

Technological improvements in creating controlled thermo-hygrometric conditions in sealed microenvironments: the Dew Point Climatic Generator

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Abstract. In this contribution a new methodology of climate control, specifically designed for Cultural Heritage artifacts storage microenvironments, is presented. Standard conditioning systems work using the subtraction of vapor in the air by means of condensation on cold surfaces as a drying strategy and the addition of water vapor, obtained in different ways, to humidify the air. Temperature (T) and Relative Humidity (RH) are controlled by two different control loops.

Using this new system, currently in patent pending status, it is possible to obtain a wide range of T and RH values circulating the air flow (via a common air circulation pump) through a water gurgling device and a heating device, using the ΔT between the water temperature in the gurgling device and the set temperature of the heating section.

The system is very robust and straightforward: the sensible-latent transformation of the air flow in each one of the 4 possible directions (heating-drying, heating-humidification, cooling-drying, cooling-humidification) is obtained by two passages operated by only two devices (bubbler device + heating device) controlled by two temperature probes, one in the bubbler and one in the heating section.

The system has been successfully implemented in some different case-studies in Italy and in the United States.

1. Introduction

Climate stability is a benefit for the preservation of works of art made using hygroscopic materials, and especially wooden objects like wooden sculptures and panel paintings [1].

Even though the debate about relaxation of climate standards is ongoing in order to reduce the carbon footprint of the Museums all over the world[2], the need of sealed microenvironments with controlled climatic conditions is crucial for many reasons:

- a lot of objects are very sensitive and reactive to microclimate fluctuations, therefore needing to be exhibited in actively controlled display cases;
- the global size of loans for temporary exhibitions makes compulsory to reduce the climate induced stress to the objects, as specifically requested in the contracts between lending and borrowing institutions.



1.1 State of the art

Conventional air conditioning systems typically use a battery for cooling and condensing air, an adiabatic saturator and two heating batteries, one upstream and one downstream of the adiabatic saturator respectively.[3]

In various types of climatic chambers, vapor is directly produced by an atomizer.

Often these systems have modest energy efficiency and control precision.. Such systems can be improved if they are equipped with modulating valves, which allow to control the recirculation of the air and to partialize the air flows, so as to increase the energy efficiency and the precision of the control. Despite this improvement, energy efficiency and control accuracy remain non-optimal.

Moreover, in traditional dry-exchange heating coils, in many operating conditions the components of a traditional air-conditioning system work in opposite directions with negative consequences on the stability and efficiency of the system itself.

Another approach to climate conditioning system currently on the market is specifically used for conditioning display cabinets or museum display cases. In such system passive control systems use buffers of suitably conditioned hygroscopic substances (e.g. silica gels). Even if there are advantages due to simplicity and affordability, there are disadvantages due to the impossibility of controlling the temperature inside the display cabinet, and operating time limits requiring frequent interventions to recondition the hygroscopic substances are needed.

Furthermore, simplified active systems with a single cooling coil, for example a Peltier cell, are often used: in addition to having a very low efficiency they act only as cooling and dehumidification system with consequent evident operating limitations and a poor or non-existent temperature control.

1.2 Designing goals of the Dew Point generator

The described device[4] aims to provide a climate generator based on an innovative climate conditioning method, assuring an air flow with set Temperature and Relative Humidity conditions stable at the outlet, having less complexity, greater reliability, a lower production cost. and reduced maintenance requirements.

In summary, the device is based on the principle of controlling the T and RH parameters of a micro-environment through the production of an air flow having the target values of Temperature and Relative Humidity, in which the target values are achieved by bringing an air flow to be conditioned, whenever initial T and RH values are not known, at its dew point at a predetermined controlled temperature - different from the target temperature - and reaching the target RH by heating the supply air flow at the dew point in order to achieve the target T.

At the target T and RH values the mixture of air (air-vapor) thus defined has a determined dew temperature.

Therefore, in order to obtain the target values of T and RH of the air flow, the right amount of steam required is reached by saturating the air flow at the dew temperature through a latent/sensitive thermodynamic transformation. The saturated air (100% RH) and the dew temperature is then heated to the target temperature (undergoing a second sensitive thermodynamic transformation), and consequently the RH decreases to the target RH value.

