

# **Ozone in direct contact spray air conditioning systems**

by

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## **Abstract**

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The basic idea for this project is to use ozone in a direct contact spray air conditioning system to inactivate pathogens like viruses, bacteria and fungi that are in the air stream.

Water is sprayed in an air stream in counter flow configuration. The supply water temperature is below the air temperature, so that energy is transferred from the air into the water. The air is cooled (and possibly dehumidified) while the water is heated. If the water temperature is below the dew point temperature of the air, water vapor from the air condenses into the water droplets and the air is dehumidified. The water spray also acts like a filter. Particles e.g. viruses, bacteria and fungi will be filtered out of the air with the spray and get into the water. If the water is ozonated, strong oxidizing properties provide an opportunity to inactivate the previously airborne pathogens.

High ozone concentrations in air are a respiratory irritant for humans. The threshold limit in workspace areas is 0.1 ppm (US EPA, 1999). The purpose of this project is to build an apparatus to determine if the required ozone concentration to inactivate pathogens in water can be reached while limiting the concentration of ozone in air to below the permissible exposure limit. Experiments were run to make sure that the apparatus is working according to the design criteria and to provide first results to indicate the direction for future experiments.



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## Nomenclature

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A	Cross section area	$[m^2]$
$C_1$	Calibration constant	$[kPa/Ohm]$
$C_2$	Calibration constant	$[kPa]$
$\ddot{a}_i$	Thickness of material i	$[mm]$
D	Diameter	$[mm]$
dissOzone	Dissolved ozone concentration in the water before the nozzle (inlet)	$[ppm]$
$\dot{E}$	Energy rate	$[kW]$
Error	Error	$[\%]$
gasOzone	Gas phase ozone concentration	$[ppm]$
h	Convection coefficient	$[W/m^2-K]$
h	Specific enthalpy	$[kJ/kg]$
I	Current	$[A]$
$k_i$	Conductivity of the material i	$[W/m-K]$
$\dot{m}$	Mass flow rate	$[kg/s]$
Pressure	Relative water pressure before the nozzle (inlet)	$[kPa]$
$\dot{Q}$	Heat flux	$[kW]$
$\rho$	Density	$[kg/m^3]$
R	Resistor	$[Ohm]$
$R_{PT}$	Resistance of pressure transducer	$[Ohm]$
T	Temperature	$[^\circ C]$

tempAirIn	Averaged temperature at the air inlet	[°C]
tempAirOu	Averaged temperature at the air outlet	[°C]
temptank	Water temperature in tank 1	[°C]
tempWatIn	Water temperature before the nozzle (inlet)	[°C]
tempWatOu	Water temperature at the main drain (outlet)	[°C]
U	Voltage difference	[V]
$\dot{V}$	Volume flow rate	[gpm]
V	Velocity	[ft/min]
V	Specific Volume	[m <sup>3</sup> /kg]
V <sub>s</sub>	Measured voltage from Wheatstone bridge	[V]
V <sub>x</sub>	Supplied voltage for Wheatstone bridge	[V]
W	Absolute humidity	[kg/kg]

#### Subscripts

1, 2, 3, ....	Different locations
in	Inlet
ins	Insulation
out	Outlet
PVC	Polyvinyl chloride (PVC)
W	Water
	Environment



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## Chapter 1 Introduction

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Virus-induced colds are the most common illness, accounting for over 40% of all respiratory illnesses in the US (Radetsky, 1991), and having an enormous financial impact in the workplace. A sick person, e.g. a staff member, can be a source for a certain illness. Pathogens like viruses, bacteria and fungi can be distributed via the air conditioning system throughout the whole building. This modality can occur especially in multi-family housing complexes, daycare facilities, public institutions, daycare facilities, healthcare facilities, prisons, homeless shelters and commercial office buildings.

### ***1.1 Current solutions***

According to the EPA (US EPA, 1999) the “*three most common approaches to reduce indoor air pollution, in order of effectiveness, are:*

- ***Source Control:*** *Eliminate or control the source of pollution;*
- ***Ventilation:*** *Dilute and exhaust pollutants through outdoor air ventilation, and*
- ***Air Cleaning:*** *Remove pollutants through proven air cleaning methods.*

*Of the three, the first approach – source control – is the most effective. This involves minimizing the use of products and materials that cause indoor pollution, employing good hygiene practices to minimize biological contaminants (including the control of humidity and moisture, and occasional cleaning and disinfection of wet or moist surfaces), and using good housekeeping practices to control particles.*

*The second approach – outdoor air ventilation – is also effective and commonly employed. Ventilation methods include installing an exhaust fan close to the source of contaminants, increasing outdoor air flows in mechanical ventilation systems, and opening windows, especially when pollutant sources are in use.*

*The third approach – air cleaning – is not generally regarded as sufficient in itself, but is sometimes used to supplement source control and ventilation. Air filter, electronic particle air cleaners and ionizers are often used to remove airborne particles, and gas adsorbing material is sometimes used to remove gaseous contaminants when source control and ventilation are inadequate.”*

Here source control is impractical since people are the reservoirs of viruses that cause the common cold. It is not possible to send everybody, who has a cold, home. Four strategies for pathogen reduction: ventilation/dilution, filtration, ultra violet germicidal irradiation (UVGI) and photocatalysis will be discussed in the following paragraphs.

**Ventilation/Dilution:** The concentration of airborne pathogens in the indoor environment can be minimized by increasing the quantity of outside air (ventilation air) delivered to the breathing zone. The net result is a dilution of airborne pathogens in the indoor environment, reducing the probability of occupant morbidity. This approach has been the primary engineering control approach used to-date as documented by ASHRAE (1989).

Advantage:           • Simple concept.

- Disadvantage:
- Higher operating costs. Fan power increases with the cube of ventilation rate. Larger amounts of outside air have to be conditioned (heating & cooling).
  - Increase of noise due to drafts.
  - Higher capital costs, in extreme climates larger equipment is required for higher capacity.
  - Problems with outdoor air contamination if air intake is located next to pathogen sources.

**Filtration:** The use of high efficient particulate arrest (HEPA) filtration offers an effective approach for sequestering relatively large particles including many bacteria and fungi.

- Advantages:
- Simple and static technology.
  - Removes 99.97% of particles that are equal or exceed 0.3  $\mu\text{m}$  in aerodynamic diameter with no more than 1 inch of water pressure drop (IES 1993).

- Disadvantages:
- Mono-dispersed or droplet nuclei pathogens may penetrate HEPA filters.
  - Higher operating costs due to pressure drop.
  - Increase in capital costs to buy filtration equipment.
  - Increase of maintenance costs to clean or replace the filtration material.

**Ultraviolet Germicidal irradiation (UVGI)** is capable of inactivating viruses and bacteria by exposure of a lethal ultraviolet radiation dose (combination of intensity and time). The biocidal properties of UV light arise from interactions between ultraviolet radiation and genetic material in living cells (DNA). DNA exhibits a peak absorbance of electromagnetic radiation at 254 *nm*, well within the UV range. Prolonged UV exposure results in modifications to the internal structure of DNA, rendering living cells incapable of replication, (Rich, 1994; PSU, 1998)

Advantages:       • Simplicity.

Disadvantages:   • Not yet field-proven technology.

- Increase in electrical load for the lamp, but also to remove the additional heat from the lamp.
- Significant maintenance/cleaning requirement to keep the lamp clean.
- Ineffectiveness resulting from bioaerosols not being directly irradiated.
- Efficiency for a wide range of pathogens has not been completely documented.
- Requires either long contact time or high intensity to inflict a fatal dose.
- Bulb or lamp performance degrades over time.

**Photocatalysis** is a relatively new technology under current investigation. It relies on the use of ultraviolet irradiation to activate a catalyst, e.g. TiO<sub>2</sub>. The catalyst, once activated,

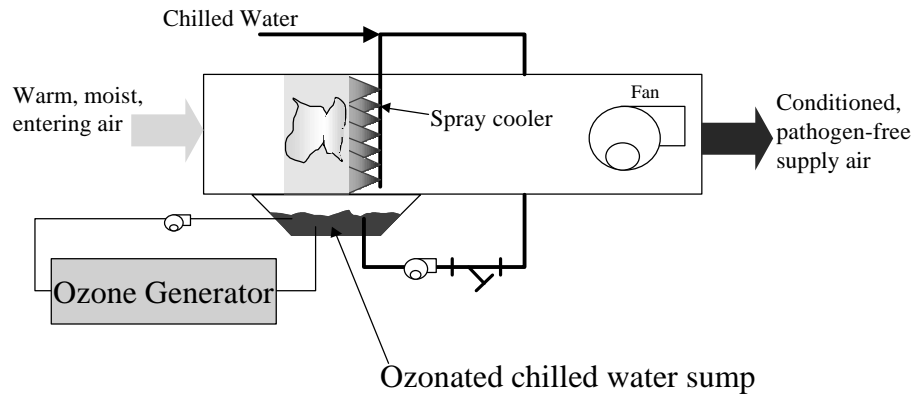
produces  $\text{OH}^-$  radicals capable of reacting with contaminants in the air stream. Ideally, the products of reaction are innocuous (i.e. carbon dioxide and water).

- Advantages:
- Potentially effective in remediating a wide array of pathogens.
- Disadvantages:
- Ideally, the products of the reaction are innocuous (e.g.  $\text{H}_2\text{O}$ ,  $\text{CO}_2$ ), but possible production of toxic byproducts due to incomplete reactions.
  - Parasitic load for HVAC system, requires high temperatures (ca. 50 C or higher) to achieve credible performance for the catalyst.
  - Very high airside pressure drop (ca. 4 inches of water or higher).
  - High capital costs, catalyst & UV light fixture are expensive (Henschel, 1998)

The problem with all these strategies is that none of them can simultaneously sanitize and space condition the air. This project is directed towards a mean of providing both air conditioning and removal of bioaerosols. To achieve this direct water spray is proposed.

## ***1.2 Project overview***

In a design, as shown in Figure 1.1, it may be possible to condition and sanitize air in one step.



**Figure 1.1** Illustration of an air-handling unit designed for simultaneous air conditioning and pathogen inactivation

Water is sprayed in counter flow direction into the air stream. It is also possible to spray the water in parallel flow, but mixing is higher using the counter flow method. Depending on the water temperature, the air can be cooled or heated. Depending on the dew point temperature of the air, it can be humidified or dehumidified. By controlling the water supply temperature, desired combinations heating/cooling with humidification/dehumidification can be achieved as summarized in Table 1.1.

**Table 1.1** Four different possible modes for the air-handling unit

Mode	Process	Water	Exiting Air Conditions	
		Temperature	Temperature	Humidity
1	Cool (sensible only)	Slightly cool	Slightly cooler	Same
2	Cool & dehumidify	Cool	Cool	Lower
3	Cool & humidify	Neutral	Cool	Higher
4	Heat & humidify	Warm	Warm	Higher

In the first mode, slightly cooled water at a temperature near the entering air dew point temperature makes contact with a mixture of warm and moist return air and outside air. Since the water temperature is lower than the entering air dry bulb temperature, the air will be cooled during the process. No moisture exchange occurs (sensible cooling only), because the water temperature is equal to the entering air dew point temperature.

In the second case, chilled water makes contact with a mixture of warm moist return and outside air. The air stream will be cooled and dehumidified, if the chilled water supply temperature is lower than the entering air dew point temperature.

The third mode operates as a traditional direct evaporative cooler. Evaporating water into the air stream sensibly cools the entering air. Air leaving the system has a depressed dry bulb temperature but significantly higher water content (i.e. absolute humidity).

The fourth mode allows for simultaneous heating and humidification of the incoming air stream by using warm water. To avoid over-humidifying air in cold climates during winter operation, an upper limit on the supply water temperature is required. In addition, a downstream heating coil would most likely be required to achieve appropriate exit air temperatures.

The net result is that the temperature and humidity of exit air can be controlled in a manner similar to a chilled water coil but with the added flexibility for humidifying during cooling (evaporative cooling) and heating modes (evaporative humidification).

The proposed technique for interrupting the pathogen chain-of-transmission is an air-handling unit that incorporates a waterside ozonation system. Ozone, in a liquid phase, is an extremely effective biocide (CTI, 1993) and virucide (Snyder and Chang, 1973; Sproul, 1973 and Sorbsey, 1989). The water spray by itself can be very effective in removing air borne particles by physical entrapment (Watt, 1963).

### ***1.3 Project goals***

The hypothesis is that, airborne pathogens can be effectively “scrubbed” from the air stream by the direct-contact spray system and deposited into the water sump. A side-stream supply of the sump water is ozonated and returned to the sump. Ozone dissolved in the liquid phase, will inactivate the formerly airborne pathogens by rapid oxidation. Sanitized air leaves the air-handling unit at a temperature and humidity as required for satisfying space cooling (or heating) loads.

The purpose of this part of the project is to build a working experiment to determine the behavior of ozone in such a system and provide preliminary test data. Details about ozone will be discussed in Chapter 2. Other parts of the whole project are the heat and mass transfer, the filtration efficiency, amount of ozone transferred from the dissolved phase into the gas phase, and ultimately tests with pathogen samples are needed to put the puzzle together. The experiment built in this project should be reusable for any of the aforementioned experiments.



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## Chapter 2 Ozone

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This Chapter should answer basic questions about ozone. What is ozone? Where does it occur? Is it harmful for humans? How is it generated?

*“Ozone is an allotropic form of oxygen; each molecule contains three atoms of oxygen instead of the standard 2. Ozone is formed naturally in the atmosphere, as a colorless gas giving a very pungent odor. It is the ozone formed by lightning discharges during a thunderstorm, which gives the air its characteristic fresh and clean smell afterwards. An ozone smell can also be detected around office copy machines and laser printers.”*

(Waterwise, 1999).

Descriptions like these can be found in chemistry books or papers about ozone. It is commonly known from the ozone shield that protects the earth from harmful UV irradiation. Up in the stratosphere, especially above the Antarctic and the southern parts of Australia and South America, the ozone layer is damaged. Large portions of UV light can reach the surface of the earth and e.g. cause skin cancer.

On the surface of the earth, ozone can cause problems. High concentrations in the summertime cause health problems, like described in the next section, to children, older people or people with respiratory problems.

## **2.1**                    *Health effects*

Ozone consists of three oxygen atoms. The third atom can detach from the ozone molecule and re-attach to molecules of other substances, thereby altering their chemical composition. These chemical properties that allow ozone to react with organic material give it the ability to react with biological material that make up the body, and potentially cause harmful health consequences. When inhaled, ozone can damage the lungs. Relatively low amounts can cause chest pain, coughing, shortness of breath and throat irritation. Ozone may also worsen chronic respiratory infections (US EPA, 1999). Recovery from the harmful effects can occur following short-term exposure to low levels of ozone, but health effects may become more damaging and recovery less certain at higher levels or from longer exposures (US EPA, 1996a, 1996b)

The Food and Drug Administration (FDA) requires ozone output of indoor medical devices to be no more than 0.05 ppm. The Occupational Safety and Health Administration (OSHA) requires that workers not be exposed to an averaged concentration of more than 0.10 ppm for 8 hours (permission exposure limit, PEL). The National Institute of Occupational Safety and Health (NIOSH) recommends an upper limit of 0.10 ppm, not to be exceeded at any time. The Environmental Protection Agency (EPA)'s National Ambient Air Quality Standard for ozone is a maximum 8-hour average concentration of 0.08 ppm.

It is possible for some people to smell ozone. But the ability to detect ozone by smell varies considerably from person to person, and one's ability to smell ozone rapidly

deteriorates in the presence of ozone. While the smell of ozone may indicate that the concentration is too high, lack of odor does not guarantee that levels are safe. (US EPA, 1999).

## 2.2 *Ozone in air and water*

The objective of this experiment is to filter the pathogens out of the air with a water spray and kill them in the water by rupturing the cell walls by exposure to O<sub>3</sub>. A good question at this point is, why not ozonate the whole building with a concentration below the limit of 0.1 ppm. That would not only inactivate all the viruses and bacteria in the air, ozone would also attack the pathogen sources inside the building.

The best way to answer this question is to provide Table 2.1 and Table 2.2. In these tables ozone concentrations are shown for various viruses and bacteria in air and in water, which are required to inactivate those pathogens.

**Table 2.1** Previous Results of Ozonation of Bacteria

Medium	Test Organism	Ozone ppm	Time sec	Survival %	Researchers
Air	S. salivarius	0.6	600	2	Elford & van de Eude (1942)
	S.epidermis	0.60	240	0.6	Heindel et al. (1993)
Water	B. subtilis	2.2	90	0.01	Botzenhart et al. (1993)
	E. coli	1.3	10	0.003	Katzenelson & Shuval (1973)
	S. typhimurium	0.36	36	0.0002	Farooq et al. (1983)
	E. coli	0.81	30	0.00003	Finch et al. (1988)
	E. coli	12	62	0.00015	Bunning & Hempel (1995)
	E. coli	2	15	0	Burleson et al. (1975)
	S. aureus	2	15	0	Burleson et al. (1975)

**Table 2.2** Previous Results of Ozonation of Viruses

Medium	Test Organism	Ozone ppm	Time sec	Survival %	Researchers
Air	pX174	0.04	480	0.1	de Mik (1977)
Water	poliovirus 1	0.20	360	1	Harakeh & Butler (1985)
	NDV	2.00	417	1	Perez-Rey (1995)
	poliovirus 1	0.21	120	0.1	Roy et al. (1982)
	poliovirus 1	1.50	8	0.5	Katzenelson et al. (1979)
	T2 phage	1.30	70	0.003	Katzenelson (1973)
	T7 phage	0.95	240	0.001	Lockowitz (1973)
	rotavirus SA-11	0.25	10	0.001	Vaughn et al. (1987)
	Hepatitis A	1.66	5	0.00001	Hall & Sobsey (1993)

Even at high concentrations, ozone may have no effect on biological contaminants embedded in porous material such as duct lining or ceiling tiles. Ozone produced by ozone generators may inhibit the growth of some biological agents, but it is unlikely to fully decontaminate the air unless concentrations are high enough to be a health concern to people. Even with high levels of ozone, contaminants embedded in porous materials may not be affected at all. (Foarde et al, 1997)

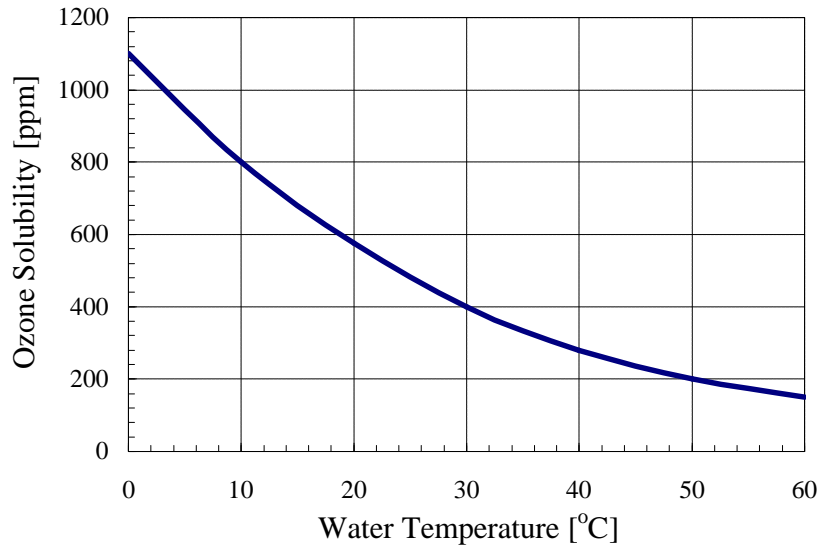
*“Gaseous ozone concentrations of 6 to 10 ppm were required to obtain the full 3 log reduction for the three fungi tested.”* (Foarde et al., 1997)

Katzenelson et al. (1973) and Broadwater et al. (1974) found values for *Escherichia coli* in water between 0.1 and 0.2 ppm. The concentrations required to inactivate pathogens in air are only slightly above the limit. These are only values with known viruses and bacteria from the literature. Dyas, et al. (1983) also mention that

*“ozone concentrations in air would have to be 5-10 times higher than public health standards allow before the ozone concentration decontaminate the air sufficiently to prevent survival and regeneration of the organisms once the ozone removed”,*

Dyas does not mention the type of pathogen used. Compared to the required ozone concentrations for air the required values for ozone in water are way higher. They are between 0.2 ppm to 2.2 ppm and up to 20 ppm. The point is that those are the concentrations in water, but they don't have to be equal the concentrations in the air resulting from the proposed system. To be able to cover a wide range of pathogens, the possible dissolved ozone concentration has to be at least in that range. A concentration of 5 ppm is a reasonable value as a maximum for planned experiments.

