Humidistat-controlled Heating and Ventilation Systems to Create Preservation Conditions in Historic Buildings in the Dutch Climate

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SUMMARY

In a marine temperate climate historic buildings that are equipped with thermostat-controlled heating systems show very low relative humidities (RH) during the heating season. This may lead to mechanical damage due to drying of hygroscopic materials like e.g. wood. Humidistat-controlled systems are investigated using two different cases. Two top monuments of the Netherlands serve for the case study: Hunting Lodge St. Hubertus and Muiden Castle.
The effectiveness of a humidistat-controlled heating system is investigated, both by simulation and by experiment. When using humidistat-controlled heating, the heating system is mainly used to maintain basic temperature levels during the heating season. During the humid seasons the heating system may be used to lower RH. Simulations are performed using Matlab Simulink. In the experimental setup a humidistat-controlled room is compared with a thermostat-controlled room. Simulation results show that humidistat-controlled heating is a good method to provide preservation conditions in historic buildings. Simulation results are validated by measurements. Though energy expenditure is significant lower, thermal comfort may decline.
A humidistat-controlled ventilation system is investigated by making use of simulation. In historic buildings with high visitor numbers, high moisture and CO_2-levels may occur. By selective ventilating with outdoor air, excessive moisture can be removed and low CO_2-levels maintained. Preservation effects mainly occur by eliminating high RH by ventilating with air that has a lower specific humidity or by slightly heating the ventilation air. To maintain healthy environment conditions, control of the system on CO_2-concentration is a priority.

INTRODUCTION

Originally, historic buildings did not have any other heating system than an open fire or some kind of local heating system. Sometimes a central heating system was installed afterwards. Measurements in one of the most valuable historic buildings in the Netherlands prove again that heating during the cold period leads to low indoor RH, causing damage to interior and objects [1]. Outside the heating season high RH often occurs, also causing risk for damage to interior and objects by e.g. mould growth [2]. In most cases the possibilities to fully control RH in a historic building, by e.g. installing a full air-conditioning system, is limited. Installing mechanical systems and ducts always will cause damage to the building and its historic authenticity. The high installation, maintenance and running costs are not even mentioned. Furthermore humidifying devices may lead to dramatic indoor air conditions with high surface humidities and condensation effects on cold indoor surfaces of the exterior walls, single glazing and roofs, or even condensation in the inner parts of the construction [3].

Theory

The principle of humidistat-controlled heating is controlling the heating system using a humidistat device [4]. High RH is prevented by starting heating. Reaching low RH during the cold season is prevented by limiting heating to maintain a certain lower temperature setpoint. The flowchart of the system is given in Figure 1a. The use of this control however is restricted. In summer it may be necessary to start heating and during wintertime it may be necessary to limit heating, causing thermal discomfort of occupants.