The saturation step to get to the dew point takes place in a bubbler where water is kept at a controlled temperature in order to bring the air flow to the T corresponding to its dew point.

The control is then carried out simply by checking two temperatures: the temperature of the water in the bubbler and the target temperature. The target RH is a function of the difference between the dew-point temperature and the target temperature. The system therefore does not require RH sensors to control this parameter, as it does not require a condenser plus a saturator for regulating it, since the bubbler, whatever the characteristics of the incoming air (to be conditioned) are, allows to obtain the right amount of steam by condensing or releasing it.

The climate generator can be sized to work with latent or sensitive high thermal loads, or it can be miniaturized to operate in tight micro-environments such as display cases or museum display cases.

The climate generator also allows to obtain air free of dust and other pollutants in solid and gaseous phase.

With a simple construction variant, the climate generator can proficiently operate as a dynamic climate conditioning system which allows to perform very rapid, almost instantaneous humidity variations under isothermal conditions.

2. Detailed process description

With reference to figure 1, a first set up of the invention is illustrated in which a climate generator - indicated in the assembly with G - includes a bubbling device, adapted to receive a flow of air G_a to be conditioned and containing a predetermined volume of water W at a controlled temperature in a closed vessel or open vessel water circulation circuit. In the first case, the bubbler is a thermally insulated closed container, with pressure seal. The goal of the bubbler is to make an exchange of heat and humidity between the aforementioned volume of water at controlled temperature (thermostated) and the flow of air in transit from T and RH values of the incoming air flow not known to a value of dew T and RH of 100% of the outgoing air flow.

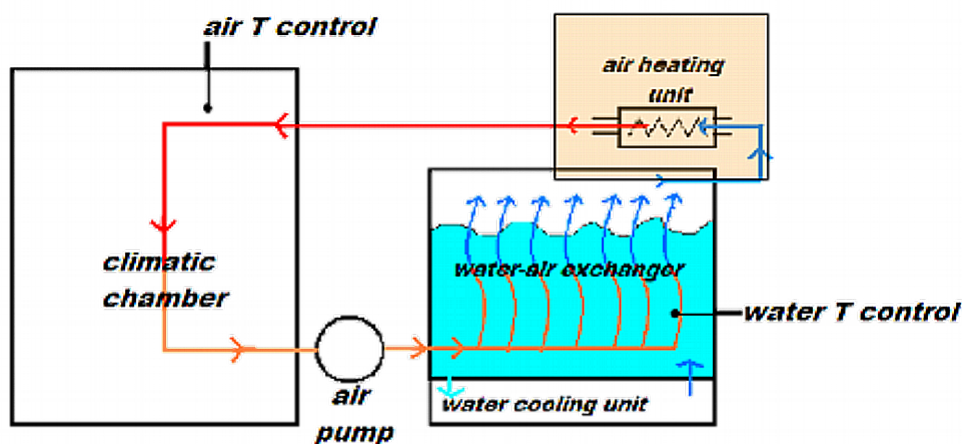


Figure 1. Design scheme of the Dew Point Climate Generator

The temperature of the water volume W in the bubbler is regulated according to the T and RH values required by the generator, as will be clearer in the following description, by means of heat exchanger, for example a heat exchange battery which can make a direct exchange if positioned inside the bubbler, or indirect exchange if positioned externally to the bubbler, when the latter is made with an open vessel water circulation circuit. The heat-exchanging devices are more generally responsible for a thermodynamic transformation of the volume of water W into the bubbler and of the flow of air to be conditioned through it, including the use of a latent amount of vaporization heat associated with the transformation from liquid to vapor phase in the volume of water W responsible for modifying the relative humidity characteristics of the air flow to be conditioned.