Some solubility data for ozone in water can be found in the literature. On the *International Chemical Safety Card* (1993) 1000 ppm are mentioned for 0 °C. In the *Handbook of Chemistry and Physics* (1972) 20 ppm are suggested at room temperature. In a report on the usage of ozone the U.S. Department of Energy (1995) published values of < 3 ppm for 40 °C and effectively zero at 43.4 °C. Evans (1971) published the data shown in Figure 2.1.



**Figure 2.1** Solubility of ozone in water (Evans, 1971)

Due to the fact that 1 *ppm* of ozone is equal to 2  $\text{mg}/\text{m}^3$  of ozone in air or 1  $\text{mg}/\text{l}$  in water, these different sources do not agree with each other.

The solution for this problem is described by Battino (1981):

*“Gases which react upon diffusing into the liquid phase presents unique problems in establishing gas-liquid solubilities. Since ozone decomposes irreversibly in water, the overall mechanism in aqueous systems can be presented as*



*The gas-liquid equilibrium involves step 1. Classical solubility measurements involving the equilibrium of a fixed volume of gas with a measured mass of solvent cannot be used when step 2 is significant relative to the ozone transfer from the gas phase. Historically,*

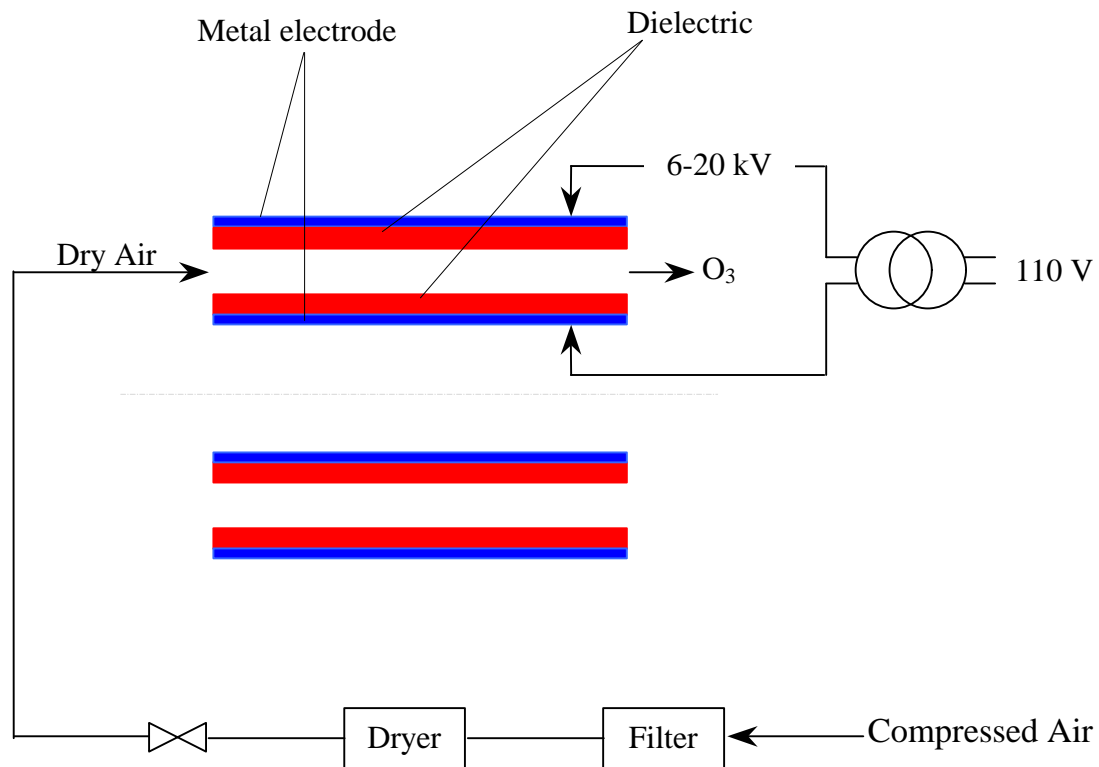
*investigators have generated ozone by passing an air or oxygen stream between electrodes across which an electrical discharge is generated. The exiting gas stream, typically 2 to 4% ozone by weight, is bubbled continuously through water. A steady state concentration is achieved as time increases. This approaches the ozone solubility only when the kinetic rate for step 2 is very slow compared to the gas to liquid mass transfer step. For the ozone water system, this occurs only in the low temperature and low pH regions. At higher relative reaction rates (step 2) however, the observed steady state concentration is not the thermodynamic equilibrium (i.e., solubility) concentration.”*

In the proposed system, the ozone concentration is not only limited by decomposition, but also by the spray. While water is sprayed into the air stream ozone molecules migrate from the liquid phase into the gas phase. To achieve thermodynamic equilibrium in the system, more ozone has to be injected into the system than is decomposed and/or transferred into the air stream. Preliminary results have shown that enough ozone can be injected to be in the planned range, but this is still far below the solubility limit proposed in the literature.

### **2.3 Ozone generation**

Generally there are two different ways to produce ozone. In nature it is generated by lightning discharge and by UV irradiation in the stratosphere. The equivalent to lightning is corona discharge (CD). Ozone generation is accomplished by passing a high-voltage alternating current (6-20kV) across a dielectric discharge gap. Filtered and dried air is injected into this gap, as shown in Figure 2.2. As air is exposed to the high voltage,

oxygen molecules disassociate and form single oxygen atoms, some of which combine with other oxygen molecules to form  $O_3$ . Different manufacturers have their own variations of components for ozone generators. Two different dielectric configurations exist - flat plates and concentric tubes. Most generators are installed using the tube configuration. To increase the efficiency of generating ozone, pure oxygen can be used instead of air.



**Figure 2.2** Dielectric Process for Ozone Generation

Ultraviolet ozone generators, on the other hand, utilize a mostly 185 nm wavelength lamp to produce ozone. Air is passed over an ultraviolet lamp, which splits oxygen molecules



in the gas. The resulting oxygen atoms, seeking stability, attach to other oxygen molecules, forming ozone (Rich, 1994).



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## Chapter 3 Experimental Analysis

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### 3.1 *Introduction*

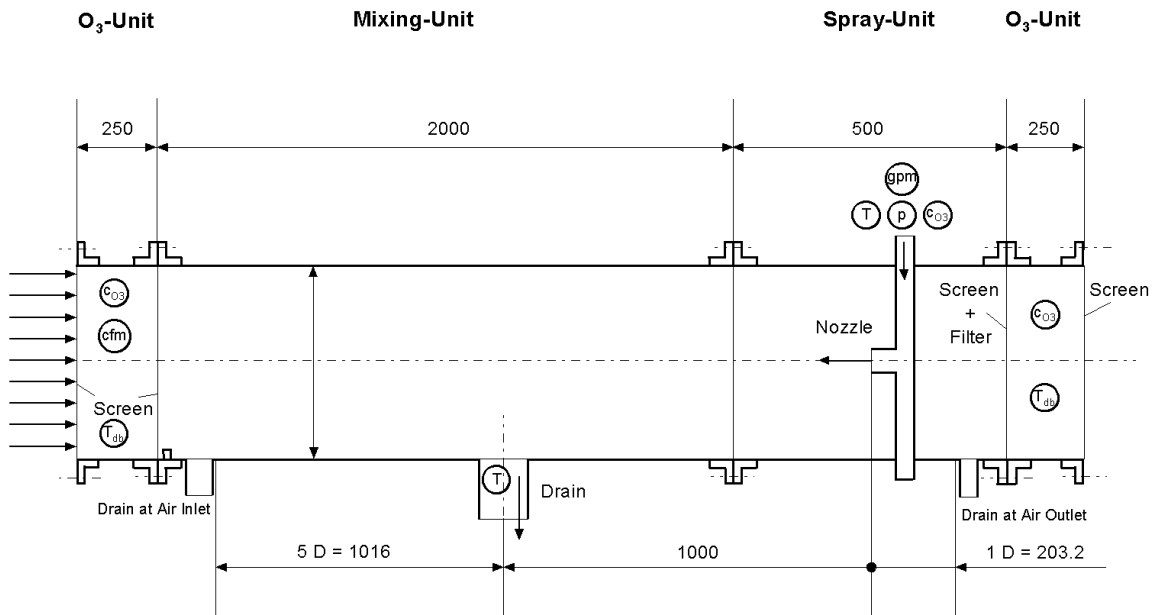
An experimental apparatus was designed and constructed to determine the increase of the ozone concentration in the air when ozonated water is sprayed into an air stream in a counter flow arrangement. The apparatus consists of a blower, a test section, a water supply system, spray system, refrigeration machine, ozone generator, electrics, insulation and the necessary equipment to measure the dry bulb temperature, humidity and ozone concentration at the air inlet and the air outlet, the temperature, the pressure, the flow rate and the ozone concentration at the water inlet and the water outlet temperature.

The blower (Greenheck, model BSQ-70-5, S/N 98D02261) draws a constant volume flow rate of air through the test section. Chilled water is sprayed in a counter flow arrangement to cool and dehumidify the air. The air velocity is measured with a vane anemometer while entering the test section. Ozone concentration dry bulb temperature and humidity are measured to determine the psychometric state of air entering and leaving the test section. In addition to the airside measurements, waterside measurements are performed to check that the energy balance is satisfied. Entering water temperature, pressure, ozone concentration and flow rate are measured in a station prior to reaching the spray nozzle. The water flow is measured using a rotameter (Kobold, model KSK 3999-T, S/N 59507). Return water temperature is measured allowing the waterside energy gain to be compared with the airside energy loss. All measurements are taken under quasi-steady state conditions. Quasi-steady state conditions are defined by airside and waterside

temperatures changing no more than 5% over a five-minute period of operation. They will be verified by continuous logging of airside and waterside temperatures in accordance with the previously mentioned criteria. Details of the test apparatus are discussed in the following sections.

### 3.2 Test Section

The motor driven blower draws ambient air from the laboratory room through the test section. The blower is located downstream of the test section to maintain a negative pressure inside the test section to make sure that there are no leaks from the test section to the surrounding environment ( $O_3$ ). An opposed blade damper on the blower inlet side is manually adjusted to achieve a constant the volume flow rate of air drawn by the blower.



**Figure 3.1** Schematic of test section

The test section consists of four units shown in Figure 3.1 the mixing-unit, the spray-unit and two O<sub>3</sub>-units. Air enters the first O<sub>3</sub>-unit where the ozone concentration, dry bulb temperature and humidity are measured. Then the air flows to the mixing-unit. Here heat and mass transfer between water spray and the air occurs. The water is sprayed into the air stream in the spray-unit, which is located downstream of the mixing-unit. Behind the spray-unit the air stream passes the second O<sub>3</sub>-unit where the ozone concentration, dry bulb temperature and humidity are measured again. A blower (not shown in Figure 3.1) is positioned to draw air into the test section from left to right. This arrangement ensures the entire test section will be under negative pressure so that ozone will not leak into the surrounding laboratory space. On the upstream side of the blower there is a manually adjustable damper that is used to control the airflow rate. The blower exhausts to an exhaust hood, to ensure no ozone gets in the ambient air.

The test section is built in modules. Each module can be replaced or reused for different experiments in the future. Each module consists of an 8" polyvinylchloride (PVC) schedule 40 pipe. PVC was chosen as duct material because of its known resistance against ozone, which is a strong oxidizer. Another possibility would be stainless steel, but this option was considerably more expensive. On the one hand, cost and handling were a reason to choose 8" and not a larger diameter. On the other hand the experiment needs to be realistic. Scaling up the results from a too small experiment is not reliable, so a duct 8" in diameter was chosen. The specifications for 8" schedule 40 pipe are given in Table 3.1.

**Table 3.1** Schedule 40 IPS Data for an 8" Pipe (Spears, 1999)

	SI-Units	English-Units
Outside Diameter	219.1 <i>mm</i>	8.625"
Inside Diameter	201.8 <i>mm</i>	7.943"
Wall Thickness	8.65 <i>mm</i>	0.322"
Max. Pressure	1103.2 <i>kPa</i>	160 <i>PSI</i>

On each side of the modules, a PVC flange is mounted so that the modules can be connected to each other. PVC cement is used to seal the fittings. All the PVC tubing connections are glued with MP-6 Multi-Purpose cement. Threaded connections are sealed with TFE Paste or Teflon Tape. Before treating the connections with the sealants, pipe cleaner was used to prepare the surface.

The mixing-unit is the space where water and air are in direct contact with each other. In order to facilitate drainage of the sprayed water, there is a main drain located approximately in the middle of the unit and an additional drain at the air-inlet of the mixing-unit, as shown in Figure C.2. At the air-inlet, there is also a barrier in front of the drain to prevent water from flowing into the O<sub>3</sub>-unit. Details are shown in Figure C.2.

In the spray-unit, water is sprayed in counter-flow direction into the air steam. The volume flow (*gpm*), temperature (*°C*), pressure (*kPa*) and ozone concentration (*ppm*) of the water entering the nozzle are measured and stored with a data acquisition system. Two different nozzles can be used. Nozzle 1 and nozzle 2 are full cone nozzles with spray angles around 88° and 64° respectively. Details of their performance are shown in Table 3.2.

**Table 3.2** Performance Data for nozzles QLG 40 and QLH 25 (Spraying Systems Co., 1993)

Nozzle Type	Capacity [ <i>l/min</i> ]										Spray Angle		
	34.5 <i>kPa</i>	48.3 <i>kPa</i>	68.9 <i>kPa</i>	137 <i>kPa</i>	206 <i>kPa</i>	275 <i>kPa</i>	423 <i>kPa</i>	551 <i>kPa</i>	689 <i>kPa</i>	1034 <i>kPa</i>	48.3 <i>kPa</i>	137 <i>kPa</i>	551 <i>kPa</i>
QLG 40	11.0	12.1	15.1	20.8	25.0	28.8	34.8	40.1	44.7	54.1	88°	91°	83°
QLH 25	6.81	7.9	9.5	13.2	15.9	18.2	22.0	25.4	28.0	33.7	64°	67°	61°

Both nozzles have a ½ BSPT connection. This makes a quick exchange possible. Therefore a nozzle body with a ½ male NPT thread is needed to connect it to a ½ PVC T-piece. As the standard Buna-N seal is not recommended for use with ozone, a more expensive VITON seal was selected. The dimensions and weight of both the nozzles and the body are given in Table 3.3.

**Table 3.3** Dimensions and Weight for nozzles with Body QJL (Spraying Systems Co., 1993)

Nozzle Type + Body QJL	Orifice Diam. Nom. [ <i>mm</i> ]	Maximum free Passage Diam. <sup>1</sup> [ <i>mm</i> ]	Length [ <i>mm</i> ]		Hex Max. [ <i>mm</i> ]	Weight [ <i>g</i> ]
			Min.	Max.		
QLG 40	6.4	3.6	70.6	72.2	28.6	212.6
QLH 25	9.5	3.1	56.4	57.2	28.6	127.6

The construction used to fix nozzle in the spray-unit can be seen from the drawing for the spray-unit in Figure C.1. There is an additional drain at the end of the spray-unit towards the air-outlet.

In each O<sub>3</sub>-unit a ½ PVC tube is led through the duct in the horizontal direction. In the front of the tube, eleven 4.7 *mm* diameter holes are drilled into the tube. Through these

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<sup>1</sup> Foreign matter with maximum diameter as listed can pass through nozzle without clogging

holes, an isokinetic air sample can be drawn from the duct to the ozone sensor or humidity sensor. Details are shown in Figure C.3.

To get an isokinetic sample, the velocity of the air drawn into the holes in the tube must be equal to the free stream velocity. For air washers a recommended value for the airflow rate is  $2.54 \text{ m/s}$  ( $500 \text{ ft/min}$ ), a constantly used design limit to prevent moisture carry-over (Watt et al., 1997). The pump used to draw the air sample has a flow rate of  $30 \text{ l/min}$  that results from a total of 11 holes with a diameter of  $4.7 \text{ mm}$  for an isokinetic sample. Due to the pressure drop in the tube, there are more holes towards the center of the duct. At both ends of the  $\text{O}_3$ -unit (inlet & exit), wire mesh is mounted to straighten the flow and to eliminate mist from the air at the air-outlet. On the downstream one of these meshes 18 thermocouples are glued to measure the averaged dry bulb temperature according to ANSI/ASHRAE Standard 111-1988, shown in Figure 3.4. Details of the  $\text{O}_3$ -unit are shown in Figure C.3.

During preliminary test runs, it was observed that water droplets were carried over into the  $\text{O}_3$ -unit sample tube and on the louvers of the damper. Employing an additional filter between the spray-unit and the  $\text{O}_3$ -unit to capture the water mist solved this problem. The filter is a double layer of polyurethane foam air conditioning filter. One layer of the filter has a thickness of  $6.35 \text{ mm}$  ( $1/4''$ ). Compared to other filters that were tried, the resistance against the airflow does not change when it gets wet. Other products act like dampers when they get in contact with water.



