Determination of evaporation rate at free water surface

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***Abstract* – There are many industrial facilities with free surface water reservoir for different technological purposes. On the free surface heat transfer and diffusion occur, whereby the vapor diffuses into the ambient air. Therefore, the water loss should be replaced. There are many empirical correlations for calculating the quantity of the evaporated water which methods largely differ from each other. The evaporation rate can be determined by the newly assembled experimental apparatus and measurement method. During the measurement the velocity and the temperature of the ambient air, the temperature of the evaporating liquid can be varied. The evaporation rate can be calculated upon the measured and recorded data.**

I. INTRODUCTION

In the contact surface of a free water surface with air, heat- and mass transfer process occurs [1], [2], when from the saturated surface of water vapor diffuses to the unsaturated air. This phenomenon is called evaporation and is shown in Fig. 1. Diffusion occurs because of the temperature-based driving forces at the first two cases and because of the humidity-based driving forces at the third case. At the fourth case the temperature is lower than the dew point, that is why condensation occurs. These four cases can be described by the following equations [3].

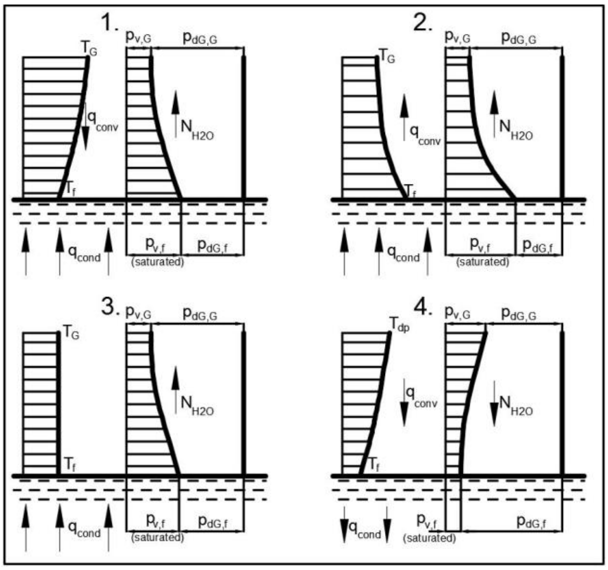

Figure 1. Partial pressure difference and temperature-based driving forces at the four cases of liquid evaporation

The temperature-based driving force between the water surface and the unsaturated air can cause heat flux, which can be given by the heat flux density:

$$q_{conv} = \alpha \left| T_f - T_a \right| . \tag{1}$$

The vapor from the water surface diffuses to the unsaturated air, which can be described by the molecular evaporation rate:

$$N_{H2O} = k_G M_{H2O} \left(p_{v,f} - p_{v,G} \right) . \tag{2}$$

The evaporation rate in terms of temperature-based driving forces, Sartori [4] established three different cases. This theory can be supplemented to four categories, where the evaporation rate can be written to the different cases:

$$1:\ N_{H2O} = \frac{q_{conv} + q_{cond}}{r_{H2O}} \text{ , } if\ T_G > T_f ; \tag{3}$$

$$2:\ N_{H2O} = \frac{q_{cond} - q_{conv}}{r_{H2O}} \text{ , } i\ T_G < T_f ; \tag{4}$$

$$3:\ N_{H2O} = \sigma \left(Y_f - Y_G \right) \text{ , } if\ T_G = T_f ; \tag{5}$$

$$4:\ N_{H2O} < 0\ (condensation), if\ T_{dp} > T_f . \tag{6}$$

Evaporation from free liquid surface occurs commonly in everyday-life and industrial processes e.g. open air reservoirs, pools and swimming pools. There are two mechanisms of the air movement: forced convection by ventilation indoor or by wind outdoor, or natural convection based on concentration difference. Evaporation intensity can differ in case of still or rippling surfaces. A number of publications discuss the measurement of surface evaporation; their results are based on experiments.

Based on the experiments, correlations to best describe the phenomenon were identified by regression analysis; in general, they can be applied only in limited conditions. According to special sources, Dalton was the first in 1802 to discuss the issue and to describe the problem of evaporation by empirical hydrodynamic approximation. He concluded that the intensity of evaporation is proportionate to the partial pressure difference of the liquid surface and the main stream of air and the velocity of air flow.

