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Design, construction, and preliminary testing of a square cross-sectional mixing chamber

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Design, construction, and preliminary testing of a square cross-sectional mixing chamber

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ABSTRACT

Throughout the US, large quantities of chlorine are produced and transported by rail. In the past, train accidents led to deadly accidental releases and the need for mass evacuation. However, moving people unnecessarily may cause pandemonium or danger to health for sensitive members of the public. In these past cases, the models used for evacuation distances did not accurately predict the impact of the chlorine release, but these models did not take into account the reactivity of chlorine. Because chlorine is a highly reactive gas, it is absorbed into the surrounding environment which reduced the amount of chlorine in the air thereby reducing the impact of an accidental release. In this context, the Controlled Environment Reactivity Test (CERT) program was created to determine the extent of the absorption of chlorine with the environment. The Chemical Hazard Research Center (CHRC) at the University of Arkansas is active member of the program. Its facility is used to conduct low wind speed dispersion modeling for various hazardous gases. For the CERT Program, the aim is to create a test chamber designed to provide chemical reactivity (deposition) data for direct use in atmospheric dispersion models.

This particular project aimed at designing and constructing a test chamber to provide gas mixtures in preparation for the CERT Tests. Preliminary tests were conducted to validate the set-up. The chamber is made of plywood and clear polycarbonate, powered by a small 2 hp fan used to push the air through the chamber to the room. Based on previous work, High Efficiency Vortex (HEV) mixer design has been adapted to mix test gas with inlet air. The HEV mixer is placed directly after the fan and uses two sets of inline baffles to produce turbulent mixing. The testing included the delivery of the gas (fog) to the chamber, the determination of the optimal setup for all experiments, and the preliminary videos. An optimal height for the inlet nozzle of five inches was determined and the similarity between the fog speed and the air speed on the

lowest fog and fan setting has been proven. Finally, the preliminary videos of the chamber flow clearly show a large scale vortical structure which is convected along the length of the test section. This undesirable structure is caused by the fan. A flow straightener could be used to reduce or eliminate this phenomenon.

INTRODUCTION

Every year, 12.2 million tons of chlorine is produced in the US. It is needed in almost every kind of industry (plastic, food products, medicine, water, etc.) (5). Chlorine gas is primarily shipped by train as a compressed liquid, and local delivery is predominately made by tank truck or one ton cylinders. (6). Over time, there have been accidents where large amounts of chlorine were released. In 2004, 120,000 lbm of chlorine was released into the atmosphere after a 90-ton freight car had crashed in Macdona, TX. Chlorine as an extremely reactive chemical can cause serious health problems or death even at low concentrations (2). It is known that chlorine will begin to affect people at concentrations as low as 1 ppm and can cause death within minutes if concentrations are above 1000 ppm (4). In the Macdona Texas release, observed concentration levels ranged from 20 ppm (2 km downwind from the release point) to well over 2000 ppm near the source (1). County officials attempted to begin evacuation about two hours after the release but could not fully agree on a distance that would be safe for the population. Originally modeling the release as an instantaneous release using a puff model, it was decided to evacuate people up to two miles away from the release, but the evacuation zone was later extended to 4.9 miles away from the release point (1). During those two hours before evacuation, 57,000 households were instructed to shelter in place and were potentially exposed to the high concentrations and yet only three people died from exposure. A possible reason why so few casualties occurred in Macdona, Texas is that chlorine likely reacted with materials in the surroundings reducing the concentration in the air.

To determine the amount of chlorine absorbed in a future potential release, a scientific program, Chemical Environment Reactivity Test (CERT), was created through the Jack Rabbit II Test Program. The CERT project is designed to “provide an experimental environment to conduct tests to expose small equipment and surfaces to known concentration of chlorine under controlled circumstances in support of the Jack Rabbit II test program" (8). The Jack Rabbit II program focuses on "addressing [the] critical knowledge, data, and capability gaps for assessment of consequences of large scale release of chlorine" (8). The CERT program in this context, would require an experimental set-up to mix chlorine with air to produce a known concentration" (8). This mixture would flow into a chamber with various objects and surfaces. Analytical techniques will be developed to measure the chlorine absorbed or reacted by the material tested. This information would be used to determine the amount of chlorine reacted with objects for emergency response and emergency planning purposes. This could benefit the response in future accidents to determine a safe distance to evacuate the population possibly preventing unneeded evacuations of facilities like airports, hospitals, nursing homes, schools, and highly populated areas.

This thesis deals with the design, construction, and early testing of the mixing chamber at the CHRC and will focus on the preliminary mixing of a gas with air. After this introduction, the first section will focus on the design and construction of the chamber. The methods and tools used to thoroughly mix gases together will then be presented in the second section. Finally, the preliminary experiments will be described and discussed in the third and final section.

