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Harbinson, J.
John Innes Institute and AFRC Institute of Plant Science Research

Burcham, K.
John Innes Institute and AFRC Institute of Plant Science Research

Wilton, D.
John Innes Institute and AFRC Institute of Plant Science Research

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A DESIGN FOR A DISEQUILIBRIUM HUMIDIFIER SUITABLE FOR GAS CONDITIONING IN PHOTO-SYNTHETIC MEASUREMENT SYSTEMS

J. HARBINSON, K. BURCHAM and D. WILTON

John Innes Institute and AFRC Institute of Plant Science Research, Colney Lane, Norwich NR4 7UH, U.K.

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HARBINSON J., BURCHAM K. and WILTON D. *A design for a disequilibrium humidifier suitable for gas conditioning in photosynthetic measurement systems.* BIOTRONICS **18**, 1–8, 1989. A humidifier is described which relies on the continuous adjustment of the temperature of a small volume of water to effect controlled, accurate humidification of a gas stream. The system features small size and robustness, and does not require equilibration to occur between the gas stream and water body.

Key words: humidifier; gas exchange.

INTRODUCTION

The control of the water vapour pressure in the gaseous phase is an essential feature of any system for measuring the gas exchange of leaves. Common practice is to produce a controlled humidification by allowing a gas stream to come to equilibrium with a source or sink of water vapour, usually pure water or a salt solution (*1*). The temperature of the water vapour source or sink, possibly combined with control of gas pressure, determines the equilibrium water vapour pressure. This approach has exploited the ease with which temperature can be measured and controlled. Though such systems provide a generally effective means of controlling humidity, the need for complete equilibration to occur between the gaseous phase and the solid or liquid phase can be source of error. As the gas flow rate increases the effective path length through the humidifier must be increased in order to ensure complete equilibration (*3*), and increasing the size of the humidifier produces difficulties in controlling the temperature of the system. To avoid the problems associated with equilibrium humidification at large gas flow rates (in our case $\sim$ 0.08 $dm^3\ s^{-1}$) we have developed a humidification system which does not depend on equilibrium between the gas and a water vapour source or sink. This disequilibrium humidification system is small, robust and has no critical moving parts. Rather than attempting to control humidity by sensing and adjusting the temperature of the water vapour source the system we have developed relies on measurement of the himidity of the gas stream. This approach has been made possible by improvements in the quality of relative humidity sensors. It allows precise and accurate control of water vapour pressure to a standard that, with a $\sim$0.08 dm^3 s^{-1} flow rate and a 10 dm^3 gas mixing vessel, allows measurements of water vapour release from leaves to be made with high accuracy. It is also possible to rapidly increase or decrease the steady state water vapour pressure of the gas stream making it especially useful in systems where leaf temperature is being varied.

DESIGN AND OPERATION

The system comprises of three units; a humidifier, a humidity sensor and a control unit (Fig. 1). The humidifier consists of a three layered assembly of a humidifier cell, two thermoelectric modules and a ventilated heat exchanger (Fig. 2). The humidifier cell is a shallow, gas-tight evaporation chamber with acrylic walls and lid, and a 1-mm thick stainless steel base. At one end of this chamber there is a water reservoir which is kept filled with distilled, deionized water. The source of water vapour in the humidifier cell is a glass fibre filter paper wick (Whatman, GF/C) which extends from the reservoir along the metal base of the chamber, gas enters and leaves the evaporation chamber *via* two fittings in the side wall and a partition extending part way across the chamber forces the gas stream to flow over the wet filter paper wick. Another partition separates the gas space above the water reservoir from the compartment containing the filter paper; the filter paper wick passes under this partition as it enters the evaporation chamber.

Immediately under the thin stainless steel base plate lie two thermoelectric modules (Cambion type 801-2000-01-00-00, Cambion Electronic Products, Castleton, Sheffield, U.K.). These can either 'pump' heat into or out of the base plate and thence the wet filter paper wick within the evaporation chamber. The ventilated heat exchanger on which the thermoelectric modules are mounted dissipates the considerable quantities of heat generated as the modules 'pump' heat out of the base plate and acts as a heat reservoir for when the thermoelectric modules are 'pumping' heat into the evaporation chamber. By this means the temperature of the water held in the wick can be adjusted. The combination of a high gas flow rate ($\sim$0.08 dm^3 s^{-1}) and a small area over which water vapour release can occur ($\sim$40 cm^2) prevents equilibrium between the gas stream and the water in wick from occurring. The steady state water vapour pressure of the gas leaving the humidifier cell will be a function of gas inlet water vapour pressure, gas temperature, water temperature, gas flow rate and gas pressure. Given this number of variables, controlling the temperature of the water film in the base of humidifier cell would result in only poor control of the water vapour pressure of the exit gas stream. In order to achieve accurate control of the humidification of the gas stream it is necessary to use a feed-back loop which senses not temperature (typical of equilibrium humidification systems) but the water vapour pressure of the exit gas stream.

