HUMIDIFICATION, A TRUE "HOME" PROBLEM FOR A CHEMICAL ENGINEER

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All teachers have observed that academic knowledge is more easily transmitted through application, especially when examples are chosen from everyday life. *Chemical Engineering Education* has often published such examples,[1-5] providing interesting matter to illustrate academic chemical engineering courses.

This paper uses this approach and aims to help students understand problems dealing with humid air as they are encountered in courses about cooling towers, humidification, dehumidification, or drying. These examples are complex because they involve coupled heat and mass transfer phenomena, but only basic knowledge about humid air and use of the psychrometric chart is needed for the example proposed here. The reader interested in an everyday problem dealing with evaporative cooling may refer to a previous author's paper.[1] In the present case the problem is suited for early material and energy balances courses and only needs the knowledge of the psychrometric chart.

PRESENTATION OF THE PROBLEM

The example is the following:

A cold spell has invaded the country and the temperature stabilizes below 0 °C. The most visible consequence of this cold is an increased heat duty in our homes. But there is also a less-known phenomenon that quite significantly affects the comfort inside the home: using a domestic hygrometer, it can be observed that the relative humidity, ε, of the air inside the house has dropped to very low values (below ε = 0.2). This value is far below what is advised by the American Society of Heating, Refrigerating, and Air Conditioning Engineers[6] (ASHRAE), which recommends relative

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TABLE 1 Data						
Area of the house S_{floor}	Height of the wall H_{wall}	Outside temperature $temp_{out}$	Indoor temperature $temp_{in}$	Mass flowrate of water W	Outside absolute humidity Y_0	Initial indoor absolute humidity Y_i
90 m^2	2.65 m	-5 °C	20 °C	0.4 kg/h	0.0025	0.0025

humidity values between 0.3 and 0.6. Below ε = 0.3, there is a "dryness zone" where people experiences skin and eye dryness and stuffy noses. People wearing contact lenses find them particularly irritating.

So the chemical engineer may ask himself or herself the following questions:

1) Why is the indoor relative humidity so low?

In relating to early chemical engineering courses that cover the humidity psychrometric chart, the student can see that even saturated, cold air has a very low absolute humidity (around Y_0 = 2.5 g/kg of dry air at -5 °C). When this air is heated inside the house at 20 °C, simple computations or reading of the psychrometric chart indicate that the relative humidity of this heated air has dropped to ε = 0.175.

2) What can be done to improve the situation?

Domestic devices for humidifying air are available. Most of them are based on ultrasonic generation of very tiny droplets that are blown into the air to evaporate. The chemical engineer would like to know how much water is needed to bring the 20 °C air up to ε = 0.5 (corresponding to absolute air humidity Y_f = 7.18 g/kg of dry air). The question might also be asked as to what is the duration of the humidification process?

From the dimensions of the house (see Table 1), the mass of air, M_{air}, referred to a dry basis (kg of dry air) is readily computed using the value of the density of air (around 1.2 kg.m^{-3} at 20 °C). The quantity of water Q_w to be evaporated is obtained using the change of absolute humidity of the air:

$$Q_w = M_{air}\left(Y_f - Y_0\right) = 1.34\,\text{kg} \tag{1}$$

Most commercial domestic humidifiers claim a maximum water flow rate W around 0.4 kg h^{-1}. So the duration of the operation to achieve is:

$$t_{final} = \frac{Q_w}{W} \tag{2}$$

This leads to a few hours duration (t_{final} = 3.3 h). This is a rather short time. But the observed results are very different: after one night, the hygrometer still indicates a low value (around ε = 0.32). Even maintaining the humidifier continuously in operation, stopping only to refill the 4 liter tank, the hygrometer indicates a slowly growing value that stabilizes around 0.37 after one day and a half.

This experimental contradiction means that an important parameter has been forgotten. It is obvious that several liters of water have been evaporated but they are not present in the air of the house. It is easy to remember that a house is naturally ventilated and the ventilation flow rate is very probably the missing parameter.

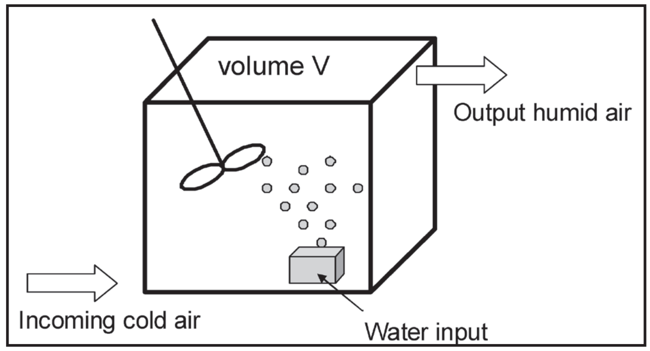

Figure 1. *Systemic sketch of the humidification of the house.*

Is a chemical engineering student able to describe the situation with the usual tools? This is indeed quite possible considering the house as a vessel with mass input and output. This closely resembles a mixing tank as described in Figure 1.

