SAN DIEGO STATE UNIVERSITY
1897

COLLEGE OF ENGINEERING
Department of Mechanical Engineering

ME 490B-Senior Project

Carbon Particle Disperser:
A method for consistently generating a carbon cloud to convert sunlight into heat for use in an open Brayton power cycle.

Team:
Aron Daria
John Terry

Sponsor:
Google.org

Advisors:
Dr. Fletcher Miller
Dr. Arlon Hunt

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Carbon Particle Disperser

December 18, 2009

Aron Daria
John Terry

Table of Contents

Abstract

Research is conducted on the viability of using a carbon particle disperser to produce a continuous, consistent, and adjustable carbon cloud from prefabricated carbon particles and air. The method of generating such a cloud is researched and many design and analysis iterations are performed to determine the optimal system configuration. The carbon cloud produced by the system will absorb concentrated solar energy and convert it into thermal energy. This energy will be used to power a gas turbine in an open Brayton power cycle. The use of a carbon particle cloud to convert solar energy into thermal energy is important because high efficiencies can be achieved resulting in lower energy costs and less environmental impacts. A final system design is chosen including a detailed timeline of the fabrication process. System components include a fluidized bed containing a diffuser plate and particle injection tube and a recirculation loop including a vacuum pump. Multiple pressure regulators are used to control both fluidization and the system output. A completed system capable of generating a uniform, consistent carbon cloud is delivered as per the project objectives.

Executive Summary

The output of the carbon particle disperser is a carbon cloud in which the overall mass flow as well as the amount of carbon is controlled. Furthermore, the cloud must be of a uniform consistency over both large and small flow rates. This is achieved by having two flow controllers strategically placed within the system to independently control fluidization and carbon cloud output. The carbon in the system is oxidized by the incoming solar energy and converted into thermal energy to power a gas turbine. Because the carbon is used to transfer solar energy to the surrounding system gases (air) the consistency, density, and particle size of the resulting cloud will determine the efficiency of this energy transfer. As stated in the abstract the system contains a fluidized bed and recirculation loop. The fluidized bed is used to initially agitate and uniformly atomize the carbon particles. This uniform distribution or atomization is achieved by the use of a cylindrical fluidized bed cylinder and a diffuser plate containing hundreds of holes. The carbon sits on top of the diffuser plate while fresh ambient air is pushed through the plate via the recirculation loop. The flow rate and pressure through the plate are controlled by a flow controller in line with the recirculation loop. Consequently, this independently regulates the fluidization without affecting the overall system output. The recirculation loop operated via a diaphragm vacuum pump, which pulls fresh air from the top of the fluidized bed and independently adds energy into the system. The overall system output is controlled by an injection tube and flow controller. By adding fresh air to the system a carbon cloud is forced out the ejection tube. The ejection tube is adjustable to accommodate varying levels of carbon and help control the density of the outgoing carbon cloud. The system was fabricated using cast acrylic material via a computer controlled 3-axis mill. Once assembled basic system testing was completed to verify the overall system operation.

Introduction

Recent recognition of the dangers associated with global warming and greenhouse gasses has sparked a heightened interest in renewable energy. Many types of renewable energy—long ignored—are once again being pursued as a viable, profitable, source of power. Solar power is one of these fields. Many types of solar power plants exist today, each having advantages and disadvantages over the other. Photovoltaics and concentrated sunlight are two such types. Our project focuses on the concentrated sunlight type, more specifically, solar tower power.

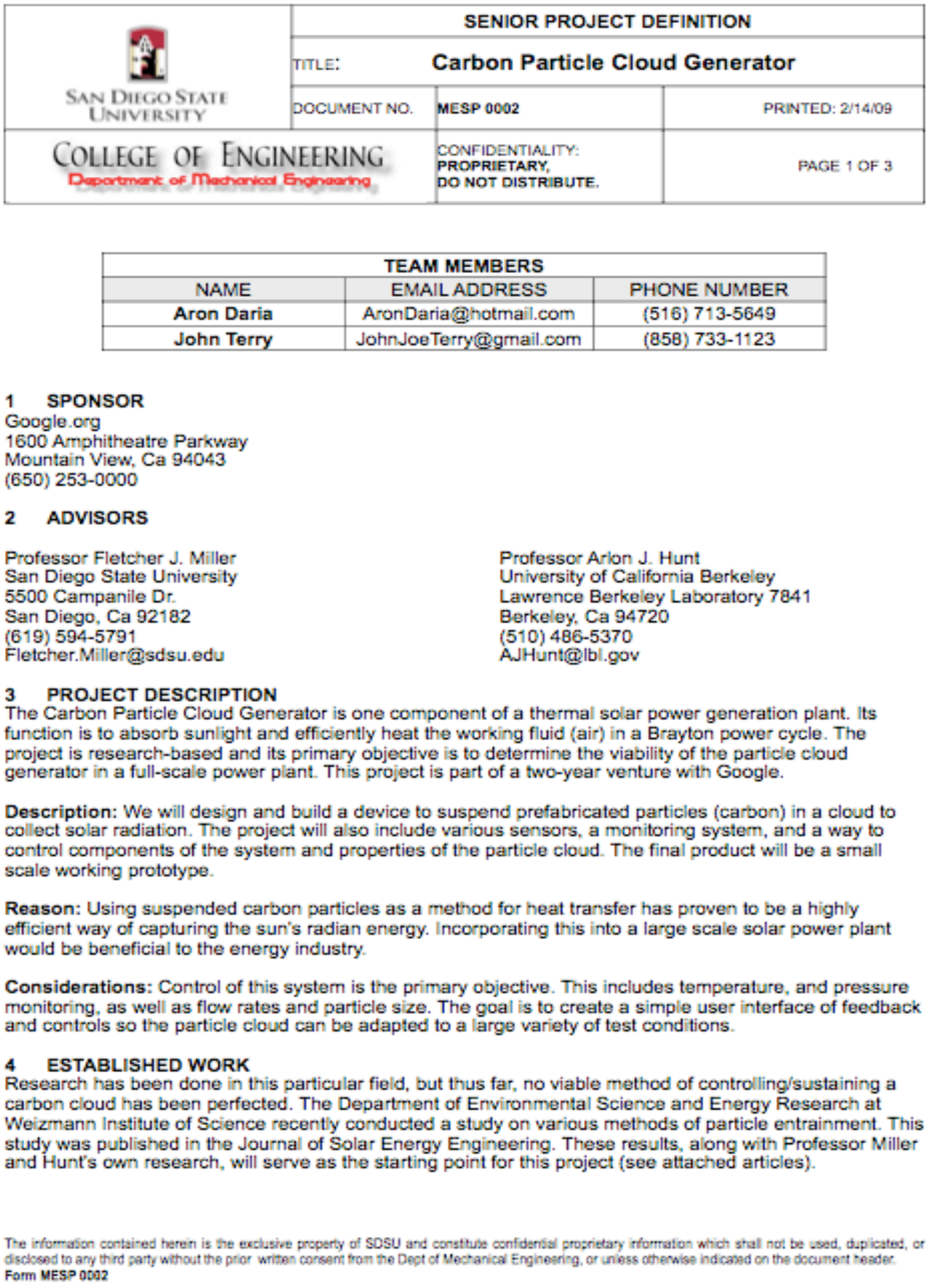
Today's solar tower power plants use a Rankine cycle as a means to produce power. This type of system uses liquid (typically water or oil) as the working fluid to transfer energy from a solar receiver to a turbine. The motivation behind this project is to replace the Rankine cycle with a much more efficient Brayton cycle gas turbine system. The Brayton Cycle requires a different working fluid, as liquids are not sufficient.

It has been shown through research and testing that small particles suspended in a cloud make an excellent absorber of sunlight provided the particle size is chosen correctly. Furthermore, carbon particles have ideal properties because they have the proper optical constants enabling the entire particle to be an active absorber of energy. Once the particles have absorbed the solar energy they rapidly give this energy to the surrounding gas. The reason for this is because of the particles' large surface area-to-mass, and surface area-to-volume ratio.

The main focus of this project is to create a scalable system capable of suspending pre-fabricated carbon particles in a cloud. The cloud will be used to absorb solar energy and transfer that energy into the surrounding air. During the energy transfer process the solar receiver will achieve temperatures of 1000 – 1300 ˚C oxidizing the carbon. The resulting super heated carbon dioxide and air will force its way through a gas turbine producing power. Essentially, the carbon particle disperser and solar receiver will take the place of a traditional combustion chamber within a Brayton cycle.

Project Definition

The following is the original project definition from the Spring 2009 semester. It established the basic description of the project and provided a set of guidelines to follow throughout the design process.



SAN DIEGO STATE UNIVERSITY	SENIOR PROJECT DEFINITION	
	TITLE: **Carbon Particle Cloud Generator**	
	DOCUMENT NO. **MESP 0002**	PRINTED: 2/14/09
COLLEGE OF ENGINEERING Department of Mechanical Engineering	CONFIDENTIALITY: **PROPRIETARY,** **DO NOT DISTRIBUTE.**	PAGE 1 OF 3

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3 PROJECT DESCRIPTION

The Carbon Particle Cloud Generator is one component of a thermal solar power generation plant. Its function is to absorb sunlight and efficiently heat the working fluid (air) in a Brayton power cycle. The project is research-based and its primary objective is to determine the viability of the particle cloud generator in a full-scale power plant. This project is part of a two-year venture with Google.

Description: We will design and build a device to suspend prefabricated particles (carbon) in a cloud to collect solar radiation. The project will also include various sensors, a monitoring system, and a way to control components of the system and properties of the particle cloud. The final product will be a small scale working prototype.