In 1918 the correlation proposed by Willis Carrier [5] is mostly applied to water surface evaporation based on laboratory experiments, then Himus and Hinchley [6] in 1924 examined evaporation in wind tunnel. In 1931 measurements results of Rohwer [7] completed achievement of Carrier, who published his research results [8] in book entitled Fan Engineering in 1949. Powell [9] created a correlation for evaporation due to forced convection in 1940.

In 1966, the WMO conference [10] published a volume, where several correlations were proposed for evaporation rate. Kohler and Parmele [11] determined equation of evaporation rate for natural convection in1967.

There are many experimental results for evaporation from a swimming pool, like McMillan (1971) [12], Ryan and Harleman (1973) [13], Czarneczki (1978) [14] Govind and Sodha (1983) [15], Szeicz and McMonagle (1983) [16] achieved significant results in this area.

An another research field is the heat loss of a solar pond through evaporation, where Kishore and Joshi (1984) [17], Subhakar and Murthy (1993) [18], Alagao et al. (1994) [19] determined the evaporation rate.

Sartori (1989) [20] created an equation depending on laminar, transitional and turbulent range.

Hahne and Kübler (1994) [21] made experiments on two outdoor swimming pools to determine the evaporation loss and checked several empirical correlations due to experiments, then based on the results created their own equation to describe the process more accurate. Similar measurements performed Molineaux et al. (1994) [22] based on results of Watmuff et al. (1977) [23] and Smith et al. (1994) [24] too.

Pauken (1999) [25] examined evaporation in wind tunnel in case of a heated tank, then proposed a correlation, that can be used for natural and forced convection too.

Tang and Etzion (2004) [26] performed their measurements outdoor on an open and a covered shallow pools, but their results are correct only for small water surfaces.

Moghiman and Jodat (2007) [27] dealt with evaporation at moving air above indoor swimming pools, where their experiments were made in a test chamber, therefore to create a connection between evaporation rate and airflow rate.

Bower and Saylor (2009) [28] examined the connection between Sherwood and Rayleigh number. Data were collected from a set of water tanks undergoing natural convection-driven evaporation. These data were reduced to a dimensionless mass transfer coefficient for evaporation.

Shah (2012) [29] worked out a measurement method, which can be used for swimming pools, other pools with quiet water surface and pools for nuclear fuels to determine the evaporation rate of water.

Raimundo et al. (2014) [30] examined the connection between evaporation of heated water surface and parameters of air stream at forced convection.

Kunmar and Arakeri (2015) [31] investigated natural convection at heated tank, where the tank on the top and as well at the bottom could be heated. Based on the results they made a connection between Sherwood and Rayleigh number.

Table I contains the correlations of evaporation rate, which were mentioned earlier.

The listed equations are valid in various interval (different gas and liquid temperature, surface area) and conditions (natural or forced convection), which reduces their usefulness. In addition, these equations are correct only for water, but in the industry there are several cases, where other, volatile components (e.g. ethanol used for cleaning, boric acid solution in power plant) can evaporated to the ambient. By exceeding concrete concentration environmental and health standards can be broken. To know the phenomenon of evaporation is important to environmental and health areas, but to energy recovery technologies too [32]. In this paper measurement results and evaporation rates are presented for the first and second categories.