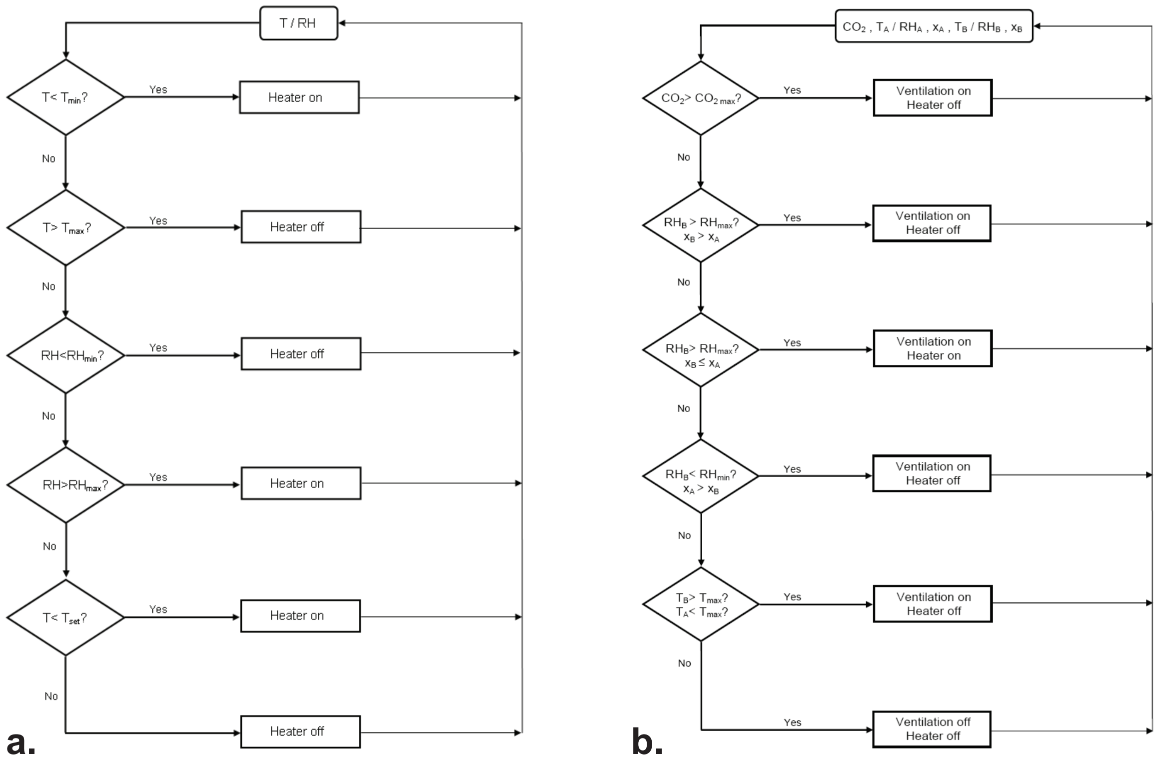

Figure 1. Flowcharts of the humidistat-controlled heating system for the case St. Hubertus (a) and the humidistat-controlled ventilation system for the case Muiden Castle (b).

The humidistat-controlled ventilation system is also being controlled by humidistat devices. Controlling RH is possible by ventilating with air that has a lower specific humidity or by slightly heating the inlet air. Humidistats and temperature sensors are installed in the location where ventilation air is extracted from, e.g. outside or an attic and in the location the where air is being supplied to (visitor zone). The specific humidity of both zones is calculated. Values are constantly monitored. To maintain a healthy and comfortable visitor zone, the CO_2 level is measured in the room the air is being supplied to. The objective of the ventilation system is to avoid high CO_2-levels and to control RH and temperature in the rooms. Ventilation only takes place if correction on CO_2 level, RH or temperature is needed. The flowchart of the system is given in Figure 1b.

Objectives

In the Netherlands there is little experience with humidistat-controlled heating and ventilation systems. The main objective of this research was to determine the suitability of humidistat-controlled systems in a maritime temperate climate like the Netherlands and to optimize the control strategy. Countries with a marine temperate climate have a cool winter, warm summer

and an uniform precipitation distribution, *Cfb* according to the Köppen climate classification system [5].
Second objective in the research was to construct heat and moisture simulation models in order to predict the suitability of humidistat-controlled systems in historic buildings.
Third objective is to gain insight on the (dis)advantages of these systems compared to basic heating systems or the use of full air-conditioning systems.

Cases

The effectiveness of humidistat-controlled systems is investigated using two cases. The first case describes the research of a humidistat-controlled heating system in Hunting Lodge St. Hubertus. The second case describes the research of the implementation of a humidistat-controlled ventilation system in Muiden Castle.

Case 1: humidistat-controlled heating
Hunting Lodge St. Hubertus was built from 1916 to 1922. Building and its interior were designed by the famous architect Berlage according to the legend of Saint Hubert. The building has the shape of the antlers of a deer's head. A large part at the ground floor level is now part of a guided tour. A part of the west wing is housed by the property manager. The building also serves as a location for weddings, receptions and occasionally, as housing for high placed guests. The annual visitor number in 2005 was 27.000.



Figure 2. An aerial view of Hunting Lodge St. Hubertus (left) and the dining room with its historic interior (right).

The exterior walls, floors and roof of the building are not thermally insulated. Exterior walls at ground floor level consist of masonry cavity walls. Floors are made of concrete, carried on metal beams. The windows consist of single glazing in steel frames. The roof is constructed out of wooden beams with slate covered sheathing.

