Eliminating Respirable Dust from the Cotton Workplace by Purifying Humidifier Water: A Cost Analysis[1]

M. H. LEONARD, S. P. HERSH, S. K. BATRA, AND C. L. DYER

School of Textiles, North Carolina State University, Raleigh, North Carolina 27650, U.S.A.

ABSTRACT

Vertical-elutriator cotton-dust samplers collect all particles with aerodynamic diameters <15 μm, including those whose origin is not in the cotton supply. One process giving rise to such non-cotton dust particles is the spray-drying of dissolved solids in the water supplied to the plant humidification system. Based on a survey of plant production, ventilation, and ambient conditions, it is shown that a cost-effective strategy for reducing the concentration of "cotton dust" in the atmosphere of textile plants could be to remove the dissolved solids from the water supplied to the humidification system to prevent their release in the plants as respirable dust. It is estimated that when atomizers are used for humidification, dust removal by demineralization of the water supplied to the atomizers can be achieved at a fraction of the cost (1/30th to 1/9th) compared with the cost of removing an equivalent amount of dust by conventional air-filtration technology. For humidification supplied exclusively by air-washer systems, the benefits of supply-water demineralization are not as dramatic.

Introduction

In a 1979 study [10] it was estimated that implementation of the Occupational Safety and Health Administration (OSHA) cotton dust standards (permissible exposure limits (PEL) of 200 μg/m^3 in yarn manufacturing and 750 μg/m^3 in slashing and weaving) would cost the cotton yarn manufacturing and weaving industries approximately $145 million and $24 million annually using conventional dust-control technology. (The 1976 "Inflationary Impact Statement" [11] estimated the total annual costs of meeting the original proposed standards of 200 μg/m^3 for yarn and fabric production to be $241.6 million and $350.1 million, respectively. The promulgated standards increased the PEL in weaving to 750 μg/m^3. The raising of the PEL in weaving was primarily responsible for the cost reductions in the 1979 cost estimates.)

The workplace dust sampled by the vertical elutriator (VE) may consist of components such as "ground-up plant matter, fiber, bacteria, fungi, soil, pesticides, non-cotton plant matter and other contaminants" [12]. Some of these other contaminants may include sizing liberated as a result of abrasion of sized yarns in weaving, minerals originating from the water supplied to plant humidification systems, oils from lubrication of both machinery and fibers, pollen and air pollution from the external make-up air. Since the VE measures all of these components, it may be more economical to reduce the amount of respirable dust present in the cotton workplace by eliminating dusts arising from these extraneous sources rather than by using conventional cotton-dust control technology.

This paper explores the cost of an alternative method of reducing the "cotton dust" concentration—namely, by removing the dissolved solids from the water supplied to the humidification system. It is hoped that this method will offer a means of reducing the cost of meeting the cotton dust standards promulgated by OSHA.

Dust Concentrations Contributed by Humidifiers

WATER SUPPLY AND EVAPORATION

The solids dissolved in the humidifier supply water have been reported to be a major source of the background dust in cotton textile operations [1, 7, 8]. As much as 840 μg/m^3 of respirable dust has been reportedly added to the plant atmosphere when atomizers are used for humidification [7].

Most textile plants use municipal or well water in their humidification systems. The suspended (undissolved) solids in these water sources are very low, but the water may contain a significant quantity of dissolved solids. The municipal water in the southeastern United States ranges from 50 parts per million (ppm) to 250 ppm, with an average of approximately 125 ppm [9]. The concentration varies widely from location to location, with coastal supplies containing higher concentrations. Well water may be within this range or even higher, depending on the depth and type of filtration strata. Surface-water supplies such as from rivers and lakes may also exceed these levels. The use of unfiltered surface water may also introduce undissolved solids into the workplace.

Mineral particles are added to the atmosphere when water containing dissolved solids is evaporated by humidification systems. These devices are of two general types: atomizers and air washers. These systems can be used, separately or together, to maintain the desired humidity in the plant. Older plants use atomizers as the major means of humidification. Newer plants generally utilize air-wash systems for humidification, but they may also employ supplementary atomizers in areas such as winding and weaving, which require higher relative humidities. Although both atomizers and air washers are capable of contributing to the background dust, much smaller amounts are usually contributed by air washers [8].

