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Control of Humidity in Small Controlled-environment Chambers using Glycerol-Water Solutions

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Summary. Solutions of glycerol and water provide a convenient and inexpensive system to control the relative humidity (RH) in small controlled-environment chambers. The relationship between the specific gravity (SG) of a glycerol-water solution and its equilibrium RH is described by the equation $SG = [-0.189\ (RH) + 19.9]^{0.0806}$. Gas can be humidified by bubbling it through jars containing solutions of glycerol-water with the desired equilibrium RH. The effects of flow rate, volume of solution, temperature, and pressure on the equilibrium RH are discussed.

Humidity is an important environmental factor that influences rates of water loss from whole plants or excised plant organs. Bates of water loss from plant cells affect many physiological processes such as cell expansion, growth, photosynthesis, and senescence. The role of humidity on the physiology of plants often has been ignored, possibly due to a lack of convenient methods to control humidity at desired levels or because of difficulty in measuring humidity accurately (Gaffney, 1978). Equilibrium atmospheres over saturated solutions of different salts can be used to control humidity (ASTM, 1983; Solomon, 1951; Winston and Bates, 1960; Young, 1967). Disadvantages of this system are that a different salt is needed for each humidity, a salt for a specific humidity may not be available, many of the salts are corrosive, and the equilibrium relative humidity (RH) formed over many solutions varies widely with temperature. Nonsaturated solutions also can be used to produce various equilibrium RHs, depending on the concentration of the solute. This method allows for the creation of a precise and evenly graded series of RHs. Solutions of sulfuric acid (ASTM, 1983; Solomon, 1951), potassium hydroxide (Solomon, 1951), and glycerol (ASTM, 1983; Braun and Braun, 1958; Solomon, 1951) can be used in this manner to control RH.

Glycerol and water solutions have several advantages for use in RH control. Solutions of 0% to 100% glycerol can be mixed easily, and their exact composition can be determined by specific gravity (SG) (Braun and Braun, 1958) or by refractive index (ASTM, 1983) measurements. Glycerol solutions are less corrosive than salt or sulfuric acid solutions, and glycerol is relatively inexpensive. This paper discusses the use of glycerol and water solutions to control humidity in controlled-environment chambers. The effects of temperature, pressure, flow rate, and volume of solution on maintaining constant, desired RH in chambers also are examined.

The relationship between glycerol concentration, measured as SG, and the equilibrium RH that forms at 24C in a closed system was described by Braun and Braun (1958), and their original data are shown in Fig. 1. To aid in determining equilibrium RH from solutions not tested by Braun and Braun, we derived an equation to fit their data (Fig. 1). The equilibrium RH decreases slowly as the glycerol content increases, but changes more rapidly as glycerol content exceeds ≈ 70%. The slower change in RH when glycerol content is < 70% allows for more accurate control of RH >60%. To aid in the determination of a solution needed to produce a desired RH, the formula in Fig. 1 can be solved for SG:

$$SG = [-0.189(RH) + 19.9]^{0.0806} \quad [1]$$

where RH is the desired percent RH and SG is the specific gravity of the glycerol-water solution needed to produce this RH. Ratios of water and glycerol needed to produce a desired SG can be estimated from Fig. 1 or calculated from Eq. [2]:

$$G_w = 383\ (SG) - 383 \quad [2]$$

where G_w is the percent glycerol by weight in the solution. The volumes of glycerol and water needed to prepare solutions can be calculated using Eqs. [3] and [4]:

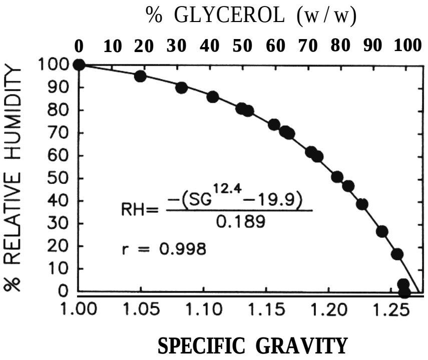

Fig. 1. ***The relationship of specific gravity (SG) and glycerol content of glycerol-water solutions and equilibrium relative humidities (RH) at 24C. Points represent actual data from Braun and Braun (1958), and the line represents a model derived using these points.***

