2

A CLIMATE CHAMBER THAT CONTROLS WATER VAPOUR FLUX

General design considerations

The climate chamber for testing the moisture absorbent properties of porous walls must be able to imitate the interior climate as it is influenced by the test wall. The chamber must be able to generate water vapour regardless of the prevailing relative humidity. This is what happens when we cook or take a shower. A few minutes inattention to the cooking can fill the kitchen with steam. An absorbent wall will mop up the water and moderate the relative humidity, which an impermeable wall cannot do: dew will form as drips on the surface. A climate chamber that defines the relative humidity cannot imitate this situation.

If we remember, we can switch on an extractor fan or open a window to reduce the high indoor water vapour concentration. The climate chamber must also be able to imitate this negative flux.

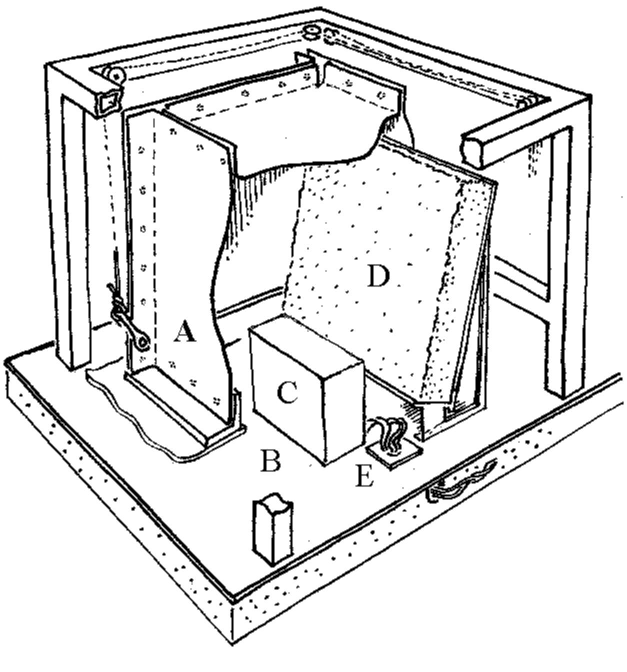

*Figure 2.1 A cut away diagram of the experimental chamber. The scale is distorted to emphasise the main features. It is a stainless steel box **A** without a base, that sits on a stainless steel plate **B**. Electrical and other services **E** are sealed through the base. The experimental wall **D** is tilted back on a support so that it can be constructed of loose blocks. The air conditioning equipment **C** is within the box.*

An orthodox climate chamber controls a potential: the relative humidity. A leak doesn't matter; the control system will notice a fall in RH and react to restore the set value by adding water, without caring what happened to the lost water. The climate chamber described in this chapter controls the quantity of water emitted into, or absorbed from the air. Leaks will destroy the accuracy of the accounting. The chamber must therefore be airtight.

A chamber that is intended to investigate convective processes within a test wall should be able to accommodate a slab of wall about one metre square. The wall might be up to 300 mm thick. The control apparatus should be within the chamber, to avoid problems with condensation caused by the different temperature outside the insulated, thermostatically controlled chamber. The air speed over the test wall should be adjustable, so there must be a reasonable space for air braking grids between the air conditioner and the test wall.

All these considerations lead to a design with a chamber volume of at least a half cubic metre.

A chamber that lifts off a heavy baseplate that extends well beyond the chamber will allow heavy, loosely piled up experimental walls to be prepared outside the chamber, then moved into place easily. The seal will extend all round the foot of the chamber, so the construction must be precise.

The chamber must also be built from non-absorbent materials so that the water is only absorbed into the experimental wall. If these conditions are fulfilled it is not necessary to weigh the wall itself. This is a great advantage, because the various test walls will be of very variable water absorption, weight and thickness, making it difficult exactly to measure relatively small variations in weight.

The chamber construction

Figure 2.1 shows the climate chamber with the design features emphasised. It is a stainless steel box without a base, that sits on a stainless steel plate which in turn rests on 100 mm of firm insulation ("Oasis"). Electrical and other services are sealed through the base. The experimental wall is tilted back on a support so that it can be constructed of loose blocks. The air conditioning equipment is within the box.

The sides are 1 mm thick, bent and spot welded to each other and to a L-section flange that forms the base. The seams are sealed with silicone. The seal with the base is a silicone skirt, 1 mm thick and about 60 mm broad. It flops down onto the baseplate under its own weight, giving a seal that is diffusion resistant but will not withstand a pressure difference. The seal is reinforced by pressing the skirt down with flexible tubes made from bicycle inner tubes filled with steel shot.

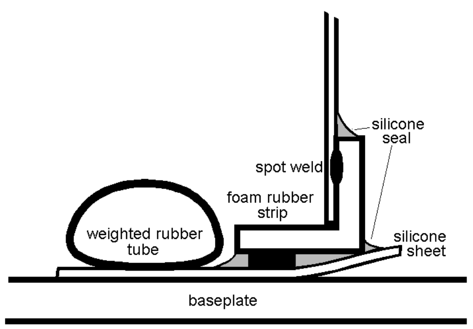

Figure 2.2 Detail of the seal. The flange around the base of the box has a foam rubber strip stuck underneath it. A wide silicone rubber strip is fixed to the flange with silicone sealant. The foam rubber gives space for the sealant and tilts the silicone so that it tends to press against the base plate. The seal is reinforced by weighted cycle inner tubes laid around the wide skirt which extends over the base plate.

The box can be lifted up within a frame of square aluminium tubes by cords attached near the base flange and brought over a system of pulleys to one point. Here the cords are attached to a tackle with a 4 times advantage.

Leakage tests, described in detail later, gave an exchange rate for water vapour corresponding to about one air change every ten days. The chamber cannot resist differential air pressure, so the natural atmospheric pressure variation will pump air in and out of the chamber. To reduce this leakage the box was given a pressure buffer

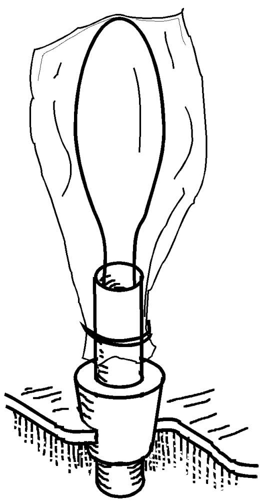

Figure 2.3 The air bag on top of the chamber which buffers pressure change

system (figure 2.3). This was a double skinned polyethylene bag, about 300 x 200 mm in area, suspended over, and sealed to, a brass tube 300 mm long x 8 mm diameter, that extended from the top of the case. The bag deforms easily to take up volume changes caused by pressure or temperature variation.

Air pumping caused by thermal expansion and contraction and leakage due to buoyancy of warm air is further reduced by placing the chamber in a room which controls its temperature with a precision of 0.2 degrees. The chamber itself is precisely controlled to about two degrees above ambient. The slight over temperature is necessary to ensure accurate control against the variable heat output of the air conditioning package within the chamber.

The empty chamber with its control apparatus has a certain water absorption. Tests on the empty chamber are described later. The error is very small for experimental walls of absorbent materials which are tested at around 45% to 65% RH, because the influence of the box absorption in this RH range is very small. Generally the RH variation was kept small, by using a large area of experimental wall, because the RH can be measured with greater precision than the other variables.

The water flux that must be provided

The environment of indoor structures will be nearly isothermal, between 15 and 25 degrees. The amount of water needed to change the RH of the chamber air from zero to 100% will be about 20 g/m^3. The amount of water that may be exchanged with the test wall is much larger. To get an order of magnitude, consider a wooden wall, 50 mm thick and half a square meter in area. This weighs about 12 kg and will exchange about 1 kg of water when the RH changes from 30% to 80%. The process is however very slow for this thickness of massive wood. Useful information about the behaviour of the wooden wall can be obtained with a smaller exchange: about 100 g of water.

