

Steam Humidification:

Reducing Energy Use, Heat Gain, Condensate

Recent advances in steam-dispersion-tube insulating materials improve system energy efficiency, water consumption

Steam humidification is considered essential for most process (e.g., semiconductor manufacturing, printing) and health applications. Given the energy and water wasted when steam is dispersed into cool air streams and the significant number of large buildings this affects,

the time to improve the energy efficiency and water consumption of steam-humidification systems has come. This article will discuss recent advances in steam-dispersion-tube insulating materials and provide data regarding their performance.

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not vary: Receive steam from a steam generator, discharge steam into a duct or air-handling-unit (AHU) air stream through calibrated openings in stainless-steel tubes, and drain condensate to a floor drain or pipe it back to the steam generator. (Note that not all steam generators are designed to accept returned condensate.)

Steam-dispersion assemblies are available in a multitude of configurations designed to meet a variety of absorption and load requirements. Whether it is a 12-in. tube or a 12-ft panel, the purpose of a dispersion assembly essentially is the same: to introduce steam to an air stream (Photo A).

While this may appear to be a simple process, effective dispersion-assembly design requires substantial thought—primarily to accommodate the complex properties of steam.

STEAM-DISPERSION BASICS

Whether dispensing pressurized steam from an on-site boiler or unfired steam generator or nonpressurized, or “evaporative,” steam from a vessel operating at or near atmospheric pressure, the function of a steam-dispersion assembly does

HOT DISPERSION TUBES HEAT AIR AND PRODUCE CONDENSATE

When operating, uninsulated stainless-steel dispersion tubes are hot, with a surface temperature of just under 212°F. When cool air—dispersion assemblies typically dispense steam into 50- to 55°F air streams—flows across hot dispersion tubes, steam inside of the tubes condenses, releasing latent heat, which passes directly through



PHOTO A. Typical panel of uninsulated stainless-steel steam-dispersion tubes spanning the height and width of an AHU. The tubes discharge steam from both sides, perpendicular to airflow.

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the tubes and into the air stream, increasing downstream air temperature. Because of the relationship between latent heat and condensate, downstream heat gain is directly proportional to the amount of condensate produced.

Following are implications of downstream heat gain:

- Every pound of condensate produced wastes about 1,000 Btu—the energy used to change a pound of water to steam.
- Every 8.33 lb of condensate sent to a drain wastes a gallon of water.
- Heat added to downstream air wastes cooling energy in applications that humidify and cool simultaneously, as air is overcooled to maintain AHU supply-air temperature.
- When steam expected to meet a humidification load becomes condensate, a humidification system can fail to meet set point. This can necessitate the

specification of a higher-capacity steam generator.

- Every gallon of condensate sent to

Effective dispersion-assembly design requires substantial thought—primarily to accommodate the complex properties of steam.

a drain wastes water-treatment chemicals (e.g., softened water, deionized or reverse-osmosis treated water, water

treated with boiler chemicals). (Note that not all humidification systems return condensate to the steam generator.)

- Heating air with a humidification dispersion assembly is inefficient. Dispersion assemblies are not designed to be heating appliances.

The rate at which heat is transferred from dispersion tubes to an air stream is determined by air-stream temperature, air-stream velocity, dispersion-tube quantity (surface area), and dispersion-tube thermal conductance. Typically, air temperature and velocity are defined by HVAC-system parameters, while dispersion-tube quantity is a function of absorption distance and load and cannot be reduced without compromising humidification performance. The only variable that can be changed to reduce heat transfer is the thermal conductance of dispersion tubes.

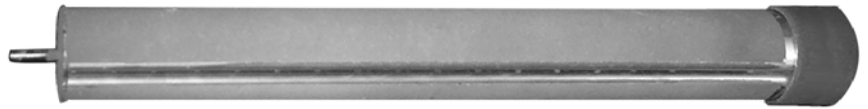


PHOTO B. Dispersion tube with a TIC.

Thermal conductance can be lowered with insulation.

INSULATE DISPERSION TUBES TO REDUCE DOWNSTREAM HEAT GAIN

Dispersion-tube insulation must be able to withstand the environmental extremes of steam humidification while meeting strict plenum requirements regarding smoke and flame. Additionally, dispersion-tube insulation must not significantly obstruct airflow, which could cause excessive pressure drop across the assembly. Two materials used to insulate dispersion tubes meet these requirements: any of various thermal insulating coatings (TICs) (Photo B) and polyvinylidene fluoride (PVDF) (photos C and D and Figure 1).

