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Experimental and theoretical studies on heat and mass transfer in anti-condensation coatings

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Abstract Anti-condensation coatings are widely used in refrigeration, air conditioning and ships technology. They can store a certain amount of water in its own volume, and then return it back in favorable conditions. Anti-condensation coatings are used also to protect structures from the moisture. This paper presents the results of experimental research on heat and mass transfer in an anti-condensation coating under natural and forced convection. Experimental results are obtained for horizontal and inclined plates. Experimental data are compared with different models of computation.

Keywords: Anti-condensation coating; Heat transfer; Mass transfer

Nomenclature

- A – area, m^2
- c – specific heat, $J\ kg^{-1}K^{-1}$
- h – heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
- k – mass transfer coefficient, $m\ s^{-1}$
- Le – Lewis number,

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\dot{m}	–	mass flow rate, kg s^{-1}
\dot{Q}	–	rate of heat, W
R	–	universal gas constant, $\text{J mol}^{-1} \text{K}^{-1}$
t	–	time, s
T	–	temperature, K
v	–	velocity, m s^{-1}

Greek symbols

ε	–	emissivity,
φ	–	effective surface coefficient,
ρ	–	density, kg m^{-3}
σ	–	Stefan-Boltzmann constant, $\text{W m}^{-2} \text{K}^{-4}$

Subscripts

<i>air</i>	–	air
<i>heat</i>	–	heat transfer
<i>mass</i>	–	mass transfer
<i>ef</i>	–	effective surface
<i>fg</i>	–	evaporation heat
<i>s</i>	–	surface
<i>surface</i>	–	surface
<i>w</i>	–	water

1 Introduction

Anti-condensation coatings are used in cooling and air-conditioning applications. They can store some water within their own volume, and release it in favourable conditions. They also prevent structures from getting wet. Large, open spaces are often covered without the need to provide thermal insulation layer. Such applications can be found at stadiums, stands, parking lots, garages, shelters and cold stores. Profiled sheet is well suited for constructing such roofing. As weather conditions change frequently, water vapour tends to condense on the bottom side of the sheet, which may lead to damages relating to the moisture presence. The capacity to store some water within their own volume makes anti-condensation coatings capable to provide better protection to cold rooms in cooling applications, since they prevent the condensate from flowing down on the room surface. Also, the dripping water significantly degrades the isolation qualities of a part of the cold room ceiling and walls, which is the consequence of increased moisture and isolation deterioration. Furthermore, keeping the water out of the materials the cold room is made of increases their durability; the lack of moisture on the cold room surface minimizes corrosion of these ma-

terials. The anti-condensation paints are used to cover sections of piping where it is impossible to implement traditional isolation techniques, and on steel parts of electronic or telecommunications devices. In shipbuilding and armament industries, the anti-condensation coatings are used to cover outer surfaces: ship decks and fighting vehicle armours. In housing industry, these coatings are found in places with high moisture content, such as bathrooms and kitchens, and the covering of mobile houses, caravans or yachts. The anti-condensation paints contain biocide-based substances that stop microbiologic contaminants from developing under increased moisture conditions. This feature makes them suitable for protecting such rooms as underground parking lots, basements, cold storage rooms, potable water tanks, grain silos, and meat and fruit-and-vegetable processing plants against moisture and microbiologic contaminants. Most anti-condensation coatings are non-flammable and atoxic, and emit no toxic gases. They can be used in rooms with food hygiene requirements. The anti-condensation coatings also protect from corrosion. They prevent the drops of water from accessing corrosion-sensitive surfaces and structures, as the water absorbed by the anti-condensation agent is distributed within a wide area of the coating. After the condensation process stops, the absorbed water quickly evaporates. Another common feature of the anti-condensation coatings is the sound absorption; they dampen the vibrations in metal sheets, which to some extent helps to bring down the level of noise caused by wind or rain.