HUMIDIFICATION SYSTEMS

An *atomizer* humidification system works on the principle of spraying water from a reservoir through a nozzle using compressed air as the propellant. The water is piped to numerous locations where it is discharged as a fine mist by the atomizer spray nozzles. The dissolved solids in the water are "spray-dried" to form particles in the atmosphere [1, 7, 8]. That this occurs is evident from the build-up of dust deposits in the atomizer spray nozzles and on the machinery and floors beneath the atomizers.

The amount of dust introduced by an atomizer humidification system into an environment is dependent on the solids content of the water, the air flow rate in the plant, and the amount of water necessary to maintain the required relative humidity. As an example, consider a weave room equipped with atomizers as the only source of humidification. Assuming a dissolved solids concentration c of 150 ppm, an airflow rate Q_a of 400,000 ft^3/min, and a water consumption rate Q_w of 13 gal/min, the contribution χ to dust concentration would be calculated by the following equation:

$$\chi = \frac{Q_w c}{Q_a} \quad , \tag{1a}$$

or

$$\chi(\mu g/m^3)$$

$$= \frac{133,500 \; Q_w(\text{gal/min}) \times c(\text{ppm})}{Q_a(\text{ft}^3/\text{min})} \quad . \tag{1b}$$

Under these conditions, the concentration of respirable dust added by the atomizers would be 651 μg/m^3. A value higher than this (839 μg/m^3) has been observed in a textile plant using water containing 300 ppm of dissolved solids [7].

Values calculated from Equation 1 are for dust introduced to the recirculated air and must be added to the background dust. If 20% of the dust is not filtered out of the recycled air, the equilibrium contribution would be about 810 μg/m^3. The assumption of 20% particle penetration may be low for installations having poor filtration equipment.

Air-washers are now the most widely used humidification system in the textile industry. The system provides not only temperature and humidity control, but also cleans dust from the incoming air stream, which may consist of a mixture of outside make-up air and recycled air. In the system, air is passed through a spray-wash tank containing many atomizer spray nozzles that saturate the air with water. The air then passes through mist eliminators, which allow only a small fraction of the water droplets to leave the washer. The air is then circulated to the workplace and is recycled back to the air-washer after nominal filtration.

Based on their method of operation, one would expect that the contribution of respirable dust particles to the workplace atmosphere by air-washers to be much less than that from atomizers. The atomized droplets of water added to the air passing through the tank wash most of the solid particles entrained in the incoming air into the water basin

(sump) instead of allowing them to pass into the workplace. Furthermore, it is believed that due to the high volume of water sprayed within the tank, few droplets, if any, are completely evaporated into the air [3]. Indeed, it is believed that most of the dissolved solids stay within the unevaporated nucleus of the droplet as water evaporates from its surface. In addition, very little dust would be added to the workplace air by efficient air-wash systems because, by analogy with cooling-tower operation, only a small quantity of water droplets pass through the mist-eliminators [8]. The concentration of solids in the basin and the droplets of water that do pass through when moisture must be evaporated, however, has been estimated to be four or five times greater than that of the make-up water (see Appendix and Ref. [8]). The concentration of solids increases when the low moisture content of the ambient air requires a large amount of water to be evaporated into the plant air. During summer, when water is actually removed from the workplace and condensed from the make-up air, the concentration of solids in the basin decreases. In addition, chemicals are added directly to the basin as bacteriocides, anti-corrosion agents, antistatic agents, etc. The concentration of these additives is generally less than 50 ppm.

Experimental measurements of the amount of dissolved mineral particles contributed by air-washers has not yet been reported. Thus, the amount contributed must be estimated. As an example, consider again the weave room discussed above, requiring an air flow Q_a of 400,000 ft^3/min, and water having a total dissolved solids concentration c of 150 ppm and a flow rate Q_w of 13 gal/min. Further, assume that a fraction a of the water reaching the mist eliminators is in the form of droplets containing dissolved solids or spray-dried particles, that a fraction b of these droplets actually escapes the mist eliminator into the workplace, and that the concentration of dissolved solids in the recirculating basin water increases by a factor f. The estimated contribution would then be:

$$\chi = cQ_w abf/Q_a \quad , \tag{2a}$$

or

$$\chi \, (\mu g/m^3) =$$
$$133{,}500 c(\text{ppm}) Q_w(\text{gal/min}) abf/Q_a \, (\text{ft}^3/\text{min}) \; . \tag{2b}$$

Values of 0.40 and 0.10 have been suggested for a and b, respectively [3], and as noted in the preceding paragraph, a value of 4 for f is reasonable. Using these values, the contribution by air-washers is estimated to be 104 $\mu g/m^3$, or about 16% of that estimated to be introduced by atomizers under the same conditions.

