Development of Adiabatic and Isotherm Humidifier Models to Compare Health, Energy and Water Use

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Abstract

In Belgium, when humidification is needed, isotherm (steam) humidification is mandatory in public buildings to prevent Legionella contaminations. The question is whether adiabatic humidification, which should be more energy efficient than isotherm humidification (Jo et al., 2017), can be used as an alternative without introducing a Legionella hazard.

Two new Modelica component models for adiabatic and isotherm (steam) humidification are developed containing a biological Legionella pneumophila growth model (Van Kenhove et al., 2019). Both humidifier models are applied in a simulated case study office building. Energy use and L. pneumophila concentrations are compared (Vandorpe, 2020).

The simulated cases show that it is possible to safely operate an adiabatic humidifier provided that correct measures are taken. This indicates that the current legislation may be too strict and opens doors to further in-depth research.

Key Innovations

- Existing humidifier models only consider mass flow of moist air. Since these models do not contain mass flow equations for water, it is not possible to estimate L. pneumophila growth as this requires knowledge of the water temperature and water renewal rate of the tank.
- These newly developed models allow to study the energy saving potential of an adiabatic humidifier installed in an air handling unit, while taking into account the L. pneumophila risk.

Practical Implications

The newly developed humidification simulation models can be used stand-alone or can be connected to a building model. The models can be used to examine the healthiness of adiabatic humidification versus isotherm (steam) humidification, which is the subject of this paper. However, they are also suitable to examine the healthiness of adiabatic cooling in summer, misting machines in grocery stores, cooling mist sprayers on terraces and in extension cooling towers.

Introduction

L. pneumophila bacteria

L. pneumophila is a bacterial pathogen and can cause legionellosis. When infected, elderly, smokers and people with a debilitation of their immune system are more prone to develop Legionnaires’ disease. Healthy people usually develop Pontiac fever. Legionnaires’ disease is a severe form of pneumonia with a high fatality rate. Pontiac fever is a much less serious and more widespread form of legionellosis without pneumonia. It is an influenza-like illness. It is clear that, considering the high fatality rate caused by Legionnaires’ disease, research about the control and limitation of L. pneumophila can possibly save human lives (Prussin et al., 2017; Batram et al., 2007; Yu et al., 2019).

The unique feature of this pathogen is that it needs a water system (e.g. pipes, boilers) or a biofilm attached to a wet surface to proliferate and grow, and that it can only cause disease when aerosolised into the air and inhaled by the host. For the bacterium to travel from the water source and eventually reach the host, several steps need to be covered. The bacteria present in natural sources are dormant and do not multiply since the water temperature is too low. When the water enters the built environment however, the conditions for proliferation are more favourable. The water temperature increases to the range of 20 °C to 45 °C, in which the bacteria are active and multiplying. Biofilms, amoebae and nutrients, which can all be abundantly present in water systems, increase the growth of the bacteria. On top of that, there is a higher proliferation risk in stagnant water. The next step is the spread and inhalation of the contaminated water. L. pneumophila has to be inhaled in order to get infected. The droplets need to be small enough to reach the alveoli in the lungs and still be large enough to contain L. pneumophila. These droplets are called aerosols and are produced by several engineering applications (e.g. showers). When these aerosols are inhaled, the host is exposed to the bacteria and will get ill. The disease outcome depends on the health status of the host (Yu et al., 2019).

As most transmission of L. pneumophila appears to involve aerosolisation of bacteria from water into air, transmission is more likely in built environments that contain aerosol-generating features like plumbing sources, cooling towers, humidifiers, but also swimming pools, spas, hot tubs, whirlpools and ornamental sources.
fountains. Mist machines (in grocery stores), sprinklers (e.g. fire sprinklers and garden watering) and mechanical aerosolisation of soil particles (for gardening) are possible sources of Legionella outbreaks as well. This research focuses on the proliferation of L. pneumophila in humidifiers.

**Why is humidification needed?**

There are two main reasons to use humidification in buildings: comfort and health.

**Comfort**
The air humidity has an impact on the thermal comfort we experience in our environments. The Fanger comfort model analyses, amongst others, the heat exchange between the individual and the environment. A person disposes heat produced by a certain activity. This disposal is done by convection and radiation, thus by surface evaporation, to the surrounding environment. Evaporation is related to the air temperature, the air velocity and the humidity. Therefore, humidity has an influence on comfort experienced by users. A constant, not-fluctuating relative humidity is recommended (Lazzarin et al., 2004).

