Modeling and Analysis of Cooling Coil for Control System Design Using Gray Box Approach

Masoud Nazari[1] & Ali Ghaffari[2]

[1] South Tehran Branch, Islamic Azad University, Iran

[2] Mechanical Engineering Faculty, K.N.Toosi University of Technology, Iran

Correspondence: Masoud Nazari, South Tehran Branch, Islamic Azad University, Tehran, Iran. E-mail: St_ma_nazari@azad.ac.ir/ghaffari@kntu.ac.ir

Abstract

The purpose of the study is to design a method analyzing dynamic behavior of cooling coil in order to be applicable in online simulations. Coils account for the highest energy consumers among other components in an Air Handling Unit (AHU). Essential data as input-output of neural network is provided using energy and mass conservation equations. An implicit numerical method is used to solve dynamic equations of coil. The results of mathematical methods are applied in the output of neural network to design an online model. The proposed model is based on an active coil used in Heating, Ventilation and Air Conditioning (HVAC) systems of clean rooms in Iran Pasteur Institute. Since in active air handlers, input and outputs are not measured, here we model air conditioning systems generally. The results in comparison with actual system data indicate an acceptable performance of the proposed method, so that combination of numerical results with a nonlinear autoregressive exogenous model (NARX) makes it possible to control system effectively by saving a significant amount of time.

1. Introduction

Buildings make up about 39% of the energy consumption in the United States in which heating, ventilation and air conditioning (HVAC) accounts for more than 40% of the proportion (Pérez-Lombard, Ortiz, & Pout, 2008).Thus, there have been increasing demands to design these equipment and systems and to control energy efficiency. Cooling, heating and dehumidifying are coils' certain functions. Controlling these functions considerably affects thermal comfort and energy consumption in the buildings. Implementing an appropriate control approach requires a comprehensive and accurate model.

Researchers have been using white and black box approaches to simulate coil performance. White box approach developed primary model on mass and energy balanced equations (Xin, Jin Wen, Theodore & Smith, 2005). Black box approach is defined by establishing a nonlinear relationship between data measured from input and output of a real device (Bourdouxhe, Lebrun & Grodent, 1998) In this regard, applying certain methods such as neural network, fuzzy logic, self-tuning and auto regressive models, researchers have defined accurate models.

White box or mathematical cooling coil modeling have been developed to illustrate the steady state or dynamic conditions of systems. Wang and Krauss developed dynamic coil modeling by differential mass - energy conservation coil equations but the proposed model was not validated (Wang Zijie & Krauss, 1993). Yao solved mass - energy conservation of differential equations using classical control. He studied the relevant parameter on the heat exchange of the cooling coil and analyzed the effect of perturbations of relevant parameter on thermal quality of cooling coil under different initial conditions. Solving complex and nonlinear equations in the study derived some conclusions which obviously can't compromise a linear model necessity (Yao, Lian & Hou, 2004). In order to obtain desirable temperature, Sarkar used by pass factors and water temperature changes instead of physical parameters to model coil performance. Data survey demonstrates that the model does not have necessary accuracy though it is a simple representation (Mridul, 2015). Yu developed cooling coil in dry and wet conditions. Solving coil dynamic equations, he has applied implicit numerical method. Although the approach has high accuracy, it is too time-consuming to be applicable.

Black box modeling approach unlike white box modeling does not require comprehend of system's behavior, and acts merely by measuring the input and output data and fitting a nonlinear relation between them (Afram & Janabi-Sharifi, 2015). This method has high accuracy but because of its weakness in its publicity, in many cases the white box method is preferred.

The purpose of this study is (1) developing a model to simulate cooling coil in dry and wet conditions, adaptable for on-line controlling to optimize energy consumption and also be applicable in modeling of the same coils. Therefore first we applied white box method to model the cooling coil employed in the clean room of   IRAN Pasteur Institute, then used data captured from white box modeling to establish   nonlinear auto regressive exogenous (NARX) model to achieve an on line model. (2) Evaluating the performance of the model with experimental data measured in a week by building management system (BMS).

