Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 148 (2018) 1206–1213

Energy Procedia

www.elsevier.com/locate/procedia

73rd Conference of the Italian Thermal Machines Engineering Association (ATI 2018), 12–14 September 2018, Pisa, Italy

Dynamic simulation of an air handling unit and validation through monitoring data

Eva Schito[a]*

[a]*Department of Energy, Systems, Territory and Constructions Engineering (DESTEC), University of Pisa, Italy*

Abstract

This paper presents the model for the simulation of the behavior of an air handling unit (AHU), consisting of two heating coils, a cooling and dehumidifying coil, and a vaporizer. The proposed model reproduces the behavior of its single components, using the suitable ε-NTU relations for the heat exchangers on the basis of actual geometries (e.g., type of heat exchanger, number of tube rows, number of passes), and mass and heat balance equations for the vaporizer and dehumidifying coils. The routine is developed as a MATLAB script and it is linked to a TRNSYS model, which simulates the building. The model is applied to a real AHU, which provides fresh air for an exhibition room of a museum, varying the supply relative humidity based on the indoor set point. During a one-month monitoring campaign in the building, several data about the external and internal climate were acquired, together with specific parameters of the AHU system (e.g., temperature and water flow rate at the heat exchangers, supply temperature and relative humidity of the air flow). These monitored data were compared with the outputs of the MATLAB script, validating the AHU model in the error band of the monitoring system.

Keywords: Dynamic simulation; air handling unit; validation; MATLAB; monitoring campaign.

* Corresponding author. Tel.: +39 050 2217111; fax: +39 050 2217160.
E-mail address: eva.schito@for.unipi.it

10.1016/j.egypro.2018.08.010

1. Introduction

Reproducing the dynamic behavior of a Heating, Ventilation and Air Conditioning (HVAC) system and its interaction with the building during operation is important to verify the maintenance of thermal comfort inside the indoor environment and evaluate the HVAC efficiency. Furthermore, as the HVAC and building system have strong interactions, change of internal conditions inside the building (e.g., number of people) can cause a variation in the HVAC system working conditions (e.g., change of flow rate of air handling unit, AHU). On the other hand, the change of some working parameters of the HVAC systems can affect indoor thermal comfort. In general, the knowledge of the real dynamic performance of HVAC system can help professionals in the implementation of the most efficient control strategies to obtain a higher energy efficiency and a better internal thermal comfort for users.

Nomenclature

c_{air}	air specific heat capacity
c_w	water specific heat capacity
g^*	moisture generation due to individuals
$\dot{m}_{AHU}$	air handling unit flow rate
$\dot{m}_w$	water flow rate at the heat pump
$x_{45\%}$	indoor specific humidity related to the relative humidity setpoint (e.g., 45%)
x_{in}	specific humidity of the supply air
x_{int}	effective specific humidity inside the thermal environment
UA	product of the overall heat transfer coefficient and heat transfer area of the heat exchanger
ε	effectiveness of the heat exchanger
ρ	air density

Afram and Janabi-Sharifi [1] provide a comprehensive review of the modeling methods for the HVAC systems, divided them into three categories: (i) data-driven methods, also known as black-box methods, in which monitored inputs and outputs are correlated through mathematic techniques, (ii) physics-based methods, also known as white-box methods, based on the governing laws of physics, and (iii) gray-box model, in which the basic structure is physics-based, while some parameters are chosen by the data acquired through tests. Li [2,3] presents the study of the behavior of an AHU model using HVACSIM+ software, using a gray-box model for its various components. A good agreement with monitoring data is found, in particular when all the building-AHU system are all linked, showing the importance of a holistic and comprehensive model that takes into account the interactions and synergic effects of all the subsystems. Afram [4] models the AHU as a black-box unit, using two different methods: the frequency domain transfer function and the time domain state-space model. For the two black-box models, data of air and water temperature and flow rates from an existing residential system have been used; other different monitoring data have been used for the validation, showing good agreement in both cases. Salsbury [5] proposes a simple AHU model based on NTU-effectiveness [6] heat exchanger equations; however, only the heating and cooling coils are modeled. Moradi [7] presents a dynamic model of the AHU, based on heat and mass transfer laws, with the aim of evaluating supply air and indoor air temperature for a better control of the AHU performance. Usually, the AHU modeling is performed for an estimation of energy requirements and choice of best solutions for energy efficiency [8–10], implementation of strategies to reduce faults [11], and evaluation of indoor thermal environment parameters [12].