**Health**
The humidity level influences the growth of contaminants. There is a higher growth of bacteria and viruses at low humidity due to the fact that those biological contaminants proliferate and evaporate from saliva and form aerosols. Considering the different zones of minimum activity for various biological and non-biological contaminants, the optimum range of relative humidity is between 40 and 60%. A range of 30 to 70% is acceptable, but the optimum range is recommended (Sterling et al., 1985).

**Research objective**
The current Belgian (Flemish) regulations regarding Legionella require the use of steam humidification, which is absolutely safe due to the high water temperature (Codex Vlaanderen, 2007). The ARAB regulations however demand high ventilation flow rates in order to provide a healthy indoor climate (FOD, s.d.). These larger flow rates imply a higher humidification load. Therefore, the share of ventilation and humidification in the total energy use increases, certainly in buildings with a highly performant building envelope.

The aim of this research paper is to examine whether a healthy operation of adiabatic humidification is possible and if so, to compare its energy and water use with an isotherm (steam) humidifier.

**Methods**

**Comparison of humidifiers**
The first step in this research is to select the types of humidifiers to focus on. Roughly speaking, two standard types of humidifiers exist. On one hand, there are isothermal humidifiers which produce a steam vapour and are considered non-aerosol-generating. On the other hand, there are adiabatic units that allow direct contact between water and airstream, producing aerosols (The National Academies of Sciences, Engineering, Medicine, 2020). The next paragraph shortly discussed the working mechanism of existing humidifiers, which is necessary to understand the model, and their risk of L. pneumophila contamination.

**General working mechanism**
The first type of humidifiers, isotherm humidifiers, humidify air by introducing steam into the airflow. When producing steam, the change of state from liquid to gas and the associated addition of enthalpy occurs by use of an external heat source. The humidification process itself occurs without lowering the air temperature. As shown in Figure 1 different types of isotherm humidifiers are available. The differences mainly depend on how steam is produced.

![Figure 1: Different types of isotherm humidifiers.](https://doi.org/10.26868/25222708.2021.30926)

The enthalpy difference between the steam introduced at atmospheric pressure and the steam in the air is low but existent. Therefore, the temperature of the air slightly increases when humidifying. When the steam has a higher pressure than the atmospheric pressure, the temperature of the air will increase more, since steam has a higher enthalpy and will transfer both latent and sensible heat. However, steam is only seldom distributed at sufficiently higher pressure (Lazzarin et al., 2004).

In the second type of humidifiers, adiabatic humidifiers, humidification is an adiabatic process, i.e. the enthalpy of air does not change. The energy needed to change the state of the water from liquid to gas is taken from the air. Consequently, the air temperature decreases (Lazzarin et al., 2004). Therefore, air is post-heated to reach the desired temperature after the humidification process (Figure 2).

![Figure 2: Thermodynamic processes of the air: pre-heating, humidifying, post-heating.](https://doi.org/10.26868/25222708.2021.30926)
In general, all types of adiabatic humidifiers operate the same. Water is introduced into the air flow at ambient temperature, part of the water is evaporated in the air and the remaining water is recirculated or drained. The water is introduced in the air flow either in the form of miniscule droplets (atomisation) or by a large water-air interface surface (evaporation). The way in which the miniscule droplets are formed, and the size of the droplets, differs from humidifier to humidifier. An overview of different adiabatic humidifier types is shown in Figure 3.

![Figure 3: Different types of adiabatic humidifiers.](image)

_L. pneumophila_ risk and decontamination methods

Lazzarin et al. (2004) ranked different humidifier types according to the associated _Legionella_ risk. As can be seen in Figure 4, isotherm (steam) humidifiers are risk-free. Isotherm humidifiers operate above 100 °C and at atmospheric pressure. This ensures the absence of all potentially harmful micro-organisms such as _L. pneumophila_. Therefore, isotherm humidifiers can guarantee a maximum hygienic safety (Lazzarin et al., 2004). Since the process itself is in fact a thermal decontamination method, no additional decontamination is needed (Lazzarin et al., 2004).

![Figure 4: Comparative probability of the risk of Legionella spreading in the environment for various humidifier types (Lazzarin et al., 2004).](image)

Adiabatic humidifiers range from risk-free to high risk depending on the size of droplets dispersed, the recirculation of water and the stagnation of water. Based on a thorough literature review it is opted to select the adiabatic washer to be modelled, being the adiabatic humidifier with the highest _L. pneumophila_ risk.