### 3.3 Water Supply System

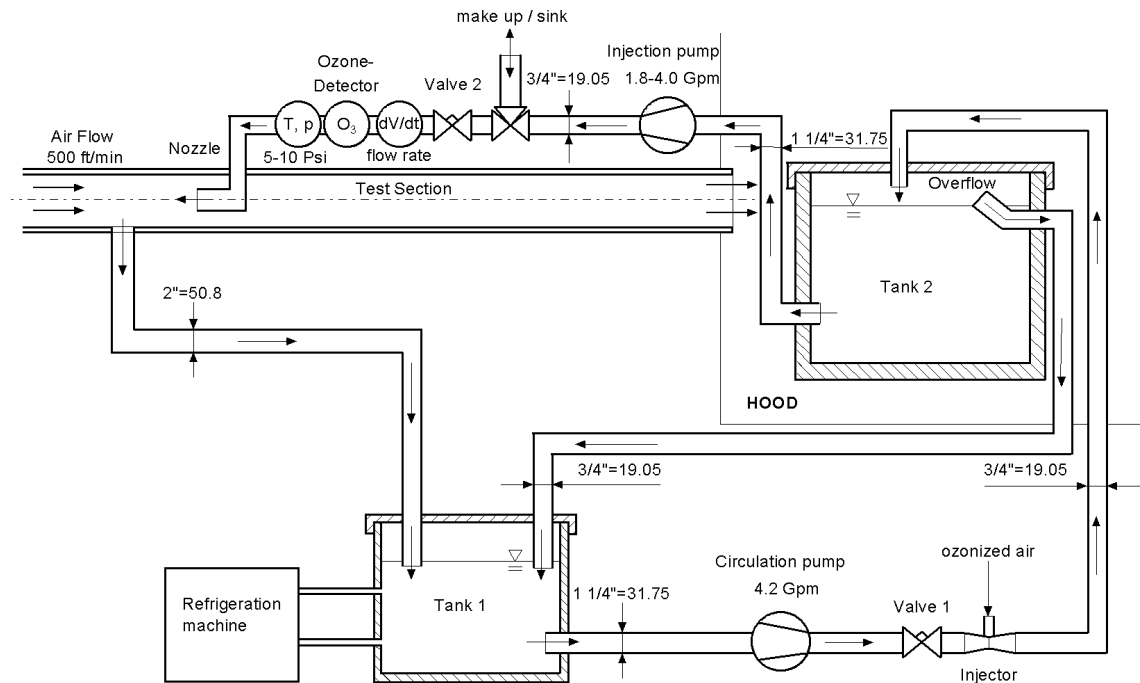


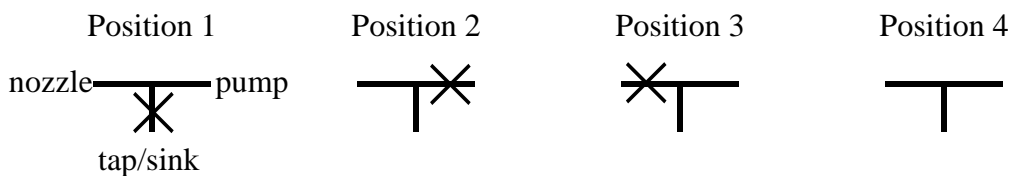
Figure 3.2 Water supply system

The main components of the system are a refrigeration machine, two storage tanks (80 l each), circulation pump, injection pump, valves (one way & 3-way), ozone injector, flow meter, dissolved  $O_3$  detector, temperature and pressure sensor and the nozzle.

Tank 1 (drainage or sump tank) is placed at a level lower than the test section to collect water that is drained by gravity from the test section. Tank 2 is located in the hood approximately the same level of the duct. Both tanks are covered to prevent  $O_3$  leakage to the surrounding. The concentrated ozonated air inside the tank on top of the water surface minimizes the rate of ozone migration from the liquid to the gas phase due to a lower concentration difference between the gas and the liquid phase.

Water is pumped from tank 1 to tank 2 by the circulation pump via the ozone injector. The flow rate through the ozone injector (Mazzei, model 584, S/N 9931A2) is regulated by a bronze butterfly valve, valve 1. In tank 2, an overflow pipe drains the water surplus back to tank 1 thus maintaining a constant water head on the injection pump (McMaster-Carr, #4291 K31, S/N 84A375). The hose used to drain the water back ends under the water surface of tank 1, so that no ozonated air can be exchanged between the tanks. This circuit is named circuit 1 shown in Figure 3.2. It is used to condition the water before the experiment. While water is exchanged between those two tanks it can be cooled with the refrigeration machine connected to tank 1 and ozonated air can be added through the injector.

The injection pump pumps water from tank 2 to the nozzle. The constant water level in tank 2 helps to maintain constant injection pressure. A 3-way, 4-position valve is installed after the pump. This valve is used to add or to remove water from the system. The valve is connected to three different hoses, but it can be used in four different positions as shown in Figure 3.3.



**Figure 3.3** Four different positions for a 3-way, 4-position valve

In position 1 water goes directly from the pump to the nozzle. This mode is used during the experiments. In position 2 water from the tap is added to the system. It is sprayed

through the nozzle and flows in the tanks. In position 3 water is pumped to the sink. With this mode water can be pumped out of the system. Position 4 is not used. Behind the valve a bronze metering butterfly valve is installed to control the flow rate. The flow rate is measured with a flow meter. Before entering the nozzle, the ozone concentration, the temperature and the pressure are checked. The water is drained back from the duct into tank 1. Only one of the three drains is shown in the schematic. The drain hoses end under the water surface so that no ozonated air can leak back into the duct and change the results of the experiment. This circuit is called circuit 2.

Circuit 1 and circuit 2 share the circulation pump. The circulation pump (McMaster-Carr, #4291 K31, 84A379) must always pump more water from tank 1 into tank 2 than is supplied to the nozzle. As a result, there is always a surplus of water pumped to tank 2, such that some has to be drained through the overflow pipe so that the water level in tank 2 remains constant.

The design values for the injection pumps are 34.5-68.9 *kPa* (5-10 *psi*) and 6.81-15.1 *l/min*. (1.8-4.0 *gpm*). These values depend on the desired nozzle performance shown in Table 3.2. For the circulation pump the values depend on the injector performance. To maintain a surplus in tank 2 under all operating conditions, the volume flow rate through the ozone injector has to be higher than 15.1 *l/min*. (4.0 *gpm*) due to the fact that the maximum flow rate at the nozzle is 15.1 *l/min* (4.0 *gpm*). At 172.4 *kPa* (25 *psi*) inlet pressure the chosen ozone injector has a flow rate of 16.2 *l/min*. (4.28 *gpm*). The air suction rate at this state is 11.8 *l/min*. (25.0 *scfh*). The injector performance table is

available from the manufacturer. So the circulation pump must deliver 16.2 *l/min*. (4.28 *gpm*) at 172.4 *kPa* (25 *psi*). For both cases, the pumps were chosen which meet this requirement. Two identical pumps are used to meet the aforementioned conditions. The performance of the pump is shown in Table 3.4.

**Table 3.4** Pump performance table

Pump head	20 <i>ft</i>	60 <i>ft</i>	80 <i>ft</i>	85 <i>ft</i>
Equivalent pressure	59.78 <i>kPa</i>	179.3 <i>kPa</i>	293.1 <i>kPa</i>	254.1 <i>kPa</i>
Flow rate	30 <i>gpm</i>	15 <i>gpm</i>	5 <i>gpm</i>	shutoff
	113.6 <i>l/min</i>	56.8 <i>l/min</i>	18.9 <i>l/min</i>	

### 3.4 *Measurements & Control*

Measurements are needed to determine the dependence of temperatures, concentrations and other variables to each other. In Table 3.5 the measuring locations and the main variables are shown. Additionally the temperature of the water in tank 1 is measured. In the following paragraphs, details about the temperature measurements at the inlet and outlet of the air and the water system, the ozone and humidity measurements in the air system, air velocity control, water flow rate control, dissolved ozone and pressure measurement at the water inlet, the data acquisition system and its program will be discussed.

**Table 3.5** Measuring locations in the experiment

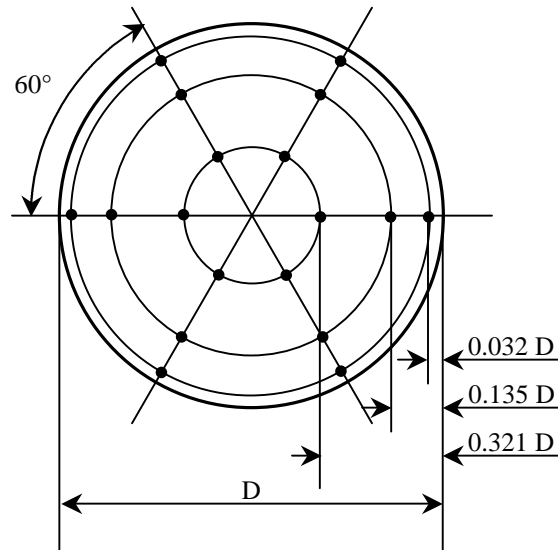
Location	Measurement	Unit
Air-Inlet	Dry bulb temperature	$^{\circ}C$
	Gas ozone concentration	<i>ppm</i>
	Humidity	%
	Flow rate, damper controlled	<i>ft/min</i>
Air-Outlet	Dry bulb temperature	$^{\circ}C$
	Gas ozone concentration	<i>ppm</i>
	Humidity	%
Water-Inlet before nozzle	Flow rate, valve controlled	<i>gpm</i>
	Dissolved ozone concentration	<i>ppm</i>
	Water inlet temperature	$^{\circ}C$
	Water inlet pressure	<i>kPa</i>
Water-Outlet at main drain	Water temperature	$^{\circ}C$

The dry bulb temperature at the air-inlet and air-outlet are measured according to ANSI/ASHRAE Standard 111-1988 as shown in Figure 3.4. The standard requires the following for measurement locations for the dry bulb temperature of the air (in the O<sub>3</sub>-units):

- Regular duct cross section
- Straight duct 5 (10 preferred) diameters upstream
- Straight duct 1 (3 preferred) diameters downstream
- Traverse plane should be perpendicular to air flow
- Uniform velocity throughout plane

As can be seen in comparing the test apparatus shown in Figure 3.1 with ASHRAE 111, all requirements are fulfilled. For each unit the same duct with the same diameter is used. Gaps at the flanges are filled with silicon rubber. The location of the upstream temperature measurement has a larger distance than five times the diameter from the main drain. The location of the downstream measurement from the nozzle is greater than one diameter. The plane of the mesh on which the thermocouples are glued on is

perpendicular to the flow direction. The actual flow profile through the test section will be compared to ASHRAE 111 as presented in Chapter 4.

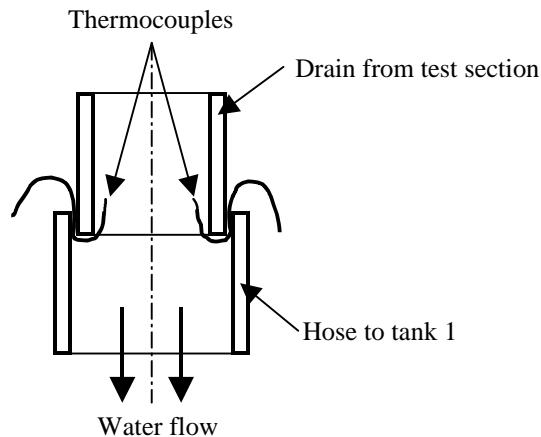


**Figure 3.4** Arrangement of thermocouples according to ANSI/ASHRAE Standard 111-1988

Eighteen thermocouples are divided into six groups, sixty degrees apart. They are glued directly on the meshes on the downstream side of the  $O_3$ -units, pointing upstream. All thermocouples are connected together in a thermopile arrangement. That means all thermocouples are connected in parallel, so that an averaged voltage difference across all thermocouples is measured, to get the averaged temperature for this plane. This thermopile is connected to a datalogger. The program for the datalogger can be reviewed in Appendix C. The thermopiles are insulated from the environment with closed cell foam, to minimize the influence of ambient temperature biasing measurements by conduction. Copper-constantan thermocouples are used as they have several advantages:

- Accuracy of  $\pm 1\text{ }^{\circ}\text{C}$
- Good performance for measuring temperatures in humid atmospheres
- Relatively inexpensive

The same type of thermocouples is used to measure the water inlet and outlet temperatures. At the water inlet only one thermocouple is used, while two thermocouples are used at the water outlet. They are introduced in at the connection between the hose and the drain and they are mounted on opposite sides. Their tip is pointing upstream as shown in Figure 3.5. Both thermocouples are connected in parallel so that the averaged temperature is measured. Thermocouple extension wire is used to connect the thermopile with the datalogger.



**Figure 3.5** Installation of thermocouples to measure the water outlet temperature

At the air inlet and outlet of the test section the humidity and the ozone concentration have to be measured. For those measurements, an air sample is drawn out of the duct. According to Figure C.3, it will be drawn out of the  $\text{O}_3$ -unit at both sides of the tube to reach a symmetric pressure drop in the tube. Both sides of the tube are connected to a 3-

way, 4-position valve with a T-piece. A choice can be the air sample should be taken from the air-inlet or the air-outlet. The air sample can be directed to the gas ozone detector or to the humidity sensor with a second valve. The ozone detector (ATI, A11 Sensor/Transmitter, S/N A11-11-0278-EC) combines an electrochemical gas sensor and an electronic amplifier that transmits the gas concentration. The range of the gas ozone detector is set to 0 – 1.00 *ppm*. According to the manufacturer, the uncertainty of the measured value is  $\pm 2\%$  of the full scale (ATI, 1998). There is one warning point set at 0.1 *ppm* (green blinking light) and one alert point at 0.5 *ppm* (red blinking light). The ozone detector has an analog output with a current from 4-20 *mA* representing the full range of the chosen scale. As suggested in the datalogger manual (Campbell, 1998) a 100-Ohm resistor is used to convert the current into a voltage difference that can be measured with the datalogger. At the outlet the gas ozone detector is connected to a pump to reach a suction rate of 30 *l/min*. The exhaust is connected to the hood, so that ozonated air does not get into the indoor environment.

The moisture content of the air is measured indirectly. The humidity ratio of the air is determined by measuring the dew point using a dew point hygrometer (General Eastern, model Hygro M1, S/N 2142) together with the dry bulb temperature measured with a thermopile. The dew point hygrometer is a general purpose optical condensation dew point hygrometer that provides a measurement range of  $-75^{\circ}\text{C}$  to  $95^{\circ}\text{C}$  with an accuracy of  $\pm 0.2^{\circ}\text{C}$ . The dew point temperature is measured by detecting the condensation on a chilled mirror, which is cooled by a thermoelectric cooler. The mirror temperature is measured with a platinum resistance thermometer. The dew point hygrometer is



calibrated against dew point standards that are traceable to the National Institute of Standards and Technology, NIST.

The airflow rate through the duct is manually controlled by a damper. The air velocity is measured with a vane anemometer. Without using the damper, a maximum flow rate of 10.16 *m/s* (2000 *ft/min*) with and 11.18 *m/s* (2200 *ft/min*) without the filter between spray- and O<sub>3</sub>-unit can be reached. With such high flow rates and without the filter, a major part of the sprayed water is drawn into and through the blower. Moisture droplet carry-over is not a problem for velocities around 2.54 *m/s* (500 *ft/min*) as suggested for air washers (Watt, 1997). With water in the blower, different problems were discovered. In the first construction, the damper was installed downstream of the blower. Due to the high-pressure drop across the blower, ozonated air leaked out of it. To avoid this problem, the damper was relocated to the air inlet of the blower and every reachable gap of the blower was filled with silicon rubber.

On the waterside of the system, the water flow rate is monitored with a rotameter installed before the nozzle. The rotameter has a scale of 1.67 – 15.1 *l/min* (0.44 - 4.0 *gpm*) with an accuracy of  $\pm 4$  % full scale. The maximum allowable temperature is 60 °C (140 °F) and the maximum pressure is 999.7 *kPa* (145 *psi*). The flow rate is adjustable with a bronze metering butterfly valve, valve 2.

The dissolved ozone concentration is measured with a liquid phase ozone detector (ATI, model A15/64, S/N 062946). The detector is based on polarography. Dissolved ozone

molecules migrate through a selective semi-permeable membrane into the electrolyte inside the sensor body. The presence of ozone in the electrolyte causes an electrode in the sensor to deliver a current to the oxygen monitor, which amplifies the current and converts it to a voltage. The voltage is directly proportional to the concentration of oxygen in the chamber. The scale is set to 0 – 20.00 *ppm* with an accuracy of  $\pm 0.01$  % full scale. The ozone detector also has an analog output with a range of 4 – 20 *mA*. The current increases linearly with the ozone concentration. As with the gas ozone detector, a 100-Ohm resistor is used to convert the current into a voltage difference that can be measured with the datalogger.