2. Model Description

2.1 Coil Description

Here coil basic characteristics are presented to realize how it works. Tubes are drawn along with the coil with a snake-like movement and return the path by reaching to the end of the coil. In some coils, cold water entrance and its exit are placed in two different sides and in some coils these are placed in one side. Tubes placed horizontally are called rows and their function is to transfer heat from the water into air. Tubes placed vertically, transfer water into tubes inside the coil (Figure 1). Airflow is perpendicular to the tubes and loses its heat and humidity in contact with the fins on outer surface of the tubes (Figure 2). In this article, we have studied coil dynamic behavior using mass and energy balance equations and the results are assessed.
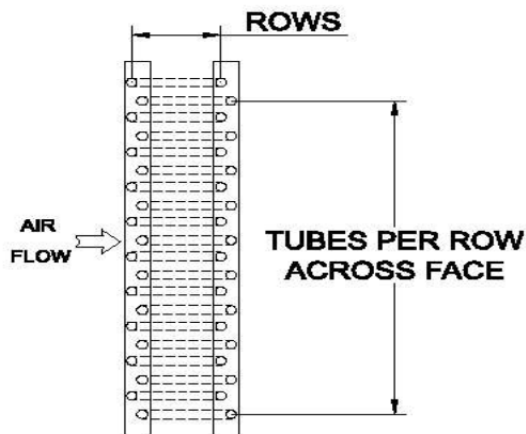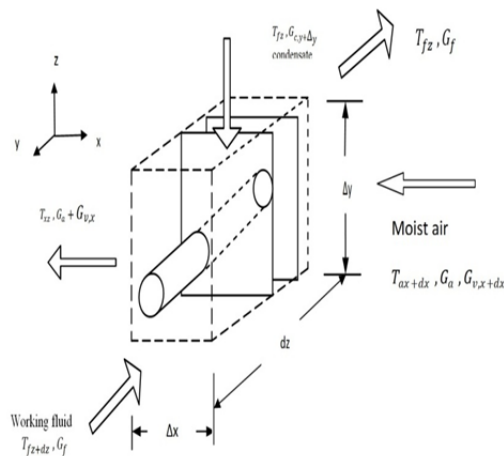

Figure 1. Coil description

Figure 2. Control volume of coil

2.2 Coil Geometry

The coils which we are studying are manufactured by Tahvieh Co. (Note 1) in Iran and are installed on Air Handling Unit (AHU) components. Abbreviations and coil geometry equations are shown in Table 1.

Table 1. Abbreviations and equations geometry

Symbol & Equations	parameter	Symbol & Equations	parameter
Nomenclature :			
a	air		
f	fluid	$M_a = \gamma_a \rho_a$	Capacity air mass per unit
t	tube	$M_f = \gamma_f \rho_f$	Mass heat capacity of water per unit
e	fin	$M_t = \gamma_t \rho_t c_t + \gamma_e \rho_e c_e$	Tube and fin heat capacity
T	Dry bulb temperature or air	$G_a = \dot{m_a}/\Delta_y\, d_z$	Mass air flow
δ_c	Thickness of condensate	$G_f = \dot{m_f}/\Delta_y\, \Delta_x$	Mass of fluid
$\dot{m_f} = Q_f \rho_f$	Liquid flow rate	$R_i = (1/h_i P_i d_z) + \left((\ln(d_o/d_i))/2\,\pi k_t d_z\right)$	Tube interior thermal resistance
$\dot{m_a} = Q_a \rho_a$	Air flow rate	$R_{oD} = (h_{os} R_{oD}\, \eta_T\, dA_o)^{-1}$	Tube thermal resistance
h_{os}	Heat transfer coefficient	$R_{oW} = (h_{oW}\, \eta_T\, dA_o)^{-1}$	Thermal resistance Humid air
Geometry :			
$\Delta x = L_x/N_r$	Length in control section	$A_e = (2\,\pi N_e(d_e^2 - d_o^2))/4)$	The surface area of the fins on a tube
$\Delta y = L_y/N_c$	Width in control section	$A_t = \pi d_o(L_z - N_e\, \delta_e)$	Exposed outside surface area of a tube
$dz = L_z/d_z$	High in control section	$A_o = (A_{t+} A_e)$	Exterior area of a tube with fins
$dv = \Delta x\, \Delta y\, dz$	Volume of control section	$\eta_T = (A_t + A_e\, \eta_f)/A_o$	Total efficiency of the tube and fins
$N_e = n_e L_z$	Number of fin on a tube	$dV_c = dA_o \delta_c$	Derivative of Exterior area of a tube with fins
$v_f = Q_f/A_i$	Volumetric water flow in tube	$dV_f = A_i\, d_z$	Derivative of liquid area
$d_u = d_e + \delta_e$	Fin coefficient	$dV_t = 1/4\,\pi\,(d_o^2 - d_i^2)\, z$	The amount of fluid in the control section
$\gamma_i = dV_i/dV$	The size of the flow function	$dV_e = 1/4 L_z(d_e^2 - d_o^2)\, N_e\, \delta_e\, dz$	Derivative of tube volume
$A_i = \pi d_i^2/4$	Cross section aria of a tube	$dV_a = dV - dV_c - dV_t - dV_e - dV_f$	The amount of air in the control unit