2 Theoretical model

Drying of the anti-condensation coating is a heat and mass transfer process. The coating is very thin so the coating surface temperature T_{surf} can be treated as temperature of the whole coating layer.

The heat supplied from outside is used to evaporate water and to change the anti-condensation surface temperature. The heat is supplied in two ways: by convection and by radiation. In our model, conduction is neglected because in the experimental apparatus the bottom plate is strongly isolated. In many models radiation is neglected too [1] but, according to our calculations, the radiation is a very significant part of the heat flux. Figure 1 shows the idea of the heat and mass transfer. We can write the following equation for the rate of heat from the coating environment [6]:

$$\dot{Q} = h_{heat} A_s (T_{air} - T_{surf}) + A_s \sigma \varepsilon (T_{air}^4 - T_{surf}^4). \quad (1)$$

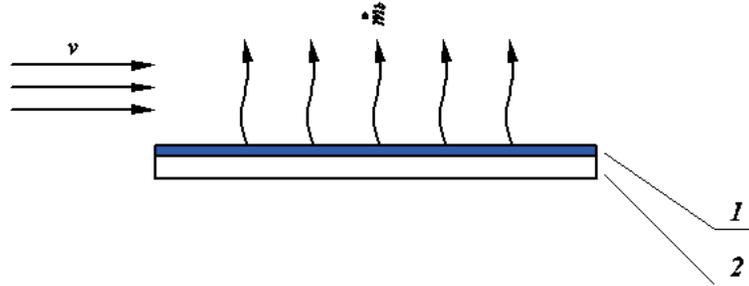


Figure 1. Idea of mass transfer in the anti-condensation coating. 1 – anti-condensation coating, 2 – aluminum plate strongly isolated from the bottom.

At the same time, water is evaporating from the anti-condensation coating at the mass flow of

$$\dot{m}_b = k_{mass} A_{ef} (\rho_{w,surf} - \rho_{w,air}), \quad (2)$$

where A_{ef} is the effective area, and it means that the water is evaporating only from the part of the surface area A_s [1],

$$A_{ef} = \varphi A_s, \quad (3)$$

where φ will be called an effective surface coefficient. Using the ideal gas equation of state, we can convert Eq. (2) to

$$\dot{m}_b = k_{mass} \varphi A_s \frac{M_s}{R} \left(\frac{P_{surf}}{T_{surf}} - \frac{P_{air}}{T_{air}} \right). \quad (4)$$

To combine the heat transfer with mass transfer we can use the Chilton-Colburn analogy [2]:

$$k_{mass} = \frac{h_{heat}}{\rho c_p Le^{\frac{2}{3}}}. \quad (5)$$

Thus

$$\dot{m}_b = \frac{h_{heat}}{\rho c_p Le^{\frac{2}{3}}} \varphi A_s \frac{M_s}{R} \left(\frac{P_{surf}}{T_{surf}} - \frac{P_{air}}{T_{air}} \right). \quad (6)$$

On the basis of the energy conservation law, we can write the following equation:

$$h_{heat} A_s (T_{air} - T_{surf}) + A_o \sigma \varepsilon (T_{air}^4 - T_{surf}^4) = \dot{m}_b h_{fg} + \frac{m_{ws} c_{p,ws} dT_{surf}}{dt}. \quad (7)$$

Another formula follows from the mass conversion law. The change in the coating mass depends on the evaporation rate.

$$\frac{dm_s}{dt} = -\dot{m}_b. \quad (8)$$

To solve the drying problem, Eqs. (7) and (8) have to be solved.

2.1 Drying kinetics

According to the theory of drying [2,4], the drying process should be divided into two periods: one of the constant drying rate and one of the falling drying rate (Fig. 2). The first stage of drying is the period of the constant rate. After crossing the critical point, the process continues with the falling drying rate.

