CHARACTERISTICS OF A CAPILLARY AIR WASHER

by

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CHAPTER I

INTRODUCTION

The Importance of Air Conditioning

The field of air conditioning has become increasingly important in the last few years. The industries concerned with the construction of air conditioning apparatus have expanded rapidly because of the increased need of equipment. This presents the realization of a great opportunity for engineers with the proper background and training.

The use of air conditioning in industry and public enclosures has increased in large proportions (5, pp.2-3). Some of the important applications are as follows:

1. Controlled humidity in the manufacture of confectionery, the processing and weaving of artificial silk, and the printing and lithographing industry.
2. Controlled humidity and temperature in automatic wrapping machines, used for wrapping food products, cigarettes, and confectionery.
3. Controlled temperature of reaction and controlled facilitating or retarding of evaporation in certain branches of the chemical industry.
4. Control of the moisture content of air supplies to blast furnaces in the manufacture of pig iron.

5. Air conditioning for human comfort in deep mines, in glazed ironware manufacturing, and in the lithographing industry.
6. Air conditioning for human comfort and perishable food preservation in hotels, restaurants, other public enclosures, and private homes.
7. Air conditioning for human comfort in theaters, office buildings, and other public buildings where large groups of people may gather.
8. Air conditioning for human comfort and perishable food preservation in the aircraft, locomotive, and other transportation industries.

The Air Conditioning Laboratory

The Mechanical Engineering Department at Oregon State College has recognized that it is important for engineers to have adequate knowledge in this field. Therefore, long-range plans were formulated for an air conditioning laboratory that would include all equipment necessary for simulating any possible outside air condition and the means of modifying that air to any desired final condition. A capacity suitable to condition three of the laboratory classrooms was considered as a basis for the calculations. The necessary calculations (3, pp.173-316; 8, pp.31-178) presented a resultant capacity of approximately 3000 cubic feet per minute (cfm) of outside air. The desired equipment was determined from this capacity.

Air conditioning (4, p.1) may be considered to be the simultaneous control of all or at least the first three of the following factors which affect the physical and chemical conditions of the atmosphere within any structure. These factors, most of which affect human health or comfort, include:

1. Temperature
2. Humidity
3. Motion
4. Distribution
5. Dust
6. Bacteria
7. Odors
8. Toxic gases

A central air conditioning system (3, p.615) implies that the equipment such as fans, coil refrigerating apparatus, heat exchangers, air washers, filters, and their encasements are designed for assembly in the field rather than in the factory as a unit. A central system may be adapted for any desired conditions, may serve several different enclosures from a distant central location, and is easily accessible for servicing. This was considered to be the suitable situation for the department because the particular pieces of apparatus could be placed in use as acquired.

The essential primary equipment necessary for operation were the air washer, fan, and circulating water pump. These pieces of apparatus, as well as two cooling and three heating coils, were obtained, and the preliminary assembly necessary for operation was completed.

Purpose of this Investigation

The air washer, because it was of a new design and of different construction than ordinary air washers, was of particular interest. Thus, it was the decision of the author that the particular characteristics of the capillary air washer, as set up in this system, might be of considerable value, not only for future instruction purposes, but also in the addition of equipment desired for laboratory development and expansion.

The thermal and flow characteristics of the air washer were considered to be of primary importance. It was recognized that this information would be needed in the near future. Therefore, because there were no immediate problems concerning the cleanliness of the laboratory air, the air cleaning effectiveness of the washer would not be considered. Thus, the project was limited to the determination of the washer thermal and flow characteristics.

CHAPTER II

AIR WASHER TERMINOLOGY AND THEORY

The Air Washer

In order that the reader may fully understand and interpret correctly the terms used in connection with the air washer, it is desirable that the terms be defined at this point.

An air washer (3, p.1) may be thought of as an enclosure in which air is drawn or forced through a spray of water in order to cleanse, humidify, or dehumidify the air. Cleansing the air refers to the removal of airborne impurities such as dusts, gases, vapors, fumes, and smoke. The increase in water vapor in a given space is called humidification, and the decrease of water vapor in a given space is the process of dehumidification.

The Psychrometric Chart

The psychrometric chart provides a convenient means of representing the different processes which are possible in the operation of an air washer and can be used to solve the problems of air conditioning which are involved.

The psychrometric chart (4, pp.65-66) shows graphically the properties of air on the basis of one pound of dry air (air free of water vapor) at standard atmospheric pressure, 29.92 inches of mercury. Psychrometric (3, p.7) pertains to psychrometry or the state of the atmosphere with reference to moisture. The air properties (4, p.66) obtainable from the psychrometric chart are represented in Figure 1, p.7, their definitions being found below. This particular chart (4, pp.67-71) is universal in that it has corrections for barometric pressure other than standard and enthalpy deviation lines for corrections of enthalpy of air for non-saturated conditions.

The following are definitions of the properties of moist air (4, p.66) found represented on the psychrometric chart:

1. Saturation Temperature (T-S). Temperature of saturated air at a particular vapor pressure.
2. Dewpoint Temperature (T-DP). Temperature at which condensation of moisture begins when the air is cooled.
3. Enthalpy at Saturation or Total Heat (TH). A thermal property indicating the quantity of heat in the air above an arbitrary datum, in Btu per pound of dry air. The datum for dry air is 0° F and for the moisture content, 32° F water.
4. Enthalpy Deviation (d). Deviation of enthalpy of unsaturated air from that of saturated air.

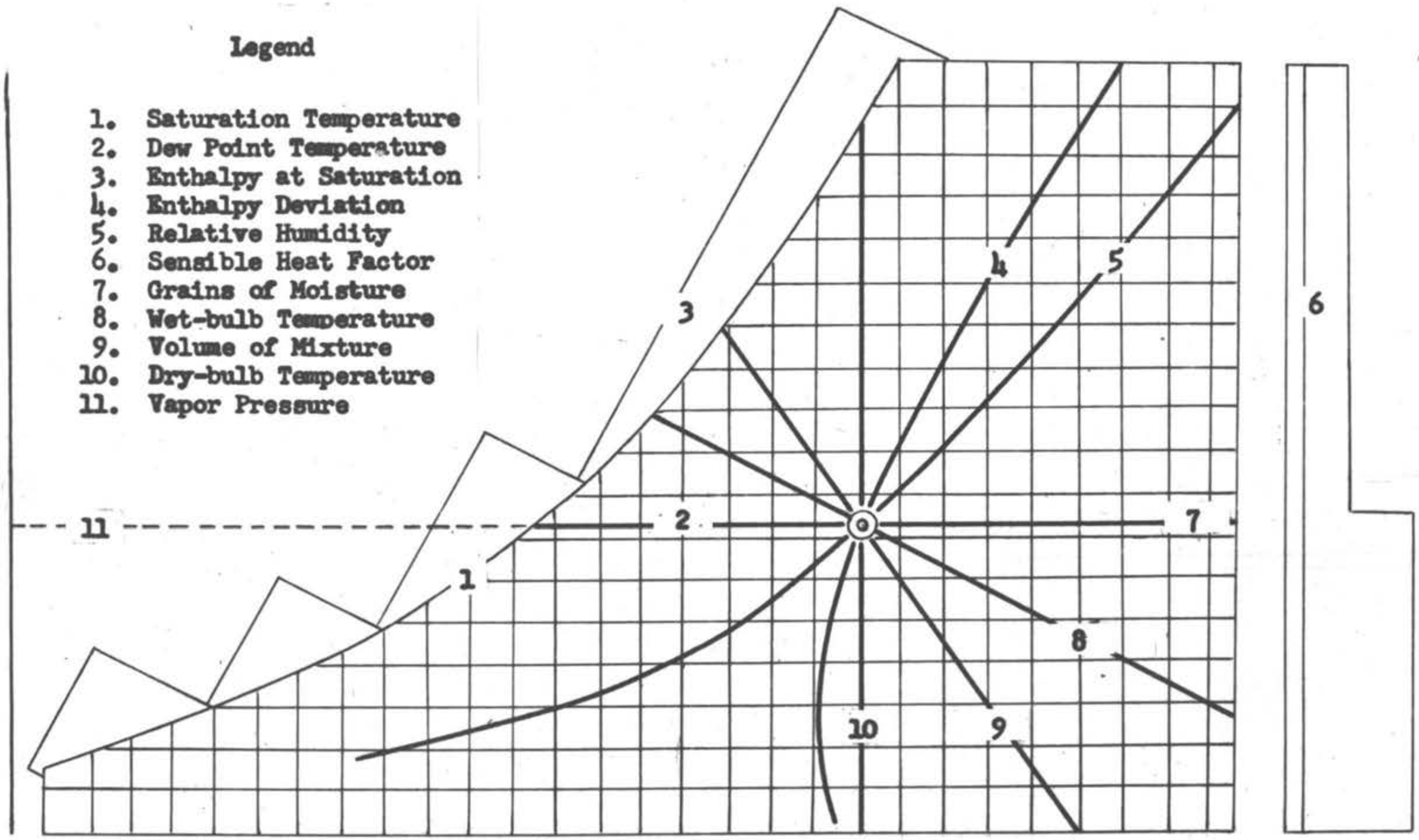


Figure 1. Properties of Moist Air Represented on a Psychrometric Chart

5. Relative Humidity (RH). Ratio of actual water vapor pressure in air to the pressure of saturated water vapor in air at the same temperature.
6. Sensible Heat Factor (SHF). The ratio of sensible heat to total heat load. The total heat load may be composed entirely of sensible heat or may also include some latent heat. Sensible heat indicates that portion of heat which changes only the temperature of the substances involved. Latent heat is a term used to express the energy involved in a change of state. In this case the term latent heat refers to the change in heat occurring when moisture is added to or removed from the air.
7. Grains of Moisture or Specific Humidity (SH). The weight of water vapor in grains or pounds per pound of dry air.
8. Wet-bulb Temperature (T-WB). Temperature registered by a thermometer whose bulb is covered by a wetted wick and exposed to a current of rapidly moving air.
9. Volume of Mixture (V). Cubic feet of the mixture per pound of dry air.
10. Dry-bulb Temperature (T-DB). Temperature of air as registered by an ordinary thermometer.

11. Vapor Pressure (P_v). The pressure exerted by the water vapor contained in the air in inches of mercury.

It may be noted from Figure 1 that the dry-bulb, wet-bulb, and dewpoint temperatures, and the relative humidity are so related that when any two are known, all the other properties represented on the psychrometric chart can be read. When air is saturated, contains all the water vapor it can hold at a given dry-bulb temperature, the dry-bulb, wet-bulb and dewpoint temperatures are the same, and the relative humidity is 100 per cent.

Adiabatic Saturation

Because the wet-bulb thermometer is important in psychrometry, it is necessary to understand the basic process behind the resulting measurement.

When air below saturation (1, pp.313-315) is brought into contact with water, some of the water will vaporize, adding to the moisture content of the air. If no heat is added, moisture will be supplied entirely at the expense of the heat of the air and of the superheat of the original quantity of water vapor. Evaporation will continue and the temperature of the air will be lowered until the air is saturated with the water vapor. This process, taking place without heat transfer to or from an outside source, is called adiabatic, and the final temperature that is approached is termed the temperature of adiabatic saturation or the wet-bulb temperature.

