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Air Dehumidification by Absorption

(A Model for Numerical Calculation)

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Synopsis

Especially in modern buildings with small capacity of humidity storage it is necessary to reduce the humidity in the supply air. Normally this was done by using a refrigeration system mostly with CFC's. There are some alternative fluids available, but mostly they show a high global warming potential. All these systems need electrical energy to be driven and therefore it is necessary to consider other possibilities with alternative systems.

The most promising systems are sorptive systems that are used now in open cycles. In these systems the air is dehumidified by a liquid sorbens and cooled indirectly by evaporating water in an open circuit. In order to calculate the process of absorption on several conditions, computer based calculations are required. A model that describes the dehumidification - process is introduced.

List of Symbols

A	transfer area	[m²]
c_p	specific heat capacity	[J/kg K]
C	water content (solution)	[kg water/kg salt]
dx	width of an element	[m]
dy	length of an element	[m]
h	specific enthalpy	[J/kg K]
k	coefficient of heat transmission	[W/m² K]
$\dot{m}$	mass flow	[kg/s]
p	partial pressure of vapour	[Pa]
p^*	partial pressure (saturation)	[Pa]
$\dot{Q}$	heat flux	[W]
r_0	specific heat of evaporation	[J/kg]
T	temperature	[°C]
$\bar{T}$	mean temperature	[°C]

V	variable of state	[-]
X	water content (air)	[kg water/kg dry air]
X*	water content (saturation)	[kg water/kg dry air]
y	concentration	[kg salt/kg solution]
	y - coordinate	[m]

Greek Symbols

α	heat transfer coefficient	[W/m²K]
β	mass transfer coefficient	[kg/m² s], [kg/m² s Pa]
η	dynamic viscosity	[Pa s]
ρ	density	[kg/m³]

Indices

CW	cooling water
G	gas (air)
i	counter of elements (x-direction)
j	counter of elements (y-direction)
L	liquid (solution)
LG	liquid-gas
S	salt
V	vapour
X	water content

1. Introduction

Heating, ventilating and air conditioning (HVAC) systems are build to process outdoor air to a special indoor air condition. The demand of the air quality depends on the kind of building. In an industrial building the quality of the products is very important, but in an office building the thermal comfort of the employees must be guaranteed. Basically the parameters temperature and humidity can be changed by special components of a HVAC-system.

Especially in modern office buildings with small capacity of humidity storage it is necessary to reduce the humidity in the supply air. The classical way to dehumidify the outdoor air is using a refrigeration system. Everybody knows the problems and the discussions about the refrigerants. For that it is very important to find alternative components to dehumidify the air.

An interesting technique to dehumidify air is using hygroscopical solid or liquid substances. The adsorption respectively absorption technology used in HVAC-systems is nowadays a good enlargement to the existing refrigeration systems but particulary by using liquid desiccants a high demand of research work is necessary. In this paper a model to calculate the dehumidification - process is described.

2. Dehumidification by Absorption

Several technologies in order to dehumidify moist air are imaginable. One possibility to remove water out of the air is to cool the air below the dew point. In this case water will condense at the surface of a chiller or water droplets. To reach the necessary dew point the condensation requires temperatures of nearly 6°C, these low temperatures can be realised by water cooled chillers. To guarantee comfort in the room the air often must be reheated after the dehumidification. Because cooling and heating of supply air consume a large amount of energy other methods of dehumidification are investigated.

By cooling the surface of a chiller below the dew point, the vapour-pressure at the surface is very low compared with the vapour pressure in the air flow. This pressure gradient will cause a movement of vapour in direction of the cold surface where condensation follows.

This mechanism is the basis to develop other methods of air dehumidification. There are materials, which reduce the vapour-pressure without being cooled and even when they are at a higher temperature than the air. Materials that reduce the vapour-pressure at their surface are called hygroscopic.

Desiccating by contact with hygroscopic materials is distinguished by the kind of the used materials, there are both solid and liquid desiccants. There is a great choice of solid materials for the use to dehumidify air. They can be used either for technical drying or in air conditioning plants. Silicagel and hygroscopic salts are privileged for the application in air dehumidifiers with solid desiccants.

This paper will introduce a model of an absorber in order to simulate the behaviour.

