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Methods for assessment of a cooling tower plume size

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ABSTRACT
Currently, several methods exist for assessment of the total size of a cooling tower plume, which is created in the space above the evaporation cooling systems. Practically all the available methods, however, allow only qualitative assessment of this size. With the development of moisture recovery systems, there is a need to quantify the cited phenomenon, particularly to allow for assessment of MRE systems. The contribution for this reason discusses the compilation of a simple mathematical model on whose basis the cited quantification may be done. At the same time, it has also been proven that not even one of the methods applied to date can give correct results

Keywords: cooling tower, moisture recovery systems, plum abatement, wet cooling

I. INTRODUCTION

The problem of formation, spread and generally the size of the plume is discussed in many publications. As a typical example, it is possible to state, for instance [1], [2], or [3]. This is an issue that is closely related to the theory of moist air, where due to the mixing of two air masses of varying states condensation of water vapour occurs in the area above the evaporation cooling systems (cooling towers of various types) forming droplets. The size of the plume, which is the major topic of this paper is then assessed using the position of the points that correspond to the individual states in the Mollier diagram h_{1+x}-x (see Figure 1) depending on three basic indicators:

a) the distance between the points of the intersections of the limit curve with the connecting line of both initial moist air states,
b) the size of the angle between the limit horizontal lines in the h_{1+x}-x diagram and the connecting line of both initial states,
c) the size of the space closed on one side by the saturation line and on the other by the connecting line between points 1 and 2.

State 1 in the Mollier diagram h_{1+x}-x corresponds to the state of the ambient air, state 2 corresponds to the heated supersaturated moist air leaving the cooling tower. If the connecting line of the given two points intersects the saturation curve at any point, it is possible to prove that condensation occurs in the area above the cooling tower and, hence, formation of a visible plume.

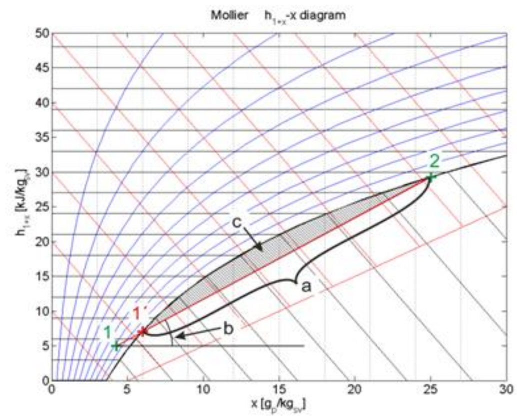

Figure 1: Individual approaches to assessment of the plume mass

II. MATHEMATICAL MODEL

For the purposes of this paper, a maximally simplified procedure was designed for calculation of the velocity field and the relative humidity deduced from it, which makes it possible to get a basic idea of the mechanism of the formation of the plume and its spread. The procedure is based on the defined velocity, temperature and concentration field derived in [4]. The derivation of the velocity field is based on the idea of maintaining the overall momentum flux carried by the effluent air-flow from the cooling tower. In principle, the case can be simplified to a non-isothermal flood flow, whose basic geometrical characteristics are given in Figure 2.

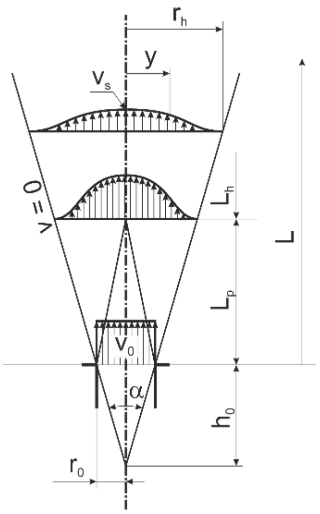

Figure 2: Implementation of the geometrical characteristics of the flood flow

If the influence of the different densities of the effluent air flow and ambient air are neglected for the first approximation, it is possible to write,

$$L_p = \frac{0{,}67 \cdot r_0}{a},$$

$$h_0 = \frac{0{,}29 \cdot r_0}{a},$$

$$r_h = 3{,}3 \cdot r_0 \cdot \frac{v_0}{v_s},$$

$$v_s = \frac{0{,}96 \cdot v_0}{\frac{a \cdot L}{r_0} + 0{,}29},$$

$$v = v_s \cdot \left[1 - \left(\frac{y}{r_h}\right)^{3/2}\right]^2$$

where L_p (m), r_0 (m), r_h (m) and h_0 (m) are defined, Figure 2, v ($m.s^{-1}$) determines the local velocity, v_s ($m.s^{-1}$) is the velocity in the flow axis, v_0 ($m.s^{-1}$) the output velocity form the cooling tower and a (1) is the correction factor relating to the turbulence intensity of the output flow.

