Design Method for the Heating/Cooling Coil in the AHU Based on Fuzzy Logic

—Part One: Basic Structure and Characteristics Analysis[1]

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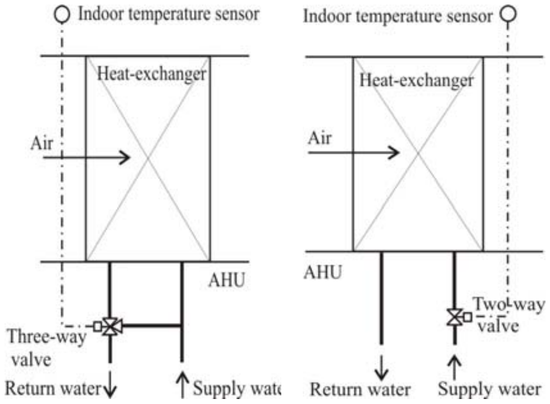
Abstract: An AHU's energy performance is greatly influenced by its heating/cooling coil energy performance, which is also greatly influenced by the different kinds of control methodologies such as PID control and fuzzy logic control. The conventional actuating device consisting of motorized control valve and finned heat-exchanger is much more suitable to PID control instead of fuzzy control. To achieve a good control performance for heating or cooling coil by the fuzzy control method, an innovative finned heat-exchanger with adjustable area has been proposed in this paper. This paper introduces the energy and hydraulic characteristics analysis of the new heat-exchanger structure. Some practical implementation issues are also addressed.

Key words: heating/cooling coil; fuzzy logic; characteristics analysis; structure.

1. INTRODUCTION

Heating and cooling coil is important equipments in air conditioning system, and improving heat transfer efficiency has been being a research focus since the energy crisis happened in 1970’s. Out-tube and in-tube enhancements are two basic improvement methods. The finned heat-exchanger and helically ribbed in-tube heat-exchanger have been used widely in air handling unit (AHU). Although great number of studies have been published to study how to improve and optimize these two enhanced heat-exchangers[1~8], few people has studied the structure optimization of the heating/cooling coil from its energy control, which is very especially used in air handling unit.

There are two common methods to control the operation of a heating/cooling coil[9~14], one is to adjust the supply air enthalpy while the supply airflow is constant by controlling supply water flow or temperature of the coil, modulating opening of air bypass valve paralleling the coil, humidifier (in winter) and re-heater; the other is to adjust the supply airflow by controlling opening of the supply air valve or modulating the supply fan speed while the supply air enthalpy is constant. In this paper, only the first one will be discussed.



(a) (b)

Fig.1 The first method to adjust the supply air enthalpy

Fig.1 provides two methods to adjust the supply air enthalpy by controlling water flow through the coil. Fig.1(a) is by a continuous three-way motorized valve in the water system, and Fig.1(b) by a continuous two-way motorized valve. They have been used widely in AHU. The different characteristics of continuous motorized valves influence the control system performance.

The second method to adjust the supply air

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enthalpy of AHU by controlling the supply water temperature is as shown in Fig.2, where a pump and continuous three-way motorized valve are installed in the water system. By adjusting the opening of three-way valve according to indoor temperature feedbacks from indoor sensors, the supply water temperature can be modulated. Although the system shown in Fig.2 has a very good control performance for indoor temperature, a pump is necessary for every coil, which results in a higher initial and operation costs.

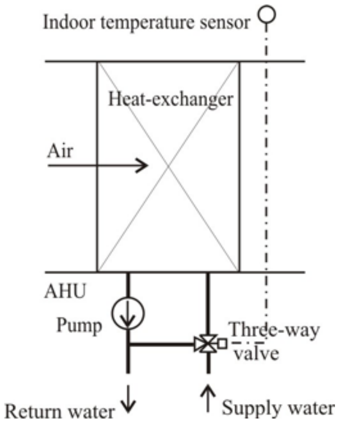

Fig.2 The second method to adjust the supply air enthalpy

The third method is to adjust the supply air enthalpy of AHU by controlling opening of air bypass valve, as shown in Fig.3. The supply air enthalpy can be controlled by modulating continuous two-way motorized valve on the return water pipe and opening of the air bypass valve according to indoor temperature where the supply air enthalpy can be maintained in a bigger range and much more energy under partial air-conditioning load can be achieved than that of above systems. But the size of AHU is increased too. In addition, coupling control strategy of water valve and air bypass valve is very complex.