In this framework, the objective of this study is to present the modeling of an AHU, constituted by its components: preheat coil, cooling and dehumidifying coil, vaporizer, and reheat coil. According to the definition given by [1], it can be defined as a gray-box model. Section 2 provides a description of the analyzed AHU; section 3 provides the AHU model; section 4 provides the comparison between the AHU simulation results and monitoring data.

2. Description of the analyzed AHU

The AHU in analysis provides fresh air for two rooms of a museum in Pisa, Italy, which hosts temporary exhibitions. The AHU is turned on from 8 a.m. to 9 p.m., every day. As previously mentioned, the AHU includes a preheat coil, a cooling coil, a vaporizer, a reheat coil, and a blower to move the air in the supply ducts. The preheat coil and the reheat coil use hot water provided by a heat pump; the cooling coil uses cold water from the same heat pump that, in current configuration, is used as chiller only in summer. The vaporizer provides steam to the air stream: steam is produced heating water with an electric resistance. The characteristics of the AHU are reported in Table 1: they refer to the various components in nominal conditions. A schematic representation of AHU and the two rooms (Reference Room – RR – and Control Room – CR) is shown in Figure 1. The AHU has to maintain a 45% relative humidity setpoint inside the exhibition rooms, as this value, together with a temperature setpoint around 20 °C, is suitable for the preservation of paper artworks [13–15], which are the usually exposed artworks. The supply temperature of the air is instead fixed: in winter, it is 19 °C. The RH sensor in the CR, controls the water flow rate at the cooling coil or the electric resistance at the vaporizer, thus regulating the inlet humidity in the supply air flow. The change of RH inside the rooms is due to the external climate conditions and the visitors' presence, which is influenced by the day of the week and by the hour of the day.

Table 1. Characteristics of the AHU in nominal conditions

Nominal parameter	Preheat coil	Cooling coil	Reheat coil
Air mass flow (m^3/h)	3200	3200	3200
Inlet air temperature (°C)	0.0	32.0	15.8
Outlet air temperature (°C)	31.1	13.5	27.7
Inlet air relative humidity (%)	-	55.0	-
Outlet air relative humidity (%)	-	94.0	-
Heating power (kW)	34.0	40.2	13.0
Water mass flow (kg/h)	5854	6919	2239
Inlet water temperature (°C)	45.0	7.0	45.0
Outlet water temperature (°C)	40.0	12.0	40.0
Number of passes	7	8	3
Number of circuits	6	6	3

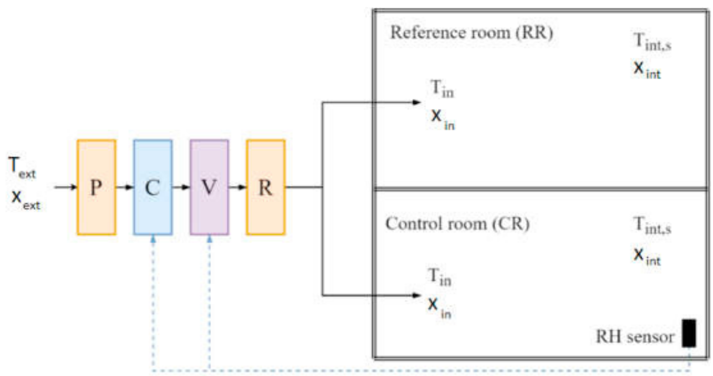

Fig. 1. Schematic representation of the AHU: "P", "C", "V", "R" mean preheat coil, cooling coil, vaporizer and reheat coil. For the explanation of the other terms, see the main text.

3. AHU model description

The AHU is modeled in MATLAB, simulating the behavior of its single components, with a time step of 15 minutes. This model is linked to a more comprehensive TRNSYS model, which simulates the envelope characteristics and the profile of the internal gains due to visitors. More details about the characteristics of the envelope can be found in [16]. The visitors' model predicts the number of individuals in the rooms based on the sold tickets at the box offices, considering the peaks during some hours of the day and during weekends. More details on this model can be found in [17]. Both the envelope model and the visitors' model were validated in previous works.