II. EXPERIMENTAL APPARATUS AND METHODS

TABLE I.
EQUATIONS OF EVAPORATION RATE

Ref. Nr.	Equations
6	$N = 10^{-9}(64.58 + 28.06 v_G)(p_{v,f} - \varphi p_{v,G})$
7	$N = (0.0850 + 0.0508 v_G)\frac{p_{v,f} - \varphi p_{v,G}}{r_{H2O}}$
8	$N = (0.088403 + 0.001296 v_G)\frac{p_{v,f} - \varphi p_{v,G}}{r_{H2O}}$
9	$N = 9.86 \cdot 10^{-8}(p_{v,f} - p_{v,G})\frac{(v_G L)^{0.65}}{L}$
10	$N = 0.0372 v_G \frac{p_{v,f} - \varphi p_{v,G}}{r_{H2O}}$
11	$N = \rho_{H2O}(0.181 + 0.00236\overline{v_G})(p_{v,f} - \varphi p_{v,G})$
12	$N = (0.0360 + 0.0250 v_G)\frac{p_w - \varphi p_G}{h_w}$
13	$N = (0.027(T_{wvir} - T_{Gvir})^{1/3} + 0.031 v_G)\frac{p_{v,f} - \varphi p_{v,G}}{r_{H2O}}$
14	$N = (0.05053 + 0.06683 v_G)\frac{p_{v,f} - \varphi p_{v,G}}{r_{H2O}}$
15	$N = (0.0741 + 0.0494 v_G)\frac{p_{v,f} - \varphi p_{v,G}}{r_{H2O}}$
16	$N = \frac{\rho_G c_p}{\gamma}(p_{v,f} - p_{v,G})\frac{\left(\ln\left(\frac{z}{z_0}\right)\right)^2}{v_G r_{H2O} \kappa}$
17	$N = (5.7 + 3.8 v_G)\frac{M_{H2O}}{M_G}\frac{p_{v,f} - \varphi p_{v,G}}{P c_{H2O}}$
18	$N = \left[(T_f - T_G) + \frac{(T_f + 237)(p_{v,f} - \varphi p_{v,G})}{268900 - p_{v,f}}\right]^{1/3}\frac{0.0144(p_{v,f} - \varphi p_{v,G})}{r_{H2O}}$
19	$N = (0.074 + 0.040 v_G)\frac{p_{v,f} - \varphi p_{v,G}}{r_{H2O}}$
20	$N = (0.00407 L^{-0,2} 0.0 v_G^{0.8})\frac{p_{v,f} - \varphi p_{v,G}}{P}$
21	$N = (0.0803 + 0.0583 v_G)\frac{p_{v,f} - \varphi p_{v,G}}{r_{H2O}}$
22	$N = \frac{3.1 + 2.1 v_G}{c_G}\frac{M_{H2O}}{M_G}\frac{p_{v,f}}{p_{v,f} + p_{v,G}}$
23	$N = \frac{2.8 + 3.0 v_G}{c_G}\frac{M_{H2O}}{M_G}\frac{p_{v,f}}{p_{v,f} + p_{v,G}}$
24	$N = (0.0888 + 0.0783 v_G)\frac{p_{v,f} - \varphi p_{v,G}}{r_{H2O}}$
25	$N = (74.0 + 97.97 v_G + 24.91 v_G^2)(p_{v,f} - p_{v,G})^{(1.22 - 0.19 v_G + 0.038 v_G^2)}$
26	$N = (0.2253 + 0.24644 v_G)\frac{(p_{v,f} - \varphi p_{v,G})^{0.82}}{r_{H2O}}$
27	$N = (0.0038 + 0.1356 v_G)(p_{v,f} - \varphi p_{v,G})^{(-1.255 v_G^3 + 2.182 v_G^2 - 1.362 v_G + 1.377)}$
28	$Sh = 0.230 Sc^{1/3} Ra^{0.321}$
29	$N = 0.00972 \rho_{H2O}(\rho_G - \rho_{H2O})^{1/3}(Y_f - Y_G)$
30	$N = 10^{-9}(37.17 + 32.19 v_G)(p_{v,f} - \varphi p_{v,G})$
31	$Sh = 0.264 Ra^{0.292}$

A. *Experimental apparatus*

During the measurements of evaporation was used the equipment that is found at the Department of Building Services and Process Engineering. The piping and instrumentation diagram is shown in Fig. 2.

For the movement of air is used a centrifugal fan (type: NVH50) (P-101-01) that is driven by an electric motor (maximum rotational speed 2890 1/min) (type: VZ32/2) made by EVIG. The suction section begins with an orifice flow meter (O-101-01) on a 200 mm diameter pipe. A U-tube manometer measures the pressure difference on the orifice flow meter. The air velocity is adjustable by using a frequency converter and a butterfly valve (V-101-01). For air heating is used an electric heater (type: Thermo-Team LF-36, accuracy: 0.5 °C) (H-101-01), that has 21 kW regulated and 9+6 kW fixed performance. In the evaporation section (E-102-01) can be found the thermo vessel (type: Grant GLS Aqua 12 Plus) (T-102-01), which contains the liquid used for evaporation. The temperature of liquid can be adjusted between ambient temperature and 99 °C (accuracy: 0.1 °C). Its maximum volume is 5 dm^3 and the evaporating surface is 325 mm x 300 mm. The thermo vessel and the scales below it are on a manually adjustable elevator (L-102-01). By modifying the height of elevator the water surface of the thermo vessel can be approximate to the bottom of the air tunnel. The humid gas leaves the system through the chimney (F-102-01) to the ambient.

