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WATER CYCLE AND ITS MANAGEMENT FOR PLANT HABITATS AT REDUCED PRESSURES

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Experimental and mathematical models were developed for describing and testing temperature and humidity parameters for plant production in bioregenerative life support systems. A factor was included for analyzing systems operating at low (10–101.3 kPa) pressure to reduce gas leakage and structural mass (e.g., inflatable greenhouses for space application). The expected close relationship between temperature and relative humidity was observed, along with the importance of heat exchanger coil temperature and air circulation rate. The presence of plants in closed habitats results in increased water flux through the system. Changes in pressure affect gas diffusion rates and surface boundary layers, and change convective transfer capabilities and water evaporation rates. A consistent observation from studies with plants at reduced pressures is increased evapotranspiration rates, even at constant vapor pressure deficits. This suggests that plant water status is a critical factor for managing low-pressure production systems. The approach suggested should help space mission planners design artificial environments in closed habitats.

Key words: Closed ecological system (CES); Water cycle; Water flux; Evaporation/condensation; Temperature; Relative humidity; Low pressure; Climate; Control

INTRODUCTION: ARTIFICIAL CLIMATE DESIGN AND WATER CYCLES UNDER REDUCED PRESSURES

Plants on Earth exist within local and global water cycles. They require liquid water and tolerable relative humidity (RH) to sustain their hydration and growth (17). The global water cycle exists on the basis of gas (vapor), liquid (water), and solid (ice) and the physical processes characterize transitions between these phases:

- evaporation and condensation (between water and vapor),
- freezing and melting (between water and ice),
- frost formation and sublimation (between vapor and ice).

Plants thrive in a certain range of temperatures and humidities and are constantly affected by the states and processes listed above. Depending on the amount of canopy cover and the vapor pressure deficit, plants use water at a rate of 1–10 L m^{-2} d^{-1} (m^{-2} here referring to per ground area) (2,5,11,15,19,21,22). While plants require this water to sustain their CO_2 uptake and growth, the water flux through the plant itself becomes a primary factor determining climate, particularly in closed systems with a limited volume, such as those that might be used for bioregenerative life support in space (15,16). In closed systems with plants, water fluxes through plants can dictate the system's humidity, while also affecting energy transfer through the processes of leaf transpiration and condensation on cooling coils. Because of this intimate relationship between plants, water, and climate, it is important to

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understand the mechanisms of water cycle functions and their interconnection with various environmental parameters, including pressure.

Experiments have been conducted from the 1960s to the present on closed ecological systems (CES) to study materials cycling and transformations (1,4,10). These studies showed that CESs can be effective for life support applications for space, underwater areas, polar regions, or other remote settings (1,4,10). Artificial CESs also can be effective tools for simulating and understating the functions of the Earth's biosphere (13,14). Unfortunately, thorough water cycling data were not gathered for many of these CES studies. On the other hand, many nonclosed controlled environment studies have shown the expected effects of vapor pressure deficit, CO_2 concentration, and light on plant water fluxes (11), but few studies have attempted to control pressure as an environmental variable (3,5). This is an important consideration for future space missions, where the baseline pressure may be less than the 101 kPa (1 atm) used on NASA's Shuttle, the Mir Space Station, and the International Space Station. The use of lower pressures could reduce the structural mass and gas leakage from vehicles and habitats, which in turn would reduce mission costs.

For future life support systems that rely heavily on bioregenerative components (and plants) to sustain a CES, it will be important to understand the water cycling through these closed systems, along with the influences of environmental factors, including atmospheric pressure on these cycles.

THEORETICAL DESCRIPTION OF WATER CYCLE

The simplest physical water cycle (WC) in a closed relatively isolated system is composed of two processes: evaporation (plus transpiration if plants are included in the system) and condensation (6,7,18,23).

Both processes are easily reproduced physically in a sealed chamber. This requires only putting inside the chamber a sample of liquid water of sufficient volume and a cooling coil. This water cycle can be described by a simple mathematical description (15). A more detailed mathematical model formulation for water flux (WF) description is needed to understand how the WC operates under different pressures.

Water Flux Mathematical Model

The general form of the differential equation for water evaporation (condensation) from a flat surface can be represented as:

$$\partial C/\partial t = D \times \partial^2 C/\partial^2 x + (F/V) \times (C_o - C) \qquad (1)$$

where
C = water vapor concentration (kg m^{-3}),
t = time (s),
x = distance from liquid water surface (m),
C_o = water vapor concentration in system environment (kg m^{-3}),
D = molecular diffusion coefficient for water vapor (m^2 s^{-1}),
F = air circulation (convection) rate in a closed system (m^3 s^{-1}),
V = volume of the system under consideration (m^3)

with some initial and boundary conditions (not required to be specified at this point) for the system under consideration.

