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Atmospheric evaporation of open, still water surface
under steady-state conditions

Thesis Booklet of PhD Dissertation

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INTRODUCTION, GOALS

The phenomenon of evaporation plays an important role in the household, in meteorology and in the field of technical applications. During industrial evaporation, the liquid loss cannot be neglected in many cases, as it must be replaced, but in some cases, the concentration of the pollutant released into the atmosphere by evaporation can also be an important parameter. Thus, in many cases it is essential to know the evaporation rate of swimming pools, water reservoirs, lakes, and cooling ponds. The correct calculation of the evaporation rate is crucial for the operational designing of an air handling system operating in a swimming pool, as well as for the determination of energy consumption. Underestimating the evaporation rate can lead to undersizing the air handling system, and overestimating it leads to higher investment costs and unreasonably high energy consumption, thus higher operating costs. There is an increasing need for a more accurate estimate of the drinking water supply, since in dry environments, part of the water in reservoirs and lakes is lost to the environment through evaporation. The loss is probably unavoidable but knowing its magnitude and the factors affecting evaporation is essential in order to be able to replace this quantity or reduce the amount of loss. In power plants, cooling ponds are also used to reduce the temperature of the cooling water used for cooling purposes, and the determination of evaporation heat loss is a critical point when sizing them.

During evaporation, the thin layer of gas above the liquid surface becomes saturated with liquid vapor as a result of molecular diffusion. If there is no gas movement, then the vapor spreads further into the bulk gas by diffusion. If there is forced gas movement, the saturated gas layer is entrained by the gas stream and replaced by drier gas, thus increasing the driving force of the rate of evaporation. In mixed convection, the effects of the buoyancy force resulting from the gas density difference and the forced movement resulting from the gas velocity are almost the same, so they must be considered together. This evaporation process is influenced by several gas and liquid conditions and properties. Currently, no correlation can be found in the literature that could be used to determine the evaporation rate with high confidence under given conditions. In addition, the literature correlations can only be used if it is known what are the validity ranges to their use, however, these are missing in most cases. In addition, the results they provide are highly dependent on the measuring equipment used and the technical conditions of the measurement.

The research of simultaneous heat and mass transfer, mainly in the field of drying, already has a history at the Department of Building Services and Process Engineering. For the evaporation of open water surface under natural, mixed or forced convection, I propose dimensionless equations with which the evaporation rate can be calculated for given gas and liquid conditions. To create the latter correlation, the convection dryer in the Stokes Laboratory (*Fig. 1*) is equipped with state-of-the-art mechanical and measurement techniques, so it is suitable for testing liquid evaporation.

Goals

During my research, I investigated the evaporation of open liquid surface under natural, mixed and forced convection. The aim of my research was to create a correlation suitable for determining the evaporation rate of water, which can give the value of the evaporation rate with a small error in a wide validity range. So my research work consisted of the following main steps:

1. Based on literature sources, the systematization of investigating and grouping the evaporation of liquids, and the collection of correlations for the determination of the evaporation rate.
2. Development of a grouping method based on gas and liquid conditions for the evaporation of the open liquid surfaces in the cases of natural, mixed and forced convection.
3. Development of a calculation algorithm for determining the parameters of dimensionless equations suitable for describing the evaporation of open liquid surface with steady state gas and liquid conditions under natural, mixed and forced convection.
4. Based on measurement and literature results, development of dimensionless equations suitable for describing the evaporation of open liquid surface with steady state gas and liquid conditions under natural, mixed, and forced convection.
5. Comparison of the new dimensionless equations with literature correlations.



Figure 1. Measuring station suitable for testing evaporation rate

LITERATURE REVIEW

Researchers have been dealing with the evaporation of liquids since the 1800s, and the large amount of publications produced during the past decades proves the complexity and importance of the phenomenon of evaporation. Evaporation can be grouped according to different aspects, such as the nature of the gas flow, the type and direction of the driving forces, the equation that determines the evaporation rate, and the type of evaporation. According to the gas flow [1]–[4], we can talk about evaporation under natural, mixed and forced convection. This grouping method is very common in the literature, however, apart from air velocity, it does not take into account the effect of other parameters affecting evaporation. The basics of the phenomenon of evaporation are used in the grouping according to the type (difference in humidity content and temperature) and direction of the occurring driving forces [5], however, this does not take into account changes in place and time. If an evaporation case is given, then based on the grouping according to the equation [6], [7] it is not possible to say which equation can be used to calculate the corresponding evaporation rate value. The grouping according to the type of evaporation [2], [7] can be suitable from the point of view of practice, since similar evaporation phenomena are grouped in one case. However, in this case, evaporation processes that can be described with the same parameters, i.e. identical phenomena are distinguished, can also be classified as separate cases.