The design of the water vapour pressure sensor required for such a scheme is shown in Fig. 3. At constant temperature, relative humidity is a linear function of water vapour pressure, so by maintaining a humidity sensor at constant temperature a means is provided by which water vapour pressure can be easily quantified. A capacitive humidity sensor (Model CCH, Lee-Integer Ltd., Kettering, Northants,

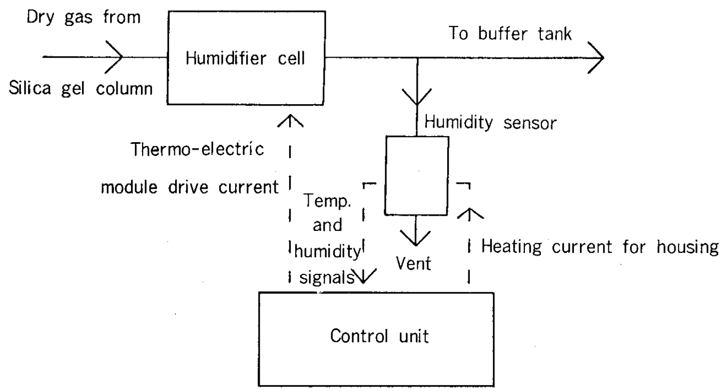

Fig. 1. A block diagram of the humidification system showing the functional relationship between the components. Solid lines indicate gas flows, and broken lines indicate electrical connections.

