The Effect on Fouling Reduction by the Ball Cleaning System in a Compressed Type Refrigerator

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Key words: Fouling factor, Cooling water, Auto ball cleaning system(ABCS)

Abstract

The present study was conducted to estimate the effect on fouling reduction in tubes of the condenser. It shows in detail how to calculate the fouling factor from the experimental results of refrigeration systems with or without the automatic cleaning system using sponge balls and to predict the variation of the factor with time. It also represents how to calculate the temperature and pressure decrease of the refrigerant vapor in the condenser and the load decrease of the compressor in the refrigeration system by fouling reduction.

Nomenclature

A : area of heat transfer [m^2]
C_p : constant pressure specific heat [kJ/kg℃]
C_v : constant volume specific heat [kJ/kg℃]
h : enthalpy [kJ/kg]
k : specific heat ratio
$\dot{m}$: cooling water mass flow rate per unit tube [kg/s]
n : polytropic exponent
P : pressure [Pa]
P_H : high pressure [Pa]
P_L : low pressure [Pa]
Q : amount of heat transfer [W]
q : heat flux [W/m^2]
R : gas constant
R_f : fouling factor [m^2℃/W]
T_i : inlet temperature of cooling water [℃]
T_o : outlet temperature of cooling water [℃]
ΔT_{lm} : log-mean temperature difference [℃]
t : time [day]
U : overall heat transfer coefficient [W/m^2℃]
W : compressor work [W]
η_p : polytropic efficiency

Superscript

— : time average

Subscripts

cl : clean (no fouling)
f : fouling
con : condensation

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ev : evaporation
comp : compressor
comp' : compressor (after fouling formation)
sat : saturation
yr : year
1 : time lapse 1, high pressure, tube #1
2 : time lapse 2, low pressure, tube #2
∞ : long time

1. Introduction

Inside tube, a pile layer, namely, a fouling layer is formed by contamination like microbe or dust. In the case of the refrigerator, since the fouling layer disturbs heat exchange, the performance of refrigeration is decreased. The fouling layer causes the rise of the saturation pressure of the condenser, so the compressor has to work more. Thus, the fouling playes a role to decrease COP of refrigerating systems.

One way to prevent fouling due to cooling water is to remove fouling by circulating the sponge balls. It is, however, difficult to find the papers verified from field data on how the circulation of the sponge balls at condenser effects quantitatively the refrigeration efficiency.[1,2]

In this study, during a certain period the fouling factors were calculated for the cases of the practical refrigeration plant with ABCS and without ABCS and were predicted from the Kern-Seaton eq. (3) and (4). The saved electric power and energy saving, before and after installing the ABCS are compared.

2. Calculation of fouling factor

2.1 Induction of fouling factor

The amount of heat transferred from the shell and tube type heat exchanger, Q, is obtained as follows.

$$Q = UA\Delta T_{lm} \tag{1}$$

$$Q = \dot{m}C_p(T_o - T_i) \tag{2}$$

from eq. (1), (2), since thermal resistance is

$$\frac{1}{U} = \frac{A\Delta T_{lm}}{\dot{m}C_p(T_o - T_i)} \tag{3}$$

fouling factor (thermal resistance) R_f is

$$R_f = \frac{1}{U_f} - \frac{1}{U_{cl}} = \frac{A[(\Delta T_{lm})_f - (\Delta T_{lm})_{cl}]}{\dot{m}C_p(T_o - T_i)} \tag{4}$$

where,

$$\Delta T_{lm} = \frac{(T_{sat} - T_i) - (T_{sat} - T_o)}{\ln\dfrac{T_{sat} - T_i}{T_{sat} - T_o}} \tag{5}$$

2.2 Formulation of fouling factor from field data

Based on field data (at 15 : 00 pm only) from the 550 RT compressor type refrigerator which is being operated with the ABCS as shown in Fig. 1, the fouling factor is predicted. The dimension of this shell and tube type heat exchanger is as follows.