Case 2: humidistat-controlled ventilation
Muiden Castle is a century old building that has played an important role in Dutch history. The castle dates back to the year 1283 and is one of the best conserved medieval castles in the Netherlands. In 1900 and 1960 the castle was renovated and since 1960 it is in use as a museum. Except from the museum function, the castle is also being used for activities like diners, parties and weddings. The annual visitor number in 2005 was 115.000.
Exterior walls are constructed out of masonry with a thickness ranging from 200 to 1600 mm. Indoor walls also consist of masonry and vary in thickness from 300 to 1300 mm. In most rooms indoor walls are decorated with plaster. The windows are all single glazed, mostly stained glass windows. The glazing is set in wooden or stone frames. Different windows of the castle can be blinded with wooden shutters. The floors consist of wooden planking on

wooden beams. Floors are mainly covered with tiles or marble. The roof is constructed out of a wooden sheathing covered with slates.

Figure 3. Muiden Castle as seen from the south side (left). The collection consists partly of medieval weaponry (right).

Apart from the historic interior, the castle houses an important collection consisting of paintings, furniture and artifacts like medieval weaponry. To optimize the visitor experience, an extensive renovation started in 2005. During times with high visitor numbers, the indoor air quality was poor [8]. In different locations throughout the castle mould growth was found on objects [9]. The planned renovation was a good opportunity to optimize indoor climate conditions by installing a humidistat-controlled ventilation system. Optimizing indoor conditions by making use of a humidistat-controlled ventilation system is not commonly used in the Netherlands. In this case, the effectiveness of the system will be investigated by making use of computer modeling.

METHODS

Case 1: humidistat-controlled heating

First, air temperature and RH measurements took place in different locations throughout the building for a period of one year. Next a simulation model for humidistat-controlled heating was developed to gain insight on the effect of the system on indoor climate, control strategies, needed heating capacities and optimal setpoints for the test set-up. The model was validated with measurements from the earlier monitoring. After the modeling an experimental set-up was installed in the monument. The experiment consisted of a humidistat-controlled room and a thermostat-controlled room. Testing started during the cold winter months and the tests were continued for a full annual cycle.

Modeling humidistat-controlled heating
Simulations on the indoor climate were performed using the heat and moisture model HAMBASE [5] coupled to Matlab Simulink [6]. The HAMBASE model contains the building model. The control strategy in the humidistat-controlled room is based on the flowchart as given by Figure 1a and modeled using Matlab Simulink [7]. First is checked if the room temperature is higher than the set minimum temperature T_{min}. If not so, the heater is switched on. Next is checked if the temperature is below the set maximum temperature. If not so the heater stays off regardless of RH conditions. If temperature is between the setpoints of minimum and maximum temperature, the controller continues to check if correction of RH is acquired by checking if the current RH is higher than the set maximum RH. If so, the controller switches the heater on until the RH is below RH_{max} or the temperature T_{max} is reached. In historic buildings where thermal comfort is needed, the possible provision of

limited thermal comfort by slightly expanding the controller is investigated. If RH is between RH_{min} and RH_{max}, heating is possible to raise indoor air temperature and increase thermal comfort. The heater will stay on until RH_{min} or the desired temperature T_{set} is reached.
The inputs of the HAMBASE-Simulink model are heat flow and moisture flow and the outputs are air temperature and relative humidity. Dependent on the input values is checked if heating is required according to the conditions as given in Figure 1. The output of the controller is zero or, if heating is required, the set heating capacity for this zone.
Setpoints of both types of controllers are given in Table 1. Settings of the thermostat-controlled room in the model and the experimental set-up are set to a constant temperature of 17°C to avoid fluctuations. Air exchange rate in the rooms was not measured and is set to an estimated value of 0.8 times per hour.

Table 1. Setpoints for the controller devices in the model.