According to current energy control methods mentioned above, the modulation of supply water flow and temperature are all realized by controlling two-way or three-way valves. The control valve flow characteristic impacts the heat-exchanger performance. Under the condition of small water flow through the coil, the practical control system of AHU often exhibits poor control performance because of the improper choice of the control valve and its quick open characteristic, and unrealized control actions, and results in the failure of AHU energy control[12].

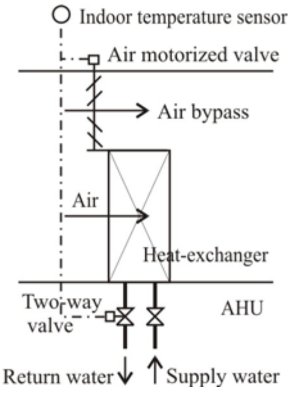

Fig.3 The third method to adjust the supply air enthalpy

Furthermore, existing researches show that the coil with the control of continuous motorized valve is much more suitable to PID control rather than fuzzy control which is non-continuous and quick response speed control method [15]. Therefore it is necessary to develop a new energy control system or improve existing system. In fuzzy control of air-conditioning system, the indoor temperature is presented by fuzzy logic such as “high, moderate and low”. Similarly, it should be convenient to realize fuzzy control if the coil in AHU is also divided into relevant several parts such as “big, medium and small” according to quantity or area of heat-exchanging. The continuous motorized valve can be replaced by on/off actuators. This is the coil with adjustable area that will be discussed in the following sections.

2. BASIC STRUCTURE OF THE COIL WITH ADJUSTABLE AREA

Fig.4 is a general coil with finned tubes, where 1 means water inlet pipe, 2 water outlet pipe, 3 fins of the heat-exchanger and 4 frame. The heat transfer area of the coil in AHU is calculated based on the design cooling load of air-conditioning system. However, the air-conditioning system often runs under partial load. The heat transfer rate is much less than that of the design condition because the water flow under the partial load is lower than that of the design condition. If the lower water flow can be modulated to flow through partial heat transfer of the coil, the heat transfer rate would not decrease greatly under partial load.

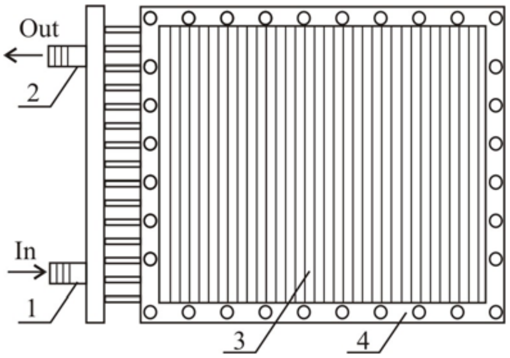

Fig.4 General heat-exchanger with fin-tubes

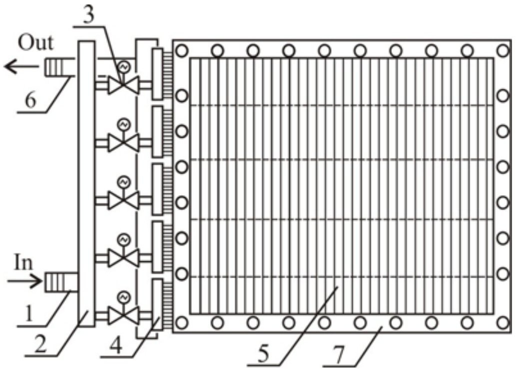

Fig.5 Heat-exchanger with adjustable area

This problem can be solved by the coil with adjustable area shown in Fig.5. Where 1 means water inlet pipe, 2 first manifold, 3 on/off motorized valve, 4 second manifold, 5 fins, 6 water outlet pipe and 7 frame.

