MODEL-BASED COMMISSIONING FOR FILTERS IN ROOM AIR-CONDITIONERS

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Summary This paper proposes a model that can estimate filter resistance. Two sorts of value are used as inputs to estimate filter resistance. One is the power consumed by the fan in the indoor unit and the other is the thermal performance. For the room air-conditioners that the real time indoor unit fan power consumption is available, fan power consumptions are used as inputs to estimate filter resistance.For the room air-conditioners that are equipped with refrigerant pressure and temperature sensors, this model estimates filter resistance using refrigerant pressure and temperature, air temperature or enthalpy difference between supply and indoor air. The maximum and average difference between estimated and measured filter resistance are 12.72% and 5.89% when using the fan power consumption as inputs. When using the air-conditioner thermal performance data, the maximum and average estimation errors are13.12% and 5.96%. Based on this model, the method for commissioning filters in air-conditioner is discussed.

Keywords: Automated commissioning; Filter resistance; Modeling; Room air-conditioner

1. INTRODUCTION

Most researches about filters in a Heating, Ventilating and Air-Conditioning (HVAC) system study the capability of a filter to retain particles, dust, bacteria and molds [1], survival and growth of microorganisms on a filter [2], releasing Volatile Organic Compounds (VOC) from a filter [3] [4]. Papers can seldom be found about the influence of filter fouling on energy consumption. However, a measurement done by this research shows that a Gas-engine Heat Pump (GHP) indoor unit fan efficiency decreased 35.8% when the filter resistance increased to twice of initial resistance because of dust accumulation, as shown in Figure 1. Furthermore, this research studied the heat produced by the GHP during winter. The heat production decreased 33.1% when the filter resistance doubled, as shown in Figure 1. So filter fouling can not only decrease fan efficiency, but also decrease the heating/cooling capacity of room air-conditioners. It is important to timely detect an over-fouled filter and clean or replace it. Generally room air-conditioners are not equipped with pressure sensor to measure air flow resistance through a filter, which represents the filter-fouling situation. So it is necessary to develop a method to estimate air flow resistance through a filter without the requirement of adding filter pressure sensor for the purpose of saving the cost of pressure sensors, which is relatively expensive.

For the purpose of detecting filters' fouling situations without pressure sensor, this research focuses on developing a model that is able to estimate the air flow resistance through a filter only using air-conditioner's thermal or energy performance data. For the increasingly spreading multi-evaporator air-conditioners, which are equipped with refrigerant pressure and temperature sensor and room air temperature sensor for the purpose of controlling and balancing the heating/cooling capacity of each indoor unit, the air-conditioners' thermal performance data can be available. So it is feasible to develop a model to estimate filter resistance using currently obtainable data.

Such a model is useful for commissioning filters in room air-conditioners. As defined by ASHRAE, building commissioning is the process of ensuring that building systems are designed, installed, functionally tested, and capable of being operated and maintained to perform in conformity with the design intent [5]. Commissioning is considered to be a viable method to help ensure energy-efficient operation of buildings and their efficiency conservation measures [6].

Based on the filter model, a commissioning method for filters in room air-conditioners is proposed for the sake of ensuring the energy-efficient operation of room air conditioners.

2. MODEL

The model proposed to estimate filter resistance is shown in the following equations.

$$\Delta P_{ft} = \Delta P_f + \frac{\rho v_i^2}{2} - \Delta P_{OC} - \frac{\rho v_o^2}{2} \tag{1}$$

$$\Delta P_f = \rho_a N^2 D^2 C_h \tag{2}$$

$$C_h = a_0 + a_1 C_f + a_2 C_f^2 + a_3 C_f^3 + a_4 C_f^4 \tag{3}$$

$$C_f = \frac{V_a}{N D^3} \tag{4}$$

$$\Delta P_{OC} = \xi \frac{\rho_a v_{fo}^2}{2} \tag{5}$$

$$v_i = \frac{V_a}{A_i},\quad v_o = \frac{V_a}{A_o},\quad v_{fo} = \frac{V_a}{A_{fo}} \tag{6}$$

$$V_a = \frac{E\eta_f}{\Delta P_f} \tag{7}$$

$$\eta_f = e_0 + e_1 C_f + e_2 C_f^2 + e_3 C_f^3 + e_4 C_f^4 \tag{8}$$

If indoor unit fan power consumption E is unavailable, indoor unit air flow rate can be estimated using thermal performance data by Equation. (9), (10), and (11) instead of Equation (7) and (8).

$$V_{as} = \frac{m_r(h_{r1} - h_{r3})}{\rho_a(h_{ao} - h_{ai})} \tag{9}$$

$$V_{aw} = \frac{m_r(h_{r2} - h_{r3})}{\rho_a C_{pa}(T_{ao} - T_{ai})} \tag{10}$$