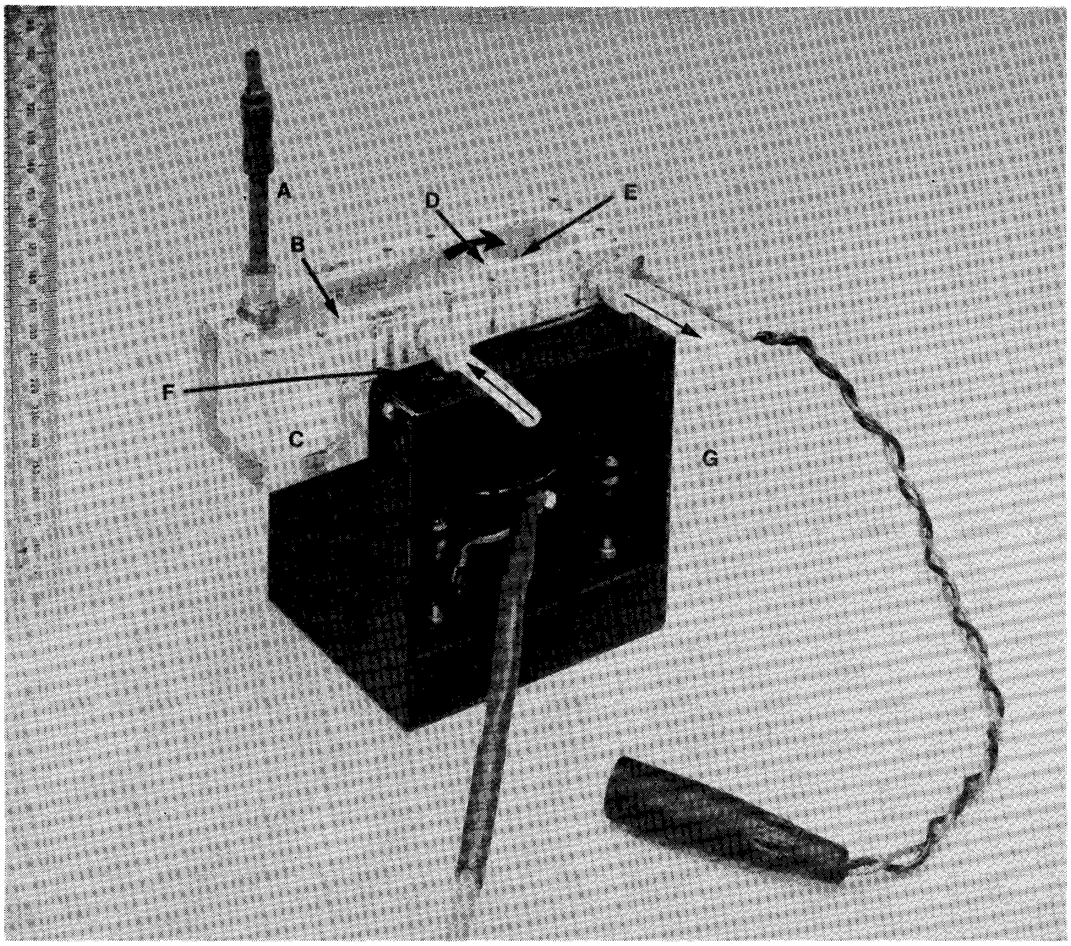

Fig. 2. The humidifier cell. A: water reservoir fill pipe, B: barrier between reservoir and humidifier chamber, C: reservoir, D: partition, E: humidifier chamber, F: Peltier units, G: heat exchanger.

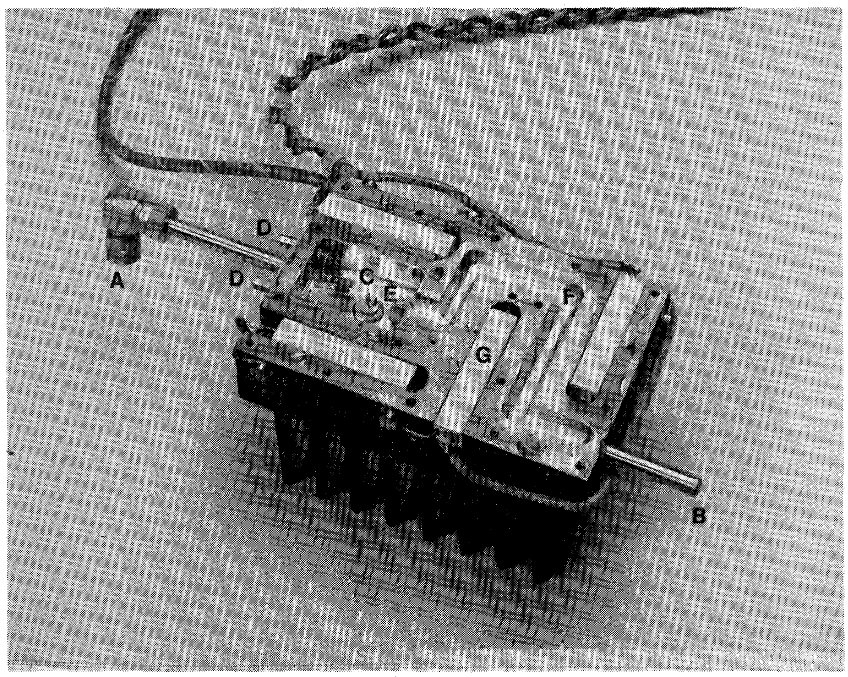

Fig. 3. The humidity sensor housing with top plate removed to show internal detail. A: gas outlet, B: gas inlet, C: humidity sensor, D: humidity sensor connections, E: temperature sensor (LM35), F: gas sinus, G: ceramic encased heater.

U.K.) is housed within a heated metal block through which a sample of the exit gas is diverted. The housing in which the sensor is mounted is a plate of metal heat sink material (Marston-Palmer 97CN.) upon which is fixed a block of brass into which a channel is milled. Continuous with this channel is a cavity in which both the humidity sensor and a temperature sensor are located. Between the turns of the channel are slots into which four ceramic encased heaters (7 W resistors KH210, VTM(UK), Greenford, Middx. U.K. or similar) are located. A metal top plate is fixed to the milled brass plate to produce an enclosed gas path in a heated metal block. All metal surfaces that come into contact with the gas stream are etched and highly polished to reduce adsorption of water vapour (*2*). The temperature of the block is maintained accurately at about 35°C, though the choice of block temperature will depend on the dew point of the desired vapour pressure. The block temperature should be several degrees above the dew point of the highest vapour pressure required to allow for any overshoots in vapour pressure. The circuit needed to control the temperature of the humidity sensor housing, to sense changes in the capacitance of the humidity sensor and to control the thermoelectric modules is given in the Appendix and shown schematically in Fig. 5.