Thermostat-controlled room		Humidistat-controlled room	
Start daytime	8 a.m.	T_{min}	10°C
Start nighttime	10 p.m.	T_{max}	25°C
T_{day}	17°C	T_{set}	17°C
T_{night}	17°C	RH_{min}	45%
		RH_{max}	55%

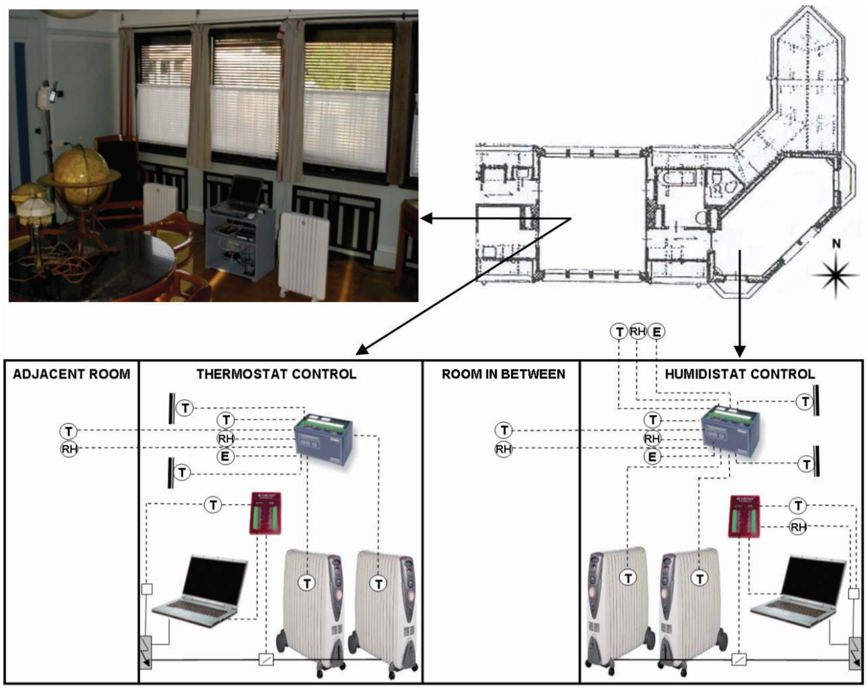

Figure 4. The upper left image shows the experimental set-up in the thermostat-controlled room. A floor plan of the two rooms where the set-up was installed in is given by the upper right image. A schematic representation of the configuration of the test set-up is given below.

Experimental set-up humidistat-controlled heating

For an experimental set-up two similar rooms in the historic building were selected on the first floor. During testing this part of the building was unused and doors and windows remained closed. There were no known moisture sources in this part of the building. Sun blinds were closed for about 60% of the window area during testing (Figure 4). The configuration used for the experimental set-up consisted in each room of a laptop computer for control, three oil filled electrical heaters of 3 kW each and a combined T/RH-sensor. The existing central heating system was switched off for these rooms. In one room the set-up was

installed to heat the room humidistat-controlled. The software was programmed according to the flowchart as shown in Figure 1. Every 10 seconds the software ran a loop with current air temperature and RH as input.
In another similar room the set-up was installed to heat the room thermostatically. Setpoints of both controllers were likewise as shown in Table 1. In the thermostat-controlled room day temperature is set to the same value as the night temperature. This is done to avoid deliberate fluctuations of RH in the historic interior and thereby limiting the risk of any damage done to the interior during the experiment. The electrical radiators were controlled by a simple on/off switch. Additional heat production was limited by using only a laptop computer per room to control the heaters. In the rooms under investigation indoor air temperature, surface temperature of north facing window and wall, RH and incoming solar radiation were monitored. In adjacent rooms air temperature and RH was measured. Outdoor climate properties like air temperature, RH and solar radiation were also monitored.

Case 2: humidistat-controlled ventilation

First, the indoor climate of the castle is modeled prior to the installation of the ventilation system. Indoor climate data unfortunately only are available for a short period of time, in the autumn of 2005. To obtain an indication of the indoor climate through the whole year, a model of the castle is created using HAMBASE. In this model only the basic heating system is integrated, like the situation prior to the installation of the ventilation system. Results are compared with the desired indoor climate conditions. The desired conditions are based on a healthy indoor air quality and conservation conditions for interior and objects (Table 2). RH boundaries are chosen to avoid e.g. mould growth and drying of organic objects. The maximum CO_2-level is based on the lowest class in the Dutch practice guidelines as given in NPR-CR 1752 [10].
Next, a model is set up to investigate the effectiveness of the ventilation system. This is done by making use of HAMBASE coupled to Matlab Simulink. In this case HAMBASE contains the building model and Matlab Simulink the model of the ventilation system and control. Obtained data are again compared with the desired indoor climate conditions. CO_2 levels are not modeled.