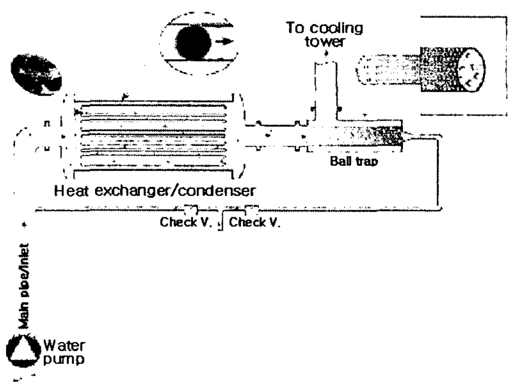

Fig. 1 Cleaning system by sponge balls in tubes.

Flow rate of cooling water : 0.256 kg/s
Inside shell : saturation steam
Inside tube : cooling water
length of a tube : 3,752 mm
Number of tube : 432
Number of Pass : 2
Material : copper
Refrigerant : R-134a
Tube I.D. : 15.7 mm
Tube thickness : 1.2 mm

Temperature and pressure measured during 40 days, from June 9, 1999 to July 19, 1999 are shown in Table 1. Based on July 19, calculation process is as follows.

2.2.1 The case of tube #1 (without circulation of the sponge balls)

Field data is as follows (see Table 1).

outlet temperature of cooling water T_o=36.4℃

inlet temperature of cooling water T_i=34.4℃

condensing temperature T_{sat}=40.8℃

ΔT_{lm}=5.34 K, q=8.358 kJ/kg, and $\frac{\dot{m}}{UA}$ =0.639 K/(kJ/kg).

2.2.2 The case of tube #3 (with circulation of the sponge balls)

Field data is as follows (see Table 1).

Table 1 Experimental result and data (#1, #2 tube; fouling, #3 tube; sponge ball cleaning)

items \ date	6/9	6/16	7/1	7/5	7/6	7/7	7/8	7/12	7/14	7/16	7/17	7/19
#1	0.514											0.638
#2	0.388			0.54					0.56			
#3				0.25					0.28			0.253
#1 T_o	31.8	31.7	32.1		31.4		32.5			34.8	35.7	36.4
T_i	29.9	28.7	29.0		28.1		28.6			31.9	33.4	34.4
T_{sat}	35.0	35.5	37.5		37.6		38.9			40.8	40.8	40.8
ΔT_{lm}	4.08	5.16	6.83		8.58		8.20			7.35	6.18	5.34
q	7.49	12.5	12.9		13.8		16.3			12.12	9.61	8.358
$\Delta T_{lm}/q$	0.514	0.413	0.529		0.622		0.503			0.606	0.643	0.639
$1/U_{f1}$ [m^2℃/kW]	0.400	0.321	0.411		0.483		0.391			0.471	0.500	0.497
#2 T_o	32.2			31.0		30.9		32.1	34.1		35.6	36.2
T_i	29.9			27.7		27.5		28.9	30.7		33.2	34.1
T_{sat}	34.9			36.9		37.4		38.1	40.8		40.5	40.8
ΔT_{lm}	3.73			7.43		8.08		7.49	8.28		6.02	5.58
q	9.612			13.8		14.2		13.4	14.2		10.0	8.77
$\Delta T_{lm}/q$	0.388			0.538		0.569		0.559	0.583		0.602	0.636
$1/U_{f2}$ [m^2℃/kW]	0.302			0.419		0.443		0.435	0.454		0.468	0.495
#3 T_o		32.1	32.5	30.9	31.5	30.9	33.2	33.0	34.6	35.9	33.8	37.4
T_i		29.9	29.0	27.7	28.2	27.5	29.3	29.3	30.7	32.1	33.6	34.1
T_{sat}		34.3	34.8	32.9	33.8	33.0	36.0	35.7	37.5	38.2	38.9	39.5
ΔT_{lm}		3.17	3.78	3.35	4.43	3.53	4.47	4.29	4.58	3.89	3.46	3.49
q		9.19	14.60	13.37	13.80	14.20	16.30	15.50	16.30	15.90	13.40	13.79
$\Delta T_{lm}/q$		0.344	0.259	0.251	0.321	0.249	0.274	0.277	0.281	0.245	0.258	0.253
$1/U$ [m^2℃/kW]		0.267	0.202	0.195	0.249	0.193	0.213	0.216	.0.219	0.191	0.201	0.215
R_{f1}: #1~#3		0.054	0.209		0.234		0.178			0.280	0.299	0.282
R_{f2}: #2~#3				0.224		0.250		0.219	0.235		0.267	0.280