DESIGN AND CONSTRUCTION OF MIXING CHAMBER

The fan available for this project is a 12 inch diameter Reliance Electric A-C fan. The fan is powered by a 2 hp motor controllable with speed settings from 5 to 60 rpm (Figure 1).

Figure 1 : 2-hp Reliance Electric fan

In addition to atmospheric flows, wind tunnels are used for testing various applications including aerospace, vehicle drag reduction, and gas dispersion (8), and consequently, several designs have been used. The objective here is to make a chamber which replicates aspects of atmospheric flows effectively. There were two major considerations identified: Pull-through or push-through flow. For this application, the main issue would be potential for interaction between reactive gases and a downstream fan in the pull through design. Consequently, the push-through design will be the focus of this study. Finally, the dimensions of the prototype chamber were made on the basis of available resources.

When considering whether the test chamber should be closed or open flow, it is important to consider the method for measuring the reactive chemical concentration. Gas phase concentration measurements of reactive gases such as chlorine can be difficult to make especially at high concentration levels. To measure the mass of a gas that reacts with a sample surface has advantages because the reacted surfaces are stable and can be analyzed at a later time. Also, the gas phase concentration may actually be decreased by reaction with the test chamber surfaces.

The next consideration is whether to use an open (Prandtl) or closed (Eiffel) system for the mixing chamber. A closed system is a tunnel in a complete circuit. Once the gas has entered the system, it does not exit the chamber, but instead travels through, around, and back into the testing chamber. An example of a closed system used for airplane testing is shown in Figure 2 (11).

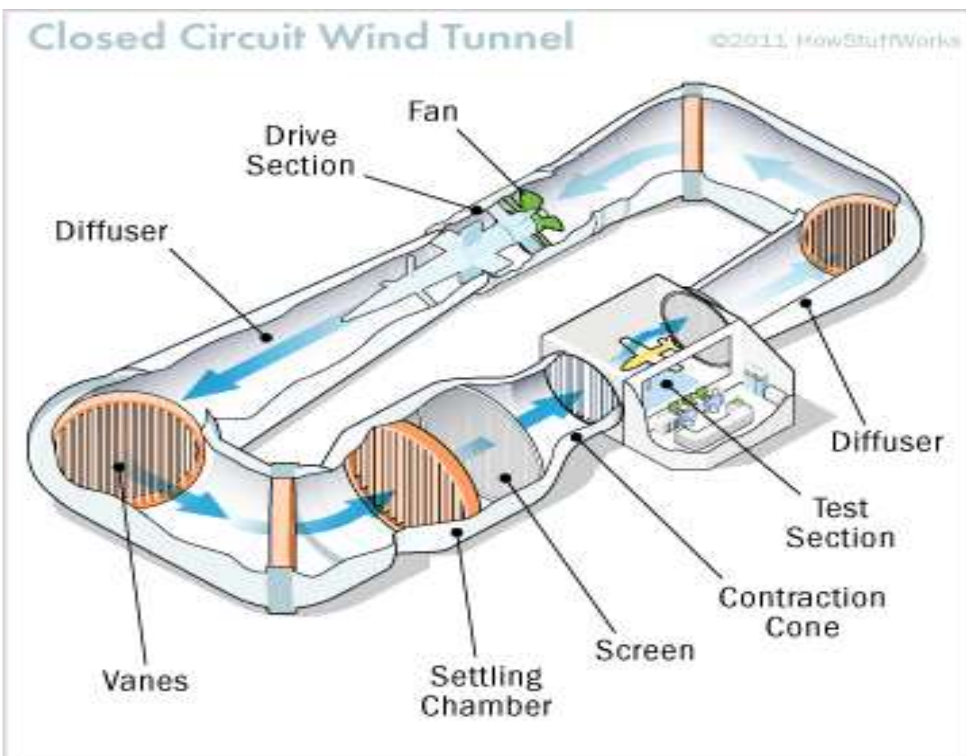

Figure 2 : Closed Circuit Wind Tunnel

This system would reduce the amount of energy required by the fans and contain the gas. Unfortunately, chlorine would be in contact with the fans. It would also make measurements of how much an object absorbs by a known amount of chlorine almost impossible, especially if chlorine is continuously re-entering the chamber. The other option is to use an open system. This would be a one pass system. The air enters through the fan, and the gas and air does not re-enter the chamber in a loop. This open system would prevent the major problems with chlorine and was used in this project design. The motion of the fan blades creates vortices that move axially through the chamber. Since the chamber is built to replicate flow in the atmosphere, these vortices will need to be removed, but the method to do so will be developed by others.

The main design for length and dimensions follow recommendations by Bakker and LaRoche who conducted a study on the mixing of gases and liquids. If the length of one side of the square cross section is denoted as D, an axial length of 2.5D was required to complete the mixing process (7). The value of D was chosen to be fan diameter of 12 in. The length of 4.5 ft was added to include an apparatus to straighten the flow and place samples for testing. A schematic of the 8 ft chamber can be seen below in Figure 3.

