THE ENERGY COST of HUMIDIFICATION

The reasons for humidification of houses in winter concern mostly comfort and health. However, humidification usually results in higher household energy consumption. In addition, chronic excess humidity can cause bubbling and peeling of exterior paint, compaction of insulation and serious structural damage. Hence, minimum humidification consistent with adequate comfort is advisable.

JAY W. SHELTON
Associate Member ASHRAE

MANY energy conservation tip lists suggest humidification. One such list states, *"Keep the humidity at a proper level with humidifiers or water supply near the furnace vents. If the air is dry, more heat is required to keep you comfortable."*[1] Another recently pamphlet suggests, *"Add a humidifier to your hot air system or employ a portable unit. ... Proper humidity permits lower indoor winter temperatures while retaining some degree of comfort."*[2]

The rationale behind these claims is probably that increasing the humidity of air without changing its temperature makes air feel warmer (at typical ambient indoor temperatures) due to suppression of evaporation of moisture from the skin. As a consequence, a house equipped with a humidifier permits lower thermostat settings than a house without humidification. The feeling of air warmth in both houses will be the same. This lowering of temperature results in a lessened sensible-heat loss from the house, since such heat loss depends principally on the temperature difference inside and outside the house.

However, the energy necessary to humidify the air is usually far greater than the decreased sensible-heat loss. It is this energy expenditure which evidentally is often neglected by authors of lists of energy-conserving suggestions. Most humidifiers themselves do not consume large amounts of energy; they are merely devices to promote evaporation of water. They may have no direct energy consumption (a water pan with evaporation plates in forced-hot-air systems, pans of water placed on radiators, or laundry hung around the house). If energy is consumed directly, it may be that of a small electric motor (portable humidifiers). A few domestic humidifiers use electric immersion heaters to increase evaporation rates, and these may consume significant amounts of energy directly. But regardless of the type of humidifier, evaporation of water is involved, and this is an energy consuming process. If heat is not supplied explicitly, this process results in cooling (sweat and other wet air-conditioning systems). For example, most portable humidifiers (those without an internal heat source) operating in a closed room, decrease the room's temperature unless extra heat is added. Typically, the cooling tendency of humidification is counteracted through increased energy consumption of the building's space-heating system. The main point is that in all kinds of humidification, the heat of vaporization of water must be supplied by some source.

If the net effect of humidification is an increase in heating energy required — as is usually the case — then, since energy is conserved, the total rate of energy loss from the house must increase. Sensible-heat loss is of course decreased due to lower indoor temperature, but latent-heat loss is increased due to higher water-vapor content of the air lost through exfiltration and ventilation. Usually, as will be shown, the increase in latent-heat loss exceeds the decrease in sensible-heat loss.

CALCULATION

A quantitative calculation of humidification's energy cost requires careful accounting of moisture. Water vapor enters and leaves a house whenever air does; and may also be generated inside a house through normal activities. Very small amounts of moisture may also diffuse into or out of a house without concurrent air exchange. This effect is neglected in this discussion, as is that part of condensation and freezing of water vapor out of the indoor air which is not subsequently returned to the air (*e.g.*, manual defrost refrigerators). Explicit humidification (or dehumidification) is necessary if the natural processes result in an undesired humidity level.

Indoor and outdoor air are constantly being exchanged due to infiltration and exfiltration through cracks around windows and doors, through chimneys, and due to the action of exhaust fans and the openings of doors and windows. Typical total air-exchange rates are from ½ to 2 air changes per hour. Entering air brings in moisture at the same concentration as that of outdoor air. Similarly exhaust air carries out moisture at a concentration equal to that of indoor air.

Some basic information necessary to calculate the moisture deficit (or surplus) due to air exchange is shown in Table 1, which gives the humidity ratio of saturated air at various temperatures. The humidity ratio is the ratio of masses of water vapor to dry air in a given example. Relative humidity is the more common measure of water-vapor content; a relative humidity of 80% indicates the water-vapor content of 80% of its maximum possible value (saturation). The data in Table 1 allow calculation of actual water-vapor content, given the temperature and relative humidity of the air. For instance, the humidity ratio of the air at 70F at 40% relative humidity is 40% of 1.56×10^{-2}. Hence, in one pound of such air there is 0.0063 lb. of water vapor.