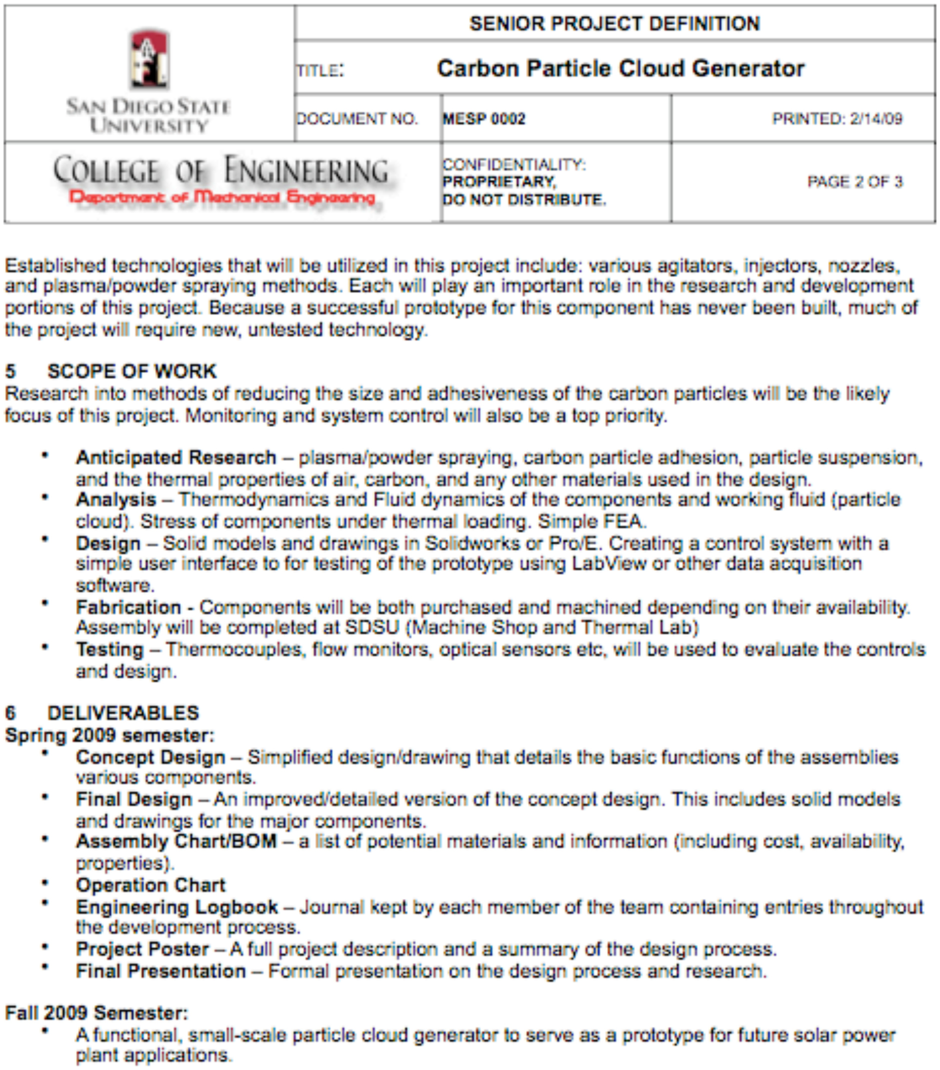
Reason: Using suspended carbon particles as a method for heat transfer has proven to be a highly efficient way of capturing the sun's radian energy. Incorporating this into a large scale solar power plant would be beneficial to the energy industry.

Considerations: Control of this system is the primary objective. This includes temperature, and pressure monitoring, as well as flow rates and particle size. The goal is to create a simple user interface of feedback and controls so the particle cloud can be adapted to a large variety of test conditions.

4 ESTABLISHED WORK

Research has been done in this particular field, but thus far, no viable method of controlling/sustaining a carbon cloud has been perfected. The Department of Environmental Science and Energy Research at Weizmann Institute of Science recently conducted a study on various methods of particle entrainment. This study was published in the Journal of Solar Energy Engineering. These results, along with Professor Miller and Hunt's own research, will serve as the starting point for this project (see attached articles).

Form MESP 0002



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Established technologies that will be utilized in this project include: various agitators, injectors, nozzles, and plasma/powder spraying methods. Each will play an important role in the research and development portions of this project. Because a successful prototype for this component has never been built, much of the project will require new, untested technology.

5 SCOPE OF WORK

Research into methods of reducing the size and adhesiveness of the carbon particles will be the likely focus of this project. Monitoring and system control will also be a top priority.

- **Anticipated Research** – plasma/powder spraying, carbon particle adhesion, particle suspension, and the thermal properties of air, carbon, and any other materials used in the design.
- **Analysis** – Thermodynamics and Fluid dynamics of the components and working fluid (particle cloud). Stress of components under thermal loading. Simple FEA.
- **Design** – Solid models and drawings in Solidworks or Pro/E. Creating a control system with a simple user interface to for testing of the prototype using LabView or other data acquisition software.
- **Fabrication** - Components will be both purchased and machined depending on their availability. Assembly will be completed at SDSU (Machine Shop and Thermal Lab)
- **Testing** – Thermocouples, flow monitors, optical sensors etc, will be used to evaluate the controls and design.

6 DELIVERABLES

Spring 2009 semester:

- **Concept Design** – Simplified design/drawing that details the basic functions of the assemblies various components.
- **Final Design** – An improved/detailed version of the concept design. This includes solid models and drawings for the major components.
- **Assembly Chart/BOM** – a list of potential materials and information (including cost, availability, properties).
- **Operation Chart**
- **Engineering Logbook** – Journal kept by each member of the team containing entries throughout the development process.
- **Project Poster** – A full project description and a summary of the design process.
- **Final Presentation** – Formal presentation on the design process and research.

Fall 2009 Semester:

- A functional, small-scale particle cloud generator to serve as a prototype for future solar power plant applications.

7. FUNDING

Source of funding: Google
Amount available: $5000

Team Assignments

This section contains the assignments completed throughout the coarse of the Fall 2009 semester. See Appendix for Weekly Meeting Reports.

Project Management Plan

Fall 2009 Timeline

Week (Monday)

9/14 – Find/ read/ understand fluidization engineering books, papers, and journals.
Determine pressures, flow rates, and complete a general fluid dynamic analysis on the system.

9/28 – Modify LabView program to experiment with different system inputs/ scenarios.
Determine tube size and general fluidized bed sizes.
Determine final system configuration.

10/5 – Complete fluidized bed and nozzle design including all dimensions.
Create a solid model and complete drawings needed to start machining.

10/19 – Acquire materials needed to start fluidized bed and nozzle fabrication.

11/2 – Acquire tubing and other components needed to test the fluidized bed and nozzle.
Start fabrication of the fluidized bed and nozzle components.

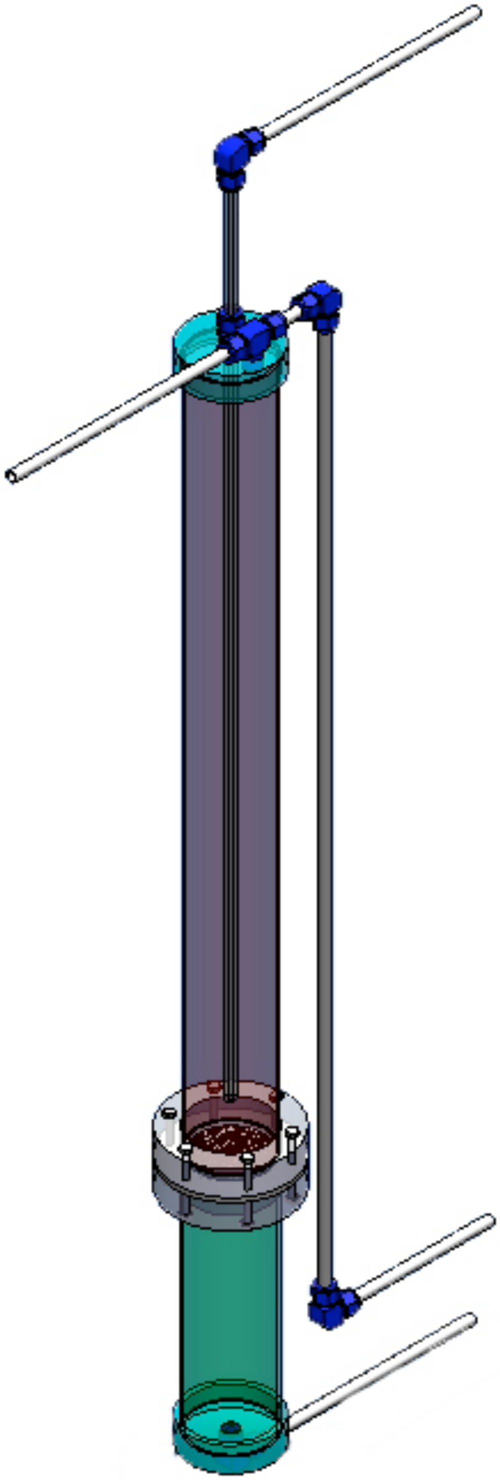
11/16 – Continue fabrication of components.

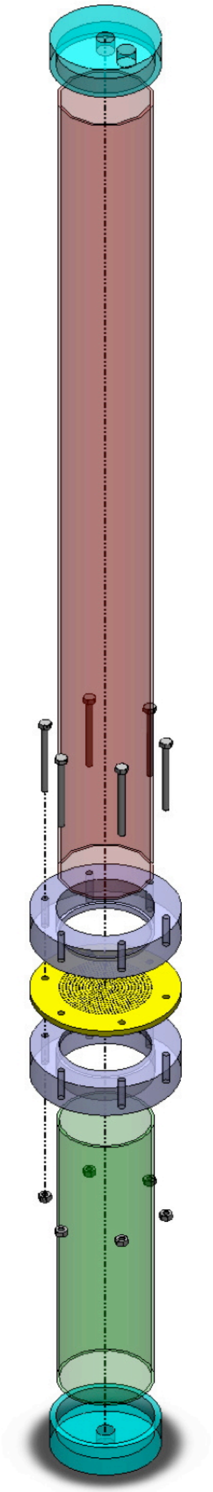
11/30 – Assemble fluidized bed, tubing, and flow controllers.
Start testing.