This simple approximation is an expression of the water balance near a flat water surface: vapor amount changes = molecular diffusion (from water surface) + convective removal/supply (from remote areas).

A flat surface is chosen as an approximation for geometrical aspects of the problem that would be more complicated for convex or concave surfaces. For steady-state evaporation, when $\partial C/\partial t = 0$:

$$D \times d^2C/dx^2 + (F/V) \times (C_o - C) = 0 \qquad (2)$$

Boundary conditions could be again chosen in the simplest form as:

$$C(\infty) = C_o$$
$$C(0) = C_s$$

where
C_s = saturated water vapor concentration under environmental conditions near a water surface (kg/m^3),
C_o = vapor concentration in the closed system at a distance from water surface beyond the boundary layer (m).

The solution for this kind of problem formulation is:

$$C = C_o + (C_s - C_o)\exp\{-[(F/V)/D]^{1/2}x\} \qquad (3)$$

On the basis of this solution it is easy to obtain (according to the classical approach) the expression for the specific (per unit of flat water area surface) water flux (closed water cycle) rate:

$$i = I/G = -D \times (dC/dx)\big|_{x=0} = (DF/V)^{1/2}(C_s - C_o) = W(T,P) \times (C_s - C_o) \qquad (4)$$

where

i = specific water flux rate (kg m^{-2} s^{-1}),

I = water flux rate (kg s^{-1}),

G = surface area of evaporation (m^2),

$W(T,P) = (DF/V)^{1/2}$ = vapor exchange rate function (conductance) expressed through the diffusion coefficient D (m^2 s^{-1}) and specific air circulation rate F/V (s^{-1}).

From this description it follows that the water cycle (flux) rate is directly proportional to the difference between saturated vapor concentration at the surface of evaporation (depends on temperature only) in the closed system and current vapor concentration in the system's air [$(C_s - C_o)$ ~ vapor pressure deficit]. The transition function depending on temperature and pressure, well known as conductance $W(T,P)$, reflects the dependence of water flux (cycle) rate on pressure and temperature.

Closed System Water Cycle Model

In the closed system (CS) the expression for the closed water cycle rate is a little different due to requirement of equivalence for evaporation and condensation fluxes for systems at constant temperature and pressure:

$$(DF/V)^{1/2}G_s(C_s - C_o) = (DF/V)^{1/2}G_c(C_o - C_c)$$

where

G_s = surface area of evaporation (m^2),

G_c = surface area of condensation (m^2),

C_s = saturated vapor concentration for system temperature (kg/m^3),

C_c = saturated vapor concentration for coolant coil (condensation surface) temperature (kg/m^3).

Here it is assumed that F/V is the same for the entire system, and that the coefficients of molecular diffusion for evaporation and condensation surfaces are practically the same due to small temperature differences ($\leq$25°C/273°C $\approx$0.092) within the Kelvin scale.

From here, an expression for vapor concentration and specific WC rate (WCR) in the CS can be expressed as:

$$C_o = (C_s + C_cG_c/G_s)/(1 + G_c/G_s).$$

Substituting the last expression into the specific water flux formula (Eq. 4) gives:

$$i = I/G_s = (DF/V)^{1/2}(C_s - C_c)(G_c/G_s)/(1 + G_c/G_s) \qquad (5)$$

Then, the expression for the specific water flux rate consists of:

- transition factor/function $W(T,P) = (DF/V)^{1/2}$ depending mainly on total pressure;
- vapor pressure deficit (VPD) factor $(C_s - C_c)$ depending on temperature differential between evaporating surfaces and coolant coil only;
- eco-engineering system design factor $(G_c/G_s)/(1 + G_c/G_s)$ related to CS design approach, which reflects the ratio between plant leaf area G_s and coolant coil area G_c.

Transition Function *W(T,P)* Description

A reduced list of constituents of the WC mathematical model can be assumed to be dependent on the value of total atmospheric pressure and temperatures of the system:

- diffusion coefficient, $D(T,P)$, in m^2 s^{-1} (7,12);
- air circulation rate, $F(T,P)$, in m^3 s^{-1} (6,8,9).