$$m_r = C_{EV} A_{EV} \sqrt{\rho_r(P_3 - P_4)} \tag{11}$$

Equation (1) is used to calculate a filter's resistance to air flow ΔP_{ft} by subtracting resistance of coil etc. ΔP_{OC} from fan pressure head ΔP_f. A typical air-conditioner indoor unit of cassette-shape, shown in Figure 3, is used as an example to explain the pressure distribution. The pressure curve of the indoor unit is shown in Figure 4. Fan pressure head ΔP_f is calculated using Equation (2), (3), and (4) using a 4th-order function of dimensionless airflow rate C_f. Equation (3) is taken from HVACSIM+ [7]. Equation (5) is used to calculate pressure drop of coil etc ΔP_{OC}. Equation (6) is used to calculate the air flow velocity at fan inlet, outlet, and air-conditioner indoor unit outlet through dividing the air flow rate V_a by inlet and outlet area respectively. Two methods are proposed to estimate air flow rate V_a. The first method uses time series fan power consumption E to calculate the air flow rate, as shown in Equation (7) and (8). If indoor unit fan power consumption is unavailable, air flow rate V_a is calculated using the heat balance equations between air side and refrigerant side, as shown in Equation (9) for summer time and Equation (10) for winter time respectively. The refrigerant enthalpy h_r in Equation (9) and Equation (10) can be calculated using refrigerant pressure P_r and temperature T_r. The refrigerant enthalpy at state point 4 is assumed to be equal to the enthalpy at state point 3. So cooling amount of refrigerant side during summer period is calculated using refrigerant enthalpy at state point 1 and state point 3. Refrigerant state points are defined in Figure 2. The refrigerant property calculation software REFPROP [8] is used to calculate refrigerant density and enthalpy by this research. The refrigerant flow rate m_r can be estimated using the expansion valve characteristics shown in Equation (11).

As mentioned above, this model gives two ways to estimate filter resistance using two sorts of different inputs respectively, i.e. indoor unit fan power consumption data and air-conditioner thermal performance data. The first method is simpler than the second method. The reason for proposing the second method is because the second method based on heat balance is also useful for commissioning other components. The following sections discuss the two different estimation methods in detail.

2.1. Estimation using fan energy consumption data

As shown in Equation (7) and (8), this method uses the power consumed by an air-conditioner's indoor unit fan to estimate air flow rate and then to estimate filter resistance. If substituting Equation (2), (4), and (8) into Equation (7), Equation (12) will be formed, which is an implicit function of dimensionless flow rate C_f. Iterative method can be used to solve this equation to obtain dimensionless flow rate C_f. Then filter resistance can be estimated.

$$C_f N D^3 = \frac{E\left(e_0 + e_1 C_f + e_2 C_f^2 + e_3 C_f^3 + e_4 C_f^4\right)}{\rho N^2 D^2 \left(a_0 + a_1 C_f + a_2 C_f^2 + a_3 C_f^3 + a_4 C_f^4\right)} \tag{12}$$

The method is suitable for the air-conditioners whose indoor unit fan power consumption is measured in real-time. Compared

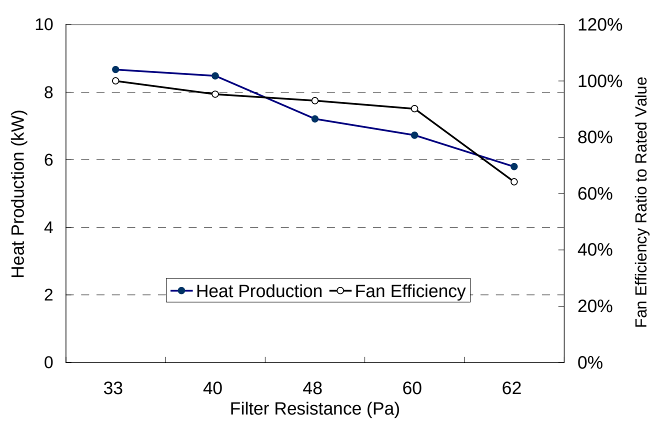


Figure 1. Heat production and fan efficiency vs. filter resistance

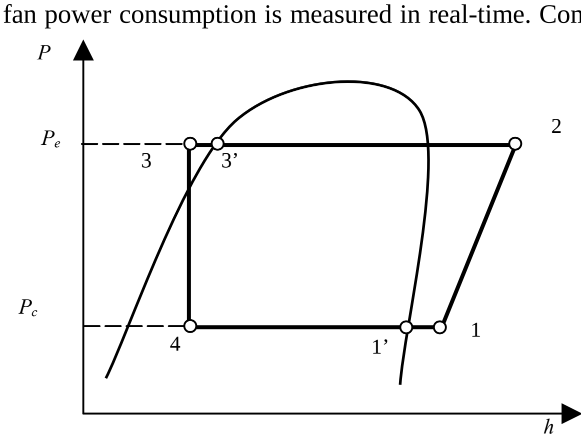


Figure 2. Refrigeration cycle state points

with the next method, which use air-conditioner thermal performance data to estimate filter resistance, this method uses less parameters and input data. The disadvantage of this method is that the fan power consumptions need to be measured in real-time.

2.2. Estimation using thermal performance data

As shown in Equation (9) and (10), an air-conditioner's thermal performance data, i.e. refrigerant condensation and evaporation pressure and temperature, supply and indoor air enthalpy or temperature, are used to calculate air flow rate and then to calculate filter resistance. For cooling operation, supply and indoor air enthalpy is used to calculate air flow rate, as shown in Equation (9), because cooling operation changes air humidity and enthalpy is necessary to calculate the total heat exchange, which includes both sensible and latent heat. For heating operation, supply and indoor air temperature is used to calculate air flow rate, as shown in Equation (10) because air humidity does not change and total heat exchange equals to sensible heat exchange.