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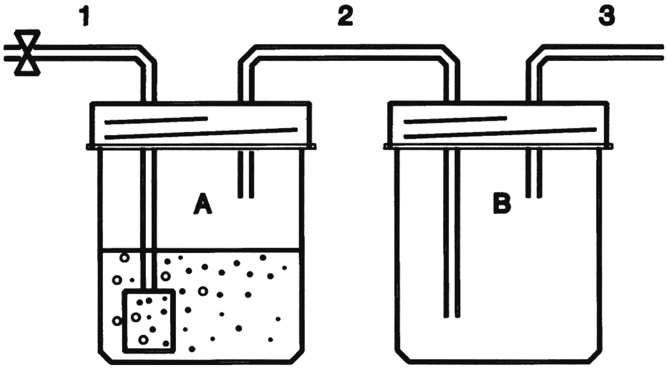

Fig. 2. ***System used to humidify flow-through chambers. Gas flows through tube 1 into the glycerol-water solution in jar A. Humidified gas then flows through tube 2 into the controlled-environment chamber (jar B) and exits into the atmosphere through tube 3.***

$$G_V = (G_W W_T)/(100 \times 1.262) \quad [3]$$

where G_V is the volume of glycerol (ml), W_T is the total weight of the solution (g), and 1.262 (gžml^{-1}) is the density of pure glycerol at 25C. The volume of water needed can be calculated using Eq. [4]:

$$H_V=[100 - G_W)\ W_T]/(100 \times 1.0) \quad [4]$$

where H_V is the volume of water (ml) and 1.0 (gžml^{-1}) is the density of water. The glycerol concentration of the solution can be determined by measuring its SG using a hydrometer or by weighing a known volume of the solution. The refractive index also can be measured and used to determine the solution's equilibrium RH (ASTM, 1983). If care is taken in the mixing of the solution, the equilibrium RH produced should fall within a percentage point of that predicted by the formula. It is recommended that the actual RH produced by the solution be measured with an accurate RH-measuring instrument such as a dewpoint hygrometer. Appropriate adjustments to the glycerol concentration of the solution can be made if needed.

The temperature of the glycerol solution has a very slight effect on the equilibrium RH (Table 1). A glycerol solution producing 40% RH at 25C will produce 38.3% RH and 41.6% RH at 0 and 50C, respectively. Solutions producing RH >40% are affected less by temperature. To obtain the predicted humidity in the controlled-environment chamber, the humidification jars, the environmental chambers, and all connecting tubing should be maintained at a similar temperature. Variation in temperature within the system will result in deviations in the resulting RH in the chamber. To maintain a constant temperature, the entire system should be held in a controlled-temperature chamber. If the incoming gas is at a different temperature, it should be passed through a coil of tubing held at the controlled temperature to allow the temperature to equilibrate before entering the humidification jar.

An example of a humidification system is shown in Fig. 2. Jar A contains a solution of glycerol-water of a predetermined concentration. The gas to be humidified may come from a variety of sources, including compressed gas tanks, air compressors, or simple diaphragm pumps used to aerate aquariums. The gas flows through tube 1 and enters the glycerol solution through an aquarium air stone that breaks up the gas into small bubbles. Breaking the gas into small bubbles increases the surface area : volume ratio of the gas and allows it to reach the equilibrium RH of the solution. The humidified gas then passes through tube 2 into the controlled-environment chamber (jar B) containing the plant or harvested plant organ, and finally exits jar B through tube 3.