Only these characteristics are related to the molecular nature of the transport processes associated with evaporation and condensation. In the previously developed approach (12), it was assumed that the transition function is related to the diffusion coefficient by $W(T,P) \sim D/h$, where h = boundary layer characteristic size (m). It is easy to see now taking into account equations (4) and (5) that $h \sim (D \times V/F)^{1/2}$ is a function of wind speed F and not only pressure P. It is commonly accepted (6,8,23) that saturated vapor concentration depends only on temperature and is not affected by pressure in the range at least between 3 and 101.3 kPa (15). So, pressure and temperature conditions are represented in the mathematical model as parameters of transport processes and characteristics of vapor saturated states.

$W(T,P) = (DF/V)^{1/2}$ can be described in more detail. Several works dealing with theoretical analysis and experimental observations support use of the assumption that the diffusion coefficient can be expressed by a series of multiplied parameters (6,8,23):

$$D = D_0 \times (T/T_0) \times (P_0/P)$$

where

D_0 = diffusion coefficient under normal atmospheric conditions ($m^2\ s^{-1}$),

T and T_0 = current system's air temperature and temperature under normal pressure consequently (°C),

P and P_0 = current system's pressure and normal atmospheric pressure consequently (kPa).

Air circulation or specific (per unit of system's volume) circulation rate can be represented as: specific air circulation rate ~ forced convection rate + free convection rate.

Forced convection from Fan Theory (9) can be expressed as $(F/V) = (F_0/V) \times (P/P_0)$ for a wide range of pressures (<10–101.3 kPa), where F_0 = forced convection rate under normal pressure P_0 ($m^3\ s^{-1}$) and P = current system's pressure (kPa).

Free convection does not have such a clear definition. Nevertheless, from Similarity Theory (6,8,9,12) we can assume that:

$$\text{Free convection} \sim (D/h) \times (G_s/V) = (D_0/h_0)(T/T_0)(P_0/P)^{1/2}(G_s/V)$$

where

$D = D_0(T/T_0)(P_0/P)$ as defined above,

$h = h_0(P_0/P)^{1/2}$ = boundary layer characteristic size (h_0 = boundary layer characteristic size under normal pressure P_0) (m) (12).

Specific air circulation rate then can be represented as:

$$F/V = \phi[(F_0/V)(P/P_0) + (D_0/h_0)(T/T_0)(P_0/P)^{1/2}(G_s/V)] \equiv [(F_0/V)(P/P_0) + (D_0/h_0)(T/T_0)(P_0/P)^{1/2}(G_s/V)]$$

where ϕ = conversion factor balancing mathematical modifications between ~, ≈, ≡, and = signs and reflecting not complete similarity between physical reality and theoretical model transformations. Assume for simplicity that $\phi \equiv 1$ and that $(T/T_0) \equiv 1$. Then, the final expression for the transition function $W(T,P)$ is:

$$W(T,P) = (DF/V)^{1/2} = [D_0F_0/V + D_0(D_0/h_0)(G_s/V)(P_0/P)^{3/2}]^{1/2} \tag{6}$$

Formula (6) explicitly shows the power dependence of the transition factor and consequently WCR on total pressure, not only VPD.

Transition Factor *W(T,P)* Experimental Investigation

The VPD ~ $(C_s - C_c)$ factor interfaces mainly with temperature dependence in the model through saturation vapor concentration temperature dependence and does not depend on pressure in the range from 3 to 101.3 kPa (15), as it was investigated in experiments and described theoretically (23). This factor changes with pressure changes due to modification of heat exchange mechanisms and shifting of open water and coolant unit surface temperatures. To investigate the transition factor performance clearly, the best way is to keep temperatures of water and coolant coil as constant as possible and represent experimentally obtained WCR values as a ratio to WCR_0 under normal pressure:

$$I/I_0 = \{[1 + (D_0/h_0)(G_s/F_0)(P_0/P)^{3/2}]/[1 + (D_0/h_0)(G_s/F_0)]\}^{1/2} \approx [1 + (D_0/h_0)(G_s/F_0)(P_0/P)^{3/2}]^{1/2} \tag{7}$$

It is assumed that during pressure tests the VPD factor was maintained constant by maintaining water, air, and coolant coil temperatures at constant levels. That was achieved by independent methods (see Experimentation section). Then the agreement between theoretical predictions (Eq. 7) and test results can be considered and compared.