Among the required variables inputted to the model, only the supply air temperature is unavailable for common multi-evaporator air-conditioners. The other variables, i.e. refrigerant condensation and evaporation pressure and temperature, and indoor air temperature, are obtainable because these variables are needed for air-conditioners' operational control. Because temperature sensor is cheaper than pressure sensor, it is reasonable to add a temperature sensor to an air-conditioner to measure outlet air temperature for estimating filter resistance instead of adding pressure sensor to measure filter resistance.

Although for heating operation adding a temperature sensor is enough to estimate filter resistance, for cooling operation it is not enough because air humidity is necessary for the calculation. It is unacceptable to add both temperature and humidity sensor only for the purpose of estimating filter resistance. So air humidity has to be estimated. The following method is proposed to estimate indoor unit outlet air humidity using air temperature.

1) Indoor air relative humidity is assumed to be 54%. The reason for this assumption is that according to the statistical analysis of the room air humidity from 9:00 to 20:00 in the summer period of July 1 to August 30, 94.3% air relative humidity fall in the range of 50% to 66%, and the most frequent humidity is 54%. The results are shown in Figure 5.

2) Outlet air humidity is determined by comparing the outlet air temperature with indoor air dew-point temperature, which can be calculated using indoor air humidity and temperature [9]. If supply air temperature is higher than indoor air dew-point temperature, the supply air humidity ratio is assumed to be equal to indoor air humidity ratio. If supply air temperature is lower than indoor air dew-point temperature, the supply air relative humidity is assumed to be equal to 99%.

This method is tested through checking the outlet air humidity of a GHP with four outlets on August 11, 2003. The estimated air humidity was compared with measured humidity, as shown in Figure 6. The average estimation error is 11.69%. The estimation error is large during the period when the GHP stopped. If only comparing the period when GHP was running, i.e. 9:31 to 12:40, 14:35 to 17:16, and 19:48 to 21:14, the average estimation error is only 5.54%. This estimation accuracy shows that this method is acceptable for estimating outlet air humidity.

The reason why the inlet and outlet air temperature and enthalpy are used to estimate filter resistance instead of other performance data, for example refrigerant flow rate, is that the inlet and outlet air temperature and enthalpy have closer relations to the filter resistance and show clearer trend accompanying the change of filter resistance than the other parameters, as shown in Figure 7. From this figure, it can be seen that on December 23, when the filters having the largest resistance of 95 Pa were installed in the four indoor units, the average temperature difference between inlet and outlet air is the highest. When filter resistance decreased, the temperature difference decreased accordingly. But other performance data, such as GHP gas

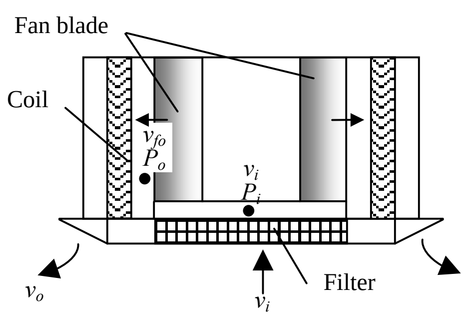


Figure 3. Measurement points in a typical cassette-shape indoor unit

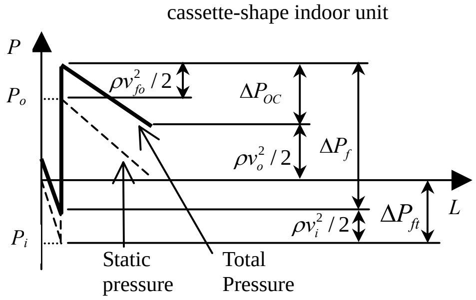


Figure 4. Pressure curve of indoor units

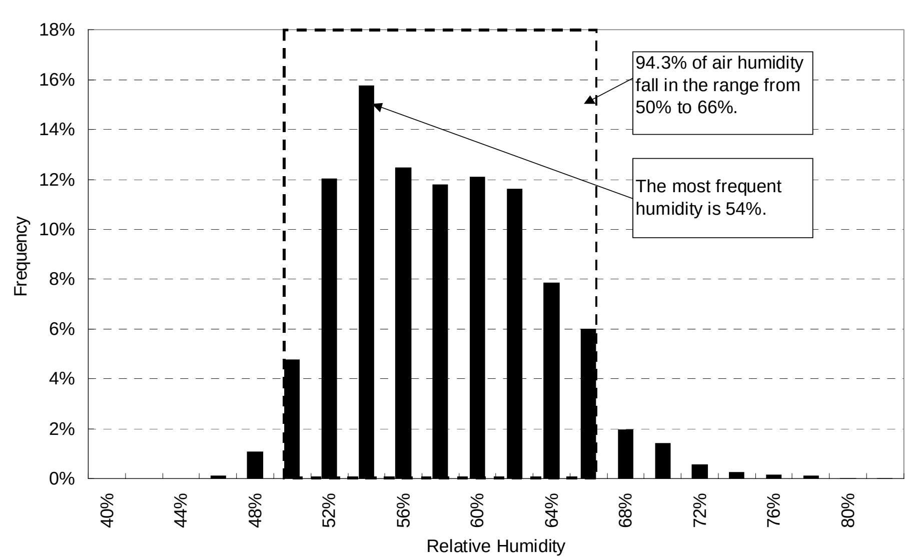


Figure 5. Statistical distribution of indoor air humidity in summer period

consumption and refrigerant flow rate did not show such a clear trend.