The first parameter that the AHU model evaluates is the specific humidity of the supply air, to be chosen to maintain the setpoint relative humidity in the rooms. This is done through the mass balance reported in Equation 1, relative to timestep "t":

$$\dot{m}_{AHU} x_{in} = -g^* + \dot{m}_{AHU} x_{45\%} + \rho V \frac{x_{45\%} - x_{\text{int}}(t-1)}{\Delta t} + K_1 A_1 \left(x_{45\%} - \bar{x}_{1.2h} \right) + K_2 A_2 \left(x_{45\%} - \bar{x}_{72h} \right) \tag{1}$$

where $\bar{x}_{1.2h}$ is the average specific humidity over the last 1.2 hours; $\bar{x}_{72h}$ is the average specific humidity over the last 72 hours; and the terms K_1A_1 and K_2A_2 refer to the sorption rate of materials present in the rooms, according to Plathner model [18]. In this case, the terms referring to sorption were found to be negligible. Naming x_{ext} the external specific humidity, if $x_{in} > x_{ext}$, the heating coils and the vaporizer of the AHU are considered turned on; if $x_{in} < x_{ext}$, the cooling coils are turned on in the model.

3.1 Preheat coil

A schematic representation of the AHU preheat coil is shown in Figure 2.a. This heat exchanger is modeled by a ε-NTU model [6], using the UA-parameter in nominal conditions calculated with the heat exchanger characteristics reported in Table 1. As the preheat coil in analysis is a cross-flow heat exchanger, efficiency is evaluated through a proper relation depending from the number of rows [19] and typical effectiveness parameters of heat capacity rate reported in Equation 2. If the minimum heat capacity rate C_{min} refers to air stream, Equation 3 applies, whereas Equation 4 applies if C_{min} refers to water stream.

$$C_{\min} = \min(\dot{m}_{AHU} c_{air}; \dot{m}_w c_w); C_{\max} = \max(\dot{m}_{AHU} c_{air}; \dot{m}_w c_w);\ C^* = C_{\min} / C_{\max};\ NTU = UA / C_{\min} \tag{2}$$

$$\varepsilon = (1 - e^{-4KC^*}(1 + C^* K^2 \left(6 - 4K + K^2\right) + 4(C^*)^2 K^4 \left(2 - K\right) + 8(C^*)^3 K^6/3)) / C^* \tag{3}$$

$$\varepsilon = 1 - e^{-4KC^*}(1 + K^2 \left(6 - 4K + K^2\right) / C^* + 4K^4 \left(2 - K\right) / (C^*)^2 + 8K^6/(3(C^*)^3)) \tag{4}$$

In Equation 3, $K = 1 - \exp(-NTU/4)$; in Equation 4, instead, $K = 1 - \exp(-NTU \cdot C^*/4)$.

The known parameters for this model are: (i) the air mass flow rate; (ii) the inlet air temperature, that is the external temperature; (iii) the exit air temperature, fixed by the users equal to 16 °C; (iv) the maximum water flow rate from the heat pump; and (v) the inlet water supply temperature from the heat pump, equal to 42 °C. Outputs of the model are: (i) the effective water flow rate in the preheat coil, after the 3-way valve; (ii) the temperature of the water exiting the preheat coil; (iii) the mixed return temperature of the water, considering the water flow rate deviated by the 3-way valve; and (iv) the heat exchanger effectiveness.

3.2 Cooling coil

For the cooling coil, a simplified model using the bypass factor (BF) is used. Using the graphs reported in [20], a BF of 0.05 has been chosen for this heat exchanger, which has 8 passes and 6 circuits. The model evaluates the desired specific humidity x_{nBP} of the non-bypassed airflow, to have the required x_{in} (from Eq. 1) when bypassed and non-bypassed flows mix. The mass balance equation reads:

$$(1-BF)\,\dot{m}_{AHU}x_{nBP} + BF\,\dot{m}_{AHU}x_{ext} = \dot{m}_{AHU}x_{in} \tag{5}$$

Outputs of this model are: (i) dew point temperature of the non-bypassed airflow; (ii) sensible and latent heat exchanged in the cooling coil; (iii) temperature of airflow exiting cooling coils (evaluated by the mixing of bypassed and non-bypassed airflows); and (iv) water return temperature at the chiller, considering a supply temperature of 7 °C. A schematic representation of the cooling coil is shown in Figure 2.b.