The rate at which moisture must be added to (or taken away from) the air in a house in order to maintain a given humidity ratio is (in lbs/hr)

$$(HR_i - HR_o)\dot{m}$$

where

HR_i = desired humidity ratio inside house
= (desired relative humidity inside house) × (humidity ratio at saturation and at the inside

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J. W. Shelton is Associate Professor, Physics Department, Williams College Williamstown, M.

temperature)

HR_o = humidity ratio of outside air
= (relative humidity of outside air) × (humidity ratio at saturation and at outside temperature)

$\dot{m}$ = dry air exchange rate in lbs/hr
= (air exchange rate in exchanges/hr) × (volume of house in ft^3) × (density of dry air (*i.e.*, excluding moisture) at inside temperature in lbs/ft^3)

For example, suppose that the outside temperature is 20F with an average humidity of 60%, and that it is desired to maintain a relative humidity of 35% in a house kept at 65F with an air exchange rate of one change per hour and a house volume of 10^4 cubic feet. The necessary humidification rate would be

$$(HR_i - HR_o)\,\dot{m} =$$
$$(0.35 \times 1.33 \times 10^{-2} - 0.60 \times 2.15 \times 10^{-3}) \times 7.5 \times 10^{-2} \frac{lb}{ft^3}\, 10^4 \frac{ft^3}{hr}$$
$$= 2.53\ lbs/hr.$$

($7.5 \times 10^{-2}\ lb/ft^3$ is the approximate density of air; it varies a little with barometric pressure. The difference between dry and moist-air densities is always less than 2% for temperature less than 75F).

Not all of this humidification rate need be supplied by an explicit humidifer since many household activities add water vapor to the air (Table 2). Cooking in an average home contributes 4-5 lbs. of moisture per day; each person in a house contributes about 6 lbs. of moisture per day due to transpiration and evaporation. Evap-