3. MODEL PARAMETERS, INPUTS, AND OUTPUT

3.1. Parameters

The necessary parameters are as follows.

a_0, a_1, a_2, a_3, a_4 – Fitted coefficients for the equation of C_h-C_f;

A_i, A_o, A_{fo} – Area of inlet, outlet and fan outlet of indoor unit, m^2;

C_{EV} – Flow rate coefficient of expansion valve;

D – Diameter of fan wheel, m;

e_0, e_1, e_2, e_3, e_4 – Fitted f coefficients for the equation of η-C_f;

ξ – Flow resistance coefficient of coil etc.;

3.2. Inputs

- Inputs for the first estimation method using indoor unit fan power consumption:

  N – Fan rotational speed;

  E –Fan power consumption, W;

- Inputs for the second estimation method using air-conditioner thermal performance data:

  N – Fan rotational speed;

  A_{EV} – Expansion valve orifice area, calculated from valve opening;

  P_{r1}, P_{r2}, P_{r3}, P_{r4}, – Refrigerant pressure at four state points;

  T_{ai} – Air temperature at the inlet of an indoor unit, ^{o}C;

  T_{ao} – Air temperature at the outlet of an indoor unit, ^{o}C;

  T_{r1}, T_{r2}, T_{r3} – Refrigerant temperature at three state points, ^{o}C;

3.3. Output

The model output is filter resistance.

ΔP_{ft} – Filter resistance to air flow, Pa;

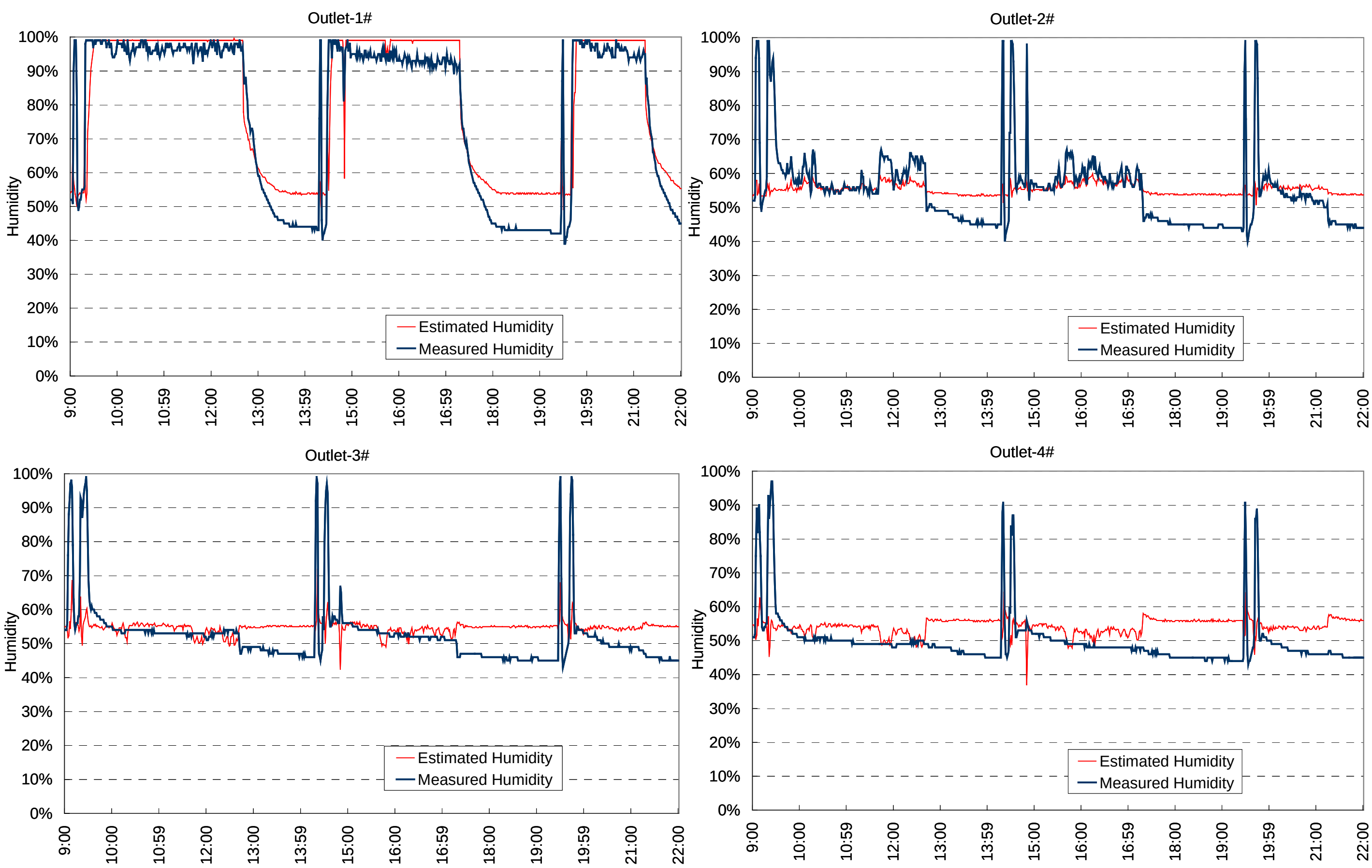


Figure 6. Estimated and measured outlet air humidity at four outlets

4. MODEL VALIDATION

In order to check the accuracy of this filter resistance estimation model, experiments were conducted during heating period since December 2003 to April 2004 on a multi-evaporator GHP system in an office building in Maibara Japan. Because this period is in winter, the GHP was running under heating operation and indoor units were running as condensers. Equation (10) was used to calculate air flow rate.