3.3 Vaporizer

The model of the vaporizer simulates how the electric humidifier controls the vapor flow rate in the supply airflow. Knowing the required x_{in} (from Eq. 1) and the external specific humidity x_{ext}, the model evaluates: (i) the used electrical energy necessary to heat the required mass of water from the temperature of the aqueduct (i.e. 15 °C) to a steam temperature of 100 °C; and (ii) the temperature T_1' of the airflow exiting the vaporizer, through an enthalpy balance of the mixing flows. A schematic representation of the vaporizer is shown in Figure 2.c.

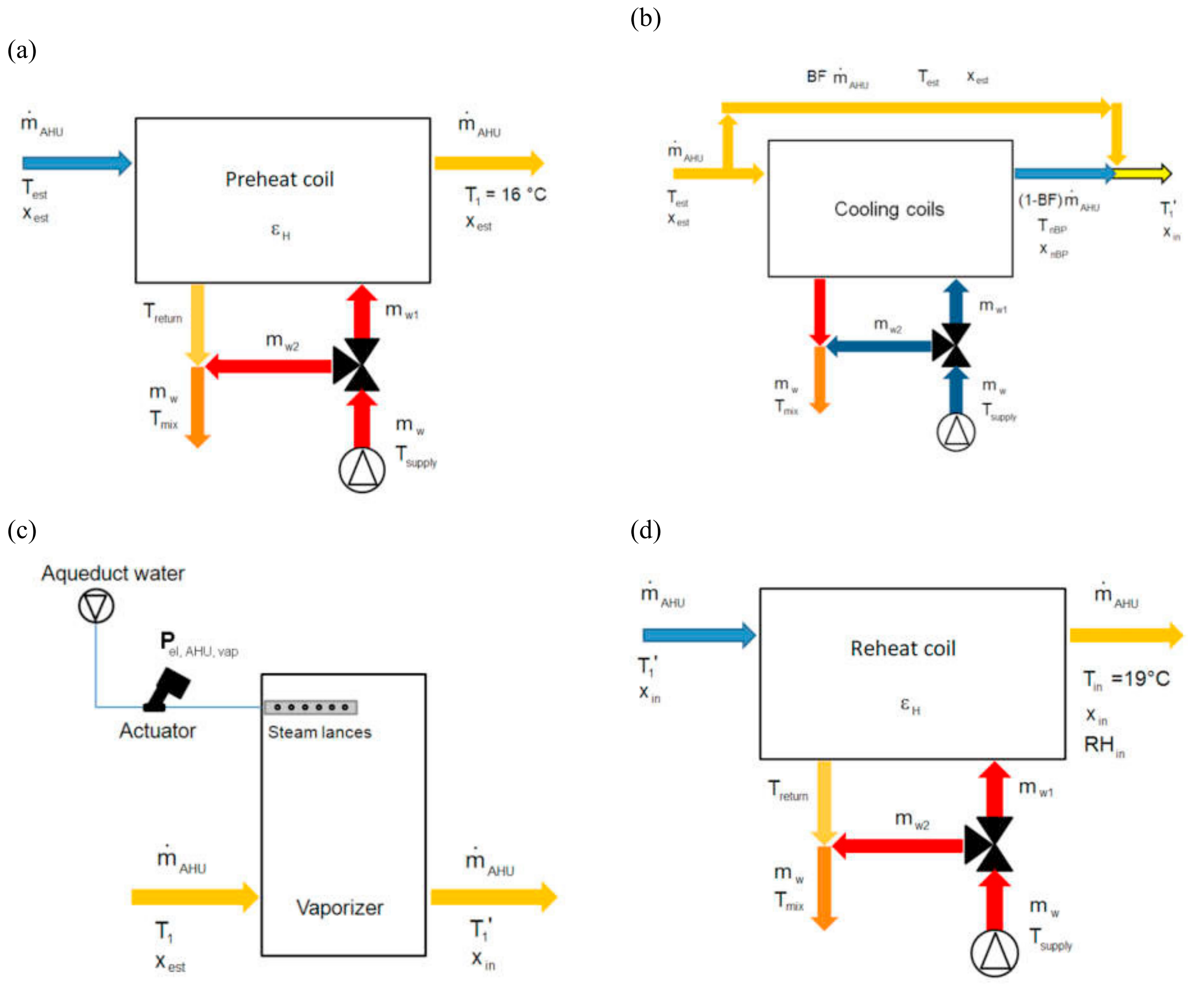

Fig. 2. Schematic representation of each component of the AHU: (a) preheat coil; (b) cooling coil; (c) vaporizer; (d) reheat coil.