2.3 Dry Conditions

To analyze cooling coil performance in dry conditions, since no condensation takes place, only energy conservation equations are applied. These equations represent dynamic performance of coils. Equations (2.1, 2.2, 2.3):

$$M_a c_{ma} \frac{\partial T_a}{\partial t} = -G_a c_{ma} \frac{\partial T_a}{\partial x} - \frac{T_a - T_t}{R_{oD} \mathrm{dv}} \tag{2.1}$$

$$M_t \frac{\partial T_t}{\partial t} = -G_a c_{ma} \frac{\partial T_a}{\partial x} - \frac{T_a - T_t}{R_{oD} \mathrm{dv}} - \frac{T_t - T_f}{R_i \mathrm{dv}} \tag{2.2}$$

$$M_f c_f \frac{\partial T_f}{\partial t} = -G_f c_f \frac{\partial T_f}{\partial z} + \frac{T_t - T_f}{R_i \mathrm{dv}} \tag{2.3}$$

In this case, inlet and outlet air has the same weight, since no condensation takes place (Katipamula & Brambley 2005) and resistance of condensate moisture between fins and air is neglected. $w_{in} = w_{out}$, $\delta_c = 0$.

Heat transfer between air, tubes and water are represented in Equations (2.4, 2.5):

$$q_a(t) = N_c G_a \Delta_y d_z c_f [T_{ai} - T_{ao}(t)] \tag{2.4}$$

$$q_f(t) = N_c G_f \Delta_x \Delta_y c_f [T_{fo}(t) - T_{fi}] \tag{2.5}$$

Average out-let air temperature is shown in Equation (2.6):

$$T_{ao}(t) = \frac{1}{N_z} \sum_0^{N_z} T_a(0, z, t) \tag{2.6}$$

2.4 Wet Condition

When the inlet water temperature is less than inlet air dew point, dew would be created on all or part of the fins surfaces. This feature contributes to reducing the humidity to the desired level.

Energy and mass conservation equations (2.6, 2.7, and 2.8) are applied expressing the dynamic behavior of the coil:

$$0 = G_a \frac{\partial w}{\partial x} dV + \frac{h_{os}}{c_{ma}} dA_o (w - w_{sc}) \tag{3.12}$$

$$M_a \frac{\partial e_m}{\partial t} = -G_a \frac{\partial e_m}{\partial x} - \frac{e_m - e_{st}}{b_t R_{ow} dV} \tag{3.13}$$

$$q_a(t) = N_c G_a \Delta_y \, dz \, c_f \, [e_{mi} - e_{mo}(t)] \tag{3.14}$$

3. Numerical Method

Due to nonlinearity and complexity of the equations representing dynamic behavior of the coils and time variance in them, the most accurate and appropriate way to solve the equations is numerical method. To solve the derivative equations, with respect to the time variation, we used the implicit method; Displacement in the coil is assumed to be consistent with the air flow (Xin, Jin Wen, Theodore, Smith, 2005). High accuracy, simplicity and convertibility into machine codes are benefits of the method to solve heat transfer equations. In this regard, we divide coil into small parts in which water and air flows pass through within any short time of sampling. The time range and coil section is formulated in Equations (3.1, 3.2). Smaller dimensions and more time steps improve accuracy but increase time to achieve final result (Kusiak, & Xu, 2012).

$$0 \leq \Delta t \leq \frac{\rho_a b_t R_{oW} \Delta V_a}{1 + \rho_a b_t R_{oW} Q_a} \tag{3.1}$$

$$\frac{Q_f \rho_f c_f \Delta z \Delta t R_i}{\rho_f c_f \Delta V_f \, R_i - \Delta t} \leq \Delta t \leq L_z \tag{3.2}$$

Assuming that entering water is uniform in whole input tubes, only relationships for a cross section of input tubes are required to be solved as the results would be identical. Surface coils is corresponding to a matrix in which entries represent a sampling space that have four levels of air temperature, water temperature, pipe temperature and humidity. Time variable is a function of the number of rows and columns in the matrix. Temperatures and humidity associated with the element are calculated at different times. The solution is obtained using Euler implicit method. The solution process was done in Computer Research Center of Islamic Azad University, South Tehran. Elapsed time to do the solution process was about 50 hours. Thus, we see the solution is too time-consuming and applying this method is virtually impossible to use control methods. Respecting three dimensions of time, width and height in coils, we use MATLAB software to solve the problem.　　It is described in following.

Table 2. Basic parameter

(c) Moist air			
Density of moist air	Ra	1.15	kg/m^3
(d) Working fluid			
Specific heat	Cf	4.18	kJ/(kg K)
Thermal conductivity	Kf	0.59	W/(m K)
Dynamic viscosity	Mf	0.000 577	N s/m^2
Density	Rf	998	kg/m^3
(e) Other			
Latent heat of evaporation	efg	2468	kJ/kg
Atmosphere pressure	P	1	atm
Thickness of condensate	δc	0.13	mm