Firstly, a duct system, as shown in Figure 8, was constructed to make filters of different fouling level. Five filters having different resistance, which are 35 Pa, 50 Pa, 65 Pa, 80 Pa, and 90 Pa, were made for purpose of making an air-conditioner work at different filter resistance conditions.

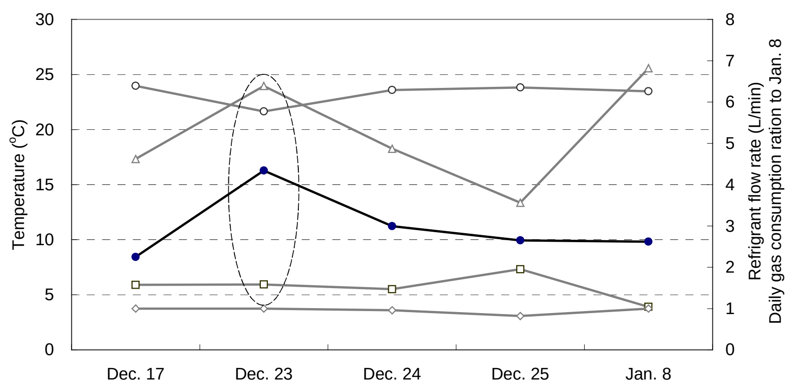
Next the five filters were installed into an air-conditioner's indoor unit respectively. Then the performance of the air-conditioner with different fouling level filter was measured.

Finally, the filter resistances were estimated using this model and compared with the measured filter resistances to check the estimation accuracy.

The profile of the experimental air-conditioner is listed in Table 1. The fan specification data used to fit the coefficients in the equations of C_h-C_f and η-C_f are listed in Table 2. The coefficients fitting results are shown in Figure 9. The parameters for the filter resistance estimation are listed in Table 3. The expansion valve orifice area is one of the inputs to the filter resistance estimation model. But in general only demanded valve opening from controller is available. It is necessary to know how to calculate valve orifice area from demanded valve opening. The relation between valve orifice area and demanded opening of the expansion valve in the experimental air-conditioner is shown in Figure 10. This figure shows the specification of the expansion valve, which can be used to calculate the valve orifice area from valve opening.

In this calculation, the refrigerant pressure loss in the coil of indoor unit is ignored during calculating refrigerant enthalpy, i.e. P_{r2} is assumed to be equal to P_{r3}.

4.1. Validation results of estimating using fan power consumption data



	Dec.1	Dec.2	Dec.2	Dec.2	Jan.8
1#	20	95	20	20	20
2#	20	95	20	20	20
3#	20	95	80	35	20
4#	20	95	65	50	20

Figure 7. An air-conditioner's performance vs. filter resistance

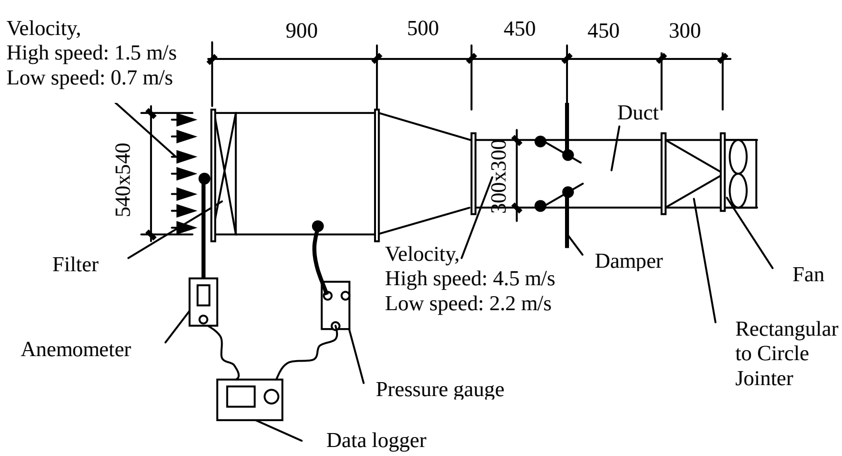


Figure 8. Ducts and instruments for making filters having different resistance

Table 1. Profile of the experimental air-conditioner

Heating/cooling capacity (kW)	42.5/35.5
Rated LPG consumption (heating/cooling kW) (LPG HHV=90.27MJ/Nm^3)	28.0/28.5
Refrigerant	R407C
Outdoor unit rated power (heating/cooling kW)	1.09/1.09
Outdoor unit fan rated air flow rate (m^3/min)	230
Indoor unit number	4

Table 2. Indoor unit fan specification data for coefficients fitting

Dimensionless flow rate C_f	Dimensionless pressure head C_h	Fan efficiency ratio to rated value * η/η_{rated}
0.3384	2.5731	100.00%
0.2956	2.6748	95.27%
0.2755	2.7579	92.97%
0.2232	3.0243	90.12%
0.1545	2.9508	64.15%

* In consideration of commercial secret, the absolute values of fan efficiency are not listed here.