A TIC, or ceramic insulation, is factory-applied to dispersion tubes as a liquid or semiliquid that dries or cures to form a coating typically 0.030-in. thick (the maximum thickness of a

single coating).

PVDF insulation also is factory-applied to dispersion tubes. It is a dense, non-fibrous, closed-cell insulation 0.125-in. ($\frac{1}{8}$ -in.) thick.

COMPARING THERMAL-CONDUCTIVITY AND THERMAL-RESISTANCE VALUES

Thermal conductivity indicates how well a material transfers thermal energy. A material with a high thermal conductivity, such as metal, transfers heat more readily than a material with a low thermal conductivity, such as plastic. Materials that resist the transfer of heat have low thermal conductivities and are called “insulators.” Thermal-conductivity values commonly are referred to as “ k factors.”

A typical k factor for a TIC is 0.0561 Btuh per foot per degree Fahrenheit ($\text{Btuh}\cdot\text{ft}\cdot^\circ\text{F}$). That means heat will transfer through the material at a rate of 0.0561 Btuh, given a 1°F temperature difference (one side of the



PHOTO C. Dispersion tube with PVDF insulation.

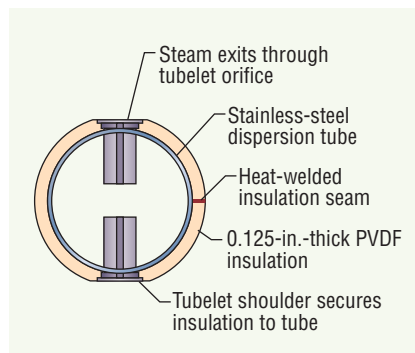


FIGURE 1. Cross-section of dispersion tube with PVDF insulation.



PHOTO D. Dispersion panel with PVDF-insulated tubes.

Insulation	Thickness, ft	<i>k</i> factor, Btuh•ft•°F	<i>R</i> value, thickness ÷ <i>k</i>
Thermal insulating coating	0.0025 (0.030 in.)	0.0561	0.045
PVDF insulation	0.0104 (0.125 in.)	0.0185	0.56

TABLE 1. Insulation *k* factors and *R* values.

example, an 8-in.-thick TIC has the same *k* factor as a 0.030-in.-thick TIC: 0.0561 Btuh•ft•°F.

material is 1°F cooler or hotter than the other) over an area of 1 sq ft through a thickness of 1 ft.

PVDF insulation has a *k* factor of 0.0185 Btuh•ft•°F.

The *k* factor of a material is independent of the material's thickness. For

The thermal-resistance (*R*) value of a material, on the other hand, is dependent on thickness:

$$R = \text{material thickness (in feet)} \div k$$

Therefore, the *R* value of a typical TIC with a thickness of 0.030 in.