For the final test chamber, the choice of material will be extremely important because of the reactivity of chlorine. Experimental results could be skewed if chlorine is preferentially absorbed by the floor and walls of the chamber rather than all by the objects being tested. Since this prototype will not require the use of chlorine, this design used plywood as an inexpensive and easily manipulated material for two sides of the chamber. It was painted black to provide contrast for white fog used in preliminary testing. Clear polycarbonate was used for the other two sides to take photographs and videos (Figure 4).

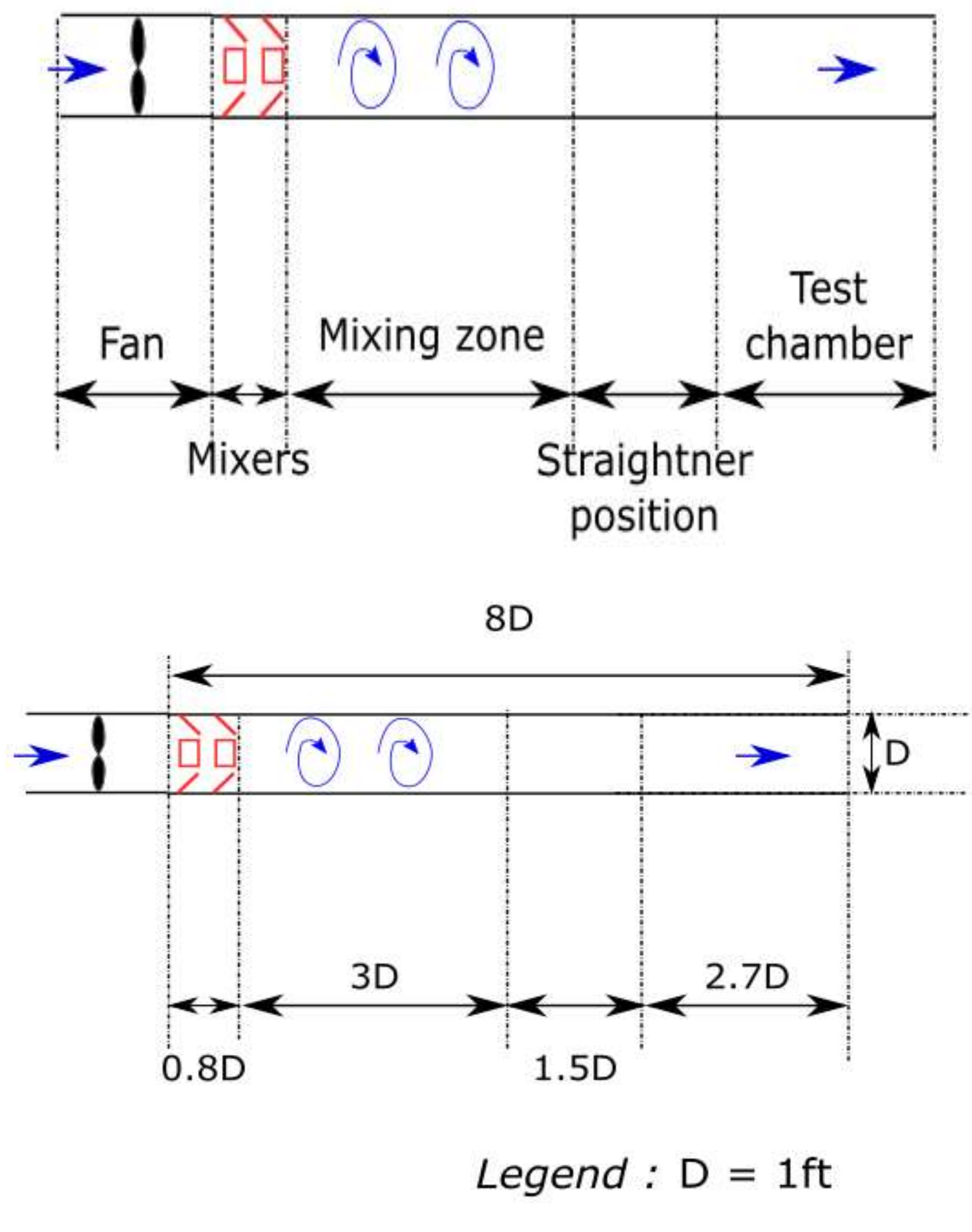

Figure 3 : Mixing chamber zones and dimensions

Figure 4 : The completed chamber

TOOLS TO THOROUGHLY MIX GASES

Choice of the Mixer

The best mixers are those that produce the lowest pressure drop and the least amount of material while meeting the needed design specifications (12). There are two major types of mixers, static and moving mixers. In addition to their inherent simplicity, a static mixer design was chosen due to potential chlorine reactivity issues.