The flux generator therefore needs to be able to control about 200 g of water. It should be able to release and absorb this water from air with an RH between 100% and 20% RH. The lower limit is set by the instrument used to measure RH in the chamber.

The flux should be able to imitate the release of water in a house. The worst case that I could measure is cooking a large pan of spaghetti, which releases a flux of about 20 g/(m^3.hr) into a small kitchen. The only source of negative flux is air exchange to the outside. A house at 20°C and 60% RH contains about 10 g/m^3 of water. Outside air at 5°C and 90% RH, a dreary winter day, contains about 6 g/m^3. So one air change per hour will move 4 g/m^3 out of the house.

Assuming a climate chamber of one half cubic metre, the flux generator should ideally be able to evaporate about 10 g/hr and condense about 6 g/hr.

The principle of operation of the flux generator

The design of the flux generator evolved at the same time as experiments were being performed. Only the final design is described here. Faults in the early designs caused some of the strange characteristics of graphs shown in chapter 4.

The principle of operation is that an open tank of water within the chamber is held at a temperature that causes water vapour to evaporate from, or condense into, the water surface.

The tank is weighed. The difference from the weight at the beginning of the experiment is water that has been gained or lost to the air in the chamber, which in turn equilibrates with the wall under test.

Design considerations

The most important concern is that all water added to, or removed from the air must pass through the surface of the water in the weighed tank. Condensation on, or evaporation from unweighed surfaces will ruin the performance. This means that the coldest part of the entire system must be the water surface.

The design should also look ahead to the development of chambers that can function at a variable temperature.

This can be achieved by having a large radiator within the chamber that can be warmed or cooled but must never be below the dew point of the air. On, or beside this radiator is mounted the weighed water tank. This tank normally operates at a lower temperature than the radiator.

The engineering challenge is to both cool and weigh the water tank.

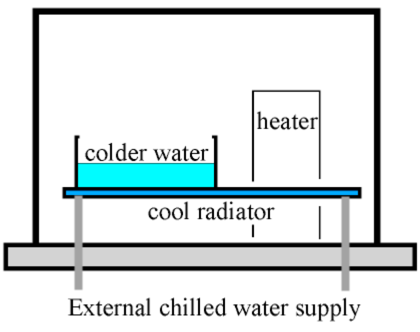

Figure 2.4 The two temperature principle in flux control: The horizontal radiator controls the air temperature, in competition with the heater. The cooler water tank condenses or evaporates water into the chamber.

More detailed design considerations

The water temperature in the tank must be controlled between about ten degrees above ambient, for rapid evaporation at high RH, to twenty five degrees below ambient, for absorbing water at low RH. It is possible to absorb water on an ice surface but the transfer of heat through ice is slow, because convection is impossible. It is better to use a solution of a hygroscopic salt, glycerol or sugar: materials that function as antifreeze but are scarcely volatile.

The addition of an antifreeze chemical has the additional advantage that it evens out the need for heating and cooling. This is best explained by pointing out that a sugar solution at ambient temperature is at equilibrium with less than 100% RH. This means that heating is necessary to achieve 100% RH and that less cooling is necessary to achieve a low RH than when pure water is in the tank. The disadvantage is that these solutions are viscous and therefore worse at conducting heat from the cooling source to the surface.

The water reservoir is weighed, so the cooling and heating must be applied without disturbing the weighing. There are two ways of doing this. One is to immerse a fixed cooling coil in the water (or solution). If the entry into the water is slim there will not be much interference with the weight through surface tension. The insulation must, however, extend below the water surface, or water drops will still accumulate on unweighed surfaces.

The other cooling method, which was the one adopted, is thermoelectric cooling of the bottom of the tank. A thermoelectric cooler (TEC), also called a Peltier cooler, is a device that uses the Peltier effect: the release of heat at the far junction between two dissimilar conductors when a voltage is applied to the near ends. The Peltier effect is the reverse of the Seebeck effect, which is the generation of a voltage between the ends of a pair of dissimilar wires joined at one end and exposed to a temperature gradient. This is the effect used in thermocouple thermometry.

Practical thermoelectric devices are made with semiconducting alloys of bismuth, antimony and other semimetallic elements. Many alternations of the two materials are arranged in series with all the cold junctions fastened to one thin ceramic plate and the hot junctions arranged on an opposite ceramic plate. A typical assembly is 40 mm square by 4 mm thick. If the hot side is held at room temperature by a heat sink and the cold side is insulated it can reach about minus 40 degrees. At this point the heat transfer backwards through the device, combined with ordinary resistive heating, prevent further cooling.

In practice it is feasible to cool a water tank thirty degrees below ambient, which gives a theoretical lower limit for absorption of water from air at 10 % RH. Since dewpoint sensors use exactly the same technology this limit matches the measurement technique used in the chamber.

Electric power must be brought to the TEC: 5 A at 12V at maximum cooling. This requires robust conductors but they must not interfere with weighing the tank.

The final design is shown in figure 2.5.

Construction of the flux generator

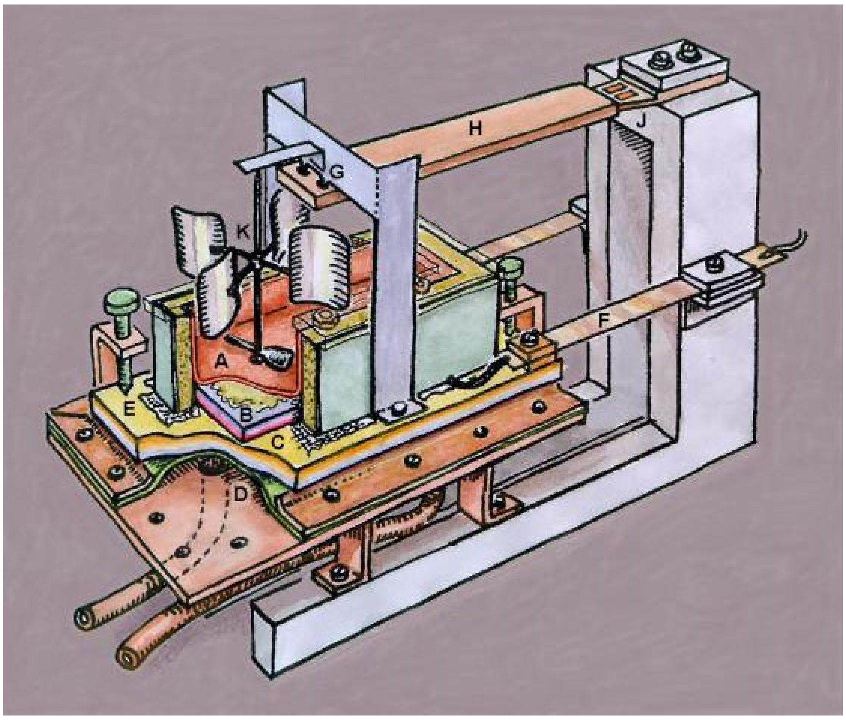

*Figure 2.5 The flux generator. The device is 350 mm long. The cold water tank **A** is made of copper and is clamped down over two thermoelectric coolers **B**. The heat sink for the coolers is the aluminium plate **C**. This is cooled by water circulating in the flat heat exchanger **D**. The top of the heat exchanger is a flexible silicone membrane which is pressed up against the heat sink by water pressure. The vertical displacement of the heat sink is limited by three screws **E**.*

*Electric power is brought to the thermoelectric cooler through thin strips of springy stainless steel **F**, which are clamped, through insulators, to the heat sink.*

*The entire assembly of heat sink, cooler and tank is weighed by suspension from a cantilever spring of hard aluminium alloy **H**, whose deflection is measured by a strain gauge bridge **J**. The cooling water pressure is reduced during weighing so that the tank hangs free on the beam. It is constrained to vertical motion by the parallel motion system of the beam and the two steel springs, which are held in slight tension by the tendency of the tank to swing away from them.*

*The wind driven stirrer **K** circulates the water, which would otherwise achieve a stable stratification with the hotter water at the top, reducing the efficiency of condensation. The wind spilled from the stirrer blades brings air to the cold water surface.*

The weighing process

Once a minute the water pump and the air circulating fan are stopped. The membrane collapses clear of the heat sink, so that the entire weight of the reservoir assembly rests on the weighing beam. The process is shown in the diagram below.