The validation results of estimating filter resistance using indoor unit fan power consumption are shown in Figure 11. The validation results show that the maximum estimation error is 12.72% and the average estimation error is 5.89%. So the estimation using fan power consumption is accurate enough for estimating filter resistance during operating an air-conditioner.

Because of error accumulation, the estimated dimensionless flow rates are deviating from the dimensionless flow rates estimated using thermal performance data. A revising coefficient of 1.1609 is introduced to improve the estimation accuracy. The average estimation error did not become so small as 5.89% until this revising coefficient was introduced.

In order to validate the model universality, the coefficients fitted using one indoor unit data are used to estimate the filter resistance of three other indoor units whose model are same as the original indoor unit. The resistances of the filters currently used, pre-made 65 Pa filter and 95 Pa filter are measured and compared with the estimated resistance. The validation results are shown in Figure 13. Although the performance of the four units a littler differ from each other, the difference is not large. The filter resistances of three other indoor units estimated using the same parameters as the original indoor unit can match the measured filter resistances well. The maximum estimation error is 11.12% and the average estimation error is 4.88%. This estimation accuracy shows that the estimation using same parameter for all same model indoor units is acceptable.

4.2. Validation results of estimating using thermal performance data

The validation results of estimating filter resistance using air-conditioner's thermal are shown in Figure 12. The validation results show that the maximum estimation error is 13.12% and the average estimation error is 5.96%. So the model estimation is accurate enough for estimating filter resistance during the operation of an air-conditioner.

One issue that should be paid attention to is that the filter resistance estimation result is sensitive to refrigerant temperature when the refrigerant is not pure substance but mixture, such as R407C used in this experiment. For mixture refrigerant, the refrigerant density changes quite much if temperature changes even a little when refrigerant is in two-phase region. For example, when the temperature of R407C changes from 36.4^{o}C to 36.5^{o}C at the pressure of 1.5484 MPa, its density changes from 544.16 to 471.77 kg/m^3 because of the evaporation of some substance. The temperature difference of 0.1^{o}C, which is in the range of temperature measurement error, can make the refrigerant density change 13.3%. This sensitivity makes the estimation accuracy not stable. So when estimating filter resistance, some strange results that suddenly occurs should be eliminated from the data set.

5. MODEL-BASED COMMISSIONING METHOD

Automated commissioning of a filter in an air-conditioner is to continuously monitor the fouling situation of the filter to determine whether the filter resistance reaches the predetermined threshold during operation. This filter resistance estimation model can fulfill this purpose using the continuously measured air-conditioner thermal performance data or indoor unit fan power consumption data. The following procedure shows how to achieve automated commissioning using this filter resistance estimation model.

1) Fit coefficients

Table 3. Parameters for filter resistance estimation

a_0, a_1, a_2, a_3, a_4	-8.6443, 179.38, -978.54, 2255.3, -1893.1
A_i (m^2)	0.2916
A_o (m^2)	0.0706
A_{fo} (m^2)	0.1444
C_{EV}	0.6648
D (m)	0.46
e_0, e_1, e_2, e_3, e_4	-3.4639, 58.124, -327.01, 810.6, -742.63
ξ	2.1069

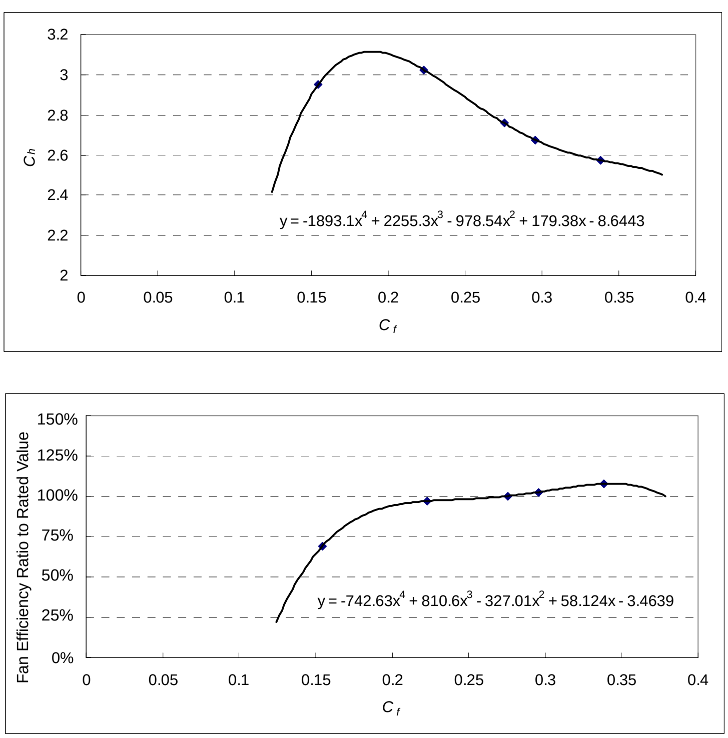


Figure 9. Coefficients fitting results of indoor unit fan

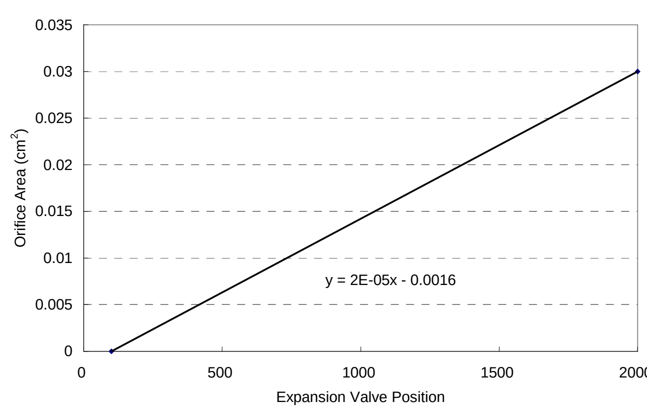


Figure 10. Expansion valve orifice area vs. controller demand

The first step is to fit the coefficients of a_0, a_1, a_2, a_3, a_4 in Equation (3) and e_0, e_1, e_2, e_3, e_4 in Equation (8). These coefficients should be fitted using the manufacturer data of the fan in the air-conditioner to be commissioned.