Table 1 : Rule of thumb for choosing mixers (12)

Flow Regime	Static Mixer Design									
	KMS	KMX	HEV	SMV	SMX	SMXL	SMR	KVM	SMF	ISG
Laminar										
Mixing/blending	c	a			c	c			a	a
High–low viscosity		a			c	a				a
Dispersion	a	a			c	a				a
Heat transfer	c				b	c	c			
Plug flow	b				c	b	c*			
Turbulent										
Mixing/blending										
High turbulence	a		c	c'				c		
Low turbulence	c			c	a	a			a	
Dispersion										
Liquid–liquid	c			c	a	a	c*		a	
Gas in liquid	c			c	a	a	a*		a	
Liquid in gas	a			c	a					
Fluidized beds					c"					

a, Applicable; b, typically applied; c, best design choice. *, Where temperature control is required; ', especially for very large diameters and nonround cross-sections; ", gas fluidized solid particles, specialized design

Many different types of static mixers are used in industry. The general design of static mixers is to use some material to change the direction of the flow to force mixing (12). Guidance provided by KLM Technology (12) was used to determine the best types of gas mixers as shown in Table 1.

Because the flow in the chamber is intended to be turbulent, three mixer types are recommended: High Efficiency Vortex (HEV), SMV, and KVM. The HEV uses tabs placed evenly apart along the length of the chamber. An example of this type of mixer is seen in Figure 5 (16). This mixer is used in both pipes and square ducts. The SMV mixer uses layers of "corrugated metal running at 30 or 45" degree angles "to the axis" (12), an example is displayed on Figure 6 (15). The last type considered is the KVM which uses one baffle angled off the chamber wall as shown in Figure 7 (14). Because of the simplicity of the HEV, this mixer type was chosen for this application.

Figure 5 : HEV Mixer

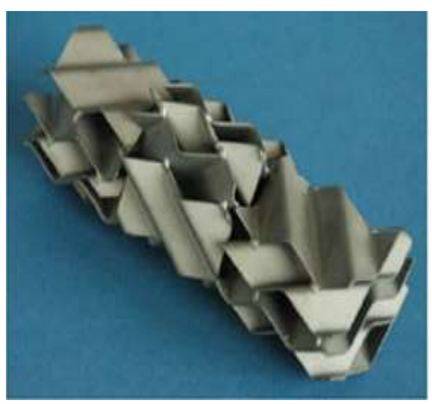

Figure 6 : SMV Mixer

Figure 7 : KVM Mixer

The HEV Mixer

Again using D to represent the length of one side of the square cross section, the HEV works by using two sets of in-line baffles spaced 0.5D apart (7). As gas flows past the two sets of baffles, multiple vortexes having "hairpin and longitudinal" shape are created and induce the mixing (7). Figure 8 depicts the schematic of the hair pin (in blue) and longitudinal (in black) vortices off the edges of the tab.

Figure 8 : Hairpin and longitudinal vortices caused by tabs (7)

The baffles are typically set at a 45 degree angle from the side of the channel in an attempt to reduce the static region mixing behind the baffles (7). The upstream set of baffles begins the mixing process but the highest amount of turbulence occurs after the downstream set of baffles as shown in Figure 9. This figure represents the evolution of the turbulent kinetic energy in a plane through the center of the baffles. The numerical simulation, shows the increase of turbulence intensity (in red) after the second set of baffles. This provides validation that the most advantageous placement of the tabs was in-line and not staggered (7).