In the course of literature research, I collected the publications that deal with the evaporation of liquids and summarized the equations that determine the evaporation rate in tables. Under the same circumstances, I observed a large difference in the results given by the correlations. Based on this, I came to the conclusion that there is currently no correlation in the literature that could be used with great certainty to calculate the evaporation rate, or that would be accepted by most researchers. These equations are largely dependent on the used measuring equipment and measuring technical conditions, so this is probably the reason why a considerable number of correlations can be found in the literature for the evaporation rate. In the publications, the data of the measuring equipment and the measuring devices used during the measurement were included in sufficient detail, however, the biggest deficiency was caused by the fact that the values of the operational parameters set during the measurement and the results were incompletely or incorrectly reported. The equation created based on the measurement results can only be used to calculate the evaporation rate if it is known for what conditions the equation was created and what the validity ranges are for its application. In many cases, these are not provided or are incomplete, so their use and the results obtained with them become questionable. In addition, specifying the measurement conditions as a range is not a sufficient condition for the reproducibility of the results, since specifying an insufficient number of conditions can lead to misleading and inaccurate results due to numerous combinations of parameters. Thus, it is essential in research to accurately describe the measurement conditions, display the results in a table or diagram, and specify the validity range of all parameters.

EVAPORATION CASES

The phenomenon of evaporation can be grouped according to different aspects (nature of gas flow, type and direction of driving forces, equation defining evaporation rate and type of evaporation). However, so far, no research has really taken as a basis the effects or parameters that influence the rate of evaporation, based on which the research results in a given case can be compared or combined with each other. Thus, a grouping criterion was needed, with the help of which a specific evaporation case can be clearly classified into the appropriate group, and which does not combine cases that cannot be treated together. If the grouping is done according to the similarity or difference of the parameters that fundamentally influence the phenomenon, then we get a much more differentiated and precise division. These parameters include the pressure of the gas above the liquid surface, material quality (content), temperature, humidity content, characteristic velocity and turbulence intensity of the gas flow; and the material quality (content, tension) and the surface temperature of the liquid, the convection and the size of the liquid surface. Thus, different evaporation cases can be categorized based on the conditions and properties of the bulk gas (T_G^G, φ_G) and the liquid surface (T_L^f) according to Fig. 2. into evaporation under natural, mixed and forced convection, if the following conditions are met:

- constant atmospheric pressure;
- liquid surface open to the environment (hereinafter open liquid surface);
- the liquid surface can be characterized by a flat surface (e.g. no waving, ripples);
- the forced movement of the liquid is negligible (e.g. no mixing or liquid flow);
- liquid loss other than evaporation is negligible.

Within a given gas flow group, we distinguish cases for evaporation with steady-state, time-varying, locally-varying and time- and locally-varying gas and liquid conditions along the surface. So, within the category of evaporation with natural, mixed and forced convection, according to the gas and liquid conditions, 4×4 , that is, 16 different cases are possible. Looking at the entire grouping, we can thus distinguish a total of $3 \times 4 \times 4$, that is, 48 cases of evaporation. The grouping of evaporation cases according to gas and liquid conditions appeared as a thesis point among my scientific results.