3.4 Reheat coil

The AHU reheat coil is modeled in analogy with the preheat coil, using the ε-NTU model, with different UA-value (evaluated considering the nominal conditions for the heat exchanger presented in Table 1). The known parameters for this model are: (i) the inlet air temperature, that is either the temperature at the exit of the vaporizer or at the exit of the cooling coils, (ii) the exit air temperature, fixed by the users equal to 19 °C; (iii) the maximum water flow rate from the heat pump; and (iv) the inlet water supply temperature from the heat pump, equal to 42 °C. Outputs of the model are: (i) the effective water flow rate in the reheat coil, after the 3-way valve; (ii) the water return temperature; (iii) the mixed return temperature of the water, considering the water flow rate deviated by the 3-way valve; and (iv) the heat exchanger effectiveness. A schematic representation of the reheat coil is shown in Figure 2.d.

4. Validation of the model

For the validation of the AHU model, the monitoring campaign data of December 2015 were used. During this monitoring campaign, several parameters were acquired every 15 minutes: external temperature and relative humidity, temperature and relative humidity inside the exhibition rooms, specific humidity of the supply air, and water return temperature to the heat pump. Data were acquired from different sensors, the main characteristics of which are reported in Table 2. These data are compared with the output of the AHU simulation for December. In Figure 3.a, the daily average supply specific humidity by MATLAB model are compared with the monitored value. The results show that, during December, there is almost no need of humidification; MATLAB results agrees with monitored data within the error band of the sensors, calculated in accordance to [21]. As the cooling coils cannot be used in winter in current state, due to the layout of the generation system, the difference in the monitored data between external and supply specific humidity can be explained as a bias error. Figure 3.b shows a detail of the results, where external monitored specific humidity, monitored and simulated supply specific humidity are compared with a 15-minute timestep. The detail shows several hours in which humidification was actually needed in December, as both simulated and measured specific humidity are higher than external monitored specific humidity. Finally, the other parameter used for the AHU model validation is the water return temperature to the heat pump. Figure 4 shows the comparison between the profile of return water temperature as evaluated by the MATLAB model and the monitored one. The comparison between the two profiles show good agreement during the whole month.

The model can be considered validated in the error band of the monitoring system.

5. Conclusions and future prospects

In this manuscript, a new model for an AHU is presented. The analyzed AHU includes a preheat coil, a cooling coil, a vaporizer, and a reheat coil. The model is provided as a MATLAB script, modeling each single component. The model was used on a real case study and the results of the simulation were compared with the profiles of some parameters acquired during a monitoring campaign.

This model will be further applied in other simulations, to verify the possibilities of improving energy efficiency of the HVAC system while maintaining optimal thermal environment for artworks. An example would be the comparison between the use of vaporizer and commonly-used humidifier, in terms of energy efficiency and thermal comfort, or the use of multi-purpose heat pump, for the concurrent production of hot and cold water, which could solve the problem of lack of dehumidification in winter. Another interesting further research would be the analysis of the energy reduction through the use of demand control ventilation (DCV), varying the supply air flow rate at the blower on the basis of the visitors inside the rooms (e.g., through a CO_2 sensor). This solution would lead to a significant energy needs reduction both at the blower (reduction of the electrical energy to move the blower) and at the AHU coils (reduction of the needed heat to warm/cool the air flow rate).