(Since Q_w is only a small part of the water circulating in the washer, and only a fraction of that ab (0.40 × 0.10 = 0.04) leaves the air washer as droplets containing solids or as spray-dried particles, it is evident that solids introduced in the workplace are only a tiny fraction of that circulating in the washer.)[2]

FACTORS INFLUENCING WATER CONSUMPTION

The quantity of water necessary to maintain the required atmospheric conditions in the workplace is a function of those conditions, together with the outside ambient conditions, the workplace ventilation air-flow rate, the fraction of make-up air used, and the internal moisture leakage.

The atmospheric conditions desired in the workplace vary from one production area to another depending on the nature of fibers being processed and their interaction with the processing machinery. To determine typical ambient conditions used in actual practice, a survey of eleven plants was made. Information gathered included the temperature, relative humidity (RH), production rate, and air-circulation rate by work area. An attempt was made to determine the amount of water consumed by the plant humidifiers, but this information was not available. A production-weighted average of temperature and RH for selected areas in these plants is listed in Table I.

TABLE I. Average temperature and RH maintained by work area in survey of textile plants.

Workplace	No. of plants	Temperature, °F (°C)	RH, %
Opening-Roving	11	77.5 (25.5)	49.5
Ring Spinning	9	80.9 (27)	42.3
Open-end Spinning	2	76.9 (25)	52.0
Winding	11	78.3 (25.5)	53.2
Weaving	6	76.2 (24.5)	74.7

Weather or seasonal conditions also play a role in determining the quantity of water necessary to maintain steady-state conditions in the workplace. During summer months the outside temperatures and humidity are often higher than those required in the workplace. Thus, air conditioning and dehumidification become necessary. Consider the situation in which a temperature of 80°F (27°C) and an RH of 50% is desired. In the southeastern United States, where

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[2]The authors are grateful to the reviewer for suggesting this clarification.

summer temperatures and relative humidities are frequently higher than this, the make-up air will have to be cooled and dehumidified. Under these conditions the contribution of dissolved mineral particles to the respirable dust levels would be minimal. Indeed, when operating in this condensing mode, large quantities of water are removed from the system.

On the other extreme, during winter months, the outside temperature and humidity are much lower than those desired in the workplace. Thus significant quantities of water must be added to the make-up air. As larger quantities of water are needed, greater amounts of dissolved solids are contributed to the respirable dust in the plant.

Another factor determining water consumption is the degree of change or "internal leakage" in the recycled workplace air. Both humidity and temperature are changed during fiber processing. Depending on the nature of fibers being processed, moisture may be absorbed or desorbed by fibers, yarns, and fabrics, which may require additional water to be evaporated or condensed to maintain the desired steady-state conditions. The thermal load of machinery and employees would also have to be considered in any accurate calculation of the moisture balance in the plant.

ESTIMATION OF WATER REQUIREMENTS AND DUST CONTRIBUTED BY HUMIDIFIERS

In order to compare the costs of controlling dust by water-demineralization with those of using conventional dust-control technology, it is necessary to estimate water consumption in plant-humidification systems. Total water consumption in a plant is known, but generally companies do not meter usage in different areas separately. Consequently a method of estimating humidifier water requirements is necessary. The scheme employed here is outlined below.

In any plant workplace the desired temperature and relative humidity as well as air-flow rates are usually known. To determine the water requirements to maintain the desired conditions over a specific time interval, one then needs to know: 1) the make-up fraction of outside air, and 2) the average (or suitably-weighted average) temperature and RH of the outside air over the specified interval (which can be obtained from the Environmental Data Service [6]).