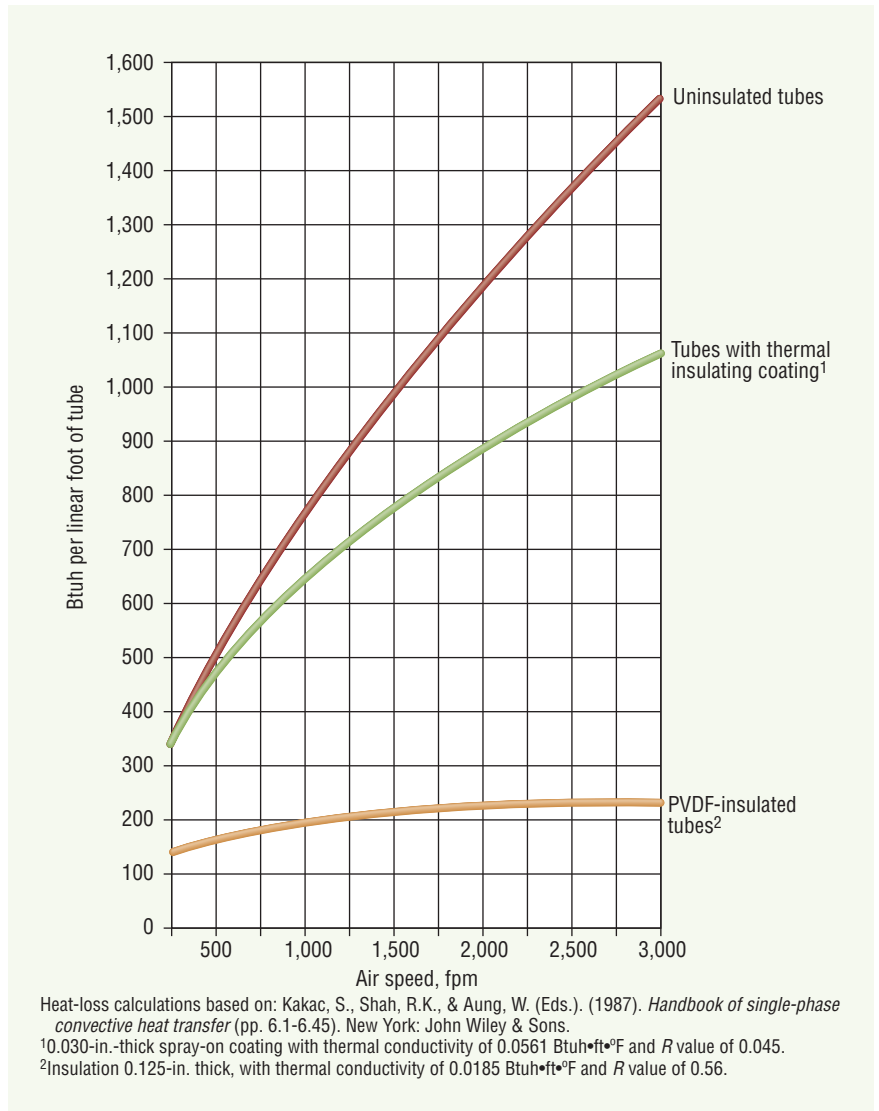
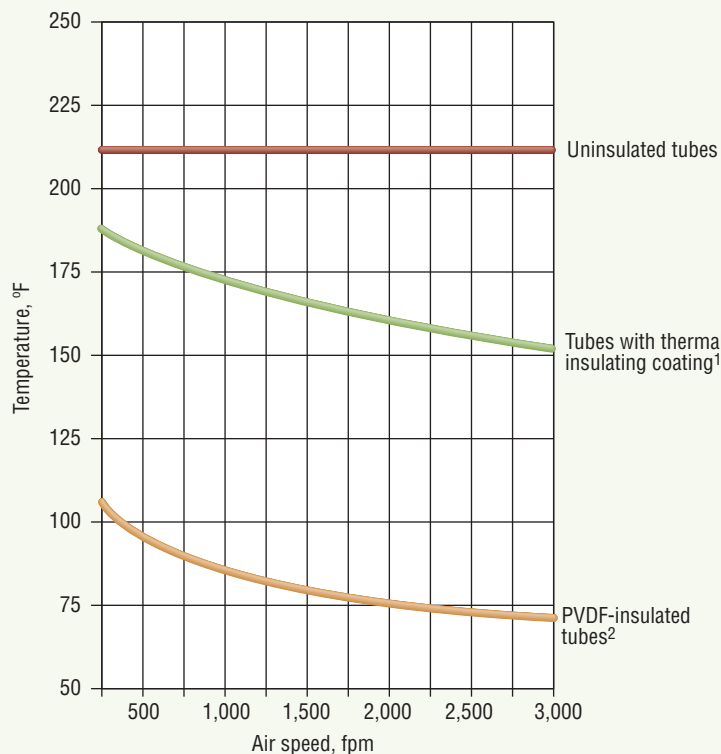


FIGURE 2. Dispersion-tube heat loss vs. air speed—50°F air stream, 3-in.-on-center tube bank, 1½-in.-diameter stainless-steel tubes, 212°F internal wall temperature.



Data obtained using North American Insulation Manufacturers Association 3E Plus software, available as a free download at www.naima.org.

¹0.030-in.-thick spray-on coating with thermal conductivity of 0.0561 Btu·ft·°F and *R* value of 0.045.

²Insulation 0.125-in. thick, with thermal conductivity of 0.0185 Btu·ft·°F and *R* value of 0.56.

FIGURE 3. Dispersion-tube surface temperature vs. air speed—50°F air stream, 1½-in.-diameter stainless-steel tube, 212°F internal wall temperature.