outlet temperature of cooling water T_o=37.4℃

inlet temperature of cooling water T_i=34.1℃

condensing temperature T_{sat}=39.5℃

Since ΔT_{lm}=3.49 K and C_p=4.179 kJ/kgK.

From eq. (5), the amount of heat transferred by cooling water, q and $\dot{m}/UA$ are as follows.

$$q = C_p(T_o - T_i) = 13.79 \text{ kJ/kg}$$

$$\frac{\dot{m}}{UA} = \frac{\Delta T_{lm}}{q} = 0.253 ℃/(\text{kJ/kg})$$

2.2.3 Calculation of fouling factor

Temperature and pressure at each point obtained through the calculation process as above, are arranged in Table 1. The thermal resistance of tube #1, $1/U_{f1}$ in Table 1, is shown in Fig. 2, and tend to increase continuously due to fouling of cooling water. Fig. 3, however, shows that the thermal resistance of tube #3 is not increased even in a certain period because of circulating of the sponge balls. The fouling factor of tube #1, R_{f1} is calculated from the thermal resistance of tube #1 and the thermal resistance of tube #3. The fouling factor is arranged in the bottom of Table 1, and shown in Fig. 4.

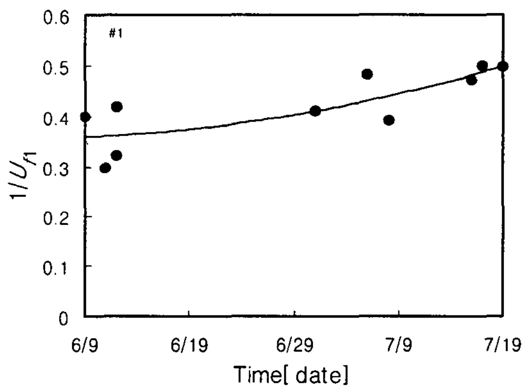

Fig. 2 Thermal resistance of #1 tube: $1/U_{f1}$ [m^2℃/kW].

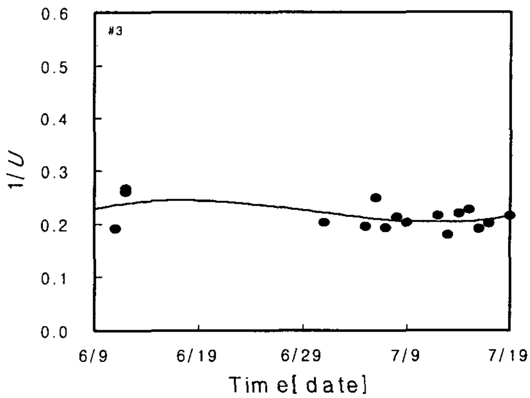

Fig. 3 Thermal resistance of #3 tube: $1/U$ [m^2℃/kW].

2.3 Prediction of the fouling factor on time

Although the data were recorded during 40 days, the fouling factor in longer time may be predicted from the following Kern-Seaton eq.

$$R_f = R_f^*(1 - e^{-t/t_c}) \tag{6}$$

If two points of time within a certain period are set t_1, t_2, two equations are obtained as follows.