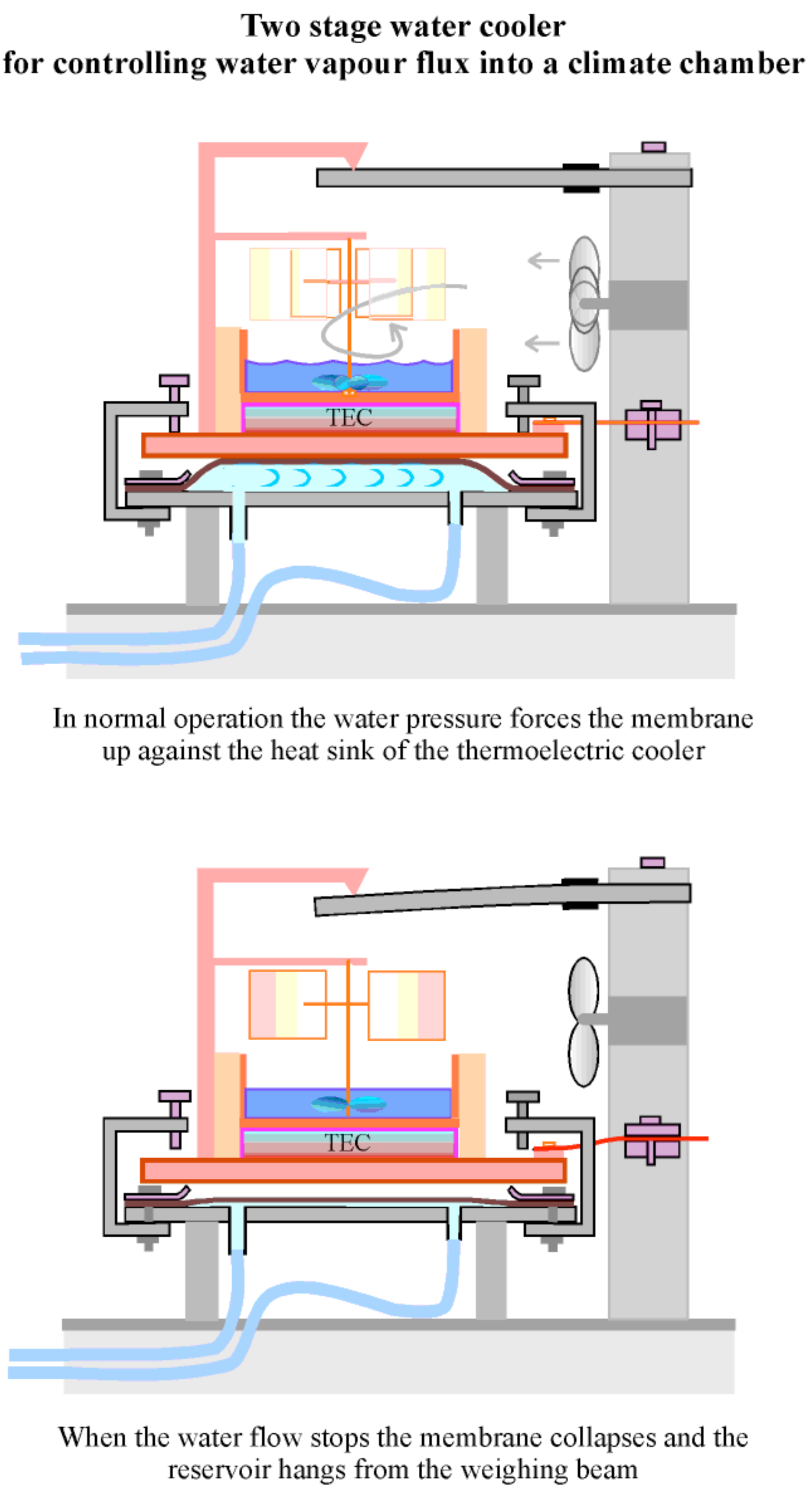

Figure 2.6 The weighing process. In normal operation (top) the pressure of the circulating cooling water presses a silicone membrane up against the TEC heat sink. When the water is to be weighed (bottom) the cooling water pump is stopped and the membrane collapses clear of the heat sink.

The point of contact between tank assembly and beam is exactly defined. The stirrup has two sharp points of stainless steel that point downwards and rest on the floors of two holes drilled 2 mm into the beam, which is 6 mm thick. Contact is maintained all the time. The springiness of the beam is an advantage here. Normally, one would use a stiffer load cell for measuring weights of about 1 kg.

The beam is 25 mm wide and has an unsupported length of 160 mm. The beam is thinned near the clamped end to 3.5 mm. The width tapers so that the sides at this point would, if extended, meet at the tip of the beam. This arrangement gives a uniform strain over the area covered by the strain gauges.

The strain gauges each have a resistance of 350 ohms. They are arranged as a full bridge, with two above and two below the beam. They are attached with epoxy glue and protected from water vapour by a thin layer of microcrystalline wax which is melted over the gauges and the fine wires that connect them. This wax gives perfect protection. The gauges show no change in signal with constant load and varying RH.

The gauges are however sensitive to temperature. In principle the bridge arrangement should compensate automatically for temperature effects but this is only exact if the bridge is without strain under the typical load. The gauges were mounted on the unstressed beam, so the approximately 800 g load of the reservoir and heat sink unbalances it enough for the temperature effect to be quite large. However, the chamber temperature is sufficiently constant for this not to be a problem.

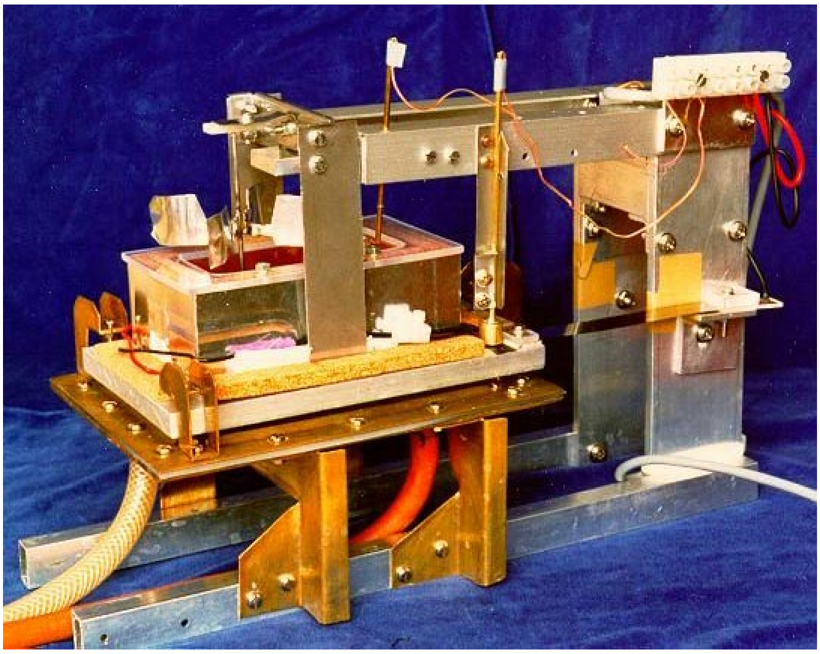

Figure 2.7 The complete flux generator. In addition to features already described, this photograph shows two rods descending from the top frame member that protects the weighing beam, whose tip only is visible. These rods hold thermocouples which measure the water temperature and the temperature of the heat sink. The heat sink thermocouple does not touch the surface but receives radiant heat focussed by a brass reflector onto its blackened surface. Its signal is used to check for failure of the primary cooling system, which would cause the thermoelectric coolers to overheat.