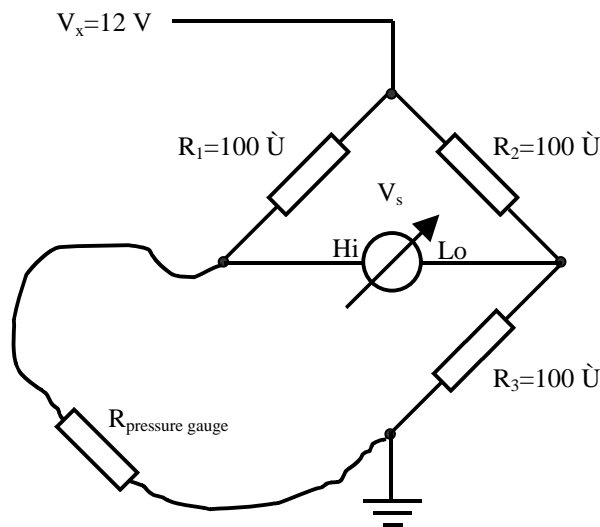
The water inlet pressure is measured with a pressure transducer (Cole-Parmer, #07356-53, S/N 60611044). The maximum measurable pressure is 689.5 *kPa* (100 *psi*). The power supply has to be between 10 and 30 V (DC) and the measured pressure is linear to the current output between 4 – 20 *mA*. The main difference between the pressure transducer and the ozone detectors is that power has to be supplied to the pressure transducer, so that there is no possibility to use a simple resistor to convert the current signal into a voltage difference. Figure 3.6 shows a Wheatstone bridge circuit designed to determine the resistance of the pressure transducer. The ratio of the supplied voltage and the measured voltage depend on the different resistances of the circuit as indicated in Equation (3.1).

$$X = \frac{2 \cdot V_S}{1000 \cdot V_X} = \frac{R_{PT}}{R_{PT} + R_1} - \frac{R_3}{R_2 + R_3} \quad (3.1)$$

The current received from the Wheatstone bridge is larger than the maximum current that the datalogger can measure. A current transformer with the ratio 2:1 is used to transform the current down. This transformation is compensated with the factor 2 in Equation (3.1). The supplied current is measured in Volts while the readout is in  $mV$ . The factor 1000 is required.  $R_1$ ,  $R_2$  and  $R_3$  are the resistances in the circuit.  $R_{PT}$  is the resistance of the pressure transducer, which should be calculated depending on  $V_S$ . Rearranging Equation (3.1) as shown in Equation (3.2) and Equation (3.3), the resistance of the pressure transducer can be calculated directly depending on  $V_S$ .

$$R_{PT} = \frac{R_1 \cdot X'}{1 - X'} \quad (3.2)$$

$$X' = X + \frac{R_3}{R_2 + R_3} = \frac{2}{1000} \cdot \frac{V_S}{12} + \frac{1}{2} \quad (3.3)$$



**Figure 3.6** Wheatstone Bridge to determine the resistance of the pressure gauge

The current in the circuit is proportional to the ratio of the voltage difference and the resistance.

$$I = \frac{U}{R_{PT}} \quad (3.4)$$

According to the manual, the current is proportional to the measured pressure. The supplied voltage is constant and can be put into the constant  $C_1$ . In Equation (3.5) in addition to  $C_1$ , the constant  $C_2$  is introduced as an offset value. The final linear equation for calibration is shown in Equation (3.5). The calibration will be discussed in Chapter 4.

$$p = \frac{C_1}{R_{PT}} + C_2 \quad (3.5)$$

A Campbell Scientific CR23X Micrologger (model CR23X, S/N 0610692) is used for the data acquisition. The datalogger is supplied with a 12 V AC current. It has several digital and analog I/O ports. Only voltage difference can be measured. The datalogger has also regulated power outputs with 5 and 12 V. It can be connected to the serial port of a PC. Campbell Scientific provides a program called “*PC208W*” Version 3.01 to write specific data acquisition programs. The program “*PC208W*” was used as a starting point to write the program shown in Appendix A. It also organizes the connection between the datalogger and the computer, data transfer and storage on the computer.

The program for the datalogger is divided into three parts, called tables. In table 1 the whole program is written, while in table 2 and 3 additional information and program parts

like subroutines can be stored. In this program only table 1 is used. The program is executed every second. It is subdivided into 37 modules. Each module consists of one procedure. In the first part the datalogger reads the values from the connected instruments. In module 1 a reference voltage for the thermocouples is received from an internal device of the datalogger to provide a reference temperature. The voltages for the different thermocouples are checked in modules 2 to 6. All readings for the thermocouples have a range of  $10\text{ mV}$  and a  $60\text{ Hz}$  rejection. The following synonyms for the temperatures that are measured:

- tempWatIn - Water temperature before the nozzle (inlet)
- tempWatOu - Water temperature at the main drain (outlet)
- tempAirIn - Averaged temperature at the air inlet
- tempAirOu - Averaged temperature at the air outlet
- temptank - Water temperature in tank 1

In modules 7 to 9 the voltage differences from the pressure gauge and from the ozone detectors are received. Here a range of  $5000\text{ mV}$  with a  $60\text{ Hz}$  rejection is used. The voltage range always depends on the maximum voltage that can be expected from the pressure gauge. A range that is too large will lower the accuracy of the measurements.  $60\text{ Hz}$  rejection is important to suppress noise coming from the power supply. In modules 10 to 21 all the outputs are averaged over a time period of 1 minute. In modules 22 to 27, the signal from the resistance of the pressure gauge is calculated depending on the voltage signal from the pressure gauge. The constants C1 and C2 for the calibration are stored in modules 28 and 29. The pressure is calculated depending on Equation (3.5) is stored in modules 30 and 31. The dissolved ozone detector is calibrated in modules 32 to 34 and



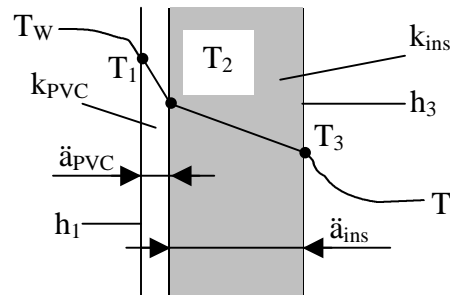
- The half-life time of ozone is assumed to be 10 *min*. According to Chapter 2, 5 *ppm* = 5 *mg/l* of ozone dissolved in water is a reasonable assumption of the reproduced ozone.

$$\dot{m}_{Ozone,generated,min} = \frac{1}{10 \text{ min}} \cdot \frac{60 \text{ min}}{1 \text{ hr}} \cdot \frac{1}{2} \cdot 5 \frac{\text{mg}}{\text{l}} \cdot 160 \text{ l} = 2400 \frac{\text{mg}}{\text{hr}} \quad (3.6)$$

Equation (3.6) shows that the minimum amount ozone that has to be generated is 2.4 *g/hr*. Equation (3.6) does not consider the ozone losses due to the spray. Also, ozone can transfer to the gas phase at the liquid-vapor surface. Moreover, not all ozone produced in the ozone generator is dissolved in the water. It can stay in the bubbles and rise to the surface of the tank. Consequently, an ozone generator with a capacity of 8 *g/hr* (8/2.4 times the minimum) was OK to provide a factor of safety.

Power supply is required for every experiment. Since water is used, safety with all the electrical equipment becomes an important issue. All important electrical devices that have to be turned on and off are connected to switches with Ground Fault Circuit Interrupters (GFCI). There is also an additional pilot light to indicate if the power is on. A total of four switches with GFCI are used: one for the blower, one for each pump and another one for the suction pump for the gas phase ozone detector. All the other components, like the ozone detectors, are connected to a power surge suppressor. The refrigeration machine is connected to a 208 V power supply. Each unit is grounded as suggested in their respective manuals.

Preliminary experiments indicated that thermal insulation is needed. Running the circulation pump without circuit 2 to cool the water in the tanks allowed a minimum temperature of  $6^{\circ}\text{C}$ . When the spray is used in addition, the temperature increased to  $9^{\circ}\text{C}$ . Due to the high price differences of different types of insulation the required insulation, thickness had to be calculated. In Figure 3.7 the schematic of the system for the wall insulation is shown. The water temperature  $T_w$  is assumed to be  $2^{\circ}\text{C}$  and the ambient temperature is  $25^{\circ}\text{C}$ . The conductivity of the insulation is  $0.4794 \text{ W/m-K}$  (McMaster-Carr, 1998). The conductivity of PVC is  $0.14 \text{ W/m-K}$  (Incropera, DeWitt, 1996). Convection coefficient values of  $2\text{-}25 \text{ W/m}^2\text{-K}$  are suggested for gases and  $50\text{-}1,000 \text{ W/m}^2\text{-K}$  for liquid (Incropera, DeWitt, 1996).



**Figure 3.7** Schematic of tank wall

The thickness of the tank wall is  $2 \text{ mm}$ . The ideal insulation thickness should be calculated depending on temperature  $T_3$ . Calculations have shown that the heat transfer coefficient on the waterside has less influence and that a value of  $220 \text{ W/m}^2\text{-K}$  is a good assumption. The outside wall temperature  $T_3$  should be above the dew point temperature of the environment. At  $25^{\circ}\text{C}$  and  $50\%$  relative humidity the dew point temperature is  $13.9^{\circ}\text{C}$ . The result for the tank wall is shown in Figure 3.8. To be on the safe side the



insulation thickness for the tank was chosen to be 25.4 mm (1") with an adhesive back. The calculation for the bottom is similar. A sheet of wood supplies additional insulation. The thickness of the wood is 15 mm. Its conductivity is 0.12 W/m-K. The results are shown in Figure 3.9.

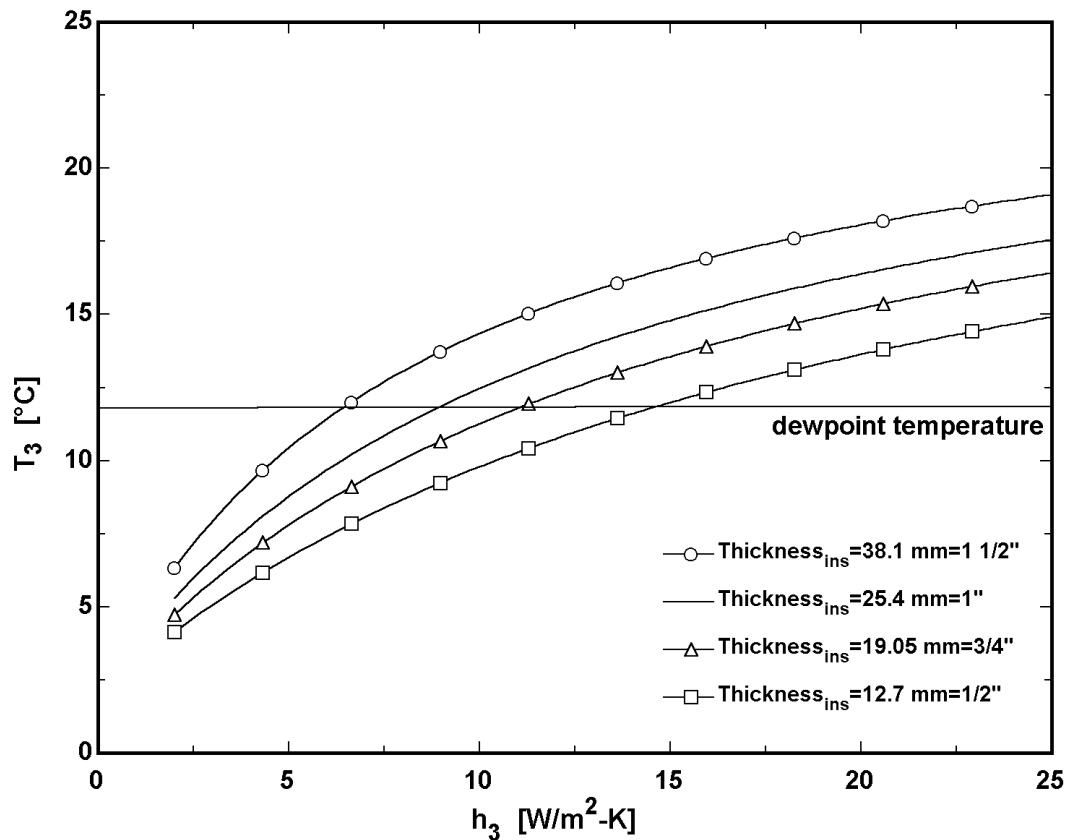
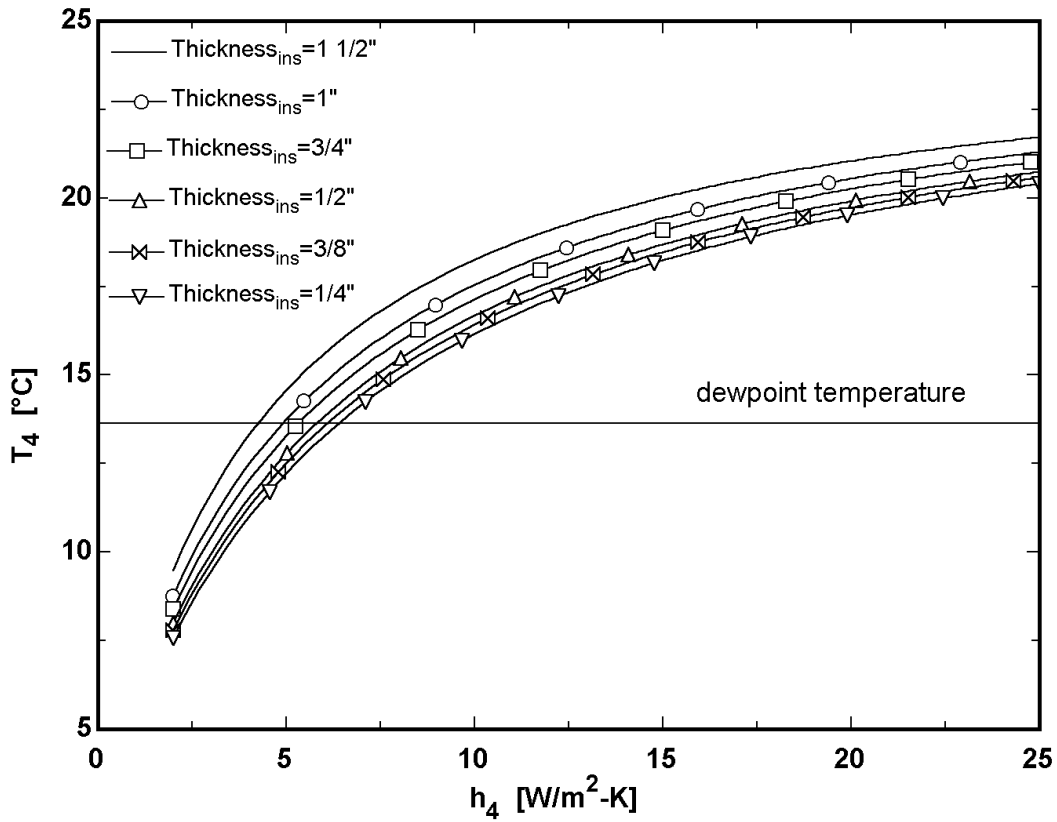
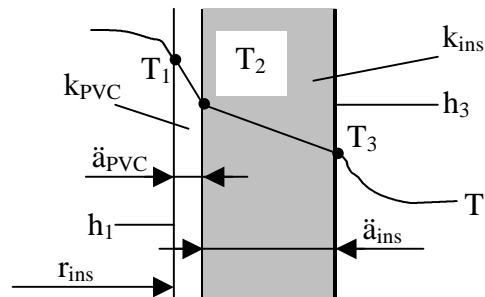


Figure 3.8  $T_3$  vs.  $h_3$  for tank wall



**Figure 3.9**  $T_4$  vs.  $h_4$  for insulating the bottom of the tank

Here additional insulation plays a minor roll. The thinnest available insulation sheet has a thickness of  $6.35 \text{ mm}$  ( $1/4''$ ). The next part of the calculations is the duct. As shown in Figure 3.10 the duct has an inner diameter of  $203.2 \text{ mm}$  ( $8''$ ). The thickness of the PVC wall is  $8 \text{ mm}$ .



**Figure 3.10** Schematic of duct wall

The material properties and convection coefficients are the same. Although it is not shown in the schematic, the duct is round and different equations are needed than in the case of a normal wall. According to Figure 3.11, a thickness of 19.05 mm (3/4") is used for the insulation.

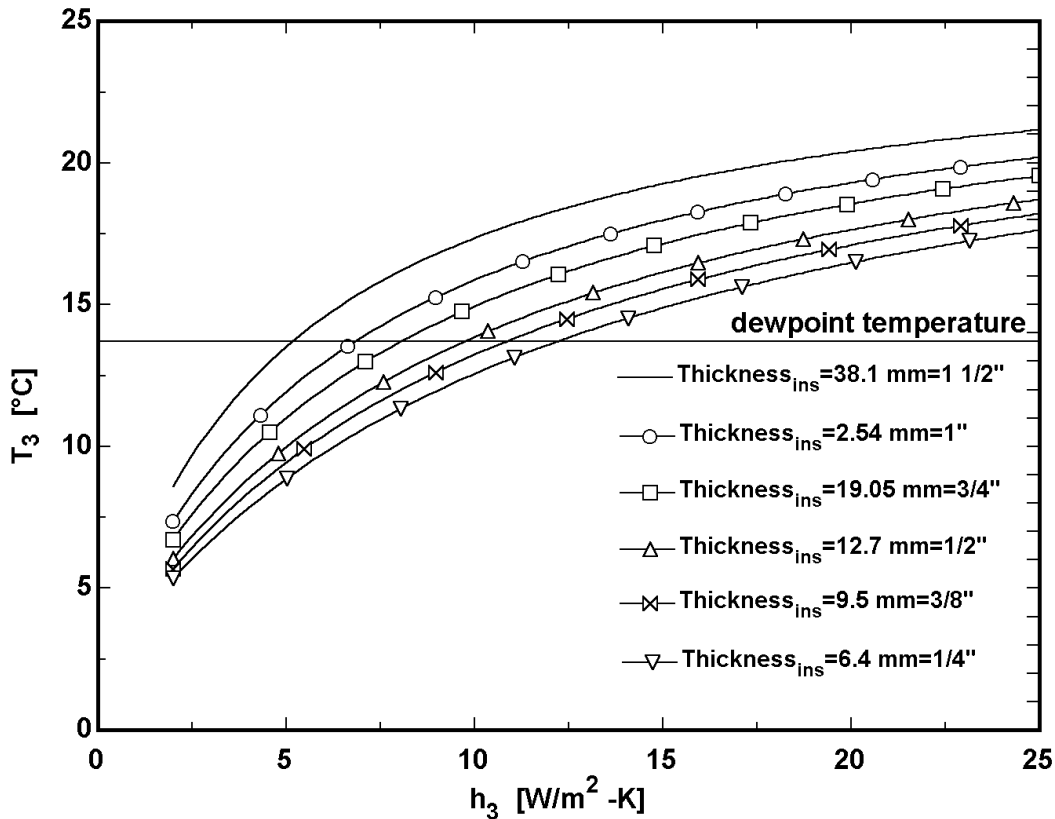


Figure 3.11  $T_3$  vs.  $h_3$  for duct insulation

The heat transfer coefficient on the waterside does not have a great influence on the temperature distribution. It is again assumed to be 220  $W/m-K$ . The results are shown in Figure 3.11. A reasonable value for the thickness is 19.05 mm (3/4"). The back of the sheets is non-adhesive. They are mounted with wire stripes around the duct.

When possible, all tubing is insulated with pipe insulation. If pipe insulation was not available for special tube diameters, condensation reducing pipe wrap was used.

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## Chapter 4 Calibration and Confirmation

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All instruments that are used for measurements have to be calibrated. In the following section, the results of the calibration for the thermocouples, the pressure gauge, the vane anemometer, the flow meter and the ozone detectors are discussed.