In Fig.5, each motorized valve is connected with a certain heat-exchanging area of the coil. There will be water flowing through the heat-exchanging area while opening its front valve and there is no water through the area while closing it. This part of the heat-exchanging area will not take part in the heat-exchanging process if there is no water in it. Then the heat-exchanging area can be modulated by controlling the valves, and heat transfer rate will be modulated too. At the same time, the heat-exchanging area, which does take part in the heat-exchanging process, will be an air bypass for the other heat-exchanging area. The bypass air and cooled/heated air of the heat-exchanger will be mixed behind the coil, and the mixed air enthalpy may be modulated in a large range by controlling the valves to change the mixture ratio of the bypass air and cooled/heated air.

Assume k is the adjustment coefficient of the heat-exchanging area of the coil, and $k\in[0, 1]$, and its definitional equation is shown as follow

$$k = \frac{F_a}{F} \tag{1}$$

where, F_a means actual heat transfer (m^2), F total heat transfer area (m^2).

According to equation (1), the adjusting coefficient k describes the ratio of the actual heat transfer area to total heat transfer area for a given coil in the actual heat-exchanging process, and accordingly k represents the ratio of the actual heat transfer rate to its total rate.

By equation (1), divide k into several grades on the domain of [0, 1], for example k=0.2, 0.4, …, 1.0. Accordingly, the total heat transfer area F can be regarded as combination of F_1, F_2, …, F_n, where each F_i (i=1, 2, …, n) is controlled by a on/off motorized valve. So each F_i is an independent heat-exchanging unit shown in Figure 5. Obviously, this kind of dividing method of the coil can be realized easily in practical design and manufacture.

3. ENERGY ADJUSTING CHARACTERIST-IC ANALYSIS OF COIL WITH ADJUSTAB-LE AREA

According to the adjustment coefficient k of the coil, total heat transfer rate equals sum of heat transfer rate of each unit, as shown in Equation

$$Q = \sum_{i=1}^{n} k_i Q_i \tag{2}$$

where Q means total heat transfer rate of the coil (W), Q_i heat transfer rate of unit F_i (W), k_i adjustment coefficient of unit F_i, $k_i\in\{0,1\}$ for double positions (on/off) motorized valve. Obviously, k_i shows whether each heat-exchanging unit F_i contributes to the actual heat-exchanging process at that time or not. When k_i equals zero, F_i does not contribute to the actual heat-exchanging process, and vice versa. According to equation (2), the heat transfer rate Q, which changes continuously in a continuous adjusting valve system, shown as line 1 in Figure 6, varies step by step with the occurance of Q_i contribution as shown line 2 in Fig.6. According to different combinations of k_i=1 or 0, it can be obtained combinations of heat-exchanging quantities, as shown in Table 1, one example of various combinations, where **NB** means negative big, **NM** negative medium, **NS** negative small, **ZE** zero, **PS** positive small, **PM** positive medium and **PB** positive big, **NB**~**PB** are fuzzy grades.

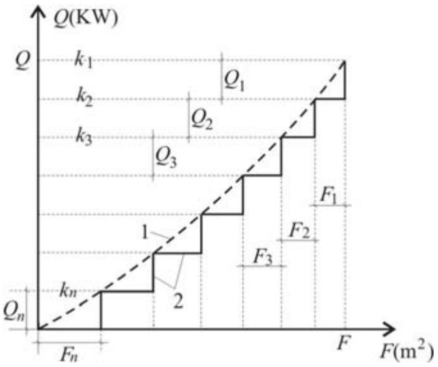

Fig.6 The heat transfer rate *Q*

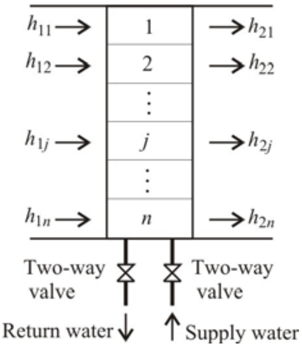

Fig.7 The heat-exchanger with an air bypass

When the coil is used in an air handling unit and k_j=0 (means an unit not to participate in the heat-exchanging process, and j=1, 2, …, n), then F_j will not participate in heat-exchanging process and the j^{th} unit will be an air bypass shown in Fig.7. That is to say, when the adjustment coefficient is adjusted by turning on or off the on/off motorized valve, the actual heat transfer area can be changed, and so as the air bypass rate. By this structure, both total heat transfer rate and supply air enthalpy can be adjusted together. However, this control scheme will also lead to stratification of the air leaving the heat exchanger. A mixing box should be added behind the coil to solve the problem.