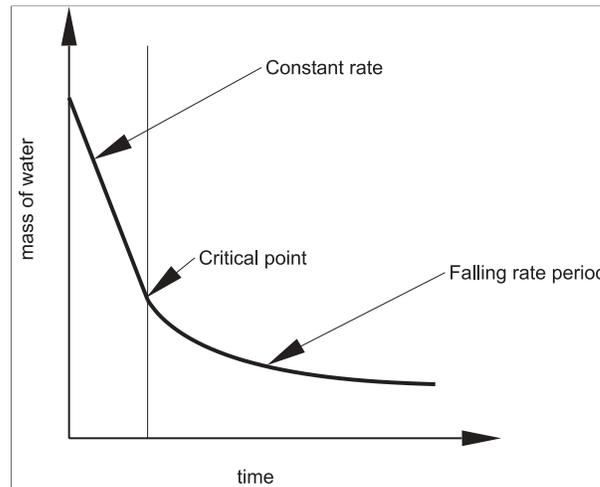


Figure 2. Drying rate periods.

At the same time, as shown in Fig. 3, the variable drying rate period consists of two subperiods. In the first one, the decline in mass flow rate is linearly proportional to the water mass, while in the second one the linearity disappears.

Figure 4 shows the change in the surface temperature T_{surf} over time. As can be seen, the temperature initially increases until it reaches a fixed value. Then, after crossing the critical point, the temperature begins to rise again, approaching the ambient temperature T_{air} .

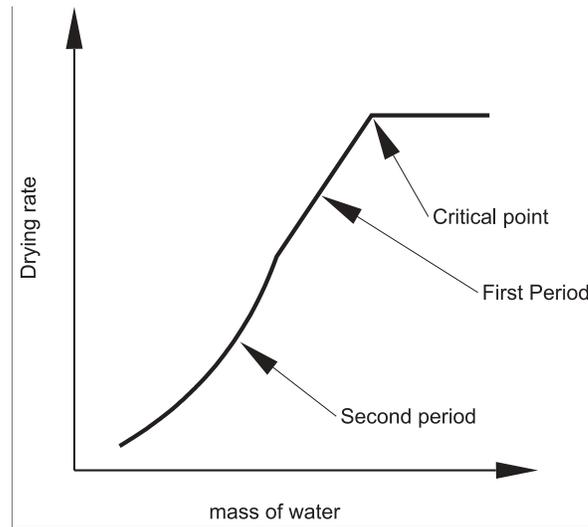


Figure 3. Change in the drying rate during the drying process.

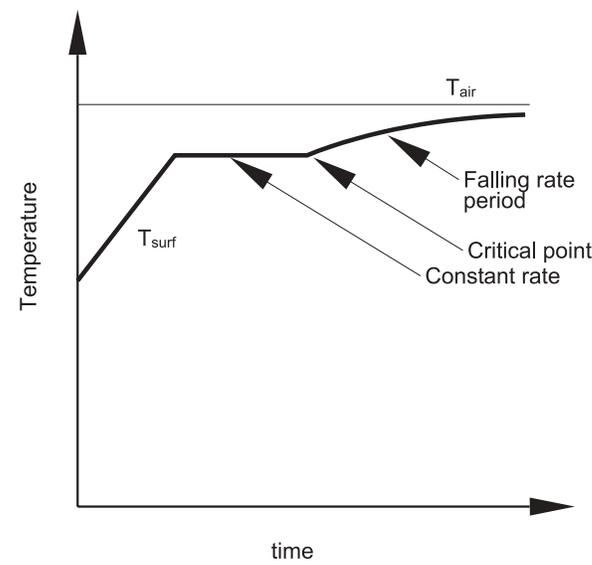


Figure 4. Surface temperature during the drying process.

3 Experiment

An experimental apparatus (Fig. 5) was built to obtain information about the water mass change in the anti-condensation layer during the drying

process. The apparatus can provide data under natural convection and forced convection at variable air flow [3].