Typical performance of the system is shown in Fig. 4. This shows that the system, even though run at only 25% maximum heat exchange capacity allows the production of a stable vapour pressure under steady state conditions at flow rates of 0.08 $dm^3\ s^{-1}$ or greater. Running the thermoelectric modules at 25% of their maximum capacity makes the device more failsafe; if the reservoir dries out

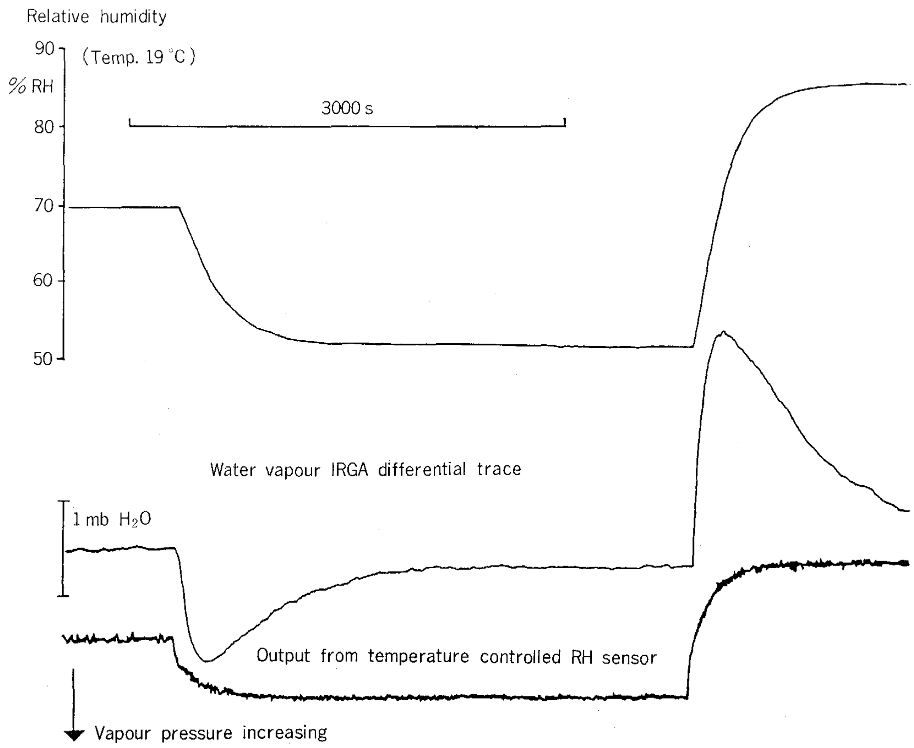

Fig. 4. Simultaneous recordings of the relative humidity of the gas stream from the humidifier unit buffered by a 10 dm^3 reservoir with a flow rate of 0.08 dm^3 s^{-1}, the output of water vapour IRGA (Series 225 Mk3, Analytical Development Co., Hoddesdon, England) operating in differential mode with reference gas being sampled before, and sample gas after, an assimilation chamber, and the output of the temperature controlled humidity sensor used to control the heat flux in the humidifier cell. In the example illustrated here the heat pumping capacity of the Peltier units was limited to 25% of their maximum capacity.

or the ventilation fan fails no dangerous overheating can occur. The noise level of the water vapour pressure is low enough to allow measurements of water vapour release by leaves to be made with high resolution. Though the half time for the change in water pressure, as measured by the control humidity sensor is only 36 s, the presence of a 10 dm^3 gas mixing vessel used in this system combined with water vapour adsorption increases the half time for the change in the humidity sensed by another humidity sensor located just before the assimilation chamber to 180 s. Following a change in water vapour pressure the output of a water vapour IRGA in differential measurement mode and with no leaf in the assimilation chamber stabilized after 1800 s.