B. *Instrumentation and methods*

The measurement begins by filling with water the thermo vessel, then the setting of accurate temperature of liquid (TRC-102-01) occurs by turning on the heating. Later turning on the fan with a given rotational speed (SIC-101-01), the required temperature of air (TIC-101-01) can be modified by the electric heater. Before starting the measurement, the apparatus shall be run empty until the stationary state is reached – stabilized values measured by the thermometers. The flow rate can be modified by the butterfly valve (FIC-101-01), and be determined from the pressure difference (PDI-101-01), that is measured at the orifice flor meter. Before the measurement the evaporated water has to be compensated, until the water surface get aligned with the bottom of the air tunnel. At the beginning of the measurement the temperature (TR-101-01) and the humidity (XR-101-01) of ambient is determined. Registration of evaporation properties occurs by a data logger (type: Ahlborn Almemo 2590-9). The mass of evaporated water (WR-102-01) by a scales (accuracy: 1 g), the surface temperature of water (TR-102-02) by an infrared thermometer (type: AMiR 7842), that is above the thermo vessel and the temperature of the gas (TR-102-01) is measured by a T-type thermometer. The measured values are registered with minute sampling by self-developed software. The measurement periods last minimum for two hours.

During measurements the ambient and gas properties and the weight of the water vessel were collected. Based on measurements results, evaporation rate can be specified in the knowledge of the quantity of moisture, is leaving the surface in a time interval:

$$N_{H2O} = -\frac{\mathrm{dm_{H2O}}}{\mathrm{dt}} \cdot \frac{1}{A}. \tag{7}$$

III. RESULTS

The summary of measurements results is shown in Table II, where the first and second cases were investigated. The results are demonstrated by the air velocity. During measurements the air velocity, temperature, humidity and water characteristic temperature were constant. The varying parameter was only the weight of water. It can be determined the weight decrease of the water by fitting a lineal to the plotted points (dm_{H2O}/dt).

TABLE II.
SUMMARY OF MEASUREMENTS RESULTS

v_G	T_G	Y_G	dm_{H2O}/dt	T_{H2O}	T_f	$Y_{f,sat}$	N_{H2O}
m/s	°C	g_{H2O}/kg_{dG}	g/s	°C	°C	g_{H2O}/kg_{dG}	kg/(m^{2}h)
0,6	50,0	3,5	-0,0144	30,0	27,9	25,9	0,531
	50,1	5,1	-0,0263	40,0	38,0	41,6	0,970
	50,1	5,1	-0,0509	50,0	47,6	70,8	1,879
	50,0	5,7	-0,0763	59,9	57,4	126,3	2,819
1,1	49,9	5,8	-0,0207	29,9	27,6	25,5	0,763
	50,0	5,3	-0,0381	40,0	37,2	39,9	1,406
	50,1	6,5	-0,0634	50,0	46,7	67,2	2,340
	50,0	5,6	-0,1100	60,0	56,1	117,0	4,061
1,8	49,9	3,7	-0,0323	30,0	27,3	25,2	1,191
	50,0	4,0	-0,0509	40,0	36,5	38,5	1,879
	50,0	5,8	-0,0891	50,0	45,8	63,6	3,291
	50,1	5,6	-0,1486	60,0	54,8	107,9	5,488