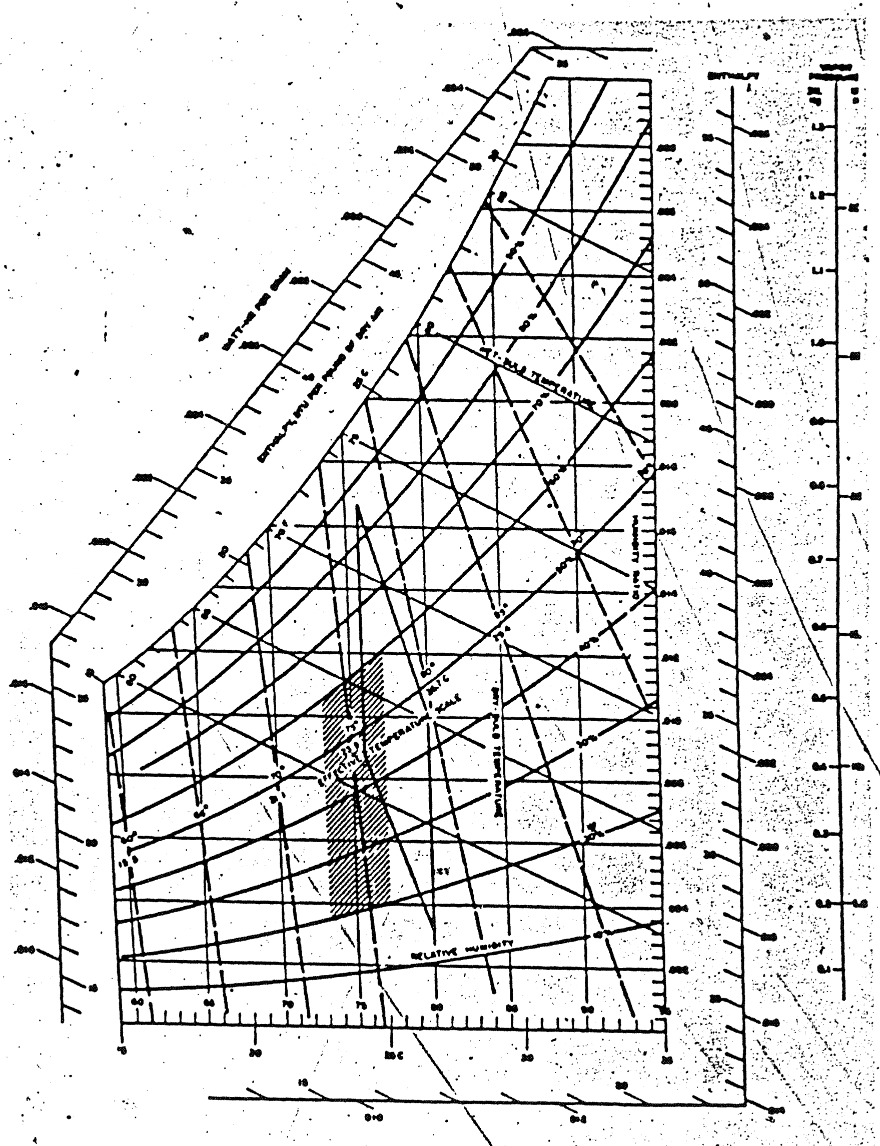

Table 1

Temperature (°F)	Humidity Ratio at 100% Relative Humidity
−50	0.416×10^{-4}
−40	0.793×10^{-4}
−30	1.46×10^{-4}
−20	2.63×10^{-4}
−10	4.61×10^{-4}
0	7.87×10^{-4}
10	1.32×10^{-3}
20	2.15×10^{-3}
30	3.45×10^{-3}
40	5.21×10^{-3}
50	7.66×10^{-3}
60	1.11×10^{-2}
65	1.33×10^{-2}
70	1.58×10^{-2}
75	1.88×10^{-2}
80	2.23×10^{-2}
90	3.12×10^{-2}
100	4.32×10^{-2}
110	5.94×10^{-2}
120	8.15×10^{-2}

Table 2. Moisture Production for Various Residential Operations

Operation				Lb of Moisture
Floor mopping — 8 × 10 kitchen (0.03 per sq ft)				2.40
Clothes Drying* (Not vented)				26.40
Clothes Washing*				4.33
Cooking (Not vented)*	*From Food*	*From Gas*		
Breakfast	0.34	0.56		0.90
Lunch	0.51	0.66		1.17
Dinner	1.17	1.52		2.69
Bathing — Shower				0.50
Bathing — Tub				0.12
Dishwashing:*				
Breakfast				0.20
Lunch				0.15
Dinner				0.65
Human Contribution — Adults				
When Resting			Per Hr	0.2
Working Hard			Per Hr	0.6
Average			Per Hr	0.4
Gas Refrigeration			Per Hr	0.12
House Plants			Per Hr	0.04

* *Based on family of four.*

(from ASHRAE Guide and Data Book, Equipment Volume, p. 38 and 39, 1972)

Table 3. Limiting Relative Humidity for No Window Condensation

(Natural Convection, Indoor Air at 74 F)

Outdoor Temp.	Double Glazing
40	59
30	50
20	43
10	36
0	30
−10	26
−20	21
−30	17

(from ASHRAE Guide and Data Book, Equipment Volume, p. 38 and 39, 1972)

oration of water during a shower or bath may contribute as much as ½ lb. moisture; a large number of houseplants does significant humidification; open (unvented) flames generate water vapor as a biproduct of combustion reactions. Typical average rates of humidification from all these implicit sources is ½ to 1 lb/hr. The energy source of most of this unintentional humidification is not the space-heating system but food, cooking energy, and energy for the hot water heater. Hence most of this humidification is free in the sense that it is a biproduct of activities done principally for other reasons. (*The one potentially significant exception is in the case of houseplants.*)

Hence, continuing the numerical example, of the approximately 2½ lbs/hr of humidification needed, let us assume ¾ lb/hr is supplied by usual household activities; hence the extra explicit humidification rate must be 1¾ lbs/hr. The energy necessary to add 1 lb of water vapor to the air is about 1060 Btu, the heat of vaporization of water. Hence the energy cost for humidification in this example is 1¾ lb/hr × 1060 Btu/lb = 1850 Btuh.

The energy savings due to humidification is based on the fact that humid air feels warmer than dry air (in the temperature region of interest here), and hence the air temperature in a humidified house can be lower without sacrificing any change in the human sensation of ambient temperature. This effect has been measured by obtaining the reactions of large numbers of human subjects exposed to various controlled conditions of temperature and humidity.[3] The size of the effect may depend on the amount of clothing worn, the amount of physical activity of the subjects, and the duration of exposure, and these factors explain some of the slight differences in various studies of thermal comfort. The effect is not large: For any fixed dry bulb temperature in the range of 65F to 70F, the range of subjectively felt temperature ("effective temperature"), as the relative humidity is raised from 0% to 100%, is only about 3F (Fig. 1).[1] The effect is approximately directly proportional to the relative humidity. Hence humidification from 20% to 30% relative humidity would allow lowering the temperature by about 0.3F, a modest adjustment whose energy savings will rarely compensate for the energy cost of humidification.