Adjustments to the water vapour pressure of the gas flow can be easily and quickly made; the system is convenient to run and requires no maintenance other than refilling the water reservoir. This refilling is due *via* a tube fixed to the water reservoir. Its small size and robustness also make it relatively portable though the heavy current demands of the thermoelectric modules when cooling the humidifier cell would make the provision of low water vapour pressures for prolonged periods

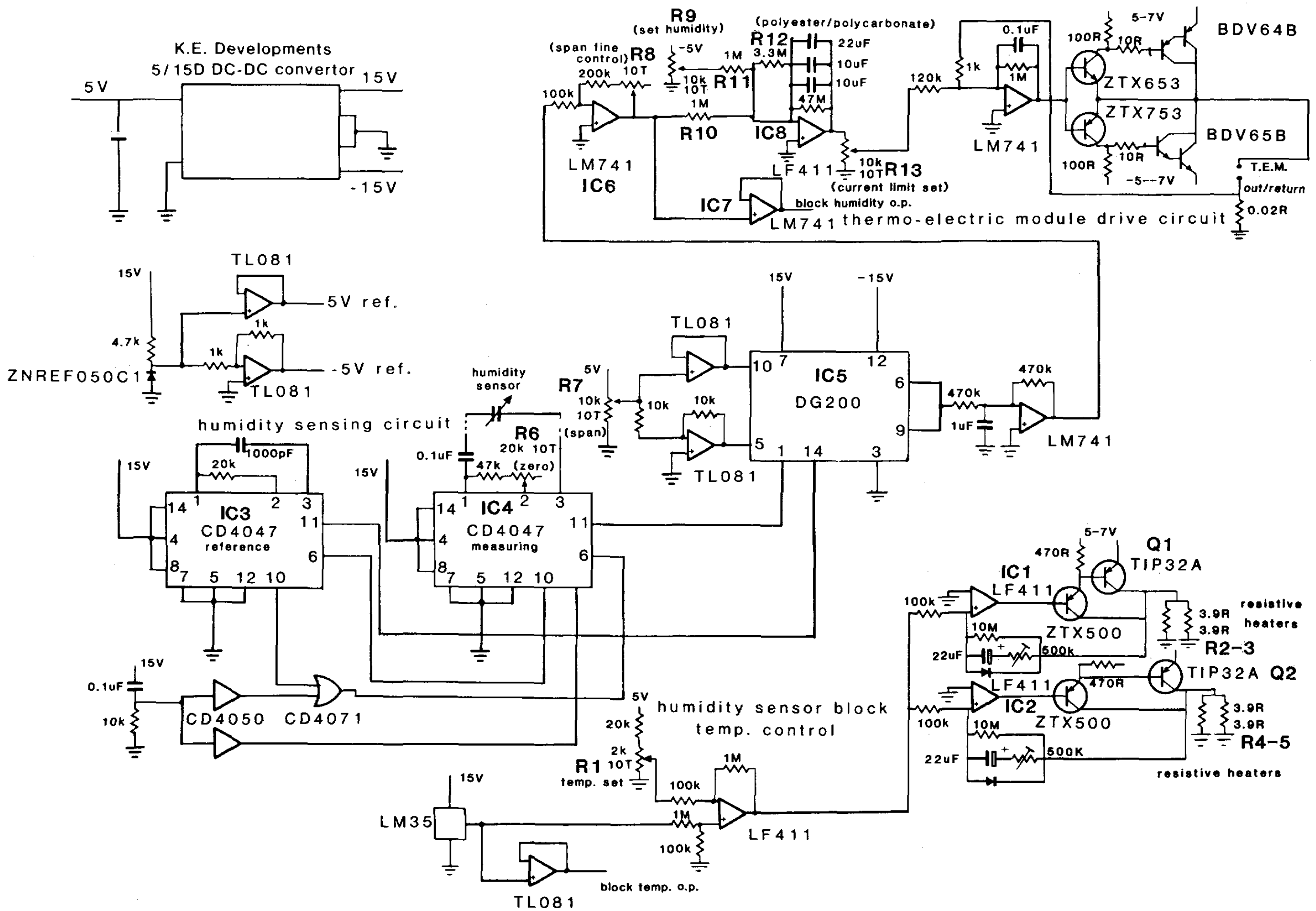

Fig. 5. A diagram showing the circuit required to control the heat flux in the humidifier cell and assay the humidity of the gas stream.

of time under field conditions difficult unless a dry-air bypass system were to be fitted. This would allow part of the pre-dried gas stream to be diverted around the humidifier cell and as water vapour is only picked up by the gas stream which flows through the cell decreasing the proportion of the gas stream which flows through the cell results in a higher steady state water temperature in the cell for a given final water vapour pressure when the gas streams are mixed.