3. The open absorption cycle

The transfer of vapour between two phases causes a simultaneous transfer of heat in mostly the same direction. The difference between the temperatures of air and liquid causes a sensible heat transfer while the condensation of vapour initiates the occurrence of latent heat. So the total heat effect can be written as follows:

$$\dot{Q} = \alpha \cdot A \cdot (\overline{T}_G - \overline{T}_L) + \beta_p \cdot A \cdot (p - p^*) \cdot r_0 \qquad (1)$$

Moist air at the surface of the desiccant is assumed to be saturated. The knowledge of the dew point in dependence of the solution's conditions [4] allows the calculation of the water content of the saturated air. The difference of the partial pressures can now be replaced by the difference of the water contents of air.

$$\dot{Q} = \alpha \cdot A \cdot (\overline{T}_G - \overline{T}_L) + \beta_X \cdot A \cdot (X - X^*) \cdot r_0 \qquad (2)$$

Both the latent and the sensible heat lead to a higher temperature of the liquid desiccant. The appearing absorption heat is neglectible. Higher temperatures cause higher dew points and a higher water content by saturation, the hygroscopicity of the solution decreases. Therefore the plates of the absorber are cooled internally with water in order to prevent this effect. The temperature of the cooling water can be higher than the dew point, a refrigerating assembly is not necessary.

An experimental apparatus was constructed to obtain the quantity of the appearing heat and mass transfer coefficients. Fig. 1 shows the structure of one plate, the test-absorber consists of five plates.

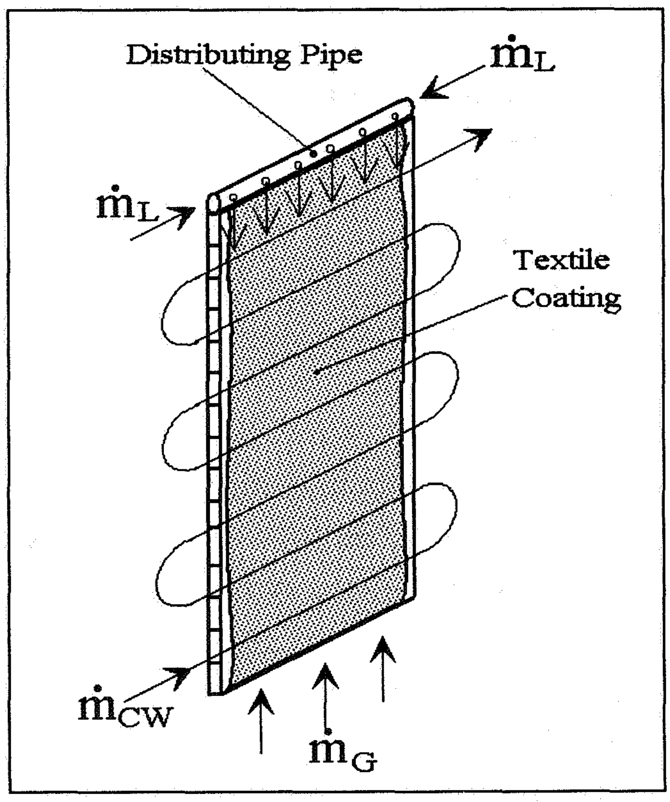

Fig. 1: Structure of an absorber plate

4. Development of the Model

4.1 Desiccants and Physical Properties

There's a great variety of hygroscopic materials for the use in the absorber. Desiccants for the purpose of technical drying are aqueous solutions of lithium-chloride (LiCl) or calcium-chloride ($CaCl_2$). The application in climate plants is also possible. In addition to this pure materials there's a mixture of $CaCl_2$, $Ca(NO_3)_2{\cdot}4H_20$ and an emulsifier „S" called „Klimat 3930 S" [2]. The behaviour of aqueous solutions of LiCl, $CaCl_2$ and Klimat 3930 S is investigated.

Some physical properties of the different solutions at varying temperatures and concentrations must be known. The most important are:
- density ρ,
- viscosity η,
- dew point at the surface of the desiccant respectively the water content at saturation,
- heat capacity of the aqueous solution.