To propose a simple model, it is necessary to assume perfectly mixed air inside the house. This implies a homogeneous humidity Y in the volume and consequently that air leaves the house at the instantaneous inner humidity Y (*stirred tank assumption*). Different locations for the hygrometer during the humidification process did not show significant differences. So, although not initially obvious, the perfectly mixed hypothesis is quite acceptable.

The universal dynamic mass balance (accumulation = input – output + generation) is written:

$$M_{air}\frac{dY}{dt} = \left(W + DY_0\right) - DY \tag{3}$$

W is the input flow rate of water by the humidifier in kg/s.

D is the renewal mass flow rate (referred on a dry basis, kg/s of dry air).

Y is the instantaneous inner absolute humidity.

Y_0 is the outside absolute humidity (assumed constant).

Eq. (3) is a simple first order differential equation to be solved with the initial condition:

$Y = Y_i$ for t = 0 where Y_i is the initial inner absolute humidity, which is equal to Y_0 in the present case.

The solution is easily found as:

$$Y(t)=Y_0+\left(Y_i-Y_0-\frac{W}{D}\right)e^{-\frac{D}{M_{air}}t}+\frac{W}{D} \qquad (4)$$

Indeed, it is a first order system with an asymptotic absolute humidity Y_{inf} (which corresponds to the steady state) given by:

$$Y_{inf}=Y_0+\frac{W}{D} \qquad (5)$$

Computation of the steady state value requires estimation of the renewal mass flow rate D. It can be obtained from the value of the time for air renewal in naturally ventilated houses, which is usually estimated around t_{renew} = 2 hours. The renewal mass flow rate D is given by:

$$D=\frac{M_{air}}{t_{renew}} \qquad (6)$$

From Eq. (5), a value Y_{inf} = 5.3 g/kg of dry air is obtained and the corresponding relative humidity is $\varepsilon_{inf} = 0.37$.

This is a very encouraging result because it corresponds to the asymptotic observed value, meaning that the estimation of the renewal time is fairly good. Indeed, the value of the final relative humidity is low because the humidifier does not bring enough water. Actually, the major part of the water is evacuated by the renewal air flow rate. The only solution would be to increase the number of humidifiers.

Now we can compute the time to reach the asymptotic value. Theoretically, this time is infinite so we have to define a criterion. A typical approach is to calculate for a percentage of the approach, for instance:

$$\left|\frac{Y(t)-Y_{inf}}{Y_{inf}}\right|=0.01.$$

With this procedure the final time is determined as t_{final} = 7.9 hours and is surprisingly short when steady state has been experimentally obtained after one and a half days.

Here also an important parameter has been forgotten. Deeper reflection reveals that the house contains many materials able to adsorb water and to equilibrate with the inner air. It could be wall coatings, like plaster or tapestry, or any other hygroscopic material. In a first approach, the adsorption phenomenon can be accounted for by using a linear equilibrium $X = K_{ads}Y$, where X is the absolute humidity of the solid (dry basis). Also, it can be assumed that the global dynamics are slow enough so that adsorption equilibrium is always reached. Introducing the mass of the wall coating (dry basis) as M_{wall}, Eq. (4) becomes:

$$M_{air}\frac{dY}{dt}+M_{wall}\frac{dX}{dt}=\left(M_{air}+M_{wall}K_{ads}\right)\frac{dY}{dt}=W+DY_0-DY \qquad (7)$$

The final correct solution for the system is then:

$$Y(t)=Y_o+\left(Y_i-Y_0-\frac{W}{D}\right)e^{-\frac{D}{M_{air}+M_{wall}Kads}t}+\frac{W}{D} \qquad (8)$$

The extra term $M_{wall}K_{ads}$ in the exponential has increased the time constant of the phenomenon (not the final value) and now explains the long observed duration.

Actually, M_{wall} should be considered as the fraction of the hygroscopic material that is likely to equilibrate rapidly with the air. It could be, for instance, the first millimetres of plaster on the walls. For plaster, the water sorption isotherm can be found in the literature[7] and a value of K_{ads} = 40 can be estimated. Let us guess a value M_{wall} = 25 kg, then Eq. (8) yields t_{final} = 35.7 h, which is quite realistic for our experiment. Anyway, although our estimation for the wall parameters is probably correct, it is reasonable to consider these values only as adjustment parameters to account for the long observed duration.