The defined velocity field may subsequently occur in the event of mixing of two different gases and field of concentration according to equation (6). The deducing of this equation is then based on the assumption of similarity between the momentum and mass transfer.

$$\sqrt{\frac{v - v_{amb}}{v_s - v_{amb}}} = \frac{c_i - c_{i,amb}}{c_{i,s} - c_{i,amb}} = 1$$

where the dimensionless coordinate ξ is defined as

$$\xi = \frac{y}{r_h}.$$

From the thermodynamics point of view, an isobaric mixing of two humid air flows at different states occurs in the area above the cooling tower. If this state is stationary (i.e. pressure, temperature, humidity as well as mass flow of both air flows stays constant in time prior to mixing), we can find the final air state in the Mollier diagram h_{1+x}-x using the lever rule (see Figure 3), while we indicate, with an arbitrarily set scale, the air mass flow corresponding to the flow of air in state 2, and on the perpendicular from point 2 (at the same scale) we indicate the mass flow corresponding to the state of air from point 1 (the mass flow must be drawn in the opposite direction to the one drawn in point 2). The point of intersection of the line between points created this way and of the join between the points 1 and 2 determines then the state of air after mixing.

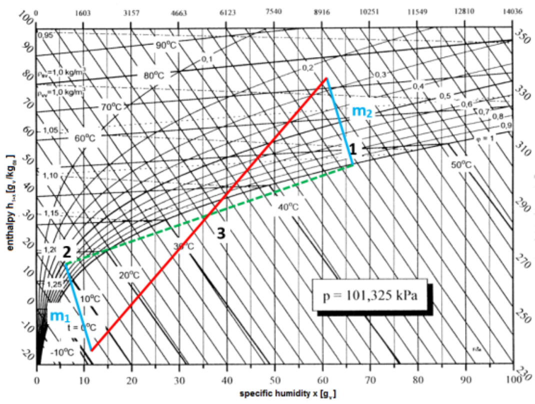

Figure. 3: Lever rule in the Molliere h_{1+x}-x diagram

Based on the statements above we can approach the calculation-based resolution of the occurrence of the cooling tower plume as a calculation of concentration field of the above mentioned components. The equation for the measured humidity in the area above the cooling tower then takes the shape (see equation 7)

$$x = x_1 + (x_s - x_1) \cdot \sqrt{\frac{v}{v_s}},$$

where x_s is determined using the equation

$$x_s = \frac{0{,}96 \cdot (x_2 - x_1)}{\frac{a \cdot L}{r_0} + 0{,}26} + x_1 .$$

The specific humidity fields calculate on the basis of the velocity field and equations (7) and (8) is in the graph in Figure 4.

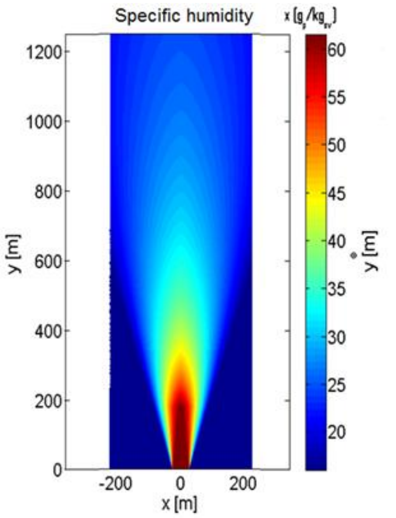

Figure 4: Specific humidity filed in the area of the cooling tower plume

From the locations of individual points within the h_{1+x}-x diagram acquired in Figure 3, it is possible to locally determine the applicable condensed volume as the difference of the actual specific humidity and the humidity at the saturation curve for the same enthalpy value.

III. RESULTS OF THE MODEL

From the results given in the preceding paragraphs, it is possible to deduce several interesting conclusions, which allow better comprehension of the behaviour of the entire multiphase system in the area above the cooling tower. In terms of the basic physical variables, which are involved in this issue, and whose influence on the sizess of the plume shall be monitored, it is possible to identify the following:

- temperature and humidity of the ambient air,temperature and humidity (respectively, supersaturation level) of the air leaving the cooling tower,
- air velocity at the outlet from the cooling tower,
- average droplet size at the exit from the cooling tower,
- outlet diameter of the cooling tower,
- coefficient of non-homogeneity of the velocity profile and, if also monitored, the shape of the plume, and at the same time the velocity of the ambient flow. In terms of the compared variables, it is then possible to consider:
- maximum percentage increase in the droplets diameter in the plume,
- volume of space occupied by the plume,
- total volume of water condensed in the plume.