(0.0025 ft) is:

$R = 0.0025 \div 0.0561 = 0.045$ sq ft per hour per degree Fahrenheit per Btu (1.5 per inch of thickness) (Table 1)

The *R* value of PVDF insulation with a thickness of 0.125 in. (0.0104 ft) is:

$R = 0.0104 \div 0.0185 = 0.56$ (4.5 per inch of thickness) (Table 1)

For the TIC to have the same *R* value as the PVDF insulation, it would have to be 0.376-in. (0.0314-ft) thick:

$$R = 0.0314 \div 0.0561 = 0.56$$

Note that the TIC would need to be increased in thickness by a factor of 12.6 to have the same *R* value as 0.125 in. of PVDF insulation.

CHARTING PERFORMANCE

Figure 2 shows dispersion-tube heat loss at various airflow speeds. Note that:

- At low air speeds, the TIC provides little or no benefit.
- Insulation efficiency increases with air speed with both types of insulation.
- Tubes with PVDF insulation reduce heat loss to a greater extent than tubes with a TIC.

If tube surface temperature can be reduced with insulation, less heat will transfer by convection to a cool air stream. Figure 3 shows how a dispersion tube’s external surface temperature is affected by air speed when its internal wall temperature is maintained at 212°F. As can be seen:

- Surface temperature is virtually constant, regardless of air speed, when the tube is uninsulated (surface-tem-

perature range: 211.7 to 210.9°F).
 • Surface temperature drops with air speed when the tube is insulated with a

TIC (surface-temperature range: 187 to 152°F).
 • Surface temperature drops with air

speed when the tube is insulated with PVDF (surface-temperature range: 105 to 71°F).

Sample Problem: Energy and Water Savings

For uninsulated steam-dispersion tubes, steam-dispersion tubes with a TIC, and steam-dispersion tubes with PVDF insulation, calculate:

- Heat loss in British thermal units.

- Condensate production in pounds per hour.
- Total downstream-air heat gain in degrees Fahrenheit.

Also, calculate British thermal units

saved per year when using PVDF-insulated tubes instead of uninsulated tubes.

SYSTEM AND CONDITIONS

- Upstream relative humidity: 20 percent.
- Downstream relative humidity: 60 percent.
- Duct air speed: 1,000 fpm.
- Humidification load: 435 lb per hour.
- Steam-dispersion assembly: 72-in.-wide-by-48-in.-high face, 1½-in.-diameter dispersion tubes on 3-in. centers, 23 48-in.-long tubes.
- Air temperature downstream of dispersion assembly: 55°F.
- Humidification-steam pressure: Atmospheric, at sea level.
- Humidification-system operating hours: 2,000 per year.

Air speed, fpm	Stainless-steel tube (uninsulated)	Stainless-steel tube with thermal insulating coating (TIC)		Stainless-steel tube with PVDF insulation	
	Heat loss, Btuh per linear foot of tube	Heat loss, Btuh per linear foot of tube	Efficiency, percent	Heat loss, Btuh per linear foot of tube	Efficiency, percent
250	316	332	-5	133	58
500	491	467	5	162	67
750	635	567	11	179	72
1,000	762	649	15	190	75
1,250	877	720	18	199	77
1,500	984	782	21	205	79
1,750	1,085	837	23	211	81
2,000	1,181	887	25	215	82
2,250	1,272	933	27	219	83
2,500	1,360	975	28	222	84
2,750	1,444	1,014	30	225	84
3,000	1,526	1,051	31	227	85

Heat-loss calculations based on: Kakac, S., Shah, R.K., & Aung, W. (Eds.). (1987). *Handbook of single-phase convective heat transfer* (pp. 6.1-6.45). New York: John Wiley & Sons.

Inputs:

- 1½-in. stainless-steel tubes
- Internal temperature of tube wall: 212°F
- Air temperature outside tube: 50°F
- Thermal conductivity of TIC: 0.0561 Btuh•ft•°F
- R value of TIC: 0.045
- Thickness of TIC: 0.030 in.
- Thermal conductivity of PVDF insulation: 0.0185 Btuh•ft•°F
- R value of PVDF insulation: 0.56
- Thickness of PVDF insulation: 0.125 in.

Shaded cells refer to sample problem.

TABLE 2. Heat loss from a 72-in.-by-48-in. dispersion panel with 1½-in. dispersion tubes installed 3 in. on center.