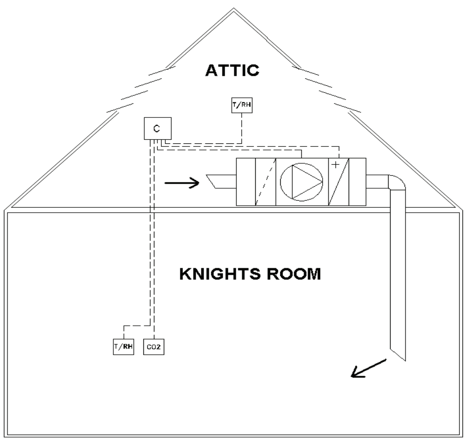

Figure 5. Principle of the humidistat-controlled ventilation system. The ventilation unit is controlled by the controller (C) which is fed with data from the sensors.

Table 2. Desired conditions for a healthy indoor climate and conservation conditions.

Relative Humidity	Maximal variation	Temperature [˚C]	Maximum CO_2-level [ppm]
40 – 65%	10	5 - 25	1520

The building is equipped with a central heating system with radiators and floor heating. During the renovation a ventilation system is installed in five important rooms, next to the existing heating system. Most of these rooms have a chimney. To minimize the impact on the construction, the existing chimneys are used to install the ducting. Each room has its own ventilation unit, which are installed on the attic. The ventilation units are composed of a ventilator, heater and filter section with EU7 quality. The ventilation system does not contain a humidifier or dehumidifier. Air is taken directly from the relatively air leak attic. Air is supplied in the underlying rooms through ducting in the existing chimneys and an inlet grille in the chimney. Inlet air leaves the room through exfiltration and opened doors. In this case the ventilation system of one of the five rooms, the Knights room, is lighted out. The ventilation unit for this room has a maximum ventilation capacity of 2200 m^3/h. This capacity is based on the amount of 35 m^3/h per person and is based on 62 persons. The ventilation capacity is controllable in different steps.

Modeling the indoor climate before the installation of the ventilation system

First a model of the situation prior to installing a ventilation system is created. In the simulation only the north part of the castle with five rooms (zones) are modeled. The Knights room is on the ground floor, with one underlying zone (cellar), one adjacent zone and three up lying zones. Non exterior or interzonal walls are modeled as adiabatic walls. The Knights room contains floor heating with a maximum capacity of 60 W/m^2 and a setpoint of 19˚C. The model is tuned using the available data as obtained in the autumn of 2005. Discrepancies between the results of model and measurements occur because the floor heating does not always have a constant temperature, which is assumed in the model. The air exchange rate of the rooms in the model is assumed to be constant 0.5 h^{-1} (Table 3).

Table 3. Settings for zone 2 (Knights room) of the models.

Before installation of ventilation system		After the installation of ventilation system	
Air exchange rate	0.5	Air exchange rate	At least 0.5
Start daytime	10 a.m.	T_{max}	25°C
Start nighttime	17 p.m.	RH_{min}	45%
T_{day}	19°C	RH_{max}	60%
T_{night}	19°C	T_{day}	14.5°C
		T_{night}	14.5°C

Modeling humidistat-controlled ventilation

Next, a model with the added ventilation system is developed. This is done by coupling the HAMBASE building model to Simulink. This model is constructed according to the flowchart as given in Figure 1b. First is checked if CO_2 levels are below the maximum desired level. Next is checked if correction on RH is needed to ventilate with possible drier air from the location air is being extracted from. Therefore both specific humidities are calculated and compared. If RH of the visitor zone is too high and the specific humidity of the extraction location is higher or equal to that of the visitor space, the ventilation air will be heated. If the measured RH is less than 5% out of the desired RH boundaries, the ventilation system will not work on full load. In this case the ventilator will work on 25% of its capacity to avoid high fluctuations in temperature and RH. If the CO_2 level and RH are within the desired boundaries, the temperature is checked. If the temperature in the visitor space is too high and the air in the extraction location has a lower temperature, ventilation starts.