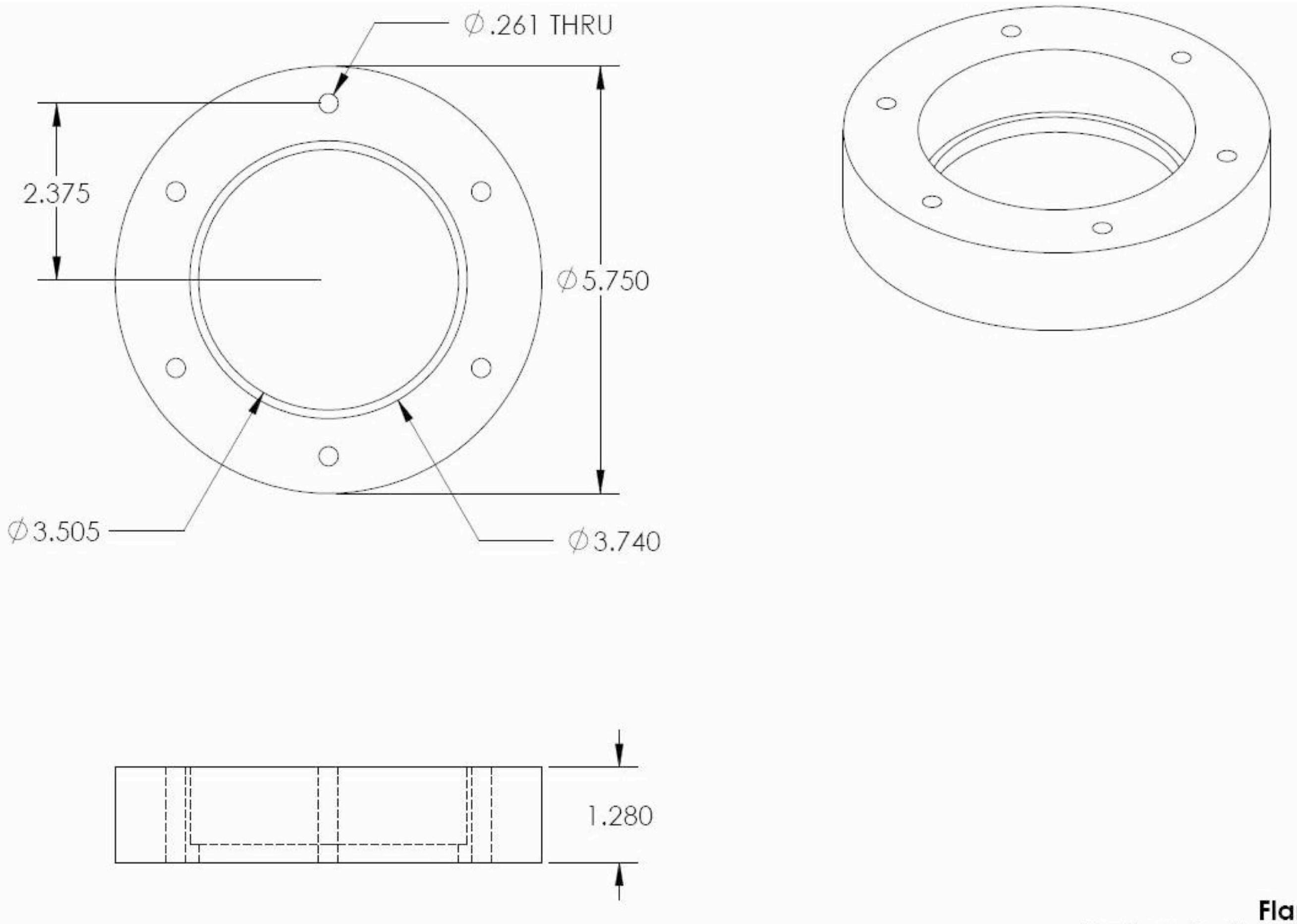
12/7 – Optimize system for efficient and desired operation.
Deliver prototype to Dr. Miller.

Design Drawings

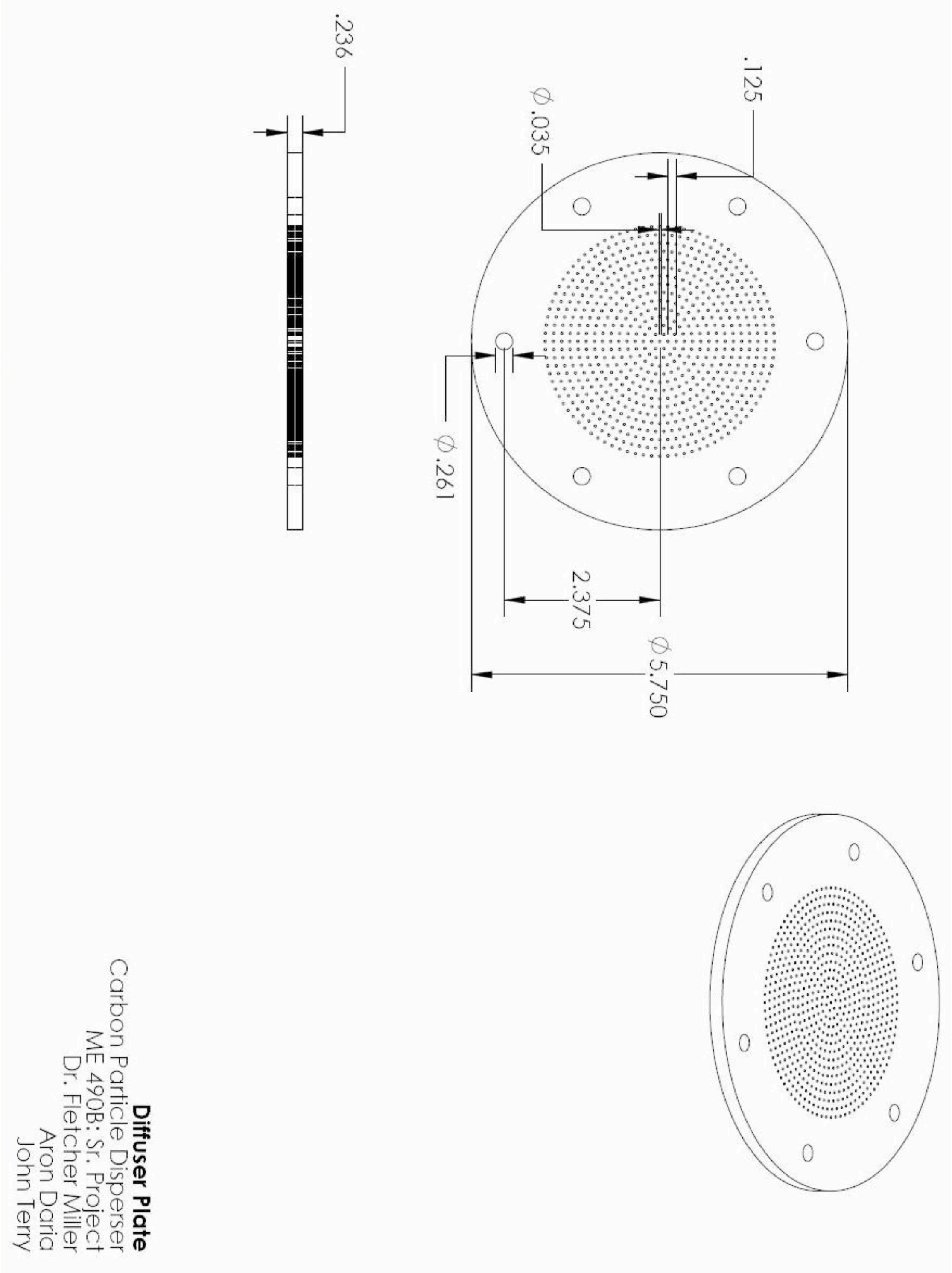
Drawings of machined parts only.