For a typical plant, it is reasonable to assume the make-up air fraction as 30%, of which 20% is due to the designed ventilation conditions (including air leakages), and 10% due to moisture absorption by the

fibers being processed. To estimate the water requirements for a cardroom during the month of December, consider the following conditions:

Desired temperature, 80°F (27°C)
Desired RH, 50%
Air-flow rate, 150,000 ft^3/min
Specific volume of air, 13.84 ft^3/lb
Outside air temperature, 40°F (4.5°C)
Outside air dew point 29°F (63% RH)
(Average conditions during December for Greensboro, NC [6])

From psychrometric charts [5] it can be shown that one lb (.45 kg) of outside air requires the addition of 54 grains (3500 mg) of water vapor to achieve 50% RH at 80°F. The amount of water required can be calculated from the relationship

$$Q_w = \Delta m \, Q_a \phi / \overline{V}_a \quad , \tag{3a}$$

where Δm = mass of added water required per unit mass of outside air, ϕ = fraction of make-up air, and $\overline{V}_a$ = specific volume of air. The other symbols are the same as defined earlier. For specified units, Equation 3a becomes

$$Q_w(\text{gals/min}) = \frac{\Delta m(\text{grains } H_2O/\text{lb of air}) \, \phi \, Q_a(\text{ft}^3/\text{min})}{58310 \, \overline{V}_a(\text{ft}^3/\text{lb})} \tag{3b}$$

for 30% make-up air, the amount of water required is 3.01 gallons per minute (190 cm^3/s).

Based on the above procedure, the water requirements per lb of material processed have been estimated for different areas of the plants surveyed. Data are listed separately (see Table II) for work areas humidified by air-washers, air-washers with supplemental atomizers, and by atomizers only. Also listed are the airflows per lb of material being processed. From these data the dust concentration contributed by atomizers and air-washers can then be estimated using Equations 1 and 2, respectively.

The data in Table II indicate that the airflow rates in plants using atomizers to provide supplemental ventilation is about one-half that of plants using only air-washers. For the one weave room in the survey using only atomizers to provide humidification, the airflows were about one-fourth that of the weave rooms using air-washers.

The calculated water-consumption rates for plants surveyed using air-washers are shown in Figure 1. The deviations from linearity result from variations in RH

TABLE II. Airflow and calculated humidifier-water requirements per pound of fiber processed by workplace in plants using air washers. (Plants using supplemental atomizers in parenthesis.)

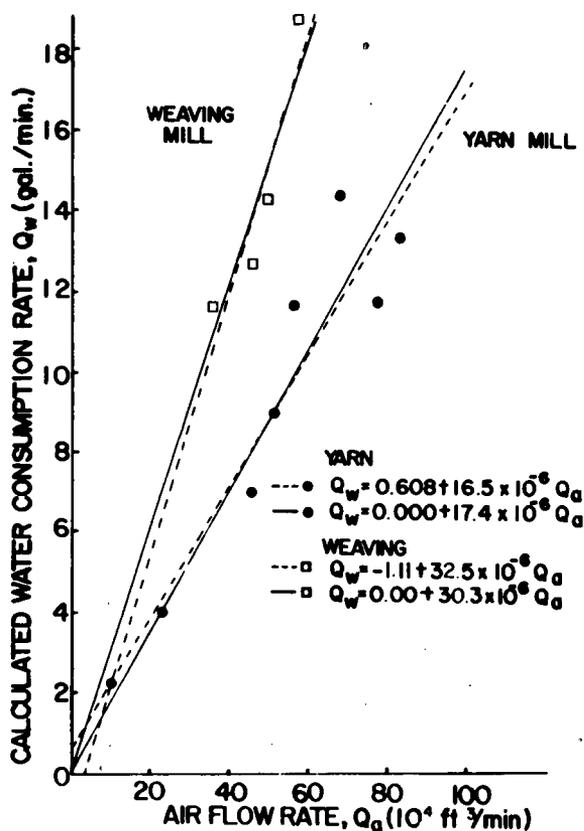| Workplace | No. of plants | Airflow/lb of fiber | | Waterflow/lb of fiber | |
		Mean, ft³/lb	C.V., %	Mean, gal/lb	C.V. %
Opening-Roving	9	6,190	12.4	0.120	21.2
	(1)	(3,320)	—	(0.067)	
Spinning	7	13,950	18.4	0.226	19.2
	(1)	(6,950)	—	(0.101)	—
Winding	5	2,087	17.7	0.043	26.1
	(3)	(1,420)	(18.9)	(0.0325)	(41.3)
Yarn Plant Total	8	21,640	16.9	0.382	14.9
Weaving	4	15,520	27.5	0.472	32.2
	(1)	(6,880)	—	(0.191)	—
	(1)ᵃ	(3,130)ᵃ	—	(0.087)ᵃ	—