2) Determine parameters

The second step of using this model for commissioning is to determine all the parameters related, as listed in section 3.1.

3) Commissioning

- For the first method using indoor unit fan power consumption

Input fan rotational speed and real-time power consumption to the model to calculate the filter resistance.

- For the second method using air-conditioner thermal performance data

Input fan rotational speed, real-time expansion valve opening, air temperature at the inlet and outlet of the indoor unit, and refrigerant pressure and temperature to estimate the filter resistance. Then compare the estimated resistance with the resistance threshold of filter-cleaning to check whether the filter should be cleaned or not. The simulation flow is described in Figure 14 in detail.

6. CONCLUSIONS

This paper proposes a model to estimate filter resistance. Two ways are proposed to estimate filter resistance. One uses the power consumed by the indoor unit fan and the other uses the thermal performance data. If indoor unit fan power consumption is available, fan power consumptions are used as inputs to estimate filter resistance. If refrigerant pressure and temperature is available, this model estimates filter resistance using thermal performance data, i.e. refrigerant pressure and temperature, air temperature or enthalpy difference between outlet and inlet air. This model was validated using a multi-evaporator GHP system. The maximum and average difference between estimated and measured filter resistance are 12.72% and 5.89% when estimating using indoor unit fan power consumption, and 13.12% and 5.96% when estimating using the air-conditioner thermal performance data. Based on this model, the method for commissioning filters in air-conditioners is proposed. This method is useful for automatically estimating filter resistance and reminding users to clean or replace a filter in time.

NOMENCLATURE

a0, a1, a2, a3, a4	Fitted coefficients of fan pressure head vs. flow rate;
A	Area, m^2;
C_f	Dimensionless coefficient of flow rate;
C_h	Dimensionless coefficient of pressure head;
C_{EV}	Flow rate coefficient of expansion valve;
C_p	Specific heat, kJ/kg.k;
D	Diameter of fan wheel, m;
e_0, e_1, e_2, e_3, e_4	Fitted fan efficiency coefficients of fan efficiency vs. flow rate;
E	Fan power consumption, W;
h	Enthalpy, kJ/kg;
N	Fan rotation speed, r/s;
ΔP	Pressure difference, Pa;
V	Volume flow rate, m^3/s;

Greek letters

η	Efficiency;
ρ	Density, kg/m^3;
ξ	Local loss coefficient of coil etc.;

Subscriptions

a	air;
EV	Expansion valve;
f	Fan;
ft	Filter;
i	Inlet;
o	Outlet;
OC	Coil etc. other components except filter and fan;
r	Refrigerant;
s	Summer;
w	Winter;
1,2,3,4	State points in a refrigeration cycle, defined in Figure 2.

