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Dehumidification of Air by Aqueous Triethylene Glycol Solution in a Spray Tower

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ABSTRACT

A spray tower in the absorber–stripper system has been designed to study the absorption of water vapor from moist air by contact with aqueous solutions that contained from 87.7 to 95.2% triethylene glycol (TEG). The design of a "U-shape" air tunnel with eliminators in the absorber and stripper is to prevent the carryover of the solution and to increase the absorption rate and the regeneration rate. This spray tower was capable of handling air flow rates from 1.94 to 3.77 kg/min and liquid flow rates from 2.17 to 3.31 kg/min. Under the operating conditions of this study, the overall mass transfer coefficients calculated from the experimental data of 95.2% TEG solution varied from 1.78 to 2.95 mol/m^{3}s. These corresponded to the heights of a transfer unit of 0.63 to 0.38 m, respectively. The efficiencies of the spray tower typically varied from 64 to 86%.

INTRODUCTION

Depending on the design, various types of absorber in air-conditioning systems are available, including spray towers, packed towers, and bubble towers. Although packed and spray towers are usually used in liquid desiccant dehumidification systems, data of mass transfer performance in packed towers are available; however, the data for spray towers are limited in the open literature. Therefore, mass transfer studies on spray towers were conducted in this work.

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Packed towers are used in liquid desiccant dehumidification systems for working solutions of lower viscosity. The most common ones are aqueous solutions of lithium chloride, lithium bromide, and calcium chloride. For higher viscosity solutions, e.g., triethylene glycol, spray towers producing very fine particles which increase the contact surface area between air and liquid particles are usually used. The vapor pressure of a desiccant solution is an important parameters for predicting absorption efficiency (1). The lower the vapor pressure of the desiccant solution, the higher the absorption efficiency. Since the vapor pressure of TEG is almost zero at room temperature, TEG was selected as the working solution in this study. Ullah et al. (2) reported that absorption efficiency is related to the temperature and humidity of the inlet air and to the temperature and concentration of the desiccant solution. A summary of studies related to the use of packed and spray towers in air-conditioning systems is presented in Table 1. There are fewer studies of spray towers than of packed towers. However, both types of tower have certain advantages and disadvantages.

To enhance the mass transfer rate and to avoid carryover of liquid particles, a "U-shape" tunnel with eliminators and fin coils in the spray tower was designed and tested in this study. In this spray tower the liquid desiccant was sprayed as fine particles by nozzles. The temperature was controlled with fin coils. Air was introduced from the top of the tower to contact the liquid particles cocurrently. This cocurrent contact of air and solution also reduced the carryover of liquid particles. The performance of the spray tower was evaluated under various conditions. The parameters we varied during the experiments included the temperature and humidity of the inlet air, the temperature and concentration of the desiccant solution, and the flow rates of the air and solution. The overall mass transfer coefficient, the height of a transfer

TABLE 1
Recent Studies on the Absorption/Regeneration Systems

	Study	
Absorber	Absorption and regeneration processes	Mass and heat transfer coefficients
Packed tower	Grosso et al., 1980 (3)	Andrew, 1982 (8)
	Peng and Howell, 1981 (4)	Howell, 1987 (9)
	Peng and Howell, 1984 (5)	Queiroz et al., 1988 (10)
	Gari et al., 1989 (6)	Hiraoka et al., 1993 (11)
	Chung et al., 1995 (7)	Chung et al., 1995 (12)
		Chung, 1997 (13)
Spray tower	Scalabrin and Scaltriti, 1985 (14)	Renar and Gaspersic, 1983 (15)
	Scalabrin et al., 1988 (16)	Scalabrin et al., 1988 (16)

unit, and the absorption efficiency of the spray tower were calculated from these experimental data. These mass transfer parameters are important in the design of a spray tower. The experimental results presented in the open literature are limited.