In Fig.7, assume air enthalpy at the inlet and outlet of the coil are respectively h_{11}, h_{12}, ..., h_{1j}, ..., h_{1n} and h_{21}, h_{22}, ..., h_{2j}, ..., h_{2n}. If k_j=0 and k_i=1(i≠j), unit F_j is the air bypass, namely $h_{2j}=h_{1j}$. Let

$$G_1=G_2=\ldots=G_i=\ldots=G_n=\frac{1}{n}G \qquad (3)$$

Tab. 1 One combination of heat-exchanging quantities

k_i								Fuzzy grades of Q
k_1	k_2	k_3	k_4	k_5	k_6	k_7	k_8	
0	0	0	0	0	0	0	0	NB
0	0	0	0	0	0	1	1	NM
0	0	0	0	1	1	1	1	NS
0	0	0	1	1	1	1	1	ZE
0	0	1	1	1	1	1	1	PS
0	1	1	1	1	1	1	1	PM
1	1	1	1	1	1	1	1	PB

where G_i and G are respectively air flow through unit F_i and total coil (m^3/s). While the application of the coil is under the dehumidifying condition, the heat-exchanging units with “on” valves remove more moisture than that with “off” valves. Therefore, there are different amounts of moisture on each unit. This will change the air flow resistance through the various sections of the coil and consequently the airflow through the various sections, then G_1, G_2, ..., G_n will not completely equal each other in this situation and a small error will be occurred. Here, this small error is not considered, then

$$h_2=\frac{1}{n}\left(\sum_{i\neq j}h_{2i}+h_{1j}\right) \qquad (4)$$

where h_2 is the mean of air enthalpy at the outlet of the coil (J/Kg$_{\text{dry air}}$).

Obviously, the air bypass resulted from k_j=0 will make supply air enthalpy h_2 have a large adjusting range in which supply air enthalpy can be adjusted by controlling k_i not by adjusting the chiller’s operation condition under partial air-conditioning load.

4. HYDRAULIC ADJUSTING CHARACTER-ISTIC ANALYSIS OF THE COIL WITH ADJUSTABLE AREA

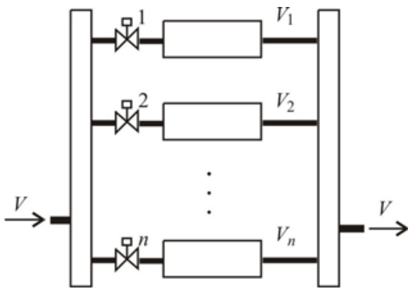

Fig.8 The physical structure of coil with adjustable area

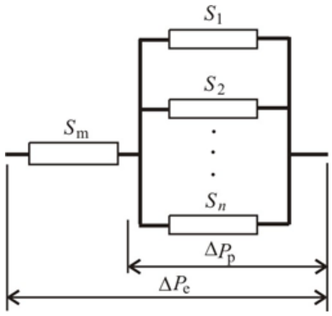

Fig.9 The impedance of coil with adjustable area

Structure of the coil shown in Fig.5 can be simplified as Fig.8, where, V means total water flow through the coil (m^3/s), V_1, V_2 and V_n are respectively the water flow through each unit (m^3/s). Impedances of Fig.8 are shown in Fig.9, Δp_e is pressure drop between the inlet and outlet of the coil (Pa). Δp_p is pressure drop between the inlet and outlet of parallel units (Pa), S_m is sum of the series impedances made of flow resistances through water inlet pipe, first manifold and water outlet pipe (Kg/m^7). S_1, S_2 and S_n are respectively impedances made of flow resistances of each parallel unit including on/off valve, second manifold and finned tube (Kg/m^7).