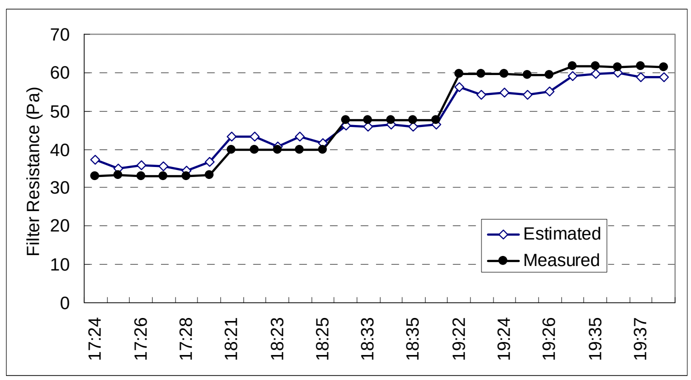


Figure 11. Validation results of estimating using fan power consumption

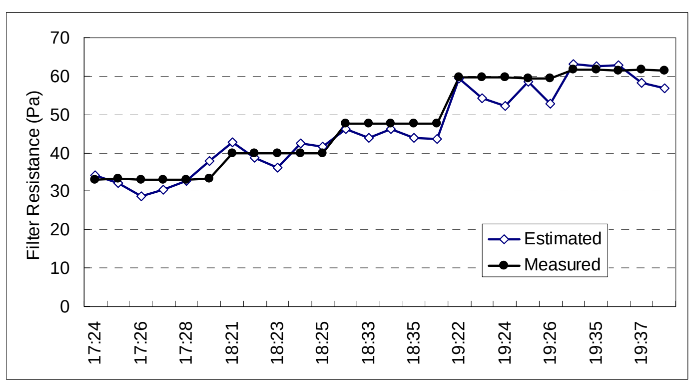


Figure 12. Validation results of estimating using thermal performance data

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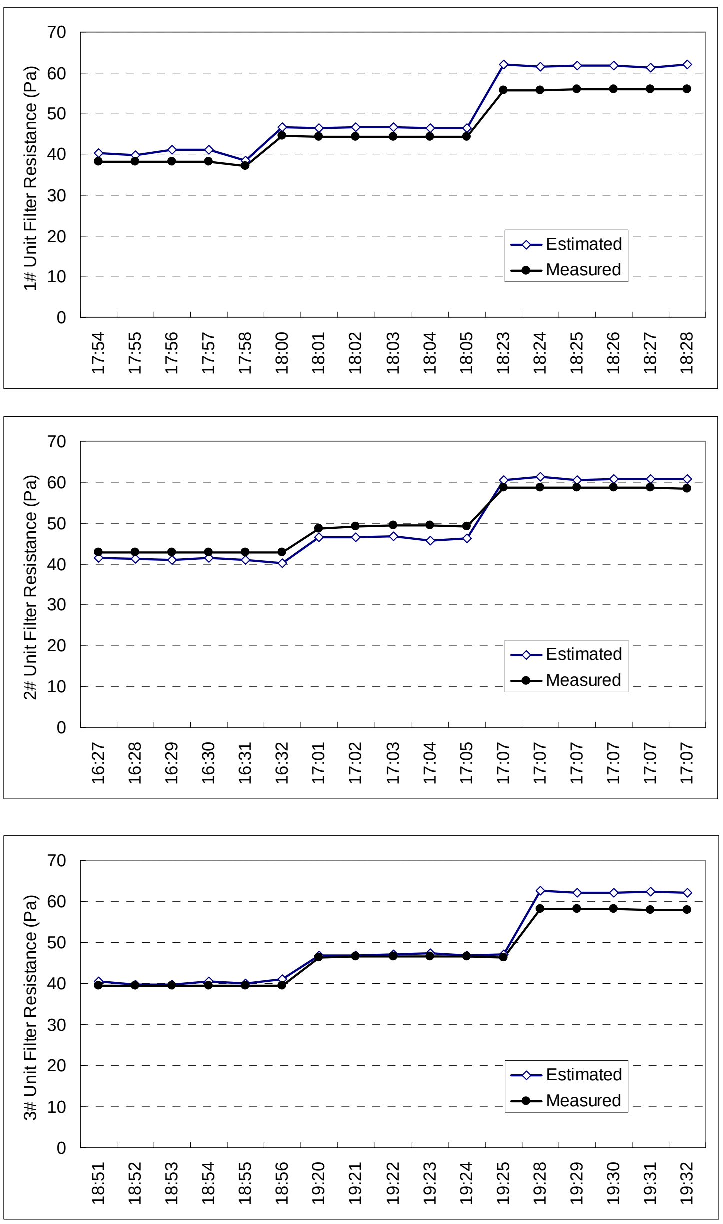

Figure 13. Filter resistance estimation results of three other indoor units

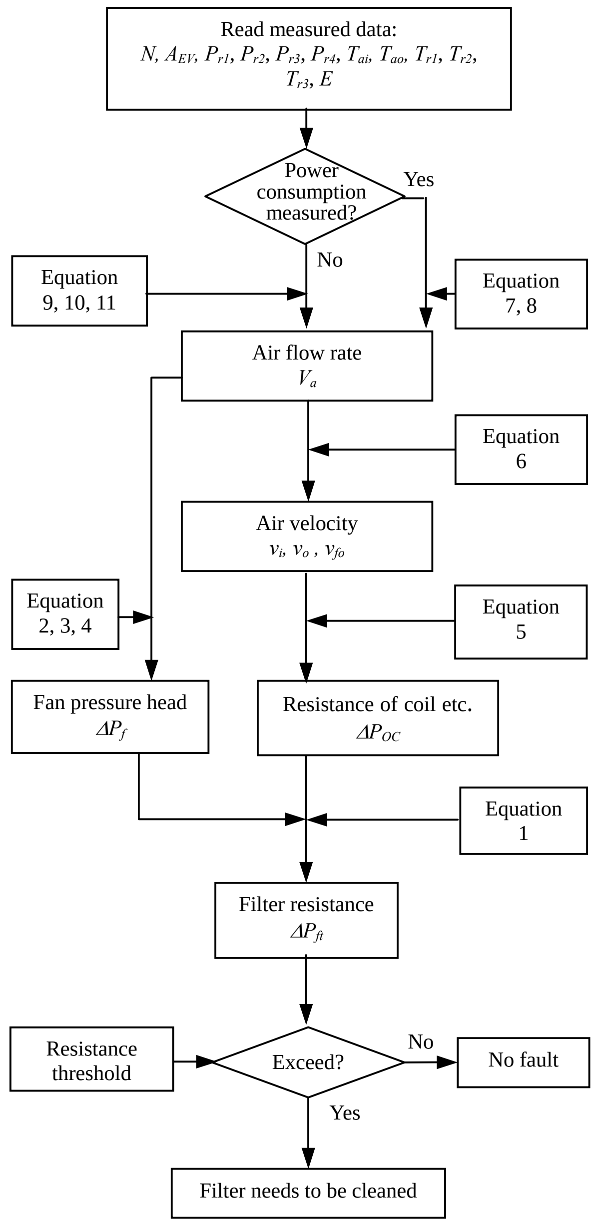

Figure 14. Flow chart of model-based automated commissioning for filters in air-conditioners