EXPERIMENTAL SYSTEM

A detailed schematic of the absorber–stripper system is shown in Fig. 1. The design of a "U-shape" air tunnel with eliminators in the absorber and stripper to allow air and solution cocurrent contact neglects carryover of the solution. In this spray tower the liquid inlet was kept about 6 cm below the air inlet and the liquid outlet was at the bottom of the absorber. The air inlet and outlet were at the top of both sides of the tower. Fin coils connected with a 3-ton refrigerator were placed 15 cm below the liquid inlet to provide the absorber at a lower temperature and to give better mass transfer performance. The absorber is made of stainless steel. The stripper has the same design as the absorber. The system can handle air flow rates from 1.94 to 3.77 kg/min and liquid flow rates from 2.17 to 3.31 kg/min. The flow meters and flow controllers used in this system were calibrated by standard procedures. Regeneration of the solution was carried out in the stripper, and the regenerated solution was cooled and returned to the absorber. The heat source for the solution regeneration was a 80-L insulated water tank with a 2-kW electric

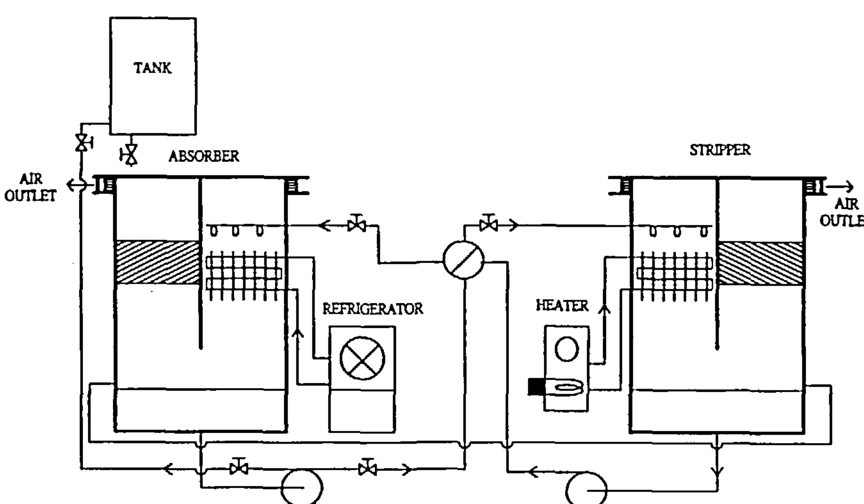

FIG. 1 Absorption–stripper system for this study.

heater. TEG solutions of 87.7 to 95.2% were employed in this study. The concentration of the solution was measured by a refractometer. A Rotronic IDL 20K hygrometer with two humidity probes, which can measure the relative humidity from 0 to 100% RH at −20 to 60°C, was used in this study. The accuracy of this hygrometer is about ±0.2% RH. The air flow rates were controlled by transistor inverters on the 0.5 HP blowers. The liquid flow rates were measured with a rotameter, and the air flow rates were measured with a hot-wire flowmeter.

RESULTS AND DISCUSSION

The performance of the absorber–stripper system was evaluated by a series of experimental runs. The main parameters that were varied during experimentation included the air flow rate, the liquid flow rate, the temperature and humidity of the inlet air, the temperature of the inlet desiccant solution, and the concentration of the solution. The operating conditions are presented in Table 2. The efficiency of the absorber was calculated as the ratio of the actual change in moisture content of the air leaving the absorber to the maximum possible change in moisture content under a given set of operating conditions. Therefore, the absorption efficiency, ϵ, can be expressed as

$$\epsilon = \frac{W_{in} - W_{out}}{W_{in} - W_{equ}} \tag{1}$$

where W_{in} and W_{out} are the water contents of the inlet and outlet air streams, respectively. W_{equ} is the water content of the air, which is at equilibrium with the TEG solution at a particular concentration and temperature. The absorption efficiencies calculated from the experimental data are provided in Table 2. As shown in Fig. 2(a), when the air flow rate is kept constant, the absorption efficiency increases as the liquid flow rate increases. Since the amount of treated air is fixed and the amount of absorbent (TEG) is increased, the column efficiency should increase. However, Fig. 2(c) shows that the column efficiency decreases with an air flow rate increase when the liquid flow rate is kept constant. Similarly, when the amount of treated air is increased and the amount of absorbent (TEG) is fixed, the column efficiency should decrease. Generally speaking, the lower the inlet liquid temperature, the higher the mass transfer rate in the absorber. Therefore, the absorption efficiency in Fig. 2(b) decreases as the inlet liquid temperature increases. This is similar to a conventional vapor compression refrigeration system. When the air and liquid flow rates are kept constant, the absorption efficiency in Fig. 2(d) increases as the inlet humidity increases. However, the change is not significant. In Fig. 2(e), the absorption efficiency does not vary linearly with a change of the solution concentration. When the concentration of TEG