Any pressure drop between the humidification jar (A) and the treatment jar (B) will lower the resulting RH in B (Fig. 2). Pressure in jars A and B can be measured with a manometer. The equilibrium RH in A (RH_A) needed to produce the desired RH_B can be calculated by the formula:

$$RH_A = RH_B(P_A / P_B) \quad [5]$$

where P_A and P_B are the absolute pressures in the humidification jar (A) and the treatment jar (B), respectively. The calculated RH_A then can be used to determine the desired SG for jar A using Eq. [1].

Humidification of a gas drier than the equilibrium RH of the glycerol-water solution will remove water from the solution. Likewise, a gas wetter than the equilibrium RH will add water. to the solution. In both cases the SG of the -solution will change over time. The volume of glycerol-water solutions needed to maintain the desired RH in the treatment chamber can be determined based on the temperature, the flow rate of gas through the chamber, the RH of the incoming gas, and the variation in the RH that can be tolerated. For example, if a 20C chamber with a flow rate of 100 mlžmin^{-1} is to be maintained at 90% RH, the SG of the glycerol solution would need to be 1.089, assuming no pressure drop (Fig. 1). Air at 90% RH, 20C, contains ≈ 16 mg water/ml, as determined from psychometric tables (ASHRAE Handbook, 1981). Dry air bubbled through the glycerol solution would remove ≈ 16 mg of water/ml of air or 1.6 mgžmin^{-1}. Therefore, ≈ 2.3 g of water would be removed from the solution each day. In 1 kg (1.095 liter) of the glycerol solution, which would contain ≈ 659 g water, 19 g of water would need to be removed to raise the SG to 1.094 and reduce the RH to 89%. At a daily loss of 2.3 g of water, it would take ≈ 8 days for this to occur. At lower flow rates and/or temperatures, loss of water would be less. Also, if the air flowing into the glycerol solution is

Table 1. ***The relationship of temperature and equilibrium relative humidities of glycerol solutions with different specificgravities. Data are taken from ASTM (1983).***

Specific gravity	Temperature (°C) 0	25	50	70
		Relative humidity (%)		
1.225	**38.3**	**40.0**	**41.6**	**42.7**
1.189	**58.4**	**60.0**	**61.4**	**62.5**
1.135	**78.8**	**80.0**	81.1	81.8
1.014	**97.7**	**98.0**	**98.2**	**98.4**

not totally dry, water loss will be slower.

More precise RH can be maintained by increasing the volume of the glycerol solution and/or by bubbling the gas through two or more jars of solutions. When using multiple jars of solutions, the first jar will adjust the RH of the gas to near the desired level, while the second or third jar will assure that the desired RH is produced even after the glycerol concentration in the first jar has been altered over time. Water can be added periodically to the jars to maintain their original volume and SG. The depth of the air stone in the glycerol solution is also important to assure that the water content of the gas reaches equilibrium with the solution. We found that when the bottom of a 2.5 -cm-long airstone is immersed ≥6 cm into the glycerol solution, the equilibrium RH is produced when gas is bubbled at a rate of 100 ml min^{-1}. If the air stone is immersed <6 cm, the gas did not reach the equilibrium RH of the solution.

Using these basic relationships, humidity can be controlled precisely and inexpensively. Solutions of glycerol can be mixed easily and their concentration determined using a hydrometer, a good refractometer, or gravimetric techniques. Temperature has a minimal effect on the equilibrium RH produced. Precise control of RH in small controlled-environment chambers can be achieved by using two or three jars containing adequate volumes of glycerol water solutions. The addition of four drops of a saturated $CuSO_4$ solution to each 100 ml of glycerol solution inhibits microbial growth and prolongs the life of the solution (ASTM, 1983). Solutions treated in this manner can be used repeatedly after needed adjustment of water content, and in our laboratory have given reliable humidity control over several years. This system has been used in our laboratory for controlling RH in storage tests of various fruits and vegetables and for insect control with controlled atmospheres (Soderstrom et al., 1990). This system also can be used under static conditions. Adjustment of seed moisture content has been performed by maintaining seeds over two glycerol water solutions producing humidities ranging from 25% to 85% (A.G. Taylor, personal communication).

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Acknowledgements

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