ᵃAtomizers only

FIG. 1. Calculated water-flow rates required to obtain desired humidities in yarn and weaving plants using air-washers as a function of air-flow rate.

and temperature levels maintained in the individual plants. The least-square regressions of water consumption as a function of airflow rates for spinning and weaving mills were found to be:

Spinning $\quad Q_w = 0.519 + 1.65 \times 10^{-5} Q_a$; (4)

Weaving $\quad Q_w = 1.11 + 3.25 \times 10^{-5} Q_a$. (5)

The intercepts of Equations 4 and 5 should be zero, since, as shown by Equation 3, with zero airflow no water would be required. The intercepts are indeed not significantly different from zero; hence the regression equations were recalculated with zero intercepts to give:

Spinning $\quad Q_w = 1.74 \times 10^{-5} Q_a$; (6)

Weaving $\quad Q_w = 3.03 \times 10^{-5} Q_a$. (7)

The ratio Q_w/Q_a of water-flow to air-flow rates given in Equations 6 and 7 (*i.e.*, the slopes of the regression equations with zero intercepts) were used to calculate the dust concentration added to the plant atmosphere by atomizers and air-washers for water containing 50, 120, and 250 ppm dissolved solids. The results are presented in Table III. The table also reports the dust added for Q_w/Q_a ratios differing from the average by ±10 and ±20%.

Cost Comparison: Dust Reduction *via* Conventional Technology *versus* Demineralization of Humidifier Water

CONVENTIONAL TECHNOLOGY

The annualized costs (capital and operating) in 1974 dollars to achieve dust concentrations of 500, 200, and 100 μg/m³ by conventional dust-removal technology were estimated in the "Inflationary Impact Statement" [11] to be $61.5, $241.6, and $620.6 million, respectively, for spinning; and $3.7, $350.1, and $990.6 million, respectively, for weaving industries. The corresponding costs per pound of material processed are 1.6, 6.3, and 16.2 ¢/lb, respectively, for spinning; and 0.13, 12.0, and 34.0 ¢/lb, respectively, for weaving. These figures represent the cost of reducing dust concentrations from 1000 μg/m³ to the PEL's considered. An updated study [10] of the final promulgated standards of 200 μg/m³ opening through spinning and 750 μg/m³ for weaving estimated total annualized costs of $145 and $24 million, respectively, for the two industries. (The adjustment in weaving costs is given on page 47 of Ref. [10].)

The estimated costs of reducing dust-concentration levels in spinning by 300 μg/m³ (from 500 to 200 μg/m³) made in the Inflationary Impact Statement is $180.1 million ($241.6 minus $61.5). This cost of 4.7 ¢/lb is 74.5% of the estimated cost to reduce the dust concentration by 800 μg/m³ (from 1000 to 200

TABLE III. Calculated concentration of dust introduced by humidifiers.

Dissolved solids ppm humidifier type mist emitted, %		50					120					250				
			Air Washer					Air Washer					Air Washer			
		Atomizer	30	20	10	5	Atomizer	30	20	10	5	Atomizer	30	20	10	5
Q_w/Q_a, gal/ft³ᵃ																
Value	Fraction					Dust Introduced—Yarn Plant, μg/m³									
2.09×10^{-5}	(+20%)	139	42	28	14	7	334	100	67	33	17	695	209	139	70	35
1.91×10^{-5}	(+10%)	127	38	26	13	6	305	91	61	31	15	635	191	127	64	32
1.74×10^{-5}	(0%)	116	35	23	12	6	278	83	56	28	14	580	174	116	58	29
1.57×10^{-5}	(−10%)	105	31	21	10	5	252	76	50	25	13	525	158	105	53	26
1.39×10^{-5}	(−20%)	93	28	18	9	5	223	67	67	22	11	465	140	93	47	23
						Dust Introduced—Weave room, μg/m³										
3.64×10^{-5}	(+20%)	243	73	49	24	12	583	175	117	58	29	1,215	365	243	122	61
3.33×10^{-5}	(+10%)	222	67	44	22	11	533	160	107	53	27	1,110	333	222	111	56
3.03×10^{-5}	(0%)	202	61	40	20	10	485	146	97	49	24	1,010	303	202	101	51
2.73×10^{-5}	(−10%)	182	55	36	18	9	437	131	87	44	22	910	273	182	91	46
2.42×10^{-5}	(−20%)	162	48	32	16	8	389	117	78	39	19	810	243	162	81	41

ᵃRatio of water to air-flow rates as estimated in survey (see Fig. 1). Fraction is that of best estimate.