TABLE 2
Experimental Data of This Study

Air flow rate (kg/min)	Liquid flow rate (kg/min)	Air inlet temperature (°C)	Air outlet temperature (°C)	Air inlet humidity ($g\ H_2O/kg$ dry air)	Air outlet humidity ($g\ H_2O/kg$ dry air)	Liquid inlet temperature (°C)	Liquid outlet temperature (°C)	Temperature below the fin (°C)	TEG concentration (% wt)	Equilibrium humidity ($g\ H_2O/kg$ dry air)	Spray tower height (cm)	Efficiency (%)	Mass transfer coefficient ($mol/m^3 \cdot s$)	Height of transfer unit (m)
1.94	3.31	21.0	23.6	13.6	5.8	22.7	25.2	26.6	95.2	3.9	70	0.80	2.09	0.54
1.94	2.93	21.1	24.2	13.6	6.3	22.6	25.3	26.6	95.2	3.9	70	0.75	1.78	0.63
1.94	2.55	21.4	24.2	13.8	6.9	22.3	24.0	26.1	94.8	4.1	70	0.71	1.57	0.72
1.94	2.17	21.5	24.1	13.7	7.6	22.4	24.6	26.5	94.8	4.1	70	0.64	1.27	0.88
1.94	2.93	25.7	27.5	16.3	8.1	25.1	28.2	30.4	93.6	6.3	70	0.82	2.52	0.56
1.94	2.93	26.3	28.4	16.2	8.5	25.8	28.7	30.6	93.6	6.4	70	0.79	2.33	0.61
1.94	2.93	26.7	29.0	16.3	9.0	27.0	29.4	31.0	93.6	6.8	70	0.77	2.10	0.68
1.94	2.93	26.9	30.4	17.1	10.4	30.0	31.0	32.6	93.6	8.1	70	0.74	1.51	0.94
1.94	2.93	24.5	27.0	17.6	7.7	24.3	28.3	29.9	94.3	5.3	70	0.80	2.18	0.51
2.55	2.93	24.9	28.1	17.8	8.8	24.7	28.7	30.2	94.3	5.4	70	0.73	2.27	0.65
3.15	2.93	25.2	28.4	17.8	9.4	25.0	28.8	30.2	94.0	6.0	70	0.71	2.48	0.74
3.77	2.93	25.4	28.4	17.4	9.9	25.2	28.7	29.9	94.0	6.5	70	0.69	2.57	0.85
1.94	2.55	25.2	27.3	16.4	7.4	23.7	27.7	29.7	95.2	4.5	70	0.76	2.33	0.48
1.94	2.55	25.1	26.4	14.8	7.2	23.5	27.0	28.2	95.0	4.3	70	0.72	2.22	0.51
1.94	2.55	24.9	26.4	13.6	7.1	22.8	26.3	27.6	95.0	4.4	70	0.71	2.02	0.56
1.94	3.31	24.5	26.5	17.2	6.5	23.3	27.8	29.1	95.2	4.8	70	0.86	2.95	0.38
1.94	3.31	24.7	26.1	15.8	6.4	23.1	27.2	28.6	95.2	4.8	70	0.85	2.91	0.39
1.94	3.31	24.8	25.7	14.1	6.3	23.6	26.2	27.1	95.2	4.3	70	0.80	2.78	0.40
1.94	2.93	26.9	29.0	17.2	8.5	25.8	29.5	31.4	95.2	4.8	70	0.70	2.09	0.53
1.94	2.93	27.4	29.3	17.9	10.1	26.5	29.6	30.8	94.3	6.0	70	0.66	1.54	0.73
1.94	2.93	27.6	28.8	17.8	11.4	26.5	29.0	29.7	91.3	8.9	70	0.72	1.16	0.97
1.94	2.93	28.1	28.7	18.0	12.8	26.7	28.6	29.0	87.7	11.3	70	0.78	0.85	1.32