SOLUTION

- Using Table 2, determine heat loss per linear foot of tube:
 - Uninsulated dispersion tubes: 762 Btuh per linear foot.
 - Dispersion tubes with a TIC: 649 Btuh per linear foot.

“EFFICIENCY” MEASURING

Table 2 (see “Sample Problem: Energy and Water Savings” sidebar)

shows the efficiency of a stainless-steel dispersion tube with a TIC and a stainless-steel dispersion tube with

PVDF insulation, based on surface temperature, heat loss, and condensate production per linear foot of tube. Note

Air speed, fpm	Downstream air temperature, °F	Upstream relative humidity, percent	Downstream relative humidity, percent	Humidification load, lb per hour	Heat gain from steam, °F	Stainless-steel tubes (uninsulated)		Stainless-steel tubes with thermal insulating coating		Stainless-steel tubes with PVDF insulation	
						Upstream air temperature, °F	Heat gain from tubes, °F	Upstream air temperature, °F	Heat gain from tubes, °F	Upstream air temperature, °F	Heat gain from tubes, °F
250	55	20	60	112	1.11	49.6	4.28	49.4	4.49	52.1	1.80
500	55	20	60	220	1.09	50.6	3.34	50.7	3.17	52.8	1.10
750	55	20	60	328	1.08	51.0	2.88	51.4	2.57	53.1	0.81
1,000	55	20	60	435	1.07	51.3	2.58	51.7	2.20	53.3	0.65
1,250	55	20	60	542	1.07	51.5	2.38	52.0	1.96	53.4	0.54
1,500	55	20	60	648	1.06	51.7	2.22	52.2	1.76	53.5	0.46
1,750	55	20	60	755	1.06	51.8	2.10	52.3	1.62	53.5	0.41
2,000	55	20	60	861	1.06	51.9	2.00	52.4	1.50	53.6	0.36
2,250	55	20	60	968	1.05	52.0	1.92	52.5	1.41	53.6	0.33
2,500	55	20	60	1,074	1.05	52.1	1.85	52.6	1.33	53.6	0.30
2,750	55	20	60	1,180	1.05	52.2	1.79	52.7	1.26	53.7	0.28
3,000	55	20	60	1,286	1.05	52.3	1.69	52.8	1.17	53.7	0.25

Air-steam heat-gain calculations based on: Kakac, S., Shah, R.K., & Aung, W. (Eds.). (1987). *Handbook of single-phase convective heat transfer* (pp. 6.1-6.45). New York: John Wiley & Sons.

Inputs:

- 1½-in. stainless-steel tubes
- Internal temperature of tube wall: 212°F
- Air temperature outside tube: 50°F
- Thermal conductivity of TIC: 0.0561 Btu•ft•°F
- R value of TIC: 0.045
- Thickness of TIC: 0.030 in.
- Thermal conductivity of PVDF insulation: 0.0185 Btu•ft•°F
- R value of PVDF insulation: 0.56
- Thickness of PVDF insulation: 0.125 in.

Shaded cells refer to sample problem.

TABLE 3. Air-steam heat gain from a 72-in.-by-48-in. dispersion panel with 1½-in. dispersion tubes installed 3 in. on center.

• Dispersion tubes with PVDF insulation: 190 Btu per linear foot.

2) Determine total length of tubing: (23 tubes × 48 in.) ÷ 12 in. per foot = 92 ft.

3) Determine total heat loss:

• Uninsulated dispersion tubes: 92 ft of tube × 762 Btu per linear foot = 70,104 Btu total heat loss.

• Dispersion tubes with a TIC: 92 ft of tube × 649 Btu per linear foot = 59,708 Btu total heat loss.

• Dispersion tubes with PVDF insulation: 92 ft of tube × 190 Btu per linear foot = 17,480 Btu total heat loss.

4) Determine hourly condensate production (latent heat of vaporization and condensation for water: 970 Btu per pound):

• Uninsulated dispersion tubes: 70,104 Btu ÷ 970 Btu per pound = 72.3 lb per hour.

• Dispersion tubes with a TIC: 59,708 Btu ÷ 970 Btu per pound = 61.6 lb per hour.

• Dispersion tubes with PVDF insulation: 17,480 Btu ÷ 970 Btu per pound = 17.9 lb per hour.

5) Using Table 3, determine total downstream-air heat gain (heat from

steam plus heat from dispersion tubes equals total heat gain):

• Uninsulated dispersion tubes: 1.07 + 2.58 = 3.65°F.