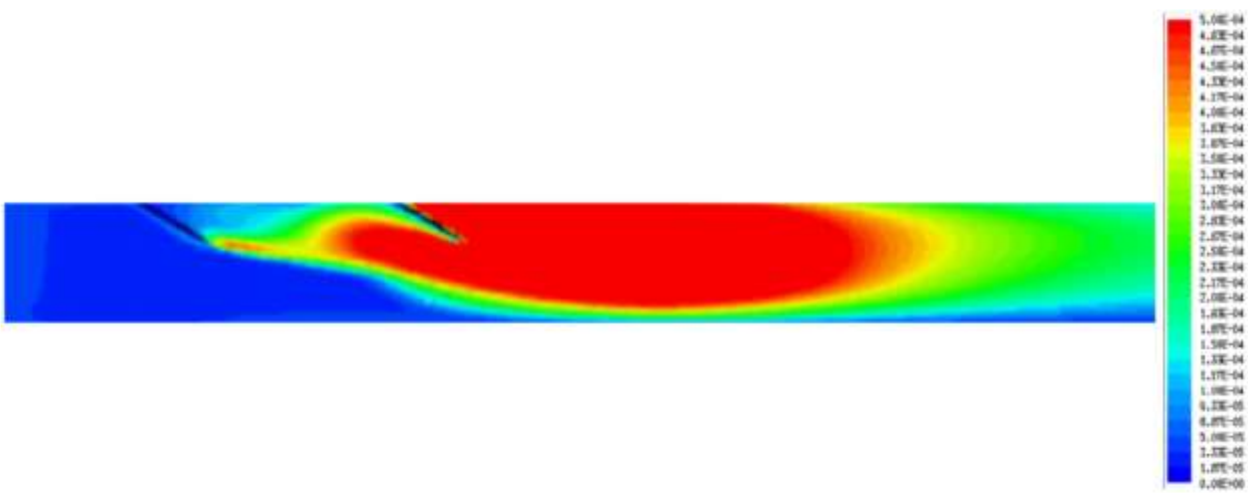

Figure 9 : Turbulent kinetic energy at the center tab (7)

Based on previous research, the project's HEV mixer uses eight baffles (four per each set) centered on each face of the chamber. The first set was placed at 0.5D and the second set was D downstream from the fan. Each baffle was trapezoidal in shape with a base length of 3.75 inches, the top length of 3.0 inches, and centered in the chamber (Figure 10 and Figure 11). With this configuration, the flow should be fully mixed at a distance 3D downstream of the mixer (7).

Figure 10 : Tabs placed in chamber

Figure 11 : Tab design and shape

EXPERIMENTS AND RESULTS

Construction of the Fog Apparatus

At the CHRC facility, two fog machines are available: ROSCO 1500 and Pencil fogger. To be able to use both machines, ducts and piping were constructed to allow either fogger to be used depending on test conditions. The fog entered into the chamber via a two inch diameter PVC pipe. The duct was not sealed, so a small amount of fog could continuously escape, but the machine was simply placed at a distance from the test chamber to avoid issues with video capture of the tests. The final configuration is shown in Figure 12.

Figure 12 : Fog to chamber setup

After connecting the fog machine to the chamber, the next piece to build was a cooler. The aim of the cooler was to reduce the effect of the buoyancy of the fog. Indeed, it was expected that the fog would rise directly to the top of the chamber. By making the fog go through a container filled with ice before releasing it in the chamber, its density would be reduced and its buoyancy would be decreased. The cooler consists of a 10 gallon plastic storage container pierced by three holes. One near the base of one end where the duct would enter, one on the top to relieve pressure from the melting ice, and the last was half way up for the exiting duct. A 20 foot duct with a diameter of 3 inches was wrapped in the container and connected to the sides with zip ties as depicted on Figure 13. The duct was spaced as evenly as possible to maximize the heat exchange. The 4 inch duct was connected to the fog machine and linked to the cooler with a 4 to 3 inch reducer. The exiting duct was attached to the inside of the PVC connector and held with rubber bands. Figure 14 show the overall setup and the construction of the cooler.