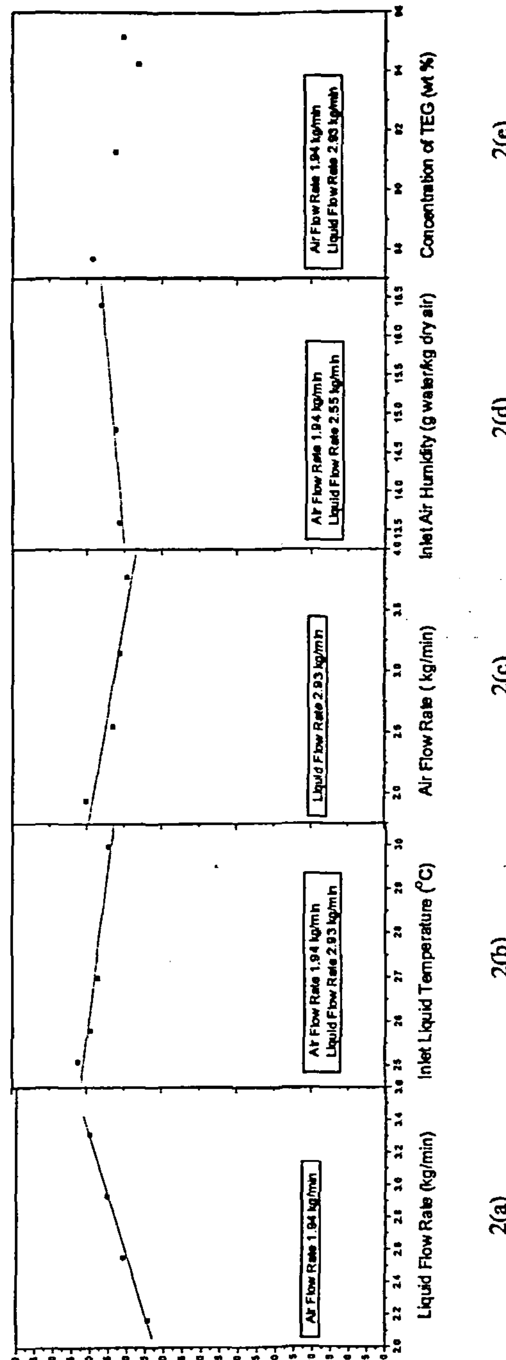

FIG. 2 Effect of various operating conditions on the absorption efficiencies.

decreases, the capacity of dehumidification should decrease and the value of equilibrium humidity should increase. Because these two variations will be competitive, the change of absorption efficiency is not stable. The fluctuation of the data points in Fig. 2(e) is expected. However, the actual change in the moisture content of leaving air should increase when the TEG concentration increases. This means that more water vapor in the leaving air is absorbed when a higher concentration of TEG is used. However, this does not guarantee that a higher absorption efficiency will be obtained, because the equilibrium humidity of the air is also changed.

The overall mass transfer coefficient was derived from Geankoplis (17). For adiabatic mass transfer in a spray tower, the rate of heat transfer due to the latent heat and sensible heat in the water vapor being transferring can be obtained as follows:

$$G\,dH_y = M_B k_y a \lambda_0 (H_i - H_G)\,dz + h_G a (T_i - T_G) \tag{2}$$

Since the ratio of the heat and mass transfer coefficients is approximately equal to the humid heat, i.e.,

$$\frac{h_G a}{M_B k_y a} \cong c_S \tag{3}$$

Equation (2) becomes

$$G\,dH_y = M_B k_y a\,dz\,[(c_S T_i + \lambda_0 H_i) - (c_S T_G + \lambda_0 H_G)] \tag{4}$$

From the definition of the total enthalpy of an air–water vapor mixture,

$$H_y = c_S (T - T_0) + \lambda_0 H \tag{5}$$

Equation (4) can be written as

$$G\,dH_y = M_B k_y a\,dz\,(H_{yi} - H_y) \tag{6}$$

Rearranging Eq. (6), the average mass transfer coefficient becomes

$$(k_y a)_{avg} = \frac{G}{M_B z} \int_{H_{y1}}^{H_{y2}} \frac{dH_y}{H_{yi} - H_y} \tag{7}$$

For the overall mass transfer coefficient, Eq. (7) can be rewritten as

$$(K_y a)_{avg} = \frac{G}{M_B z} \int_{H_{y1}}^{H_{y2}} \frac{dH_y}{H_y^*} - H_y \tag{8}$$

where H_y^* is the equilibrium total enthalpy of an air–water vapor mixture and is determined by the equilibrium line in the temperature–enthalpy diagram of the spray tower. As expected, the effect of various operating conditions on the overall mass transfer coefficients shown in Fig. 3 is similar to