$$\ln\left(1 - \frac{R_{f1}}{R_f^*}\right) = -\frac{t_1}{t_c} \tag{7}$$

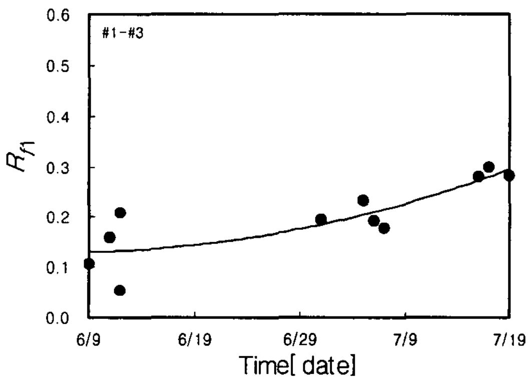

Fig. 4 Fouling factor of #1 tube: $R_{f1} = 1/U_{f1} - 1/U$.

$$\ln\left(1-\frac{R_{f2}}{R_f^*}\right) = -\frac{t_2}{t_c} \tag{8}$$

The following eq. can be obtained from eq. (7) and (8).

$$\frac{\ln\left(1-\frac{R_{f1}}{R_f^*}\right)}{\ln\left(1-\frac{R_{f2}}{R_f^*}\right)} = \frac{t_1}{t_2} \tag{9}$$

From eq. (8) and (9) R_f^* and t_c can be obtained using $1/U_1=0.182$ on June 29, in 20 days after installation day and $1/U_2=0.309$ on July 19, in 40 days after installation day in Fig. 4. The results are $R_f^*=0.6021$ and $t_c=55.6$ days.

So, the final fouling factor, R_f is as follows.

$$R_f = 0.6021(1-e^{-t/55.6}) \tag{10}$$

And in a long period of time

$$t\to\infty:\ R_{f,\infty} = R_f^* = 0.6021\ \mathrm{m^2℃/kW}.$$

Then, for tube #1 the fouling factor, R_f of eq. (10) is shown in Fig. 5.

Meanwhile, during a certain period, T, average fouling factor, $\overline{R_f}$ can be calculated as follows.

$$\overline{R_f} = \frac{R_f^*}{T}\int_0^T(1-e^{-t/t_c})\,dt \tag{11}$$

So, for 1 year (T=365 days), average fouling factor, $\overline{R_{f,yr}}=0.51\ \mathrm{m^2℃/kW}$.

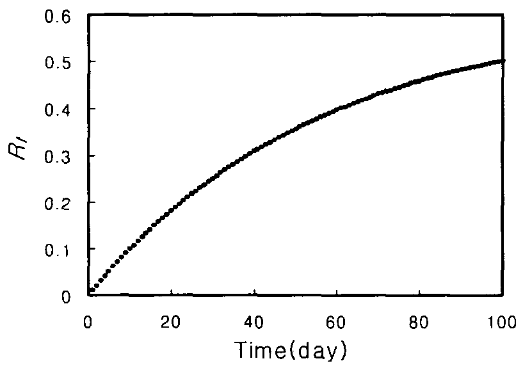

Fig. 5 Behavior of fouling factor of #1 tube: R_f [$\mathrm{m^2℃/kW}$].

3. Prediction of power saving effect

3.1 Calculation of temperature at condenser

Condensing temperature, $T_{sat,\infty}$ risen due to fouling in a long time can be obtained by making a iteration from eq. (4) and (5) and the result is $T_{sat,\infty}=49.2℃$. The values used in the calculation are as follows.

$A=0.1991\ \mathrm{m^2}$, $C_p=4.182\times10^3\ \mathrm{J/kg℃}$

$\dot{m}=0.256\ \mathrm{kg/s}$, $R_{f,\infty}=0.6021\times10^{-3}\ \mathrm{m^2℃/W}$

Based on July 16, the results of the calculation are shown in Table 2.

Table 2 Data at 7/16 [℃]

Tube	T_{ev}	T_{con}	T_i	T_o
# 1	7.9	40.8	31.9	34.8
# 3	7.1	38.2	32.1	35.9

The saturation temperature of refrigerant in the condenser of the refrigerator (#1) is predicted to rise from 40.8℃ to 49.2℃ due to fouling of tube (Table 3) in a long time period.