To prevent a _Legionella_ contamination, different decontamination methods can be used. A first possibility, chemical treatments with possibly toxic by-products, should be avoided as the water of the humidifier will reach the lungs. Especially chlorination and chlorine dioxide should be avoided because of their toxicity and unpleasant odour. Thermal decontamination is also not recommended. Too hot water may disturb the adiabatic process and it is unfavourable in terms of energy. If membrane filtration, UV irradiation or nanomaterials would decontaminate the water sufficiently and would be allowed, they would probably be the most preferred methods in humidifiers. However, since those methods are not allowed under the current regulations, ionisation, anodic oxidation or phentox-processes are favoured. Draining the recirculation sump frequently could also be an effective prevention method. Additional drying of the sump by keeping it empty can also reduce the bacteria number in biofilms.

**Modelica Dymola simulation models**

Dymola, a simulation environment based on the open Modelica modelling language, is used to develop a component model of the isotherm humidifier and adiabatic washer (adiabatic humidifier). This environment is chosen for multiple reasons. It is suitable for modelling both simple and complex physical systems in multiple engineering domains (e.g. thermal, fluid, electrical, biological). Additionally, a biological _L. pneumophila_ growth model has already been developed in Modelica that estimates _L. pneumophila_ concentrations in domestic hot water systems (Van Kenhove et al., 2019). In this paper, this bacterial growth model is broadened for the use in humidifier models.

Although there is no health problem associated with the isothermal humidifiers, both systems are modelled to be able to compare energy and water use. Well-known Modelica libraries are screened for existing humidifier models to model the adiabatic and isotherm humidifier (Buildings 6.0.0 (Wetter et al., 2014), BuildSysPro 3.3.0 (Plessis et al., 2014), IDEAS 2.1.0 (Jorissen et al., 2018) and AixLib 0.7.3 (Müller et al., 2016)). None of the existing models contain the possibility to model the water flow. In other words, these models contain the conservation equations for air flow with a moist air medium. The humidity in this medium is increased or decreased by a source term in this medium. As a consequence, these models cannot take into account _L. pneumophila_ growth. As the _L. pneumophila_ growth prediction is a key part of this research, it definitely has to be considered.

The screening pointed out that one of the existing models is a useful basis for the isotherm humidifier. Nevertheless, some essential parts are still missing. This model ‘SteamHumidifier_X’ is therefore extended in order to implement these missing features. For the adiabatic humidifier, none of the screened models is suitable for the purpose of this research. Therefore, a new model for adiabatic humidification is developed.

**Case study building**

To examine the healthy operation of the adiabatic humidifier, a case study of an office building is studied. Simulations are performed for a period of two weeks in winter. The energy and water use of a healthy adiabatic humidifier are compared to those of an isotherm one.
Simulation models

The constructed humidifier models are intended to be inserted in ducts and air handling units, and can thus be seen as a sub-model of the HVAC model. This means that in both humidifier models, an in- and out-port for air are provided (fluid ports with medium ‘Air’), that are necessary to connect to fluid ports of other components of the HVAC system (e.g. a heat exchanger). Additionally, an in-port for water is provided (fluid port with medium ‘Water’). An out-port for water is not provided as it is assumed that water is absorbed into air or drained (modelled as sink).

Isotherm (steam) humidification model

The ‘SteamHumidifier_X’ (Wetter et al., 2014; Plessis et al., 2014; Iorissen et al., 2018) is extended by adding a water circuit. The diagram view of the extended simulation model is shown in Figure 5.

This model can be divided into two parts. Part 1 contains the component that models the moist air flowing through the humidifier. Part 2 contains the components to model the water circuit. Part 2 allows to calculate the water and energy use. To start, the needed amount of water that will be added to the air is calculated (this is the same amount as calculated by ‘SteamHumidifier_X’). Additionally, losses by the device are taken into account (expressed as efficiency). This calculated amount of needed water is retrieved from the ‘Water in-port’. Next, this water at ambient temperature is heated to steam by the ‘Heater’. After taking into account the efficiency of this process, the amount of water is split into an evaporated water fraction that goes to the air and an amount of water that is drained (‘Water out-port’). It must be remarked that the evaporated water is not introduced to the air stream of part 1. Instead, the water flow of part 2 is dumped in a sink and the same amount of water is added to the air flow using a real input. For more information, the reader is referred to the Buildings library (Modelica Buildings Library, 2021). The reason for not connecting the fluid flows of part 1 and part 2 is to avoid unnecessary complexity of mixing two boundary volumes (boundary volume ‘Air’ and ‘Water’), and to be able to use the other existing components of the Buildings library.