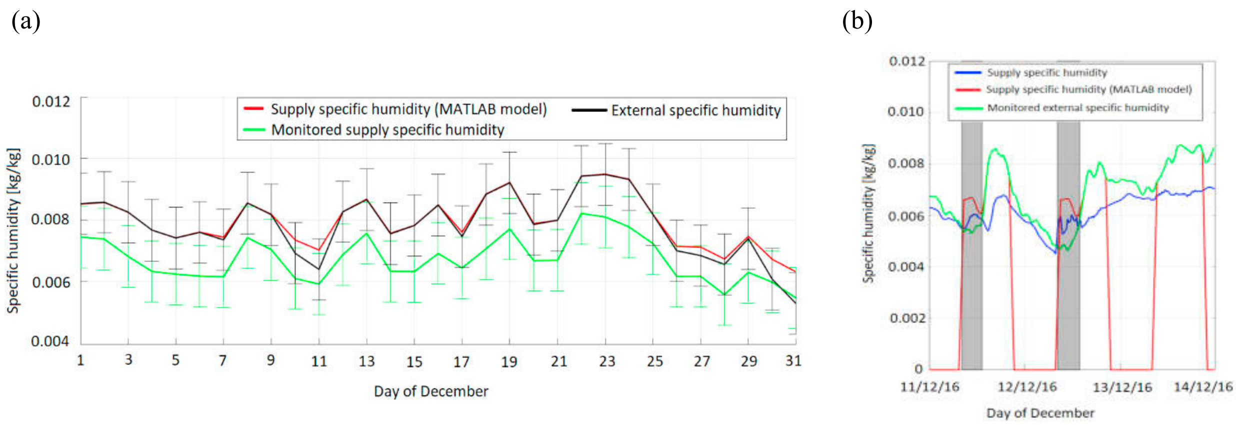

Fig. 3. Comparison between monitored data and MATLAB model: (a) comparison between daily average data; (b) detail on a 15-minute timestep for some days of the simulation.

Table 2. Specifics of the sensors used for the monitoring campaign.

Model	Position	Monitored parameter	Measuring range	Accuracy
SIEMENS QAA24	RR and CR	T	-50…+80 °C	± 0.6 K
SEMITEC NTC	RR and CR	T	-50…+110 °C	± 0.2 K
4-NOKS THL-M	RR and CR	T	-40…+120 °C	± 0.2 K
		RH	0…100 %	± 3 %
SIEMENS QFM21160	AHU dampers	T	0…50 °C	± 0.7 K
		RH	0…100 %	± 3 %
DICKSON TM325	AHU entrance	T	-20 … +70 °C	± 0.5 K
		RH	0… 95%	± 3 %
SIEMENS QAD2030	Heat pump return pipe	T	-30…125 °C	± 0.3 K

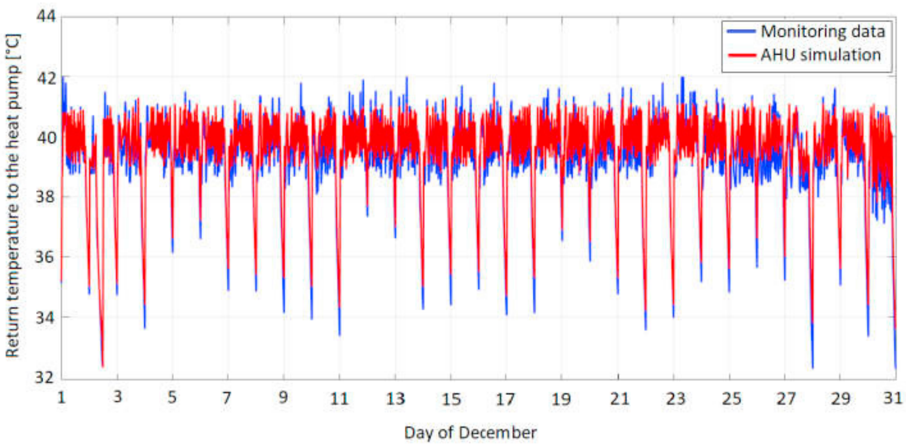

Fig. 4. Return temperature to the heat pump: comparison between the MATLAB simulation and monitored data.

Acknowledgements

The author would like to thank Daniele Testi and Paolo Conti, for their suggestions and comments that improved the manuscript, and Davide Della Vista, for his help during the monitoring campaign.

References

[1] A. Afram, F. Janabi-Sharifi, Review of modeling methods for HVAC systems, Appl. Therm. Eng. 67 (2014) 507–519. doi:10.1016/j.applthermaleng.2014.03.055.