Table 3 Condition of each refrigerator

Date	item / tube	P_H (kPa)	P_L (kPa)	T_{ev} (℃)	T_{con} (℃)
7.16	# 1	938.0	307.3	9.5	40.8
$t\to\infty$	# 1_∞	1191.3	307.3	9.5	49.2
7.16	# 3	867.8	295.14	8.6	38.2

Meanwhile, the average condensing temperature in the condenser for a year, $\overline{T_{sat,yr}}$

can be obtained from $\overline{R_{f,yr}}$ =0.51 m²℃/kW and with the above method and the result is $\overline{T_{sat,yr}}$ =47.7℃. So, the saturation temperature of refrigerant in the condenser is predicted to be from 40.8℃ to 47.7℃.

3.2 Calculation of power of extra-compressor

In the refrigerator using R-134a[5] as refrigerant, in a long period of time, if the saturation temperature of refrigerant in the condenser is 49.2℃, then refrigerator condition is as Table 3. And $P-h$ diagram are shown in Fig. 6.

As shown in Fig. 6, while the pressure of the condenser is 867.8 kPa in the case of the ball cleaning tube, the pressure of condenser without ball cleaning system rises to 1191.3 kPa due to formation of fouling, so the compressor has to work more.

Meanwhile, if the average saturation temperature of refrigerant in the condenser for a year is 47.7℃, the saturation pressure of refrigerant becomes 1142.9 kPa. That average pressure of the condenser for a year rises from 867.8 kPa to 1142.9 kPa due to the formation of fouling and the rise of the load of compressor.

The power consumption of the compressor due to the pressure rise of refrigerant can be calculated as follows. The compression process is assumed to be polytropic, then polytropic efficiency, η_p, is considered. If the compressor work in the case of formation of fouling (tube #1) is set $W_{comp'}$ and that in the case of the ABCS (tube #3) is set W_{comp}, the ratio is as follows.

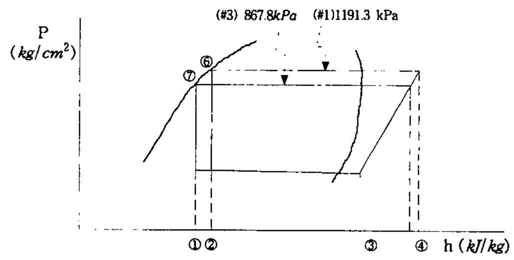

Fig. 6 $P-h$ diagram of R-134a refrigeration cycle.

$$Ratio = \frac{W_{comp'}}{W_{comp}} = \frac{W_{comp,\#1}}{W_{comp,\#3}} = \frac{\frac{n}{n-1} RT_1' \left[\left(\frac{P_2'}{P_1'} \right)^{\frac{n-1}{n}\frac{1}{\eta_p}} - 1 \right]}{\frac{n}{n-1} RT_1 \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}\frac{1}{\eta_p}} - 1 \right]} \qquad (12)$$

At 5℃, the evaporating temperature of R-134a the specific heat ratio is as follows.

$$k = \frac{C_p}{C_v} = \frac{0.825}{0.730} = 1.13 \qquad (13)$$

The fouling in the evaporator is not considered as follows.

$$T_1 = T_1', \quad P_1 = P_1' \qquad (14)$$

And we assumed the polytropic efficiency, η_p=0.8 and the polytropic exponent, $n = k$, respectively.

From those assumptions and eq. (12), the Ratio on July 16, in 37 days after installation day is 1.037. The compressor work in the case of tube #1 is consumed 3.7% more than in that of the ABCS (tube #3).

For a year, the average compressor's pressure of 1142.9 kPa is calculated, and the Ratio is 1.239, the compressor work is 23.9% more.

4. Calculation for power saving from field field data during long period of time

COP rises just after cleaning chemically or mechanically, fouling, however, is formed again as time lapsing. Comparing the effect after installation of the ABCS, a point of time in a long period of time after cleaning is selected a standard point.