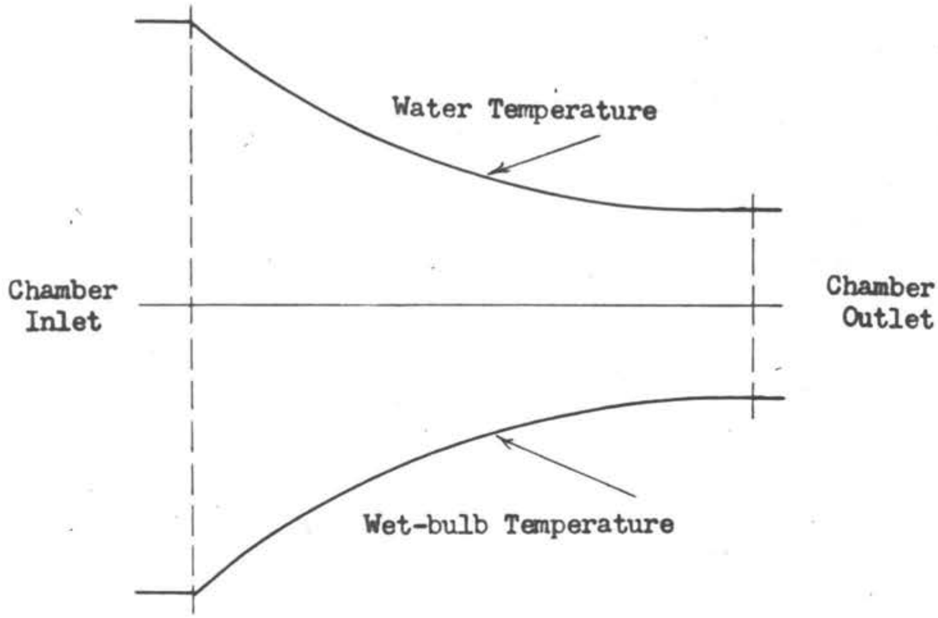
Actually, the mixing of water vapor and air at the wetted surface of a wet-bulb thermometer is not adiabatic (1, pp.313-315) because the bulb "sees" objects at the dry-bulb temperature. The result is a radiation error and a higher reading than the true adiabatic saturation temperature. Also, because of the difference of rate of diffusion between the air and water vapor, a wet-bulb thermometer will tend to read lower than the true temperature of adiabatic saturation. Hence, the errors are largely compensated and account for the largely close agreement between the observed wet-bulb temperature and the true temperature of adiabatic saturation.

Heat Exchange Between Air and Water

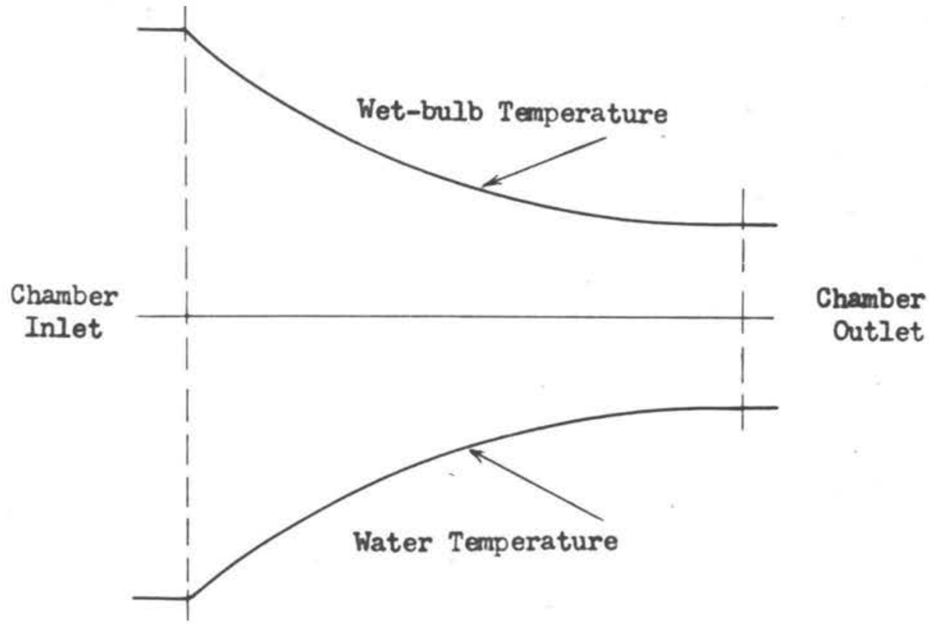
When air is brought into contact with water at a temperature different than the wet-bulb temperature of the air (9, p.68), there will be an exchange of heat, as well as moisture, between the air and water. In any exchange of heat between air and water, the temperature of the water can never fall below the initial wet-bulb temperature of the air if the initial water temperature is greater than the initial wet-bulb temperature. Also, the converse is true; if the initial water temperature is below the initial wet-bulb temperature of the air, the final water temperature will never rise above the initial wet-bulb temperature. This relationship is shown in Figure 2, p.12. The diagram is shown as parallel flow because the test air washer was of this type.

There is only one exception to the rule that whenever there is an exchange of heat occurring when air is brought into contact with water, the temperatures of both must change. This occurs in an air washer when the spray water is continually recirculated without external heating or cooling. The temperature of the spray water will soon assume the initial wet-bulb temperature and will not change thereafter. Aside from this, there is always a change in the temperature of the spray water when it is brought in contact with air.

In order to humidify air with spray water, the temperature of the spray water must be higher than the required final dewpoint temperature of the air. Such an amount of water must be used that, as the water cools from its initial temperature, its final temperature will still be above the required final dewpoint temperature. When dehumidifying, the exact converse is true; the final water temperature must be below the required final dewpoint of the air.



A. Air in Contact With Heated Water



B. Air in Contact With Cooled Water

Figure 2. Parallel Flow of Air and Water Through a Spray Chamber

Thus far, the relation between the dewpoint temperature of the air and the water temperature has been discussed. In addition, the relationship between the temperature of the water and the initial dry-bulb and wet-bulb temperatures of the air must be discussed. There are five general cases (9, pp.69-79) which can possibly be simulated in an air washer. The final air condition in each case depends entirely upon the characteristics and construction of the particular air washer in use. The five cases are as follows:

1. The temperature of the water is higher than the initial dry-bulb temperature of the air.
2. The temperature of the water is at a point between the initial dry-bulb and wet-bulb temperatures of the air.
3. The temperature of the water is at a point between the initial wet-bulb and dewpoint temperatures of the air.
4. The temperature of the water is lower than the initial dewpoint temperature of the air.
5. The temperature of the water is constant and equal to the initial wet-bulb temperature of the air. This is the only case in which there is no variation in water temperature.

Case 1. If the temperature of the water could be maintained at a constant point above the initial dry-bulb temperature of the air, the dewpoint, wet-bulb, and dry-bulb temperatures of the air would increase, represented by line AC in Figure 3, p.15. Point A represents the initial state of the air, point B the final condition of the air leaving the spray chamber, and point C the constant temperature of the water. The water temperature can be represented on the psychrometric chart by a point located on the saturation curve.

As the air passes through the spray chamber, its condition is always represented by a point on the line AC. This point moves toward C from the initial condition A. The air leaves the spray chamber at some final condition B. The longer the air is in contact with the water the closer B will approach C.

In the actual case, the water temperature is not kept constant but drops as it heats and humidifies the air. Thus, a straight line no longer represents the condition of the air, but a curve such as AD will represent the air condition. The point E represents the final condition of the air. The curve CD represents the falling water temperature with point D being representative of the final temperature of the water.

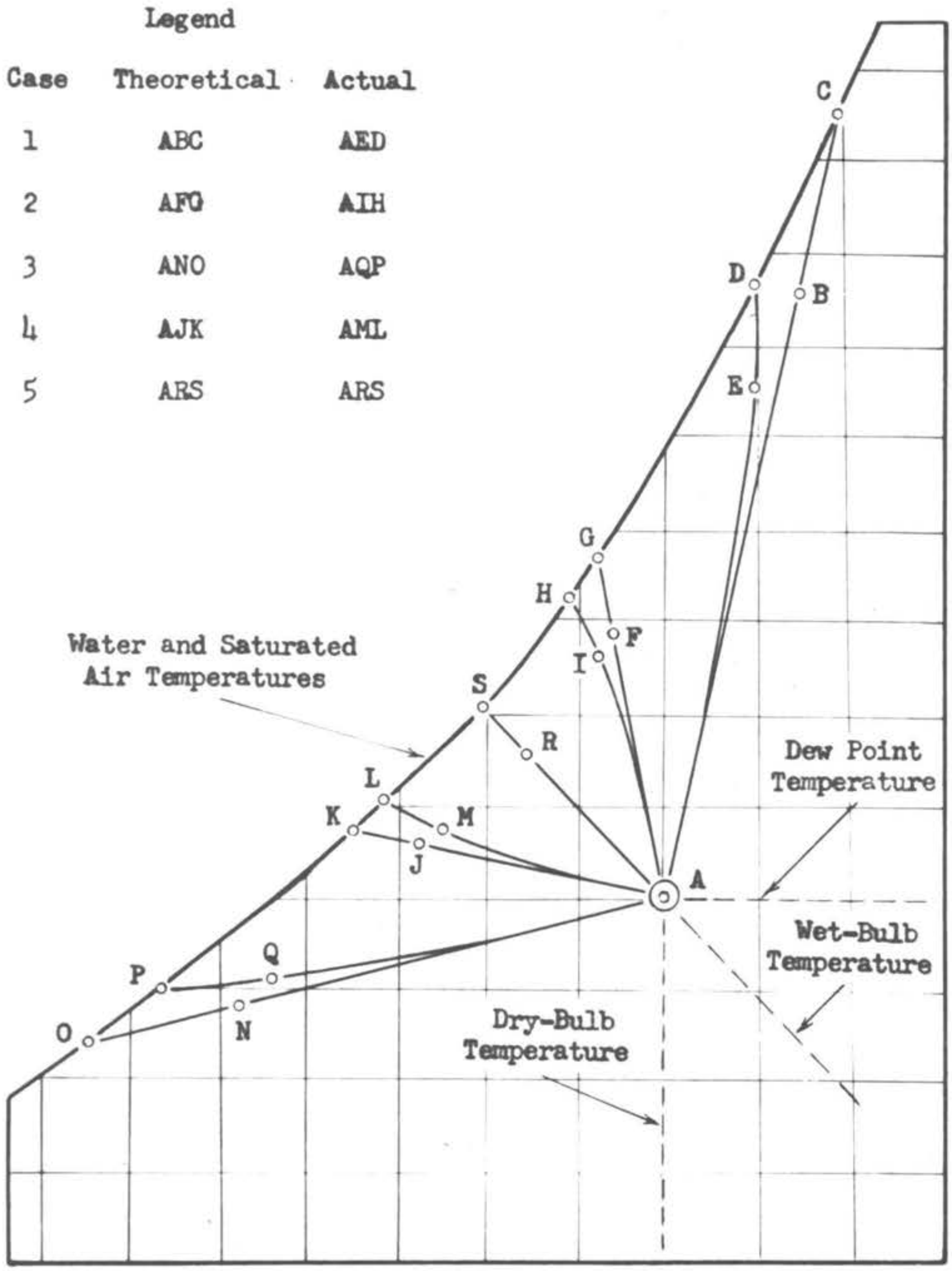


Figure 3. The Five Possible Cases Obtainable in an Air Washer

The air washer, with either steam coils in the tank bottom or a heater on the water circulating line, is typical of a humidifier in which the water cools as it surrenders heat to warm the air and to evaporate a small part of the spray water into the air stream. The steam coil or heater replaces the heat that the circulating water loses.

Case 2. If the water temperature could be held constant at a temperature between the initial dry-bulb and wet-bulb temperatures of the air, the condition of the air could be represented by a point traveling from point A toward G on line AG as it passes through the spray chamber. The point F represents the final air temperature and G the constant water temperature.

When the water is allowed to cool to such a point that its final temperature lies between the initial dry-bulb and wet-bulb temperatures of the air, the air will be both cooled and humidified. The dry-bulb temperature of the air will drop, but its wet-bulb temperature will rise. The increase in the wet-bulb temperature is caused by the fact that the latent heat gain by the air is greater in amount than the sensible heat that it loses.

In this case, the condition of the air can be represented by a point located on the curve AH in Figure 3. Point A is the initial air condition, point I the final air condition, and point H the final water condition.

If the air is to be both heated and humidified, the initial and final temperatures of the water must both be kept above the final dry-bulb temperature of the air. On the other hand, if the air is to be humidified without being heated, the final temperature of the water must fall to a point equal to or below the initial dry-bulb temperature of the air. This can be readily seen by referring to the diagram of the psychrometric chart.

There is one important fact that applies to both Cases 1 and 2. When water in contact with air cools, it surrenders heat and moisture to the air, and the final temperature to which the water can be cooled is higher than the final wet-bulb temperature of the air.

Case 3. If the water temperature could be held constant at a temperature lower than the initial wet-bulb temperature but higher than the initial and final dewpoint temperatures of the air, the condition of the air could be represented by a line AK in Figure 3. Point K represents the constant water temperature and point J the final air condition.

If the water temperature is not constant, as is the case in the air washer, but changes as the water flows through the spray chamber, the condition of the air can be represented by a point on the curve AL. Point M on the curve is the final air condition and point L the final water temperature.

The temperature of the water rises in spite of the fact that it is humidifying the air. In this case the air surrenders sufficient sensible heat to warm the water and also to evaporate a small part of it.