3.1 Flowchart Programming

Since the equations solved by numerical methods are very time consuming and the aim of this paper is to provide a model for control methods, coil performance should be displayed in a variety of circumstances. We have converted equations to machine code as illustrated in Figure (7) and then solved it for the coil. Codes written by MATLAB are given in Appendix (C).
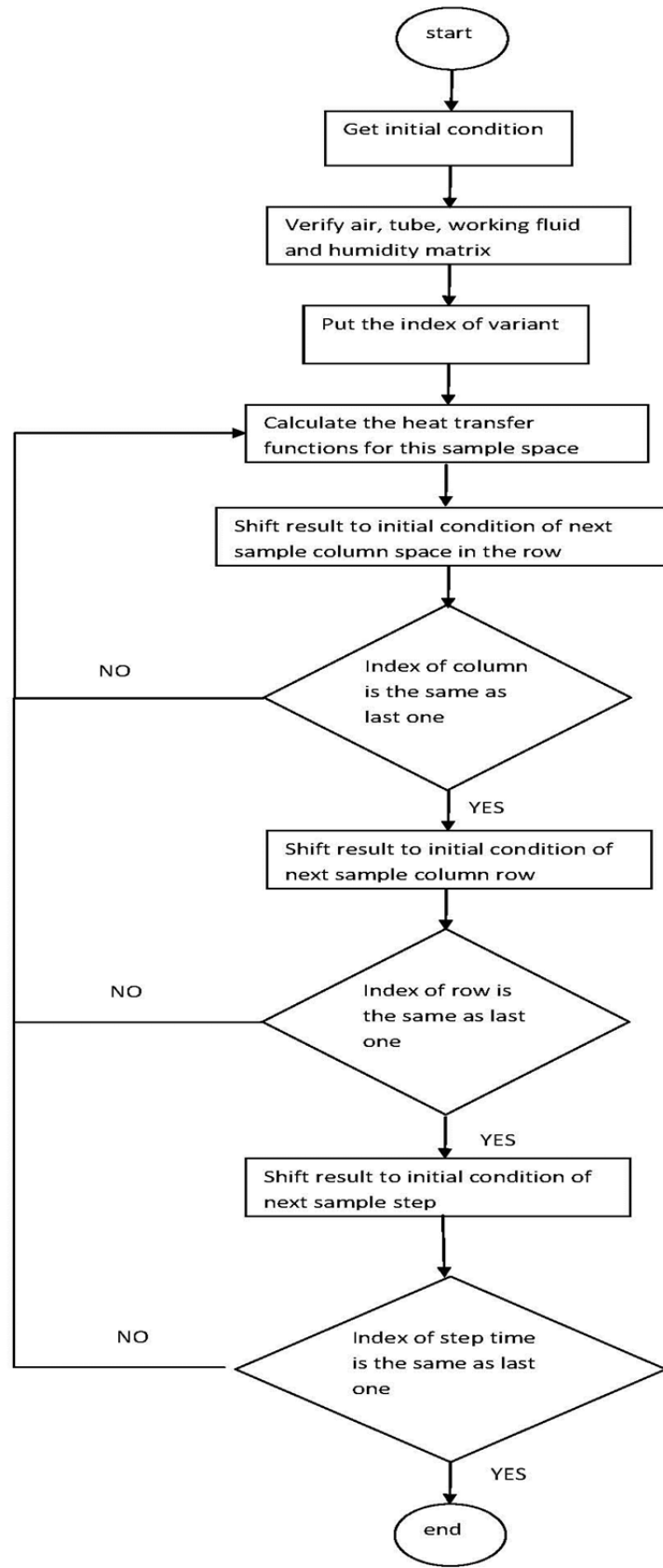
Figure 7. Flowchart of machine code solving the equations numerically

According to equations (3.1), (3.2) and terms in section 2, Δt and Δz are 0.012s and 4.5mm respectively. Note that c_{ma}, b_t and R_o vary with local humidity ratio variations. In this paper, we assume that cooling coil is active in wet conditions

4. Nonlinear Auto Regressive with External Input (NARX) Modeling

(NARX) accounts for one of the most applicable approaches in black box modeling. The performance of the method is stated in Equations (4.1, 4.2, 4.3, and 4.4).

$$\hat{x}(t + d) = f_1(x(t), x(t - d), \ldots, x(t - n_4 d), u_x(t), u_x(t - d), \ldots, u_x(t - n_5 d)) \tag{4.1}$$

$$\hat{y}(t + d) = f_2(y(t), y(t - d), \ldots, y(t - n_1 d), x(t), \ldots, x(t - n_2 d), u_y(t), u_y(t - d), \ldots, u_y(t - n_3 d)) \tag{4.2}$$

$$x(t + d) = \hat{x}(t + d) + e_x(t + d) \tag{4.3}$$

$$y(t + d) = \hat{y}(t + d) + e_y(t + d) \tag{4.4}$$

Where $x(t)$ and $y(t)$ are system outputs at t, $u_y(t)$ and $u_x(t)$ are inputs, $\hat{y}(t + d)$ and $\hat{x}(t + d)$ are predicted values with time delay d, $x(t + d)$ and $y(t + d)$ real system outputs at $(t + d)$, $e_x(t + d)$ and $e_y(t + d)$ are corresponding errors. In recent Equations, predicted value ($\hat{y}(t + d)$), is highly influenced by accuracy of real system outputs. We may use Equation (4.5) instead of Equation (4.2) to increase the accuracy of predicted value.