μg/m³). The updated study reports only the cost of reducing dust concentrations in opening and spinning from 1000 to 200 μg/m³ ($145 million as noted above). The cost of removing the final, more costly, 300 μg/m³ of dust from 500 to 200 μg/m³ can be estimated by assuming the same percentage distribution of costs. This calculation gives an annualized industry cost of $145 million × 74.5% = $108.0 million or 2.82 ¢/lb. The cost would be 0.0094 cents per pound of cotton processed per μg/m³ of dust removed in the spinning area. Although this value is 40% lower than that given in the original Inflationary Impact Statement, it will be used as the basis for cost comparisons to provide a conservative estimate of the benefits to be achieved by water demineralization.

The total annualized cost of reducing dust levels in weaving by 250 μg/m³ from 1000 to 750 μg/m³ was estimated to be $24 million or 0.823 ¢/lb in the updated study [10]. This results in a cost of 0.0033 ¢/lb of cotton processed per μg/m³ of dust removed in the weaving area by conventional technology. Similar cost estimates for weaving are not available in the original Inflationary Impact Statement, since that study did not consider a PEL concentration of 750 μg/m³ in weaving.

DEMINERALIZATION OF HUMIDIFIER WATER

Two commonly employed methods for demineralizing water are de-ionization and reverse-osmosis. The relative costs of the two methods vary, depending on many factors such as the capacity of the system, the nature and amount of impurities in the water, the desired purity of the treated water, etc. In general, de-ionization involves less capital costs but higher operating costs. Purification costs utilizing either method should range between $3 and $7 per thousand gallons [2, 4]. A value of $4 has been used here for cost comparisons with conventional technology.

The cost to reduce dust levels using demineralized water depends not only on the water-purification costs, but also, as shown by Equations 1 and 2, on the water flow rate, the concentration of dissolved solids in the water, the air-flow rate, and the means of humidification. Table IV presents estimated costs for typical conditions in spinning and weaving plants. These figures have been calculated based on the average ratio of waterflow to airflow rates per pound of cotton processed for each work area, a water solids concentration of 120 ppm, and production rates of 15,000 lbs/day for spinning and 20,000 lbs/day for weaving. Although up to 50 ppm of chemicals are deliberately added to the water in air-washers, as noted earlier— and thus some solids would be added to the workplace air by air-washers supplied with demineralized water—the costs calculated for removing solids from the workplace by water-demineralization are not affected.

COMPARISON OF COSTS

The results suggest that the cost of lowering dust contributions by purifying the water supply to the humidifiers by ion-exchange or reverse-osmosis is well

TABLE IV. Comparison of costs for removing cotton dust by conventional technology and by demineralization of water supplied to humidifiers.[a]

Humidification system	Water Demineralization				Conventional Technology			
	Purification Costs		Dust removed, $\mu g/m^3$	Cost of dust removed, ¢/lb/$\mu g/m^3$	Removal, cost, ¢/lb of cotton	Dust removed, $\mu g/m^3$	Cost of dust removed, ¢/lb/$\mu g/m^3$	Cost ratio conventional/ demineralize
	(¢/gal H_2O)	(¢/lb cotton)						
				Spinning plant				
Atomizer	0.40	0.154	290	0.00053	2.82	300	0.0094	17.7 (29.5)[b]
Air Washer,								
30% Mist	0.40	0.154	87	0.00177	2.82	300	0.0094	5.3 (8.8)[b]
20% Mist			58	0.00266				3.5 (5.8)[b]
10% Mist			29	0.00530				1.8 (3.0)[b]
5% Mist			15	0.01060				0.9 (1.5)[b]
				Weave room				
Atomizer	0.40	0.190	506	0.00038	0.823	250	0.0033	8.8
Air Washer,								
30% Mist	0.40	0.190	152	0.00125	0.823	250	0.0033	2.6
20% Mist			101	0.00188				1.8
10% Mist			51	0.00376				0.9
5% Mist			25	0.00752				0.4