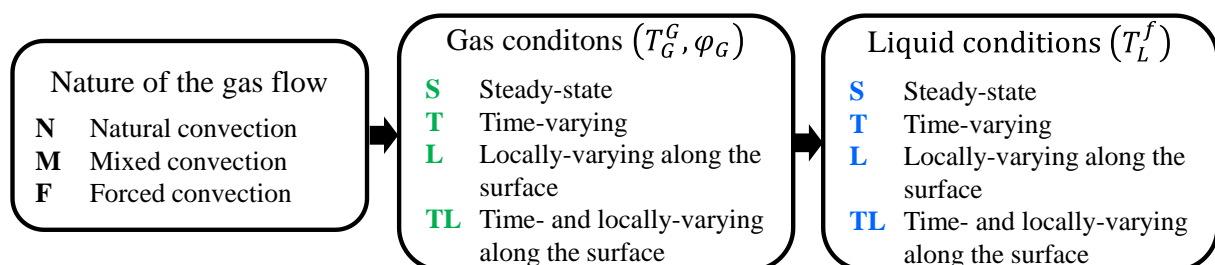


Figure 2. Grouping of evaporation cases at constant air pressure

EVAPORATIONS MEASUREMENTS AND METHODS

The aim of my work was to create correlations giving evaporation rate for evaporation cases with steady-state gas and liquid conditions under natural, mixed or forced convection, which can be applied in a wide range of validity, and the conditions for their application are specified in sufficient detail. The dimensionless numbers included in the correlations were produced by dimensional analysis. The advantage of dimensionless equations is that they can be considered general, as they include the temperature dependence of the material properties and the characteristic length of the evaporating surface. In the case of mass transfer under natural convection, the Sh number can be obtained using the following equation:

$$Sh = ARa_m^B Sc^C \phi_T^D \phi_p^E,$$

while in the case of evaporation under mixed or forced convection:

$$Sh = ARi^B Re^C Sc^D \phi_T^E \phi_p^F.$$

To create the new dimensionless equations, I used measurement results found in the literature, which I supplemented with the results of the evaporation measurements performed at the department's measuring equipment. The measuring equipment is suitable for testing evaporation with steady-state gas and liquid conditions under mixed or forced convection, the technological process diagram of which is shown in *Figure 3*, with the addition of instrumentation elements. During the measurement, the temperature, relative humidity and pressure of the ambient air, the pressure difference measured at the orifice flow meter, the temperature, relative humidity and pressure of the air flowing in the channel, the surface and bulk temperature of the water, the mass of evaporated water and the time elapsed during the measurement were recorded. The evaporation rate of water at different air velocities, air temperatures and humidities were measured. Using the measurement results found in the literature, I checked my own measurement results, and also took into account the deviations arising from different measurement methods and measuring devices and created an equations for a wider validity range.

The creation of dimensionless equations is only possible if sufficient measurement data is available for the calculation. In order to create the dimensionless equations, the value of the evaporation rate, gas temperature, gas velocity, relative humidity of the gas, air pressure above the liquid surface, surface temperature of the liquid, as well as the size and geometry of the liquid surface must be known. Using these data, I developed a calculation method for determining the dimensionless numbers in the equations, which appeared as a thesis point among my scientific results. I used the MathWorks MATLAB software to determine the exponents of the dimensionless numbers and the coefficient in the equation by regression analysis. During the optimization, the goal was to minimize the average relative error between the measured and calculated Sh -numbers from the measurement data. The validity range of the equations, i.e. the limit values of the application for each parameter, can be determined from the minimum and maximum values of the used data series.

RESULTS

Based on the measurement results found in the literature and carried out on the department's equipment, I created dimensionless equations suitable for determining the evaporation rate with the help of regression analysis for evaporation cases with steady-state gas and liquid conditions under natural, mixed or forced convection. These dimensionless equations appeared as thesis points among my scientific results.

The created new dimensionless equations were compared with the correlations suitable for calculating the evaporation rate found in the literature. For this, I performed a statistical analysis, during which I compared the *Sh*-number values calculated from the measurement data and from correlations found in the literature based on the four statistical indicators (mean absolute error, average relative error, root mean square error, coefficient of determination). In order to be able to take into account the results given by all the four statistical indicators and to choose the best correlation for the calculation of the evaporation rate, I organized the equations according to the individual statistical indicators. For this, in the case of a given statistical indicator, a score between 0 and 100 were given to the equations, depending on how close they are to the ideal value of the statistical indicator. In the case of a given correlation, I averaged the scores obtained by the four statistical indicators to establish the final order. According to the final, averaged score, the equations can be ranked, and the correlation with the highest score can be used with the highest confidence to determine the evaporation rate. The new dimensionless equations best approximated the measured *Sh*-numbers and thus also the measured evaporation rate values, because they gave the smallest error values, as well as the largest determination coefficient value, which I also confirmed with the help of the Bland-Altman method.