In order to obtain a good temperature control, the temperature is controlled by a Proportional-Integral-Derivative control, commonly abbreviated as PID. The climatic generator further includes parts for supplying the flow of air G_a to be conditioned to the bubbling device, which includes an air duct, having for example a tortuous path such as a coil provided with a high density of micro holes positioned on the bottom of the bubbler in such a way as to fractionate the air in transit in the volume of water W into bubbles which allows an optimal sensitive and latent exchange between air and water, or in order to optimally saturate the air and cool it to the dew temperature. It is connected to an air pump suitable for circulating the air in the duct and producing enough pressure to allow the air flow to overcome the pressure of the water column formed by the volume of water W present in the bubbler.

The air pump has also the purpose of providing air circulation, pushing the air up into the micro-environment to be conditioned.

More specifically, the pump has an inlet particulate filter and operates with a capacity and pressure sized to compensate for pressure losses and to overcome the pressure of the water column of the

bubbler; for instance, the required minimum flow must be great enough to guarantee sufficient exchange and distribution of the air in the micro-environment to be conditioned and climatic stability, based on the latent-sensitive load in the environment and at the desired rate of achievement of these conditions. For example, an ultra-stable air-conditioning pump in a museum case is sized for around 100 air exchange/hour (determined by the ratio between pump flow and casing volume). Empirical tests showed acceptable performance around 1 air exchange / hour (using a pump flow rate of 1 m³/h for a 1 m³ case). For museum display cases placed in stable conditions and requiring specific restrictive effects on sound emissions, lower values may be sufficient.

The bubbler is designed and sized in order to optimize the height of the water column, of the water volume W and of the minimal size of the bubbles as a function of the air flow to be treated, so that the air-water exchange efficiency is maximized.

In the bubbler, the air flow G_a bubbles through the volume of water W present, saturating it with water vapor and reaching the temperature of the volume of water, an air flow collector is located in the upper part of the bubbler, suitable for canalize the flow of saturated air G_b towards the micro-environment to be conditioned by the climate generator.

Heating devices, such as a heating coil, are arranged downstream of the bubbler and suitable for heating the flow of air G_b at the outlet of the bubbler before being pushed into the climatic chamber.

In a cyclic setup, the deteriorated air flow G_a is taken from the climatic chamber to be re-conditioned. In the currently preferred setup, shown in figure 2, the bubbler is a watertight, pressure-tight, thermally insulated container; its volume is filled with 3/4 of water thermostated to the dew point temperature (T_r) of the air flow. The container has a sealed cap on the upper side for topping up the water volume and the inspection. The container is connected on the upper side with two ducts, respectively for air supply and outflow. The air supply duct reaches the bottom of the container where it is connected to a porous tube. The air outflow duct is equipped with a goose neck trap to prevent any liquid being transported with air up to the heating device. The shape and volume of the container are sized so that the thermodynamic transformation of the incoming air is complete. Water volume should be oversized, in order to reduce the variations in water level.

The porous tube is preferably placed on the bottom of the container and connected to the air flow supply duct. The porous tube allows to introduce the air flow into the water as small bubbles, increasing the surface/volume ratio of the bubbles as much as possible in order to maximize the air/water exchange.

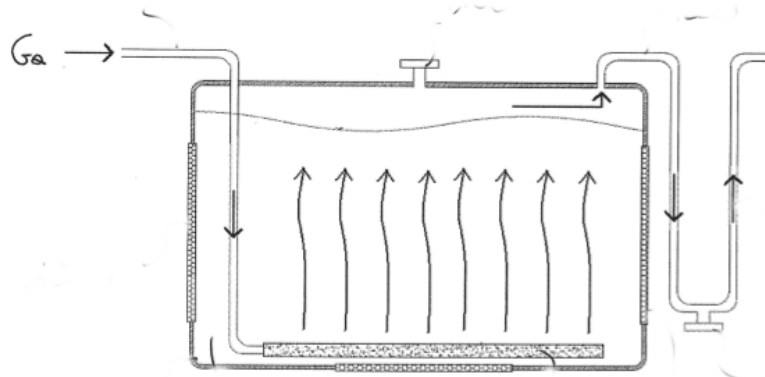


Figure 2. Design scheme of the bubbler

The heat-exchanging device is a system for thermostating the volume of water W of the bubbling device, and includes heat exchange batteries placed directly inside the container or externally in open vessel setup. The heat exchange batteries are made using a coil of thermally conductive material (such as copper) in which a refrigerated gas circulates from a refrigerating unit, or by means of peltier cells integrated on the walls of the container, which have a reduced efficiency but no working noise (which is a benefit in exhibiting locations).