The condition curve, in this case, sweeps upward to the right, whereas in Cases 1 and 2 the curves turn downward and to the left. If the initial water temperature is below the initial wet-bulb temperature of the air, the water temperature will rise, thus bending the curve upward to the right. If the initial water temperature is above the initial wet-bulb temperature of the air, the water temperature will fall causing the representative curve to bend down to the left.

Because, in this case, the initial water temperature is below the initial wet-bulb temperature of the air, the water temperature will rise and both the dry-bulb and wet-bulb temperatures of the air will fall. The maximum possible final water temperature lies below the final wet-bulb temperature of the air.

Case 4. If the water temperature could be held constant at a temperature below the initial dewpoint temperature of the air while in contact with the air, cooling and dehumidification of the air would take place along a line such as AO in Figure 3. Point N represents the final air condition and Point O the constant water temperature.

In the actual case, the water temperature will rise while it is in contact with the air. This is represented by the curve OP on the saturation curve in the diagram. The condition of the air will be represented by the curve AP, with point Q as the final condition of the air.

In this case the water will dehumidify the air if sufficient water is provided to hold the final water temperature down to a point below the initial dewpoint temperature of the air. If the final water temperature is allowed to rise above the initial dewpoint temperature of the air, the air will be cooled, but it will be humidified as well. The final water temperature cannot rise to the final wet-bulb temperature of the air.

Case 5. In this case, the water is constantly recirculated without being heated or cooled by an external source. When the initial water temperature is the same as the initial wet-bulb temperature of the air, the temperature of the water will not change as it is brought into contact with the air. Water that is continually recirculated without being heated or cooled from an outside source will soon assume the wet-bulb temperature of the entering air. The water temperature will then remain constant as long as the initial wet-bulb temperature is not changed. Evaporation of moisture must take place, however, since the temperature of the water is above the dewpoint temperature of the air. In addition, since the water temperature is below the dry-bulb temperature of the air, there must be a drop in the dry-bulb temperature of the air.

There is no change in the total heat content of the air and no change in the wet-bulb temperature in this case. Thus, the process is called adiabatic saturation. The latent heat required for the evaporation of the water can be obtained only from the sensible heat that the air loses as its dry-bulb temperature falls. The air loses sensible heat but gains an equal amount of latent heat.

The process of adiabatic saturation can be represented by a straight line AS in Figure 3 because the water temperature is constant. The process can be represented on the line coinciding with the wet-bulb line on the psychrometric chart since there is no change in total heat content. Point R represents the final air condition.

This case is important because the action is applied commercially on a large scale. Air washers utilizing this principle are in wide use for humidification in winter.

CHAPTER III

AIR WASHER CONSTRUCTION AND PERFORMANCE

Construction

Air washers (3, pp.725-729) consist primarily of a spray chamber wherein the air is brought into contact with a dense spray of water, a tank at the bottom of the chamber where the spray water is collected, and an eliminator section at the rear of the chamber where any entrained moisture is removed from the delivered air. Heat transfer takes place between the air and water resulting in humidification or dehumidification of the air, the extent depending upon the construction of the washer, the particular application, and the relative temperatures of the spray and water. Considerable cleaning of the air may also be attained, the degree depending upon the construction and application of the washer. Air washers may also include such auxiliary apparatus as inlet air baffles and heating and cooling coils, and may, as a matter of fact, be purchased as a complete unit including fan and water circulating pump.

The essential requirements (3, pp.725-729) in the operation of common air washers are:

1. Uniform air distribution across the chamber section.
2. Moderate air velocity from 250 to 650 feet per minute through the washer chamber.
3. An adequate amount of spray water broken up into fine droplets throughout the air stream, at pressures from 15 to 30 psig.
4. Sufficient length of travel through the water spray and wetted surfaces.
5. Elimination of entrained moisture from the outlet air.

The expected performances, physical size, length, number of sprays, etc. will vary greatly depending upon the application. In general, the width and height of the washer are dictated by the space available. Washers of nearly equal height and width are desirable from an air flow and economic standpoint although not necessary.

When an increase in the overall heat transfer is required, multistage washers are used. The washers are equivalent to a number of washers in series, and the water is often pumped from one stage to the other where conditions permit.

Intimate contact between the air and water may be secured by one of the three following methods:

1. By breaking the water into fine drops.
2. By passing the air over surfaces continually wetted by water.
3. By a combination of the first two.

The wetted surfaces in an air washer may be of metal, scrubber plate, or fiber-glass construction. The scrubber plate washers contain several baffle-type plates upon which water is sprayed from above. The metal and fiber-glass surfaces generally use a coarse spray of water at low pressure. The water spray may be set at an angle with the air flow and may be parallel or concurrent to the flow of air. This type of air washer performs not only the necessary heat transfer functions, but also removes dust and dirt from the air streams. The capillary or fiber-glass wetted surface type air washer will be discussed more fully later, because it is this type of washer with which the laboratory is concerned. However, since most of the construction and performance of the capillary air washer is similar to that of the ordinary air washer, the general air washer is discussed here, and any differences will be noted later.

The spray chamber, casing, and tank (5, pp.221-223) may be made of copper, wood, concrete, stainless steel, or galvanized iron, the latter being most common. Both the tank and casing are water-tight, all joints and rivet heads being soldered over. Standard tanks are about 18 inches deep and the water level is maintained about an inch or two above the bottom of the eliminator plates. The washers vary in length from five to ten feet depending upon the design and number of spray banks. Generally, about two and one-half feet are allowed for each spray bank, one and one-half feet for the eliminators, and one foot for the inlet baffles or diffusers. Of course, a unit air washer would be of extra length in order to contain necessary coils and other auxiliary equipment.

The eliminators act to remove any entrained moisture in the air stream and also may act as scrubbers to remove dirt. The cleansing action depends upon the wetted surface exposed so the eliminators are placed one inch to two and one-half inches apart to obtain as much surface as possible in a limited space. Eliminators used particularly for air cleaning generally have flooding nozzles which keep the plates continually wet. The eliminator plates are commonly of the six-bend type but may be less. The standard construction is of galvanized iron with right angle bends, the surfaces being at 45 degrees to the inlet air stream. There are generally hooked edges at each of the bends to catch the entrained moisture. The eliminators are installed vertically to insure moisture runoff. The plates are removable.

The baffles or diffusers at the chamber inlet serve a dual purpose. They distribute the air uniformly over the entire cross-section of the chamber and prevent any backsplash of the spray water. The baffles are of simple construction and placed farther apart than the eliminator plates.

The interior piping is generally provided by the manufacturer. Standard practice is to provide galvanized heavy steel pipe for the main spray header and the necessary standpipes. The nozzles are usually made of brass of suitable design for the particular washer.

The washers are provided with a ball float to maintain the water level in the tank. A quick-fill and overflow and drain connections are standard washer fixtures.

A circulating pump suction strainer, a marine light inside the washer, and an observation window for access to the nozzles and washer interior may or may not be provided.

The circulating pump, cooling and heating coils and other such equipment must generally be purchased aside from the washer unless the washer is bought as a unit conditioner.

Air washers (9, p.219) are designed to be installed on the suction side of the fan. They should never be installed on the discharge side unless specifically built for that purpose. There will be no difficulty with water leaking through the joints of a washer installed on the suction side of the fan. However, if installed on the discharge side, even the slight air pressure developed by the fan might cause water leakage through the joints, in spite of rubber gaskets which are usually installed.

Performance and Utilization

There is no generally accepted method of rating air washer performance (5, p.218). Manufacturers' rating tables are generally reliable, but it is necessary for application engineers to know the characteristics of the various types of equipment in order that they may select the proper one for a given application.

Air humidification can be accomplished with an air washer by three methods (3, pp.727-729). These are:

1. Use of recirculated spray water without prior treatment of the air.
2. Heating the spray water.
3. Preheating the air and washing it with recirculated spray water.

In any installation, the air should not enter the spray chamber at a dry-bulb temperature less than 35° F in order to eliminate the danger of freezing the spray water.

The first two of the above methods have been previously discussed in principle. The third method involves the same process as the first but the preheating of the air increases the sensible heat content of the air, thus allowing a greater amount of moisture to be absorbed by the air. The final desired conditions are secured by adjusting the amount the air is preheated to give the required wet-bulb temperature of the inlet air.

In the first and third methods, the extent to which the final temperature of the air approaches the wet-bulb temperature of the entering air, and the extent to which complete saturation is approached, is conveniently expressed by a ratio known as the humidifying or saturating effectiveness (3, p.727; 7, p.401; 2, p.7), defined as

$$e_h = \frac{t_1 - t_2}{t_1 - t'}$$

e_h = humidifying effectiveness, per cent.

t_1 = dry-bulb temperature of the entering air, Fahrenheit degrees.

t_2 = dry-bulb temperature of the leaving air, Fahrenheit degrees.

t' = wet-bulb temperature of the entering air, Fahrenheit degrees.

The principal factors (5, pp.218-219) affecting the saturating effectiveness are:

1. Air velocity.

2. Quantity of water sprayed per unit volume of air.

3. Fineness of spray.

4. Contact period of water with air.

Provided the velocity is correct and the air is uniformly distributed over the entire cross-sectional area, the effectiveness of a washer with a given type of spray nozzle is directly related to the number of spray banks and the direction in which they spray. Values vary for different types of equipment, but a general comparison of saturating effectiveness with regards to spray banks and spray direction is given in the following table (3, p.727; 5, p.219):

Banks	Direction	Per cent Effectiveness
1	Downstream	50-70
1	Upstream	65-75
2	Downstream	85-90
2	Opposing	90-95
2	Upstream	92-97

Adiabatic saturation or evaporative cooling is only applicable to comfort conditions in localities where the wet-bulb temperatures are low and the dry-bulb temperatures are comparatively high. This is because the resulting air humidity would otherwise be above that suitable for comfort. Adiabatic saturation is unsuitable for installations where large groups of people convene in a single enclosure because the high internal latent heat content produced by the occupants will raise the air condition in the enclosure above comfort standards.

Dehumidification with air washers can be accomplished by the previously described process where the final water temperature must be below the entering dewpoint of the air. Washers with two or more banks of sprays are generally used for dehumidifying installations, whether for industrial or comfort installations. Such washers will generally cool the air to within one or two degrees of the leaving spray water temperature. The differential will increase somewhat when the difference between the entering wet-bulb and leaving dewpoint temperature is relatively large.

Washers are generally not rated according to their humidifying or dehumidifying effectiveness. There is one relationship, however, which is applicable and possibly could be used. For dehumidification (7, p.402), air washers have been compared by a ratio of the difference between the leaving wet-bulb and leaving water temperatures to the difference between the entering wet-bulb and the entering water temperatures. The following is a table of the results obtained; the most effective washer having a zero rating, of course, because the leaving wet-bulb and water temperatures would be equal.

Spray banks	Direction	Dehumidification effectiveness
3	1 down 2 up	0
2	2 up	5
2	1 up 1 down	15
1	up	20
1	down	35

Humidification effectiveness could be figured on the same basis. Of course, the leaving water temperature would be higher than the wet-bulb of the leaving air.

The action of air washers concerning (1) cleaning effectiveness, (2) odors, (3) noise, (4) resistance, and (5) spray flow, may be considered as part of their performance (5, pp.218-220).

1. Air washers are not entirely effective in the removal of air impurities. Large particles are washed out by the washer spray or when passing through the eliminator plates, but soot and grease particles are not easily removed. Washers which are used for the removal of fine particles of dust, soot, and greasy particles generally must employ a detergent.

2. Washers canot be expected to remove odors from the air. Vapors causing odors are not always soluble in water. Odor filters of cocoanut shell carbon may be used in a bank ahead of the washer.

3. Air washers which emit spray water at high pressures (20 to 30 pounds per square inch) generate noise.

Suitable design and location of systems must be made in order to prevent the noises from reaching the controlled areas.

4. Air resistance varies approximately as the square of the velocity through a given area. Most of the air resistance encountered in ordinary air washers is caused by the inlet diffusers and eliminator plates. The resistance will vary with different spacing and a difference in the number of deflections and angle of deflection of the air. At standard rated capacities, usually 500 feet per minute air velocity through the washer, the air friction has been found to vary between 0.2 and 0.5 inches of water.

Most manufacturers base their rating tables on a face velocity of 500 feet per minute face velocity through the air washer. Velocities above 750 feet per minute and below 350 feet per minute may result in faulty elimination of entrained moisture.