WC Parameters Classification & Control Capabilities

Parameters of the mathematical model for WC description (Eqs. 5, 6) can be classified in relation of their control properties and capacities. Table 1 shows that the WCR depends not only on the VPD but also on atmospheric pressure. WC control capabilities (CC) are represented by:

- engineering and technical design of the system through G_c/G_s changes (design control),
- G_c numerical value can be suggested at the system design stage,
- G_s has expected range of changes during plant growth,
- coolant unit temperature changes through coolant liquid temperature and circulation rate,
- regulation (operational control),
- air circulation rate changes through fan speed control (operational control).

General consideration and preliminary estimates of an operational CC can be done on the basis of the system's control matrix equation:

$$\Delta i=[\Delta F_0 \Delta C_c]\times\begin{bmatrix}\partial i/\partial F_0\\ \\ \partial i/\partial C_c\end{bmatrix}=$$

$$[\Delta F_0 \Delta C_c]\times\begin{bmatrix}\left(\dfrac{D_0 i}{2V}\right)\Big/\left[\dfrac{D_0F_0}{V}+\left(\dfrac{D_0^2}{h_0}\right)\left(\dfrac{G_s}{V}\right)\left(\dfrac{P_0}{P}\right)^{\frac{3}{2}}\right]\\ \\ \dfrac{-i}{(C_s-C_c)}\\ \end{bmatrix} \tag{8}$$

Here, as was determined above, $i = I/G_s = (DF/V)^{1/2}(C_s - C_c)(G_c/G_s)/(1 + G_c/G_s)$.

Equation (8), after algebraic manipulation, shows that the changes of specific WCR Δi to given control parameters changes ΔF_0 and ΔC_c varies with pressure by:

- sensitivity of $\partial i/\partial F_0$ related to air circulation rate changes ΔF_0 decreases with decreasing pressure and vice versa,
- sensitivity of $\partial i/\partial C_c$ related to coolant unit temperature changes ΔC_c increases with pressure decreasing and vice versa.

Table 1. Preliminary Classification of Water Cycle Parameters

Parameter	Definition	Relations	Control Capabilities
D (m^2 s^{-1})	Molecular diffusion coefficient	Depends on total pressure and temperature	Cannot be controlled for $T \sim$ Const and $P \sim$ Const
F/V	System specific air exchange rate	Depends on fan power and total pressure	Could be controlled to a limited degree by fan power changes
D/h (m s^{-1})	Coefficient of vapor transportation	Depends on total pressure as $\sim P - 1/2$	Cannot be controlled for $T \sim$ Const and $P -$ Const
G_c/G_s (non-dimensional)	Coolant coil surface area/ Evaporation surface area ratio	Does not depend on artificial environment parameters and depends only system design	Can be controlled in preliminary system's design and manufacturing
C_s (kg m^{-3})	Saturated vapor concentration under evaporation surface temperature	Does not depend on total pressure and is determined by water surface temperature	Can be controlled to a limited degree by changing the heat load (temperature)
C_c (kg m^{-3})	Saturated vapor concentration under coolant coil temperature	Does not depend on total pressure and is determined by coolant coil temperature	Can be controlled to a high degree by coolant system temperature changes

This means that coolant unit temperature changes are preferable as a control instrument in low-pressure environments. Coolant unit temperature changes have to be correlated with proper system temperatures maintenance in the range optimal for plant growth.

PRELIMINARY THEORETICAL CONCLUSIONS

Preliminary analysis of the closed WC (CWC) mathematical model allows the formulation of theoretical conclusions in advance of experimentation.

In the process under consideration, only the parameters D/h, F, C_s, and C_c of the mathematical model must be dependent on temperature and total atmospheric pressure, because they are only related to characterization of the physical structure and interaction of substances.

The values of D/h have to increase with increasing temperature and decreasing total pressure (increasing vacuum), because conditions for substance transport become more favorable. The air circulation rate F and consequently forced convection processes should decrease with decreasing total pressure.

WCR increases with decreasing total pressure even under constant VPD, because the values of transition factor (function) $W(T,P) = (DF/V)^{1/2}$, which are incorporated into the formula for WCR, increase for the same conditions.

It is possible to construct the class of parameters describing CWC and to choose some of them (coolant unit temperature and air circulation rate) for purposes of WC control.

EXPERIMENTATION

Setup

The theoretical description of WC was evaluated in the experimental system shown in Figure 1. This included a vacuum chamber (Bell Jar) with instrumentation that allowed simultaneous measurement, maintenance, and recording of temperature of air, temperature of evaporating water, relative humidity, air circulation rate under normal pressure, and atmospheric pressure level.