4.2 The Model

To formulate the problem, the following assumptions are made:
- the flow is fully developed and laminar
- diffusion thermal effects are negligible
- the surface temperature of the liquid is equal to the bulk temperature
- the only gradient of variables of state occurs in the direction of flow
- the main resistance for the mass transport is in the air

The behaviour of the different substances are described by a system of differential-equations. These equations cannot be solved in an analytic way, the integration must procced numerically. The point-slope method developed by Euler and Cauchy allows an easy solution of the system [1]:

$$V_{j+1} = V_j + dy \cdot V_j'(y_j, V_j) = V_j + \Delta V_j \quad j = 0, \ldots, m \qquad (3)$$

y ... place, V ... variable of state

y_0, V_0 ... quantities at the beginning of the calculation (estimation)

(to estimate the properties of cooling water, j has to be substituted by i, y by x)

Because the gradient of the variables will change across the plate, the absorber must be devided into a number of elements. The gradients will be calculated in each element. Fig. 2 shows the model for the calculation of the absorber. Equation 3 shows that the variables and it's gradients must be calculated to estimate the quantities in the following element. Fig. 3 illustrates the method of calculation when the gradients in two adjacent elements are known.

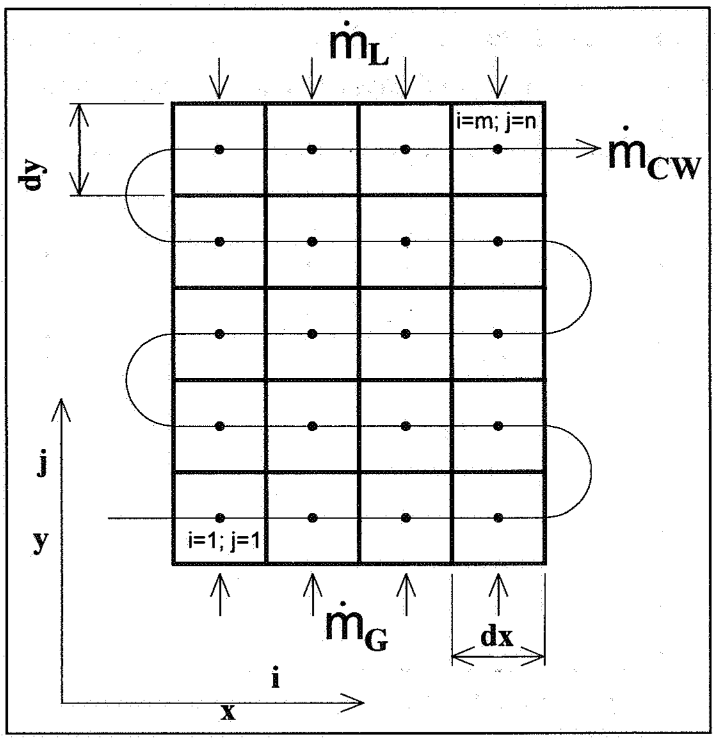

Fig 2 : Model of the absorber (one plate)

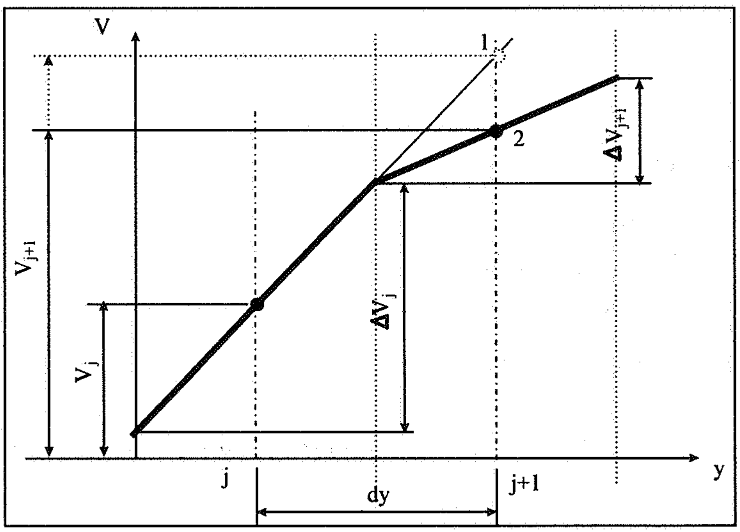

Fig. 3 : Calculation of variables of state in adjacent elements

Without knowing the value of ΔV_{j+1} point 1 in Fig. 3 is calculated:

$$V_{j+1} = V_j + dy \cdot V_j'(y_j, V_j) = V_j + \Delta V_j \quad (4)$$

Knowing the gradient of V_{j+1}, V_{i+1} can be calculated at point 2 in Fig. 3:

$$V_{j+1} = V_j + dy \cdot 0{,}5 \cdot \left(V_j'(y_j, V_j) + V_{j+1}'(y_{j+1}, V_{j+1})\right) \quad (5)$$

The gradients of the variables of state are evaluated by solving the mass and energy balance and the basic equation for the heat- and mass transfer in each element. Fig. 4 shows one element and the mass flows.