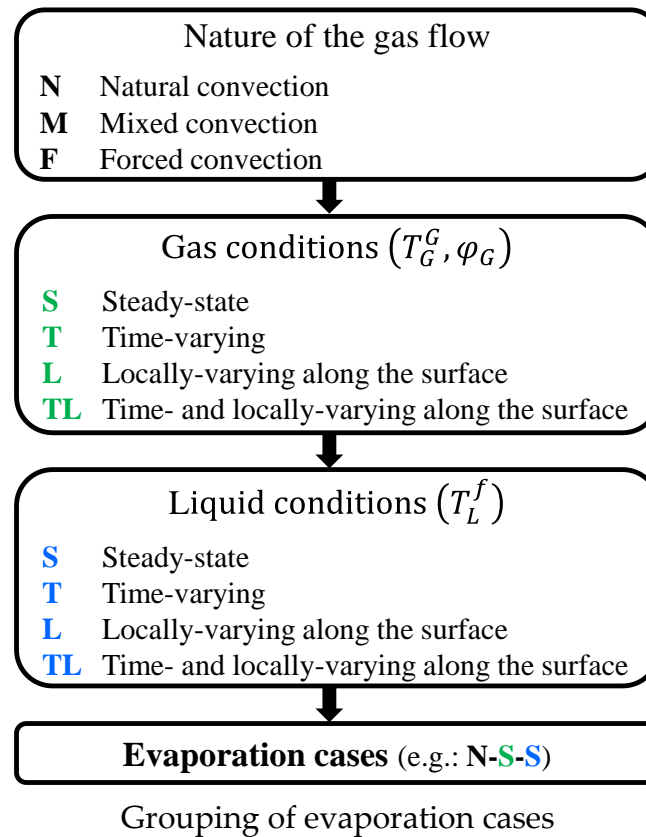
New scientific results

Thesis 1

The process of evaporation can be grouped according to the gas and liquid conditions and properties, if the following conditions apply to the given evaporation process:

- constant atmospheric pressure;
- liquid surface open to the environment;
- the liquid surface can be characterized by a flat surface;
- the forced movement of the liquid is negligible;
- liquid loss other than evaporation is negligible.

Thus, the evaporation process that meets the conditions can be classified into one of the 48 cases shown in the figure.



Meanings of the symbols in the figure:

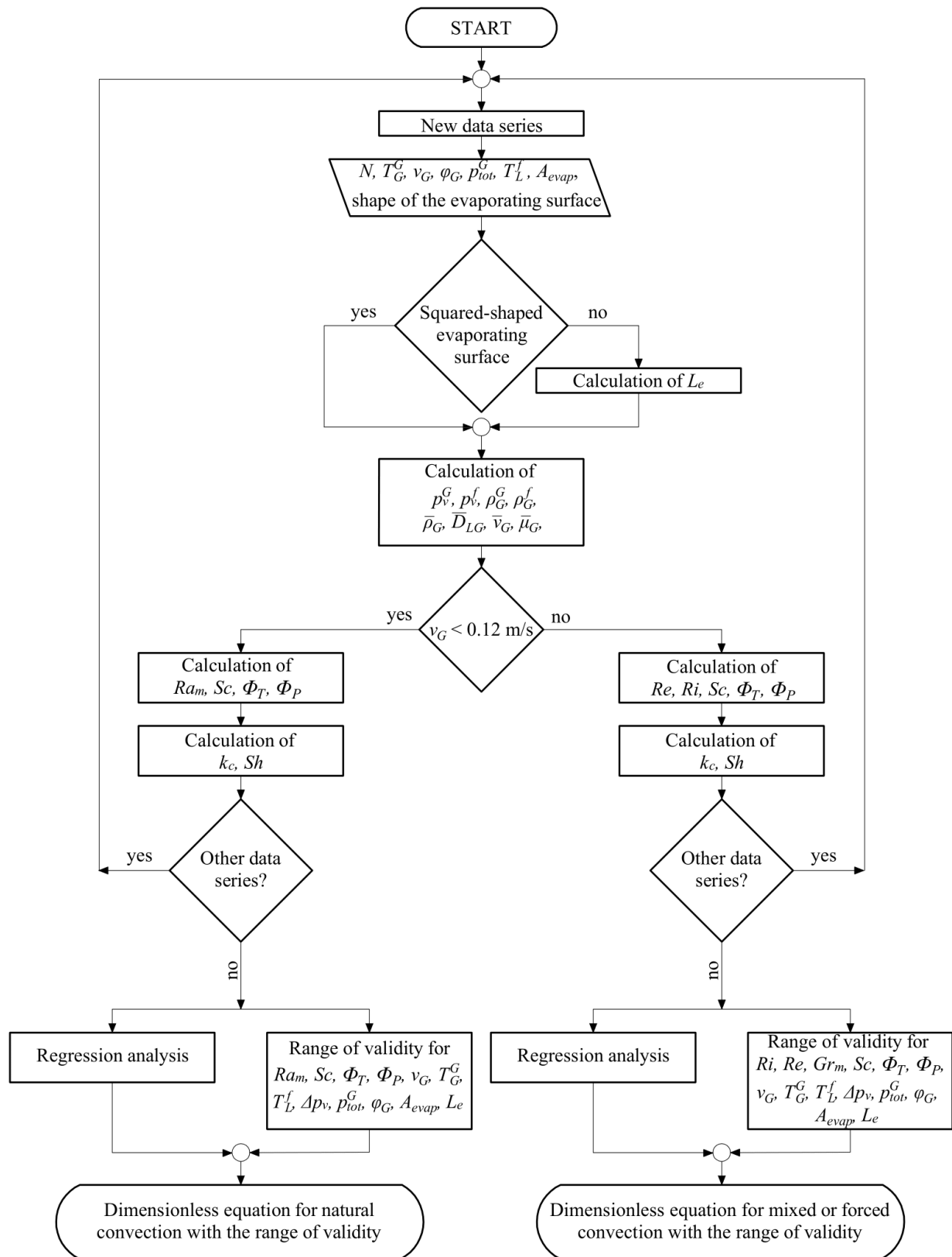
T_G^G [$^{\circ}\text{C}$]	bulk gas temperature;
φ_G [1]	relative humidity of the gas;
T_L^f [$^{\circ}\text{C}$]	liquid surface temperature.

Related publications: [S1], [S2], [S3].

Thesis 2

A dimensionless equation containing the terms Sh , Re , Ri , Ra_m , Sc , ϕ_T , ϕ_p can be created for evaporation cases with steady-state gas conditions and steady-state liquid temperature under natural, mixed or forced convection, using the calculation algorithm based on the block diagram shown in the figure, which:

- recording the measured data needed to create the dimensionless equation (N , T_G^G , v_G , φ_G , p_{tot}^G , T_L^f , A_{evap});
- using the equivalent characteristic length (L_e);
- and applying the arithmetic mean of the material properties calculated for the bulk gas and liquid surface temperature to the dimensionless numbers.



Logical block diagram for the creation of dimensionless equations describing evaporation based on measurement data

The following data are required to apply the calculation algorithm:

1. evaporation rate (N);
2. bulk gas temperature (T_G^G);
3. gas velocity (v_G);
4. relative humidity of the gas (φ_G);
5. gas pressure above the liquid surface (p_{tot}^G);
6. liquid surface temperature (T_L^f);
7. size (A_{evap}) and geometry of the liquid surface.

Meaning of the symbols in the figure:

N [$kg/(m^2s)$]	evaporation rate (mass flow density);
T_G^G [$^{\circ}C$]	bulk gas temperature;
v_G [m/s]	gas velocity;
φ_G [1]	relative humidity of the gas;
p_{tot}^G [Pa]	pressure of the gas;
T_L^f [$^{\circ}C$]	liquid surface temperature;
A_{evap} [m^2]	size of the evaporating liquid surface;
L_e [m]	equivalent characteristic length of the liquid surface which $L_e = \sqrt{A_{evap}}$;
p_v^G [Pa]	the partial pressure of the liquid vapor at the bulk temperature of the gas;
p_v^f [Pa]	the partial pressure of the liquid vapor at the temperature of the liquid surface;
ρ_G^G [kg/m^3]	the wet gas density at the bulk gas temperature;
ρ_G^f [kg/m^3]	the wet gas density at the liquid surface temperature;
$\bar{\rho}_G$ [kg/m^3]	the average density of the wet gas at the liquid surface and bulk gas temperatures;
\bar{D}_{LG} [m^2/s]	the average molecular diffusion coefficient between gas and liquid at the liquid surface and the bulk gas temperatures;
$\bar{\nu}_G$ [m^2/s]	the average kinematic viscosity of the wet gas at the liquid surface and bulk gas temperatures;
$\bar{\mu}_G$ [m^2/s]	the average dynamic viscosity of the wet gas at the liquid surface and bulk gas temperatures;
Gr_m [1]	Grashof number, $Gr_m = (\rho_G^G - \rho_G^f) \frac{gL_e^3 \bar{\rho}_G}{\bar{\mu}_G}$, where g [m/s^2] is the gravitational acceleration;
Re [1]	Reynolds number, $Re = \frac{v_G L_e}{\bar{\nu}_G}$;
Ri [1]	Richardson number, $Ri = \frac{Gr_m}{Re^2}$;
Ra_m [1]	Rayleigh number, $Ra_m = (\rho_G^G - \rho_G^f) \frac{gL_e^3}{\bar{\nu}_G \bar{\rho}_G \bar{D}_{LG}}$;
Sc [1]	Schmidt number, $Sc = \frac{\bar{\nu}_G}{\bar{D}_{LG}}$;

Φ_T [1]	the correction term from temperatures, $\Phi_T = \frac{T_G^G + 273.15}{T_L^f + 273.15}$;
Φ_p [1]	the correction term from partial vapor pressures, $\Phi_p = \frac{\Delta p_v}{p_{tot}^G}$, where Δp_v [Pa] is the partial pressure difference of the liquid vapor between the bulk wet gas and the wet gas above the liquid surface, which $\Delta p_v = p_v^f - p_v^G$;
k_c [m/s]	mass transfer coefficient interpreted in the terms of molar concentration, which $k_c = \frac{N}{M_L \left(\frac{p_v^f}{R(T_L^f + 273.15)} - \frac{p_v^G}{R(T_G^G + 273.15)} \right)}$, where R is the universal gas constant, $R = 8.314$ [J/molK];
Sh [1]	Sherwood number, $Sh = \frac{k_c L_e}{\bar{D}_{LG}}$.

Related publications: [S1], [S2], [S3].

Thesis 3

The evaporation rate can be calculated from the following dimensionless equation for the air-water system in the case of evaporation of an open liquid surface with steady-state gas conditions and steady-state liquid temperature under natural convection:

$$Sh = 0.7 Ra_m^{1/4} Sc^{1/3} \Phi_T^{-0.6} \Phi_p^{-0.05}.$$

The upper limit of the 90% confidence interval belonging to the equation is +26%, while the lower limit is -22%, and the average relative error of the equation is 11.9% in the following validity range and measurement conditions:

$$\begin{aligned} 3.67 \cdot 10^5 \leq Ra_m \leq 2.48 \cdot 10^8 & & 7^\circ C \leq T_G^G \leq 27^\circ C \\ 0.58 \leq Sc \leq 0.7 & & 53\% \leq \varphi_G \leq 98\% \\ 0.8 \leq \Phi_T \leq 1 & & 5 \text{ g/kg} \leq Y_G \leq 19 \text{ g/kg} \\ 0.003 \leq \Phi_p \leq 0.8 & & 220 \text{ Pa} \leq \Delta p_v \leq 80000 \text{ Pa} \\ & & 84300 \text{ Pa} \leq p_{tot}^G \leq 102300 \text{ Pa} \\ & & 8^\circ C \leq T_L^f \leq 94^\circ C \\ & & 0.023 \text{ m}^2 \leq A_{evap} \leq 0.278 \text{ m}^2 \\ & & 0.15 \text{ m} \leq L_e \leq 0.52 \text{ m} \end{aligned}$$

where

Sh [1] Sherwood-number, $Sh = \frac{k_c L_e}{\bar{D}_{LG}}$, where k_c [m/s] is the mass transfer coefficient interpreted in the terms of molar concentration between air and water; L_e [m] is the equivalent characteristic length of the liquid surface, which $L_e = \sqrt{A_{evap}}$, where A_{evap} [m²/s] is the size of the evaporating liquid surface; \bar{D}_{LG} [m²/s] is the average molecular diffusion coefficient between gas and liquid at the liquid surface and the bulk gas temperatures;