$$\hat{y}(t + d) = f_2(y(t), y(t - d), \ldots, y(t - n_3 d), \hat{x}(t + d), x(t), \ldots, x(t - n_4 d), u_y(t), u_y(t - d), \ldots, u_y(t - n_5 d)) \tag{4.5}$$

In this paper the results of numerical solutions are supposed as input and output of neural network. Since coil behavior is different in dry and humid conditions, we have made two different models to simulate the coil behavior. As we mentioned in section 2, the behavior of cooling and heating coils are the same in dry conditions. Here, the coil behavior is investigated in different conditions with different inputs as NARX inputs and outputs. In wet conditions, we have applied 212 data sets with 5 inputs (inlet air temperature, inlet water temperature, inlet moisture, and inlet water flow and, inlet air flow rates) and 3 outputs (outlet air temperature, outlet water temperature and outlet moisture) and in dry conditions we have applied 212 data sets with 4 inputs and 2 outputs. In wet conditions the model has 19 neurons in the hidden layer and in dry conditions the model has 10 neurons in the hidden layer. The results are shown in Figures (8, 9):
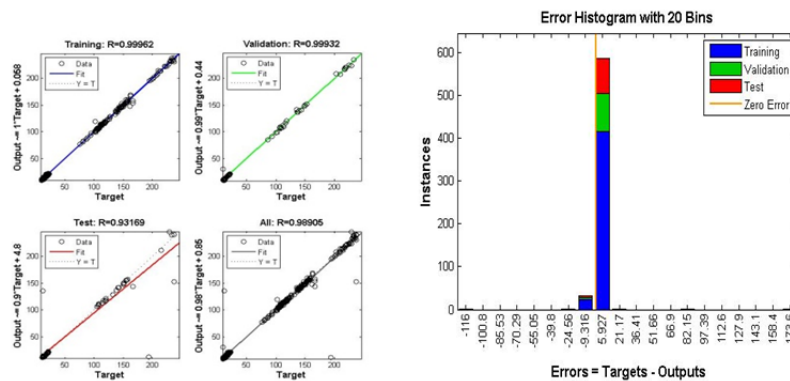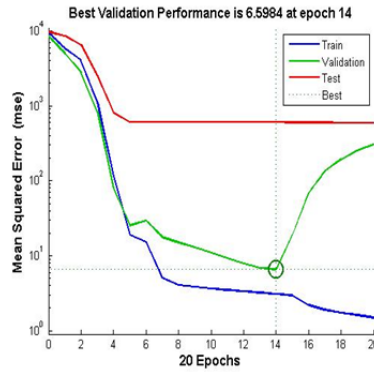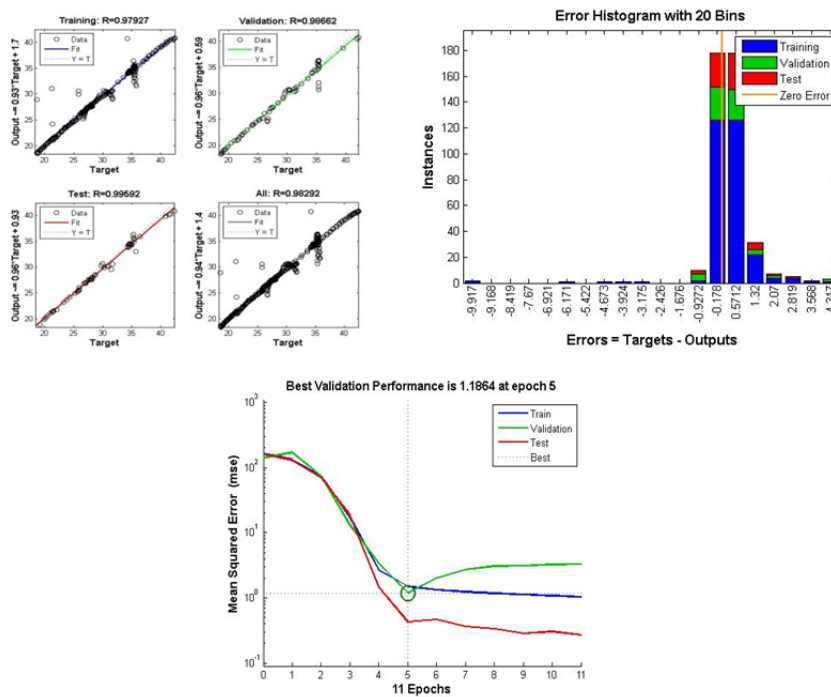
Figure 8. Wet cooling coil NARX results

Figure 9. Dry cooling coil NARX results

According to the Figures (8, 9), proposed model in dry conditions in comparison with the one in wet conditions has more accurate performance. This is due to the removal of moisture changes. MSE in cooling coil was $23 * 10^{-1}$ and was $3.45 * 10^{-1}$ in heating coil.