Fig. 7 shows the thermal resistance measured. The thermal resistance before June 1, 1999 shows high value relatively. The thermal resistance rises up to 0.774 on Feb. 6, 1999. Especially on March 6, 1999, just before cleaning the thermal resistance is 0.663, a relatively high value, but after March 8, 1999, cleaning day, the thermal resistance as rapidly decreased to 0.269. That is to say, the thermal resistance is highly fluctuated on cleaning or not. After June 2, 1999, when the ABCS has installed, however, the thermal resistance was

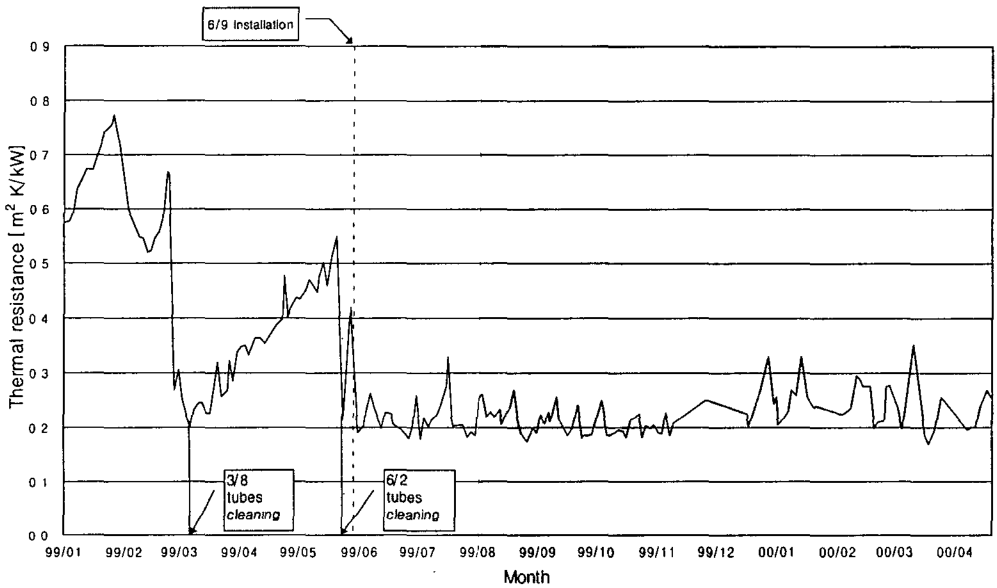

Fig. 7 Time dependent thermal resistance variation of tubes.

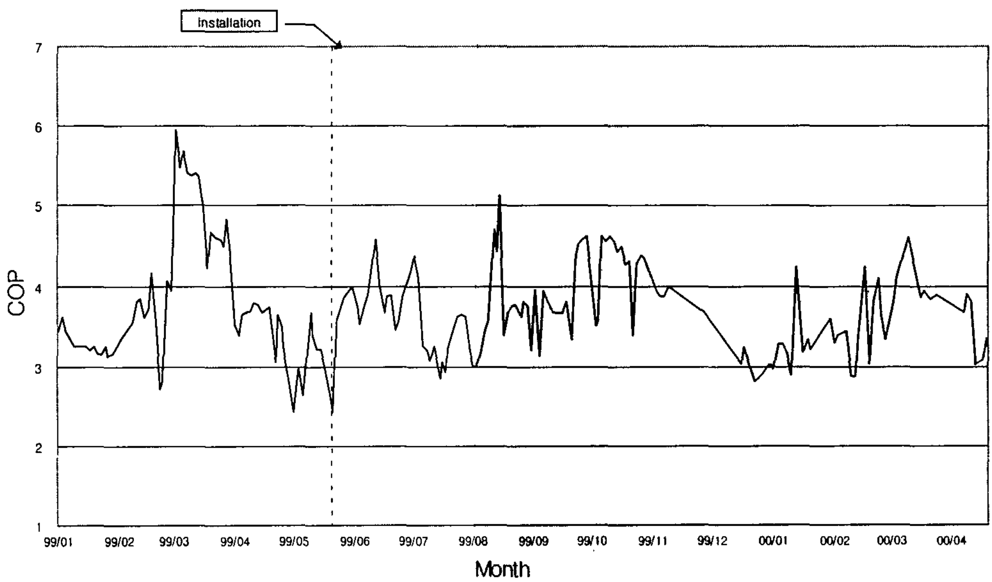

Fig. 8 Time dependent COP in the refrigeration system.