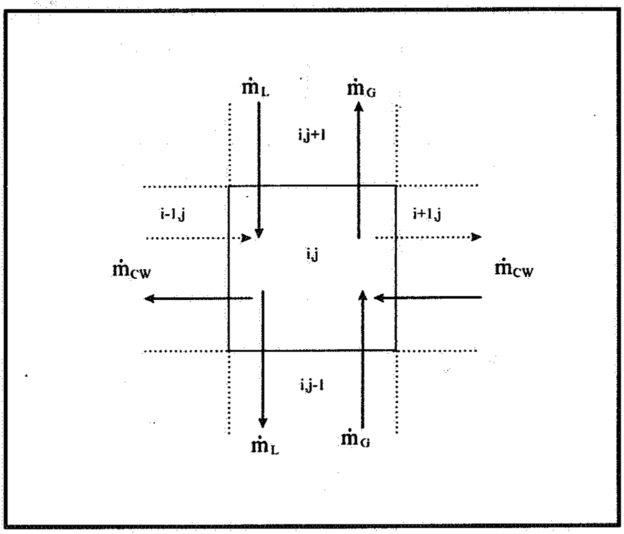

Fig. 4: Element and mass flows (mass flow of cooling water: dotted: j odd, continuos: j even)

The derivation of the equations to calculate the gradient of the air temperature and enthalpy is shown below exemplary.

Air:

IN: $T_{G\,in} = T_{G\,i,j-1} + ½\, \Delta T_{G\,i,j-1}$

$X_{in} = X_{i,j-1} + ½\, \Delta X_{G\,i,j-1}$

$h_{G\,in} = h_{G\,i,j-1} + ½\, dh_{G\,i,j-1}$

OUT: $T_{G\,out} = T_{G\,i,j-1} + ½\, \Delta T_{G\,i,j-1} + \Delta T_{G\,i,j}$

$X_{G\,out} = X_{G\,i,j-1} + ½\, \Delta X_{G\,i,j-1} + \Delta X_{G\,i,j}$

$h_{G\,out} = h_{G\,i,j-1} + ½\, \Delta h_{G\,i,j-1} + \Delta h_{G\,i,j}$

The modification of the specific enthalpy in element i,j can be calculated as follows:

$$\Delta h_{G\,i,j} = c_{pG} \cdot \left(T_{G\,i,j-1} + \frac{1}{2} \cdot \Delta T_{G\,i,j-1} + \Delta T_{G\,i,j} \right) + \left(X_{G\,i,j-1} + \frac{1}{2} \cdot \Delta X_{G\,i,j-1} + \Delta X_{G\,i,j} \right) \cdot \left(r_0 + c_{pV} \cdot \left(T_{G\,i,j-1} + \frac{1}{2} \cdot \Delta T_{G\,i,j-1} + \Delta T_{G\,i,j} \right) \right) - c_{pG} \cdot \left(T_{G\,i,j-1} + \frac{1}{2} \cdot \Delta T_{G\,i,j-1} \right) - \left(X_{G\,i,j-1} + \frac{1}{2} \cdot \Delta X_{G\,i,j-1} \right) \cdot \left(r_0 + c_{pV} \cdot \left(T_{G\,i,j-1} + \frac{1}{2} \cdot \Delta T_{G\,i,j-1} \right) \right) \quad (6)$$

Equation 6 is used to determine the change of temperature in element i,j. The variation of the enthalpy is given by change of temperature and humidity (equation 7).

$$\Delta h_{G\,i,j} = \frac{1}{\dot{m}_G} \cdot \alpha_{LG} \cdot dx \cdot dy \cdot \left(\bar{T}_{G\,i,j} - \bar{T}_{G\,i,j} \right) + r_0 \cdot \Delta X_{i,j} \quad (7)$$

y is known as the concentration (kg salt/kg solution) and C characterises the water content of the salt (kg water/kg salt). The relation between y and C is given in equation 8.