Settings of the HAMBASE model are likewise as given in Table 3. In addition to the added ventilation system the setpoint of the floor heating system is lowered from 19.5˚C to 14.5˚C.

The air heater in the ventilation unit for the Knights room has a maximum heating capacity of 24 kW.

RESULTS

Case 1: humidistat-controlled heating

Figure 6 shows simulation results of temperature and RH zoomed in on January 14th to February 14th 2006 of the humidistat-controlled room in Hunting Lodge St. Hubertus. Simulation results are validated with measurements. Minor discrepancies occur possibly due to the estimated air exchange rate of 0.8. Visible is that with a T_{min} set to 10˚C it is not possible to maintain a minimum of 45% RH due to the low specific humidity of the outdoor air, which mostly occurs during wintertime (Figure 6: 22/01–04/02). Over the simulated period T_{min} has to be lowered to about 4˚C to maintain 45% RH in the Dutch climate.

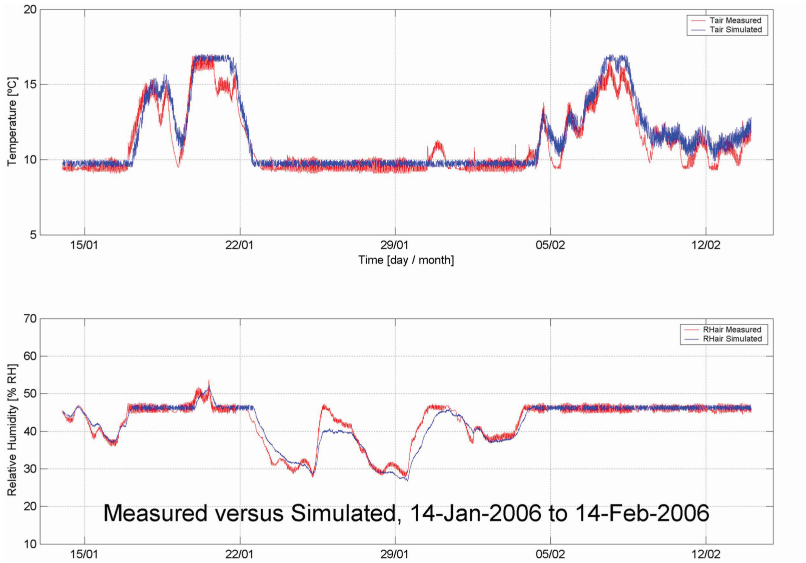

Figure 6. Simulation results of temperature and RH in the humidistatically heated room over the period from January 14th to February 14th 2006.

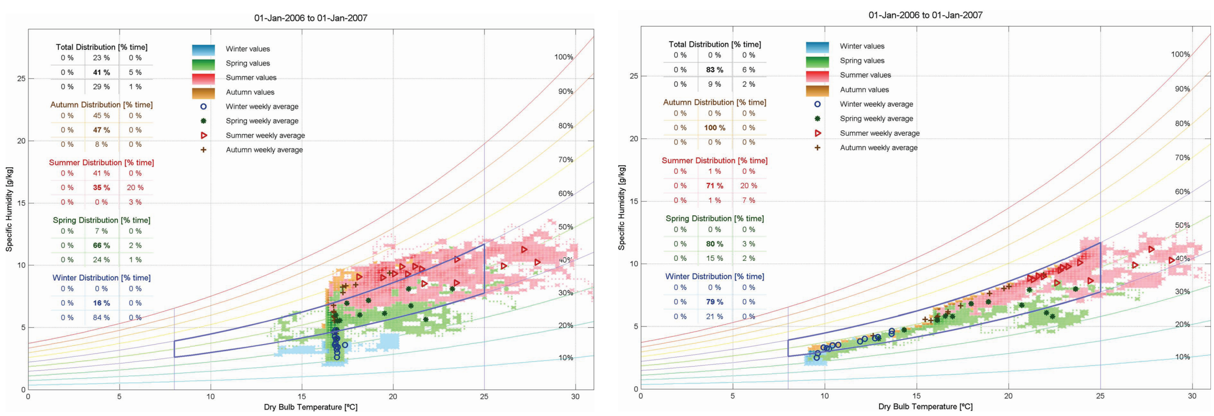

Figure 7. Psychrometric charts showing measurement results of the thermostat-controlled (left) and the humidistat-controlled (right) room from January 1st 2006 to January 1st 2007. In the thermostat-controlled room RH is for 30% of the data under 40% RH and for 23% of the data over 60% RH. RH in the humidistat-controlled room is for 11% of the data under 40% RH and for less than 1% over 60% RH.