Without explicit humidification the humidity ratio would be that of the outside air plus the contribution from household activities. For our numerical example this humidity ratio would be

$$HR_o + \frac{S}{\dot{m}} = 0.00129 + \frac{0.75\ \text{lb/hr}}{750\ \text{lb/hr}} = 0.00229$$

where S is the contribution of internal moisture sources in pounds of water per hour.

This corresponds to 17% relative humidity at 65F. With humidification to 35%, the thermostat may be set back 18% (35% − 17%) of the 3F set-back corresponding to humidification from 0% to 100% relative humidity, or 0.54F. For an outdoor temperature of 20F this corresponds to a change in the difference between indoor and outdoor temperatures of 1.2%, and hence will result in a decreased sensible heat loss of about 1.2%. In a house with a heat loss of 20,000 Btu per degree-day, the heat-loss rate under these conditions is about 37,500 Btuh. Hence the savings due to decreased sensible-heat loss is about 450 Btuh. This is much smaller than the roughly 1850 Btuh necessary to humidify. Hence the net energy cost of humidification in this example is about 1400 Btuh, which is about a 3.7% increase in the nonhumidified heating-energy consumption rate.

It is possible for humidification to result in a net savings of energy. Generalization of the above calculation leads to the energy cost term (associated with the humidification process, and equal to the increased latent heat-loss rate),

$$q_l = (\dot{m}HR_i - \dot{m}HR_o - S)h \qquad (1)$$

where

HR_i = humidity ratio inside building
HR_o = humidity ratio of outside air
S = internal humidity sources contribution (mass/time)
$\dot{m}$ = mass flow rate of dry air into (or out of) building
h = heat (enthalpy) of vaporization of water. ($h \approx 1060$ Btu/lb at 50 to 60F and at 1 atmosphere).

Similarly the energy-savings term associated with being able to lower the thermostat is the decrease in temperature permitted by humidification times the overall heat-loss-rate coefficient of the building. This decrease in sensible heat-loss-rate is

$$q_s = (\dot{m}HR_i - \dot{m}HR_o - S)\alpha H_c/\dot{m} \qquad (2)$$

where

α = (minus) the change in dry-bulb temperature per unit change in humidity ratio, at constant effective temperature.
H_c = overall heat-loss-rate coefficient for the building (e.g., Btu/degree-day)

The net change, q, in the energy-consumption rate is the difference between these two terms:

$$q = q_l - q_s = (\dot{m}HR_i - \dot{m}HR_o - S)(h - \alpha H_c/\dot{m}) \qquad (3)$$

Let us now determine under what circumstances humidification results in a net savings of energy. This requires that q be negative. The first term in the product in Eq. (3) is positive when humidification is required. Hence, q will be negative when the second term is negative,

$$h - \alpha H_c/\dot{m} < 0 \qquad (4)$$

or

$$\frac{H_c}{\dot{m}} > \frac{h}{\alpha} \approx 5\ \text{Btu/lb°F} \qquad (5)$$

where $\alpha \approx 200$F has been used, which is valid for effective temperatures from 60F to 75F. (see Fig. 1 and Reference 4).

In the previous numerical example, the ratio $H_c/\dot{m}$ was 1.1 Btu/lbF. Hence this condition would be satisfied for a five-fold increase in the heat-loss-rate coefficient, or, a five-fold increase in the heat-loss-rate coefficient, or, a five-fold decrease in the air-exchange rate, both of which are drastic changes from the numerical example. Values of $H_c/\dot{m}$ for various conditions are given in Table 4. For a house with an effective temperature within the typical range of 65F to 75F, humidification can result in a net energy savings only for a small, tight house with a large heat loss, an unlikely combination.