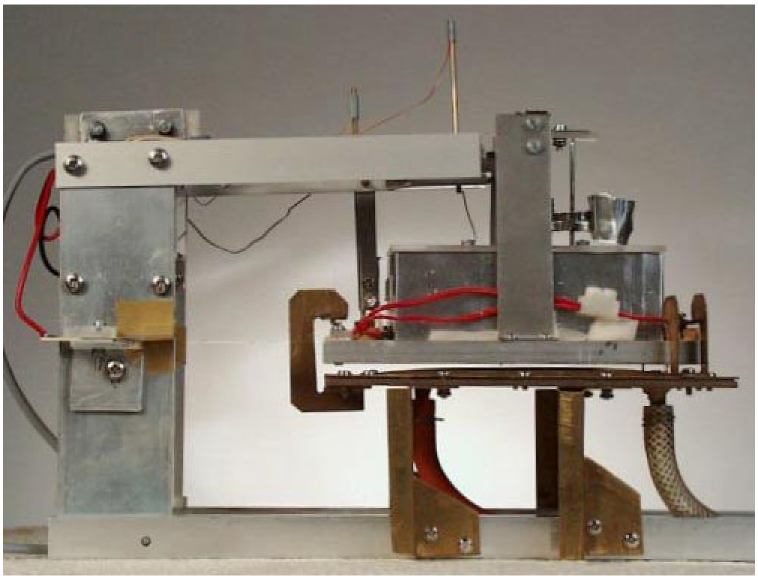

Figure 2.8 A side view of the apparatus with the cooling water stopped and the membrane collapsed, so that the water tank and heat sink hang free on the weighing beam. Notice the brackets with adjustable screws that restrain the upward movement of the heat sink when the membrane is expanded. These screws are adjusted so that the pins in the stirrup rise just clear of the beam, relieving it of stress and reducing creep. Photo: Christian Bramsen.

Measured drawings are in the appendix.

The primary cooling circuit

The cooling water serves two purposes. It cools the TEC heat sink as low as possible without causing condensation. Its pressure also holds the tank assembly firmly fixed in its frame until a few seconds before it needs to be weighed.

The cooling water, like the water in the tank, has a variable temperature. It is always controlled at one degree over the dew point in the chamber (the exact difference can be set by the operator) so that condensation cannot occur on the exposed parts of the primary cooling system.

The cooling water is held in an insulated reservoir outside the flux chamber. When its temperature rises more than the set difference over the chamber dew point temperature a valve opens to allow chilled water, at 6°C, to circulate through a coil of copper tube immersed in the reservoir.

Theoretically, it should be necessary to heat the reservoir water when the flux generator is heating the weighed water tank to evaporate water into a high RH in the chamber. The heat sink will then be cooling the circulating water. In practice enough heat is generated by the pump and by friction and heat gain from the room to ensure that the water temperature never falls below the chamber dew point.

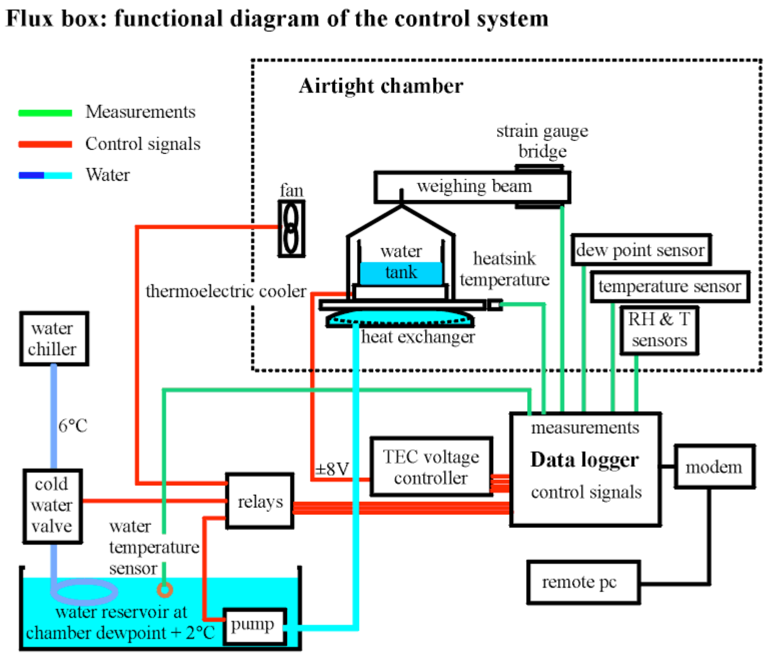

Figure 2.9 The control system for the flux generator. Sensors report the cooling water temperature in the reservoir and the dewpoint in the chamber. The datalogger controls a valve which lets even colder water cool the reservoir. The cooling water that runs through the experimental chamber is always above the dewpoint of the air in the chamber.

The diagram, figure 2.9, shows the control system. The reservoir is a standard laboratory water bath of about 7 litre capacity. The pump of the bath is used both to mix the water and to circulate it through the experimental chamber. The cooling coil is about 3 m of 10 mm diameter soft copper tube. It is connected to the house chilled water supply through a solenoid operated valve. The data logger operates the valve to keep the cooling water temperature a set number of degrees above the dewpoint in the chamber.

Controlling the temperature of the water tank in the chamber

The datalogger has preprogrammed instructions to calculate the intended weight of the water tank at any moment. The datalogger looks at the actual weight, compares it with the intended weight and calculates a voltage to apply to the thermoelectric device to cause evaporation or condensation to correct the weight. These control algorithms are described later.

Thermoelectric devices cannot be controlled by simply switching them on and off in a cycle, as is done with most control systems. The thermal cycling will fatigue the semiconductor device and shorten its life considerably. The TEC has to be fed a gently changing voltage. The data logger works out a suitable voltage, which is sent out as serial bits through an optical isolation stage. A shift register assembles the pulses into a parallel digital representation of the voltage. This is converted into a voltage by the digital to analog converter. A buffer amplifier adjusts the amplitude and level to suit the power control stage (1.2 to 10V).

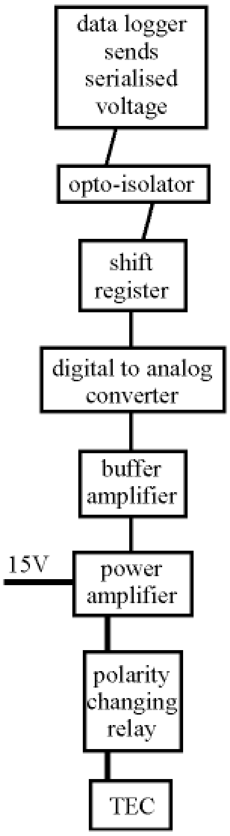

Figure 2.10. Block diagram of the train of instructions from the data logger to the thermoelectric cooler. The TEC takes a high current from a separate power supply, so the data logger control signal is sent first through an optical isolator to guard against electrical interference.

The data logger can only send out a digital signal. This is decoded and turned into a voltage. A buffer amplifier adjusts this voltage to match the characteristics of the power amplifier which controls the current through the TEC.

The final stage is a power MOSFET, which follows the input voltage with a constant difference. It provides the high current, at 0 - 8V required by the TEC. A separate signal from the data logger sets the polarity of the voltage: to make the TEC cool or warm the water tank.

The electronic circuits are described in an appendix. The data logger program is described later in this chapter.

Summmary of the flux control system

The water vapour flux into the chamber is controlled by the surface temperature of a ventilated water surface in a small tank within the chamber. This temperature is controlled by a two stage cooling process. The first stage uses an external supply of cold water which is held always just above the dewpoint of the inside air. This cold water supply cools the hot side of a thermoelectric cooler which pushes the temperature of the internal water container below the dewpoint, if condensation is required. If evaporation is required the thermoelectric cooler is operated with a reversed voltage, so that it heats the water tank (and cools the cooling water, which has such large heat sources in its circuit that it doesn't matter).