In Figure 7 temperature and RH of the test set-up are plotted in a psychrometric chart both for a thermostat-controlled room as for the humidistat-controlled room.
In the thermostat-controlled room low RH occurred during periods of low specific humidity (winter time). In the same periods RH in the humidistat-controlled room is higher due to a lower indoor temperature.

In Table 4 annual energy expenditure of three different heating strategies is compared for one identical room. Values are obtained by HAMBASE simulation using the outdoor climate data of the year 2005. Results show that humidistat-controlled heating without limited comfort function uses about 30% less energy in comparison to a thermostat control.

Table 4. Annual energy use of the identical zone using different heating strategies.

Heating strategy	Settings T/RH	Annual energy expenditure [kWh]
Thermostat-controlled[1]	15-20˚C / -	6133
Humidistat-controlled with limited comfort function[2]	10-25˚C / 45-55%	5431
Humidistat-controlled without limited comfort function	10-25˚C / 45-55%	4329

[1] day temperature 20˚C with a 5 K drop between 10 p.m. and 8 a.m.
[2] T_{set}= 17˚C

Case 2: humidistat-controlled ventilation

Indoor climate conditions are monitored from November 24th to December 1st 2005. In Figure 8 the measured results of the Knights room are compared to the simulation results over this period.

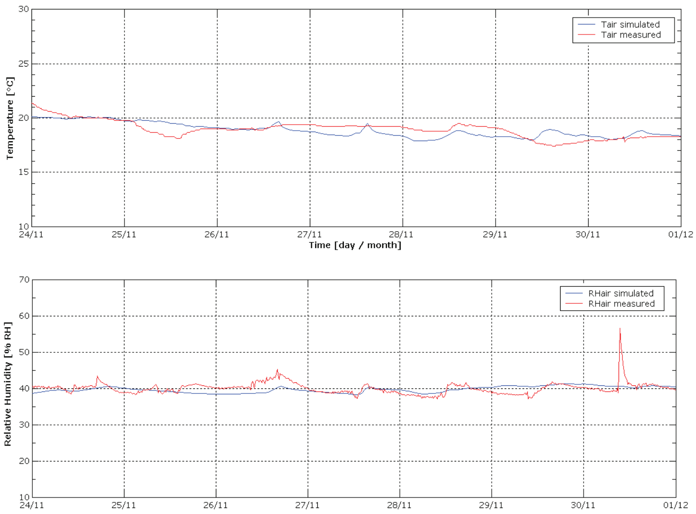

Figure 8. Results of the HAMBASE model compared with results obtained by measurement. The measured RH peak on the 30th of November is possibly caused by cleaning activities.

For the whole year, simulation results of the model prior to installation of the ventilation system show low RH during the heating season and high RH outside the heating season. In Figure 9 simulation results of the Knights room of the situation prior to installation and after the installation of the ventilation system are both plotted in the psychrometric chart. Results of the situation after installing the ventilation system show less low RH during the heating season. The main reason for this is a decrease in setpoint of the heating system from 19.5 to 14.5˚C. In the situation prior to installation 31% of the RH is below the desired minimum level of 40% RH. After the installation of the ventilation system this is 17%. Outside the heating season less high RH occurs thanks to the humidistat-controlled ventilation. In the situation prior to installation 28% of the RH is above the desired maximum level of 65% RH. After the installation of the ventilation system this is only 2%.