Adiabatic humidification model (adiabatic washer)

The adiabatic humidifier is a newly developed component. There are five types of atomising humidifiers of which the adiabatic washer is one of them. The diagram view of the component is shown in Figure 6.

Similar to the model of the isotherm steam humidifier, part 1 contains components to model moist air flowing through the humidifier, and part 2 contains the water flow. A schematic representation of part 1 is shown in Figure 7. Air enters the system with a flow rate $G_a$ [kg/s], a dry bulb temperature $T_{db,in}$ [°C] and a specific humidity $x_a$ [kg/kg]. The desired temperature $T_{db,set}$ [°C] and relative humidity $\varphi_{set}$ [/] are defined by the user (model parameters) and used to calculate the specific humidity $x_{set}$ [kg/kg]. In case the specific humidity of the incoming air is too low, water vapour will be added to the air. The added amount of water per second is expressed as $G_w$ [kgvapour/s]. This value is communicated to part 2 and is used to calculate the water flow.

On Figure 7, also preheating and post-heating is indicated, and this is also included in the simulation model of the case study building. Sometimes incoming air must be preheated to a minimum temperature prior to the humidification process to ensure that the air can absorb enough moisture to reach the set point conditions ($T_{db,set}$ and $x_{set}$). In this model the air is heated to a minimum temperature at which the air can contain at least the amount of water as defined by $x_{set}$. Furthermore, in case of putting moisture in the air (and thus increasing the humidity from $x_a$ to $x_{set}$), the temperature of the preheated air will decrease due to natural evaporation. Therefore,
the adiabatic humidification can sometimes involve post-heating to achieve the specified temperature $T_{\text{db,set}}$.

Part 2 intends to model the adiabatic washer and consists of a collection sump, a recirculation pump, spray nozzles and a mist eliminator. The collection sump is an open reservoir, containing water. The ‘OpenTank’ model from the Modelica library is used to model this open reservoir. This ‘OpenTank’ is adapted to include the biological $L. pneumophila$ growth model (Van Kenhove et al., 2019) which is needed in order to estimate the healthiness of this humidifier. To do so, a source term is added in the conservation equation for $\frac{\text{d}m}{\text{d}t} = \text{mC}_\text{flow} + \text{C}_\text{internal}$. Hence, in case the predicted concentration will become too high, the sump will be emptied by opening the draining valve (see further: ‘Control’). The recirculation pump draws water from the collection sump and forces it through the spray nozzles ($G_{\text{enn}}$). Part of this water is evaporated into the air and part of this water returns to the collection sump. Similar to the isotherm humidifier model, the amount of evaporated water ($G_{\text{evi}}$) is fictively dumped in a boundary. As can be noticed on the schematic representation (Figure 7), the division of the mass flow rate $G_m$ into the evaporated ($G_{\text{evi}}$) and the recirculated/drained water in atomising adiabatic humidifiers is determined by the absorption ratio $\varepsilon$. For an adiabatic washer, the ratio is between 1:30 and 1:100 depending on the humidifier’s efficiency (Lazzarin et al., 2004).

**Control**

In addition to the ‘classic’ control of humidity and temperature, the humidifier component also takes into account the predicted $L. pneumophila$ concentration in the collection sump and the nozzles.

In case the specific humidity set point is lower than the incoming specific humidity ($x_{\text{set}} > x_n$), no humidification is needed and the water circuit is not operative (the mass flow rate of the pump is zero). In case the set point for specific humidity is higher than the incoming absolute humidity ($x_{\text{set}} < x_n$), humidification is turned on as long as the $L. pneumophila$ concentration in the system is not too high (below 100 cfu/l). If the concentration is too high the humidification process will not continue, even when humidification is needed. Furthermore, the sump is emptied. The water in the sump is assumed to be perfectly mixed, thus the $L. pneumophila$ concentration is the same in the whole sump (no stratification or subzones in the sump’s volume are assumed). The sump is emptied to achieve a fluid level of zero, in order to avoid that fresh water can enter the sump while emptying and will get contaminated.