5. Depending upon the design and application of the air washer, the water sprayed will vary between one and one-half and five gallons per minute per spray bank for 1000 cubic feet of air per minute. The fineness of the spray will depend upon the nozzle design and the spray pressure. The necessary fineness of spray will depend upon the washer construction. Commonly used water pressures vary between 15 and 30 pounds per square inch.

The maintenance of an air washer is an important item if the washer is expected to perform effectively. Manufacturers (5, p.223) recommend weekly cleaning of nozzles and tank and interior painting once a year. The spray water should be checked for corrosive properties and chemicals should be used to treat the water whenever necessary.

CHAPTER IV

CAPILLARY AIR WASHERS

Comparison with Other Air Washer Types

Capillary air washers are similar in construction and performance to ordinary washers but employ multiple cells as a wetted surface which act as air cleaners in addition to providing a large contact area for the air to come into contact with the spray water.

The standard cells (5, p.225; 2, p.4) are 20 inches by 20 inches in face area and eight or eight and one-half inches deep. The cells are capable of handling 1000 to 1100 cfm air flow. Each cell is filled with spun glass filaments. The cells are placed in banks, both horizontally and vertically, the number depending upon the capacity of the unit.

The water is sprayed over the face of the cells and flows directly through the cells along and between the glass filaments. This provides (7, p.407) a large surface area for intimate and efficient contact between the air and the water. It also permits the use of a larger spray drop size at lower pressure and power consumption than ordinary washers.

The air cleaning efficiency of the capillary cells and the large size of the water particles leaving them permit the use of elimination plates which are fewer in number and of a more simple construction than the ordinary washer.

The capillary air washer may be used in the following special applications because of their particular characteristics (2, p.10):

1. Industrial comfort cooling.
2. Hospital air conditioning.
3. Motor and generator cooling.
4. Diesel and gas engine air supply.
5. Industrial air supply.
6. Spray booth air supply.
7. Chemical process contact surface.

Basic patents were granted on this revolutionary method of providing a large surface area for contact between air and water in an air washer.

The American Blower Capillary Air Washer

The American Blower Corporation has several basic patents for the particular type of capillary air washer with which this project was concerned.

The manufacturer (2, p.3) produces three classes of capillary air washers which are available in many different capacities and of several different materials. The three classes are defined as follows:

Class 1 - concurrent type.

Class 2 - counter-current type.

Class 3 - concurrent type with enclosed coils.

The Class 1 washers have the spray nozzles located at the entering side of the capillary cells. The flow of air and water are thus concurrent. This class of washer is considered to be suitable for all normal air cleaning, humidifying and evaporative cooling application.

In Class 2 washers, the spray nozzles are located on the leaving side of the capillary cells. The air passes upward through the cells in counter-current flow to the descending water. The counterflow affords a higher cooling efficiency than the Class 1 washers when using chilled water but the evaporative cooling and air cleaning efficiencies are approximately the same. One disadvantage of this class of washer is the high air resistance created by the counter-current flow of the air and water. A large amount of spray would entirely cut off the air flow.

The Class 3 washer consists of a Class 1 washer with cooling or heating coils or both between the capillary cells and the eliminator plate. These washers are especially suitable for well water applications where great heat extraction from the air by the cold well water is possible.

The capillary cells (2, p.9) consist of metal frames with coarse and fine wire screen faces housing glass fibers or filaments. The fundamental capillary cell data is presented in Table 1.

Table 1

Capillary Cell Data (2, p.4)

Size (Nominal)		20 x 20 x 8½ in. deep
Weight - Dry and Wetted		15 lbs.-23 lbs.
Fibers per Cell -	Number	57,000
	Diameter	0.011 in.
	Length	9 in.
Air Passages per Cell -	Number	60,000
*(Approximate)	Diameter - Average	0.07 in.
	Length	9 in.
Percentage Fiber Volume in Cell		1.48 per cent
Effective Glass Contact Area per Cell		125 sq. ft.

*Average Air Passage Diameter is estimated from the Glass and the Normal Retained Water Volume and is given as Diameter of a Circular Passage equal to the Average Inner-Strand Space.

It can be seen from Table 1 that the fibers are slightly curved since they are longer than the casing depth. The fibers are held in place by projecting slightly through a cross-mat of glass fibers on each face of the cell and by a lacing of glass strings between the wire face screens. The mat of glass cross-fibers both assists in holding the filling in place and, with the fine wire screen, aids in water distribution, thus permitting the use of coarse low-head sprays.

The cells are designed for a maximum air volume of 1100 cfm and for a maximum water quantity of 9 gpm per cell. Water carryover and cell plugging may occur if these maximum values are exceeded.

The capillary cells can be successfully cleaned by use of a wetting agent. This is necessary whenever the cells become clogged with dirt. Regular monthly or semi-monthly cleaning is good practice.

The spray nozzles are of a low-head coarse spray type which give a solid spray of large droplets well distributed. Each nozzle is adjustable by means of double elbows to cover one entire cell face. The washers are supplied with two or three nozzles per cell, however, so that if one nozzle is plugged, the cell will still be covered.

The efficiency of the washer is determined by the area of wetted glass fiber surface in the cell. It is not affected by change in water quantity as long as the glass surface is thoroughly covered. Five gpm per cell water flow is recommended for normal operating conditions so that the cells will receive a good wetting even with one nozzle plugged. Seven to nine gpm per cell may be used to keep the cells well flushed if there is much dust in the air being conditioned.

The moisture eliminators are of a light-duty type because the moisture leaves the cells in coarse streams with little visible mist. The eliminators consist of corrugated metal blades of the three-surface, two-hook type with 45 degrees deflections and spaced two and one-fourth inches between centers. Each blade can be removed independently.

The water pump suction strainer provided with each washer consists of a cylindrical screen with openings smaller than the spray nozzle orifice so that no particles larger than the orifices will go through the pump to the nozzles and possibly plug them. The strainer can be removed from the tank for cleaning. The strainer is equipped with an anti-cavitation hood to insure full flow of water into the suction.

Each washer is equipped with a float valve for make-up water lost by evaporation and quick-fill water connections for filling the tank initially and after cleaning. A dilution connection is provided for keeping down the concentration of solids and dissolved gases which would otherwise accumulate in the tank and hamper the efficiency of the washer. This connection should have a valve for providing fresh city water. The valve should be slightly cracked during operation to provide continuous dilution.

CHAPTER V

THE LABORATORY TEST UNIT

The laboratory test unit was composed of an air washer, a water pump, a fan, and a reheat coil. The washer was provided with city water, both at normal temperature and heated. The complete unit is pictured in Figure 4, p.40.

The Air Washer

The laboratory air washer is a Unit No. 2 - 2, Class 1, American Blower Capillary Air Washer containing four capillary cells and employing 12 spray nozzles in two spray banks. The washer specifications are given in Table 2, p.43. A diagram showing the washer dimensions and location of the component parts of the washer is presented in Figure 7, p.42. The air washer is presented in three different views in Figures 4, 5, and 6, pp.40-41.

The Water Pump

The water pump used for recirculating the washer tank water is a Bell and Gossett, 1/2-hp uni-built centrifugal type. It has a one and one-half inch suction and a one and one-fourth inch discharge connection. The pump is rated at 30 gpm for 11.7 psi.

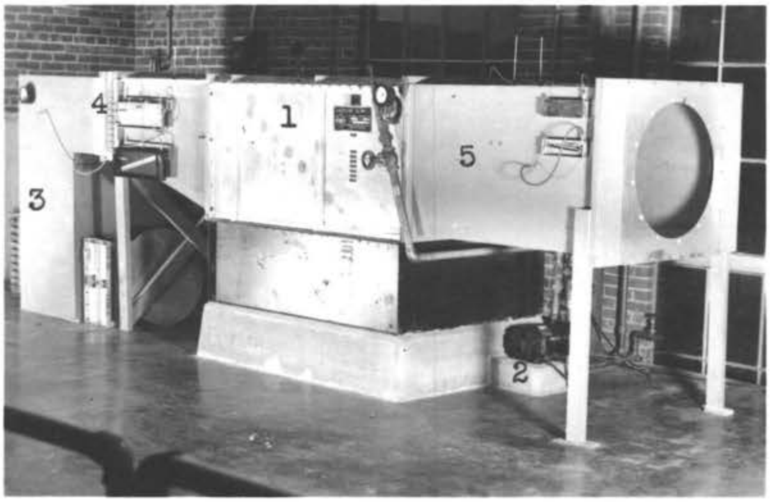


Figure 4. The Laboratory Air Washer Test Unit

1 - Air Washer
2 - Water Pump
3 - Fan Housing
4 - Reheat Coil
5 - Orifice Section

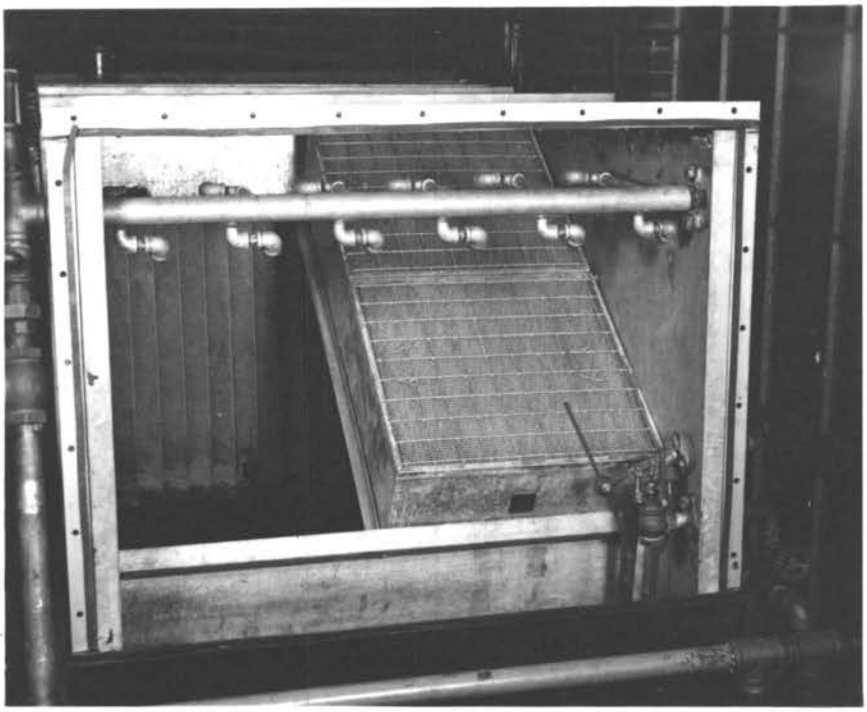


Figure 5. Air Washer Inlet with Two Capillary Cells Removed Thereby Exposing the Eliminator Plates in the Rear of the Spray Chamber

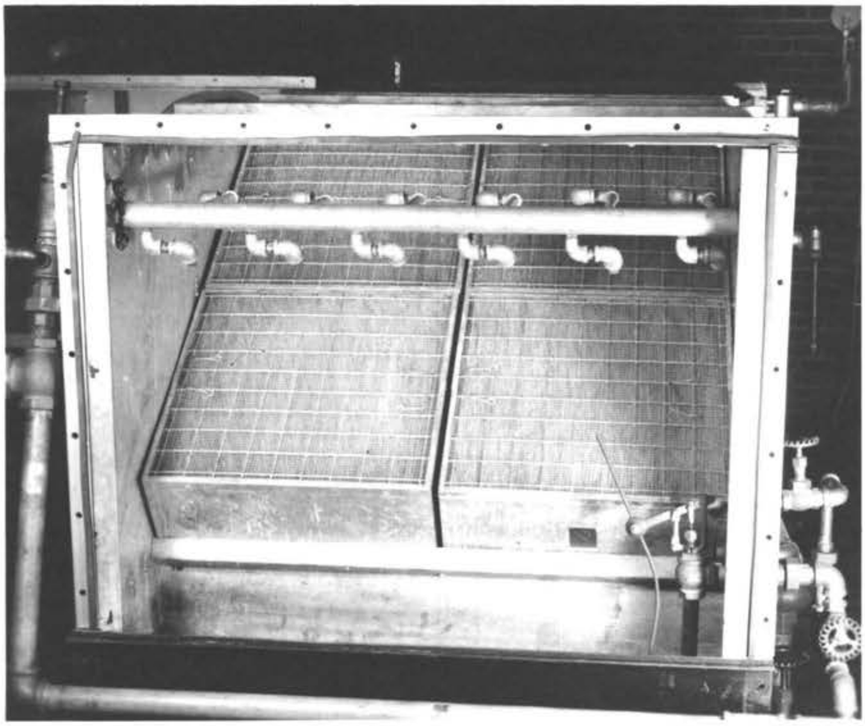


Figure 6. Air Washer Inlet Showing the Four Capillary Cells and the Spray Nozzles