5. Model Evaluation

The proposed model is based on the active coil of AHU in Iran Pasteur Institute clean rooms (Figure 7). Since coil's input-output data is not measured by building manager systems (BMS) we use whole AHU unit model to assess coil performance. Modeling of other components including supply fan and humidifier modeling are illustrated in appendix (1).
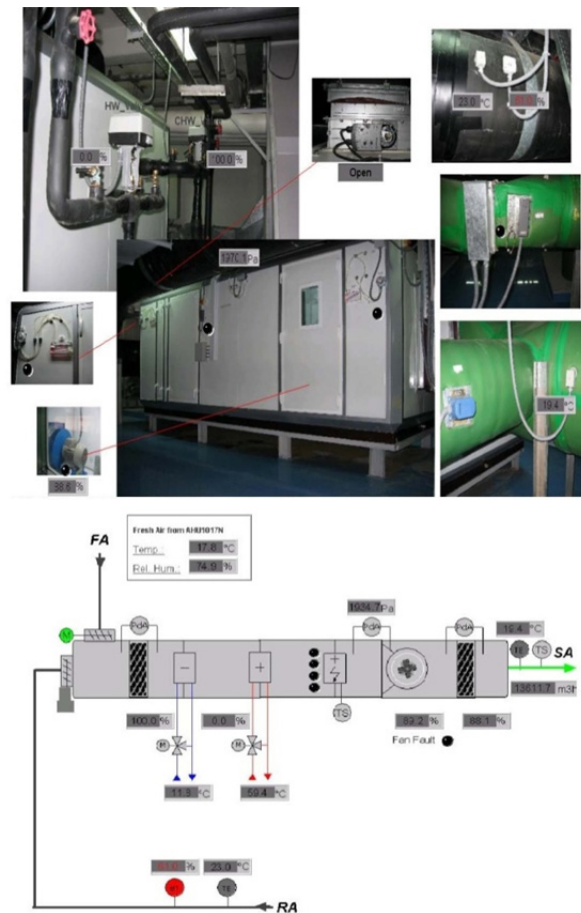
Figure 6. IRAN Pasture institute AHU unit

The information obtained from BMS in the interval from14[th] to 28th June 2015 has been used to assess the performance of the model. The results are shown in table 3.

6. Results and Conclusion

In this study, a simple and practical model with acceptable accuracy is proposed. Proposed approach in this article allows to model active coils whose input-output data are not available. Thus, it is applicable in control methods as an online model. Availability limitation of coil input - output data and unpopularity of black box method cause the data needed in NARX method be obtained by implicit method of numerical solution for dynamic equations. The coil is modeled in dry and wet conditions to present cooling coil performance more accurately. Providing more input-output data the accuracy of the model increases significantly. Numerical approach inherently is too time-consuming to be actually applicable into control system, but NARX method allows us to use the model in an effective way, using numerical results. Hence, we see the combination of numerical results with NARX method contributes to controlling system effectively.

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Notes

Note 1. http://www.tahvieh.com/en/

Appendix A

Fan Modeling

A first order simple linear equation is applied to perform fan modeling (A.1, A.2). Fan does not affect the air humidity in an ideal mode. In the case, motor doesn't placed in air flow path, outlet temperature would be unchanged; otherwise it may increases 1-2℃ . Power consumption in fan and energy transfer to the air flow is represented in Equations (A.1, A.2).

$$q_e = \frac{\Delta p \, \dot{v}}{\mu_{motor}} \tag{A.1}$$

$$q_{air} = (\mu_{motor} + (1 - \mu_{motor})f_{motorloss})q_e \tag{A.2}$$

Where q_e engine power (watt) is, Δp is pressure dropped, $\dot{v}$ air flow rate (m^3 /s), μ_{motor} is motor efficiency. $f_{motorloss}$ is fan losses transferred to the air (Song & Wang, 2015).

Appendix B

Humidifier Modeling

The humidity of the air in clean rooms is the most important factor of thermal comfort.   The humidifier spreads out dry and clean vapor inside AHU air. Controlling the amount of moisture in the air is one of the most important tasks of BMS. Mass and energy conservation equations represent humidifier behavior. Equations (B.1, B.2).

$$C_h \frac{dT_h}{dt} = f_{sa} C_{pa}(T_{si} - T_h) + \propto_h (T_o - T_h) \qquad (B.1)$$

$$V_h \frac{dW_h}{dt} = f_{sa} (W_{si} - W_h) + \frac{h(t)}{\rho_a} \qquad (B.2)$$

Where C_h is overall heat capacity of humidifier, T_h is inlet air temperature, f_{sa} is air flow rate, C_{pa} is air specific heat, $\propto_h$ is heat transfer coefficient, T_o is outside temperature, V_h is volume of humidifier, W_h is inlet air humidity ratio, and $h(t)$ is velocity of moist air provided in the humidifier.