**Case study office building**

The models of the steam and adiabatic humidifier are used in a case study of an office building. In the office 90 people are present. The temperature set point is 20 °C and the relative humidity set point is 40 %. A relative humidity up to 60 % is allowed. People are present during weekdays between 8 AM and 6 PM. The incoming air is 100 % outside air. The ventilation rate is a fixed value, according to the prescriptions for hygienic ventilation and is based on the number of employees present. Heat is recovered from the return air by a heat exchanger to minimise the preheating energy needed. The efficiency of the heat exchanger is 60 %. When the office is closed, the return air is recirculated and the heaters and humidifier are turned off. In the adiabatic humidifier case, the absorption ratio $\varepsilon$ and saturation efficiency $\eta$ are set at 3 % and 90 %.

Two winter weeks are studied, and for both types of humidifiers the energy and water use is compared. The heating energy in isotherm humidifiers may be attributed to the preheating of the air, which is calculated directly by a heating component, the heating of the water (evaporated and condensed) to 100 °C, which is also calculated directly by a heating component, and the heating of 100 °C water to steam (evaporated and condensed). The calculated heating energy for the adiabatic humidifier can be allocated to pre- and post-heating of the air. The energy use can be directly derived from the heating components in the simulation model. The authors are aware that other processes are involved, but in the context of this exploratory study, it was decided not to go into too much detail. In that respect an additional energy use for the adiabatic humidifier to take into account the energy use of recirculating the water is estimated. The direct energy of an adiabatic washer is considered to be 6 W/(kg/h of evaporated water) (Lazzarin et al., 2004).

For the isotherm humidifier, the water use is calculated by adding the amount of evaporated and condensed water in the ducts. For the adiabatic humidifier, water use is calculated by adding the evaporated water and the water lost due to emptying the sump when the $L. pneumophila$ concentration is too high.

**Results**

Figure 8 shows the set point of the specific humidity (i.e. 5.76 g/kg for $T=20$ °C and RH=40 %) and the specific humidity of the air after adiabatic humidification. The demand flow rates of the water sprayed through the nozzles is shown in Figure 9. It can be noticed that from day 1 until day 4, the specific humidity is above the set point and therefore no humidification is needed. On the other days (day 5, day 9-12 and day 15), humidification is operative and the set point humidity is achieved quite well.

![Specific humidity [kg/kg]](image)

**Figure 8**: Set point ($x_{\text{set}}$) of the specific humidity [kg/kg] (i.e., 5.76 g/kg for $T=20$ °C and RH=40 %) and specific humidity ($AHU_{\text{out}}$) [kg/kg] of the outgoing air using an adiabatic humidifier.
Health

In case a steam humidifier is used, there is no *L. pneumophila* contamination risk. Therefore, only the results of the adiabatic washer are discussed. Because there is no demand during the first days, the water in the collection sump is stagnant. This is shown in Figure 10. Consequently, the *L. pneumophila* concentration increases and the sump needs to be emptied after 3.5 days in order to stay below the specified boundary of 100 cfu/l. During the 5th day of the workweek, the demand is low and in the weekend the humidifier is turned off. Therefore, the *L. pneumophila* concentration reaches the maximum limit at day 7 and the sump is emptied again. During the second week, more humidification is needed. Due to the higher demand, the water in the tank is changed more frequently and thus replenished with new water with a low concentration. This can be observed on Figure 10. Each time the minimum water level is reached in the collection sump, the collection sump is filled to its maximum level. This is linked with a decrease in concentration. As a result, the *L. pneumophila* concentration never reaches the critical value during the second workweek. However, after a whole weekend with stagnant water in the sump, the concentration increases up to 70 cfu/l and will probably increase again in the coming days.

![Figure 9: Demand and supply of sprayed water, water flow rates of supply pump $G_w$ [kg/s].](image)

![Figure 10: Water level in the collection sump [m] and predicted *L. pneumophila* growth [cfu/l] when using an adiabatic humidifier.](image)

![Figure 11: Level of water in the collection sump [m] and *L. pneumophila* concentration [cfu/l] using an adiabatic humidifier with control optimization 1.](image)

In practice, a humidifier will not be controlled by monitoring the *L. pneumophila* concentration permanently. Therefore, in this situation, it is suggested to empty the collection sump twice a week: once after three working days and once in the weekend. Figure 11 shows the simulated *L. pneumophila* concentration using this control (control optimization 1). As in the previous simulated case, the collection sump is full at the start. After working day 3, the collection sump is emptied and remains empty until the next morning. The same applies for the weekend.