### Pressure Gauge

To calibrate the pressure gauge, the constants  $C_1$  and  $C_2$  mentioned in Equation (3.5) have to be determined. For a linear dependence, the pressure and the output signal have to be known for two points. The first point is the ambient pressure. It is defined as  $0 \text{ kPa}$  on the scale used in the experiment. For convenience the second pressure is around  $10 \text{ kPa}$ , because this is the equivalent for the hydrostatic pressure of  $1 \text{ m H}_2\text{O}$ . To achieve a pressure of  $10 \text{ kPa}$ , a tube was filled with water up to a height of  $1045 \text{ mm}$  ( $41.15''$ ) measured from the centerline of the pressure gauge up to the water free surface. Both pressure points can be measured easily with this construction. First, the pressure gauge is fixed in the tube, then the signal for the ambient pressure is measured. The tube is then filled with water until water comes out of an overflow. The relative pressure on the pressure gauge is now exactly  $10 \text{ kPa}$ . The second signal is measured and the constants can be determined. In

Table 4.1 the values from the calibration are shown.

**Table 4.1** Calibration values for the pressure gauge

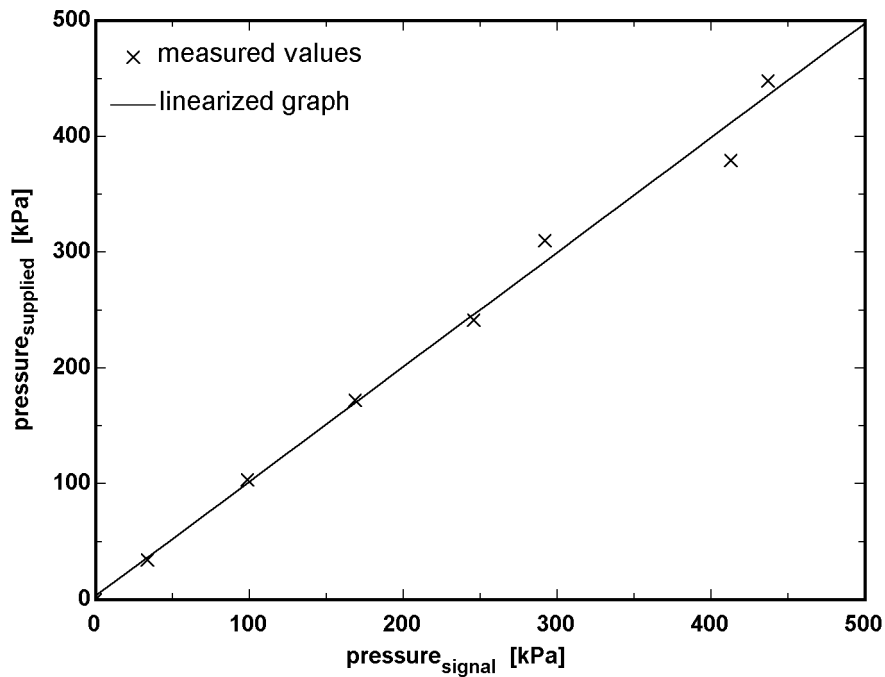
Supplied pressure [ $kPa$ ]	Received signal [ $\square$ ]
0	16,308
10	12,309

The resulting values for  $C_1$  and  $C_2$  are:

$$C_1 = 501,963 \text{ [kPa/Ohm]}$$

$$C_2 = -30.78 \text{ [kPa]}$$

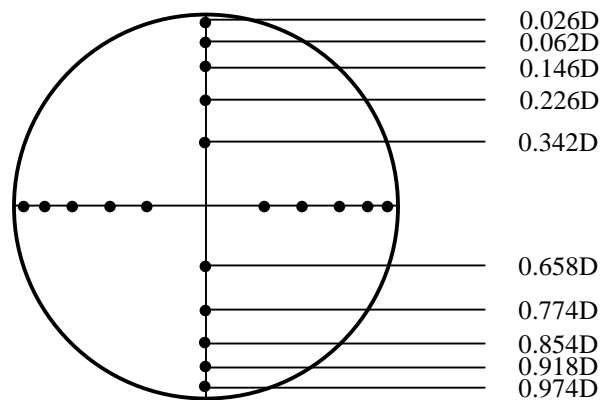
Additionally the constants were confirmed with a dead weight pressure tester. A weight supplies a known force on a piston with known diameter. The pressure gauge and the piston are approximately on the same level to avoid additional static pressure due to the height difference and the weight of the transmitter fluid. The results are shown in Figure 4.1. According to the results from the dead weight pressure tester the accuracy of the pressure transducer is  $\pm 5\%$  of the full scale for a range of 0 – 100 psi.



**Figure 4.1** Calibration curve for the pressure gauge

## Temperature

The dry bulb temperature is measured according to ANSI/ASHRAE Standard 111-1988. The standard has special requirements for the flow profile. 75% of the profile must be above 10% of the maximum flow velocity. To determine the flow profile, the flow velocity is measured at specified points on the horizontal and the vertical traverse, as



**Figure 4.2** Hot wire measuring locations for round duct

shown in Figure 4.2 using a hotwire anemometer. The measurement is repeated six times for each of the ten points on each traverse. The averaged values are shown in Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.6 for the horizontal and vertical traverse at the air inlet and outlet. The graph is shown over the unified diameter  $D$ .  $1D$  is equal to  $203.2\text{ mm}$  or  $8''$ . The hot wire is calibrated by fixing it in the wind tunnel of the University of Wisconsin-Madison.

In none of the diagrams in Figure 4.3, Figure 4.4, Figure 4.5 and Figure 4.6 the velocity is below this value, so that no changes are required to fulfill the standard.

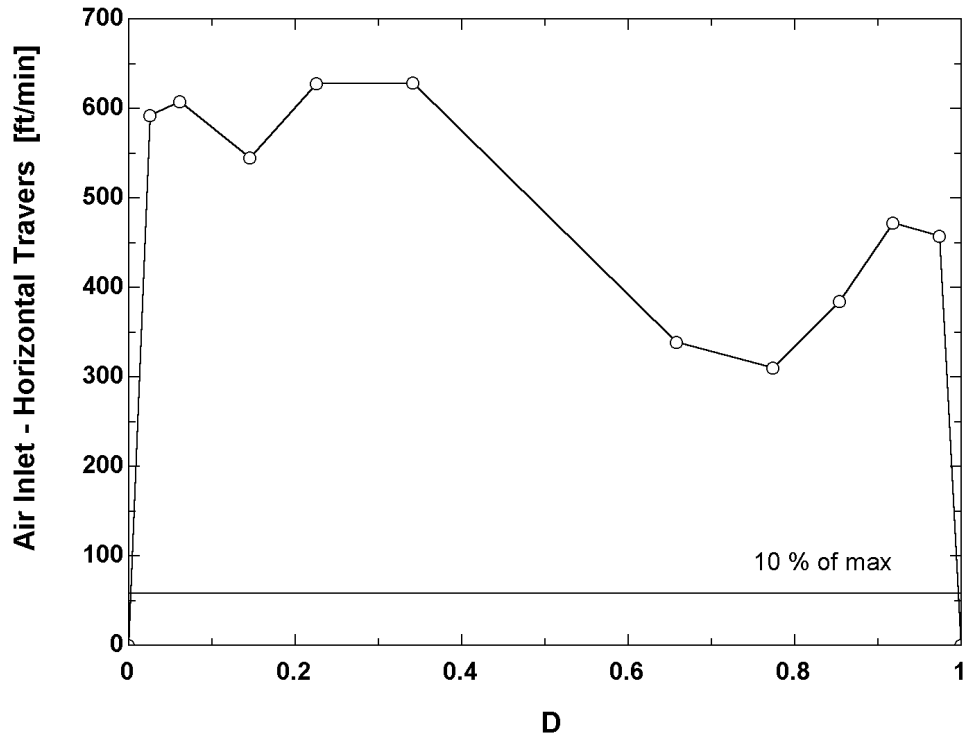


Figure 4.3 Flow profile at the air inlet – Horizontal traverse

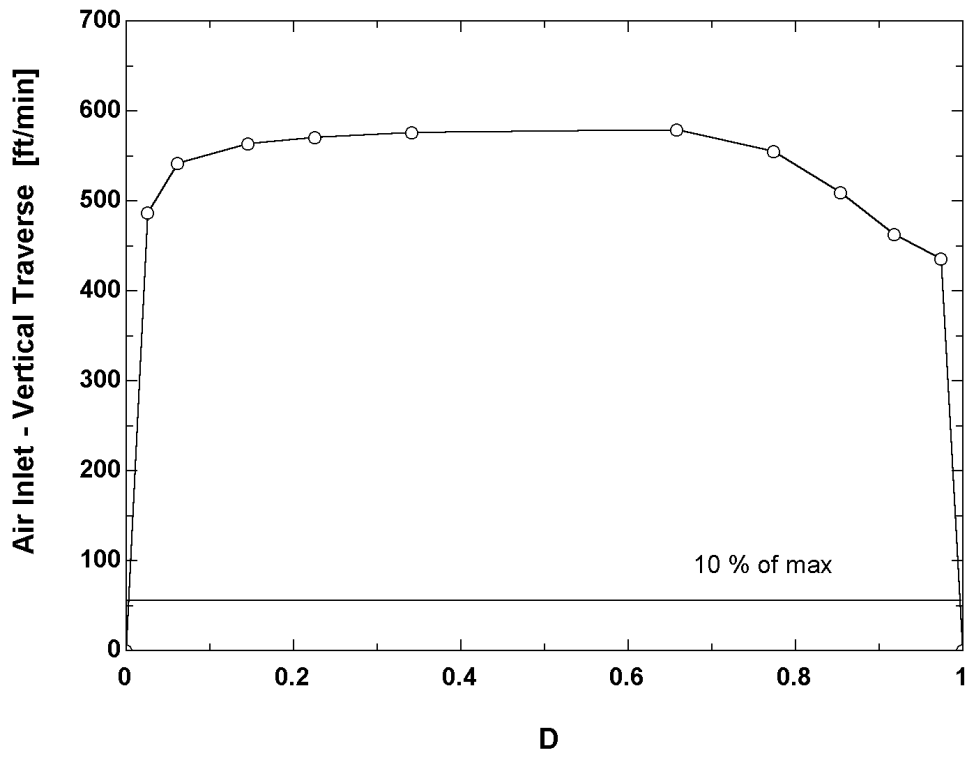


Figure 4.4 Flow profile at the air inlet – Vertical traverse



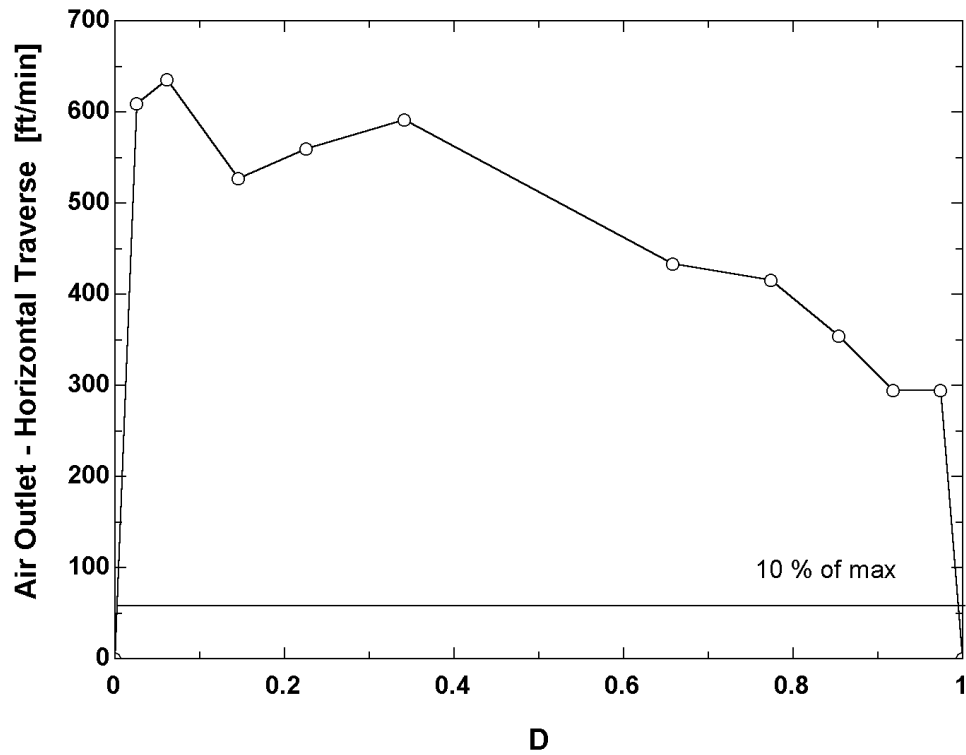


Figure 4.5 Flow profile at the air outlet – Horizontal traverse

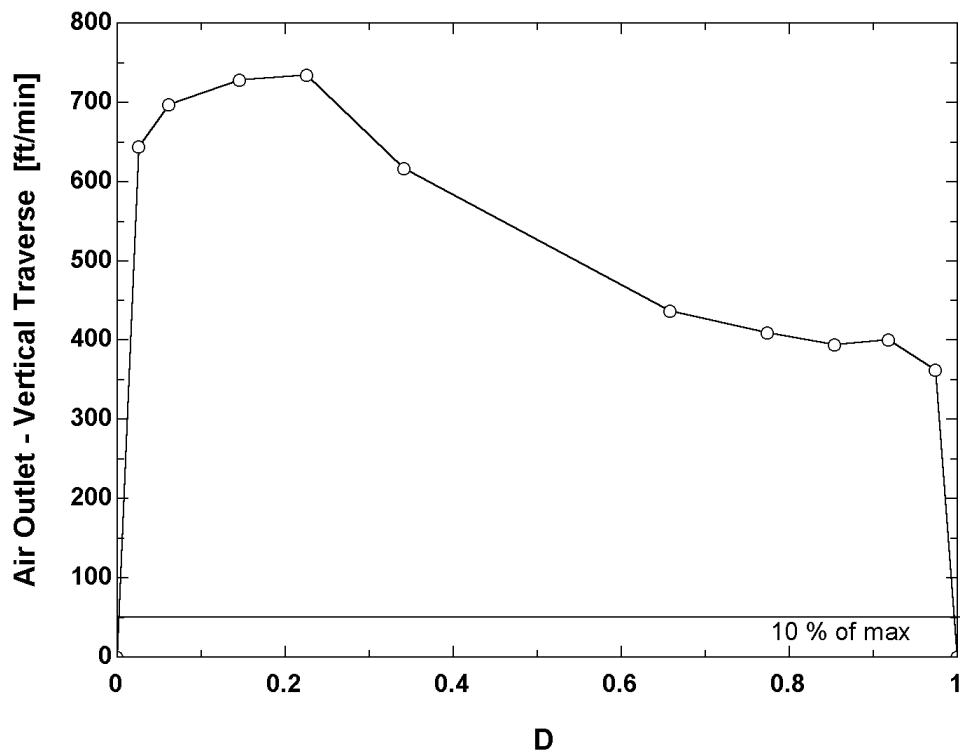


Figure 4.6 Flow profile at the air outlet – Vertical traverse

The thermocouples have been calibrated with a water/ice bath. The accuracy of the thermocouples is in a range of  $\pm 0.1$  °C. The accuracy of the flow meter is according to the manufacturer  $\pm 4$  % of the full scale. For a maximum of 15.1 *l/min* (4 *gpm*) this value is  $\pm 0.6$  *l/min* ( $\pm 0.16$  *gpm*). For the vane anemometer, data from the manufacturer is not available. The accuracy increases with longer time intervals used to average the velocity. Tests in the wind tunnel have shown that the read off accuracy with  $\pm 10$  *ft* is much higher than the accuracy of the instrument itself over a time interval of 1 minute.

#### Ozone Detector Calibration

For the first runs, the gas ozone detector is not calibrated. The manufacturer offers calibration. The accuracy for the instrument is  $\pm 2$  % of the full scale. Here the maximum is 1 *ppm*. The resulting accuracy is  $\pm 0.02$  *ppm*.

To calibrate the dissolved ozone detector the ozone concentration of a water sample has to be determined. To get the ozone concentration of the sample an ozone test kit from Hach, Model OZ-2, 0-2.3 *mg/l* is used. The ozone concentration is indicated by the change of color when an indicator powder is added to the sample. Using a colored disk the sample can be compared to a sample without indicator. The color of the sample without the indicator is varied with the disc until the color of both samples looks the same. On the disc is a scale for the ozone concentration. The accuracy of the system is  $\pm 10$  %. For the calibration the experiment was repeated three times on different days. The lower point was at ambient conditions without ozone generation and a concentration around 0.06 *ppm* in the water. The higher point was around 2 *ppm* due to the fact that the

test kit only allows to measure values up to 2.3 *ppm*. Detailed descriptions how to use the test kit and how to calibrate the sensor can be found in the manuals. The calibration has to be checked in regular time periods. Dirt on the membrane has a big influence on the measurement. Small changes can be adjusted with recalibrating the detector. For large changes cleaning or even changing the membrane is recommended.



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## Chapter 5 Results

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Experiments have been conducted to indicate the direction for future experiments. The measured variables are volume flow rate of water, air inlet velocity, air inlet temperature (dry bulb and dew point), air outlet temperature (dry bulb and dew point), gas phase ozone concentrations at air inlet and air outlet, water inlet temperature, water inlet pressure, ozone concentration in the water at the inlet and the water. With those variables, mass and energy balances are examined to determine if the first law of thermodynamics is satisfied. Additionally, relative uncertainties for the mass flow rate of air, mass flow rate of water, the rate of energy transferred out of the water, and transferred in the air are analyzed. Finally, the dependence on the gas phase ozone concentrations of the water inlet temperature and the ozone concentration in water is presented.

The experiments were conducted with nozzle QLH 25 (Spraying Systems Co., 1993). For all experiments, the air velocity was constant at  $2.54 \text{ m/s}$  ( $500 \text{ ft/min}$ ) and the water flow rate at  $9.46 \text{ l/min}$  ( $2.5 \text{ gpm}$ ). Several sets of experiments were performed. For each set of runs, the apparatus was allowed to reach thermal equilibrium. In each, set the resulting ozone concentration in the water was varied and the ozone concentration in the gas phase was measured. The gas phase ozone detector was not recalibrated since it was received from the factory, so that all the result gives a general trend.

On the airside of the experiment, the gas phase ozone concentration, the dry bulb and dew point temperatures of the air at the inlet and the outlet of the test section are known.