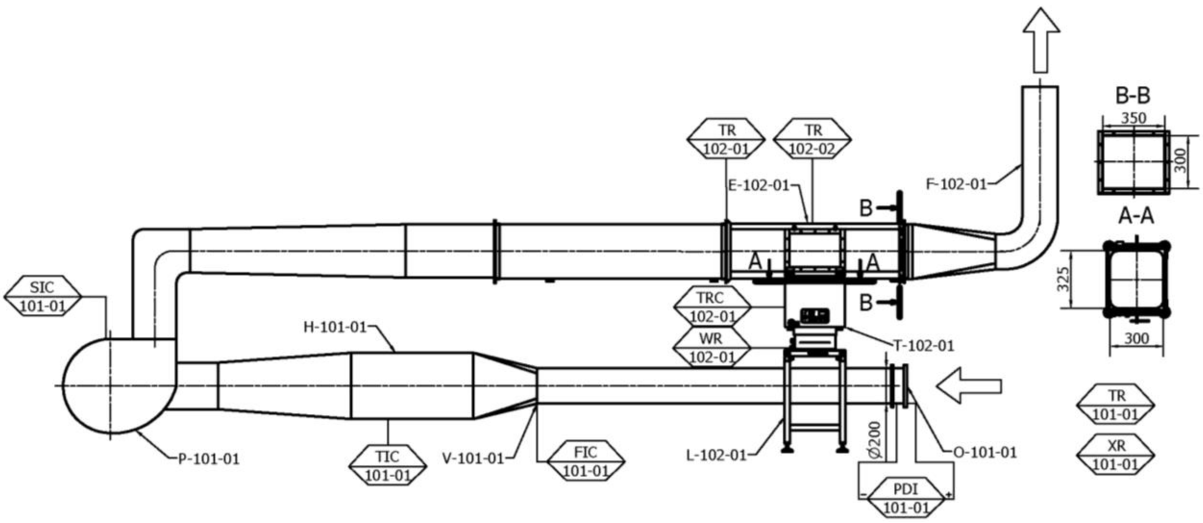

Figure 2. Instrumented flow diagram of the measurement equipment

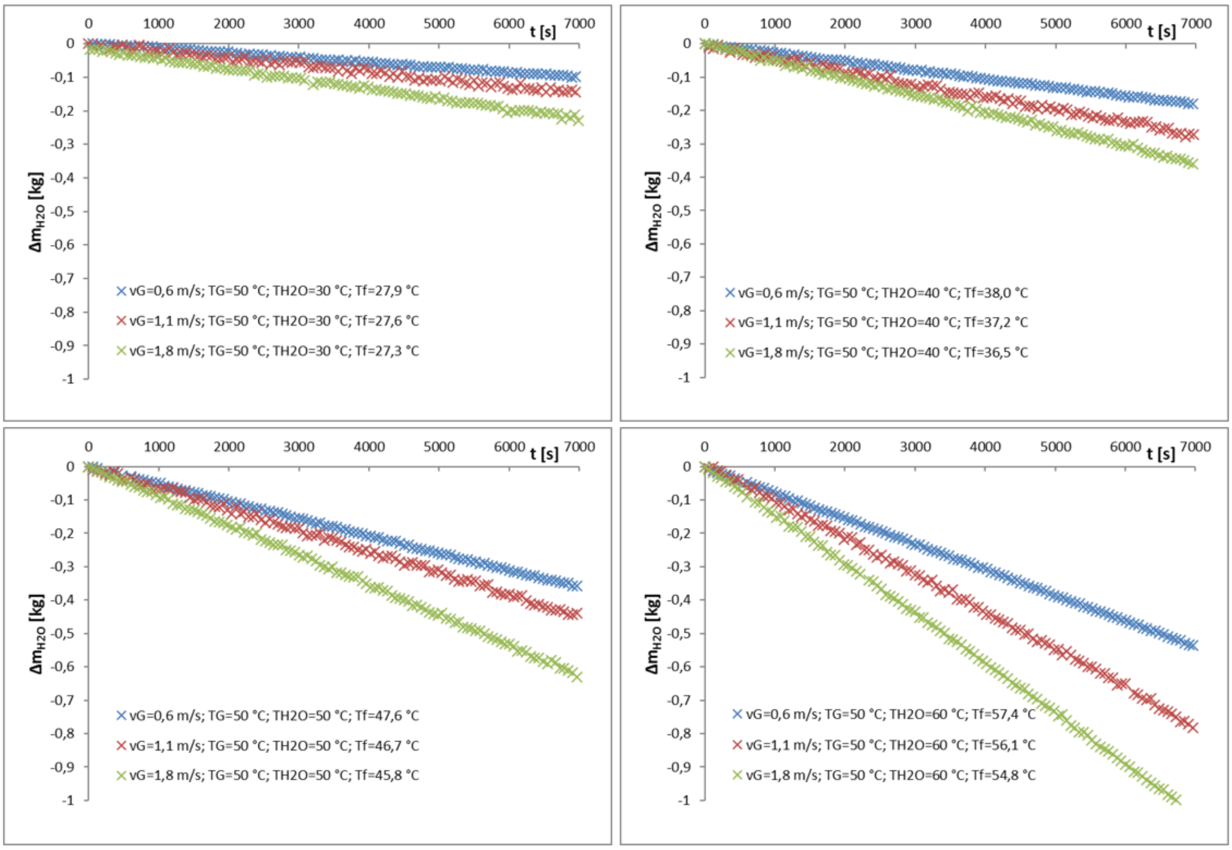

Figure 3. The weight of evaporated water at different temperature-based driving forces in function of time

During measurements water is being evaporated at different air flow rate and liquid temperature. Three cases were investigated at constant air temperature: the water temperature is higher, the air and liquid temperature are equal, the water temperature is lower than the air temperature. In all three cases, the measurements were done at three different air velocities. The weight of evaporated water in function of time is shown in Fig 3. On the diagrams can be clearly seen the effect of the water temperature and the air velocity on the evaporation rate.