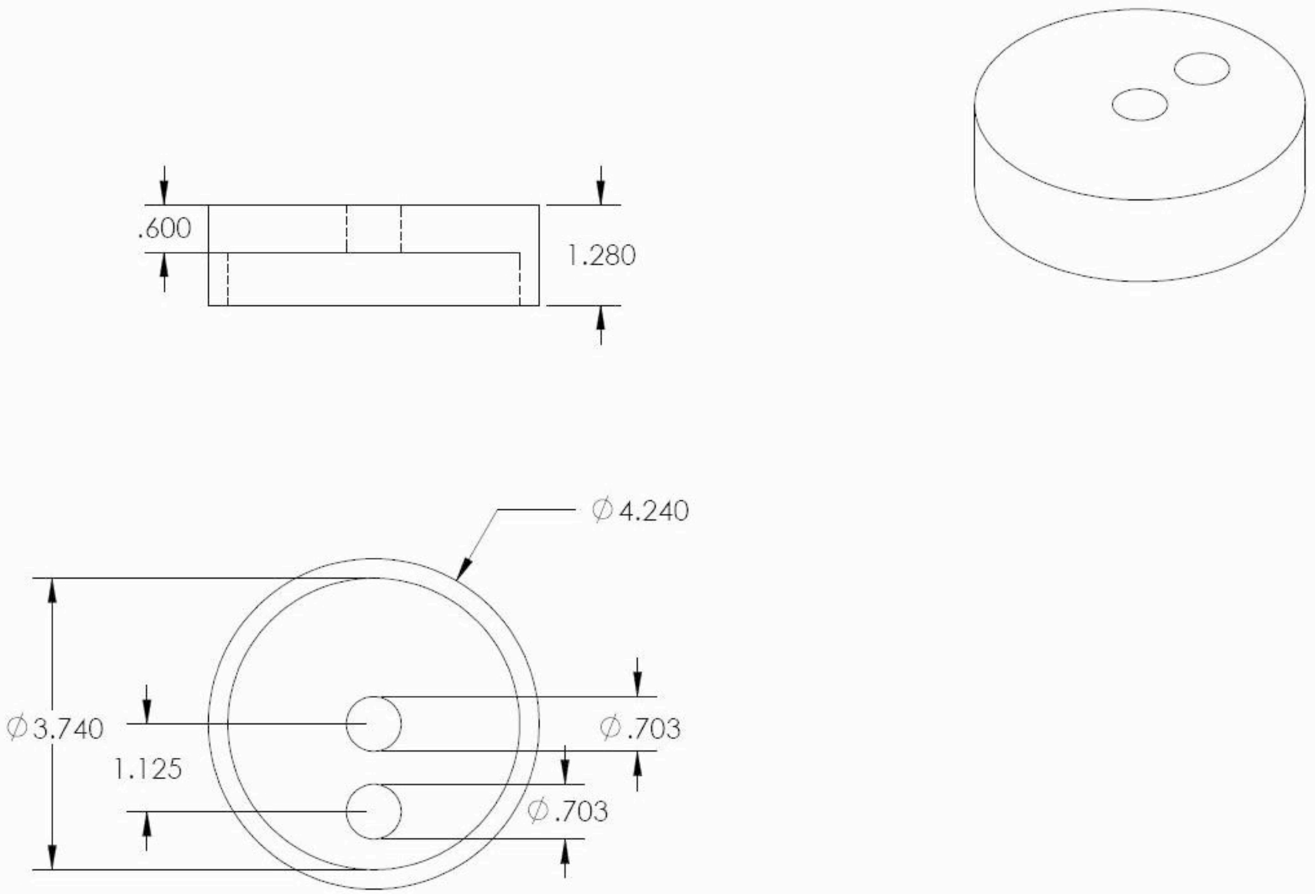




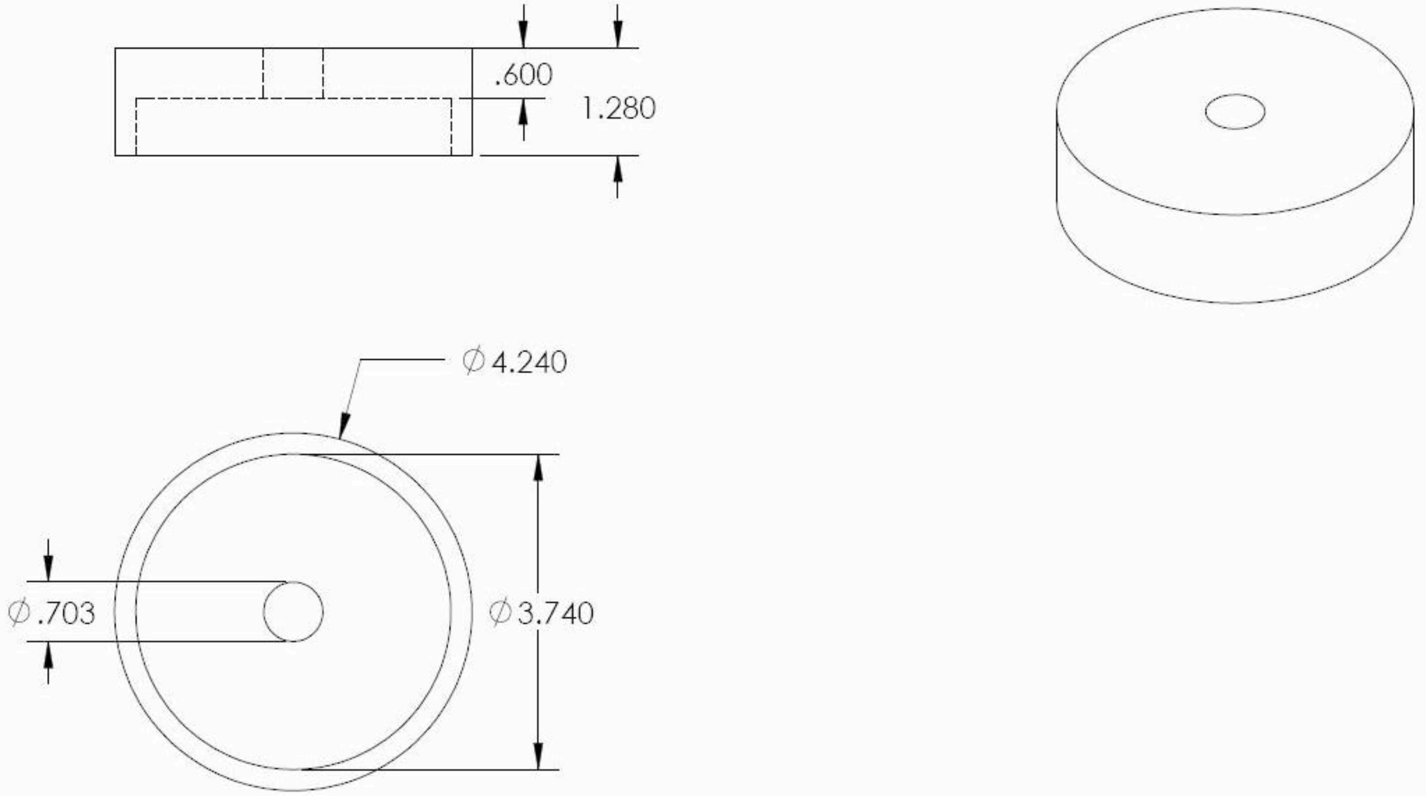


Flange (2X)
Carbon Particle Disperser
ME 490B: Sr. Project
Dr. Fletcher Miller
Aron Daria
John Terry


.125
⌀.035
.236
⌀.261
2.375
⌀5.750
Diffuser Plate
Carbon Particle Disperser
ME 490B: Sr. Project
Dr. Fletcher Miller
Aron Daria
John Terry



Top End Cap
Carbon Particle Disperser
ME 490B: Sr. Project
Dr. Fletcher Miller
Aron Daria
John Terry



Bottom End Cap
Carbon Particle Disperser
ME 490B: Sr. Project
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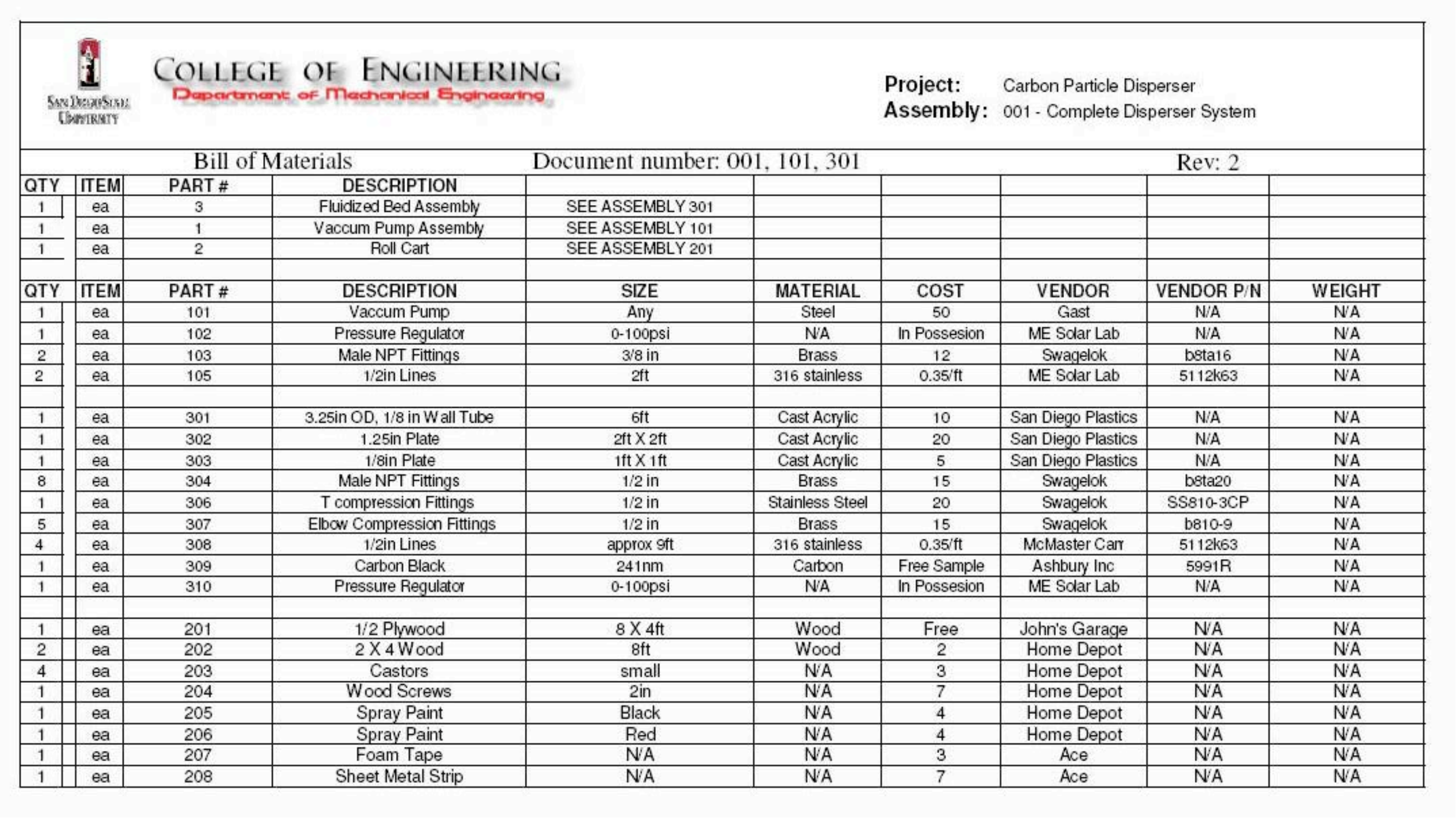
John Terry

Bill of Materials



COLLEGE OF ENGINEERING
Department of Mechanical Engineering

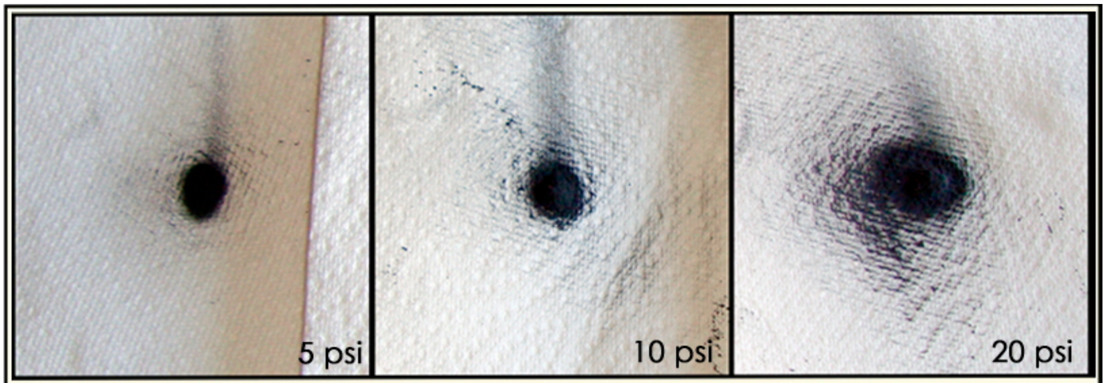
San Diego State University

Project: Carbon Particle Disperser
Assembly: 001 - Complete Disperser System

Bill of Materials | Document number: 001, 101, 301 | Rev: 2

QTY	ITEM	PART #	DESCRIPTION						
1	ea	3	Fluidized Bed Assembly	SEE ASSEMBLY 301					
1	ea	1	Vaccum Pump Assembly	SEE ASSEMBLY 101					
1	ea	2	Roll Cart	SEE ASSEMBLY 201					
QTY	**ITEM**	**PART #**	**DESCRIPTION**	**SIZE**	**MATERIAL**	**COST**	**VENDOR**	**VENDOR P/N**	**WEIGHT**
1	ea	101	Vaccum Pump	Any	Steel	50	Gast	N/A	N/A
1	ea	102	Pressure Regulator	0-100psi	N/A	In Possesion	ME Solar Lab	N/A	N/A
2	ea	103	Male NPT Fittings	3/8 in	Brass	12	Swagelok	b8ta16	N/A
2	ea	105	1/2in Lines	2ft	316 stainless	0.35/ft	ME Solar Lab	5112k63	N/A
1	ea	301	3.25in OD, 1/8 in Wall Tube	6ft	Cast Acrylic	10	San Diego Plastics	N/A	N/A
1	ea	302	1.25in Plate	2ft X 2ft	Cast Acrylic	20	San Diego Plastics	N/A	N/A
1	ea	303	1/8in Plate	1ft X 1ft	Cast Acrylic	5	San Diego Plastics	N/A	N/A
8	ea	304	Male NPT Fittings	1/2 in	Brass	15	Swagelok	b8ta20	N/A
1	ea	306	T compression Fittings	1/2 in	Stainless Steel	20	Swagelok	SS810-3CP	N/A
5	ea	307	Elbow Compression Fittings	1/2 in	Brass	15	Swagelok	b810-9	N/A
4	ea	308	1/2in Lines	approx 9ft	316 stainless	0.35/ft	McMaster Carr	5112k63	N/A
1	ea	309	Carbon Black	241nm	Carbon	Free Sample	Ashbury Inc	5991R	N/A
1	ea	310	Pressure Regulator	0-100psi	N/A	In Possesion	ME Solar Lab	N/A	N/A
1	ea	201	1/2 Plywood	8 X 4ft	Wood	Free	John's Garage	N/A	N/A
2	ea	202	2 X 4 Wood	8ft	Wood	2	Home Depot	N/A	N/A
4	ea	203	Castors	small	N/A	3	Home Depot	N/A	N/A
1	ea	204	Wood Screws	2in	N/A	7	Home Depot	N/A	N/A
1	ea	205	Spray Paint	Black	N/A	4	Home Depot	N/A	N/A
1	ea	206	Spray Paint	Red	N/A	4	Home Depot	N/A	N/A
1	ea	207	Foam Tape	N/A	N/A	3	Ace	N/A	N/A
1	ea	208	Sheet Metal Strip	N/A	N/A	7	Ace	N/A	N/A

Test Analysis



These results demonstrate the controllability of the system. Particles were passed onto a filter for incoming flow rates of 5, 10, and 15 psi for 5 seconds. The flow in the recirculation loop was kept constant for each test.