• Dispersion tubes with a TIC: 1.07 + 2.20 = 3.27°F.

• Dispersion tubes with PVDF insulation: 1.07 + 0.65 = 1.72°F.

6) Determine annual energy savings in British thermal units using PVDF-insulated tubes instead of uninsulated tubes, assuming 2,000-hr-per-year operation (annual heat loss of uninsulated tubes

minus annual heat loss of insulated tubes equals annual energy savings): (70,104 Btuh × 2,000 hr per year) – (17,480 Btuh × 2,000 hr per year) = 105,248,000 Btu per year.

	Uninsulated tubes	Tubes with thermal insulating coating	PVDF-insulated tubes	PVDF-insulated tubes vs. uninsulated tubes	
				Savings	Percent improvement
Heat gain to downstream air from dispersion tubes	2.58°F	2.20°F	0.65°F	1.93°F	75
Heat loss per hour	70,104 Btu	59,708 Btu	17,480 Btu	52,624 Btu	
Heat loss per year	140,208,000 Btu	119,416,000 Btu	34,960,000 Btu	105,248,000 Btu	
Condensate production per hour	72.3 lb (8.68 gal.)	61.6 lb (7.39 gal.)	17.9 lb (2.15 gal.)	54.4 lb (6.53 gal.)	
Condensate production per year	144,600 lb (17,359 gal.)	123,200 lb (14,790 gal.)	35,800 lb (4,298 gal.)	108,800 lb (13,061 gal.)	

Results summary for sample problem.

that efficiency varies with air speed; it also varies with air temperature, but air temperature is assumed constant in this table.

(The efficiencies listed in Table 2 are for dispersion tubes only; they do not

include dispersion-assembly headers.)

Efficiency does not change with load. If a tube has hot steam running through it, it will produce condensate and give up heat at the same rates, regardless of load. Statements of efficiency, then,

should not be based on load. For example, whether the humidification load in the sample problem is 100 or 1,000 lb per hour, condensate will exit a PVDF-insulated tube at a rate of 17.9 lb per hour (17.9 and 1.8 percent of

Heat Transfer and TICs

Heat transfer occurs three ways: by conduction, by convection, and by radiation.

Conduction is the transfer of thermal energy in solids and liquids at rest.

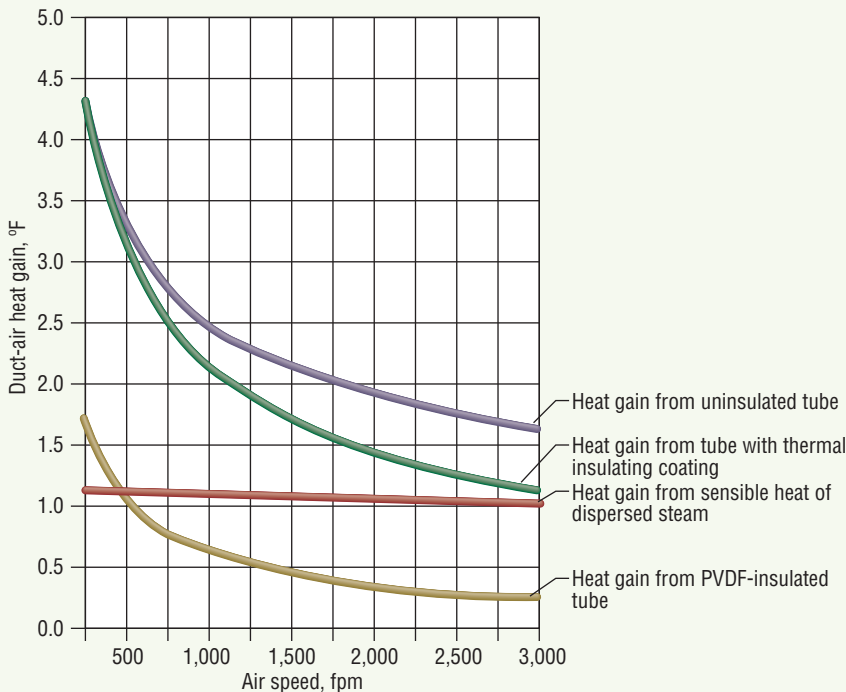
Convection is the transfer of thermal energy between a solid surface and a fluid moving over the surface.