The heating section is a thermostating system for the air aiming to heat the air flow coming out of the bubbler from the dew point temperature and at 100% RH to the target temperature value. It involves e.g. electrical resistances located inside a thermal insulated duct and air ducting towards the case, in which the electrical resistances are arranged near the display case or directly inside the case.

During the passage in the bubbling device, the incoming air flow G_a , which has an enthalpy value h_a , an absolute moisture content x_a , temperature t_a and relative humidity i_a , undergoes a sensitive transformation, i.e. it is heated or cooled to a temperature t_b , and is saturated with water vapor making a latent transformation, whereby the output air flow G_b has enthalpy value h_b , absolute humidity x_b , temperature t_b and relative humidity $i_b = 1$.

Thereafter, the flow of air G_b is heated from the temperature t_b to the temperature t_c , to obtain the conditions of the air flow produced by the climate generator G_c conditioned to the desired values of enthalpy h_c , with an absolute humidity x_c , temperature t_c and relative humidity i_c , respecting the following proportions $x_c = x_b$, $t_c \geq t_b$ and $i_c \leq i_b$.

By setting the temperatures t_b and t_c , it is possible to obtain the desired climatic conditions at the set values of controlled temperature t_c and of controlled humidity i_c . In fact, once the desired controlled temperature t_c is established, the desired relative humidity condition is obtained by adjusting the water temperature of the bubbling device at the dew point temperature t_r of the air flow, i.e. by adjusting $t_b = t_r$, that is a function of the desired temperature t_c and of the desired relative humidity i_c .

The RH control i_c is then carried out by controlling the water temperature in the bubbling device, which is assumed for simplicity to correspond to the temperature of the air flow exiting from there at t_b . For this purpose, a function $t_b = f(t_c, i_c)$, in which the temperature value t_b is obtained as a function of the controlled temperature t_c and the controlled relative humidity i_c , can be directly implemented in the control. This function is expressed by the following formula, also known as Magnus equation[5]:

$$t_b = \frac{237.7 \cdot \frac{17.27 \cdot t_c}{237.7 + t_c} + \ln i_c}{17.27 - \frac{17.27 \cdot t_c}{237.7 + t_c} + \ln i_c} \quad (1)$$

where the symbols are previously specified and \ln is the natural logarithm, and the calculated isotherms are displayed in the chart of figure 3.