The testing equipment that will be used on the carbon cloud output has not been completed or calibrated. This includes the Extinction Tube and the Diesel Particle Spectrometer. Until this equipment is ready, visual tests will be conducted.

Test 1: The first of these visual tests involved passing the carbon output through filters (paper towels) and comparing the deposits. For each trial, the fluidization rate was kept constant, and the cloud was passed through the filter for five seconds. This test was conducted at successively higher incoming fresh air flow rates. After the trials were conducted, the results were compared.

Results: Initial results showed the carbon particle disperser provides a desirable control over the cloud output. A carbon cloud is produced at all ranges of flow; this includes low flow rates, which is a problem for other fluidized beds.

Project Poster

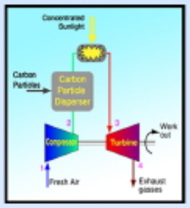
Carbon-Particle Disperser

What is a Carbon-Particle Disperser?

A carbon particle disperser mixes air and prefabricated carbon particles to produce a continuous, consistent cloud.

What is it used for?

The carbon cloud produced by this system will absorb concentrated sunlight and convert it to thermal energy. This energy will eventually power a turbine in an open-Brayton power cycle.



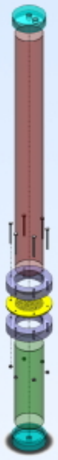
An Open-Brayton Cycle with our Carbon-Particle Disperser.

Why is this important?

Using a carbon-particle cloud to absorb solar flux is more efficient than current coolant-driven systems. Higher efficiencies mean lower energy costs for the consumer.

How does it work?

Fresh air passes into the top of the cylinder, forcing a carbon cloud out of the ejection tube. The adjoining recirculation loop independently controls particle mixing.



Fluidized Bed:

The term, "Fluidized bed" refers to the bubbling carbon-air mixture that sits on the diffuser plate (yellow) inside the acrylic cylinder. This may also include the upper chamber (Flange, endcap, and cylinder).

Particle Ejection Tube:

This is the 1/2 in. tube can easily be adjusted to match the height of the fluidized bed. This gives the user greater control over the final cloud.

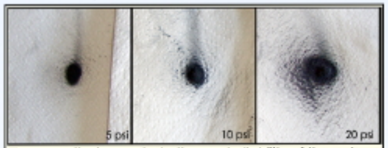
Recirculation Loop:

This takes air from the top of the upper chamber to the lower chamber. A diaphragm pump coupled with a pressure regulator control the flow of air. This unique feature generates a consistent fluidized bed for any fresh-air flow rate.

Diffuser Plate:

This evenly distributes re-circulated air throughout the bed of carbon particles. Future plates will incorporate small motors to further agitate the carbon.

Preliminary Results:



These results demonstrate the controllability of the system. Particles were passed onto a filter for incoming flow rates of 5, 10, and 15 psi for 5 seconds. The flow in the recirculation loop was kept constant for each test.

Pictured (from left): Dr. Fletcher Miller, Aron Daria, and John Terry

Acknowledgements:
Sponsor: Google.org
Advisers: Dr. Arlon Hunt
Dr. Fletcher Miller
Special Thanks:
Dr. Kee Moon
Dr. Sam Kassegne
Asbury Carbons

Design

Specifications

Quick Comparison:

Table. 1. Original Target Specifications

Gas Flow Rate:	25 – 60 L/min = 125 – 600 SLPM = 0.0004167 – 0.001 m3/s = 1.5 – 3.6 m3/hr
Particle Density:	1 – 3 g/m3 = 0.001 – 0.003 kg/m3
Particle Injection Rate:	1.5 – 10.8 g/hr = 0.0015 – 0.0108 kg/hr
Pressure:	5 – 10 atm = 506.6 – 1013 kPa = 73.48 – 146.96 psi
Extinction Coefficient (α):	2m-1
Particle Diameter:	0.5 – 1.0 μm
Budget:	$5,000

Table. 2. Final Specifications

Gas Flow Rate:	25 – 60 L/min Adjustable
Particle Density:	1 – 3 g/m3 = 0.001 – 0.003 kg/m3
Particle Injection Rate:	1.5 – 10.8 g/hr = 0.0015 – 0.0108 kg/hr
Pressure:	0 atm Potential to increase to high pressure system
Extinction Coefficient (α):	2m-1
Particle Diameter:	0.5 – 1.0 μm
Final Cost:	$365.00

Detailed Specifications:

Input:

Carbon Particles: Asbury, 230nm diameter carbon black
Air: Compressed air from .25” line

Output:

Carbon Cloud

Performance Requirements:

Air Lines: Compressor (must maintain adequate pressure)
Pump: 120V AC Power outlet

Environmental Conditions:

Humidity: Low humidity conditions will keep the carbon from agglomerating

Constraints (Including Economic):

Materials:

- Acrylic:
  - Upper/Lower Chamber: 3.75” OD cast acrylic tube
  - Diffuser Plate: 0.125” cast acrylic plate
  - Flanges/End Caps: 1.25” cast acrylic plate
- Lines: 0.5” stainless steel tube
- Fittings: Assorted Brass Swagelok compression fittings
- Stand:
  - Base: (2) 0.5” plywood sheets
  - Legs: (3) 2X4”

Concepts

ME490A:

These are the original concepts for the overall system design and its individual components.

General Assembly Concepts:

1. **Spray Gun:**

   This concept is a single-piece fixture that would take a gas and particle input and automatically generate a particle cloud of the desired density and consistency.

   Pros: Simple – A one-piece design would minimize assembly time, components and overall cost.

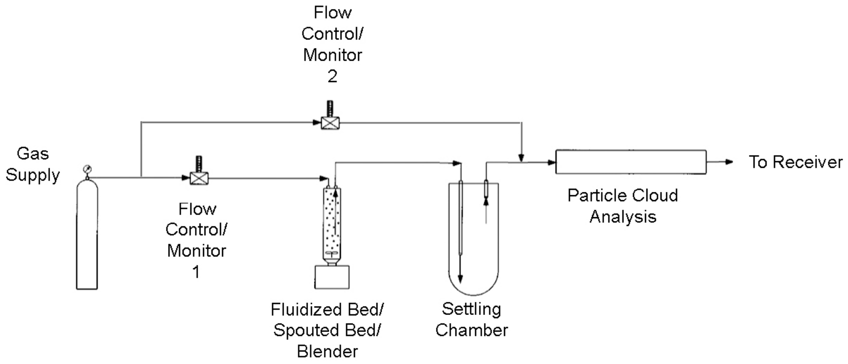
   Cons: Design and testing phase will be difficult. Any changes would require an entire revision, beginning with the concept designs. Because of the way ME 490A (design) and ME 490B (assembly) is structured, a nozzle design is not a realistic option.

2. **Mobile Radiation Absorbing Surface:**

   This concept will include several components. Each will have a specialized function in generating the carbon particle cloud (mobile radiation absorbing surface). The components will be: a gas supply (intake), two combination flow controllers/monitors, a particle-gas mixer (a fluidized bed, spouted bed, or a blender), a separator (settling chamber or cyclone separator) and a particle cloud analyzer.

   Pros: Separate specialized components make the alterations during the design, testing and prototyping phases easier. Also, all of the research on cloud generators thus far has been based on this concept.

   Cons: This concept also relies heavily on the testing phase. Several designs will need to be prototyped and tested for this project to be a success.



General Concept Conclusion:

Based on the structure of the ME 490 A-B course sequence, the Mobile Radiation Absorbing Surface Concept will be the best choice for the assembly design.

Component Concepts:

1. Flow Controllers/Monitors:

Flow controllers and monitors already exist, so we will buy one. There will be no need to design or modify any part of it. Target specifications for our carbon particle cloud generator are provided in the appendix of this report.

2. Particle-Gas Mixer:

The Particle-Gas mixer component will require a great deal of design and testing. This is because it, along with the separator, will have the greatest affect over the final particle cloud. Our research shows that the mixer has been used only to get the carbon particles into a cloud state. The separator would then be used to remove the agglomerated particles. We would like to improve upon these designs by including a way to break up the agglomerated particles. This will decrease the demand upon the separator.

A. Fluidized Bed:

One option for the Particle-Gas Mixing component is a fluidized bed. This has been used in several prior particle-cloud generation experiments to date. So far, however, fluidized beds have not been able to sustain a consistent cloud for prolonged periods of time. Figure 1 shows a diagram of a fluidized bed.

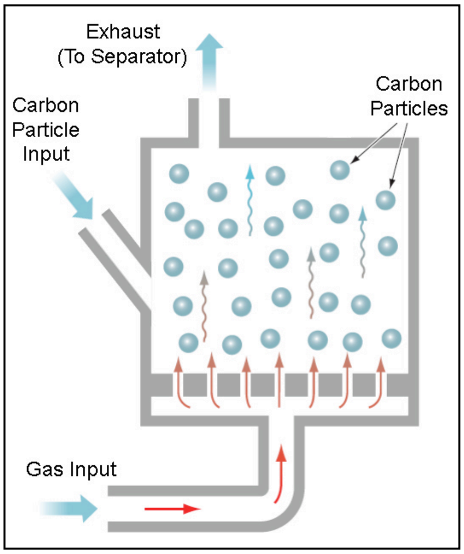


Fig. 1. Fluidized bed diagram.

B. Spouted Bed:

The spouted bed has shown the most promise, in terms of sustainability over a large range of flow rates. Unfortunately, few specifications are given into the equipment and lab setup. Figure 2 shows a diagram of the internal operation of a spouted bed.

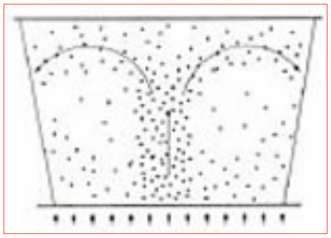


Fig. 2. Spouted bed diagram.

C. Blender:

Blenders have shown promise in terms of consistency but have only worked for limited flow rates. This is because at higher rates, the cloud begins to rotate and become a vortex. Only rotating mixers have been used so far. We would like to research vibrating mixers for a possible application in our carbon particle-cloud generator.