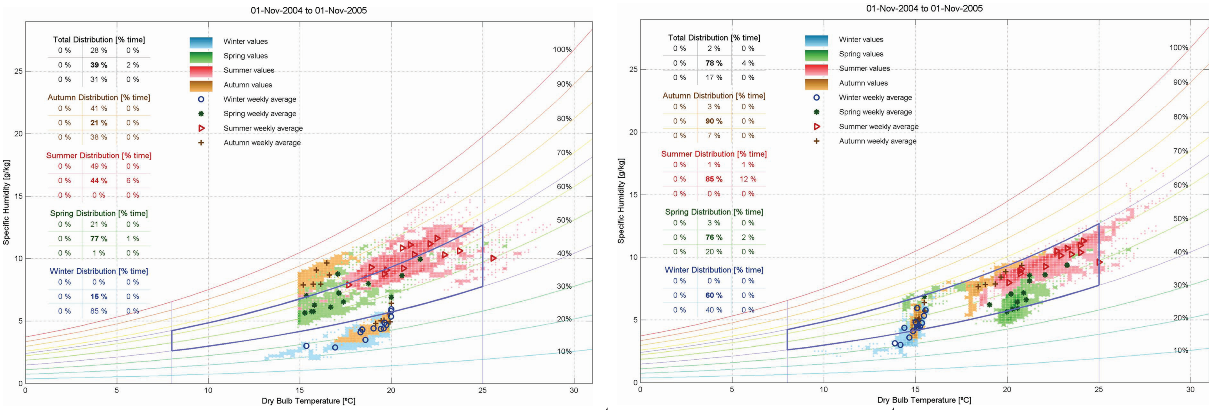

Figure 9. Simulation results from November 1st 2004 to November 1st 2005 before and after the installation of the ventilation system. Results show less low RH due to a decrease of the temperature setpoint and less high RH outside the heating season due to humidistat-controlled ventilation.

DISCUSSION

Humidistat-controlled heating is an efficient technique to create preservation conditions in historic buildings in the Dutch climate. The largest benefit is elimination of extremes in indoor RH. Temperature and RH fluctuations also are lower compared to thermostat-control with a night setback. Apart from providing improved conservation conditions energy expenditure is far lower compared to conventional heating to provide thermal comfort. Improved comfort can be provided by limited heating when RH is between desired boundaries, but this strongly depends on the specific humidity (g/kg) of the outdoor air. Historic buildings that are closed for winter season are ideal to implement a humidistat-controlled heating system. For humidistat-controlled heating T_{min} can be set to a lower value of about 4˚C to obtain a lower RH limit of around 45% in the Dutch climate. When comfort is required during specific times, the control strategy can be switched to a thermostat control in order to provide thermal comfort. In this case it is important to use a limiter to prevent too quick heating of the room. The use of a limiter in the control is also useful for situations that the installation restarts after e.g. a malfunction. The experimental set-up showed a side effect when having a room with humidistat control next to a room with thermostat control. This resulted in a wooden door that bend due to the difference in temperature and related RH. It is recommended to reduce these differences. Also literature shows heating may run out of control in rooms with a small air exchange rate and a high amount of hygroscopic materials, due to the release of moisture [11].

Historic buildings with high visitor numbers can be equipped with a ventilation system controlled by a humidistat device and a CO_2-sensor to improve indoor air quality and preservation conditions. Simulation results show that the implementation of a humidistat-controlled ventilation system can create more suitable conservation conditions in historic buildings. Indoor climate improvements consist of less low RH during the heating season due to a lower temperature setpoint. Outside the heating season high RH is corrected by slightly heating the ventilation air. Additional advantages of this system are the possibilities to filter the air and maintain healthy indoor air conditions by controlling CO_2-levels. Disadvantages

are the necessary ducting and a lower thermal comfort during the heating season due to a decrease of the temperature setpoint.
It is possible to maintain preservation conditions in historic buildings in the Netherlands without the use of (de)humidification. Values of the controller have to be selected for minimum use of the system, to be energy efficient and promote longevity of the components. Setting can differ per project and are dependent on both building physics and collection. If no comfort is needed the lower temperature setting has to be determined by assessing temperature sensitivity of collection or the presence of water filled pipework. Modeling is a useful tool to predict the impact of humidistat-controlled systems on the indoor climate, to determine optimal controller settings and to gain insight on energy expenditure.

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