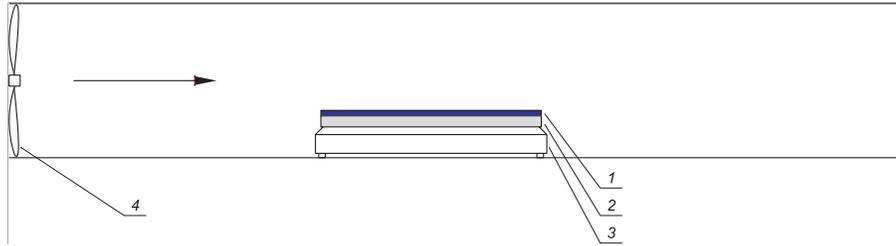


Figure 5. Experimental apparatus. 1 – anti-condensation layer, 2 – aluminum layer, 3 – weight, 4 – fan.

For the test purposes, flat aluminum 193 x 193 x 2 mm plates were prepared, covered with 0.45 mm-thick triple-layer anti-condensation coating. Before the tests, each surface of the plates was wetted with water at 180 g/m². Then each plate was put on a pre-calibrated scale. This test aimed at analyzing the convection of the mass from the surface of the plate, with the aid of a precision scale connected to a computer which recorded changes in the mass values. The ambient conditions as recorded during the test: temperature 22.5 °C, pressure 1013.25 hPa, relative humidity 0.38. A water table evaporation test under natural convection conditions was also performed to compare the results.

Three cases were studied: one under natural convection, and two others at the duct air flow of 0.8 m/s and 1.2 m/s. Figure 6 shows the results

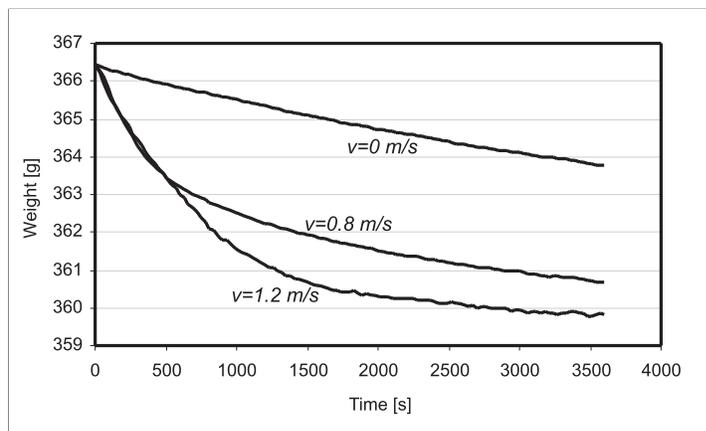


Figure 6. Experiment results.

of the experimental drying of the anti-condensation coatings in the above mentioned three cases. The weight shown is the weight of the plate with the paint and water. As expected, the shortest drying time occurred in the process with the highest air flow.

4 Calculation results

According to the theory of drying, and the experiment, it is clear that the drying process consists of two periods. The first stage is drying with a constant stream of evaporated water, while the other starts, after passing the critical point, when the water flow decreases. Both these steps must be considered separately. Quite significant is the fact that the critical point has to be determined experimentally. In the case of the natural convection ($v = 0$) the identification of the critical point proved to be impossible. This follows from the fact that the experiment lasted so long that the assumed conditions of work, mainly adiabatic conditions of the aluminum plate, were not maintained. Therefore, the natural convection was not taken into account in further analysis.