Radiation is the transfer of thermal energy by electromagnetic waves. It does not require a medium. Heat loss from a dispersion tube by radiation is only 1 to 2 percent of that by convection. Heat loss by radiation depends strongly on surface emissivity and surface temperature to the fourth power. For example, a 1-ft section of 1½-in. tubing with a surface emissivity of 0.3 and a surface temperature of 211.5°F radiates only about 27 Btuh. The surface temperature of the tube is too low to contribute any

significant heat loss by radiation. With very hot surfaces, however, radiation can become the dominant heat-transfer mechanism. For example, at 1,000°F, a 1-ft section of 1½-in. tubing with a surface emissivity of 0.3 radiates about 1,835 Btuh—68 times what it radiates at 211.5°F.

TICs are most effective at reducing heat transfer by radiation. As a result, they often are used on roofs to reduce heat transfer caused by solar radiation. At 0.010 in. to 0.030 in., however, TICs do not provide much resistance to heat transfer through roofs by conduction.

Exercise care when comparing the effectiveness of insulating materials. First, understand the difference between *k* factor and *R* value, and know the type of heat transfer you wish to reduce. Then, choose the appropriate insulating material.



AHU/duct-air heat gain from steam and dispersion tubes. The first source of heat gain is the sensible heat of steam injected into the air. This heat gain is attributable to the inherent properties of steam and cannot be reduced. The second source of heat gain is the convective transfer of heat from hot dispersion tubes to a cooler air stream. This heat gain can be reduced significantly with insulated dispersion tubes.

load, respectively) (Figure 4).

CONCLUSION

The obvious solution to the problem of AHU/duct heat gain is insulated dispersion tubes. At typical air speeds of 500 to 1,000 fpm, PVDF-insulated tubes are 67- to 75-percent more efficient than uninsulated tubes. The benefits of this efficiency are considerable: sizeable reductions in downstream heat gain and dispersion-tube-generated condensate leading to significant reductions in energy and water consumption. The energy savings resulting from the use of PVDF-insulated tubes can yield paybacks of less than one year for electric humidification systems and about 1½ years for natural-gas systems.

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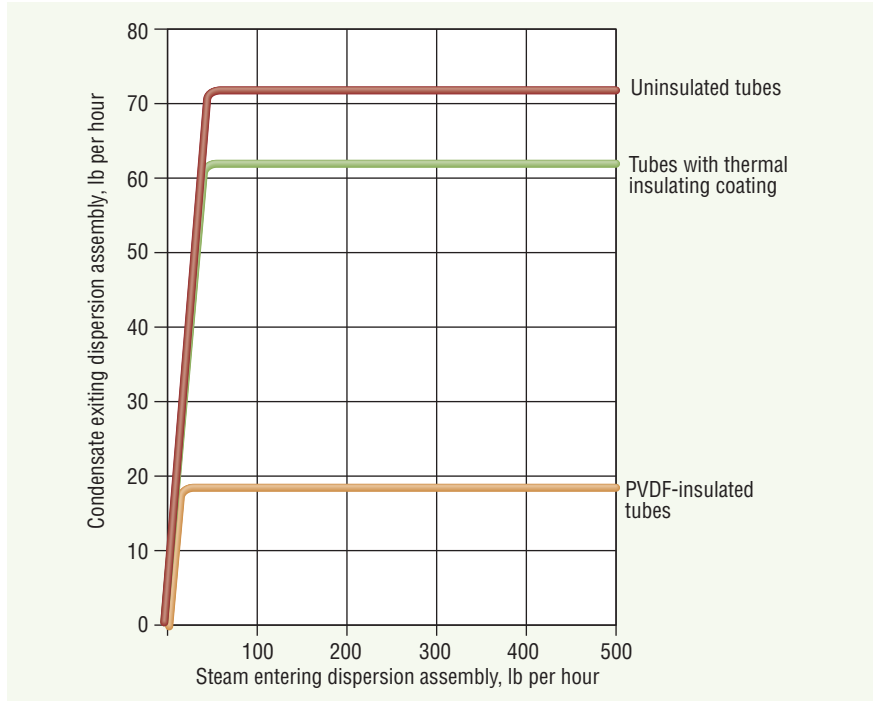


FIGURE 4. Condensate loss vs. humidification steam entering a 72-in.-by-48-in. dispersion panel with 1½-in. dispersion tubes installed 3 in. on center.