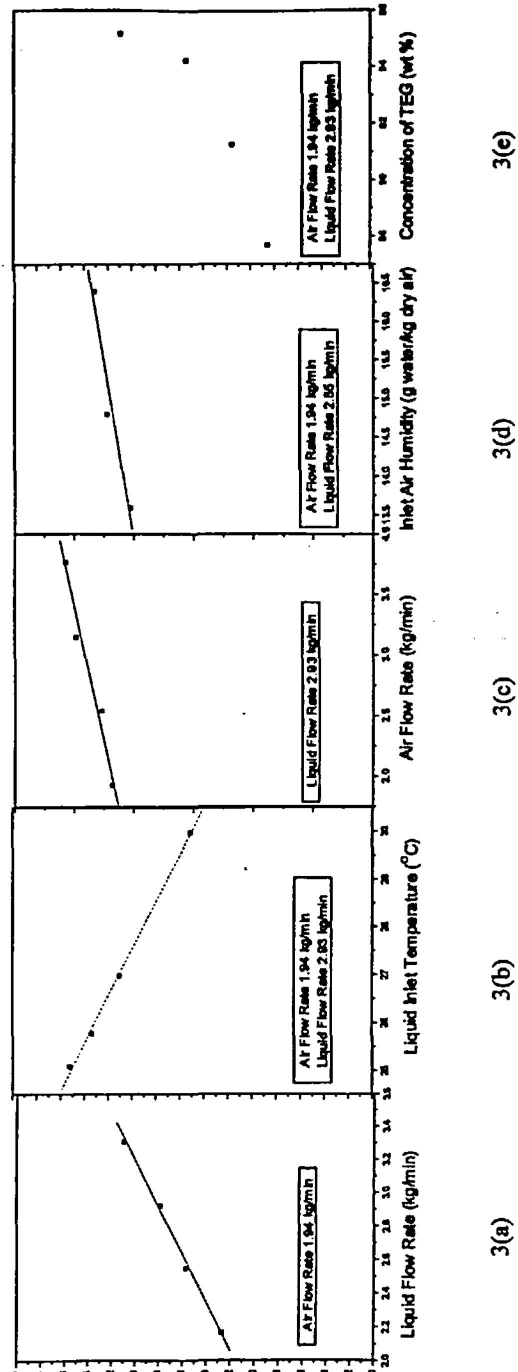

FIG. 3 Effect of various operating conditions on the mass transfer coefficients.