After determining the critical point it was possible to determine the boundary conditions for Eqs. (2) and (7). Hence, it was possible to complete the analysis of drying conditions of the anti-condensation layer. Figure 7 shows the temperature change under forced convection at $v = 0.8$ m/s,

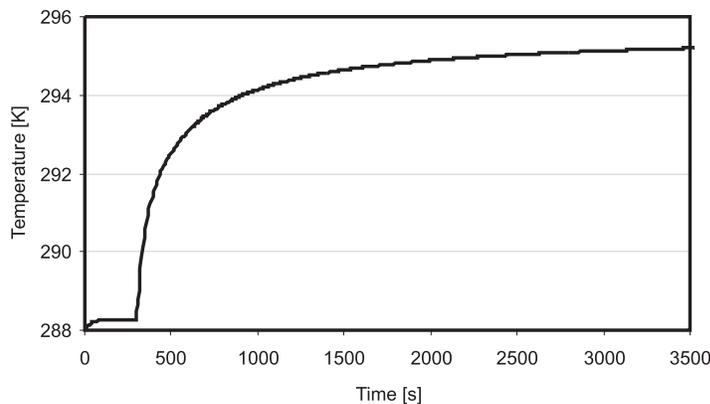


Figure 7. Surface temperature change during drying at the air velocity $v = 0.8$ m/s.

while Fig. 8 shows the change in the water mass flow rate as a function of weight content in the coating. Figure 9 shows the comparison of the simulation results to experimental studies of forced convection at the air velocity $v = 0.8$ m/s.

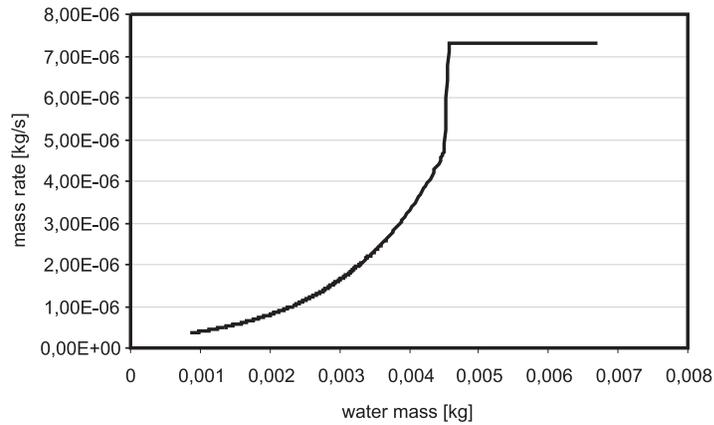


Figure 8. Mass flow rate change during the drying process at the air velocity $v = 0.8$ m/s.

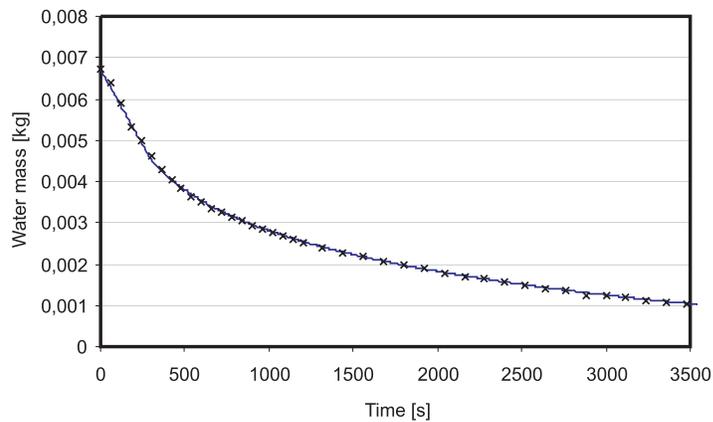


Figure 9. Water mass change during the drying process. Solid line – calculation, sharps – experiment.

Figures 10, 11 and 12 show the results of calculations for the air velocity $v = 1.2$ m/s.