[2] S. Li, J. Wen, Development and Validation of a Dynamic Air Handling Unit Model , Part I, ASHRAE Trans. 116 (2010).

[3] S. Li, J. Wen, X. Zhou, C.J. Klaassen, Development and Validation of a Dynamic Air Handling Unit Model , Part 2, ASHRAE Trans. 116 (2010).

[4] A. Afram, F. Janabi-Sharifi, Black-box modeling of residential HVAC system and comparison of gray-box and black-box modeling methods, Energy Build. 94 (2015) 121–149. doi:10.1016/j.enbuild.2015.02.045.

[5] T.I. Salsbury, A Temperature Controller for VAV Air-Handling Units Based on Simplified Physical Models A Temperature Controller for VAV Air-Handling Units Based on Simplified Physical Models, HVAC R Res. 4 (1998) 265–279.

[6] F.P. Incropera, D.P. DeWitt, T.L. Bergman, A.S. Lavine, Fundamentals of Heat and Mass Transfer, John Wiley & Sons, 2007. doi:10.1016/j.applthermaleng.2011.03.022.

[7] H. Moradi, M. Saffar-avval, F. Bakhtiari-nejad, Nonlinear multivariable control and performance analysis of an air-handling unit, Energy Build. 43 (2011) 805–813. doi:10.1016/j.enbuild.2010.11.022.

[8] A. Afram, Janabi-S, F. Harifi, Gray-box modeling and validation of residential HVAC system for control system design, Appl. Energy. 137 (2015) 134–150. doi:10.1016/j.apenergy.2014.10.026.

[9] A. Kusiak, M. Li, Cooling output optimization of an air handling unit, Appl. Energy. 87 (2010) 901–909. doi:10.1016/j.apenergy.2009.06.010.

[10] A. Kusiak, Y. Zeng, G. Xu, Minimizing energy consumption of an air handling unit with a computational intelligence approach, Energy Build. 60 (2013) 355–363. doi:10.1016/j.enbuild.2013.02.006.

[11] J. Liang, R. Du, Model-based Fault Detection and Diagnosis of HVAC systems using Support Vector Machine method, Int. J. Refrig. 30 (2007) 1104–1114. doi:10.1016/j.ijrefrig.2006.12.012.

[12] B. Tashtoush, M. Molhim, Dynamic model of an HVAC system for control analysis, Energy. 30 (2005) 1729–1745. doi:10.1016/j.energy.2004.10.004.

[13] Ente Italiano di Normazione, UNI 10829. Condizioni ambientali di conservazione, UNI. (1999).

[14] E. Schito, P. Conti, D. Testi, Multi-objective optimization of microclimate in museums for concurrent reduction of energy needs , visitors ' discomfort and artwork preservation risks, Appl. Energy. 224 (2018) 147–159. doi:10.1016/j.apenergy.2018.04.076.

[15] E. Schito, D. Testi, Integrated maps of risk assessment and minimization of multiple risks for artworks in museum environments based on microclimate control, Build. Environ. 123 (2017) 585–600. doi:10.1016/j.buildenv.2017.07.039.

[16] E. Schito, D. Testi, W. Grassi, A Proposal for New Microclimate Indexes for the Evaluation of Indoor Air Quality in Museums, Buildings. 6 (2016) 41–56. doi:10.3390/buildings6040041.

[17] E. Schito, D. Testi, A visitors' presence model for a museum environment: Description and validation, Build. Simul. (2017) 1–11. doi:10.1007/s12273-017-0372-1.

[18] P. Plathner, J. Littler, A.W. Cripps, Modelling water vapour conditions in dwellings, in: 3rd Int. Symp. Humidity Moisture, London, 1998.

[19] H.A. Navarro, L.C. Cabezas-Gomez, Effectiveness-NTU computation with a mathematical model for cross-flow heat exchangers, Brazilian J. Chem. Eng. 24 (2007). doi:http://dx.doi.org/10.1590/S0104-66322007000400005.

[20] N. Rossi, Manuale del termotecnico, Hoepli, 2014.

[21] R.J. Moffat, Describing the uncertainties in experimental results, Exp. Therm. Fluid Sci. 1 (1988) 3–17. doi:10.1016/0894-1777(88)90043-X.