Ra_m [1]	Rayleigh-number, $Ra_m = (\rho_G^G - \rho_G^f) \frac{gL_e^3}{\bar{v}_G \bar{\rho}_G \bar{D}_{LG}}$, where ρ_G^G [kg/m^3] is the wet gas density at the bulk gas temperature; ρ_G^f [kg/m^3] is the wet gas density at the liquid surface temperature; $\bar{\rho}_G$ [kg/m^3] is the average density of the wet gas at the liquid surface and bulk gas temperatures; g [m/s^2] is the gravitational acceleration; \bar{v}_G [m^2/s] is the average kinematic viscosity of the wet gas at the liquid surface and bulk gas temperatures;
Sc [1]	Schmidt-number, $Sc = \frac{\bar{v}_G}{D_{LG}}$;
Φ_T [1]	the correction term from temperatures, $\Phi_T = \frac{T_G^G + 273.15}{T_L^f + 273.15}$, where T_G^G [$^\circ C$] is the bulk gas temperature; T_L^f [$^\circ C$] is liquid surface temperature;
Φ_p [1]	the correction term from partial vapor pressures, $\Phi_p = \frac{\Delta p_v}{p_{tot}^G}$, where Δp_v [Pa] is the partial pressure difference of the liquid vapor between the bulk wet gas and the wet gas above the liquid surface, which $\Delta p_v = p_v^f - p_v^G$; where p_v^f [Pa] is the partial pressure of the liquid vapor at the temperature of the liquid surface; p_v^G [Pa] is the partial pressure of the liquid vapor at the bulk temperature of the gas;
p_{tot}^G [Pa]	pressure of the gas;
φ_G [1]	relative humidity of the gas.

Related publications: [S2], [S5], [S7].

Thesis 4

The evaporation rate can be calculated from the following dimensionless equation for the air-water system in the case of evaporation of an open liquid surface with steady-state gas conditions and steady-state liquid temperature under mixed or forced convection:

$$Sh = 0.24 Ri^{0.03} Re^{0.7} Sc^{1/3} \Phi_T^{-2} \Phi_p^{0.1}.$$

The upper limit of the 90% confidence interval belonging to the equation is +26%, while the lower limit is -24%, and the average relative error of the equation is 12.4% in the following validity range and measurement conditions:

$2.34 \cdot 10^{-6} \leq Ri < 7.4$	$-19^\circ C \leq T_G^G \leq 79^\circ C$
$1400 \leq Re \leq 1.85 \cdot 10^5$	$0.17 \text{ m/s} \leq v_G \leq 5.7 \text{ m/s}$
$3.27 \cdot 10^4 \leq Gr_m \leq 8.47 \cdot 10^9$	$4\% \leq \varphi_G \leq 99\%$
$0.58 \leq Sc \leq 0.7$	$0.5 \text{ g/kg} \leq Y_G \leq 47 \text{ g/kg}$
$0.88 \leq \Phi_T \leq 1.15$	$25 \text{ Pa} \leq \Delta p_v \leq 10000 \text{ Pa}$
$0.0003 \leq \Phi_p \leq 0.1$	$84300 \text{ Pa} \leq p_{tot}^G \leq 101400 \text{ Pa}$
	$1^\circ C \leq T_L^f < 61^\circ C$
	$0.015 \text{ m}^2 \leq A_{evap} \leq 1.09 \text{ m}^2$
	$0.12 \text{ m} \leq L_e \leq 1.04 \text{ m}$