APPENDIX

The temperature of the humidity sensor housing is sensed by an LM35 (National Semiconductor) solid state temperature sensor with an output buffered and balanced against a potential divider (R1) which is used to set the temperature of the block. An imbalance between the temperature sensor and the potential divider unbalances two augmented integrators (IC1 and IC2) which in turn change the current flow through the power transistors Q1 and Q2. By this means the power dissipation of the block heaters (resistors R2-5) mounted in the humidity sensor housing is adjusted and the temperature changed. The value of the time constant of the augmented integrator cannot be specified exactly as it will depend on the design of the humidity sensor housing and the power dissipation of the power resistors. The given values of components produce a stable temperature in our system but may need to be adjusted if an alternative design is adopted. This can be done by increasing or decreasing the value of the input resistors or, alternatively, by decreasing or increasing the value of the integrating capacitors.

The humidity sensing circuit is a modification of a balanced demodulator circuit. Two monostables (IC3 and IC4) are employed in this circuit to control two analogue gates. One of these monostables produces a reference pulse whereas the pulse length of the other monostable is variable being affected by the capacitance of the humidity sensor, and by the trimmer R6. Each monostable is used to trigger the other so they effectively produce a pair of pulse trains one of which is the logical inversion of the other. These are used to open or close a pair of analogue gates (IC5 DG200). A positive voltage, whose value is adjustable *via* trimmer R7, is applied to one gate and its analogue inverse is applied to the other. If both monostable pulse lengths are identical then the net voltage at the output of low pass filter should be zero and the trimmer R6 can be used to null the circuit with the humidity sensor in air of 0% relative humidity. As the capacitance of the humidity sensor increases with increasing humidity then the pulse length of the measuring monostable will also increase and net voltage at the output of the low pass filter will be a linear function of the capacitance of the humidity sensor. The scale of the increase can be adjusted *via* trimmer R7. As configured, the output of sensing circuit becomes more negative as the capacitance of the humidity sensor increases. However the polarity of the voltage change can be simply reversed by switching the connections to pins 1 and 14 of the DG200 analogue switch.

The output of the humidity sensing circuit is passed to the thermoelectric module driving circuit. Some extra fine scaling of the voltage corresponding to the humidity is available *via* the feedback resistance (R8) at IC6 and the output of this amplifier is buffered (IC7) to provide an output voltage which corresponds to vapour pressure. The value of the desired water vapour pressure deficit is set by R9; the voltage input of this potential divider is balanced against the output of IC6 by an augmented integrator (IC8). The capacitors used in the integrator section of the augmented integrator must be reversible and have a low leakage current; either polyester or polycarbonate types will suffice. If high quality high value resistors can be obtained the resistors R10 and R11 (which have values of 1 M in the schematic diagram) could be replaced, along with the R12, with higher value resistors; this would allow the value of the integrator capacitance, to be reduced to a more convenient value. The output from the augmented integrator drives the current source/sink for the two thermoelectric modules and the maximum current can be set by adjusting trimmer R13. The thermoelectric modules used in this design were Cambion type 801-2000-01-00-00. These have a maximum pumping power of 29 W at 6 V and 9 A but the current flow through each thermoelectric module was limited to 4 A. The use of higher currents, with the associated increase in the rate of heating or cooling the water film in the evaporation chamber, did not have a corresponding effect on the rate of increase or decrease of the humidity in the assimilation chamber because of water vapour adsorption along the gas path. If this problem could be reduced then the use of higher currents, or more powerful thermoelectric modules, could allow greater rates of change of humidification.

The supply of power to the sytem is a critical factor in the construction. The thermoelectric modules can draw large currents (up to 9 A each) at a low operating voltage (6 V). Consequently it is important that all cabling and connectors be as heavy as possible to avoid excessively large voltage drops. If possible the heater system of the humidity sensor housing should be powered from a separate supply as many simple power supplies will suffer a voltage drop if heavy currents are drawn and voltage drops can also occur along the power supply cables. If this happens the voltage across ceramic encased resistive heaters will fall and they will dissipate less heat, resulting in a temporary fall in the housing temperature with an increase in relative humidity of the gas around the humidity sensor. This in turn will cause a decrease in thermoelectric module cooling current, and can lead to small damped oscillations. All the control electronics are powered separately from a DC-DC convertor to avoid problems of this kind.

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