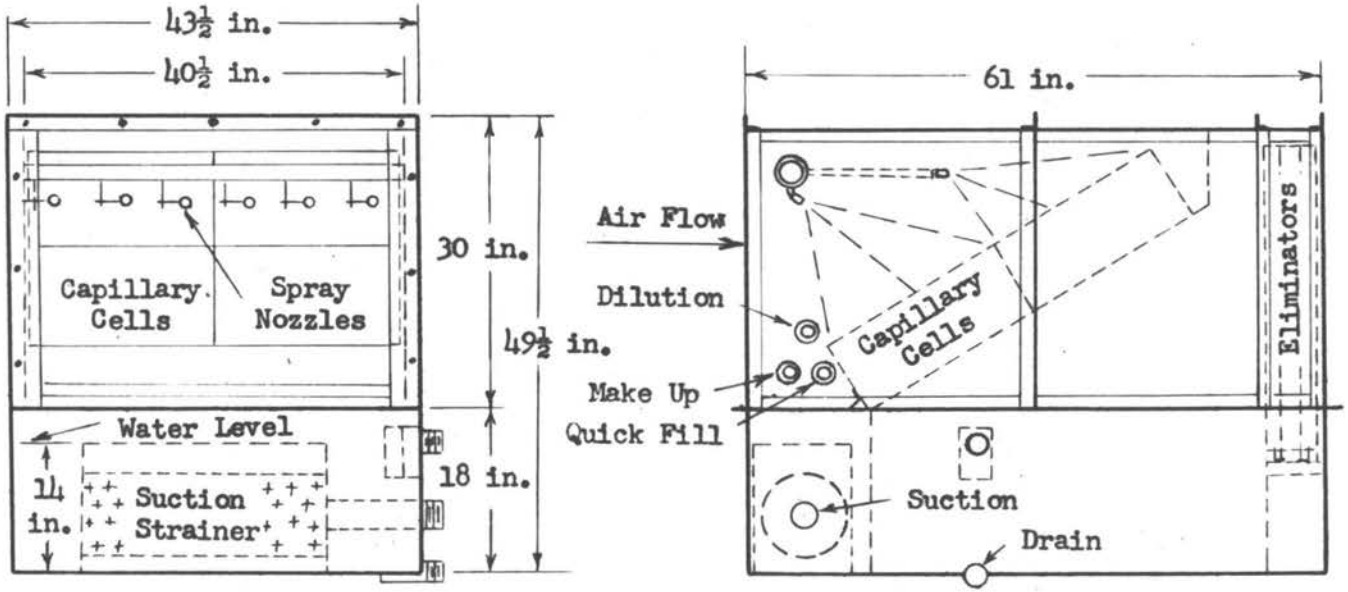


Figure 7. The Capillary Air Washer Dimensions and the Location of Its Integral Parts

Table 2

Washer Specifications (2, pp.9-14)

	Materials	Description
Tank	3/16 in. welded steel Length, 61 in. Width, 40½ in. Depth, 18 in. Outside flanges, 1 in.	Painted with corrosion resisting paint Furnished with: 1. Makeup float controller and valve 2. Overflow and drain connections 3. Quick-fill and dilution connections
Suction Strainer 1. Frame 2. Screen	 Galvanized steel Bronze	Removable
Casing	20-gage galvanized steel Length, 61 in. Width, 40½ in. Depth, 30 in. Outside flanges, 1 in.	Galvanized external angles Joints riveted and soldered
Cell Supports	Welded steel	Angles welded to casing
Capillary Cells 1. Casing 2. Screens 3. Filaments	 Galvanized steel Hot-dipped galvanized steel Glass	Removable Loaded with not less than 125 square feet of glass scrubbing surface in the form of 9 in. long by 0.011 in. diameter glass fibers oriented parallel to the air stream
Nozzles	Brass	Removable Low-head coarse spray Adjustable for direction
Eliminators	24-gage galvanized steel	3 surfaces 2 hooks 45° angle to air flow 2 1/4 in. spacing

The Fan

The fan is an Iron Fireman centrifugal type with double air intake. Its capacity is approximately 3000 cfm at one inch of water pressure with a shaft speed of 900 rpm. The fan was driven by a General Electric 3-hp induction motor.

The Reheat Coil

The reheat coil was placed between the washer and the fan because the unit was constructed to be used for future tests. The project was not concerned with this coil except as to its effect upon the washer characteristics in its particular location.

Water Supply and Drainage

City water was supplied to the unit through the quick-fill and makeup water connections and to the spray header. Thus, the washer could be run with city water or with recirculated water.

Heated water was supplied to the washer through the dilution connection. It was decided that dilution would be unnecessary during the test runs because of the short and intermittent usage of the washer. Also, in full-time operation, the quick-fill connection could supply the necessary dilution water. Thus, the dilution connection could be used for other purposes in any case.

The tank drain and overflow connections were piped to a laboratory drain.

Assembly of the Laboratory Test Unit

The location of each section of the unit was determined by the space available, the desired usage, and general design practice. The unit was assembled according to the following procedure:

1. Washer assembly. The washer was received unassembled. It was constructed in the laboratory and placed on a concrete mat poured especially for the washer.
2. The fan. The fan was secured to the floor in its proper position.
3. The reheat coil. The foundation for the reheat coil was constructed; the reheat coil was secured to it; and then the combination was placed in position. The coil was supported by the foundation and in position horizontally by the ductwork.
4. The water pump. The pump was secured to a small concrete mat which was poured integral with the mat beneath the washer.

5. Piping. All the necessary piping to the washer pump and drain was completed.
6. The ductwork. The component parts of the unit were connected by means of hardboard ductwork. The ductwork was assembled by nailing the hardboard to wooden braces, and then screwing the end braces to the flanges of the different sections of the unit. The ductwork was secured to the floor at the fan with adequate distance left between the ductwork and fan inlets for proper air flow.

CHAPTER VI

TEST APPARATUS AND PROCEDURE

Test Apparatus

The test apparatus consisted of the following equipment:

Inclined Draft Gages	2 - 0 to 3 in. H_2O
	2 - 0 to 1 in. H_2O
Thermometers	2 - 20 to 120° F
	3 - -30 to 120° F
Pressure Gage	1 - 0 to 15 psi
Electrical Tachometer	1 - 0 to 2000 rpm
Manual Regulating Valve	1
Weigh Tank and Scales	1
Stop-Watch	1
Air Cut-off Plate	1
Orifice Section	1 - 24 1/8 in. orifice

The draft gages were attached to the unit in the positions shown in Figure 8, p.48. The two three-inch gages were placed at the rear of the washer. The gages were connected to pressure taps in the ductwork by means of rubber tubing. They were installed to read negative pressure drops through the unit.

The thermometers were calibrated in a constant temperature water bath. They all indicated the same temperature as the bath. Therefore, no calibration curves were necessary. The thermometers were installed in positions as shown in Figure 8, p.48. The dry-bulb thermometers were placed in front of the wet-bulb thermometers to

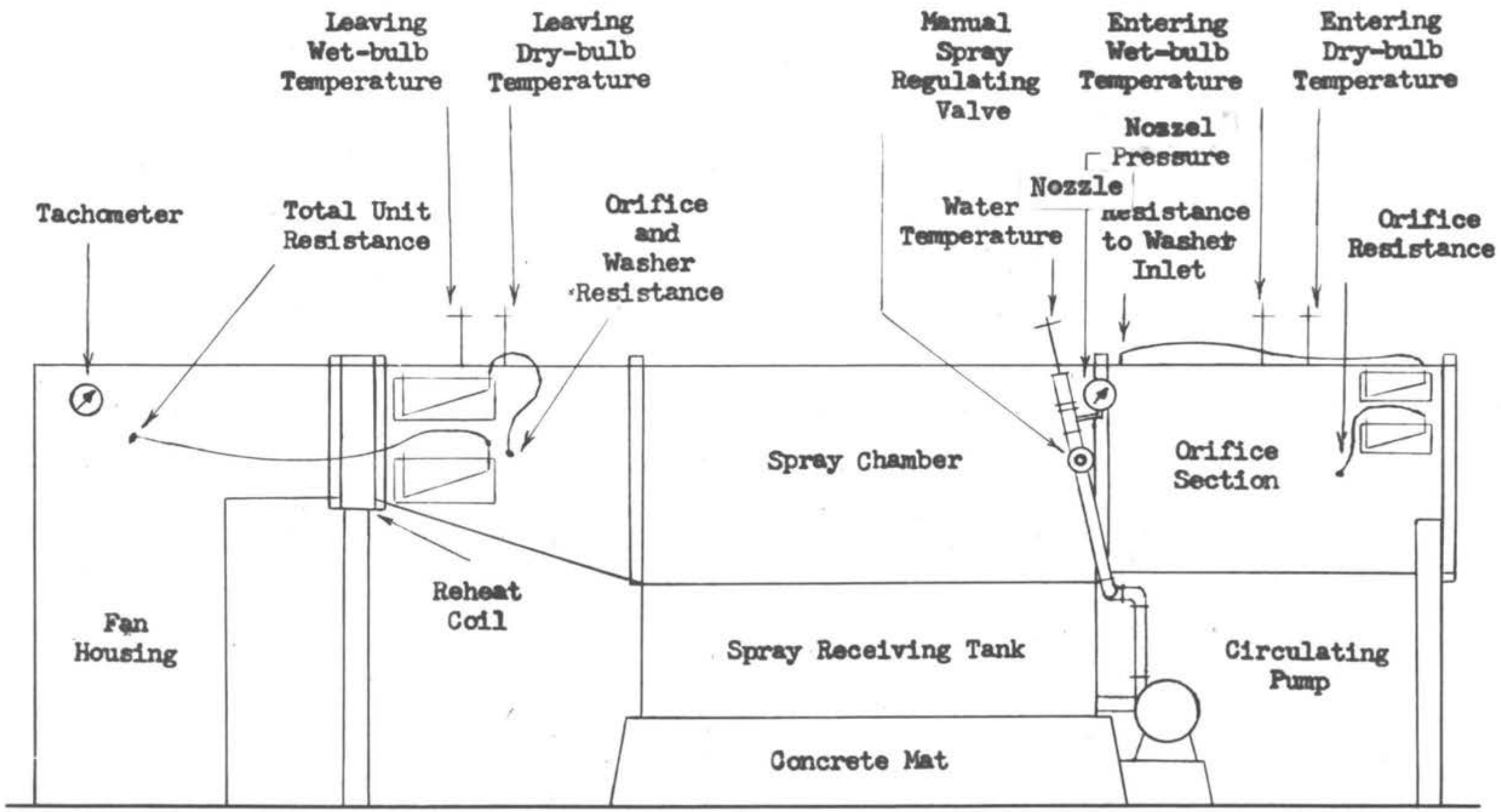


Figure 8. Laboratory Unit Test Instrument Locations

prevent them from "seeing" any moisture evaporated from the wet-bulbs. The water temperature thermometer was placed in a thermometer well containing oil to increase the rate of heat transfer through the piping to the thermometer.

The pressure gage was used to indicate the nozzle pressure from which the nozzle flow could be determined. The pressure necessary for a given water flow rate was determined by use of the weigh tank, scales, and stopwatch. The regulating valve was used to regulate the water flow.

The air flow through the unit was regulated by means of a plate arranged to cut off increments of flow at the fan discharge.

The orifice section, for measurement of air flow, was constructed of hardboard with a sheet aluminum orifice plate fastened to the inlet. This is shown in Figure 4, p.40. The orifice section was constructed in the same manner as the rest of the ductwork.

Test Procedure

Before proceeding with the actual tests on the washer, it was necessary to determine the size of sharp-edged orifice that could be used in order to give a pressure drop across the orifice within the range of the test instruments and for the desired air flow rates. The pressure drop across the orifice was calculated for various orifice diameters at several different rates of air flow. The flow formula (4, pp.91-93) and table of resulting calculations appear in Appendix, Table 1, p.70.