From Fig.8 and Fig.9, it can be got the following equations

$$V = \sum_{i=1}^{n} V_i \qquad (5)$$

$$\Delta p_p = \frac{\Delta p_e}{1+\frac{S_m}{S_p}} \qquad (6)$$

$$\frac{1}{\sqrt{S_p}} = \frac{1}{\sqrt{S_1}} + \frac{1}{\sqrt{S_2}} + \cdots + \frac{1}{\sqrt{S_n}} \qquad (7)$$

$$V_i = \sqrt{\frac{\Delta p_p}{S_i}} \qquad (8)$$

According to equation (6) and (8), the water flow through each unit V_i is proportional to S_m/S_p and its impedance S_i while Δp_e is a constant. While the impedance S_i is a constant (the i^{th} valve is not modulated), V_i is only proportional to S_m/S_p. While all valves are not modulated, S_p is a constant, and V_i is directly proportional to S_m. Then S_m should be maintained small enough to remove impact of the first manifold impedance on V_i, namely the first manifold is designed with a larger diameter than that of all the behind pipes. Another benefit to increase the diameter of the first manifold is that water flow rate in the first manifold can be decreased greatly. The dynamic pressure in the first manifold will be small enough not to be considered and the change of static pressure along the first manifold will be small at the same time. Under this condition, the water flow through each unit V_i will be equal.

Assume R and R_i are respectively the diameters of the first manifold and its behind pipes, v_m water flow rate (m/s), P_d dynamic pressure in the first manifold (Pa) and P_s static pressure in the first manifold (Pa). Let water flow rate in the behind pipes is 1.2 m/s, the total pressure in the water inlet pipe is 29400Pa ($3mH_2O$), the number of the behind pipes is 5, and water density is 1000 kg/m^3. The changes of the P_d and P_s are as shown in Table 2 with the change of R/R_i. According to Table 2, change of P_s is very small along the first manifold while $R/R_i>4$, which can help to confirm the first manifold diameter according the behind pipes diameter.

In addition, according to Equation (6), when the first manifold has a large diameter, then $S_m<<S_p$, namely $\Delta p_p \approx \Delta p_e$. The pressure drop between inlet and outlet of each unit approximately equals that of the coil. The impedance of each heat-exchanging unit will impact on the hydraulic performance of the water system if one valve is modulated, and the water flow rate through other valves will be changed. In order to increase the hydraulic stability of the whole water system, the control valve resistance is preferred to be as high as possible in order to increase S_e[16].

Therefore, the design principle of the coil with adjustable area can be obtained as follow. One is to increase the diameter of the first manifold to make it 4 times larger than that of the behind pipes at lest. The other is to select the valve with a great resistance coefficient for each heat-exchanging unit.

Based on the analysis of the energy and hydraulic adjusting characteristics of the coil, following conclusions have been achieved. Firstly, by replacing a continuous motorized valve with large diameter in the coil with several on/off valves with small diameter, such as on/off motorized valve and electromagnetic valve, the problem that the energy modulating range of a coil is limited by the practical flow characteristics of the control valve is solved with lower costs of the energy control system. Secondly, by generating an air bypass automatically while turning on or off the on/off valves, the body size of the air handling unit can be reduced compared with an air bypass system shown in Figure 3. Thirdly, it is also easy to realize the automatic control for the energy control equipment by the digital control method.

5. STRUCTURE OF THE COIL WITH UNEQUAL ADJUSTING AREA

The coil shown in Fig.5 is a coil with several equal heat-exchanging units, so which brings two problems needed to be solved. One is whether the equal heat-exchanging unit is the best or not. If it was the best one, what is the optimal number of the equal heat-exchanging unit? The other is what size of its minimum unit of the heat exchanger should be if the equal heat-exchanging unit is not the best one? According to these problems, it can be found that the equal heat-exchanging unit of the heat-exchanging unit is not the best one, then an unequal adjustable area of the coil is put forward shown in Fig.10.