For assessment of the size of the plume, from the parameters stated above, it is best to assess the overall volume, which the plume covers in the space above the cooling tower.

It is possible to show that dependence of the size of the plume on the diameter of the cooling tower is cubic in character (see Figure 5) and is based on the equation

$$V_{plume} = K \cdot D^3, \quad \text{where} K = f\left(t_{in}, t_{OK}, \varphi_{in}, \varphi_{OK}\right)$$

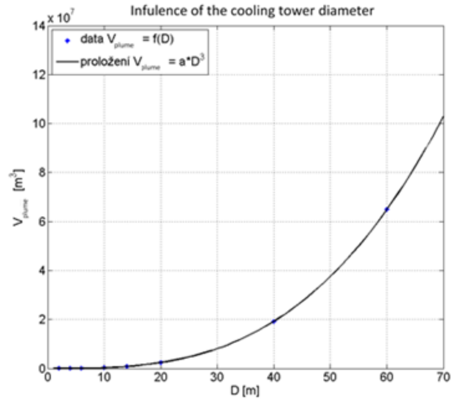

Figure 5: Influence of the outlet diameter of the cooling tower on the size of the plume

The last question that remains is what this dependence of coefficient K in the above equation (9) on the parameters of the ambient air and cooling tower output air really is. It can be demonstrated that the size of coefficient K can best be defined using the ratio of the distance of the intersection of the connecting line of the initial states of both air masses with the state at the cooling tower output to the distance of the that same intersection with the state of the ambient air. This dependence is again cubic and can be expressed in the form of an equation (10)

$$K = C_1 \cdot \left(\frac{x_2 - x_{1'}}{x_{1'} - x_1}\right)^3$$

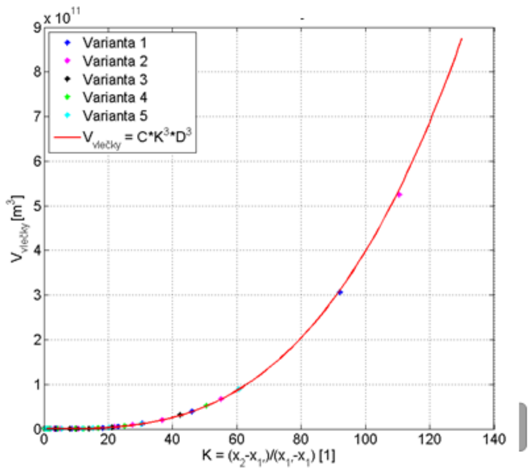

Figure 5: Influence of the outlet diameter of the cooling tower on the size of the plume

The independence of coefficient C_1 can best be demonstrated by interpolation of the results of the model acquired for various combinations of the cooling tower diameters and conditions of both air masses. This interpolation is given in the graph in Figure 6 together with the calculated spreadsheet data

Table 1: Independence of coefficient C

No.	t_{in} [°C]	t_{amb} [°C]	C [1]
1	40	20	2.50
2	30	10	2.47
3	40	25	2.58
4	30	15	2.55
5	20	5	2.55

IV. CONCLUSION

Among the major conclusions, it is possible to include mainly the derived dependence of the size of a plume on the geometrical parameters of the cooling tower and, mainly, on the characteristics of both air masses involved. The resultant equation may be written in the format

$$V_{plume} = C_1 \cdot \left(\frac{x_2 - x_{1'}}{x_{1'} - x_1}\right)^3 \cdot D^3$$

It is a very simple relationship that makes it possible, not only, to assess whether the plume has formed, but mainly directly calculate its assumed size. At the same time, it is also important that the size of the plume according to the cited model does not depend on parameters other than those given in equation (11). Among other things, for instance, the size of the plume does not depend on the inlet velocity of the air from the cooling tower, supersaturation of wet air, etc.

The model makes it possible to also deduce other variables, for instance, overall condensed water volume in the plume, etc., which may be significant, e.g. when deducing the efficiency of MRE systems.

ACKNOWLEDGEMENTS

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