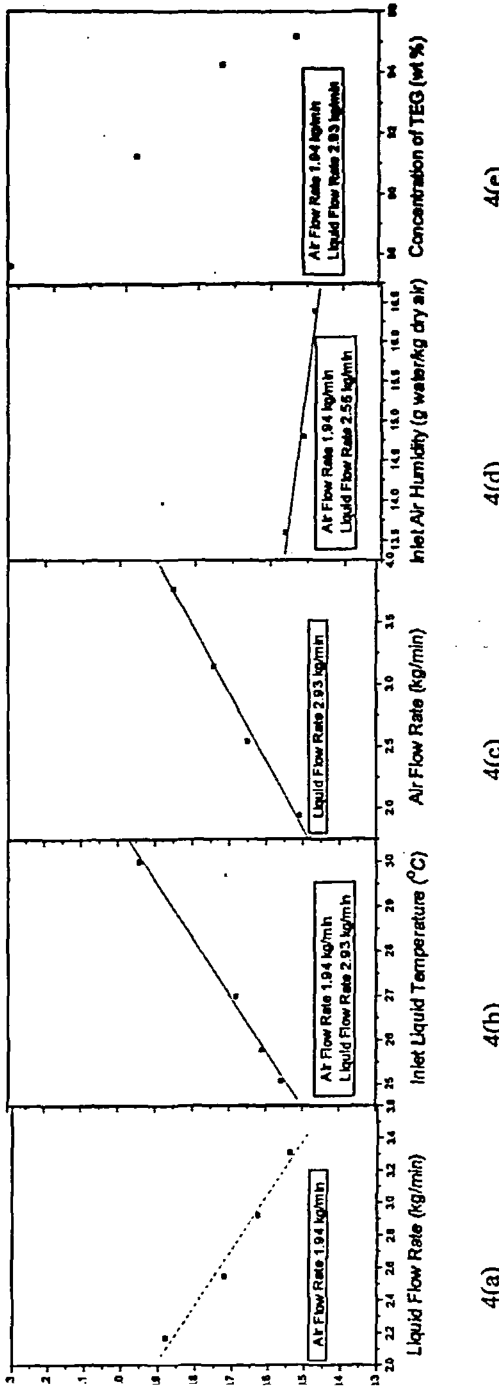

FIG. 4 Effect of various operating conditions on the heights of a transfer unit.

the effect on the absorption efficiency except for the effect of the air flow rate. An increase in the overall mass transfer coefficient with increasing air flow rate is observed in Fig. 3(c). This trend is different from that shown in Fig. 2(c). Since the molar flux of this system is proportional to the air flow rate, the mass transfer coefficient is also proportional to the air flow rate. Similar to the effect on absorption efficiency, the overall mass transfer coefficient in Fig. 3(e) does not varied linearly with the change of the solution concentration.

Most experimental data on packed towers are generally given in terms of the height of a transfer unit (HTU) rather than the mass transfer coefficient, because the HTU is less dependent on liquid or gas flow rates. It provides a means to evaluate system performance under different operating conditions. Therefore, the height of a transfer unit, H_{OG}, in the spray tower was calculated in comparison with the HTU in the packed tower. The definition of the height of a transfer unit is .

$$H_{OG} = \frac{G}{M_B(K_y a)_{avg}} \tag{9}$$

From this definition, the effect of various operating conditions on the height of a transfer unit shown in Fig. 4 should be contrary to the effect on the overall mass transfer coefficient except for the effect of the air flow rate. An increase in the height of a transfer unit with increasing air flow rate is observed in Fig. 4(c). Because in this, the effect of the air flow rate is larger than the overall mass transfer coefficient on the height of a transfer unit. It should also be noted that the height of a transfer unit in Fig. 4(e) does not vary linearly with a change of the solution concentration. Compared to the literature data of the HTU in packed towers (18, 19), the values of the height of a transfer unit calculated in this study are similar to those literature data at the solution concentrations used in most commercial systems.

CONCLUSIONS

A "U-shape" spray tower in a absorber–stripper system has been designed and tested successfully for dehumidification of air. For a given spray tower height the absorption efficiency increases as either the air flow rate decreases or the liquid flow rate increases. The overall mass transfer coefficients increase with increasing air and liquid flow rates. As expected, lowering the liquid temperature significantly improves column performance. Also, increases in the concentration of TEG and the inlet air humidity lead to increases in the overall mass transfer coefficient and a darease in the height of a transfer unit.

NOMENCLATURE

c_S	humid heat of air–water vapor mixture (kJ/kg dry air·K)
G	dry air flow (kg/m^2·s)
$h_G a$	volumetric heat-transfer coefficient in the gas (W/m^3·K)
H	humidity of air (kg water/kg dry air)
H_G	humidity of the gas in the bulk gas phase (kg water/kg dry air)
H_i	humidity of the gas at the interface (kg water/kg dry air)
H_{OG}	height of a transfer unit (m)
H_y	enthalpy of air–water vapor mixture (J/kg dry air)
H_{y1}	enthalpy of air–water vapor mixture at the inlet of absorber (J/kg dry air)
H_{y2}	enthalpy of air–water vapor mixture at the outlet of absorber (J/kg dry air)
$k_y a$	volumetric mass transfer coefficient (kmol/m^3·s)
$K_y a$	overall mass transfer coefficient (kmol/m^3·s)
M_B	molecular weight of air (kg/kmol)
T_i	interface temperature (K)
T_G	gas temperature (K)
W_{equ}	minimum possible water content at the outlet of absorber (kg water/kg dry air)
W_{in}	water content of air at the inlet of absorber (kg water/kg dry air)
W_{out}	water content of air at the outlet of absorber (kg water/kg dry air)
Z	height of the spray tower (m)
ϵ	absorption efficiency of the spray tower (%)
λ_0	latent heat of water (J/kg water)

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