On the waterside of the experiment, the water temperature at the inlet and outlet and the water pressure at the inlet are measured. The ambient pressure is assumed to be 101.325 *kPa* and the inner diameter of the duct is 201.8 *mm* (7.943 *inch*) as reported in Table 3.1. With the known volume flow rate for water and the density before the nozzle, the mass flow rate of water can be calculated according to Equation (5.1).

$$\dot{m}_{water,in} = \dot{V}_{water,in} \cdot \rho_{water,in} \cdot 0.00006309 \frac{m^3 / s}{gpm} \quad (5.1)$$

The mass flow rate of air at the inlet can be calculated from the air velocity, the area of the duct and the specific volume of air as shown in Equation (5.2)

$$\dot{m}_{air,in} = \frac{V_{air,in}}{v_{air,in}} \cdot A_{duct} \quad (5.2)$$

As shown in Equation (5.3), the air at the inlet is a mixture of dry air and water vapor. The absolute humidity is defined as the mass of water vapor per mass of dry air shown in Equation (5.4).

$$\dot{m}_{air,in} = \dot{m}_{dryair,in} (1 + w_{air,in}) \quad (5.3)$$

$$w_{in} = \frac{\dot{m}_{watervapor,in}}{\dot{m}_{dryair,in}} \quad (5.4)$$

The same equations can be used for the outlet side, as shown in Equation (5.6) and Equation (5.7), after the mass flow rate of dry air is calculated with Equation (5.5)

$$\dot{m}_{dryair,in} - \dot{m}_{dryair,out} = 0 \quad (5.5)$$

$$\dot{m}_{air,out} = \dot{m}_{dryair,out} (1 + w_{air,out}) \quad (5.6)$$

$$w_{out} = \frac{\dot{m}_{watervapor,out}}{\dot{m}_{dryair,out}} \quad (5.7)$$

With the now known mass flow rates of water vapor going into the system and coming out of the system and the mass flow rate of water supplied to the system, the mass flow rate of water coming out of the system can be calculated as shown in Equation (5.8).

$$\dot{m}_{water,in} + \dot{m}_{watervapor,in} - (\dot{m}_{water,out} + \dot{m}_{watervapor,out}) = 0 \quad (5.8)$$

With known temperatures and pressures the enthalpies of air and water leaving and entering the system can be calculated. Multiplying the enthalpies with the mass flow rates, the energy flow into the system and out of the system can be calculated as shown in Equations (5.9) - (5.12).

$$\dot{E}_{water,in} = \dot{m}_{water,in} \cdot h_{water,in} \quad (5.9)$$

$$\dot{E}_{water,out} = \dot{m}_{water,out} \cdot h_{water,out} \quad (5.10)$$

$$\dot{E}_{air,in} = \dot{m}_{air,in} \cdot h_{air,in} \quad (5.11)$$

$$\dot{E}_{air,out} = \dot{m}_{air,out} \cdot h_{air,out} \quad (5.12)$$

The rate of energy transferred from the water is defined in Equation (5.13) and the rate of energy transferred to the air is defined in Equation (5.14).

$$\dot{Q}_{water} = \dot{E}_{water,in} - \dot{E}_{water,out} \quad (5.13)$$

$$\dot{Q}_{air} = \dot{E}_{air,in} - \dot{E}_{air,out} \quad (5.14)$$

The test section is assumed to be adiabatic. The energy balance error is then defined by Equation (5.15).

$$Error = \frac{|\dot{Q}_{water}| - |\dot{Q}_{air}|}{|\dot{Q}_{water}|} \cdot 100 \quad (5.15)$$

The results from the error calculation are shown in Table 5.1.

**Table 5.1** Calculated Error for the conducted experiments

Set #	avg. $T_{water,in}$ [°C]	# measurements per set	avg. Error [%]	min. Error [%]	max. Error [%]
1	8.2	4	88.81	87.31	90.54
2	12.0	7	54.71	48.52	73.32
3	20.6	7	10.99	9.65	12.05
4	25.5	7	5.36	3.46	8.45
5	26.6	7	7.50	5.21	9.48
6	27.6	7	9.73	8.32	12.26

The influence of uncertainty of the measured variables is analyzed in Figure 5.1 - Figure 5.10. Depending on the uncertainty of the measured value, the uncertainty of the mass flow rate of water, the mass flow rate of air, the rate of energy exchanged between the water and the rest of the system and the air and the rest of the system changes. The figures present the calculated relative uncertainty in % vs. the water inlet temperature in °C. This uncertainty for the mass flow rate, as an example, is defined in Figure 5.1:

$$rel. \text{uncert.} = \frac{\text{uncert. of } \dot{m}_{water,in} (\dot{V}_{water} \pm 0.6l / \text{min})}{\dot{m}_{water,in}} \quad (5.16)$$

If the measured variable has no influence on the calculated value, that result in an uncertainty equal to zero. Those uncertainties are not shown in Figure 5.1 - Figure 5.10.



In Figure 5.10 the calculated uncertainty is shown depending on the uncertainties of all measured variables.

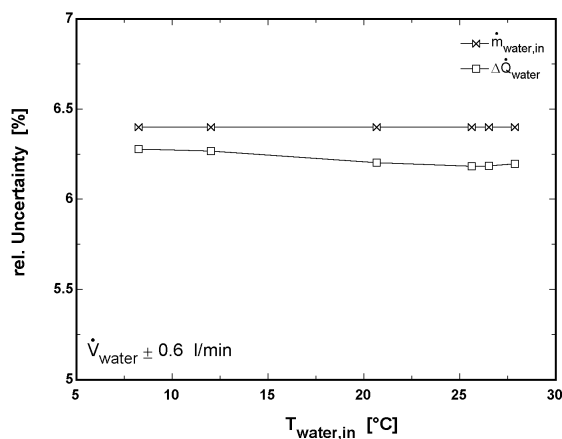


Figure 5.1 Uncertainty for the water flow rate

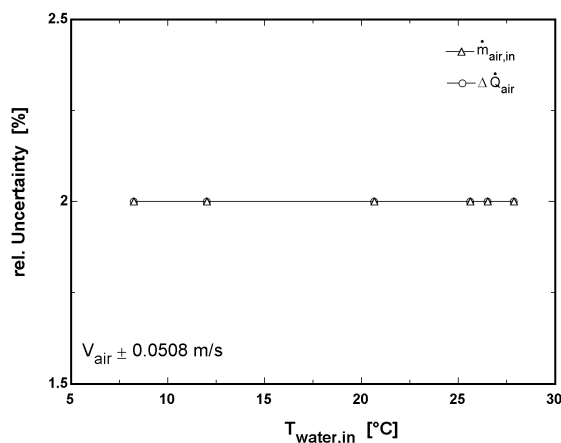


Figure 5.2 Uncertainty for the air velocity

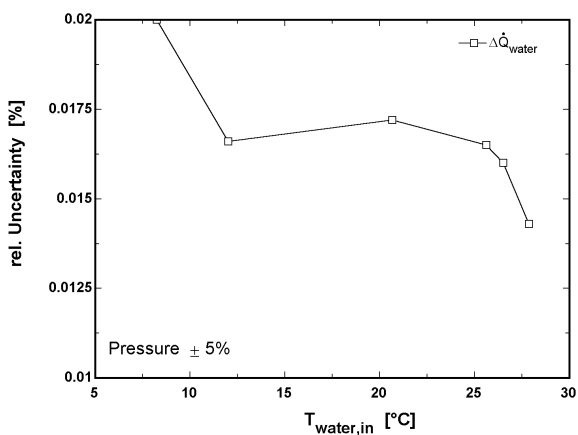


Figure 5.3 Uncertainty for the pressure

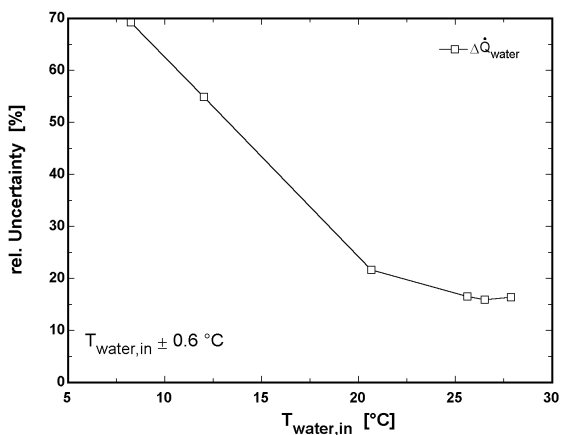


Figure 5.4 Uncertainty for  $T_{\text{water,in}}$

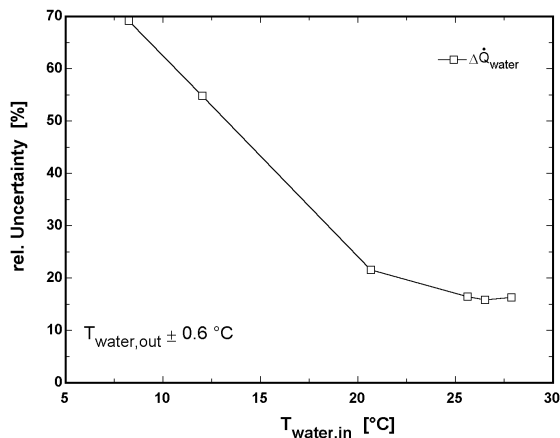


Figure 5.5 Uncertainty for  $T_{\text{water,out}}$

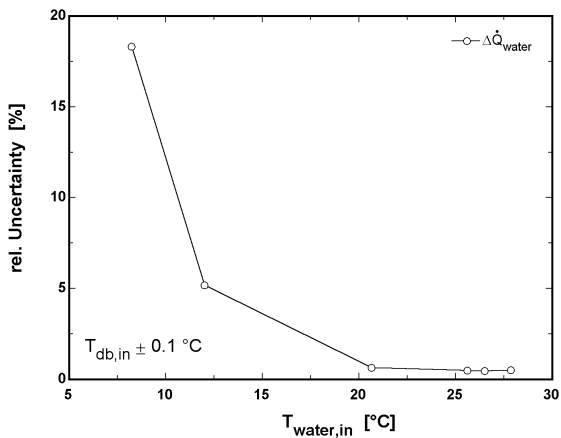


Figure 5.6 Uncertainty for  $T_{\text{db,in}}$

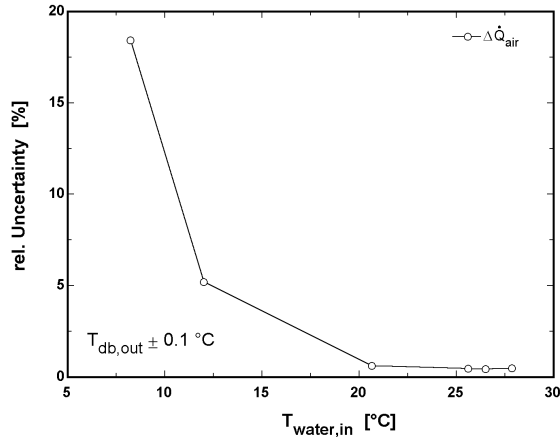


Figure 5.7 Uncertainty for  $T_{\text{db,out}}$

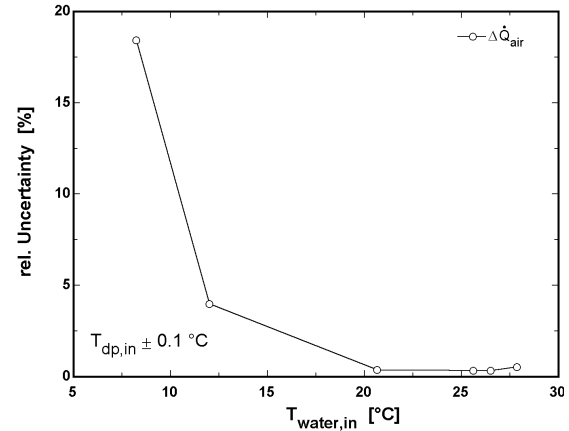


Figure 5.8 Uncertainty for  $T_{\text{dp,in}}$

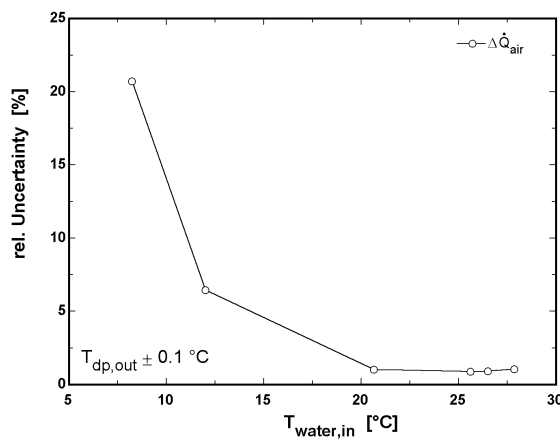


Figure 5.9 Uncertainty for  $T_{\text{dp,out}}$

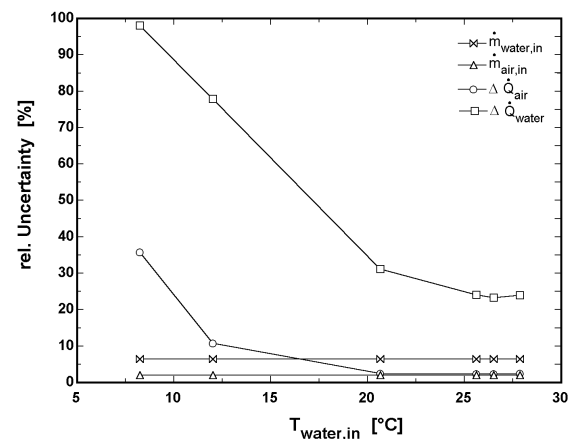
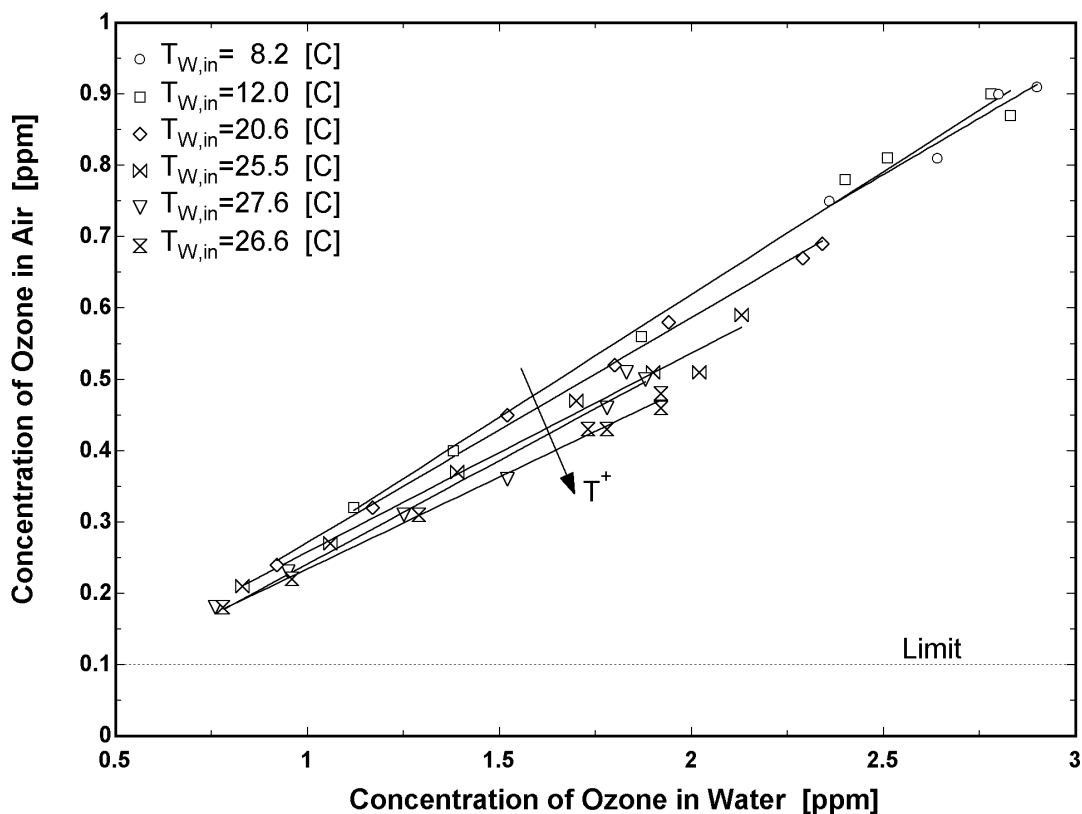


Figure 5.10 Uncertainty for all measured values

In general the measured temperatures shown in Figure 5.4 - Figure 5.9 have an influence on the energy terms, but no influence on the mass flow rate. The water volume flow rate and the air velocity influence the mass flow rates. For the analysis of only one variable the maximum relative uncertainty is 69.5 % recorded for the water inlet and the water outlet temperature. For the analysis with all uncertainties for all measured variables the maximum calculate uncertainty is 98 % for the rate of energy transferred out of the water.

### Result of the ozone measurements

For the ozone analysis the ozone concentration in *ppm* in the gas phase vs. the concentration of ozone in water is shown for various temperatures in Figure 5.11. A linear curve fit was added for the different temperatures.



**Figure 5.11** Concentration of ozone in air vs. Concentration of ozone in water for various temperatures

Water is sprayed as droplets in the air stream. Assuming that the droplets stay long enough in the air that a state of equilibrium between the concentration of ozone in the gas and the liquid phase is reached, Raoult's law (Atkins, 1997) can be applied, to obtain a general suggesting what should happen under ideal conditions.

$$y_{O_3} \cdot P = x_{O_3} \cdot P_{part,O_3} \quad (5.17)$$

Raoult's law indicates that the products of fraction of ozone in air and the partial pressure of ozone is equal to the molar fraction of ozone in water times the partial pressure of ozone dissolved in water. When the temperature of the water goes up, the partial pressure on ozone in water should increase. When the concentration of ozone dissolved in water is forced to be constant and the ambient pressure is constant the concentration of ozone in air should increase.