Appendix C

Codes written by MATLAB

```
%%%%%%%%%%%%%%%%%%%%%%%coil dimension
di=10.9*10^-3
do=12.7*10^-3
Lx=0.3
Ly=0.67;
Lz=0.91
Nc=18
Nr=6
di=10.9*10^-3
do=12.7*10^-3
Lx=0.3
Ly=0.67
Lz=0.91
Nc=18
Nr=6
ne=377
te=0.19*10^-3
de=46.7*10^-3
ce=0.902
ct=0.38
ke=177
kt=400
pe=2702
pt=8933
pa=1.15
cf=4.18
kf=0.59
uf=0.000577
pf=988
efg=2468;
P=1
tc=0.13*10^-3
%%%%%%%%%%%%%%%%%%%coil geometric
Ne=Lz*ne
At=pi*do*(Lz-(Ne*te))
Ae=(pi*do*(de^2-do^2))/4
```

Ao=At+Ae
dz=4.5*10^-3
dAo=Ao*(dz/Lz)
dVc=dAo*tc
dVt=(pi*(do^2-di^2)*dz)/4
dVe=(pi*(de^2-do^2)*te*Ne*dz)/(4*Lz)
Ai=(pi*di^2)/4
dVf=Ai*dz
V=Lx*Ly*Lz
sx=Lx/Nr
sy=Ly/Nc
dV=sx*sy*dz
dVa=dV-dVc-dVt-dVe-dVf
%%%%%%%%%%%%%%%uler metric steps
la=dVa/dV
lf=dVf/dV
lt=dVt/dV
le=dVe/dV
Ma=pa*la
Mt=(pt*lt*ct)+(pe*le*ce)
Mf=pf*lf
hos=23.8
Qa=944
Qf=0.63
hi=4.36
Pi=pi*di
ht=(At+Ae)/Ao
RoD=((hos*ht*dAo)^-1)
Ga=(Qa*pa)*(sy*dz)
Gf=(Qf*pf)*(sx*sy)
Ri =((1/(hi*Pi*dz))+((log(do/di))/(2*pi*kt*dz)))
cf=4.18
cma=1
st=0.012
how=63.1
Row=(how*ht*dAo)^-1
%%%%%%%%%%%%%%%inlet air&fluid characteristic
initialairtemperature=31
initialfluidtemprature=4.4
initialhumidityratio=45
%%%%%%%%%%%%%%phsycrometric calculations
kelvinairtemprature=initialairtemperature+273.15
farenhidetemprature=(kelvinairtemprature*(9/5))-459.67
saturatedvapor=6.335+(0.6718*initialairtemperature)-(2.0887*0.01*initialairtemperature^2)+(7.3095*0.0001*initialairtemperature^3)
vapordensity=initialhumidityratio*saturatedvapor*100
landa=log(initialhumidityratio/100)+((17.67*initialairtemperature)/(243.5+initialairtemperature))
dewpoint=(243.5*landa)/(17.67-landa)
ps=exp(20.386-(5132/kelvinairtemprature))/7.5006
pv=ps*initialhumidityratio/100
p=101.3
w=.622*(pv/(p-pv))
ws=.622*(pv/(p-ps))
initialentalpy=((0.24*initialairtemperature)+(w*(1062+(0.44*initialairtemperature))))*3.0398
initialentalpysat=((0.24*initialairtemperature)+(ws*(1062+(0.44*initialairtemperature))))*3.0398
%%%%%%%%%%%%%Euler solution

```
AIR=ones(2,204,415)
FLOUD=ones(1,204,310)
TUBE=ones(1,204,310)
WO=ones(2,204,415)
if initialfluidtemprature > initialairtemperature
        for f=1:100
i=1
for j=1:202
t=(i*203)-(203-j)
FLOUD(i,j+1,t+f)=(((-Gf*cf*((FLOUD(i,j+1,t+f-1)-FLOUD(i,j,t+f-1))/dz))+((TUBE(i,j+1,t+f-1)-FLOUD(i,j+1,
t+f-1))/(Ri*dV)))+(((FLOUD(i,j+1,t+f-1))*(Mf*cf))/(st)))*(st/(Mf*cf))
TUBE(i,j+1,t+f)=(((em(i,j+1,t+f-1)-es(i,j+1,t+f-1))/(bt*Row*dv))+((TUBE(i,j+1,t+f-1))*((Mt/st)-(1/Ri*dv))))*(