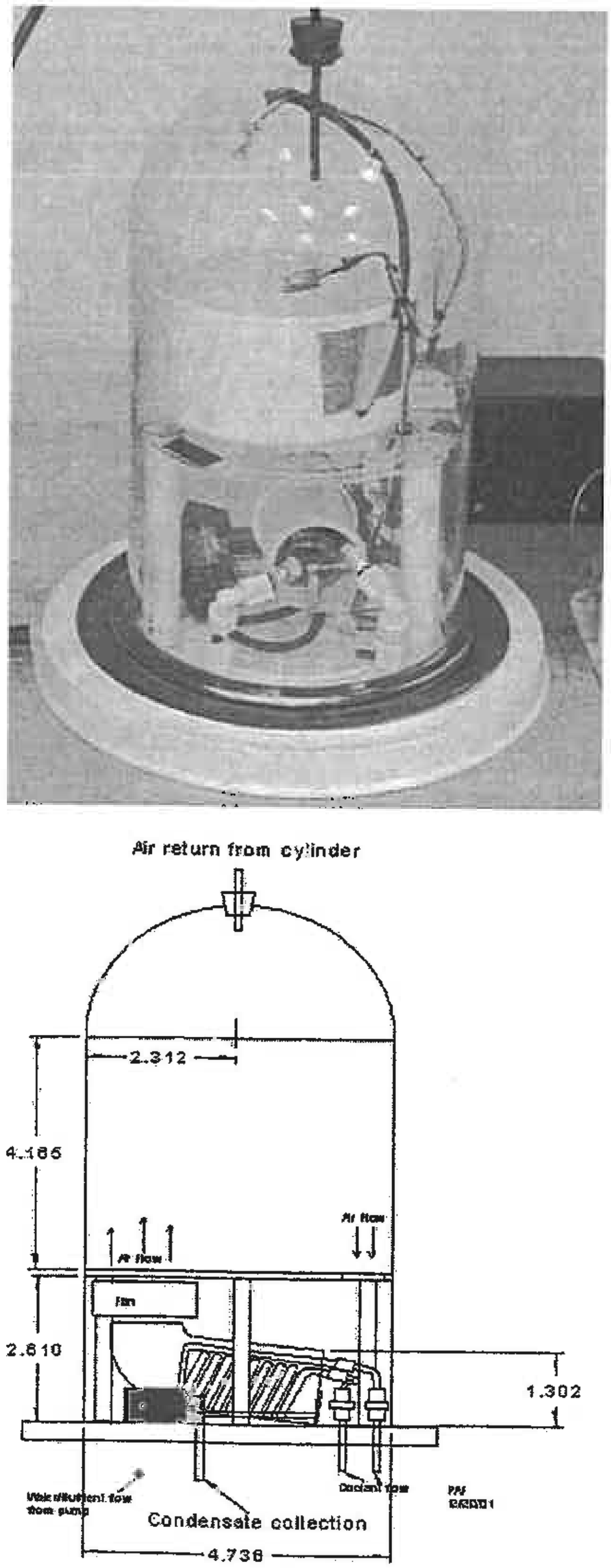

Figure 1. Setup for measurement of water cycle (WC) parameters.

This instrumentation included two separate gages for measurement of vacuum (Setra Model 470 Digital Pressure Transducer, Heise 30 in Hg bourdon tube vacuum gauge), thermocouples, humidity sensor (Vaisala Model HM40). A small fan was mounted inside the chamber for quick mixing of air. A water bath was used to cool the chamber by circulating chilled water through a copper coil placed inside the chamber, and a vacuum pump (Labport, PU845-N842.0-1.97) with pressure controller (Labport, PU842) was mounted outside the chamber. An open plastic container was used as a source of water vapor. Vapor was collected from the coolant coil and accumulated in a flask placed on a digital scale outside the chamber. A diaphragm pump was used to collect water from the cooling coil section and pump into the flask. The condensate collection pump was activated every 30 s. The weight of water collected within the water cycle at different values of total pressure and different temperatures was continuously recorded. By using of this data, the water flux (cycle) rate was calculated at different levels of vacuum (Fig. 2).

Protocol of the Experiment

The tests conducted are shown in Table 2. Temperatures and RH were maintained at constant levels during each test: air temperature, 22°C; water temperature, 20°C. Water accumulation was monitored and recorded for each test. A representative set of results is shown in Figure 2.