It is useful to compute the different quantities of water involved in the operation. In Table 2 the different equations for these values are given.

TABLE 2
Different Equations for Different Quantities of Water Involved

Q_w evaporated water	$Q_w = Wt_{final}$	Eq. (9)
Q_{air} water contained in the inner air at the end	$Q_{air} = M_{air}Y_{inf}$	Eq. (10)
Q_{wall} water contained in the walls at the end	$Q_{wall} = M_{wall}K_{ads}Y_{inf}$	Eq. (11)
Q_{input} water input by incoming cold air	$Q_{input} = DY_0t_{final}$	Eq. (12)
$Q_{accwall}$ water accumulated in the walls	$Q_{accwall} = M_{wall}K_{ads}(Y_f-Y_i)$	Eq. (13)
Q_{accair} water accumulated in the air	$Q_{accair} = M_{air}(Y_f - Y_i)$	Eq. (14)

The water quantity that has been transported outside by the ventilation is Q_{evac} and can be computed by integration

$$Q_{evac}=D\int_0^{t_{final}}Y(t)dt$$

using Eq. (8) whose integral is:

$$\int Y(t)dt=\left(Y_0+\frac{W}{D}\right)-\frac{M_{air}+K_{ads}M_{wall}}{D}\left(Y_i-Y_0-\frac{W}{D}\right)e^{-\frac{D}{M_{air}+M_{wall}Kads}t} \qquad (15)$$

Numerical values are given in Table 3, and the time evolution of the absolute and relative humidity are presented in Figure 2.

Checking the mass balance $Q_{input} - Q_{evac} + Q_w = Q_{accair} + Q_{accwall}$ ascertains the computation.

TABLE 3 Quantities of Water Involved in the Humidification of the House						
Q_w	Q_{air}	Q_{wall}	Q_{input}	Q_{evac}	Q_{accair}	$Q_{accwall}$
14.3 kg	1.5 kg	5.25 kg	12.8 kg	23.5 kg	0.79 kg	2.76 kg

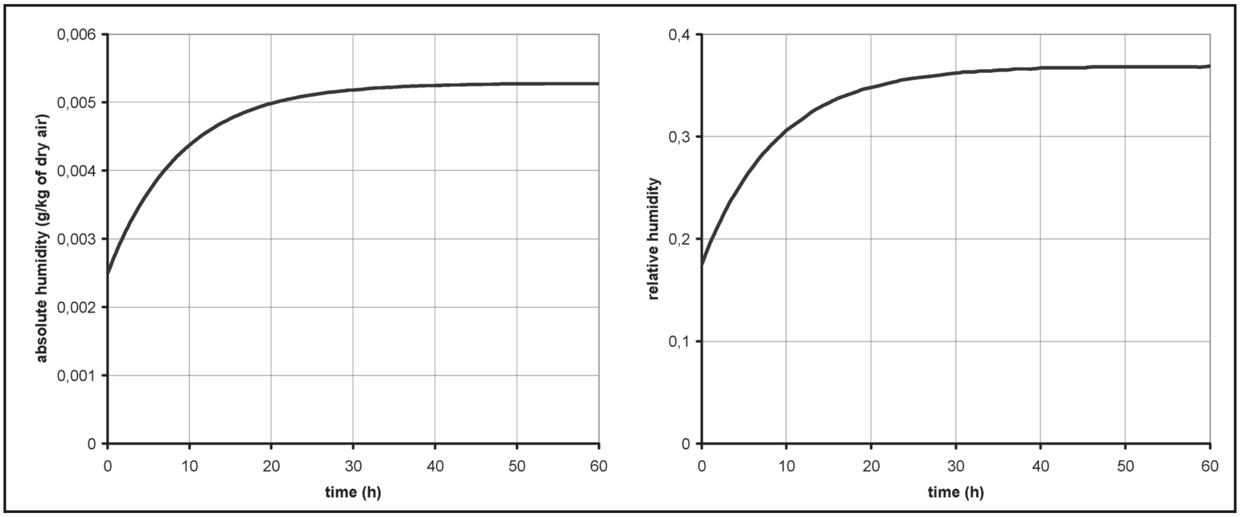

Figure 2. *Time evolution of the indoor absolute and relative humidity.*

It is very surprising that the quantity of water effectively brought to the air (Q_{accair} = 0.79 kg) is very low in comparison to all other values and especially to the quantity of water produced, Q_w = 14.3 kg. A lot of water has been inefficiently produced, adsorbed, or transported! Also, to maintain $\varepsilon = 0.37, 0.4$kg/h of water now has to be continuously injected in the air by the humidifier.

All computations were done using the Mathcad® software and corresponding files can be found at <http://lgc.inp-toulouse.fr/internet/pers/condoret.htm>.