$$C = \frac{1-y}{y} \quad (8)$$

Because the mass flow of salt and dry air are constant, the specific enthalpy is related to them, equation 9 correlates the change of humidity and water content of the solution.

$$\Delta C_{i,j} = -\frac{\dot{m}_G}{\dot{m}_S} \cdot \Delta X_{i,j}; \quad \dot{m}_S = \dot{m}_L \cdot y \quad (9)$$

The physical properties and the gradients depend on temperatures and water contents. The solution of the system of differential equations requires an iterative calculation. The following equations show the complete system.

I. Water content of the air:

$$\Delta X_{i,j} = \frac{\beta_{i,j}}{\dot{m}_G} dx\, dy \left(X_{i,j} - X^*_{i,j} \right)$$

II. Water content of the solution

$$\Delta C_{i,j} = -\frac{\dot{m}_G}{\dot{m}_S} \Delta X_{i,j}$$

III. Specific enthalpy of the solution:

$$\Delta h_{L;i,j} = -\frac{2\, \dot{m}_G\, \Delta h_{G;i,j} + 2\, \dot{m}_S\, \Delta C_{i,j}\, h_{L;i,j+1} + 2\, \dot{m}_{CW}\, c_{p;CW}\, \Delta T_{CW;i,j} + \dot{m}_S\, \Delta C_{i,j}\, \Delta h_{L;i,j+1}}{\dot{m}_S \left(2 + 2\, C_{i,j+1} + 2\, \Delta C_{i,j} + \Delta C_{i,j+1} \right)}$$

IV. Temperature of the air:

$$\Delta T_{G;i,j} = -\frac{2\,\Delta X_{i,j}\left(r_0 + c_{p;V}\,T_{G;i,j-1}\right) - 2\,\Delta h_{G;i,j} + \Delta X_{i,j}\,c_{p;V}\,\Delta T_{G;i,j-1}}{2\,c_{p;G} + c_{p;V}\left(2\,X_{i,j-1} + 2\Delta X_{i,j} + \Delta X_{i,j-1}\right)}$$

V. Temperature of the cooling water:

$$\Delta T_{CW;i,j} = \frac{k_{i,j}\,dx\,dy\left(T_{L;i,j+1} + \frac{1}{2}\left(\Delta T_{L;i,j+1} + \Delta T_{L;i,j}\right) - T_{CW;i+1(-1)^j,j} + \frac{1}{2}\left(\Delta T_{CW;i+1(-1)^j,j} + \Delta T_{CW;i,j}\right)\right)}{\dot{m}_{CW}\,c_{p;CW}}$$

VI. Specific enthalpy of the air:

$$\Delta h_{G;i,j} = \frac{1}{\dot{m}_G}\,\alpha_{LG;i,j}\,dx\,dy\left(T_{G;i,j-1} + \frac{1}{2}\left(\Delta T_{G;i,j-1} + \Delta T_{G;i,j}\right) - T_{L;i,j+1} + \frac{1}{2}\left(\Delta T_{L;i,j+1} + \Delta T_{L;i,j}\right)\right) + r_0\,dX_{i,j}$$

VII. Temperature of the solution:

$$\Delta T_{L;i,j} = f(\Delta h_{L;i,j}) = \frac{\Delta h_{L;i,j}}{c_{pL}\left(y, T_{L;i,j}\right)}$$

A function that correlates enthalpy (or specific heat capacity), concentration and temperature of the solution must be known to calculate the change of the solution temperature. This interrelation depends on the composition of the solution.

While the properties of the different desiccants are well known, the calculation of the heat and mass transfer coefficients is difficult, investigations and measurements are essential for each type of absorber.

5. Conclusions

The introduced activity at the University of Essen is supported by the German *Bundesminister für Bildung, Wissenschaft, Forschung und Technologie (BMBF)*. The aim of this work is the investigation of an absorptive dehumidifier for the inset in air conditioning plants. The attention is turned on energetic aspects and the calculation of these systems. In order to calculate the complete cycle (with evaporative cooling of the air and regeneration of the solution) the model has to be expanded. Several results of measurements are made available from the Bavarian Center of Applied Energy Research (ZAE Bayern), Munich.

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