Original Data and Processing

Temperatures of water, air and coolant coil, pressure and relative humidity values, and water accumulation were measured and recorded for each test. WCR in the system was calculated as the linear approximation of the slope of water accumulation. Then, the I/I_0 (I_0 = WCR under normal pressure 101.3 kPa = water accumulation rate under normal pressure 101.3 kPa) ratio for each test was calculated and presented graphically (Fig. 3).

Table 2. Water Flux Experiment Matrix

		System Pressure (kPa)				
Test	Cooling Coil Temperature (°C)	10	25	50	75	101.3
1	5	++	++	++	++	++
2	10	+++	+++	+++	+++	+++
3	15	+++	+++	+++	+++	+++
4	17	++	++	++	++	++
5	18	++	++	++	++	++

+ indicates replications.

RESULTS

The results of measurements and further calculation of the I/I_0 ratio, which have similar variations as WCR at different levels of total pressure, are presented in Figure 3. These data show:

- decreasing total pressure lower than 25.0 kPa causes WCR ratio to significantly increase by more than 80%,
- deviation of the WCR ratio around some average trend (more than 40%),
- there is decreasing of the WCR ratio values below 25 kPa in some cases,
- WCR ratio deviations do not correlate with coolant coil temperature changes,
- a power approximation is good enough for WCR ratio description in dependence on total pressure changes.

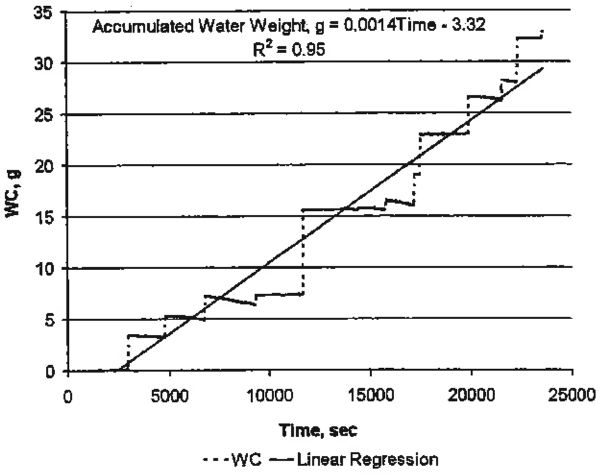

Figure 2. Example water collection test data for coolant coil $T = 20°C$ and $P = 50$ kPa. WC: accumulated water weight (g). Linear regression: least squares approximation for accumulated water weight (g).

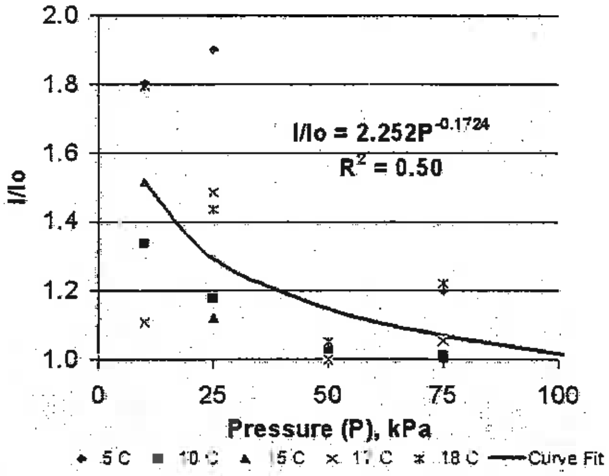

Figure 3. Ratio of WCR (P) to WCR (P_0) under normal pressure as related to total atmospheric pressure in the closed system (CS).

Theoretical analysis shows that the power approximation for all tests would be quite appropriate. The scatter in values of the WCR ratio around the approximating function in the range of low total pressures and temperatures of the coolant coil (17°C and 18°C) when close to air temperature (22°C) can be explained by different leak rates for each pressure level. The decreasing WCR ratio in the low-pressure region probably was caused by the accelerated leak rate and the resulting maintenance of pressure level by the pump.

DISCUSSION

Experimental observations confirm most parts of the theoretically obtained conclusion that WCR is pressure dependent even under constant VPD and goes up when total pressure goes down. It is well described by the transition function $W(T,P)$ introduced earlier. Some deviations around the average value probably were caused by test instabilities (leak rate not const, pump/controller interaction, voltage changes during round-the-clock day). Figure 3 shows that a power approximation is acceptable for these data in most of the cases.