D. **Hybrid Combination**:

This concept would be a combination of two of the particle-gas mixer concepts above. The most promising combination would be a spouted bed/blender. This would allow a sustained cloud over a wide range of flow rates, which can also break apart many of the agglomerated particles. This would lighten the load for the separator.

3. Separator:

1. **Settling Chamber:**

   This concept would involve passing the particle cloud through a large chamber. The large cross-sectional area would slow the velocity of the flow enough that the larger agglomerated particles can settle to the bottom of the tank. Only the particles of the desired size would pass to the next component in the assembly.

2. **Cyclone Separator:**

   A cyclone separator would utilize a high-speed vortex to separate the larger particles from the cloud due to centrifugal force. Figure 5 shows a simplified design of a cyclone separator.

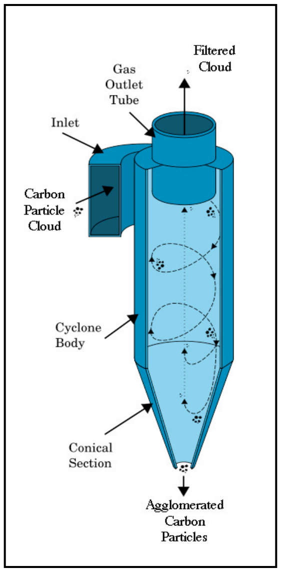


Fig. 3. Cyclone separator diagram

C. Nozzle:

A nozzle is different from a settling chamber or cyclone because it would directly separate the agglomerates directly. This would be beneficial because it would eliminate the need to manually remove these agglomerates from the collection chambers.

One problem with nozzles, however, is they tend to clog. Therefore, it may be necessary to use a nozzle in combination with a cyclone or settling chamber. The remaining question is then: Should the nozzle be placed before or after the cyclone/settling chamber?

Before: This would break apart the agglomerates so the separator would not have to remove as many particles but would also leave the nozzle more susceptible to blockage.

After: Placing the nozzle after the separator would reduce the likelihood of blockage, but would increase the load on the separator.

Note: Because the lines connecting each component will be flexible and have quick release attachments, we will be able to move and interchange the components in the testing phase of this project.

4. Particle Cloud Analyzer:

We will be using existing SDSU lab equipment for the data acquisition and analysis portion of this project. No design will be necessary.

Final Concept:

The mathematical modeling provided the team with the information needed to design a nozzle for system. Our research has show, thus far, that a spouted bed would produce the most consistent cloud over a range of flow rates. Because the ability to operate under a range of flow rates is such a high priority to this project, the spouted bed is included in this design. Figure 4 shows the complete system design including the fluidized bed.

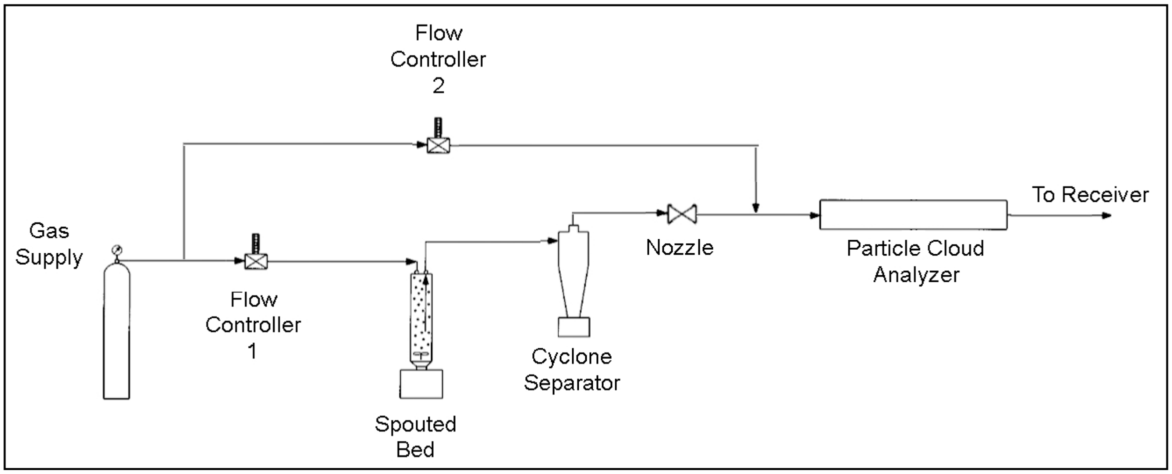


Fig. 4. The Preliminary Design for the Carbon particle Disperser.

-Flow Controllers/Monitors (2):

Flow controller 1 will fluidize the particles.

Flow controller 2 will adjust the cloud density (particles per volume).

-Spouted Bed: This will disperse carbon particles, to form a rough cloud

-Cyclone Separator: This component will remove the larger particle agglomerates

-Nozzle Assembly: The nozzle assembly will break up the smaller agglomerates leaving only particles between 0.2 and 1.0 µm.

-Particle Cloud Analyzer: Measures cloud properties/feedback so adjustments can be made with the flow controllers.

ME490B:

This system (right) concept was a direct result of a pressure analysis of the system. It was determined that 200 psi would be needed at the beginning of this system to accommodate the supersonic nozzle and the high-pressure solar receiver.

Because high-pressure components are expensive, the decision was made to remove the supersonic nozzle and build a low-pressure system to prove the concept.

The concept, seen to the right is the first low-pressure concept. It should be noted at this point, that this concept stood up to future analysis and remained as the final design for ME490B: Senior Project.

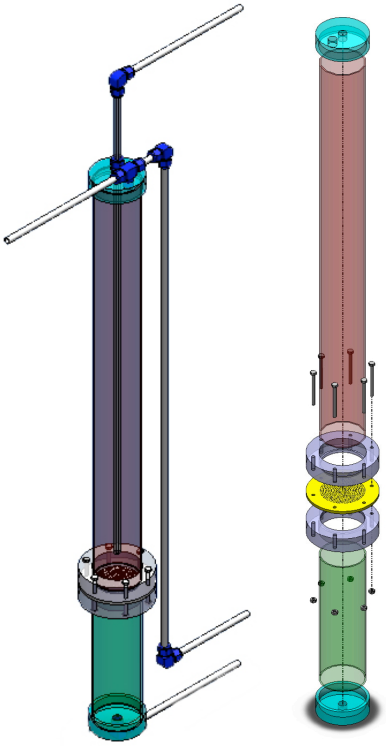


Fig. 5. Final System concept. Solidworks.

Analysis/Preliminary Testing

Hand Calculations:

The analysis performed in the first semester of this project was based in hand calculations. The nozzle, mentioned in the 490A-design section, was supposed to separate agglomerated particles by generating a shear force between the particles and the nozzle walls.

The following calculations deal with the shear force and Van Der Waals forces in the nozzle:

Equations:

Nozzle equation (conservation of mass):

$$\boldsymbol{\rho_0 \bullet A_0 \bullet V_0 = \rho^* \bullet A^* \bullet V^*} \qquad \textbf{(1)}$$

ρ = Density
A = Cross-sectional area
V = Flow velocity

Shear force equation (viscous fluid):

$$\mathbf{F = \mu \bullet A \bullet (du/dy)} \qquad \textbf{(2)}$$

F = Shear force on particle
μ = Dynamic viscosity
A = Surface area
du = Velocity
dy = distance from the adjacent surface.

Van Der Waals force between two spherical particles:

$$\mathbf{F_{vdW} = A \bullet d_1 \bullet d_2 / 6 \bullet D_p{}^2 (d_1 + d_2)} \qquad \textbf{(3)}$$

A = Hamaker Constant (about 10^{-19} J)
D_p = Distance between particles (surface to surface. About 0.4 nm)
d = Particle diameter (230 nm)

Nozzle Diameter Calculations:

First, the force bonding these carbon particles must be estimated. The Van Der Waals equation (eqn. 3) is used. The Hamaker constants are found experimentally, and have been tabulated for many material combinations. Unfortunately, we could not find a value for a carbon-carbon interface. Average values for Hamaker constants are from 10^{-19} to 10^{-21} Joules. The largest value of these two was used, because it will yield a more conservative estimate for Van Der Waals force.

d_1 and d_2 are 230 nm, since this is the primary size of the carbon black particles we will be using. 0.4 nm will be used for D_p since research has shown that this is a typical value for spheroid particles. Figure 6 shows a diagram of the distance between the particles.

$F_{vdW} = (1 \cdot 10^{-19}\ \mathrm{J}) \cdot (230 \cdot 10^{-9}\ \mathrm{m})^2 / 6 \cdot (0.4 \cdot 10^{-9}\ \mathrm{m})^2 \cdot 2(230 \cdot 10^{-9}\ \mathrm{m})$

$F_{vdW} = 1.198 * 10^{-8}\ \mathrm{N}$

$\mathbf{F_{vdW} = 11.98\ nN}$

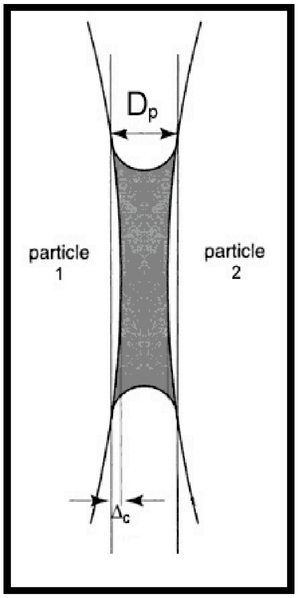


Fig. 6. Van Der Waals forces between two spherical Particles

12 nN is the estimate for the maximum Van Der Waals force between carbon particles in our carbon particle cloud. Therefore, this will also be the minimum shear force needed to separate the carbon agglomerates. To find the nozzle throat diameter needed to break up the agglomerates, we put our result into equation two and solved for the throat diameter. Figure 7 shows a cross sectional view of the nozzle throat with an agglomerated particle passing through it.