Figure 13 : Cooler construction with 20' duct

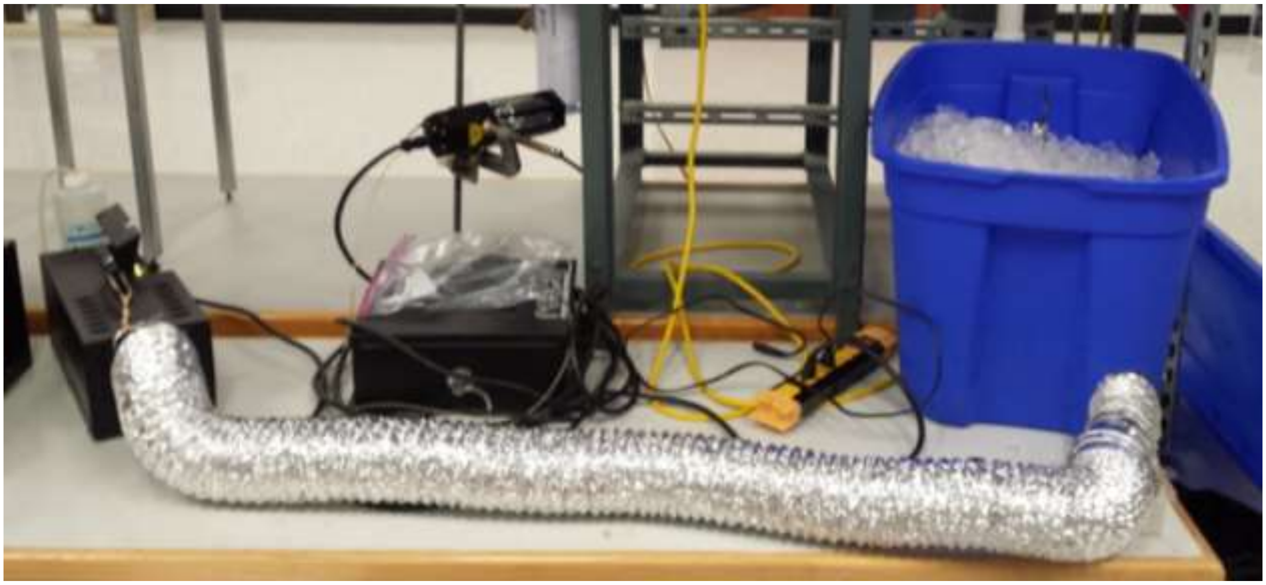

Figure 14 : Fog machine to cooler setup

Setup of the Experiments

After the construction, preliminary experiments were conducted to validate the set-up presented and constitute a primary data base for the future development of the chamber. All the experiments presented here were conducted with the fan set to 5 rpm or a streamwise velocity of 0.5 m/s. A parametric study was proposed to:

- determine which fog machine was appropriate
- find the optimal height of the nozzle above the base of the chamber
- confirm that the cooler decreased the buoyancy of gas
- verify that the fog leaving the nozzle did not created a jet effect (fog entering faster than the air velocity in the chamber).

To determine whether the 1500 ROSCO fog machine or the Pencil fogger had higher visibility, videos were recorded with each fog machine for a similar set-up. There are ten levels on the 1500 fogger and a turn dial on the Pencil fogger. The videos showed that ROSCO 1500 produced not only a larger amount of fog but also allowed a continuous fog release. The latter was not possible with the pencil fogger which produced a more transient fog release. Consequently, the ROSCO 1500 was to be used in all the subsequent experiments.

After the fog machine was chosen, the height of the nozzle (i.e. the length between the center of the nozzle and the base of the chamber) was examined. Five videos were recorded with the nozzle height ranging from 2 to 6 inches in 1 inch increments. The optimal position was at a height of 5 inches. By comparing Figure 15 and Figure 16, which correspond to a nozzle height of 6 and 5 inches respectively, the most centered evolution of the fog can be seen with a height of 5 inches.