WCR Ratio Approximations

Water fluxes rates ratio can be represented as in the Appendix:

$$
\begin{aligned}
I/I_0 &= W(T,P)/W_0(T,P) = \\
&\{[1 + (D_0/h_0)(G_s/F_0)(P_0/P)^{3/2}]/[1 + (D_0/h_0)(G_s/F_0)]\}^{1/2} = \\
&\{[1 + \alpha(P_0/P)^{3/2}]/(1 + \alpha)\}^{1/2} \approx \\
&[1 + \alpha(P_0/P)^{3/2}]^{1/2} \propto (P_0/P)^{3/4\alpha/(1+\alpha)}(P_0/P)^{3/4\alpha}
\end{aligned}
\qquad (9)
$$

The last approximation $\propto (P_0/P)^{3/4\alpha}$ is less precise and consequently is applicable only for $\alpha \to 0$. Here $\alpha = (D_0/h_0)(G_s/F_0)$. Power functions are often used to represent nonlinear experimental data. From above, it is possible to see that power degree $(3/4\alpha)$ in the last formulae is dependent on the experimental conditions (α), which include surface area of evaporation G_s (changes during plant growth), and air circulation rate F_0 (changes also during plant growth period).

These conditions can vary strongly for different experimental systems and experiments. This explains (besides Fig. 3) reasons for different experiments, what were done in area low-pressure evapotranspiration, and show different power approximations for numerical data. When α varies between 0 and ∞, the power degree can change between 0 and 3/4 (=0.75). Experimental design (F_0, G_s, G_c, etc.) strongly affects water flux (water cycle) performance.

Water Flux Charts Under Low Pressure

It would be useful to build three-dimensional (transition function value, temperature, pressure) water flux charts (WFC) as a representation of the transition function:

$$
W(T,P) = (DF/V)^{1/2} = [D_0F_0/V + D_0(D_0/h_0)(G_s/V)(P_0/P)^{3/2}]^{1/2} \propto (101.3/P)^{3/4\alpha}
$$

For numerical values $F_0 = 1\ \mathrm{m\ s^{-1}}$ and $G_s = 1\ \mathrm{m^2}$ for enclosure $V = 1\ \mathrm{m^3}$.

This WFC then can be considered as a fundamental constant and in combination with the suggested approximation can be applied to the closed systems of other configurations.

GENERAL CONCLUSIONS

For the investigated range of total pressure between 10 kPa and 101.5 kPa:

- The rate of the water cycle in closed systems increases significantly with decreasing total atmospheric pressure in the system lower than 25.0 kPa. Under pressures above 25 kPa the WCR is relatively constant. Its magnitude depends on VPD and CS general design.

- The dependence of the water cycle rate on total pressure P kPa in a CS can be described (approximated) by a power function ~ $(101.3/P)^{-0 \text{ to } 3/4}$ with power degree varying between the limits of 0 to 3/4 depending on the ratio of free convection rate to forced convection rate, which is greenhouse design function and can change in a range between 0 and ∞.
- Climate control capabilities for a water cycle in a closed system are provided mainly by coordination between heat load and heat removal processes with proper correlation for plant growth requirements.
- The approach suggested allows further development of existing evapotranspiration equations to low-pressure range.

Extension of Conclusions

Cultivation of plants at atmospheric pressure equal or higher than 25.0 kPa should not be significantly affected because changes of environmental conditions are not great. Under 25.0 kPa, there are possible difficulties connected with incompatible values of the water cycle intensity with plant physiology (water conductivity stress). This range of pressures should be further investigated in relation to plant transpiration physiology.

FUTURE WORK

Based on the conclusions above, the next phase of studies should be:

- Creation of a reliable closed water cycle in a scaled up experimental system at different levels of total atmospheric pressure.
- Calculation and creation of an artificial atmosphere in an experimental system appropriate for higher plant cultivation under low pressure.
- Investigation of long-term abilities of higher plants to grow at the lowest levels of total atmospheric pressure.
- Calculation of engineering parameters for enclosures for plants growth on Martian surface (<1 kPa outside pressure).