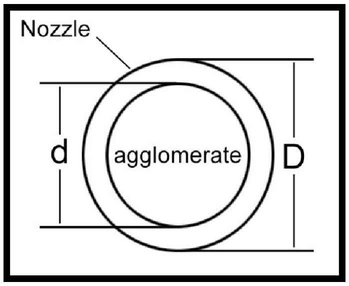


Fig. 7. Cross sectional view of the nozzle throat with a spherical agglomerate passing through it

$\mathbf{11.98\ nN = F_s = \mu A(du/dy)}$

μ = Dynamic Viscosity ($1.8 \cdot 10^{-6}$ Pa•s)

A = Surface area = πd^2 ($d_{max} = 1.0\ \mu m$)

$dy \approx y_{avg} = D - 0.7854\ \mu m$

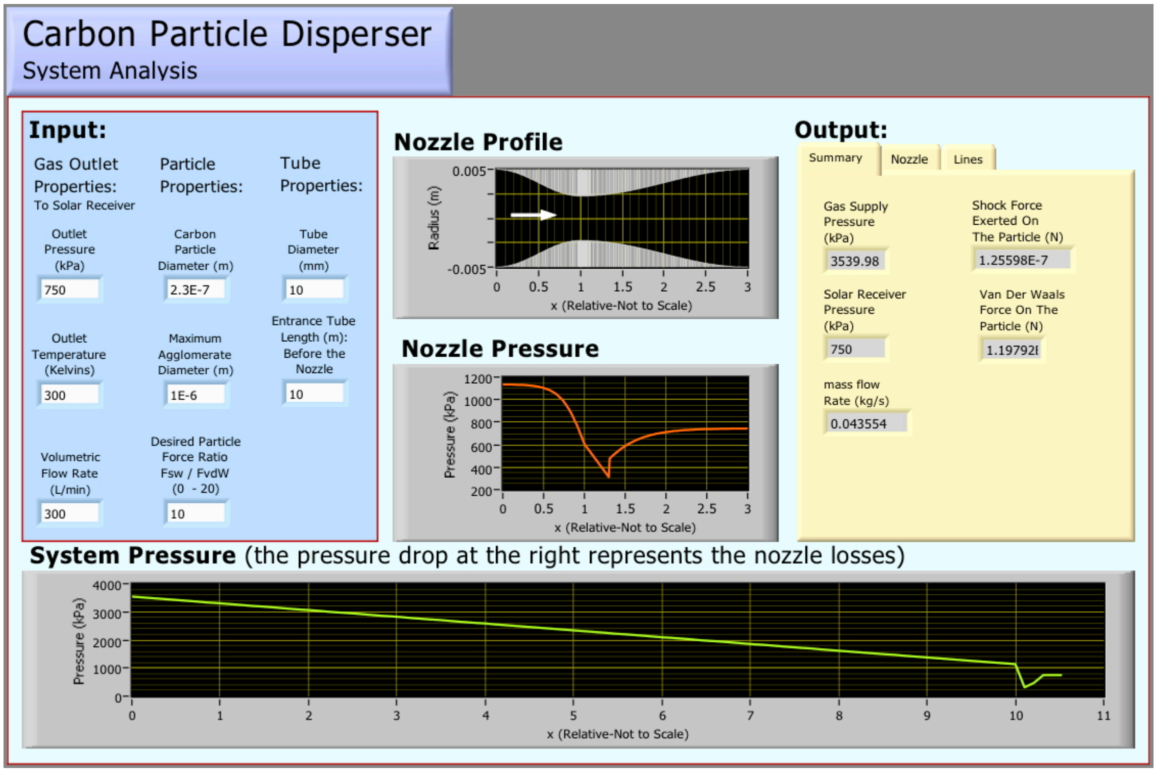
$du = V$ = constant over particle

Note: To simplify things, y_{avg} was used for dy and V (a constant velocity) was used for du. This assumption means that our particle model is a cylinder of length, d_{max}, and radius, 0.7845μm. The surface area for a sphere is still used however. We are currently refining this model, and hope to have an accurate shear force equation for a sphere in a pipe soon.

LabVIEW

After performing hand calculations, it was determined that the shock wave within the supersonic nozzle would impart more force on agglomerated particles that the shear force would. For this analysis, a complete pressure profile of the system was desired.

A program was created in LabVIEW to calculate all of the important properties in the system based on a few simple input parameters.



Carbon Particle Disperser
System Analysis

Input:

Gas Outlet Properties: To Solar Receiver
Outlet Pressure (kPa): 750
Outlet Temperature (Kelvins): 300
Volumetric Flow Rate (L/min): 300

Particle Properties:
Carbon Particle Diameter (m): 2.3E-7
Maximum Agglomerate Diameter (m): 1E-6
Desired Particle Force Ratio Fsw / FvdW (0 - 20): 10

Tube Properties:
Tube Diameter (mm): 10
Entrance Tube Length (m): Before the Nozzle: 10

Output:

Summary | Nozzle | Lines

Gas Supply Pressure (kPa): 3539.98
Solar Receiver Pressure (kPa): 750
mass flow Rate (kg/s): 0.043554
Shock Force Exerted On The Particle (N): 1.25598E-7
Van Der Waals Force On The Particle (N): 1.19792I

Fig. 8. The front panel of the LabVIEW program, showing results for a set of input parameters. Results (Outputs) include a Nozzle Profile, Nozzle Pressure Profile, System Pressure Profile, and several tabulated system properties.

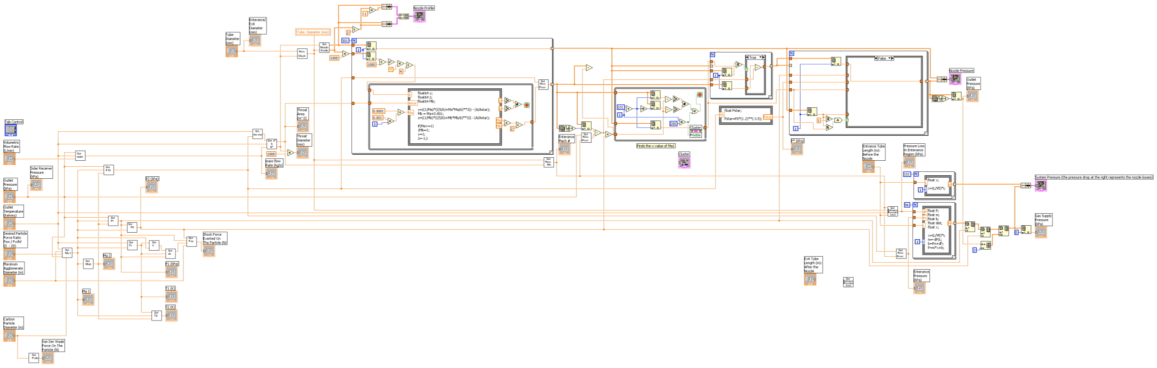


Fig. 9. The main block diagram for the LabVIEW program. Most of the property solving is performed within the SubVIs seen at the far left. The right 2/3 of the diagram are concerned with displaying the results.

Design Solution

The LabVIEW analysis showed that the high-pressure design was feasible. High-pressure components are expensive, however; and it was decided to build a low-pressure system to prove the carbon particle disperser as a concept.

Prototype Design

Fig. 10. Carbon Particle Disperser Prototype

The prototype (left) was machined from acrylic and bonded together with acrylic cement and bolts. A modified compressor pump was used to move air through the recirculation loop. A 35 gallon, compressor was used to force fresh air into the system. 1/2 “ acrylic lines were used to connect the compressor pump to the system. Swagelok fittings were used to attach all plumbing.

Testing was performed on this mockup to determine weather the carbon would fluidize in the upper chamber. All test performed with this rough prototype were visual in nature, meaning no numerical data was recorded.

Result: The prototype was successful in fluidizing the carbon. We determined, from the visual inspection of the cloud produced by the system, that no major changes were necessary in the design.

One recommendation was to acquire a more powerful pump, as the fluidization rate with the modified compressor pump was low. We hypothesized that a higher rate of fluidization would equate to a more consistent, uniform cloud.

Calculations/Verification:

Acrylic is not capable of handling high pressures. The design attempts to keep all pressure in the system to a minimum, however high recirculation rates can cause pressure buildup in the lower chamber.

Because our pumps were donated, not much was known about their flow rates. Calculations were performed to determine the maximum allowable pressure in the lower chamber. A safety factor of 3 was chosen for the system:

Maximum working pressure of a cast acrylic cylinder:

$$\sigma_t = \frac{pr}{t} \qquad p = \frac{\sigma_t t}{r} \qquad p_w = \frac{p}{n}$$

σ_t – *tensile hoop stress (5800psi - Matweb)*
p – *pressure*
t – *wall thickness (.125in)*
r – *inside radius (1.75in)*
p_w – *maximum working pressure*
n – *safety factor (assume 3)*

$$p = \frac{(5800\,psi)(.125\,in)}{(1.75\,in)} = 414.3\,psi$$

$$p_w = \frac{414.3\,psi}{3} = 138.1\,psi$$

These results are promising since the maximum pressure produced by our pumps is 150 – 175 psi. Because the pumps are regulated to operate below those pressures, and because the lower chamber is partially open (air must pass through the diffuser plate), the lower chamber should not fail.

Final Design and Test Results

For the final iteration in the system's design, several improvements were made over the prototype. The final design (right) has a permanent stand, with wheels for easy transportation, a vacuum diaphragm pump, two pressure regulators, ½" stainless steel plumbing, and a quick-connect ¼" air line adapter.

The stand was painted red and black to match SDSUs school colors. The hex bolt/nut connection at the diffuser plate allows for quick disassembly to enhance cleaning, maintenance and transportation.

Fig. 11. Carbon Particle Disperser: Final Design

Description

Upper Chamber:

- Easy to assemble disassemble
- Simple to clean, perform maintenance, and swap parts

Diffuser Plate:

- Interchangeable
- Different hole arrays accommodate various carbons
- Future plates may have small electric motors to enhance fluidization

Recirculation Loop:

- Unique to fluidized beds
- Allows independent control of fluidization and cloud production

Particle Ejection Tube:

- Adjustable height provides some control over cloud density

Fig. 12. Upper Chamber, Diffuser Plate, Recirculation Loop, and Ejection Tube (from top)

Diaphragm Vacuum Pump:

- Gast DAA-V717-GB Diaphragm Pump
- Sealed compression chamber eliminates the possibility of carbon-particle malfunction

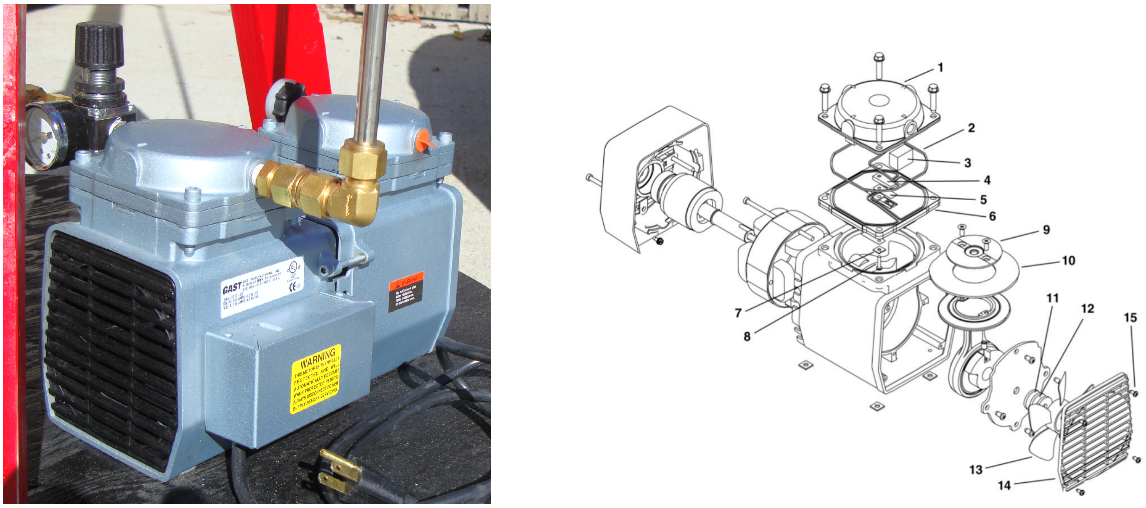


Fig. 13. Gast Daa-V717-GB Diaphragm Pump

Operating Procedure

1. Make sure all components and equipment are clean and in safe operating condition.
2. Turn all pressure regulators to their off setting (0psi)
3. Connect the lower chamber—diffuser plate—upper chamber assembly with the six ¼ 20 hex bolts.
4. Fill the upper chamber with a desired amount of carbon black.
5. Put the top end cap onto the upper chamber. Make sure the top end cap is seated snuggly on the upper cylinder.
6. Connect all stainless steel lines to their matching fittings.
7. Before turning on the pump, increase the flow/pressure in the lower pressure regulator slightly (1/2 turn)
8. Plug in the pump (turn on the pump)
    a. If the pump will not start, open the lower pressure valve further.
9. When desired fluidization level is achieved, adjust the height of the ejection tube
10. Slowly increase the upper pressure regulator until you achieve the desired cloud output.