st/Mt)
AIR(i+1,j+1,t+f+g)=((-Ga*(em(i,j+1,t+f-1)/sx))+(em(i-1,j+1,t+f-1)*((Ga/sx)+(Ma/st)))-((em(i,j+1,t+f-1)-es(i,j+1
,t+f-1))/(bt*Row*dv)))*(st/Ma)
n=1
end
        end
for n=2:5
AIR(1,:,2:308)=AIR(2,:,2:308)
FLOUD(1,1,1:106)=FLOUD(1,203,203:308)
g=203
        for f=1:100
i=1
for j=1:202
t=(i*203)-(203-j)
FLOUD(i,j+1,t+f)=(((-Gf*cf*((FLOUD(i,j+1,t+f-1)-FLOUD(i,j,t+f-1))/dz))+((TUBE(i,j+1,t+f-1)-FLOUD(i,j+1,
t+f-1))/(Ri*dV)))+(((FLOUD(i,j+1,t+f-1))*(Mf*cf))/(st)))*(st/(Mf*cf))
TUBE(i,j+1,t+f)=(((em(i,j+1,t+f-1)-es(i,j+1,t+f-1))/(bt*Row*dv))+((TUBE(i,j+1,t+f-1))*((Mt/st)-(1/Ri*dv))))*(
st/Mt)
AIR
end
        end
end
end
    for f=1:100
i=1
for j=1:202
t=(i*203)-(203-j)
FLOUD(i,j+1,t+f)=(((-Gf*cf*((FLOUD(i,j+1,t+f-1)-FLOUD(i,j,t+f-1))/dz))+((TUBE(i,j+1,t+f-1)-FLOUD(i,j+1,
t+f-1))/(Ri*dV)))+(((FLOUD(i,j+1,t+f-1))*(Mf*cf))/(st)))*(st/(Mf*cf))
TUBE(i,j+1,t+f)=((((AIR(i,j+1,t+f-1))-(TUBE(i,j+1,t+f-1)))/(RoD*dV))-((TUBE(i,j+1,t+f-1)-FLOUD(i,j+1,t+f))
/(Ri*dV))+(TUBE(i,j+1,t+f-1)*(Mt/st)))*(st/Mt)
AIR(i+1,j+1,t+f)=(((-Ga*cma*((AIR(i+1,j+1,t+f-1)-AIR(i,j+1,t+f-1))/sx))-((AIR(i+1,j+1,t+f-1)-TUBE(i,j+1,t+f)
)/(RoD*dV)))+(((AIR(i+1,j+1,t+f-1))*(Ma*cma))/(st)))*(st/(Ma*cma));
end
end
n=1
for n=2:5
AIR(1,:,2:308)=AIR(2,:,2:308)
FLOUD(1,1,1:106)=FLOUD(1,203,203:308)
g=203
for f=1:100
        for j=1:1:202
            t=(i*203)-(203-j)
            FLOUD(i,j+1,t+f-1)=FLOUD(i,j,t+f-1)
```

```
FLOUD(i,j+1,t+f)=(((-Gf*cf*((FLOUD(i,j+1,t+f-1)-FLOUD(i,j,t+f-1))/dz))+((TUBE(i,j+1,t+f-1)-FLOUD(i,j+1,
t+f-1))/(Ri*dV)))+(((FLOUD(i,j+1,t+f-1))*(Mf*cf))/(st)))*(st/(Mf*cf))

TUBE(i,j+1,t+f)=((((AIR(i,j+1,t+f))-(TUBE(i,j+1,t+f-1)))/(RoD*dV))-((TUBE(i,j+1,t+f-1)-FLOUD(i,j+1,t+f))/(
Ri*dV))+(TUBE(i,j+1,t+f-1)*(Mt/st)))*(st/Mt)

AIR(i+1,j+1,t+f+g)=(((-Ga*cma*((AIR(i+1,j+1,t+f+g-1)-AIR(i,j+1,t+f))/sx))-((AIR(i+1,j+1,t+f+g-1)-TUBE(i,j+
1,t+f))/(RoD*dV)))+(((AIR(i+1,j+1,t+f+g-1))*(Ma*cma))/(st)))*(st/(Ma*cma));
            AI(f,j)=AIR(i+1,j+1,t+f)
            TU(f,j)=TUBE(i,j+1,t+f)
            FL(f,j)=FLOUD(i,j+1,t+f)
        end
end
end
F=plot(1:f,FL(:,202))
hold on
A=plot(1:f,AI(:,202))
hold on
W=plot(1:f,(WA(:,202))/8)
vd=6.335+(0.6718*32)-(2.0887*0.001*32*32)+(7.3095*0.0001*32^3)
vd=5.018+(0.32321*32)+(8.1847*0.001*32*32)+(3.1243*0.0001*32^3)
else
```

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