Finally, the model with the proposed estimated parameters is very likely to give a good description of the humidification process of a house. Indeed, one experiment (which could be done only by measuring the steady state relative humidity and the needed time to reach it) allows identifying all parameters and the model can be used to predict other scenarios. Indeed, the modeling is also valid for the case of dehumidification, which is necessary in summertime. In this case incoming warm humid air is dehumidified using devices where excess water in the air is condensed on cooled surfaces at a temperature below the air dew point. In this case, the term W in the equations has only to be set to a negative value.

There is an additional interesting computation about the energetic cost of humidifying the air compared to the energetic cost for a simple heating of the air. In other words, how much does it cost to improve the quality of life in the house?

It is obtained from:

$$\frac{\text{power for humidification}}{\text{total power transferred to the air}} = \frac{D\left(H_{20°C}^{Y_{inf}} - H_{20°C}^{Y_0}\right)}{D\left(H_{20°C}^{Y_{inf}} - H_{0°C}^{Y_0}\right)} = \frac{\left(H_{20°C}^{Y_{inf}} - H_{20°C}^{Y_0}\right)}{\left(H_{20°C}^{Y_{inf}} - H_{0°C}^{Y_0}\right)} \quad (16)$$

where $H_{t°C}^{Y}$ is the enthalpy of humid air at t °C and absolute humidity Y.

The computation is done at steady state for the relative humidity of 0.5 that we initially targeted. Eq. (5) gives the needed water flow rate W = 0.67 L/h. It corresponds to the use of two humidifiers. Now, we understand the sentence "this device is adequate up to 40 m^2 rooms" written on the notice of the device. Nevertheless, note that all computations are done here without taking account of people in the house, while a four-person family is estimated to produce 0.2 kg/h of steam.[8]

Values of enthalpy can be computed or read on the psychrometric chart. It yields a humidification power that represents 37% of the total power, which is an unexpectedly high value. In fact, it corresponds to the heat power for the vaporization of the water droplets. This heat power is provided by the heating system of the house, which maintains the inner temperature at 20 °C. Nevertheless the total power for air (around 1.3 kW in this case) does not represent the total heating demand for the house. Indeed, the major part of heating power in the house is used for compensation of heat losses through walls, windows, and the roof.

CONCLUSIONS

In this example the concept and the importance of the relative humidity of air, which is not always well understood by students, is pointed out. Furthermore, it is worth remembering that this parameter is always related to the thermodynamic activity of the water contained in solids in equilibrium with the surrounding air. Students usually encounter this concept during the course about drying of solids. Here the relation between relative humidity of air and human comfort is indeed an indirect relation and water activity of physiological tissues is the pertinent parameter. This example can be further commented to students to emphasize the importance of the water activity (drying, conservation, vegetal extraction, enzymatic reactions, and many other domains where natural products are involved).

The main objective of this case study, however, is to show that the foundational approach that is taught in chemical engineering is able to provide solutions for problems that are outside this discipline. The pedagogical interest is maximum if the problem is presented to students in its iterative form, as is done in this paper. Because this example has dealt with an everyday problem, it is hoped that the students are interested and develop their physical sense as well as their critical sense in facing unexpected experimental results. At least, it has been shown here that methods of chemical engineering can have very diverse applications.

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NOMENCLATURE

H_{wall}	height of the house wall	(m)
$H^{Y}_{t°C}$	enthalpy of humid air at t °C and absolute humidity Y	(J kg^{-1})
K_{ads}	water adsorption constant on the wall coatings	(-)
M_{air}	mass of dry air in the house	(kg)
M_{wall}	equivalent mass of hygroscopic material	(kg)
Q_{w}	evaporated water	(kg)
Q_{air}	water contained in the inner air at the end	(kg)
Q_{wall}	water contained in the walls at the end	(kg)
Q_{input}	water input by incoming cold air	(kg)
$Q_{accwall}$	water accumulated in the walls	(kg)
Q_{accair}	water accumulated in the air	(kg)
Q_{evac}	water transported by the ventilation	(kg)
S_{floor}	surface of the house	(m^2)
$temp_{out}$	outside air temperature	(°C)
$temp_{in}$	inner air temperature	(°C)
t_{final}	final time	(s)
t_{renew}	time for air renewal	(s)
V	volume of the house	(m^3)
W	evaporation mass flow-rate	(kg s^{-1})
X	absolute humidity of the hygroscopic material	(-)
Y_0	absolute humidity of the outside air	(-)
Y_f	absolute air humidity at final time	(-)
Y_{inf}	absolute air humidity at infinite time	(-)
Greek letters		
ε	relative humidity of the air	(-)
ε_{inf}	relative humidity of the air at infinite time	(-)