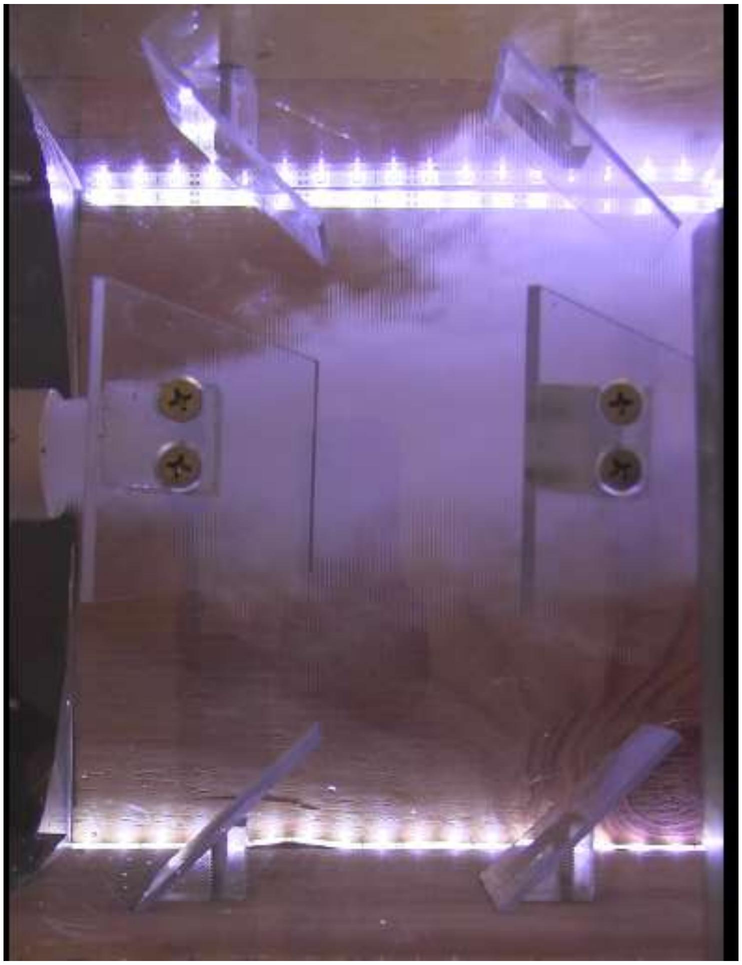

Figure 15 : Fog flow six inches above base

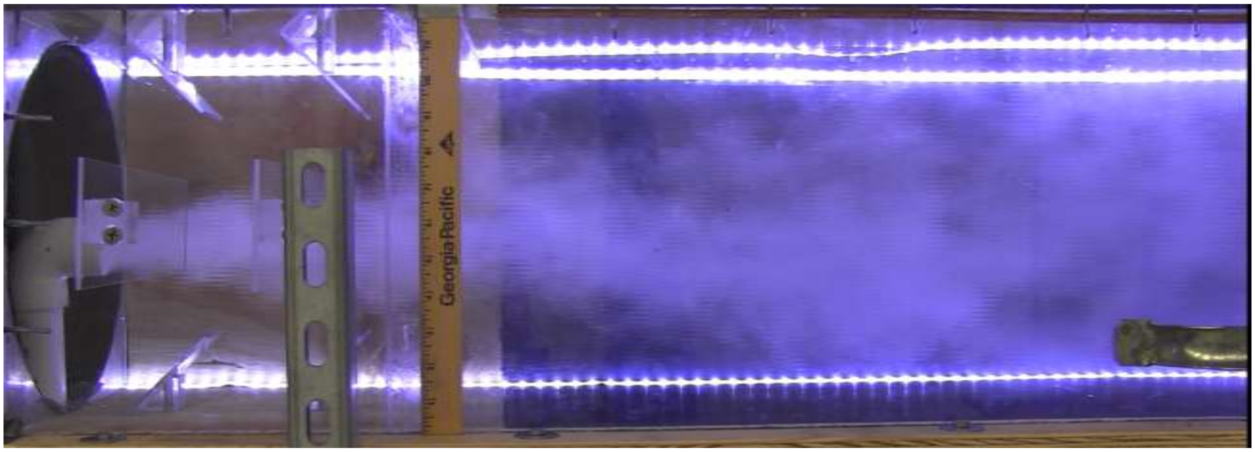

Figure 16 : Flow of fog at nozzle five inches above base of chamber

Next was to determine if the cooler would have any effect on the fog. This was completed by taking several videos with and without the cooler from three different angles. The results were that the buoyancy changed very slightly with the ice, as seen in Figure 17 Figure 18. The changes were not significant enough, and it was decided that the subsequent experiments would not require the cooler.

