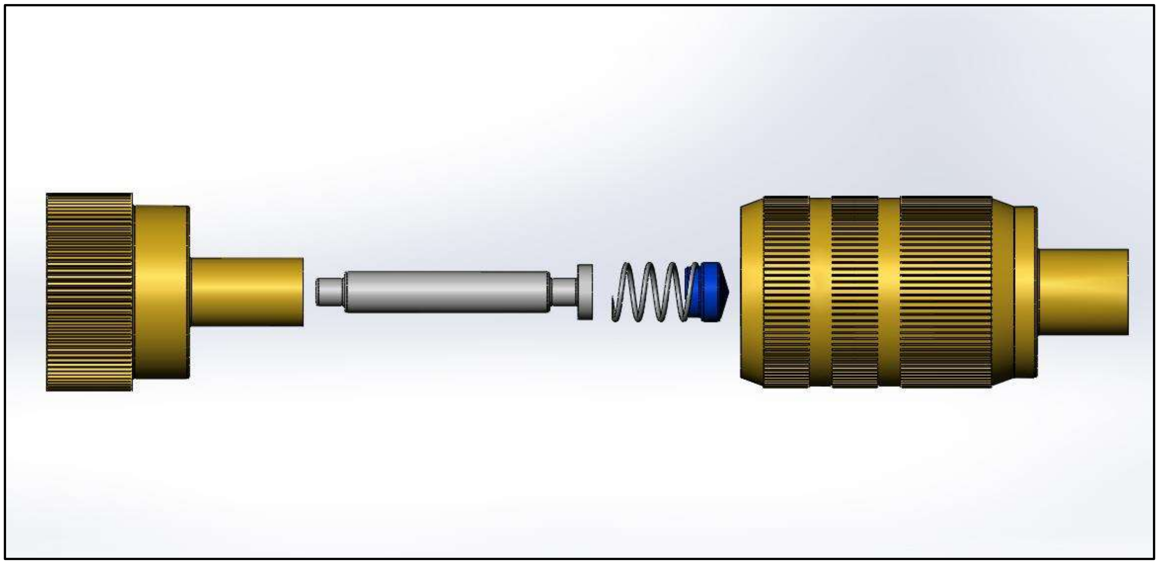


Figure 14 – Misting Nozzle (Exploded View)

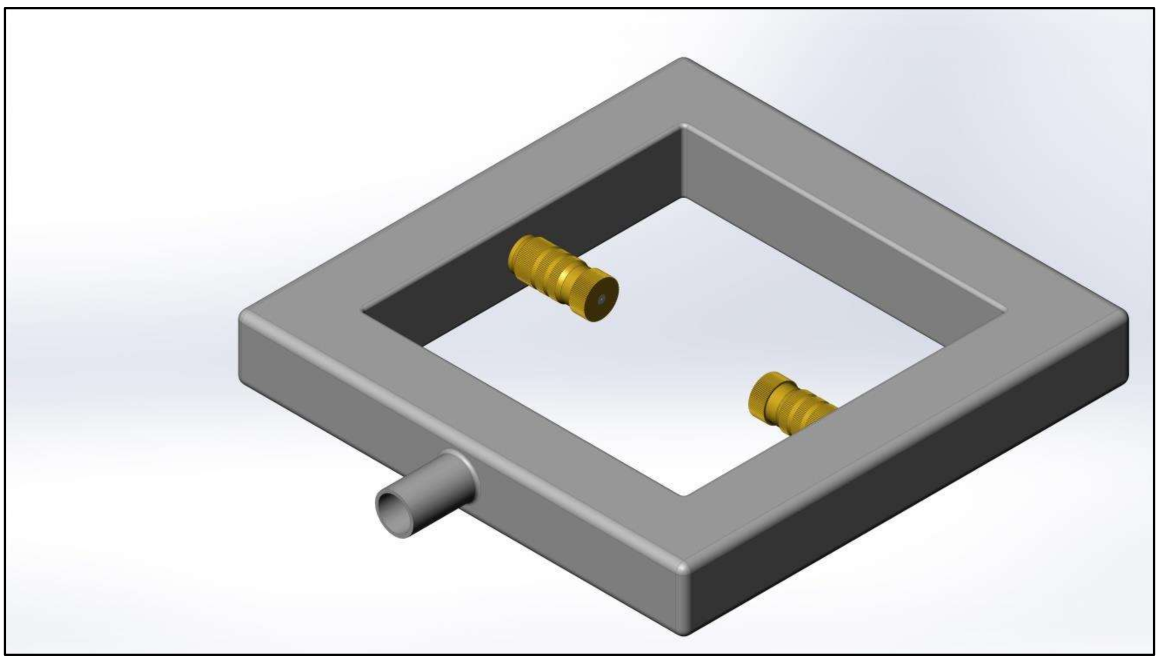


Figure 15 – Nozzles Supporting Bracket