All parts of the instrument that can be below the dewpoint are weighed, so the amount of liquid water in the system is always known, and is always in the tank. The water in the original filling that has left the tank must be either in the air, where the amount can be calculated from the measured dewpoint and the known volume, or in the experimental wall. In this way the water content of the wall is known, indirectly, so that its performance as a buffer of humidity can be described quantitatively.

Temperature measurement and control within the chamber

All the experiments were made at constant temperature. Very good temperature constancy is important because a one degree rise in air temperature would cause the RH in the empty chamber to fall by about 3%. The RH within the test walls, however, increases slightly with temperature, because here the RH is controlled by the material. The relative progress of RH in the chamber and within the test wall will be difficult to interpret if the temperature is allowed to wander more than a few tenths of a degree.

The heat released into the chamber is rather variable. The primary cooling circuit, operating just above the dew point, tends to cool the chamber more as the RH decreases. The cooling effect of the water in the weighed tank reinforces this cooling effect. On the other hand the heat given off by the heat sink just under the TEC will tend to warm the chamber, depending on how hard the TEC is working. When the flux generator is evaporating water strongly at high RH the heat output to the chamber is large.

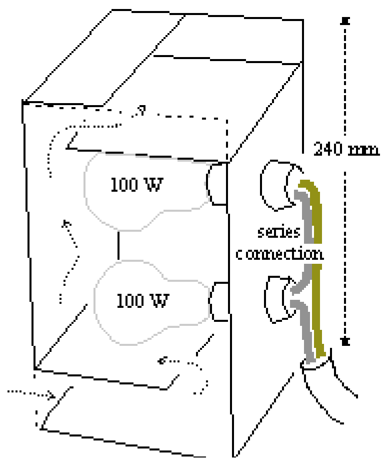

Figure 2.11 The chamber heater, cut away to show two light bulbs, wired in series to reduce their operating temperature and to increase their lifetime in a regime of constant switching. The case is designed to give good ventilation while allowing little light and radiation to escape.

The chamber temperature is controlled by a heater which holds the interior at 22.7 degrees, which is 2.5 degrees over the room temperature. Heat loss through the 1 mm stainless steel walls is enough to ensure accurate temperature control by heating alone.

The heater consists of a pair of 100 W bulbs wired in series so that they give much more heat than light. They are mounted in a stainless steel labyrinth designed to allow good air circulation with little light or radiant energy emission. Radiation towards the test wall is further reduced by a second screen of crumpled aluminium foil.

Air is forced through the heater by a fan mounted in a square metal tube. The 240 V supply to the lamps is controlled by a standard PID controller. This is a type of controller which adjusts the 'on' time during a cycle of, typically, one minute. This gives much more accurate control than a thermostat which only switches on when the temperature falls below a certain value and switches off again when the temperature exceeds a higher temperature, so that the temperature cycles within a "dead band".

The temperature is not under computer control, because it does not ever need to be adjusted. A copper constantan thermocouple within the chamber is connected directly to the controller. The chamber temperature is measured independently by a thermistor placed inside a copper block in the air stream entering the heater.

The dew point temperature within the chamber is measured by a thermoelectric sensor (General Eastern). This has a small mirror with a precious metal alloy surface which reflects the light from a light emitting diode (LED). The mirror is cooled by a small thermoelectric cooler. When the temperature reaches the dew point the water droplets on the mirror reduce the specular reflection of the LED into a light sensitive transistor. The power to the TEC is then automatically reduced until a steady state is reached with the mirror lightly misted and at the dewpoint. A platinum resistance temperature sensor just beneath the mirror is measured by the data logger. The dew point sensor is placed in the flow of air entering the heater. A loose cap over the sensor reduces the air velocity and functions as a radiation shield.

Other temperatures are measured within the chamber and outside. These are the water temperature in the tank and in the reservoir of the primary cooling water. The temperature of the heat sink under the water tank is measured as a safety precaution. In some experiments the psychrometric wet temperature was measured. All these measurements were made with type K (chromel-alumel) thermocouples. This type was chosen, rather than the more traditional type T (copper-constantan), because the metals are relatively poor thermal conductors, so that the temperature of the junction dipping into the water tank, for example, is not made inaccurate by heat conduction from the air above the water surface. The wires are also quite strong, so that very fine wire can be used, with a further reduction in heat flow.

All the thermocouples are connected to copper wires close to the copper block containing the thermistor which measures the air temperature in the chamber. The copper conductors connect to the data logger through a sealed hole in the base of the chamber. The data logger uses the temperature derived from the thermistor resistance as the reference temperature for the thermocouples, which only measure temperature difference.

The control software

The experiments are all conducted at constant temperature so the temperature is set by hand. All other activity in the chamber and its associated supplies is controlled by a Campbell Scientific data logger (Type CR10X). This data logger can be programmed in a rather primitive language which has standard instructions for processing most standard sensor measurements. It can also control other devices through a set of eight ports which can be set to 0 or +5V (TTL logic levels). The data logger can be programmed and milked for collected data either directly from a nearby computer or by telephone via a modem. This is rather useful because most of the experiments last about a week, need little attention after setting up and can therefore conveniently be checked remotely.

Various safety tests are programmed into the logger so that the most likely faults, such as failure of one of the cooling systems, can be prevented from damaging the apparatus.

The processing of the signals from the various sensors is quite standard, except for the RH measurements within the test wall, which will be described later.

The essential measurements and control settings

The measurements that the data logger needs in order to control the system are the weight of the water reservoir, the temperature and dewpoint in the chamber, the circulating water temperature, and, for safety checking, the heatsink temperature.

The user-defined data that the logger needs are the weight cycle for the reservoir. This is defined as a cycle time in hours, a half amplitude in grams and a waveform: triangular or sine.

There are several other parameters that the user must define: the offset between dewpoint and cooling water temperature, the smoothing constants for the reservoir temperature control (discussed in detail below) and a correction factor for weight calibration.

The logger ensures that the weight of the reservoir follows the defined cycle. It does this by noting the time, and working out the target weight of the reservoir. It then looks at the actual weight and adjusts the voltage applied to the TEC to compensate for the error, by cooling or warming the water. The details of this process are described later.

Finally, the logger checks for overheating of the TEC, to which it responds by setting the TEC voltage permanently to zero and setting an alarm flag for the operator to notice.

A typical experiment

The graph in figure 2.12 shows the course of a typical experiment. The chamber temperature and relative humidity are shown in the two upper curves. The other curves show the various control values: the water temperature, the cooling water temperature, the heat sink temperature, the voltage applied to the TEC and the intended and measured weights.

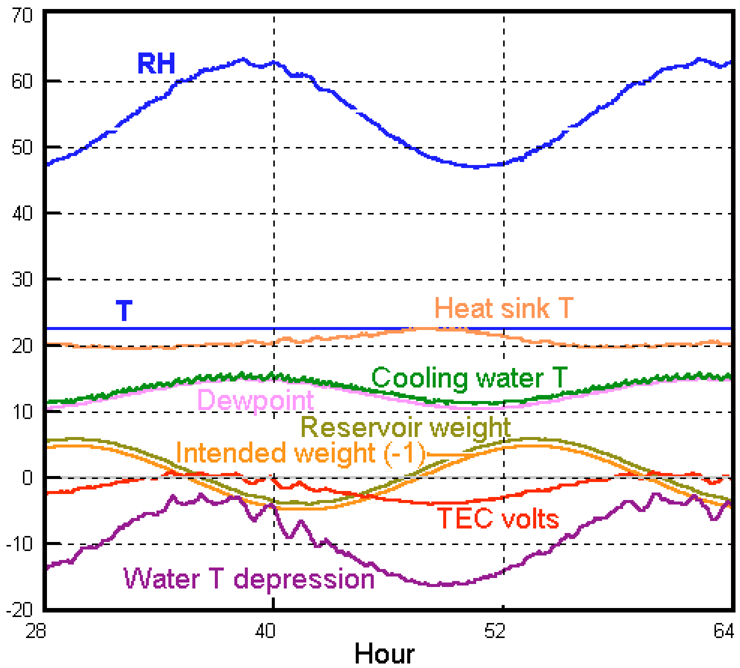

Figure 2.12 Graph of the control signals. The values of variables used to control the chamber are shown for a typical experiment. The intended weight and the reservoir (tank) weight are separated by one unit for clarity. The water tank temperature is expressed as the depression below the ambient temperature.