Preliminary tests with a 27-inch hardboard orifice indicated that the air resistance through the systems was quite large. It was desirable to keep the air resistance at a minimum and yet keep within the range of the instruments. It may be seen from Figure 9, p.51, that, for the desired range of pressure drop, 0.05 to 0.3 inches of water, an orifice diameter of approximately 24 inches would give the desired range of air flow, 1500 to 4000 cfm. A 24 1/8-inch orifice plate was constructed and used during the tests for the purpose of determining the air flow.

The flow of water through the nozzles was determined by the use of a weigh tank, scales, and stop-watch in conjunction with a flow regulating valve and pressure gage at the inlet to the spray header. The water was pumped from the weigh tank to the nozzles by the circulating water pump. The time was recorded for the pump to remove 200 pounds of water from the weigh tank for a particular pressure at the nozzles. This was done for several different pressures by regulating the flow with the valve which

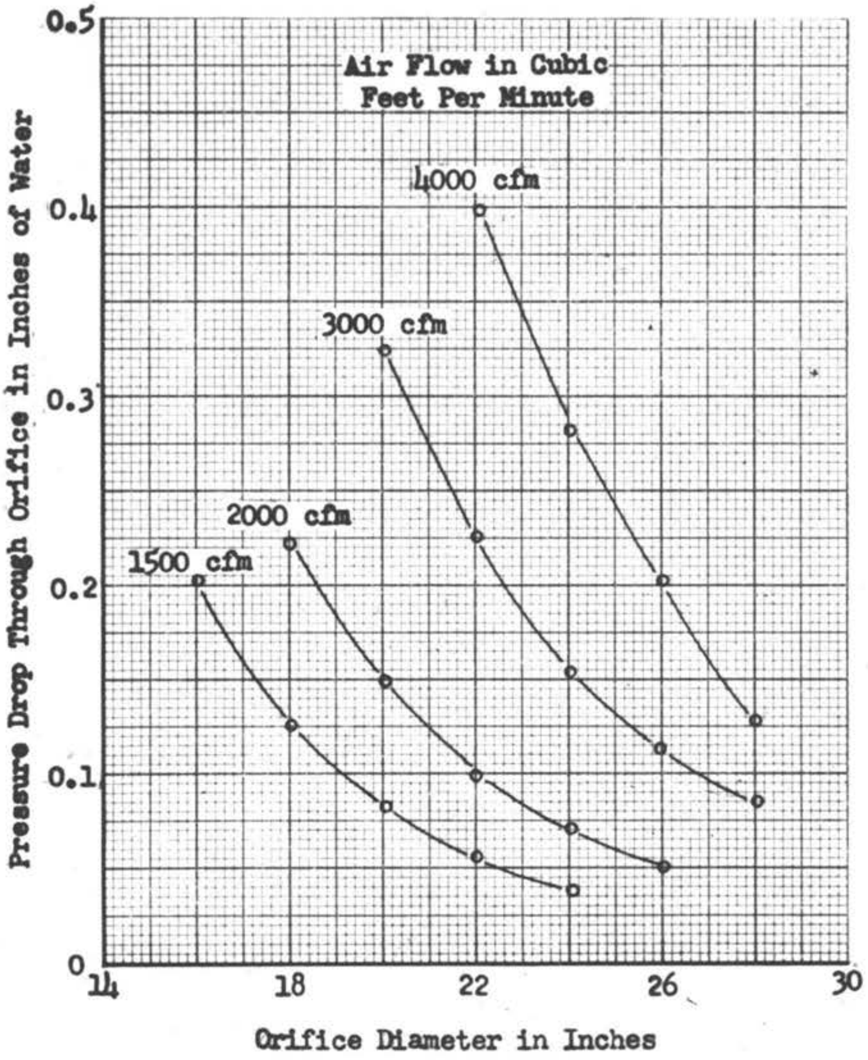


Figure 9. Air Flow Through Orifices of Different Sizes at Various Pressure Drops

preceded the pressure gage. The rate of water flow was converted to gallons per minute (gpm) and the resulting data appears in Appendix, Table 2, p.72. The data, plotted with pressure at the nozzles as ordinate and the water flow as abscissa, appears in Figure 10, p.56, in comparison with the manufacturer's rating of the nozzles.

The air resistance through the washer was tested, the resulting data being tabulated in Appendix, Table 3, p.73. The data is presented in Figure 11, p.58, with total washer resistance, eliminator resistance, and cell resistance as ordinates versus the air flow through the washer as abscissa. The data is also compared with the manufacturer's ratings of resistance.

During the first resistance tests, the tank was maintained full of water and the sprays were not operated. All instruments were checked at a zero reading before each test was started. The fan was turned on and readings were taken from all instruments for different rates of air flow. The air cut-off plate was used to vary the air flow by reducing the area of the fan discharge. Tests were run with the washer complete, without the eliminators, without the cells, and without both the eliminators and the cells.

The washer resistance was the difference between the readings of static pressure at the inlet and outlet of the washer. The resistance of the washer without the eliminators and cells was negligible.

The air flow was determined from the formula in Appendix, Table 1, p.70.

Additional resistance tests were run in the same manner as the first but with different quantities of spray water. This data is presented in Appendix, Table 3, p.73. It was not necessary to plot this data because any resistance increase caused by the spray water was negligible.

The saturating effectiveness of the washer was tested with runs similar to those for the washer resistance tests with variable spray flow. The spray water was allowed to circulate until it was essentially the same as the entering wet-bulb temperature. Then simultaneous readings were taken from all instruments for given quantities of air and water flow. This was done for several different water quantities and four different air rates. Sufficient time was allowed, after each setting of air and water flow, for the instruments to reach an equilibrium position.

The saturating effectiveness was calculated by the formula on p.27 and the air flow by the formula from Appendix, Table 1, p.70.

The data was tabulated as shown in Appendix, Table 4, p.75. Saturating effectiveness for a given water flow at a particular air rate was plotted as shown in Figure 12, p.60.

Hot water was allowed to recirculate through the washer in order that final air conditions at varied water temperatures could be investigated. The same was done with cold water. The tests were run in the same manner as the saturating effectiveness tests except that readings were taken for one rate of air flow at one spray water flow as the temperature of the water decreased in the case of the hot water and increased in the case of the cold water. The resulting data is tabulated in Appendix, Table 5, p.76, and was plotted as shown in Figure 13, p.62.

All humidity determinations from the wet-bulb and dry-bulb temperatures were obtained from the psychrometric chart referred to on p.5. The barometer readings during the tests were so close to the standard that the variation was considered negligible. Therefore, there were no corrections for deviations of pressure.

CHAPTER VII

DISCUSSION OF RESULTS

The quantity of air flowing through the air washer at a particular instant was determined from the flow formula appearing in Appendix, Table 1, p.70. The air flow ranged from 1500 to 4000 cfm, being limited to the lower value because of inaccuracy in reading of the test draft gage pressure drops at low rates of flow. The air flow of 4000 cfm as the upper limit was determined by the air resistance preceding the fan. The fan developed a capacity of 3000 cfm at one inch of water pressure. The total resistance preceding the fan was slightly less than this, giving a maximum capacity slightly greater than 3000 cfm.

The characteristic curve of the flow from the 12 spray nozzles is shown in Figure 10, p.56. The curve illustrates agreement with the manufacturer's specifications. The spray water flow for all the tests was determined from this curve, the nozzle pressure having been recorded during the test runs.

It is apparent from the spray nozzle flow curve that the circulating water pump capacity was not great enough to reach the 36 gpm maximum flow at which the manufacturer rates the washer. The maximum available pressure at the spray nozzles was 6.5 psi giving a flow of 26.5 gpm. It

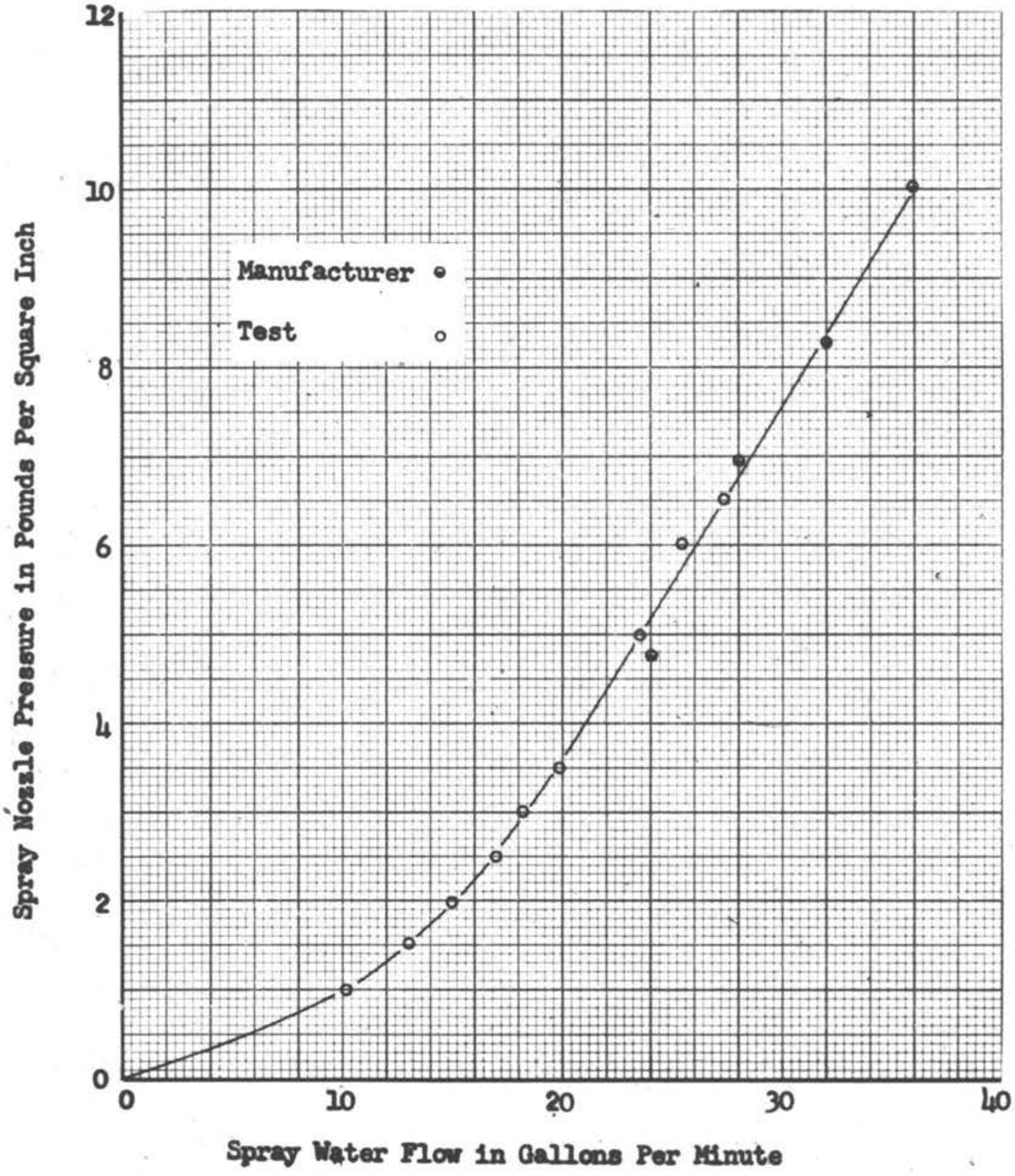


Figure 10. Capillary Air Washer Spray Nozzle Flow Characteristics

was noted, however, that the capillary cells appeared sufficiently covered with the spray at two psi or 15 gpm. Thus, the pump capacity was sufficient for test purposes.

The maximum city water pressure available at the nozzles was only 3.5 psi or 20 gpm because of the pressure drop in the water line. This capacity was sufficient to wet the cells but was not great enough for determining the effect of variable water flow at capacities above the minimum cell coverage. Therefore, the city water was first supplied to the washer tank and then circulated by the water pump.

The air resistance through the completely assembled washer, the eliminator plates, and the capillary cells, as well as any increase in resistance caused by the spray water, was of interest. These resistances, at several different rates of air flow, are presented in Figure 11, p.58.

It is apparent from Figure 11 that the eliminators cause approximately two-thirds of the air resistance through the air washer, the remaining one-third being chargeable to the capillary cells. The washer resistance without the eliminators and mats was negligible by test.