The first step, that the partial pressure increases when the temperature goes up can be shown with Henry's law:

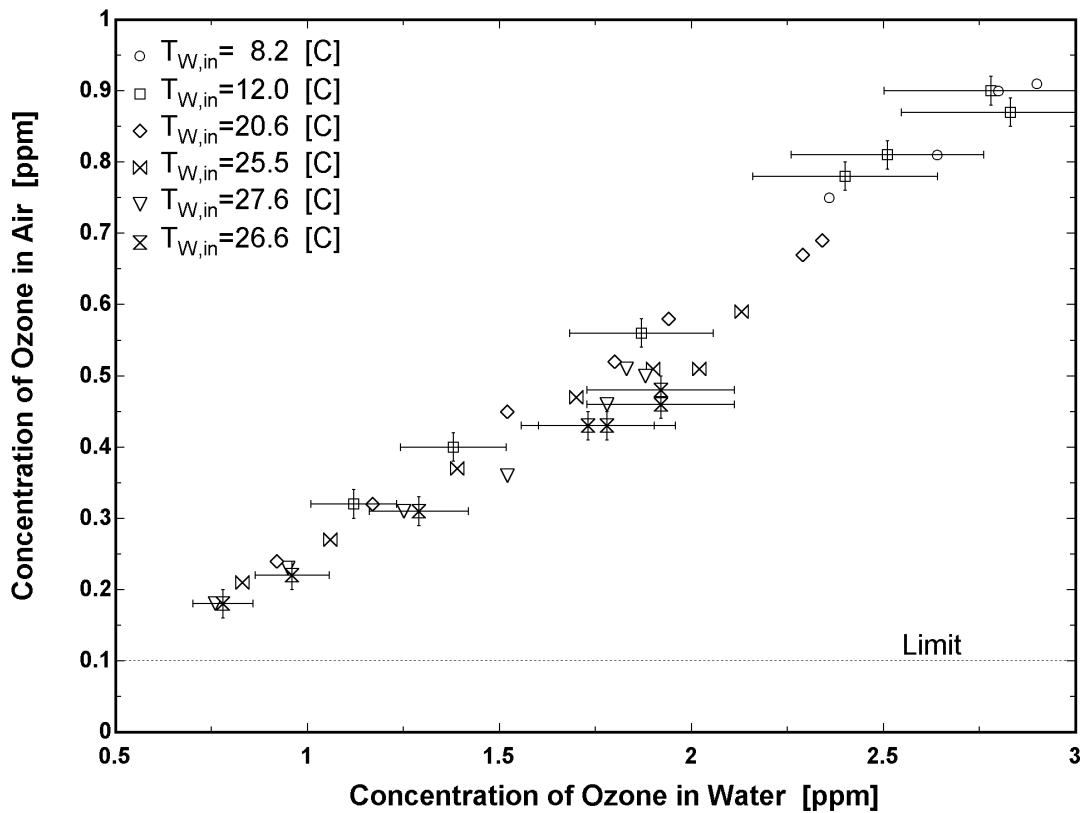
$$P_{part,O_3} = x_{O_3} \cdot K_H(T, pH, \dots) \quad (5.18)$$

From Sotelo (1998) can be seen that the temperature dependence can be modeled like shown in Equation (5.19).  $C_1$  and  $C_2$  are positive constants.

$$K_H \approx C_1 \cdot e^{\frac{C_2}{T}} \quad (5.19)$$

This function shows that with increasing temperature the  $K_H$  and so the partial pressure increases.

Drawing a vertical line in Figure 5.11 e.g. at 2 ppm the ozone concentration in air decreases with increasing temperature. This result does not agree with Raoult's law. In Figure 5.12 the ozone concentration in air vs. the ozone concentration in water for varying temperature is shown without curve fits. Instead error bars are added for 12°C and 25.5°C.



**Figure 5.12** Concentration of ozone in air vs. Concentration of ozone in water for various temperatures with error bars

As the horizontal error bars show, the uncertainty in the ozone water measurement is large with respect to each successive datapoint. However, the uncertainty does not explain the trend in concentration in which the concentration in the air decreases with increasing water inlet temperature.



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## Chapter 6 Conclusions and Recommendations

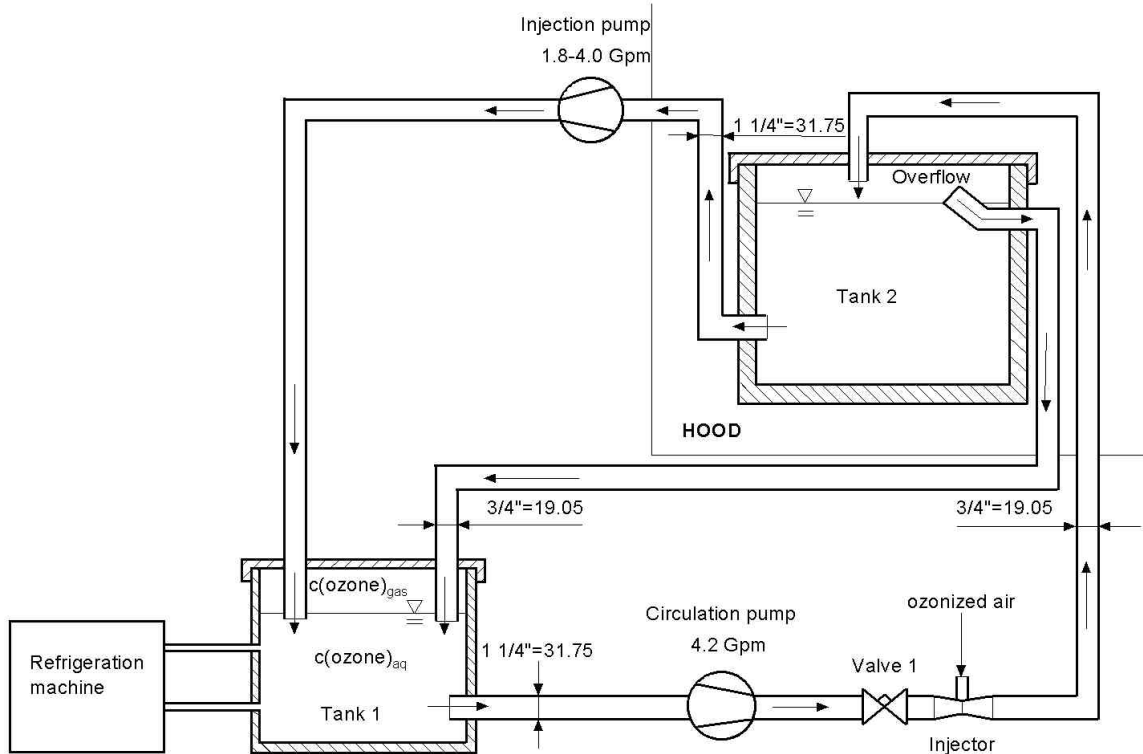
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### 6.1 Conclusions

An apparatus was built to determine the ozone concentration in air in a direct contact spray system in which the water is ozonated. The results are shown in Figure 5.11. In all cases the ozone concentration in air is above the limit of 0.1 *ppm*. The trend of a decreasing ozone concentration in air with an increasing water inlet temperature does not agree with the trend predicted by Raoult's law.

### 6.2 Recommendations

The use of a field uncalibrated ozone detector presents a major problem. All the measurements have to be repeated with a factory calibrated detector. This might change the values of the ozone concentration measurements and shift the ozone measurements below the limit, 0.1 *ppm*, for a part of the investigated area. On the other hand, the probability that the new measurements change the trend that with increasing water temperature the ozone concentration in air decreases is low. Besides providing more theoretical background what is going on in that process and review the literature the apparatus can be modified to measure the ozone concentration in air depending on the ozone concentration in water and the water temperature in a state of equilibrium. This type of experiment is possible with some changes in the configuration of the apparatus as shown in Figure 6.1.



**Figure 6.1** Suggested system to measure the ozone concentrations in thermal equilibrium

Water is pumped from tank 1 to tank 2 and back. Ozone is injected behind the circulation pump and the water temperature is controlled with the refrigeration machine. The hoses from the overflow and the injection pump are kept under the water surface of tank 1. Tank 1 has to be sealed so that there is no interference with the ambient air. Now the concentration of ozone in the liquid phase and the gas phase of tank 1 can be measured. Together with the water temperature those results can be compared with the results shown in Figure 5.11 and Raoult's law.

If the new measurements do not show a decrease of the magnitude of the ozone concentration in air below 0.1 ppm additional ideas have to be investigated to keep the ozone concentration of the exiting air under the required limit. This can be achieved by



two methods. The first method includes decreasing the ozone concentration in the water to an acceptable level before the water is sprayed into the air stream. The second method includes the removal of ozone from the air stream downstream of the nozzle.

Reduction of ozone in water is possible by using decomposition of ozone in water. The half-life-time of ozone in water is about 10 *min*. Storing the water after treating it with ozone and before pumping it to the nozzle for a certain amount of time so that the ozone concentration decreases.

For ozone removal in air two different types of filters are suggested. As a long life filter a metal oxide catalyst is possible. The catalyst can be impregnated on a honeycomb structure (NICHIAS, 2000) or it can be used in a pebble bed (Enercon, 2000). Enercon reports a concentration reduction of 150 *ppm* to below the limit of 0.1 *ppm*. The second type of filter is activated charcoal, but it has to be replaced from time to time (NICHIAS, 2000). For Museums (Los Angeles County Museum of Art, Huntington Art Gallery and J. Paul Getty Museum) with air conditioning and activated charcoal filtration, indoor concentrations below 0.005 *ppm* are reported in the area of Los Angeles (WAAC, 1995).



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## Appendix

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### Appendix A                      Manual

The purpose of this section is to document the procedure to set up the experiment, run it and turn it off again. Figure 3.2 helps to understand the procedures.

#### Preparation of the Apparatus

The water was removed and the power supply was disconnected, but most the sensors still don't have to be recalibrated. The first thing to do is to reinstall the dissolved ozone sensor. Remove the red cap and replace the membrane according to the manual. Screw the sensor in its place and connect it to the transmitter. Check if all connections between the tube and hoses look good to avoid leakage. The tanks must be filled with fresh water. Connect the hose, which is coming from the 3-way, 4-position valve that is located before the nozzle with the tap. Use a clamp for a compression fitting. Turn on the blower and adjust the airflow rate to around  $550 \text{ ft/min}$ . Use the damper to control the airflow and the flow anemometer to measure it. Position the 3-way, 4-position valve that water can flow from the tap to the nozzle, but not back to the pump (the red dot has to be at the connection that goes to the pump). Open valve 2, which is used to control the water flow rate supplied to the nozzle completely. Open the tap. Check if there is water flowing out of the air inlet and if you can see water droplets on the blades of the damper. The damper blades can be seen if you look through the transparent PVC pieces upstream of the damper. Adjust the water flow rate and the airflow rate so that all water is drained out of

the system through the three drains. Check the water level in tank 1 from time to time. If tank 1 is filled to 75 %, close valve 1 that controls the flow rate from tank 1 to tank 2. Turn on the circulation pump and open valve 1. Adjust the valve so that the circulation pump does not run dry and that all the surplus in tank 2 can be drained back through the over flow to tank 1. When tank 2 is completely filled and tank 1 is filled to 75 %, close the tap. Close valve 2. The water level in tank 2 is above the level of the nozzle. If valve 2 is not closed, water will flow through the nozzle into tank 1. If the circulation pump is not running, so that the water is pumped back into tank 2, tank 1 will overflow and flood the lab. Turn the circulation pump off. Recalibrate the dissolved ozone sensor and start to prepare the experiment.

#### Preparation of an Experiment

To prepare the experiment before measurements can be made turn the ventilation and the light in the hood on. Turn the refrigeration machine on and adjust the temperature to a minimum. The refrigeration machine does not have sufficient capacity to freeze the water in the internal heat exchanger. Open the screen of the hood. The heated exhaust air from the refrigeration machine rises and a major part of it is sucked into the hood. Turn on the circulation pump and adjust the flow rate, so that the water level in tank 2 stays constant. Open the box of the ozone generator and check the suction rate of the injector, when the valve at the flow meter is completely open. Turn the ozone generator with the switch at the bottom on and adjust the flow rate to the same value, so that ozone is always sucked from the injector, but never pumped into it or through a leak into the environment. Ozone in the environment can be recognized as a fresh odor. To be on the safe side turn off the

ozone generator and leave the lab when you can smell it. So far we are only circulating water from one tank to the other. During this procedure we cool the water and dissolve ozone into it. Turn the datalogger on and press “\*” and then “A”. Press “A” several times till “05: Alloc Program Bytes” appears in the first line. Enter “98765” and “A”. Now all data in the datalogger will be deleted. Turn the computer on and start from the desktop the program “PC208W 3.0”. With this program you can control the datalogger. Click on “Connect” and send the program “ozone.dld” to the datalogger. It is possible to see the exact values and plot some graphs. Open diagram window 1 to get all the temperatures for a time interval of about four hours. That is approximate time that it takes to cool the water to the possible minimum. If possible stay in the room and control if ozone is leaking out of the apparatus.

When the water temperature is below the desired temperature turn the blower on and close the screen of the hood. Adjust the airflow rate roughly to 550 *ft/min*. Turn the injection pump on and adjust the flow rate to the nozzle to the desired value. Readjust the flow rate from tank 1 to tank 2 so that the water level stays constant and don't forget to readjust the flow rate in the ozone generator also. Adjust the water flow rate through the nozzle again and regulate the airflow rate through the duct to 500 *ft/min*. The water temperature can be controlled with a regulator at the refrigeration machine. Be careful, the scale does not show the correct value. The only way to control the ozone concentration is to de- or increase the flow rate of ozonated air. To do this, use the valve inside the ozone generator at the flow meter. Turn on the pump to get the air sample from the air in- or outlet. Delete the memory in the datalogger again. Transfer the program

“*ozone.dld*” again and start new diagrams. Choose between the air inlet and the air outlet with the first of the 3-way, 4-position valves. With the second valve choose if the ozone concentration of the humidity should be measured. Wait for steady state conditions.

### Shut-Down

Turn off the ozone generator. Close valve 2. Turn off the injection pump. Turn off the circulation pump. Turn off the suction pump for the air sample, the blower and the light in the hood. Transfer the data file from the datalogger. Don't turn the blower in the hood off. There is still ozone dissolved in the water.

### Preparation of the Apparatus for a longer Shut-Down

To shut the experiment down for a longer time the water from the tanks must be pumped into the sink. To do this, use the circulation pump and the injection pump. Adjust the 3-way, 4-position valve, so that water is pumped from the injection pump into the sink. Disconnect the hose from the tap and hold it in the sink. The force is large enough that you have to hold it. Control the volume flow with the 3-way, 4-position valve. Turn off the pumps and disconnect the dissolved ozone sensor from the transmitter. Screw it out of the thread and put the red cap over the membrane.

## Appendix B                      Program Code for Datalogger

```

;{CR23X}
;

```

```

*Table 1 Program

```

```

    01: 1.0 Execution Interval (seconds)

```

```

1:   Panel Temperature (P17)

```

```

    1:   1   Loc [ reftemp ]

```

```

2:   Thermocouple Temp (DIFF) (P14)

```

```

    1:   1   Reps

```

```

    2:   21  10 mV, 60 Hz Reject, Slow Range

```

```

    3:   7   DIFF Channel

```

```

    4:   1   Type T (Copper-Constantan)

```

```

    5:   1   Ref Temp (Deg. C) Loc [ reftemp ]

```

```

    6:   2   Loc [ tempWatIn ]

```

```

    7:   1.0 Mult

```

```

    8:   0.0 Offset

```

```

3:   Thermocouple Temp (DIFF) (P14)

```

```

    1:   1   Reps

```

```

    2:   21  10 mV, 60 Hz Reject, Slow Range

```

```

    3:   10  DIFF Channel

```

```

    4:   1   Type T (Copper-Constantan)

```

```

    5:   1   Ref Temp (Deg. C) Loc [ reftemp ]

```

```

    6:   3   Loc [ tempWatOu ]

```

```

    7:   1.0 Mult

```

```

    8:   0.0 Offset

```

```

4:   Thermocouple Temp (DIFF) (P14)

```

```

    1:   1   Reps

```

```

    2:   21  10 mV, 60 Hz Reject, Slow Range

```

```

    3:   8   DIFF Channel

```

```

    4:   1   Type T (Copper-Constantan)

```

```

    5:   1   Ref Temp (Deg. C) Loc [ reftemp ]

```

```

    6:   4   Loc [ tempAirIn ]

```

```

    7:   1.0 Mult

```

```

    8:   0.0 Offset

```

```

5:   Thermocouple Temp (DIFF) (P14)

```

```

    1:   1   Reps

```

```

    2:   21  10 mV, 60 Hz Reject, Slow Range

```

```

    3:   9   DIFF Channel

```

- 4: 1 Type T (Copper-Constantan)  
 5: 1 Ref Temp (Deg. C) Loc [ reftemp ]  
 6: 5 Loc [ tempAirOu ]  
 7: 1.0 Mult  
 8: 0.0 Offset
- 6: Thermocouple Temp (DIFF) (P14)  
 1: 1 Reps  
 2: 21 10 mV, 60 Hz Reject, Slow Range  
 3: 11 DIFF Channel  
 4: 1 Type T (Copper-Constantan)  
 5: 1 Ref Temp (Deg. C) Loc [ reftemp ]  
 6: 22 Loc [ tempTank ]  
 7: 1.0 Mult  
 8: 0.0 Offset
- 7: Volt (Diff) (P2)  
 1: 1 Reps  
 2: 25 5000 mV, 60 Hz Reject, Fast Range  
 3: 1 DIFF Channel  
 4: 6 Loc [ pressure1 ]  
 5: 1 Mult  
 6: 1.0 Offset
- 8: Volt (Diff) (P2)  
 1: 1 Reps  
 2: 25 5000 mV, 60 Hz Reject, Fast Range  
 3: 3 DIFF Channel  
 4: 20 Loc [ dissOzon1 ]  
 5: 1 Mult  
 6: 1.0 Offset
- 9: Volt (Diff) (P2)  
 1: 1 Reps  
 2: 25 5000 mV, 60 Hz Reject, Fast Range  
 3: 2 DIFF Channel  
 4: 21 Loc [ gasOzon1 ]  
 5: 1 Mult  
 6: 1.0 Offset
- 10: If time is (P92)  
 1: 0 Minutes (Seconds --) into a  
 2: 1 Interval (same units as above)  
 3: 10 Set Output Flag High (Flag 0)
- 11: Set Active Storage Area (P80)



- 1: 1 Final Storage Area 1  
2: 124 Array ID
- 12: Real Time (P77)  
1: 0111 Day,Hour/Minute,Seconds (midnight = 0000)
- 13: Average (P71)  
1: 1 Reps  
2: 1 Loc [ reftemp ]
- 14: Average (P71)  
1: 1 Reps  
2: 2 Loc [ tempWatIn ]
- 15: Average (P71)  
1: 1 Reps  
2: 3 Loc [ tempWatOu ]
- 16: Average (P71)  
1: 1 Reps  
2: 4 Loc [ tempAirIn ]
- 17: Average (P71)  
1: 1 Reps  
2: 5 Loc [ tempAirOu ]
- 18: Average (P71)  
1: 1 Reps  
2: 17 Loc [ pressure ]
- 19: Average (P71)  
1: 1 Reps  
2: 7 Loc [ dissOzone ]
- 20: Average (P71)  
1: 1 Reps  
2: 8 Loc [ gasOzone ]
- 21: Average (P71)  
1: 1 Reps  
2: 22 Loc [ tempTank ]
- 22:  $Z=X*F$  (P37)  
1: 6 X Loc [ pressure1 ]  
2: 2 F  
3: 9 Z Loc [ pressure2 ]