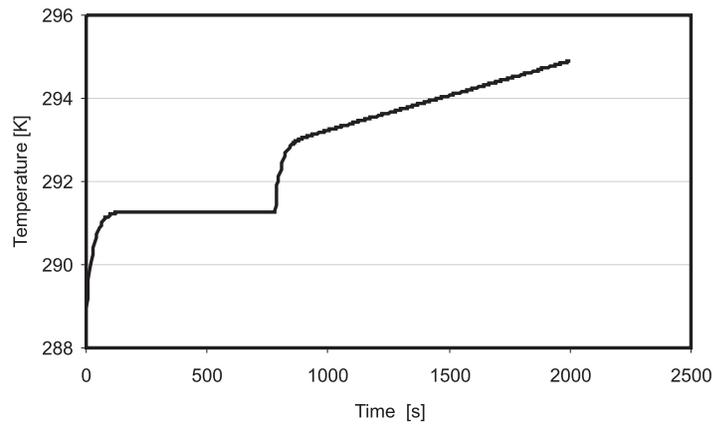


Figure 10. Surface temperature change during drying at the air velocity $v = 1.2$ m/s.

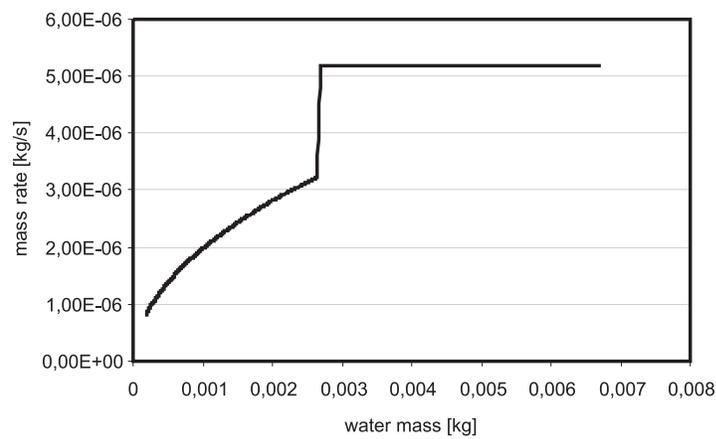


Figure 11. Mass flow rate change during the drying process at the air velocity $v = 1.2$ m/s.

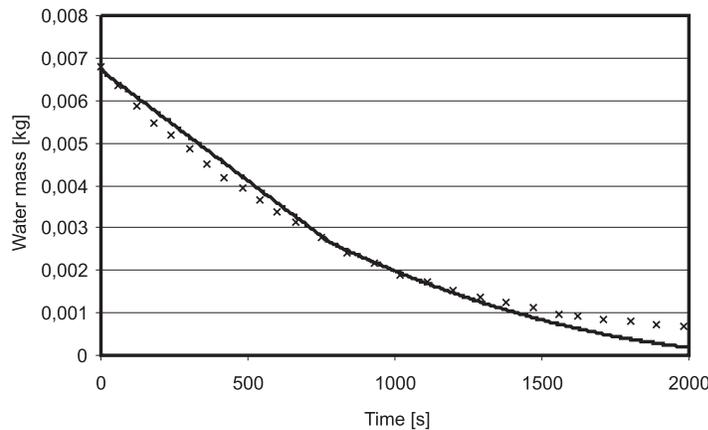


Figure 12. Water mass change during the drying process at the air velocity of $v = 1.2$ m/s. Solid line – calculation, sharps – experiment.

5 Conclusions

Modeling of the drying process involves a combination of heat and mass transfer. The exchange of mass in the case of drying consists of several steps that must be considered separately. Some scientists say that the solution of the conservation of mass equation can be one equation in the whole range [5]. In contrast, our study did not confirm this. It is impossible to correctly solve in the same way the equation for the fixed-ratio phase evaporation stage with a variable coefficient. Moreover, the main problem of the simulation is determination of the drying critical point. It depends on the rate of the heat and mass transfer, the dried material, and the ambient conditions. Without knowing the critical point, carrying out a drying simulation can be very difficult, but when the critical point is determined, the simulation results are very consistent with experimental research, which can be observed in Figs. 9 and 12.

The process involving higher air flow rates is more efficient for continuous evaporation and results in lower concentration of water in the dried material.

With regard to certain anti-condensation coatings used in refrigeration, it is worth noting that they were often used in the area of variable evaporation rates, so the modeling of this type of application should focus only on that area.

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