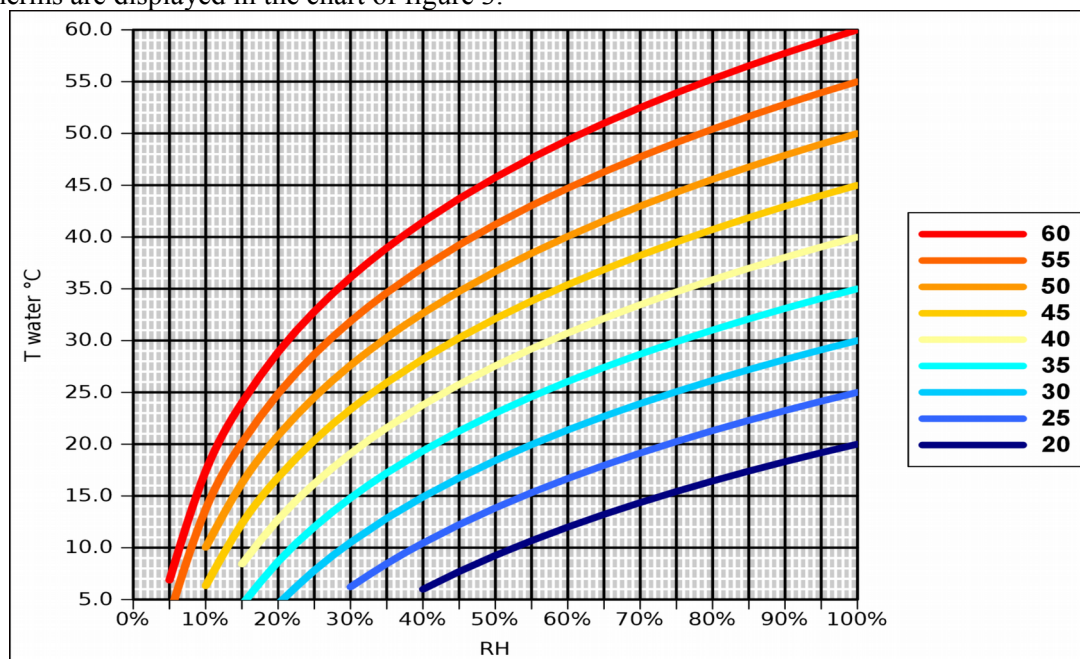


Figure 3. The curves representing the obtainable values according to formula 1. On x axis the i_c target values of relative humidity, on y axis the t_b values at the outflow of the bubbler. On the right legend the family of curves at constant t_c is displayed.

In an alternative setup as a dynamic climatic generator, the bubbling device includes a first bubbler and a second bubbler, the latter maintained at different water temperature conditions with respect to the water temperature of the first bubbler, e.g. through the use of the heat exchange coil which, by means of a modulating valve adapted to regulate a flow of water intake in the first and second bubbler respectively, as a function of the water temperature, serves both the bubblers. Means for diverting the flow of air to be conditioned, such as for example a three-way valve, are adapted to selectively deviate the flow of air to be conditioned to the first or to the second bubbler.

Using this setup, it is possible to obtain a system able to make sudden changes in relative humidity under isothermal conditions. Such a dynamic generator is necessary for some types of laboratory tests, as in the execution of some types of environmental simulation tests.

The advantage achieved by the climate generator and the corresponding climate conditioning process of the DPCG consists in the fact that only two transformation steps are necessary to control the climate of an environment. Thanks to this, a minor complexity, a greater reliability, lower production costs and reduced maintenance of the climate generator are obtained, despite of having a wide range of use and a stable and accurate control of the climatic parameters of T and RH.

Due to the need for dynamic systems where rapid and wide variations are required, the climate generator is highly efficient and has much lower manufacturing costs compared to known laboratory equipment, which are mainly constituted by a double climatic chamber served by a double climate control system.

Moreover, the treated air will be free of dust and pollutants thanks to the fact that the air passes into the water in the bubbler.

3. Case studies

The Dew Point Climatic Generator has been successfully used during the restoration of a big panel painting by Jakob Seisenegger stored in Trento, Italy[6]. During the structural intervention aiming to re-design the crossbeams system, the technical need of measuring on site the response of the panel at different climate conditions and to follow the dynamics in achieving a new equilibrium with the surrounding microclimate has been possible thanks to the stability assured by the DPCG in keeping a setpoint and to its rapidity in passing from one setpoint to another.

Some tests (unpublished) carried out at the Metropolitan Museum of Art of New York on the response of dummies simulating panel paintings to temperature step variations at constant relative humidity were successfully completed thanks to the stability of the microclimate provided by the DPCG: the variations in moisture content of the dummies were so small to be otherwise unreadable using standard climate control systems because of the noise induced by the intrinsic micro-fluctuations.

4. Conclusions

An innovative climate control system specifically designed for museum display cases is described.

Its use of dew point as the starting point to produce an airflow at the desired T and RH conditions is intrinsically stable because not based on a feedback approach, which usually induces microfluctuations around the set point in traditional systems: using the traditional approach the required parameters are achieved by two systems working in parallel and often in opposition.

The tests carried out during the monitoring of a big panel painting in Trento and on dummies in a test climate chamber at the Metropolitan Museum of Art in New York showed how robust and reliable is the device and how tight can be the fluctuation range of the climate inside the display cases.

Its accuracy, long-term reliability and customizable size make it a challenging improvement for the best preventive conservation of works of art.

5. References

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