The water spray caused no additional increase in the air resistance through the washer as seen in Appendix,

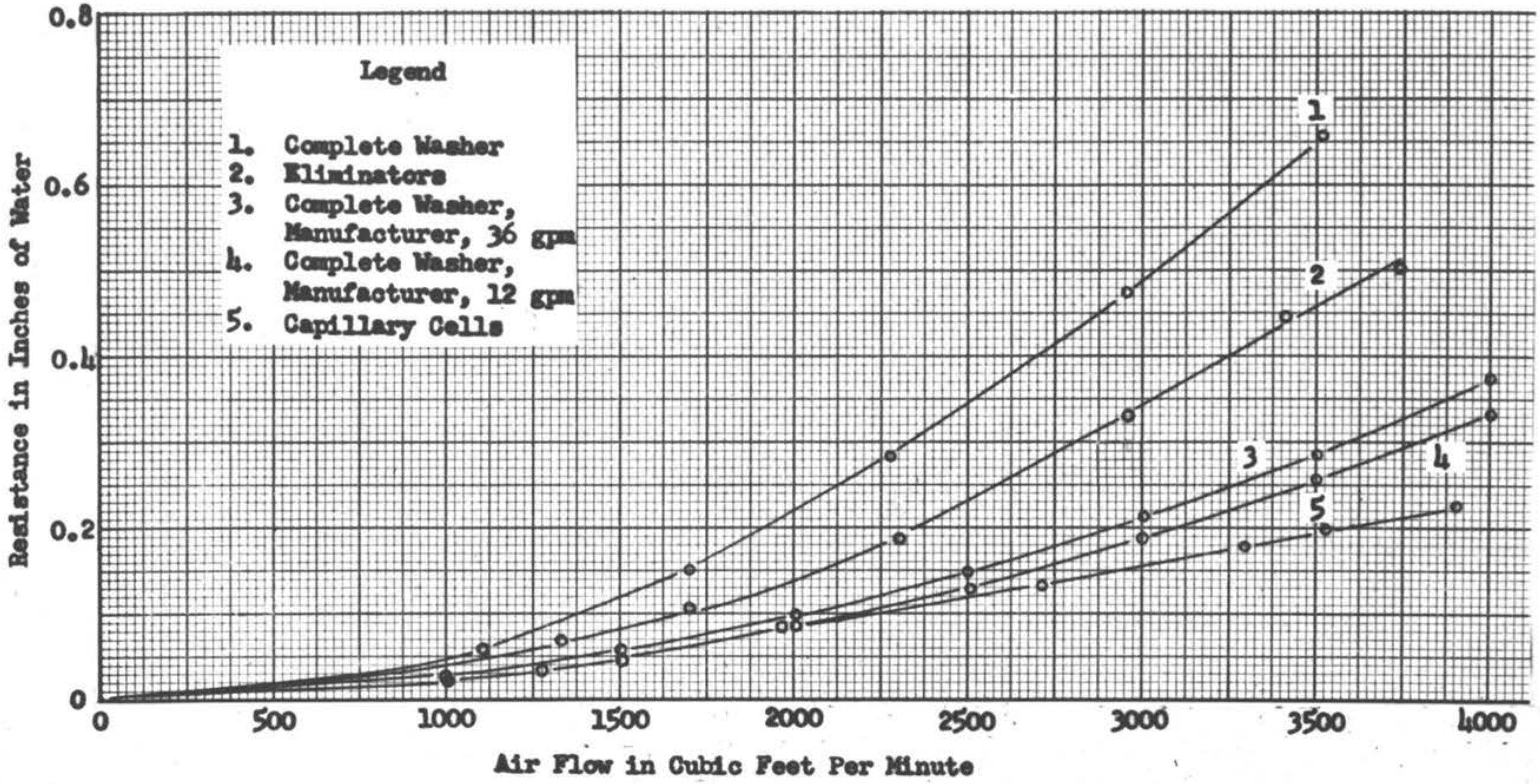


Figure 11. Capillary Air Washer Resistance

Table 3, p.73. This was found to be true for spray water flow rates up to the maximum available in the laboratory.

The air resistance of the complete washer is seen to be 0.5 inches of water pressure at 3000 cfm as compared to the manufacturer's rating of approximately 0.2 inches of water pressure at the same air rate. This result is disturbing and must be thoroughly investigated because the complete laboratory unit was designed from the manufacturer's information on ratings. An attempt must be made to decrease the washer resistance, mainly caused by the eliminators as previously stated, or a fan of greater capacity must be provided. It is possible to speed up the existing fan to obtain greater air flow.

Appendix, Table 4, p.75, shows that the spray water temperature became essentially the same as the inlet air wet-bulb temperature when it was allowed to circulate without heating or cooling from an external source. Thus, the process was one of adiabatic saturation as previously described (p.9).

The resulting data from the adiabatic saturation tests are illustrated in Figure 12, p.60. It is apparent that the saturating effectiveness of the air washer is inversely proportional to the air flow and increases with an increase in the spray water rate up to 36 gpm.

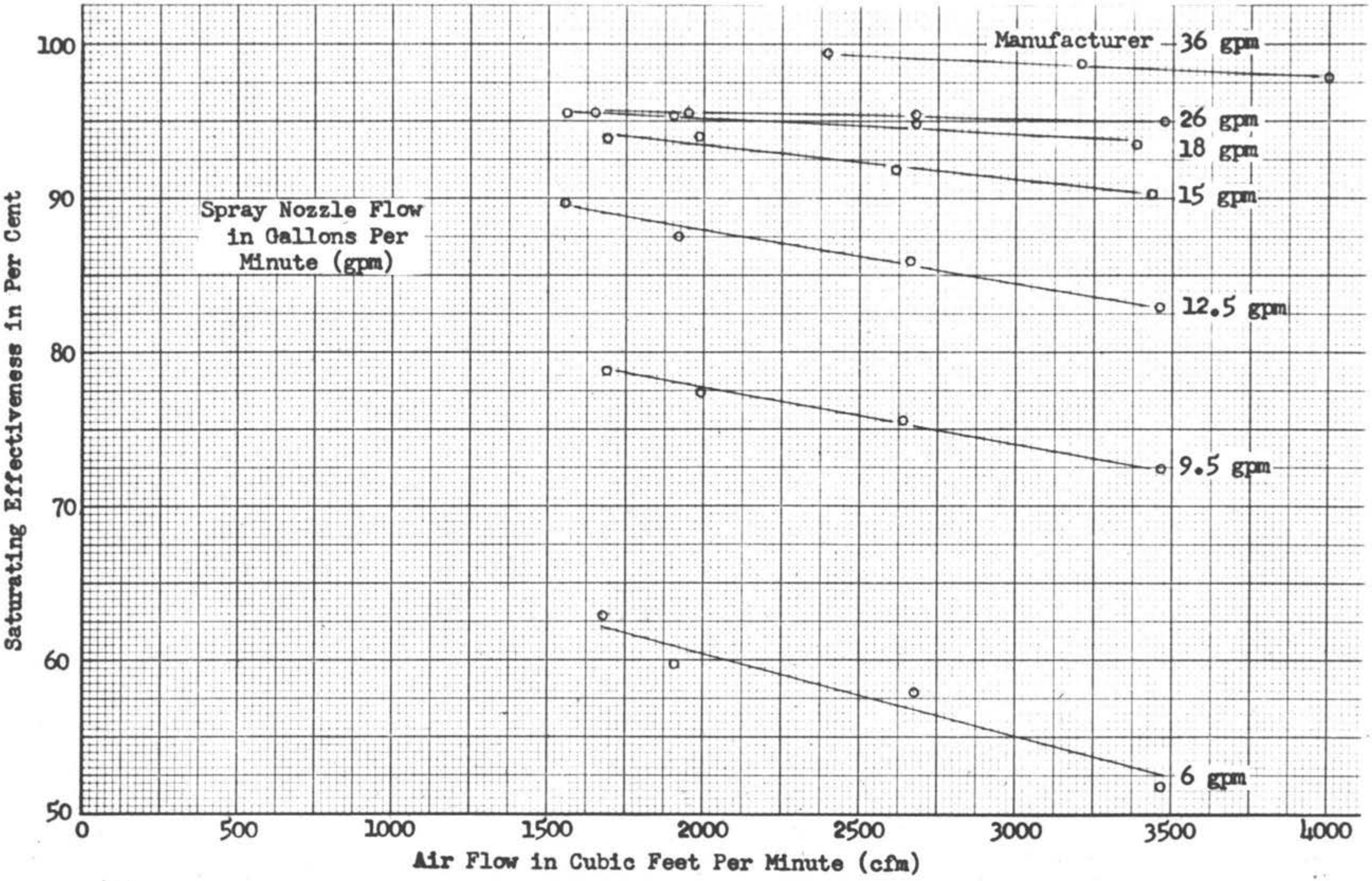


Figure 12. Capillary Air Washer Saturating Effectiveness

The saturating effectiveness begins to level off at about 15 gpm water flow which was the observed flow for complete coverage of the capillary cells with the water. It is, therefore, essential that the cells be thoroughly covered, if high effectiveness is to be attained.

It can be seen from Figure 12 that the saturating effectiveness ranges from 90 to 95 per cent between 1500 and 3500 cfm air flow over the range of 15 to 26 gpm water flow. Thus, it appears feasible that the effectiveness would possibly approach the manufacturer's rating if the spray water flow was increased to 36 gpm.

The deviation of the points from the curves of Figure 12 were caused by inaccurate readings of the thermometers. The thermometers for indicating the wet-bulb temperatures were calibrated in one-half degree increments, and the remaining thermometers in one degree increments. The readings were estimated to the tenth of a degree because of the small differences in temperature between the inlet and leaving conditions. Therefore, errors were encountered.

The test results obtained with variable spray water temperatures at constant air flow and spray water rate are presented in Figure 13, p.62.

The air flow was held constant at approximately 3500 cfm and the water flow was held at 25.5 gpm. These rates

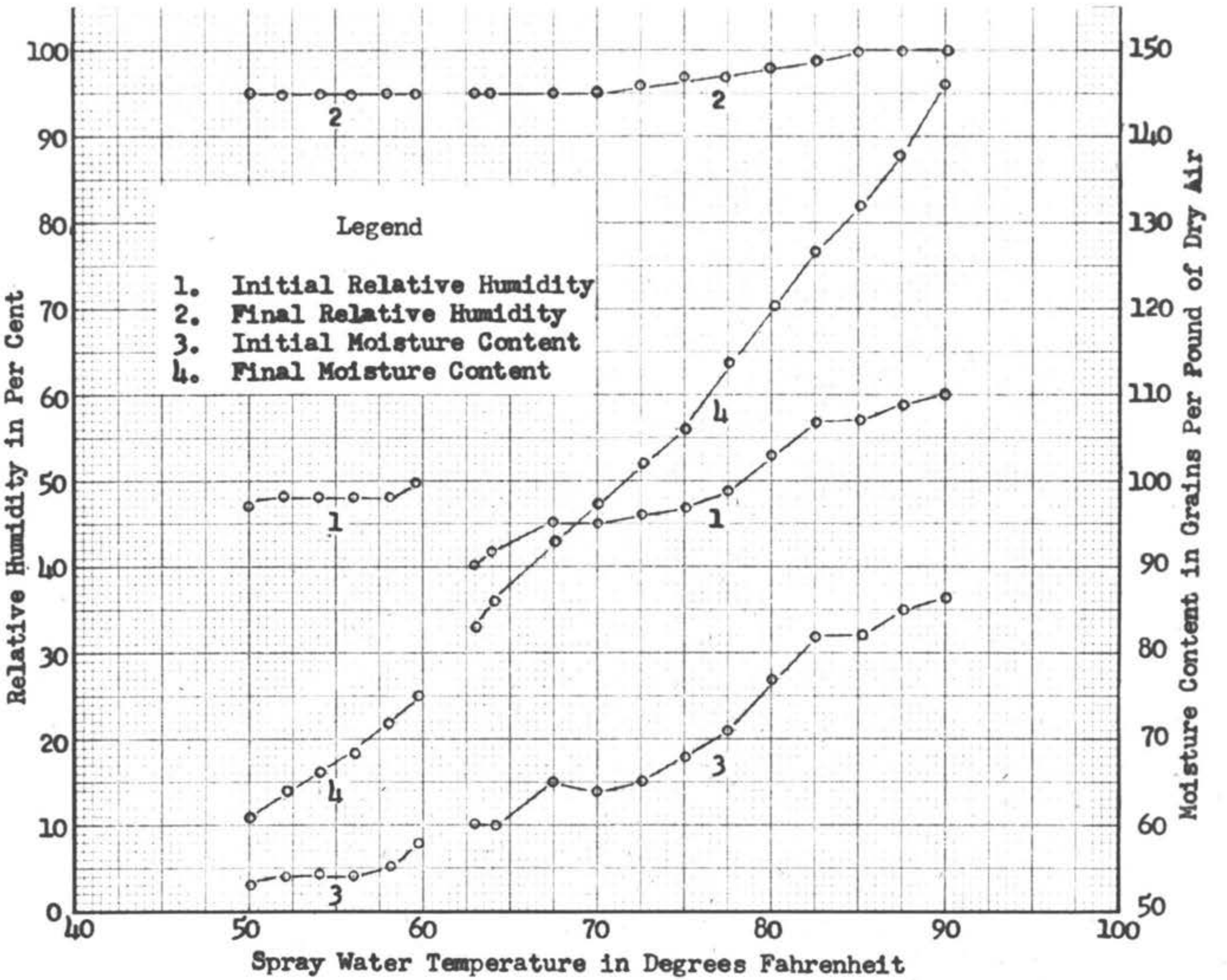


Figure 13. Variable Water Spray Temperature Tests

were approximately the maximum capacities of the unit as tested.