The actual weight follows the intended path so closely that the curves are artificially separated on the diagram.

The oscillation in the RH curve shows up the limitations of the control algorithm at cycle times of one day or less. The controller has to cope with considerable inertia in the temperature of the water, an ever changing set value, and an unpredictable RH, which is controlled by the absorptive power of the experimental wall, which the controller can know nothing about in advance.

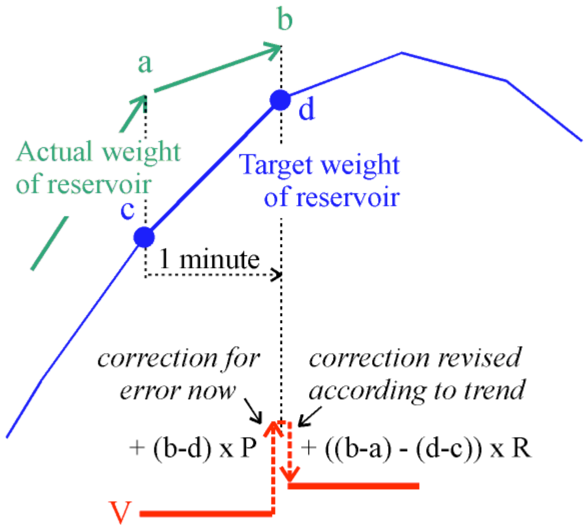

Figure 2.13 A diagrammatic explanation of the control algorithm for the thermoelectric cooler. Time is moving from left to right. A portion of a sinusoidal curve of intended water weight is shown with two solid circles indicating two successive control calculations, one minute apart. Below the curve, the expression on the left is the correction for the instantaneous error. This gives a large rise in voltage (more cooling). However, the error is less than the previous error a minute before. The expression on the right is the correction for the rate of approach to the correct weight. This reduces the correction suggested by the immediate error. The result of these two calculations is sent out as a serial signal to the voltage controller described earlier.

The control algorithm for the thermoelectric cooling is shown in figure 2.13. In the first calculation the absolute difference between actual and intended weight is used to raise the existing voltage, in this example, because the reservoir is too heavy, so water must be evaporated away. This can be regarded as a combination of proportional control with a measure of integration, because the existing voltage is the result of previous calculations.

This correction alone would cause oscillations about the correct value. A damping signal is added by calculating that the weight, in this example, is converging towards the correct value. The first correction is therefore partly reversed to anticipate, and delay, the crossing of the curves.

Each of these two corrections includes a user-set multiplier. These can be adjusted by experience as the run proceeds, to give a relatively smooth graph.

This is clearly a task that needs an intelligent program which learns about the performance of the wall as the run proceeds! Such a program is beyond the capacity of the data logger to store and maybe beyond the capacity of the author to write. The oscillations seen in figure 2.12 have no significant influence on the scientific results.

The control sequence

The controller is activated once a minute. The data logger stops the fans and the water pump. It waits eight seconds for the air to become calm and for the rubber membrane to collapse clear of the suspended water tank. It then measures the strain on the beam and calculates the weight. The error is computed and the new TEC voltage is calculated as described above. This voltage is sent to a controller as described earlier. The fans and the water pump are then re-started and the data logger sleeps for the rest of the minute. Once every five minutes the data logger records in its permanent memory the average values for several calculated and measured parameters. An annotated example of the control and measurement program is included in an appendix on the CD-ROM.

The performance of the chamber

The limitations to the accuracy of experiments conducted in the chamber are set by air leakage to the room and by water absorption on the interior surfaces. Imprecisions in measurement and calibration of the various sensors are minor problems in comparison with these fundamental limitations.

Residual absorption is shown in figure 2.14. The measured RH swings much less than that predicted from the actual weight of water in the tank and the standard properties of moist air. Notice that the actual RH leads the theoretical value. This confirms that there is some residual absorption which causes the RH to bounce back quicker than expected as the flux is reversed.

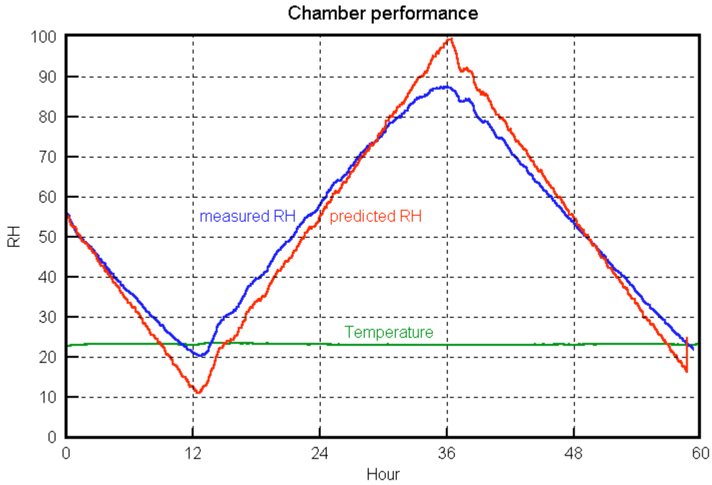

Figure 2.14 The measured RH in the chamber, compared with the RH expected for an inert chamber.

This graph demonstrates that RH buffering is a universal phenomenon! The surface area of materials in the chamber is quite large because of the intricacy of the equipment. Some parts are slightly water absorbent. There are aluminium parts for heat sinks and beams and also for some components which would be difficult to form in stainless steel.

The materials of the bought components, such as the dew point sensor, cannot be chosen for low water absorption. Further reduction of the water absorption would require considerable extra effort.

Above 85% RH the measured RH curve flattens out, giving a very rounded peak. 80% RH is the practical limit for experiments in the chamber. The rounding at the lower end of the RH range further limits the linear range to 30% - 80% RH.

The leak rate of the chamber

The leak rate is shown in figure 2.15. The actual RH is the wavy line. The smooth curve is an exponential best fit, assuming an end point at the 59% RH ambient condition. The air exchange rate is once per 12 days. The RH comes more steeply up to the exponential curve at the beginning of the test. This is certainly due to buffering of the RH by interior surfaces. The fit to an exponential curve becomes closer as time passes. There is still some buffering, so the real air exchange rate is somewhat faster, maybe around ten days. More accurate data could be obtained by using fluorinated trace gases but this is unnecessarily elaborate for the experiments that were performed in the chamber, which involved much more effective RH buffers and short cycle times.

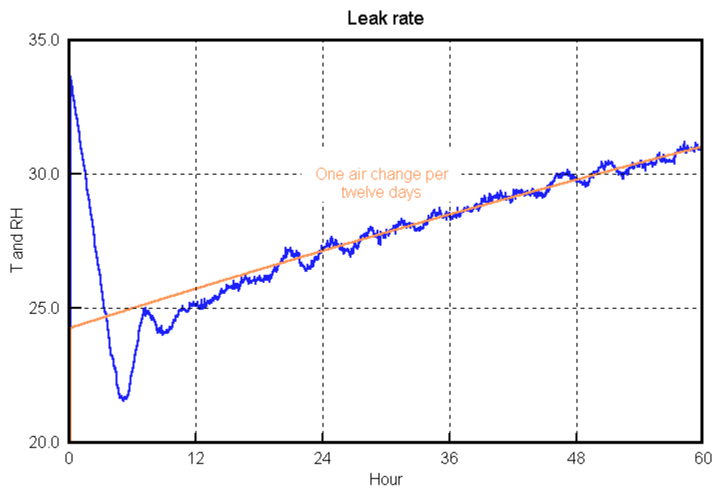

Figure 2.15 The drift of RH caused by air leaking between the case and the 59% RH in the room. The wobbly curve is the measured RH. The smooth curve is the exponential fit with a half time of 12 days. The dip in measured RH at the beginning is caused by instability of the control system when the forced downward trend of RH is suddenly stopped.