Conclusions and Recommendations

The initial tests are promising; a sustainable, controllable cloud is produced, which is the major requirement of the project. The consistency and density of the cloud, however, are not yet known. Further testing will determine whether the carbon particle disperser meets these criteria.

Testing Recommendations:

Extinction Tube: An extinction tube is a device that measures the extinction coefficient of a substance (usually a gas). The extinction coefficient tells us how much incident light the gas absorbs. The carbon cloud should have a coefficient of $2m^{-1}$. This means that 98% of the incident light is absorbed within the first 2m of entering the cloud.

Diesel Particle Spectrometer (DPS): The DPS allows properties such as particle size, and cloud density to be measured and recorded in real time. This test would give valuable insight into the sustainability

Further Recommendations:

Ultimately, the carbon particle disperser's acrylic components should be swapped with steel ones to create the high-pressure system. In the mean time, several things may be done to improve the functionality of the system

1. Create a system to easily add/remove carbon once the system is permanently cemented together. Currently the stainless tubes are loosely fitted together. Once they are tightly fastened, it will be difficult to remove the top endcap. This will make adding carbon and swapping diffuser plates difficult.
2. Add a pressure relief valve to the lower chamber.
3. Add pressure gages to the lower and upper chamber.
4. Fine tune the carbon particle disperser and upgrade the components to accommodate high-pressure.

Acknowledgements

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Mike Lester

Companies: Asbury Carbons
San Diego Plastics, Inc.
San Diego Fluid System Technologies
Marshall's Industrial Hardware, Inc.
Bell Pipe & Supply Co.
B&K Electric Wholesale

Appendix

Weekly Meeting Reports

Meeting Date and Time:

Thursday September 10th 2009, 3pm

Attendance:

Aron Daria, John Terry, Dr. Miller

Agenda:

- Discuss the assembly the of system components including the spouted bed, nozzle, flow meters, centrifugal blower, number of air inlet ports and their placement.
- Discuss fabrication of the final nozzle and its function relative to producing an oblique shock wave.
- Provide Dr. Miller with fluidized bed text books.
- Discuss fabrication of the spouted bed and specifically how fittings will be welded to the bed housing.
- Discuss whether the bed housing should be cut and secured with a V-band clamp.
- Discuss possibilities for the centrifugal motor, estimated flow rate, and how high pressure fittings will be adapted to it.

Issue List:

-Solved Issues

- Stress calculations
- Safety Factors
- Gas flow rates
- Particle cloud density
- Particle injection rate
- Pressure
- Extinction coefficient
- Housing Selection

-Unsolved Issues

- Bed housing fabrication specifics
- Blower selection
- High pressure sealing of the system
- How fittings will be adapted to the housing

Agenda for next meeting:

- Review fluidized bed textbooks.
- Report on possible suppliers and provide a list of needed components, especially for the blower.
- Discuss experimentally determined flow rate needed for fluidization.
- Discuss funding issues.
- Address nozzle clogging issues, and specific nozzle dimensions.

Meeting Date and Time:
Wednesday September 16th 2009, 3pm

Attendance:
Aron Daria, John Terry, Dr. Miller

Agenda:

- Discuss the assembly the of system components including the spouted bed, nozzle, flow meters, centrifugal blower, number of air inlet ports and their placement.
- Discuss fabrication of the final nozzle and its function relative to producing an oblique shock wave.
- Discuss fluidized bed books and how they can help or design.
- Talk about funding issues.
- Discuss possibilities for the centrifugal motor, estimated flow rate, and how high pressure fittings will be adapted to it.
- Discuss how the flow rate will be calculated for sizing the blower.

Issue List:

-Solved Issues

- Stress calculations
- Safety Factors
- Gas flow rates
- Particle cloud density
- Particle injection rate
- Pressure
- Extinction coefficient
- Housing Selection

-Unsolved Issues

- Bed housing fabrication specifics
- Blower selection
- High pressure sealing of the system
- How fittings will be adapted to the housing
- How 3/8in lines from the flow controllers will mate with 1/2in steel lines

Agenda for next meeting:

- Report on possible suppliers and provide a list of needed components, especially for the blower.
- Address nozzle clogging issues, and specific nozzle dimensions.

Meeting Date and Time:
Wednesday September 30th 2009, 3pm

Attendance:
Aron Daria, John Terry, Dr. Miller

Agenda:

- Discuss the assembly the of system components including the spouted bed, nozzle, flow meters, centrifugal blower, number of air inlet ports and their placement.
- Discuss small scale testing results and decide if a plate instead of a nozzle should be used for the fluidized bed.
- Talk about funding issues.
- Discuss possibilities for the centrifugal motor.
- Get codes to the solar lab.
- Discuss concept testing at 0psig.

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Issue List:

-Solved Issues

- Stress calculations
- Safety Factors
- Gas flow rates
- Particle cloud density
- Particle injection rate
- Pressure
- Extinction coefficient
- Housing Selection

-Unsolved Issues

- Bed housing fabrication specifics
- Blower selection
- High pressure sealing of the system
- How fittings will be adapted to the housing
- How 3/8in lines from the flow controllers will mate with 1/2in steel lines
- Budget Issues

Agenda for next meeting:

- Budget Issues
- Cheaper concept testing using cast acrylic

Meeting Date and Time:
Wednesday October 6th 2009, 3pm

Attendance:
Aron Daria, John Terry, Dr. Miller

Agenda:

- Discuss budget issues and if the final design should be at 0 psig or at high pressure.
- Talk about funding issues and the possibility of getting more money.
- Discuss possibilities for the centrifugal motor.
- Discuss fluidized bed fabrication using acrylic and specifically how the end caps and plate will be machined.

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Issue List:

-Solved Issues

- Stress calculations
- Safety Factors
- Gas flow rates
- Particle cloud density
- Particle injection rate
- Pressure
- Extinction coefficient
- Housing Selection

-Unsolved Issues

- Bed housing fabrication specifics
- Blower selection
- High pressure sealing of the system
- How fittings will be adapted to the housing
- How 3/8in lines from the flow controllers will mate with 1/2in steel lines
- Budget Issues
- Acrylic fluidized bed fabrication process

Agenda for next meeting:

- Budget Issues

Meeting Date and Time:
Tuesday October 13th 2009, 3pm

Attendance:
Aron Daria, John Terry, Dr. Miller

Agenda:

- Discuss budget issues and if the final design will include a nozzle.
- Talk about funding issues and the possibility of getting more money.
- Flow rate for the centrifugal motor.
- Start machining and testing parts.

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Issue List:

-Solved Issues

- Stress calculations
- Safety Factors
- Gas flow rates
- Particle cloud density
- Particle injection rate
- Pressure
- Extinction coefficient
- Housing Selection
- Bed housing fabrication specifics
- Acrylic fluidized bed fabrication process
- How fittings will be adapted to the housing

-Unsolved Issues

- Blower selection
- High pressure sealing of the system
- How 3/8in lines from the flow controllers will mate with 1/2in steel lines
- Budget Issues
- Agglomerate separation

Agenda for next meeting:

- Budget Issues
- Testing

Meeting Date and Time:
Wednesday October 28th 2009, 4pm

Attendance:
Aron Daria, John Terry, Dr. Miller

Agenda:

- Discuss the results/findings from the initial fluidized bed tests.
- Discuss possibility of using a compressor as a pump/blower.
- Decide what components of the fluidized bed can be permanently bonded together.
- Discussed Solar Lab testing options.

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Issue List:
-Solved Issues

- Stress calculations
- Safety Factors
- Gas flow rates
- Particle cloud density
- Particle injection rate
- Pressure
- Extinction coefficient
- Housing Selection
- Bed housing fabrication specifics
- How fittings will be adapted to the housing
- Budget Issues
- Acrylic fluidized bed fabrication process

-Unsolved Issues

- Blower selection
- Fluidized Bed Stand

Agenda for next meeting:

- Test Results

Meeting Date and Time:
Monday November 2th 2009, 4pm

Attendance:
Aron Daria, John Terry, Dr. Miller

Agenda:

- Discuss the results/findings from fluidized bed tests.
- Discuss the new blower and parts needed to fit it into the system.
- Discussed Solar Lab testing options.
- Determine test data can be taken with and without the laser particle scanner.

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Issue List:
-Solved Issues

- Stress calculations
- Safety Factors
- Gas flow rates
- Particle cloud density
- Particle injection rate
- Pressure
- Extinction coefficient
- Housing Selection
- Bed housing fabrication specifics
- How fittings will be adapted to the housing
- Budget Issues
- Acrylic fluidized bed fabrication process

-Unsolved Issues

- Blower selection
- Fluidized Bed Stand

Agenda for next meeting:

- Test Results

Vendors

Carbon:

Asbury Carbons
Asbury Graphite Mills, Inc.
(Asbury, NJ Division)
405 Old Main Street
Asbury, NJ 08802
Phone: 908-537-2155
Fax: 908-537-2908
e-mail: asburyinfo@asbury.com
Contact – Scott Bartolacci

Compression Tube Fittings:

Swagelok
San Diego Fluid System Technologies
6350 Nancy Ridge Drive
Suite 101
San Diego, Ca 92121
Phone: 858-320-4000

Acrylic:

San Diego Plastics Inc.
2220 McKinley Ave.
National City, Ca 91950
Phone: 619-477-4855
Fax: 619-477-4874