[a] Spinning-plant processing 15,000 lb of cotton/day and requiring 4.0 gal/min of water as determined from Table II. Weave-room processing 20,000 lb of cotton/day and requiring 6.6 gal/min of water as determined from Table II. Total dissolved solids in water reduced by 125 ppm. Outside conditions 40°F, 63% RH (average for Greensboro, NC, in December). Conventional technology costs from Ref. [10]. Assumes recirculated air is dust-free. [b] Values in parenthesis are for conventional technology costs based on ref. [11].

below that of conventional technology for both spinning and weaving areas when humidification is by atomizers. In spinning, the cost/lb of material processed is approximately 1/18th of that by conventional technology, and in weaving it is about 1/9th. For costs based on the Inflationary Impact Statement, the costs in spinning would be even more favorable: about 1/30th. With air-washers the cost savings become less favorable and reach the point where the costs are equal to that of conventional technology when the contribution from the air-washer becomes 10% that of the atomizer.

Conclusions

During periods such as winter months, when water has to be added to the make-up air of the plant-humidification system to achieve the desired RH, the respirable fraction of the dust in the workplace can be reduced by demineralizing the supply water. Removal of dust contributed by the humidification system by demineralization is shown to be more cost effective compared with conventional dust-control technology. Cost benefits of demineralization are quite dramatic in the case of humidification systems using atomizers (ranging from 1/30th to 1/9th the cost of removing

cotton dust by conventional technology). The benefits are considerably less in the case of humidification systems using air-washers, and they reach the point where conventional technology might even be lower in cost.

Appendix: Prediction of Concentration Factor in Air-Washer Water Sump Basin

Consider the volume of water V in the air-washer sump to be constant with respect to time t. Let q_1 designate the volumetric rate of water inflow and $c_1 =$ the concentration of dissolved minerals in the supply water. Let the concentration of dissolved minerals in the sump at any time be c. Then conservation of mass in the sump dictates that the volumetric flow rate of water going out with the humidified air must also be q_1. Inasmuch as only a fraction h ($h < 1$) of the dissolved solids escape with the humidified air, their concentration in the escaping moisture (vapor plus aerosol) may be taken as hc. Thus the rate of change of concentration in the sump can be written as:

$$\frac{dc}{dt} = \frac{1}{V}(q_1 c_1 - q_1 hc) \quad . \tag{8}$$

Defining $p \equiv q_1 h / V$, Equation 8 can be written as:

$$\frac{dc}{dt} + pc = \frac{q_1 c_1}{V} \quad . \tag{9}$$

Equation 9 can be solved subject to the initial condition that at $t = 0$, $c = c_1$. The solution is:

$$c = c_1 \left(1 - \frac{1}{h}\right) e^{-pt} + \frac{c_1}{h} \quad . \tag{10}$$

To determine the concentration factor, it is reasonable to assume that after startup a steady-state equilibrium will be reached. Thus

$$\lim_{t \to \infty} c = \frac{c_1}{h} \quad .$$

For a water-supply concentration c_1 of 150 ppm and 20% escape fraction ($h = 0.2$),

$$\lim_{t \to \infty} c = \frac{150 \text{ ppm}}{0.2} = 750 \text{ ppm} \quad ;$$

that is, the concentration fraction ($c/c_1 = 1/h$) is 5.

A closer examination of this model for the derivation of the concentration factor f in Equation 2 reveals a paradox. Note that the fraction of solids h escaping is equivalent to the product ab in Equation 2; also the concentration factor $1/h$ is equivalent to f in Equation 2. Thus $abf \equiv h \cdot (1/h) = 1$; *i.e.*, the quantity of solids introduced into the workplace by air-washer systems should be the same as that introduced by the atomizer system (Eq. 1). This conclusion suggests the argument that any reduction in the amount of water droplets containing solids that reach the plant atmosphere (decrease in the values of ab or h) is exactly compensated by the increase in concentration of solids in the droplets that do escape into the workplace (f or $1/h$).

ACKNOWLEDGEMENTS

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