![Figure 12: Level of water in the collection sump [m] and *L. pneumophila* concentration [cfu/l] using an adiabatic humidifier with control optimization 2.](image)

Water use

Figure 13 shows the water used in each system. The amount of evaporated water is identical for both humidifiers. However, more water is wasted due to emptying the collection sump of the adiabatic humidifier than due to water condensation in the steam pipes of the...
The adiabatic humidifier uses more water than the isotherm one although the difference is limited. In this two week period, it is only 30 l or 7 %.

Figure 13: Comparison of water use [m²] of adiabatic versus isotherm humidifier for a two week period.

Energy use
The results also show that for these two weeks the total energy use of the adiabatic humidifier is lower (3.8 %) than the energy use of the isotherm humidifier (Figure 14). The difference is small, due to the limited humidification load and the limited amount of water that needs to be heated. However, it is expected that in case the adiabatic humidifier is used in summer as an adiabatic cooler, this humidifier may be even more advantageous.

Figure 14: Comparison of total energy use (heating and pump energy) [kWh] of adiabatic versus isotherm humidifier for a two week period.

Conclusions & discussion
Adiabatic and isotherm (steam) humidifier models are developed and tested in a simulated case study of a fictive office building. Energy use, water use and \textit{L. pneumophila} concentrations are compared for both humidifiers for a period of two weeks during winter.

In some buildings, like the case study of the office building, there may be no humidification demand for several days, even in winter. This means that the water in the collection sump is stagnant and \textit{L. pneumophila} concentration increases. Therefore, measures should be taken in order to ensure a healthy operation. It is recommended to empty the collection sump every weekend and during the holidays. In the simulation study in mid-season, no humidification is needed (results are not shown). Dependent on the boundary conditions for the collection sump and the demand, it can be necessary to additionally drain the collection sump. In this case, the sump has to be emptied after three days of no use.

Due to the (frequent) emptying of the sump because of health issues, the water use of the adiabatic humidifier is higher than that of the isotherm one, although in this case study, the difference is minimal (7 %). Comparing this to the energy and maintenance cost, it is expected that this additional water use will be of less importance.

The office case study shows that it is possible to safely operate an adiabatic humidifier provided that the correct measures are taken, i.e. sufficiently emptying the tank or flushing the system with hot water. These measures will strongly depend on case by case and the corresponding water demand and stagnation of water in the water tank.

At this moment, adiabatic humidification is prohibited in public buildings in Belgium (Flanders) because of health concerns. This research, where the worst case is examined (adiabatic washer), indicates that this legislation may be too strict and opens doors to further in-depth research. It should be emphasized that these findings still need to be confirmed by verifying the simulation model with laboratory and in situ tests.

Future research
The simulations in this research only cover two week periods and only take into account the humidification of the air. Therefore, the potential total energy savings of an adiabatic humidifier installed in an air handling unit, compared to an isotherm humidifier, should still be assessed over a whole year. In that sense, it should be noted that in summer, when there is no humidification demand, more moisture can be added in order to cool the building. The relative humidity will then be near the maximum of the allowed range (40-60 %). Therefore, choosing an adiabatic humidifier over an isotherm one in an office is thus potentially more advantageous since adiabatic cooling can be used in summer. The cooling capacity of an adiabatic humidifier is not tested since this is not the aim of this research, but its opportunity should be kept in mind.

The newly developed simulation model also offers some opportunities. Besides the healthiness of adiabatic humidification, the healthiness of adiabatic cooling in summer, misting machines in grocery stores and cooling mist sprayers can also be examined. Moreover, the model can be transformed into a cooling tower model by replacing the post-heater with a heat exchanger between the cooled air and the water circuit which cools the building, and by modifying the control. The air does not have to be preheated and has to be humidified to near-saturation in order to cool the air to the maximum.
In this research, results are obtained with a newly developed simulation model which should be calibrated based on a test setup. Due to the current COVID-19 pandemic and associated measures of the government and Ghent University, it was not possible to verify the simulation model by laboratory tests. However, the simulation model is based on and compared with already validated components and models. Therefore, the results can be assumed to be valuable although not verified. It should thus be emphasized that these findings still need to be confirmed by validation of the biological part of the simulation model in a laboratory experiment, once the COVID-19 measures allow.

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