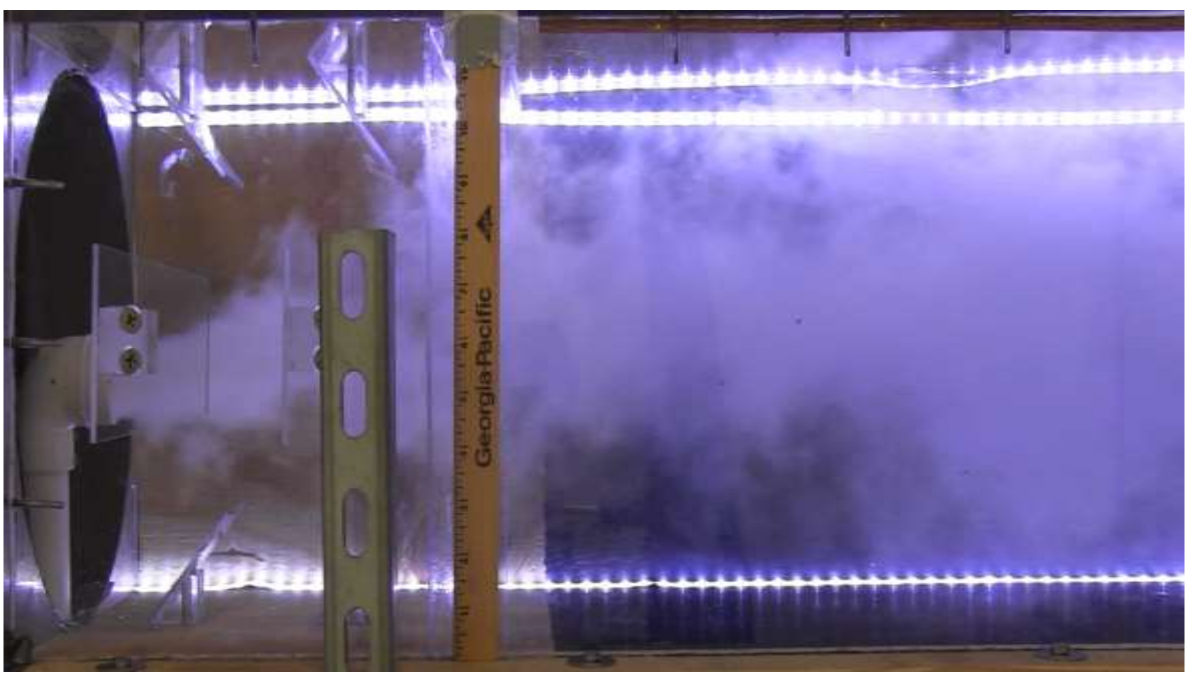

Figure 17 : Fog flow obtained without cooler

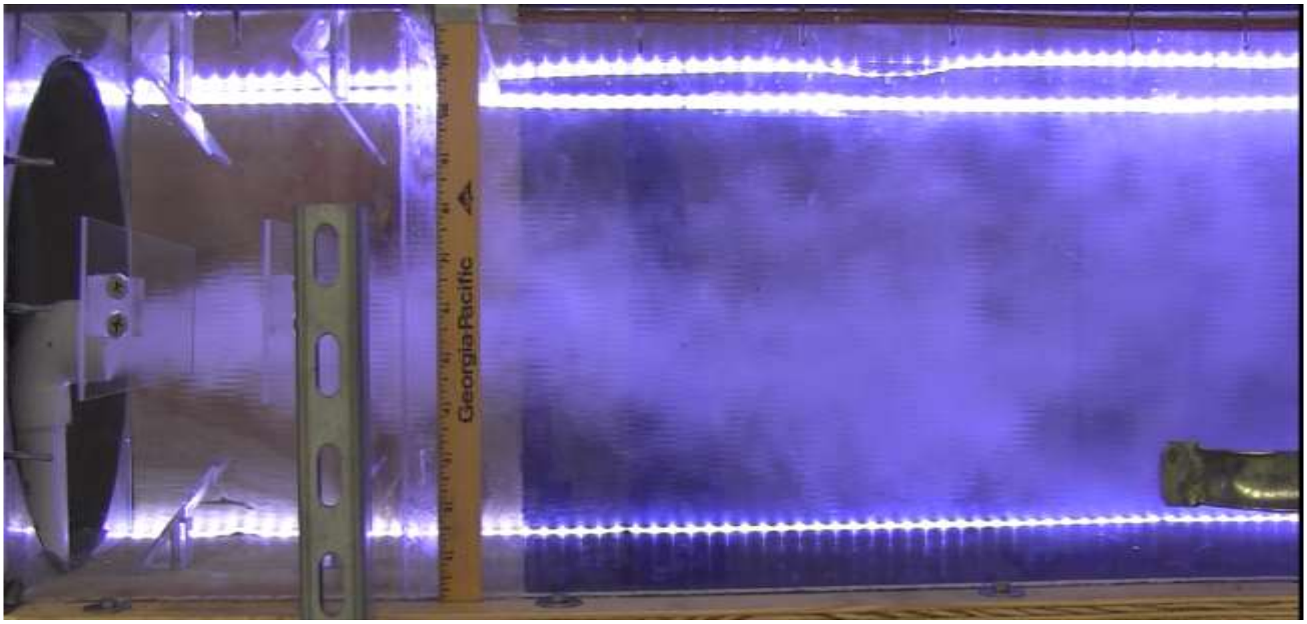

Figure 18 : Fog flow obtained with cooler

Lastly, the streamwise velocity of fog fluid would be analyzed to determine if a jet effect exist. If the fog entered the chamber faster than the air flow, the fog would add momentum to the flow. That scenario is unlikely to occur in the atmosphere and should be avoided.

To calculate the velocity of the fog fluid, videos were acquired without any wind. In addition, calibration pictures where used to determine the pixel to meter ratio. Through image processing developed by the Chemical Hazard Research Center, the speed of the fog was calculated. The result concluded that the speed of the fog on its lowest setting was less than the fan speed of 0.5 m/s. This validates that the jet effect does not occur for the current settings.

Preliminary Video Experiments

In order to constitute a primary data base for the future development of the chamber, several video were recorded for 3 different positions of the camera. There were two sets of videos taken: one with the cooler filled with 10 gallons of ice and one without. Using all the preliminary findings, the settings were as follows: the ROSCO 1500 fog machine volume control was set to one and the height of the nozzle from the base of the chamber was 5 inches.

CONCLUSION

The design, construction, and preliminary tests of a chamber, created to mix a test gas in an air inlet stream, were conducted. The prototype chamber consists of an eight feet long and one foot high square section with a push-through and open wind tunnel design. In order to conduct optical measurement techniques and visualization, the chamber was built with plywood and polycarbonate sheets. The gas used for visualization was injected through a nozzle just downstream of the fan before the entry of the section. A high efficiency vortex (HEV) mixer was built into the inlet of the chamber to mix the test gas with air. The preliminary testing of the chamber concluded that the optimal height of the nozzle was five inches above the base of the chamber, out of the two fog machines used, the ROSCO 1500 produced a better visualization, the best volume of fog for the lowest fan speed was at the control level 1, and the cooler only reduced the buoyancy slightly.

In the future, a flow straightener apparatus will have to be design to reduce swirl and will have to be adapted to the problematic developed in this thesis. Prototypes will be created and tested in the chamber. Moreover, measurements of the velocity profiles across the section, and eventually measurements the concentration of the gas in the air mixture will have to be done. Indeed, a characterization the evolution of the flow in the chamber is necessary to confirm the ability of the latter to properly mix gases within the conditions defined by the CERT program.

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