The evaporation rate from the measurements results in function of Reynolds-number is shown in Fig. 4. The same temperature-based driving forces are plotted in the same

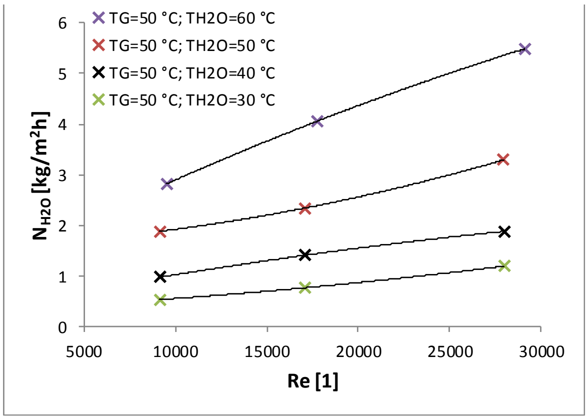

Figure 4. The evaporation rate at different temperature-based

colour, which for can be fitted a trend line. In order to determine the equations of the trend lines more measurements are needed.

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IV. Conclusions

In the course of our work, evaporation from a liquid surface was examined based on laboratory measurements. In this paper, a critical review on several well-known equations employed for the calculation of evaporation rate from free water surfaces has been carried out. Both empirical and theoretical working formulas have been analysed. Since up to now there was not consensus on which equations were better to employ, a large scattering of evaporation rates has resulted.

A measurement method has been developed and a measurement station has been established for testing heated fluid vessel, suitable for identifying evaporation processes increased by heat sources in the course forced convection. The velocity and the temperature of the humid gas and the temperature of the liquid can be regulated in a wide interval. Therefore, the tests were investigated not only in natural evaporation, but helping with heated liquid too. In the cases examined, evaporation was not only consequent upon environ-mental impacts, but it was also assisted by the heat source of the liquid. This case has been discussed deficiently by literature on the description and calculation of evaporation.

Our equipment is suitable to research the first, second and third evaporation categories, which appears the evaporation in traditional sense. Measurements were carried out for two cases: the temperature of the gas is higher than the liquid's, and for the opposite case. The measurement objectives are to determine vapor evaporation in various flow conditions, and to calculate the evaporation coefficient. The measurement results are plotted on diagrams. Our future plan is to establish an equation system, which can describe the phenomenon of evaporation in wide range of interpretation, taking into account the different categories.

NOMENCLATURE

A	Surface of heat- and mass transfer	m^2
c	Specific heat	J/(kg°C)
k_G	Mass transfer coefficient with partial pressure difference	mol/Ns
L	Characteristic length	m
m	Mass	kg
M	Molecular weight	kg/mol
N	Evaporation rate	$kg/(m^2s)$
p	Pressure	Pa
P	Total pressure	Pa
q	Heat flow density	W/m^2
r	Latent heat of vaporization	J/kg
Ra	Rayleigh-number	1
Re	Reynolds-number	1
Sc	Schmidt-number, υ_G/D	1
Sh	Sherwood-number, k_cL/D	1
T	Temperature	°C
t	Time	s
v	Velocity	m/s
Y	Absolute humidity of gas on dry basis	kg_{H2O}/kg_{dG}
z	Height above ground level	m
z_0	Roughness length for water	m
α	Heat transfer coefficient	$W/(m^2°C)$
ρ	Density	kg/m^3
φ	Relative humidity	1
γ	Psychrometric constant, γ=66	Pa/K

Subscripts

amb	*Ambient*
cond	*Conductive*
conv	*Convective*
dG	*Dry gas*
dp	*Dew point*
f	*Water surface*
G	*Humid gas*
H2O	*Water*
v	*Vapor*
vir	*Virtual*
‘	*Modified*

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