The accuracy of flux control can be judged from the deviations from a straight line shown by the 'predicted RH' curve in figure 2.14. The instability is worst when the flux is suddenly reversed. The measured RH line in figure 2.15 also shows a regular cycling. These errors are due to imperfect tuning of the proportional control. The response to the instantaneous error and the error trend is adjusted by the operator, who has two constants to play with. These two settings depend on the load, that is on the buffering by the test wall. In practice one setting was arrived at by trial and error on a moderately absorbent wall and then used for all experiments. The instability is insignificant when the test wall is present to buffer the RH in the chamber. Improvement would require two fundamental changes in the apparatus. The correction algorithm could be refined, which would require replacing the data logger with full computer control. The programming language of the data logger is too primitive and the number of instructions that it can hold is too small to allow subtle manipulations. The strain gauge weighing system would also need to be changed to a professionally made load cell, as used in balances. The beam system weighs to 0.1 gram precision. An improved control algorithm could use 0.01 g precision to get a more reliable indication of the trend of the error.

The measurement of RH within the test walls

Many of the experiments described in later chapters report values of RH in small cavities hollowed out within the experimental wall. Some of the values are a long way from theoretical predictions, so it is important to know the performance of the sensors with considerable accuracy.

There is not much choice of sensor for this job. The sensor must be small and it must not absorb water in amounts that compete with the processes it is measuring. There are two types of small RH sensor, apart from exotic experimental devices. The resistive sensor is a wafer of polymer with a surface coating that absorbs water according to the RH and becomes more, or less electrically conductive. Capacitive sensors detect the presence of absorbed water through its influence on the capacitance between two porous electrodes plated on the surface.

Figure 2.16 The General Eastern RH sensor. It is about 10 mm high. The base is coated with a thin layer of a water absorbent polymer. The resistance between the two gold electrodes is measured.

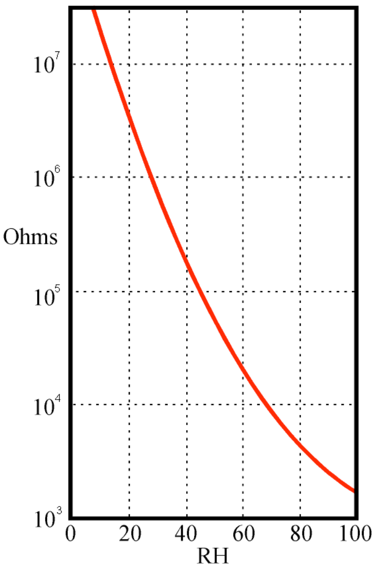

Figure 2.17 Characteristic curve of the General Eastern RH sensor. The resistance varies nearly as the logarithm of the logarithm of the RH.

The capacitive sensor can be obtained with on-chip electronics but resistive sensors are cheaper and have some advantage in precision over a small RH range.

For this job a resistive sensor from General Eastern was chosen. It is shown in figure 2.16.

The variation of resistance with RH is very large. It is shown in figure 2.17. The data logger provides a pulsed voltage to the sensor. Constant current will cause electrolytic processes in the sensor and destroy it very fast. The resistance is measured by a simple bridge circuit.

It is linearised over the RH range of the various experiments by using a resistor network as shown in figure 2.18.

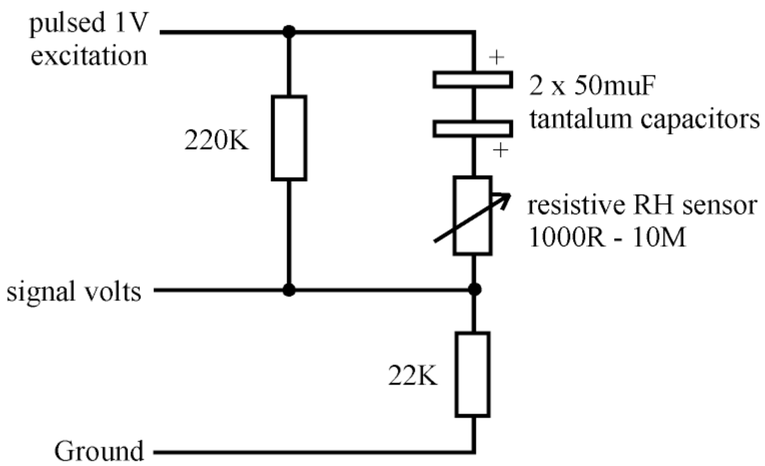

Figure 2.18 The circuit which linearises the voltage - RH curve of the sensor. The two capacitors are to block direct current, which will destroy the sensor.

A team of four sensors is permanently installed ready to probe various parts of the test wall. The sensors are individually calibrated in the display software by applying a multiplier and offset to the raw results from the data logger bridge circuit. The calibration is shown in figure 2.19. Between 40% and 65% RH the sensors and the dew point meter give identical readings. Beyond these limits the sensors can still be used but require extra manipulation of the signal in a spreadsheet program. Most of the experimental runs lie within the limits of linearity of the circuit.

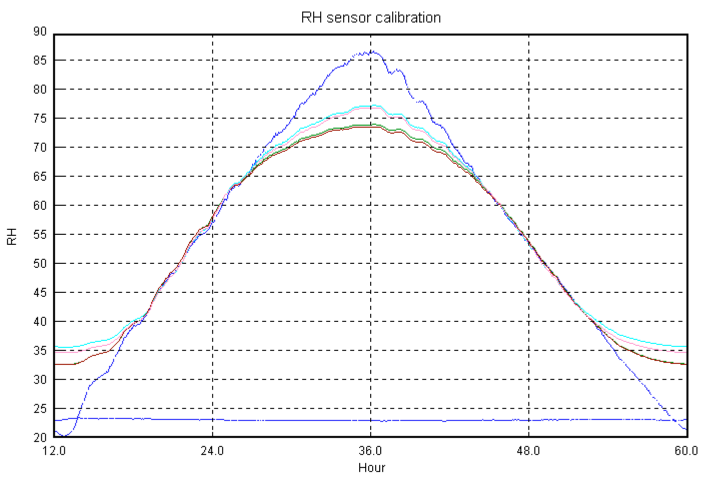

Figure 2.19 A comparison of the RH indicated by the dew point meter (the curve with the greatest amplitude) with the RH given by four polymer resistance sensors. The values all agree closely between 40% and 65% RH

.

Notice that there is negligible hysteresis; the agreement between the RH from the sensors and the RH from the dewpoint is the same going up as coming down. The sensors are very precise, because they give a very large signal and are therefore very suitable for showing the tiny variation in RH deep within a water absorbent test wall. The response time of the sensors is very fast compared with the rate of change of the RH within the specimens, even though they were sometimes wrapped in permeable plastic to protect them from powdery materials.

The air flow over the test wall

The air in the chamber is moved around by the fan which blows air over the flux generator. The air stream is directed downwards to optimise several processes. The water stirrer is pushed round by the spiral air flow at the edge of the airstream. The main air stream scours the inside surfaces of the water tank. It also plays on the heat sink, providing a little extra cooling, particularly when the TEC is working hard. The stirrer blades and the tank impede the flow and disperse the air so that the air flow at the test wall beyond is quite uniform, though turbulent, with an average speed of 0.2 m/s. This is at the high end of the acceptable indoor air speed. More would be regarded as a draught. This air speed is about right for this experiment, where the surface resistance is a hindrance to accurate measurement of the properties of the absorbent wall. On the other hand the air speed is not unrealistically fast.