A higher temperatures, the value of α increases significantly, to about 400F at 80F and about 600F at 85F (effective temperature). (At these higher

TABLE 4

Air Exchange rate House Volume per hour	House Volume ft³	Mass Exchange rate, ṁ lb/hr	Heat Loss Rate Coefficient, H_c			
			10,000 $\frac{\text{Btu}}{\text{degree-day}}$ or 417 $\frac{\text{Btu}}{\text{degree-hr}}$	20,000 835	30,000 1250	40,000 1670
½	5,000	188	$\frac{H_c}{\dot{m}} = 2.2 \frac{\text{Btu}}{\text{lb°F}}$	4.4	6.7	8.9
½ 1	10,000 5,000	375	1.1	2.2	4.4	6.7
½ 1 2	20,000 10,000 5,000	750	0.56	1.1	2.2	4.4
1 2	20,000 10,000	1500	0.28	0.56	1.1	2.2
2	20,000	3000	0.014	0.28	0.56	1.1

Values of $H_c/\dot{m}$ for various conditions. For $H_c/\dot{m} \leq 5$ Btu/lb°F humidification from and to any levels, at any constant effective temperature between 60F and 75F, results in a net increase in the energy loss from the house. A net energy savings results only for $H_c/\dot{m} \leq 6$ Btu/lbF, corresponding to the unlikely combination of a small tight house with a large heat loss.

temperatures, humidity has a larger effect on thermal comfort). The corresponding critical values of H_c/m are about 3 and 1.7 respectively. As can be seen from Table 4, these values begin to correspond to more reasonable houses, but few occupants would be comfortable at these high temperatures. Hence the conditions are rare indeed under which humidification can result in net energy savings.

q is also negative for

$$\dot{m}HR_i - \dot{m}HR_o - S < 0 \qquad (6a)$$

$$h - \alpha H_c/\dot{m} > 0 \qquad (6b)$$

This corresponds to a situation requiring dehumidification in order to attain desired interior humidity, due to a large internal load and/or a relatively tight house. In this case, it is possible to save heating energy by dehumidification. Dehumidification usually involves condensation of water, which releases the same amount of heat as is consumed in evaporation. But whether or not dehumidification results in a net savings of energy during the heating season will depend on whether the condensation heat is in fact used for space heating or is exhausted to the external environment.

The ASHRAE Comfort Chart (reproduced as Fig. 1) includes lines of constant enthalpy (which coincide with lines of constant wet-bulb temperature) and hence permits partial graphical solution of the energy cost of humidification. The difference in the enthalpy coordinate (in Btu per pound of dry air) between two points of different relative humidity but of the same effective temperature gives this cost directly. Coupled with an air-exchange rate and a computation of sensible-heat savings, this solution is equivalent to the algebraic one presented above.

DISCUSSION

The net energy cost of humidification depends sensitively on the details of each situation. The air exchange range is a very important parameter and very difficult to know accurately. Its importance lies in the fact that the required total humidification rate is directly proportional to the air exchange rate since that is essentially the only way for water vapor to leave a house. In a very "tight" house the humidity load from natural internal sources can be excessive, in some cases requiring dehumidification even in winter. Electrically heated houses are more likely candidates for the excess-humidity problem because of the higher standards to which they are generally built. On the other hand older houses are often rather leaky; houses with air exchange rates of more than 2 per hour are not uncommon and would, in cold climates, be very costly to humidify (just as they are to heat).

Another important parameter is the water-vapor content of the outside air which enters the house at the air exchange rate. As the outside temperature falls, the amount of water vapor and air can hold, at any given relative humidity, also falls dramatically. For example, saturated air at −15F contains only about one tenth as much moisture as saturated air at 30F (Table 1). This is why air in houses tends to be drier in cold weather. However, try to maintain a relative humidity of 35% in sub-zero weather is not advisable, since in most houses it will result in excessive condensation inside exterior walls and other places, causing, in the long run serious structural damage. Table 3 shows recommended maximum relative humidites as a function of outside temperature in order to avoid serious condensation problems. (*Continuous condensation on large portions of thermopane windows, or ordinary windows with storm windows, is an indication of excess humidity; in its absence, humidity levels are probably not excessive*).

The benefits of humidification are mainly related to comfort and/or health. One possible additional benefit is related to the fact that wood shrinks as its moisture content falls. By maintaining relatively constant humidity possibly harmful stress and dimensional changes are avoided. One interesting but probably very small effect of the drying out and contraction of wood could be an increase in air infiltration due to widening of cracks in the structure. ◻◻

REFERENCES

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3. See, for example, R. G. Nevins et al, "Temperature-Humidity Chart for Thermal Comfort of Seated Persons," ASHRAE Transactions, Vol. 72, Par I, 1966, p. 238.
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