Figure 13 shows that the final relative humidity increases slightly at high temperatures to 100 per cent from 95 per cent over the remainder of the range covered by the tests. This could possibly be slightly improved by increasing the water flow and/or decreasing the air flow.

The curves showing moisture content indicate that high humidification of air is possible in the washer but actual dehumidification would be slight without actually applying refrigeration to cool the spray water. Obviously, the spray water temperature can never be lower than 32° F for the water would then be frozen. No dehumidification occurred in the test runs because water of low enough temperature was not available. An increased amount of cold spray water would have reduced the moisture content somewhat. Reducing the air flow would have had the same effect.

Higher humidification and even heating of the air would have been accomplished by increasing the quantity of heated spray water and/or decreasing the air flow.

The noticeable increases in the moisture content and relative humidity of the entering air with an increase in water temperature were caused by changes in the wet-bulb temperature of the entering air. These changes were caused backsplash of the spray water into the region of the wet-bulb thermometer, by recirculation of the discharged air, and by steam in the air escaping from other laboratory machinery. The situation could not be alleviated without extensive altering of the test unit. Equipment for controlling the air entering the air washer will provide a means of obtaining more accurate and extensive results.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

The test results on the capillary air washer thus far seem to justify the following conclusions:

1. The capillary air washer is more efficient than the ordinary air washer of comparable size. The saturating effectiveness in adiabatic saturation and the final relative humidity obtainable throughout the washer's range of operation are higher than the ordinary air washer of comparable size and same number of spray banks because of the greater contact of the air with the water in the capillary cells.

2. The air resistance through the washer is caused mainly by the eliminator plates. The eliminator plates could possibly be spaced farther apart, have only two air bends, and only one hook. This would cut down the air resistance considerably. It might even be feasible to leave the eliminator plates out entirely. The amount of entrained moisture in the air is negligible because the droplets of spray rate falling from the cell are large.

3. There is considerable backsplash of spray water at the washer inlet when operating with high rates of water flow. It would be advisable to baffle this

moisture. The baffles could also serve to evenly distribute the air entering the washer.

4. The washer could be run on an on-off basis because the capillary cells remain wet for a considerable length of time after the spray water has been shut off.

5. Observation windows at the front and rear of the washer and a marine light are desirable accessories for a laboratory test washer. It is desirable to see the spray action both as it enters and leaves the washer.

6. In further investigations, it would be desirable to be able to read the thermometers more accurately than was done for this project. Thermometers calibrated to tenths of a degree would be good.

7. A large pulley should be installed on the fan motor for future tests. The fan must have an increased capacity in order to overcome the increased resistance to be encountered when additional test equipment and ductwork are installed. A variable speed pulley could be used to give a range of suitable capacities for different tests.

8. The spray flow should be increased in order to determine the capacity of the capillary cells. A capacity could be reached when the cells would become clogged and water carryover would occur.

9. Washer maintenance is important. Frequent cleaning and occasional repainting of the tank is necessary.

The complete laboratory test unit will contain all the equipment which is needed to simulate any possible inlet air condition and the equipment necessary to modify that air to any desired final condition. It will be necessary to completely investigate all aspects of the air washer in order to determine the necessary equipment that will be needed and the capacity of such equipment.

The following are projects which will need to be contemplated before the laboratory unit can be considered complete:

1. The investigation of various types and combinations of eliminator plates to see if the washer resistance can be decreased.

2. Washer reaction to varied inlet air conditions in order to note the action of the washer under all possible conditions.

3. Investigation of possible on-off operation as an economy measure.

4. The air cleaning efficiency of the air washer for use in industrial dust elimination and for human comfort.

5. The possible types of controls that could be used and would be necessary for the operation of the unit and the desirable locations of such controls.

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APPENDIX

Table 1

Air Flow and Orifice Calculations

Formulae	Symbols	Units	Definitions
$Q = CAV$	Q	ft^3/min	Air flow
	C	0.6	Coefficient of discharge
	A	ft^2	Area
	V	ft/min	Velocity
$A = \frac{\pi d_o^2}{4}$	d_o	ft	Orifice diameter
$V = 60\sqrt{2gh}$	g	32.2 ft/sec^2	Acceleration of gravity
	h	ft of H_2O	Pressure head
$h = 3.91 \frac{\Delta P_o T_a}{P_b}$	ΔP_o	in. of H_2O	Pressure drop through orifice
	T_a	R^o	Absolute temperature
	P_b	in. H_g	Barometric pressure

Resulting equations by substitution and simplification:

$$Q = 450\, d_o^2 \sqrt{\frac{\Delta P_o T_a}{P_b}}$$

$$Q = 1820 \sqrt{\frac{\Delta P_o T_a}{P_b}}$$ for 24 1/8 in. orifice

$$\Delta P_o = \left[\frac{V}{4005}\right]^2$$ for air at standard conditions

Table 1 (Cont.)

Air Flow and Orifice Calculations

Q cfm	d_o in.	V fpm	P_o in. H_2O
	16	1800	0.202
	18	1415	0.125
1500	20	1140	0.082
	22	950	0.056
	24	795	0.039
	18	1890	0.223
	20	1520	0.149
2000	22	1270	0.100
	24	1060	0.07
	26	900	0.05
	20	2280	0.325
	22	1900	0.225
3000	24	1590	0.158
	26	1350	0.114
	28	1175	0.086
	22	2530	0.400
4000	24	2120	0.282
	26	1800	0.202
	28	1560	0.153

Table 2

Spray Nozzle Flow

1. Manufacturer's Rating (2, p.5)

Flow gpm	Pressure required at nozzles psi
24	4.77
28	6.93
32	8.29
36	10.00

2. Test Data - At 50° F Water Temperature

Flow gpm	Pressure required at nozzles psi
10.1	1.0
13.0	1.5
14.9	2.0
17.0	2.5
18.1	3.0
19.8	3.5
23.5	5.0
25.5	6.0
26.5	6.5

Table 3

Resistance Tests

1. Manufacturer's Rating

Air Flow cfm	Washer Resistance 12 gpm in. H_2O	Washer Resistance 36 gpm in. H_2O
0	0	0
1000	0.021	0.023
1500	0.046	0.052
2000	0.083	0.093
2500	0.129	0.145
3000	0.187	0.21
3500	0.254	0.286
4000	0.331	0.372
4400	0.40	0.45

2. Test Data - Using 24 1/8 in. Orifice

Air Flow cfm	Washer Resistance in. H_2O
Complete Washer	
0	0
1100	0.058
1700	0.15
2280	0.285
2950	0.473
3500	0.655
Eliminators only	
0	0
1320	0.063
1700	0.105
2290	0.19
2950	0.329
3400	0.447
3720	0.501
Mats only	
0	0
1270	0.034
1965	0.083
2710	0.13
3300	0.178
3530	0.193
3900	0.222

Without Eliminators and Mats
Negligible resistance over air flow range

Table 3 (Cont.)

Air Flow cfm	Washer Resistance in. H_2O
Complete Washer Over Entire Spray Flow Range	
3460	0.641
2650	0.401
1910	0.220
1670	0.168

Table 4

Saturating Effectiveness Tests

1. Manufacturer's Rating (2, p.7)

Effectiveness is inversely proportional to air flow.

Air Flow cfm	Sat. Eff. at 36 gpm Per cent
2400	99.4
3200	98.6
4000	97.8
4400	99.4

2. Test Data - Using 24 1/8 in. Orifice, P_b = 29.79 in. Hg

Temperatures - Degrees F							
Dry-bulb Initial	Wet-bulb Initial and final	Dry-bulb Final	Water	Final relative humidity Per cent	Air flow cfm	Sat. eff. Per cent	Water flow gpm
78.1	64.4	71.0	65.0	71	3460	51.8	6
78.2	64.4	70.2	65.5	74	2680	58.0	
78.3	64.4	70.0	65.5	76	1910	59.8	
78.2	64.4	69.5	65.5	78	1670	63.0	
78.1	64.2	68.0	65.0	82	3460	72.5	9.5
77.9	64.1	67.5	64.9	85	2620	75.5	
77.9	64.4	67.4	65.0	87	1970	77.5	
78.0	64.3	67.2	65.0	88	1670	78.8	
77.9	64.3	66.6	64.9	90	3460	83.0	12.5
77.8	69.2	66.1	64.9	91	2650	86.0	
77.5	64.3	65.9	64.9	93	1910	87.5	
77.2	64.4	65.6	64.9	95	1540	89.7	
77.7	64.2	65.5	64.8	94	3420	90.3	15
78.0	69.0	65.1	64.8	95	2590	92.0	
77.5	64.4	65.2	64.8	96	1970	93.8	
77.6	64.4	65.2	64.8	96	1670	93.8	
79.1	65.3	66.2	65.5	95	3380	93.5	18
78.9	65.3	66.0	65.5	96	2660	95.0	
78.8	65.4	66.0	65.5	96	1910	95.5	
78.6	65.9	66.0	65.5	96	1540	95.5	
77.0	61.0	61.9	61.0	96	3460	95.0	26
76.6	61.0	61.8	61.0	96	2660	95.5	
76.6	61.0	61.8	61.0	96	1950	95.5	
76.6	61.0	61.8	61.0	96	1640	95.5	

Table 5

Variable Spray Water Temperature Tests

Test Data - 6 psi or 25.5 gpm at 3500 cfm, P_b = 29.70 in. Hg

Temperatures - Degrees F					Relative humidity Per cent		Moisture content Grains per lb dry air	
Initial		Final						
Wet-bulb	Dry-bulb	Wet-bulb	Dry-bulb	Water	Initial	Final	Initial	Final
Heated Spray Water								
68.0	78.0	78.0	78.0	90.0	60	100	86	146
67.7	78.0	76.5	76.5	87.5	59	100	85	138
67.0	78.0	75.0	75.0	85.0	57	100	82	132
67.0	78.0	74.0	74.1	82.5	57	99	82	127
66.1	78.5	72.5	73.0	80.0	53	98	77	120
65.0	78.5	71.0	71.5	77.5	49	97	71	114
64.4	78.7	69.0	69.5	75.0	47	97	68	106
64.0	78.7	68.0	68.7	72.5	45	96	65	102
63.8	79.0	66.8	67.5	70.0	44	95	64	97
64.0	79.1	65.5	66.3	67.5	44	95	65	93
63.0	78.9	63.4	64.2	64.0	42	95	60	86
62.6	78.1	62.6	63.3	63.0	40	95	60	83
Cooled Spray Water								
58.5	71.1	54.1	55.0	50.0	47	95	53	61
58.9	71.3	55.0	55.7	51.0	48	95	53	63
58.9	71.0	55.2	56.0	52.0	48	95	54	64
58.7	70.9	55.6	56.5	53.0	48	95	54	64
58.9	71.0	56.2	57.0	54.0	48	95	54	66
58.9	71.1	56.7	57.5	55.0	48	95	54	67
58.9	71.1	57.3	58.1	56.0	48	95	54	68
59.0	71.3	57.8	58.6	57.0	48	95	55	70
59.0	71.1	58.3	59.0	58.0	48	95	55	72
59.5	72.0	59.5	60.0	59.0	48	95	56	75
59.8	71.4	59.6	60.2	59.6	51	95	58	75