tional blade type or glass mat eliminators. With water drainage provided for each cell tier, most of the stratification found in spray-type washers is avoided.

An essential requirement of operation of this type of air washer is good distribution of water over the face of the cells. When compared with conventional spray-type washers, the water requirements are much lower, approximately 4 gpm per 1000 cfm for ordinary washing and evaporative cooling, and the pumping head is approximately one-half the head of conventional spray-type washers.

Humidification with Air Washers

Air humidification can be accomplished in three ways with an air washer. These are: (1) use of recirculated spray water without prior treatment of the air; (2) preheating the air and washing it with recirculated spray water; and (3) using heated spray water. In any air washing installation the air should not enter the washer with a wet-bulb temperature less than 35 F. This is a precaution to eliminate the danger of freezing the spray water.

Method 1. Except for the small amount of energy added from outside by the recirculating pump in the form of shaft work, and for the small amount of heat leakage from outside into the apparatus, including the pump and its connecting piping, the process would be strictly adiabatic. Evaporation from the liquid spray would therefore be expected to bring the air immediately in contact with it to saturation adiabatically; and, since the liquid is recirculated, its temperature would be expected to adjust to the thermodynamic wet-bulb temperature of the entering air.

It does not follow from the foregoing reasoning that the whole air stream is brought to complete saturation, but merely that its state point should move along a line of constant thermodynamic wet-bulb temperature as explained in Chapter 3. The extent to which the leaving air temperature approaches the thermodynamic wet-bulb temperature of the entering air, or the extent to which complete saturation is approached, is conveniently expressed by a ratio known as humidifying effectiveness or saturating effectiveness, and is defined in Equation 1 as

$$e_s = \frac{t_1 - t_2}{t_1 - t'} \times 100 \qquad (1)$$

where

e_s = humidifying or saturating effectiveness, percent.
t_1 = dry-bulb temperature of the entering air, Fahrenheit.
t_2 = dry-bulb temperature of the leaving air, Fahrenheit.
t' = thermodynamic wet-bulb temperature of the entering air, Fahrenheit.

The following may be taken as representative of the humidifying or saturating effectiveness of a spray-type air washer for the arrangements stated:

Arrangement	Length Ft	Effectiveness—%
1 bank downstream	4	50-60
1 bank downstream	6	60-75
1 bank upstream	6	65-80
2 banks downstream	8 to 10	80-90
2 banks opposing each other	8 to 10	85-95
2 banks upstream	8 to 10	90-98

The humidifying or saturating effectiveness of a washer is dependent upon the essential items of design mentioned in the section Air Washers. Other conditions being the same, a low velocity of air flow is conducive to high humidifying effectiveness.

Method 2. The preheating of the air increases both the dry- and wet-bulb temperatures, and lowers the relative humidity, but does not alter the humidity ratio (pounds of water vapor per pound dry air). At a higher wet-bulb temperature, but the same humidity ratio, more water can be absorbed per pound of dry air in passing through the washer, assuming that the humidifying effectiveness of the washer is not adversely affected by operation at the higher wet-bulb temperature. The analysis of the process occurring in the washer itself is the same as that explained under *Method 1.* The final desired conditions are secured by adjusting the amount of preheating to give the required wet-bulb temperature at the entrance to the washer.

Method 3. Even if the heat is added to the spray water, the mixing occurring in the washer itself may still be regarded as adiabatic. The state point of the mixture should move in a direction determined by the specific enthalpy of the heated spray as explained in Chapter 3. It is possible, by elevating the water temperature, to raise the air temperature, both dry-bulb and wet-bulb, above the dry-bulb temperature of the entering air.

In each of the methods, 1, 2, or 3, the air leaving the air washer may require reheating to produce in the conditioned space the required dry-bulb temperature and relative humidity.

Dehumidification and Cooling with Air Washers

Lowering of the wet-bulb temperature of an air-vapor mixture can be accomplished by an air washer if the temperature of the spray water is lower than the wet-bulb temperature of the air. Moisture removal is obtained when the spray water temperature is lower than the dew point of the entering air. In these cases the final dry-bulb temperature and relative humidity of the leaving air are dependent upon the design factors of the air washer.

Both sensible and latent heat are removed in the process of dehumidification by cold spray water. Extraction of sensible heat occurs during the entire time that the air is in contact with the spray medium. Latent heat removal takes place as condensation occurs. Therefore, the lower the spray temperatures, the greater the amount of moisture removal per pound of dry air, all other conditions remaining the same.

Where a limited supply of cold water is available, multiple-stage washers may be used to great advantage. In such washers the cool water is pumped through the multiple spray systems in series and counterflow to the air flow. Such an arrangement brings the delivery air in contact with the coldest water, securing a maximum amount of cooling and saving water.

When using cold well water or water from city water mains, care should be used to secure accurate data on the water temperatures. Table 2 lists some approximate water main averages which may be used as a guide but should be verified from local records. This is particularly true with city water main temperatures. In the case of well water temperatures, Fig. 4 shows the approximate temperatures of water to be expected from wells at depths of 30 to 60 ft.