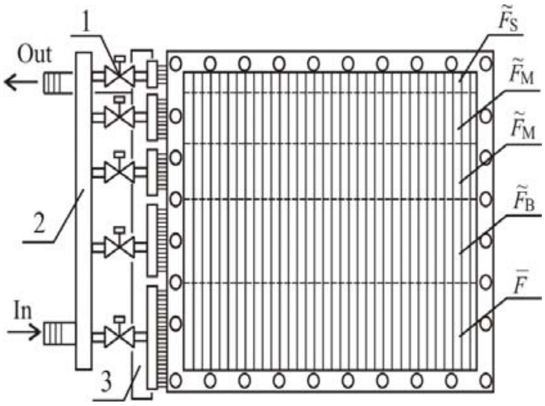

Fig.10 The unequal adjustable area of the coil

In the unequal adjustable area of the coil, heat transfer rate of the coil is divided into two parts, one is fundamental heat transfer rate $\overline{Q}$ and adjustable heat transfer rate $\tilde{Q}$, as is given in Equation (9).

$$Q=\overline{Q}+\tilde{Q} \tag{9}$$

$$F=\overline{F}+\tilde{F} \tag{10}$$

Equation (10) discusses heat transfer area, where $\overline{F}$ denotes fundamental heat transfer area (m^2), $\tilde{F}$ denotes adjustable heat transfer area (m^2). It is noted that $\overline{F}$ takes part in heat-exchanging process all the time, while $\tilde{F}$ is adjusted to meet with indoor air-conditioning load during the peak time. Divide $\tilde{F}$ into various fuzzy grades such as “big”, “medium”, “small”, as is shown in Fig.10, where 1 is on/off control valve, 2 first manifold, 3 second manifold. Define opened valve as “positive”, and

Tab. 2 Change of the P_d and P_s with the change of R/R_i

R/R_i	1	2	3	4	5	6	7	8	9	10
$v_m=6/(R/R_i)^2$ (m/s)	6	1.5	0.667	0.375	0.24	0.167	0.122	0.094	0.074	0.06
$P_d=500\,v_m^2$ (Pa)	18000	1125	222.2	70.3	28.8	13.9	7.5	4.4	2.7	1.8
$P_s=29400-P_d$ (Pa)	11400	28275	29178	29330	29371	29386	29393	29396	29397	29398

closed as “negative”, then $\tilde{F}$ can be adjusted based on the fuzzy grades such as “positive big, positive medium, positive small, negative small, negative medium and negative big”. The grades “large”, “medium”, “small” have a certain relationship in heat transfer area.

$$\begin{cases} \tilde{F} = \tilde{F}_{\mathrm{S}} + 2\tilde{F}_{\mathrm{M}} + \tilde{F}_{\mathrm{B}} \\ \tilde{F}_{\mathrm{M}} = 2\tilde{F}_{\mathrm{S}} \\ \tilde{F}_{\mathrm{B}} = 2\tilde{F}_{\mathrm{M}} + \tilde{F}_{\mathrm{S}} \end{cases} \quad (11)$$

In the interest of easy designing and adjusting, $\tilde{F}$ is divided in term of Equation (11), where $\tilde{F}_{\mathrm{S}}$ is minimum heat-exchanging unit. And then $\tilde{F}_{\mathrm{M}}$ and $\tilde{F}_{\mathrm{B}}$ are obtained by $\tilde{F}_{\mathrm{S}}$.

Thus, no matter how large the coil is, if only $\tilde{F}$ is divided into $\tilde{F}_{\mathrm{S}}$, $\tilde{F}_{\mathrm{M}}$, $\tilde{F}_{\mathrm{M}}$, $\tilde{F}_{\mathrm{B}}$ and accompanied with $\overline{F}$, it would be able to be controlled with five on/off valves. With different combinations of $\tilde{F}_{\mathrm{S}}$, $\tilde{F}_{\mathrm{M}}$, $\tilde{F}_{\mathrm{M}}$ and $\tilde{F}_{\mathrm{B}}$, various adjustable heat transfer area can be obtained easily.

6. CONCLUSIONS

This paper presents a finned coil with adjustable area based on the exiting energy control method of the AHU. The energy and hydraulic adjusting characteristics have been discussed. Finally, an unequal adjusting area of the coil has been introduced. Based on previous discussion, several conclusions can be drawn as following.

a) It has larger energy control range and more convenience to accomplish adjustment for the coil because of several on/off valves or electromagnetic valve replacing a continuous motorized valve.

b) An air bypass in the coil is generated and disappeared automatically, so there is no need for additional air bypass.

c) According to the hydraulic adjusting characteristics of the coil, it is easy to manufacture this coil.

d) It is easier to accomplish energy control in actual control systems for the unequal adjusting area of the coil than the coils mentioned in this paper.

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