where

- Sh [1] Sherwood number, $Sh = \frac{k_c L_e}{\bar{D}_{LG}}$, where k_c [m/s] is the mass transfer coefficient interpreted in the terms of molar concentration between air and water; L_e [m] is the equivalent characteristic length of the liquid surface, which $L_e = \sqrt{A_{evap}}$, where A_{evap} [m²/s] is the size of the evaporating liquid surface; \bar{D}_{LG} [m²/s] is the average molecular diffusion coefficient between gas and liquid at the liquid surface and the bulk gas temperatures;
- Re [1] Reynolds number, $Re = \frac{v_G L_e}{\bar{\nu}_G}$, where v_G [m/s] is the air velocity; $\bar{\nu}_G$ [m²/s] is the average kinematic viscosity of the wet gas at the liquid surface and bulk gas temperatures;
- Ri [1] Richardson number, $Ri = \frac{Gr_m}{Re^2}$, where $Gr_m = (\rho_G^G - \rho_G^f) \frac{g L_e^3 \bar{\rho}_G}{\bar{\mu}_G}$, where ρ_G^G [kg/m³] is the wet gas density at the bulk gas temperature; ρ_G^f [kg/m³] is the wet gas density at the liquid surface temperature; $\bar{\rho}_G$ [kg/m³] is the average density of the wet gas at the liquid surface and bulk gas temperatures, g [m/s²] is the gravitational acceleration; $\bar{\mu}_G$ [Pa · s] the average dynamic viscosity of the wet gas at the liquid surface and bulk gas temperatures;
- Sc [1] Schmidt number, $Sc = \frac{\bar{\nu}_G}{\bar{D}_{LG}}$;
- Φ_T [1] the correction term from temperatures, $\Phi_T = \frac{T_G^G + 273.15}{T_L^f + 273.15}$, where T_G^G [°C] is the bulk gas temperature; T_L^f [°C] is liquid surface temperature;
- Φ_p [1] the correction term from partial vapor pressures, $\Phi_p = \frac{\Delta p_v}{p_{tot}^G}$, where Δp_v [Pa] is the partial pressure difference of the liquid vapor between the bulk wet gas and the wet gas above the liquid surface, which $\Delta p_v = p_v^f - p_v^G$; where p_v^f [Pa] is the partial pressure of the liquid vapor at the temperature of the liquid surface; p_v^G [Pa] is the partial pressure of the liquid vapor at the bulk temperature of the gas;
- p_{tot}^G [Pa] pressure of the gas;
- φ_G [1] relative humidity of the gas.

Related publications: [S1], [S3], [S4], [S5], [S11], [S12].

PRACTICAL APPLICATION OF THE RESULTS

Knowledge of the heat and mass transfer processes taking place during evaporation can be important from the point of view of various industrial equipment and operations, as well as environmental processes, during which liquid loss cannot be neglected in many cases, as it needs to be replaced. Many studies have dealt with the evaporation of liquids, but due to the complexity of the phenomenon, the clarification of simplified models and relationships is still a current research topic.

The phenomenon of evaporation was grouped according to the gas and liquid conditions that affect the rate of evaporation, based on a more differentiated and more accurate division can be obtained, so that the research results belonging to a given case could be compared or combined with each other. Researchers can later on classify their results and equations according to this grouping. The publications available in the literature and the correlations suitable for calculating the evaporation rate were summarized according to the evaporation cases in tabular form. These tables can serve as a basis or starting point for other research, thereby simplifying the work of researchers.

A measuring equipment suitable for measuring the rate of evaporation was presented, which is equipped with modern mechanical and measuring techniques. It was explained in detail what parameters need to be recorded in order to determine the evaporation rate, as well as under what circumstances and conditions the measurement must be carried out. Based on the data from the measurement results, a dimensionless equation suitable for determining the evaporation rate was created to describe evaporation under natural or mixed or forced convection. Currently, the equations consisting of these dimensionless numbers give the most accurate value of the evaporation rate in the given validity range. A calculation algorithm was created, which shows how these dimensionless equations can be created, which is also suitable for expanding the validity range of the equation or making the results given by the equation more accurate using new measurement results. The created new dimensionless equations can be integrated into simulation software and serve as a basis for describing more complicated cases than steady-state evaporation. In cases of evaporation with a time- or locally-varying conditions the evaporation rate can be described by the succession of difference sections that can be considered constant in terms of time or space, which can already be calculated from the new dimensionless equations.

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Publications related tot he thesis

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