Air washers for dehumidifying and cooling usually have separate recirculating pumps for each washer. These pumps deliver a mixture of cold and recirculated water under the control of a three-way valve.

Table 2 .... Average Maximum Water Main Temperatures*

State	City	Temp. F	State	City	Temp. F	State	City	Temp. F	State	City	Temp. F
Ala.	Birmingham	84	Iowa	Cedar Rapids	78	N. Y.	Albany	68	Texas	Amarillo	70
	Mobile	80		Des Moines	77		Buffalo	78		Austin	90
Ark.	Little Rock	83		Sioux City	62		Jamaica	56		Beaumont	86
Ariz.	Phoenix	82	Kans.	Concordia	57		Mt. Vernon	74		Dallas	86
	Tucson	80		Kansas City	86		New Rochelle	75		El Paso	85
Calif.	Anaheim	60		Topeka	88		New York	72		Fort Worth	85
	Berkeley	69		Wichita	72		Rochester	70		Galveston	90
	Fresno	80	Ky.	Louisville	85		Schenectady	60		Houston	83
	Fullerton	75	La.	Baton Rouge	85		Syracuse	74		Port Arthur	83
	Glendale	68		New Orleans	90		Utica	69		San Antonio	78
	Los Angeles	80		Shreveport	88		Yonkers	70		Wichita Falls	85
	Oakland	69	Me.	Augusta	60	N. C.	Asheville	74	Utah	Logan	44
	Ontario	70	Md.	Baltimore	75		Charlotte	85		Salt Lake City	65
	Pasadena	82	Mass.	Boston	80		Raleigh	92	Va.	Fredericksburg	75
	Pomona	75		Cambridge	70		Winston-Salem	82		Lynchburg	73
	Riverside	78		Fall River	76	N. M.	Albuquerque	65		Norfolk	80
	Sacramento	72		Lowell	50	Ohio	Akron	76		Richmond	85
	San Bernardino	65		Lynn	68		Canton	50	Wash.	Olympia	58
	San Diego	84		New Bedford	70		Cincinnati	84		Seattle	62
	San Francisco	71		Salem	68		Cleveland	77		Spokane	51
	Whittier	75		Worcester	76		Columbus	84		Tacoma	57
Colo.	Denver	75	Mich.	Detroit	77		Dayton	60	W. Va.	Charleston	85
Conn.	Bridgeport	66		Flint	70		Lakewood	82		Huntington	78
	Hartford	73		Grand Rapids	84		Springfield	72		Wheeling	78
	New Haven	76		Highland Park	77		Toledo	83	Wis.	LaCrosse	54
	Waterbury	72		Jackson	56	Okla.	Oklahoma City	82		Madison	58
D. C.	Washington	84		Kalamazoo	53		Tulsa	86		Milwaukee	75
Del.	Wilmington	83		Lansing	64	Ore.	Eugene	60		Racine	68
Fla.	Jacksonville	86		Saginaw	82		Portland	65			
	Miami	82	Minn.	Duluth	55	Pa.	Altoona	74	Province	City	Temp. F
	Tampa	77		Minneapolis	85		Erie	75			
Ga.	Atlanta	85		St. Paul	80		Johnstown	74			
	Macon	80	Mo.	Jefferson City	82		McKeesport	82			
Idaho	Boise	60		Kansas City	84		Philadelphia	85	Alta.	Calgary	64
Ill.	Chicago	78		Springfield	82		Pittsburgh	86			
	Cicero	76		St. Joseph	84	R. I.	Providence	68	B. C.	Vancouver	60
	Evanston	73		St. Louis	85						
	Moline	83		Springfield	74	S. C.	Charleston	83	Ont.	London	50
	Peoria	67	Nebr.	Lincoln	70		Greenville	81			
	Rockford	59		Omaha	85		Spartanburg	78		Toronto	63
	Springfield	82	Nev.	Reno	70	S. D.	Rapid City	65			
Ind.	Evansville	88	N. H.	Manchester	76				P. E. I.	Charlottetown	48
	Gary	75	N. J.	Jersey City	63	Tenn.	Chattanooga	84			
	Indianapolis	84		Newark	75		Knoxville	90	Que.	Montreal	78
	South Bend	61		Paterson	78		Memphis	85			
	Terre Haute	82		Trenton	79		Nashville	90		Quebec	68

* These averages taken from various city water main locations, with some actual values slightly higher and some lower than values shown. Some values were supplied by H. E. Degler, Marley Company. Some were obtained from City Water Department records. The highest values given by the various authorities are usually those listed.

Performance of an air washer, when cooling and dehumidifying, depends upon a number of factors, among which are:

(1) Air velocity through spray chamber area.
(2) Spray nozzle pressure.
(3) Size factor (larger washers are more efficient than smaller ones).
(4) Spray density (gpm/sq ft/spray bank).
(5) Water temperature rise.
(6) Air wet-bulb temperatures—entering and leaving.
(7) Water-to-air weight ratio.
(8) Water temperatures—entering and leaving.
(9) Length of air washer in direction of flow.
(10) Number and arrangement of spray banks.

Where increase of overall heat transfer between the air