- 23:  $Z=X \cdot F$  (P37)  
 1: 9 X Loc [ pressure2 ]  
 2: 0.001 F  
 3: 10 Z Loc [ pressure3 ]
- 24:  $Z=F$  (P30)  
 1: 12 F  
 2: 00 Exponent of 10  
 3: 11 Z Loc [ Vx ]
- 25:  $Z=X/Y$  (P38)  
 1: 10 X Loc [ pressure3 ]  
 2: 11 Y Loc [ Vx ]  
 3: 12 Z Loc [ pressure4 ]
- 26:  $Z=X+F$  (P34)  
 1: 12 X Loc [ pressure4 ]  
 2: 0.5 F  
 3: 13 Z Loc [ pressure5 ]
- 27: BR Transform  $Rf[X/(1-X)]$  (P59)  
 1: 1 Reps  
 2: 13 Loc [ pressure5 ]  
 3: 100.0 Multiplier (Rf)
- 28:  $Z=F$  (P30)  
 1: 50196 F  
 2: 1 Exponent of 10  
 3: 14 Z Loc [ C1 ]
- 29:  $Z=F$  (P30)  
 1: -28.27 F  
 2: 00 Exponent of 10  
 3: 15 Z Loc [ C2 ]
- 30:  $Z=X/Y$  (P38)  
 1: 14 X Loc [ C1 ]  
 2: 13 Y Loc [ pressure5 ]  
 3: 16 Z Loc [ pressure6 ]
- 31:  $Z=X+Y$  (P33)  
 1: 16 X Loc [ pressure6 ]  
 2: 15 Y Loc [ C2 ]  
 3: 17 Z Loc [ pressure ]

32: Z=X+F (P34)  
 1: 20 X Loc [ dissOzon1 ]  
 2: -400 F  
 3: 23 Z Loc [ dissOzon2 ]

33: Z=X\*F (P37)  
 1: 23 X Loc [ dissOzon2 ]  
 2: .01273 F  
 3: 24 Z Loc [ dissOzon3 ]

34: Z=X+F (P34)  
 1: 24 X Loc [ dissOzon3 ]  
 2: .06964 F  
 3: 7 Z Loc [ dissOzone ]

35: Z=X+F (P34)  
 1: 21 X Loc [ gasOzon1 ]  
 2: -400 F  
 3: 25 Z Loc [ gasOzon2 ]

36: Z=X\*F (P37)  
 1: 25 X Loc [ gasOzon2 ]  
 2: .000617 F  
 3: 26 Z Loc [ gasOzon3 ]

37: Z=X+F (P34)  
 1: 26 X Loc [ gasOzon3 ]  
 2: .000247 F  
 3: 8 Z Loc [ gasOzone ]

\*Table 2 Program  
 02: 0.0000 Execution Interval (seconds)

\*Table 3 Subroutines

End Program



# Appendix C Drawings

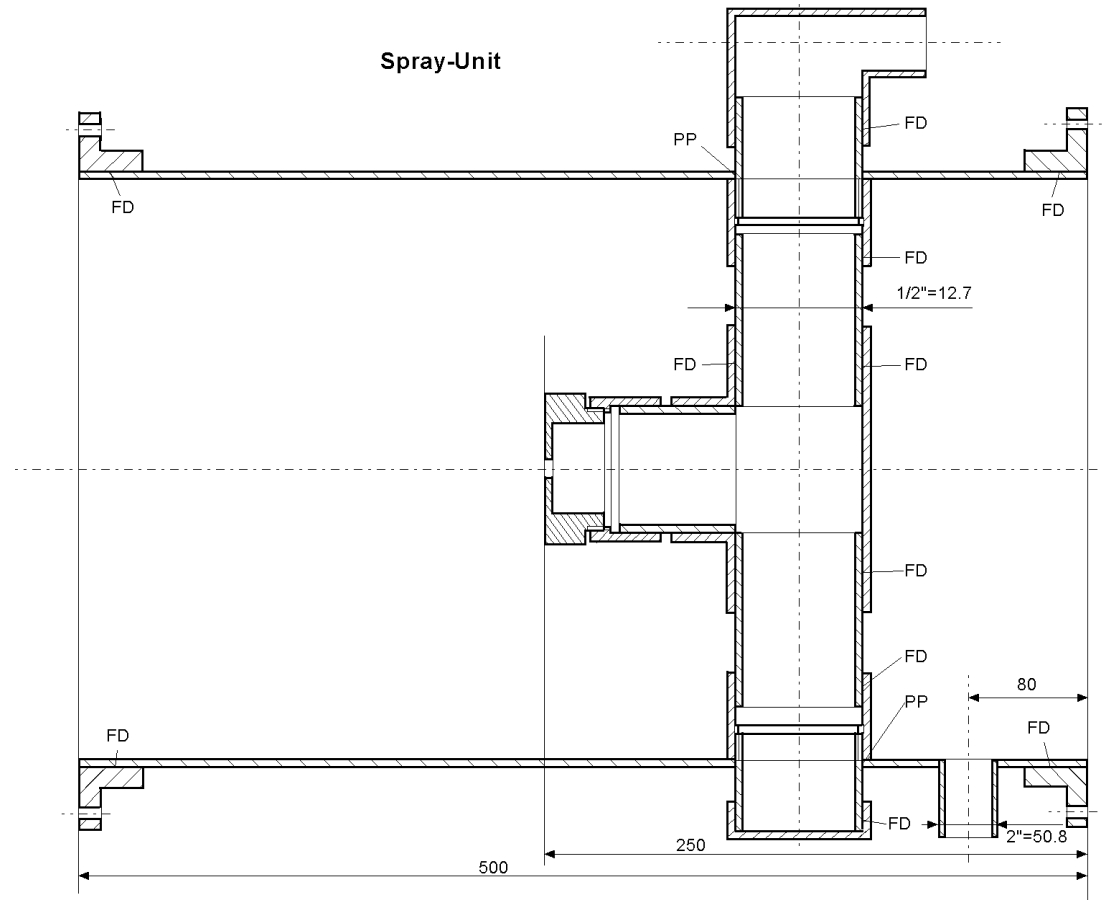


Figure C.1 Spray-Unit

# Mixing-Unit

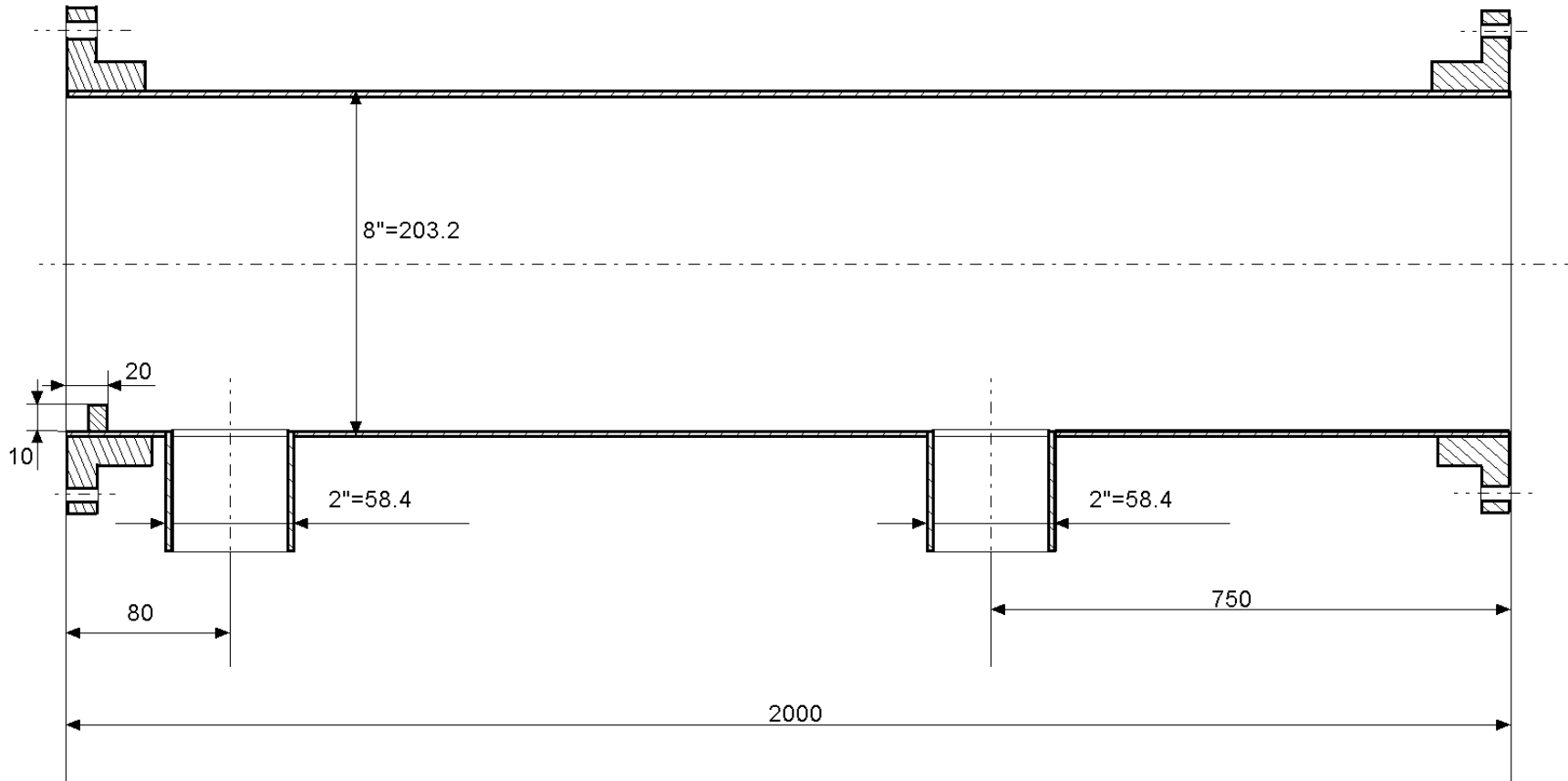


Figure C.2 Mixing-Unit







**Appendix D****Contacts / Addresses of companies**

ABBOTT PLASTICS CO.

Contact: Dean H. Hanson

3225 E. Washington Ave.

[www.abbottplastic.com](http://www.abbottplastic.com)

Madison, WI 53704

Phone: (608) 242-5353

Fax: (608) 242-5350

Analytical Technology,

Contact: Tim Ruesch

c/o Dorner Company

Phone : (414) 355-8118

8585 W. Bradley Rd.

Email : [truesch@dornerdoes.com](mailto:truesch@dornerdoes.com)

Milwaukee, WI 53224

[www.dornerdoes.com](http://www.dornerdoes.com)

Phone: (414) 355-8685

Fax: (414) 355-3556

Analytical Technology, Inc

Contact: John Boswell

680 Hollow Rd., Box 879

Phone: (610) 917-0991

Oaks, PA 19456

Email: [jboswell@analyticaltechnology.com](mailto:jboswell@analyticaltechnology.com)

Phone: (800) 959-0299

[www.analyticaltechnology.com](http://www.analyticaltechnology.com)

Fax: (610) 917-092

Campbell Scientific, INC

[www.campbellsci.com](http://www.campbellsci.com)

815 W. 1800 N.

Logan, Utha 84321

Phone: (435) 753-2342

Fax: (435) 750-9540

Cole-Parmer Instrument Company

[www.coleparmer.com](http://www.coleparmer.com)

7425 North Oak Avenue

Niles, IL 60714

Phone: (800) 323-4340

Fax : (708) 647-9660

Greenheck

Contact: Michael Zingsheim

Vyron Corporation

[www.greenheck.com](http://www.greenheck.com)

1011 N. Mayfair Rd.

Milwaukee, WI 53226

Phone: (414) 257-0211

Fax: (414) 257-4221

Hach Company

P.O. Box 389

[www.hach.com](http://www.hach.com)

Loveland, CO 80539

Phone: (800) 227-4224

Fax: (970) 669-2932

KOBOLD Inc.

Contact: Peter J. Barna

1801 Parkway Drive

Email: [kobold@koboldusa.com](mailto:kobold@koboldusa.com)

Pittsburgh, PA 15205

[www.koboldusa.com](http://www.koboldusa.com)

Phone: (800) 998-1020

Fax: (412) 788-4890

Mazzei injector corp.

Contact: Gregg Lipscomb

J. C. Cox & Associates

Email: [Lipscogr@spray.com](mailto:Lipscogr@spray.com)

2825 N. Mayfair Road

[www.spray.com](http://www.spray.com)

Milwaukee, WI 53222

Phone: (414) 778-2311

Fax: (414) 778-2332

McMaster-Carr

P.O. Box 4355

[www.mcmaster.com](http://www.mcmaster.com)

Chicago, IL 60680

Phone: (708) 833-0300

Fax: (708) 834-9427

OMEGA Engineering, INC.

One Omega Drive

[www.omega.com](http://www.omega.com)

Stamford, Connecticut 06907

P.O. Box 4047

Phone: (800)-848-4286

Fax: (203) 359-7700

PolyScience

Email : [polysci@polyscience.com](mailto:polysci@polyscience.com)

6600 W. Touhy Ave.

[www.polyscience.com](http://www.polyscience.com)

Niles, IL 60714

Phone : (800) 229-7569

Fax : (847) 647-1155

Spraying Systems Co.

J. C. Cox & Associates

2825 N. Mayfair Road

Milwaukee, WI 53222

Phone: (414) 778-2311

Fax: (414) 778-2332

Contact: Gregg Lipscomb

Email: [Lipscoqr@spray.com](mailto:Lipscoqr@spray.com)

[www.spray.com](http://www.spray.com)

TriO<sub>3</sub>

2254 N. US Highway One

Fort Pierce, Fl 34946

Phone : (561) 467-1406

Fax : (561) 467-1986

Contact : Clarence Marsden

Email : [ozone@trio3.com](mailto:ozone@trio3.com)

[www.trio3.com](http://www.trio3.com)



## Appendix E Parts and Components

3-Way, 4-Position valve 3/4", # 45695K35, McMaster-Carr

3-Way, 4-Position valve 1/4", # 45695K32, McMaster-Carr

Blower, BSQ-70-5, Greenheck, S/N 98D02261

Bronze metering butterfly valve, # 4682K75, McMaster-Carr

Condensation Reducing Pipe Wrap, # 5541K11, McMaster-Carr

CR23X Micrologger, Campell Scientific, INC, S/N 2142

Damper, VCD-23 OB 12x12, Greenheck

Dew point monitor, Hygro M1, General Eastern, S/N 0610692

Dissolved ozone monitor, Model A 15/64, ATI, S/N 062946

Flow meter, #KSK 3999-T, Kobold, S/N 59507

Hot Wire, MPM 500e, Solomat, S/N 72598

Injector, # 584, Mazzei, S/N 9931A2

Insulation 1", adhesive back, # 9349K24, McMaster-Carr

Insulation 1/4", # 9349K9, McMaster-Carr

Insulation 3/4" # 93 49K3, McMaster-Carr

MP-6 Multi-Purpose Cement from Harvey's, Menards

Nozzle 1, QLG-SS-40, Spraying Systems Co.

Nozzle 2, QLH-SS-25, Spraying Systems Co.

Nozzle body, QJL -SS, Spraying Systems Co.

Ozone gas monitor, A11 Sensor/Transmitter, ATI, S/N A11-11-0278-EC

A14 Receiver Module, ATI, S/N A14-14-0278-EC

## A 17 Universal Power Supply, ATI

Ozone generator, TC-8, TriO<sub>3</sub>, S/N 3047

Ozone test kit, 0-2.3 mg/l, Model OZ-2, Cat. No. 20644-00, Hach

Pipe Cleaner from Harvey's, Menards

Pipe insulation, # 4734K114, McMaster-Carr

Pressure Transducer, # 07356-53, Cole-Parmer, S/N 60611044

PVC cement, WELD-ON 4052 Low VOO, Abbott Plastics

PVC flange, PVCF-8000-854-08, Abbott Plastics

Polyurethane Foam Air Conditioning Filter manufactured by Frost King, Menards

Pumps, # 4291K31, McMaster-Carr, S/N 84A375 & 84A379

Refrigerated Recirculator, Model 575, PolyScience, S/N 913194

Teflon Tape, Menards

TFE Paste with Teflon from Harvey's, Menards

Thermocouple wire with a tinned copper overbraid, PP-T -24S-PCB, Omega

VITON seal, CP18756-VI, Spraying Systems Co.



## Appendix F      Pictures



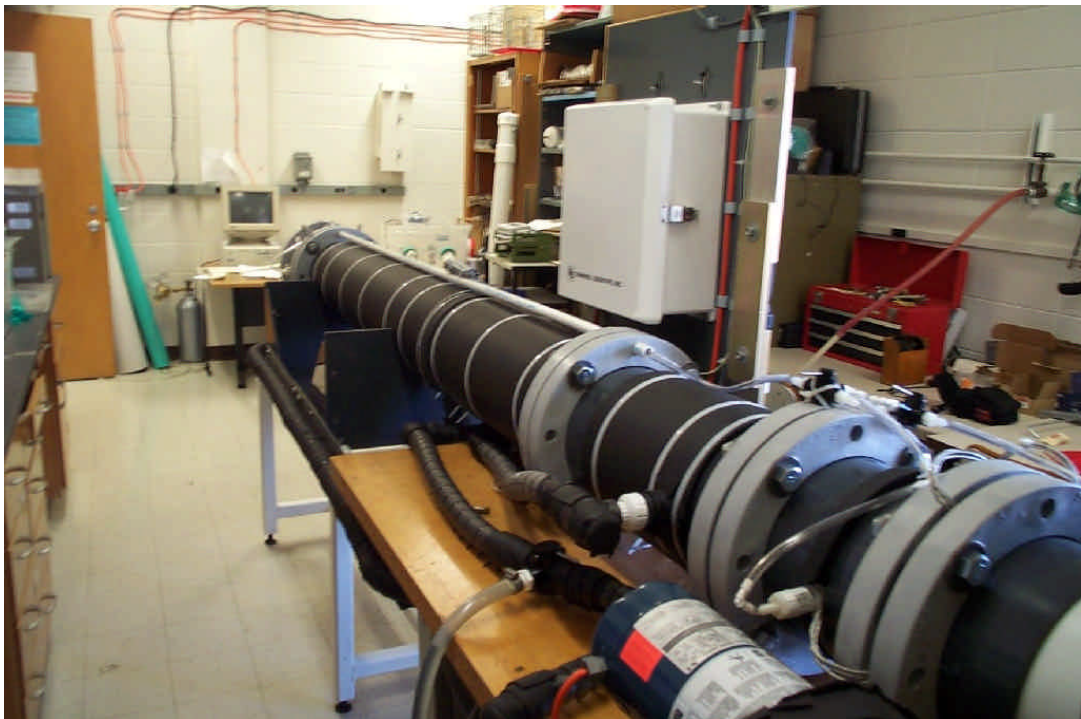
Figure F.1      View on the apparatus



Figure F.2      View on spray unit, ozone unit, blower and exhaust duct



**Figure F.3** View on the control panels



**Figure F.4** View on the ozone unit, mixing unit, data logger, spray unit and ozone unit