The air speed was measured with the chamber in normal operation. A slim hot wire anemometer on a long rod was inserted through the hole normally occupied by the neck of the pressure buffering balloon. The air speed was measured in a grid at about 50 mm from the wall surface. The variation from place to place was 0.3 m/s opposite the fan to 0.2 m/s at the farthest edge of the wall. These values were measured with a 6 second time constant. The instantaneous measurements showed turbulent conditions with the air speed varying from 0.04 to 0.4 m/s.

The complete chamber for controlling water vapour flux

Figure 2.20 shows the complete chamber open, with a test wall of mud bricks

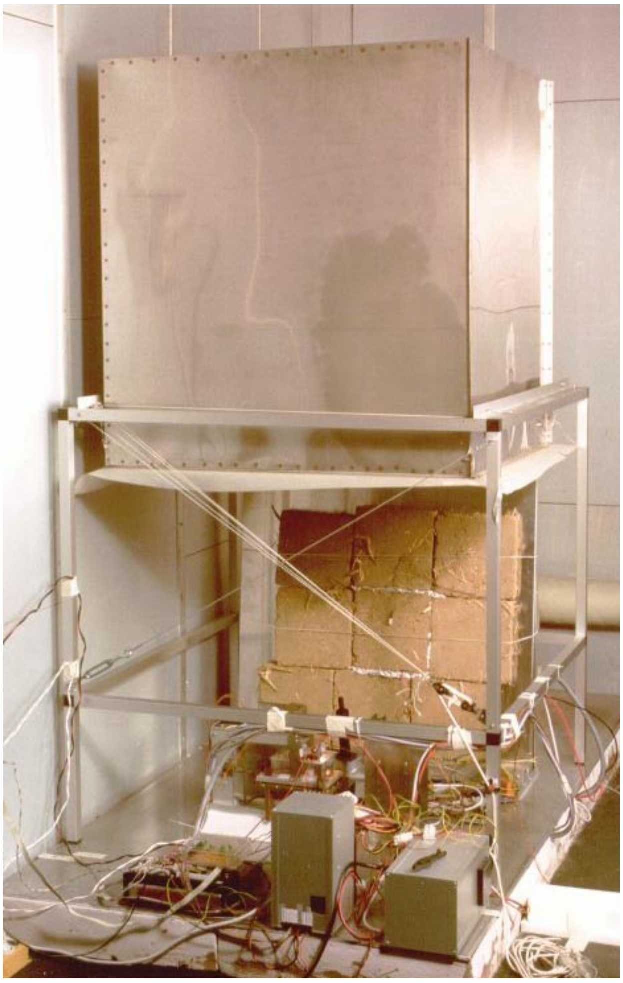

Figure 2.20 The flux controlling chamber with a wall of stacked mud tiles. The middle tile contains buried sensors. The flux generator and the heater are in the middle distance. In the foreground from left to right: the data logger, the voltage controller for the TEC and the temperature controller. The white object on the right is the insulated water supply to the heat exchanger.

The usefulness of the flux chamber in materials research

The reader may by this point be wondering if the flux chamber was worth the trouble. It is much more complicated than an orthodox RH chamber. What can it do beyond what a RH chamber can?

The purpose of the exercise was to investigate what happens when various sources force water vapour into a room with abundant absorbent materials. The water will absorb into the walls according to the RH gradient between the room air and the boundary layer next to the wall surface. However, in this enclosed environment the RH gradient is itself defined through this absorption process. The flux chamber is therefore the only direct way to investigate the processes influencing indoor climate.

A double flux chamber, with the experimental wall sandwiched between the chambers, would be even more useful, providing fresh information that cannot be obtained by conventional means. The flux through a wall subjected to a difference of both temperature and humidity can only be investigated by a system that measures the quantity of water transmitted, and the quantity received on the other side. Such a chamber does not appear in this thesis. I do however present data which hint at the need for such a chamber.

It seems therefore worthwhile to review the qualities and faults of this prototype and suggest how the performance could be improved in later versions.

A review of the performance of the chamber

The chamber has proved very reliable, needing no repairs over its year of operation in its final form. The principle of using thermoelectric cooling backed up by water cooling to near the dew point works well and solves the main disadvantage of the TEC: its inefficiency, with consequent overheating of the chamber. The principle could be used to give up to ten times the flux rate of this chamber without requiring substantial change in design. The chilled water could also be driven through a large cooling radiator, controlled by an independent valve, to allow operation below ambient temperature. This is an important consideration in a double chamber designed to imitate the outer wall of a house.

One serious miscalculation was the construction of the chamber. It should be really airtight, not just resistant to diffusion without pressure difference. The chamber was made by spot welding thin stainless steel plates to each other and to a more substantial L section frame at the bottom. The heat of welding distorted the structure so that the base of the frame was not plane. At one corner there was a gap of 2 mm between the box and the baseplate that it rests on. This gap was filled by the silicone elastomer used to provide the seal, but the variable thickness of elastomer gave uneven pressure on the baseplate and thus allowed flow of air under very low differential pressure. In retrospect the box should have been bolted together or glued with epoxy. The seal at the base should also have been a proper O ring seal with closely spaced screws holding the box to the base plate.

The other weak link in the design is the weighing beam. The strain gauge bridge is working at the very limit of attainable precision. The electrical interference, unavoidable in a research institution with masses of electrical machines, limits the weighing precision to 0.1 g., even with repeated weighing at each measuring interval. This very moderate precision does not affect the interpretation of the experimental runs but it spoils the accuracy of the flux control, because the datalogger/controller needs to have good information on the rate of approach to the set value. A professionally constructed load cell would give much more accurate information for the control calculation and allow use of control algorithms that would more quickly suppress oscillations of the water vapour flux.

The condensing power of the water tank could be improved. It turns out that most condensation occurs on the copper sides. A high water level markedly reduces the condensing efficiency, in spite of vigorous stirring. It may be that copper fins should stick up through the water surface to ensure uniform performance as the tank fills.

The heat exchanger is too small. The silicone membrane blows up to touch only an area of the heat sink that is about equal to the area of the TEC. The heat sink reaches 40°C when the TEC is working hard. The area of contact with the water chilled membrane needs to be several times as big.

Other uses for the flux chamber

The flux chamber can be used as an orthodox RH chamber. The temperature of the water tank is adjusted to maintain a constant dew point reading from the sensor. The sorption isotherm of materials can then be found by stepping the RH and measuring the water absorbed or lost by the water tank at each step. Similarly the water vapour permeability can be measured by mounting the test material over a tray of saturated salt solution and running the chamber at a fixed, different RH. The rate of change of the tank weight at constant RH would then give the permeability of the material. The chamber could in fact have been used to measure all the hygroscopic material properties used in this thesis but the flux experiments used all the available time so these static properties were measured in more orthodox instruments, as described below.

Other instrumental techniques used in this research

The sorption curves of some of the experimental materials were measured by weighing them after equilibration with the atmosphere over various saturated salt solutions. The full isotherm was not determined because nearly all experiments were confined between 70% and 40% RH. Most of the sorption data were determined in a RH chamber in which a dry and a saturated air stream were mixed. The streams were switched by a proportional controller which took its signal from an electronic RH sensor which was in turn calibrated against a dew point sensor. The weight of the specimens was determined by hanging them from a balance which was mounted above the chamber. At the moment of weighing a clear passage was briefly opened for the thin connector between specimen and balance.

Water vapour permeability was measured by the "cup" method. The experimental material forms the lid of a container which is filled to 15 mm from the underside of the test material with a drying agent, water or a saturated salt solution, according to the RH region for which the permeability is to be measured. The upper surface is ventilated by a constant velocity air flow at 50 % RH, measured by a chilled mirror dew point sensor and a platinum resistance temperature sensor. The cup is weighed at intervals. The permeability is calculated from the rate of change of weight when the system has reached a steady state.

The methods described above measure the equilibrium value for absorption and the steady state value for permeability. The results from the flux chamber are in principle able to give both the absorption curve and the permeability from dynamic tests at different frequencies. However, data from the flux experiments gave very different values for the permeability, and lesser differences for the sorption. This matter is discussed in detail later.