APPENDIX: DESCRIPTION APPROXIMATION OF WATER CYCLE RATE (WCR)

Any function can be approximated by certain sums of other nonlinear functions. A power function semiempirical approximation for

$$I/I_0 = \{[1 + (D_0/h_0)(G_s/F_0)(P_0/P)^{3/2}]/[1 + (D_0/h_0)(G_s/F_0)]\}^{1/2} = \{[1 + \alpha(P_0/P)^{3/2}]/(1 + \alpha)\}^{1/2}$$

where $\alpha = (D_0/h_0)(G_s/F_0)$ and $0 < \alpha < \infty$ can be constructed on the basis of the following reasoning (ideas obtained from Academician G. Migdal, 1970, 1977; Moscow State University and Russian Academy of Sciences; private communications):

- there should be just one power component in series,
- the approximation should be $\propto [(P_0/P)^{3/2}]^{1/2}$ for $\alpha \geq 1$,
- the approximation should be $\propto 1$ for $\alpha < 1$,
- the approximation should give a close approximation to Taylor or another series,
- the approximation should be in agreement with physical

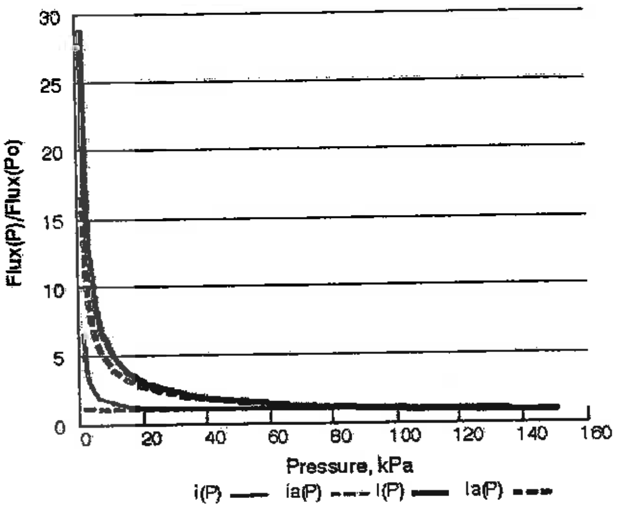

Figure A1. Semiempirical power approximations for WCR ratio for different pressures. $i(P)$ = exact calculation for I/I_0 under realistic value $\alpha \sim 0.043$ (forced convection and small evaporating area); $i_a(P)$ = power approximation for I/I_0 under realistic value $\alpha \sim 0.043$; $I(P)$ = exact calculation for I/I_0 under realistic value $\alpha \sim 0.043 \times 100$ (free convection and developed evaporating area); $I_a(P)$ = power approximation for I/I_0 under realistic value $\alpha \sim 0.043 \times 100$.

reality [e.g., it should work well in the range of pressure changes of interest: $0 < (P_0/P) < 1$].

In the case under consideration, the following approximation satisfies these requirements:

$$I/I_0 \propto (P_0/P)^{3/4}[\alpha/(\alpha + 1)]$$

BIOGRAPHICAL NOTES

Vadim Y. Rygalov, Biophysicist, has worked in the area of Closed Ecological Systems (CES) study and bioregenerative life support since 1989. He received his Ph.D. in 1986 from the Institute of Biophysics Siberian Branch Russian Academy of Sciences (Krasnoyarsk, Russia). His Ph.D. topic was System's Analysis of Environment—Macro-Algae Growth and Development Interaction. Vadim is interested in the investigation of principles of closure for the functions of ecological systems and their applications for life support in different areas.

Philip A. Fowler, Biological Engineer, received his Ph.D. in Agricultural and Biological Engineering, University of Florida, 1998. He has been employed by Dynamac Corporation KSC NASA since fall of 1998, responsible for systems and controls of environmental chambers at the Space Life Sciences Laboratory. Phil is lead engineer for the Mars Greenhouse Project. He is currently involved in low-pressure studies and effects on plants and is responsible for design of low-pressure environmental chambers and for monitoring and control systems associated with low-pressure chambers.

Raymond M. Wheeler received his Ph.D. in 1981 (Plant Science Physiology) from Utah State University. Ray worked as postdoctoral researcher at the University of Wisconsin conducting studies with potatoes as a candidate crops for Advanced Life Support systems, and then took a job as a research plant physiologist with Bionetics Corp. at Kennedy Space Center, FL, in 1988. Ray currently works for NASA and Kennedy Space Center, where he works as a senior scientist in the Biological Sciences Branch.

Ray A. Bucklin is an Agricultural Engineer and Professor in the Agricultural and Biological Engineering Department of University of Florida, Gainesville. He received his Ph.D. in Agricultural Engineering from University of Kentucky in 1982. Ray is interested in Greenhouse modification and applications for growing plants in different extreme environments.

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