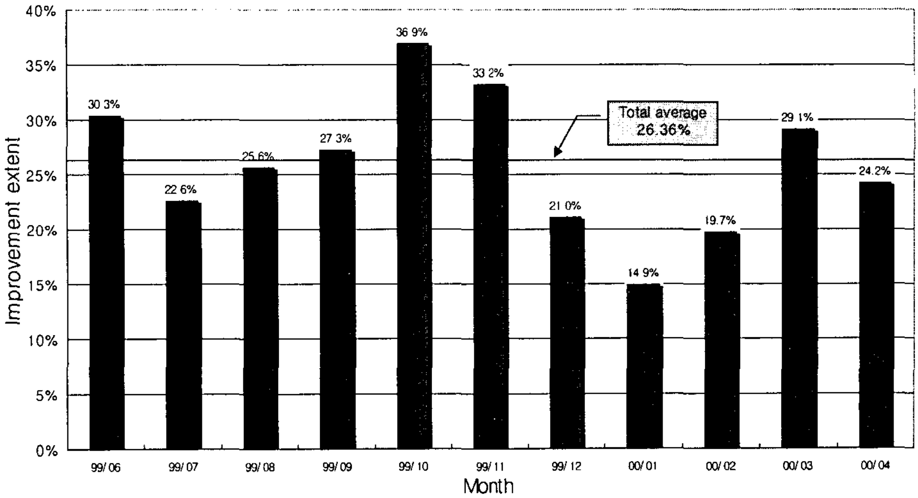

Fig. 9 Time dependent average of energy saving amount.

kept constantly in the range 0.2~0.3 m^2℃/kW.

Before June 2, 1999, when the ABCS was installed, the width of change (calculated from Fig. 7) for the thermal resistance, namely, standard deviation risen continuously from January to February, and the width of change for that was rapidly decreased on March, after cleaning. The width of change for that, namely, standard deviation, however, was nearly constant as extent to 0.03 after June, when the ABCS was installed.

The COP, namely, the amount of cold heat generated per unit electric power on time is shown in Fig. 8. As the result is predicted from the width of change for the thermal resistance, the COP is rapidly increased from 2.809 on March 6, before cleaning, to 4.074 on March 9, after cleaning. After the installation of the ABCS, COP is increased by 3.583 and kept more than 3.

COP is 2.978, 2.628, and 2.432, respectively, on May 28, May 31, and June 1, 1999, before installation of the ABCS and tend to decrease. It is adequate that average of COP of the refrigerator before installation of the ABCS is estimated as 2.678 considering a measurement error. So, we set COP_f as a standard of COP in a long time period after cleaning chemically, when the effect of cleaning is disappeared and the formation of fouling is very hard. The saving electric power with installation of the ABCS is calculated as follows.

$$\frac{\left(\frac{1}{COP}\right)_f - \left(\frac{1}{COP}\right)_{cl}}{\left(\frac{1}{COP}\right)_f} \times 100 \qquad (15)$$

Fig. 9 shows the amount of energy saving by installing of the ABCS. Comparing the data on the end of May, 1999, just before cleaning with the data on October, 1999, energy is saved up to 36.9% and the average saved energy in a year is 26.36%.

That is a little higher than the theoretically predicted maximum energy saving, 28.2%, and average energy saving 23.9%, however, seems to approximate to the predicted value relatively.

5. Conclusions

If the formation of fouling is restrained due to installation of the ABCS, the pressure of the compressor is low as much as that, the load of the compressor is reduced. So, the energy cost to be consumed is saved. The energy saving by the ABCS is predicted theoretically as much as 23.9% for a year and the energy saving by the ABCS is measured as 26.4% from the field data for a year.

The thermal resistance increases continuously from 0.27 m^2℃/kW to 0.55 m^2℃/kW as time goes by however, after installation of the ABCS the thermal resistance is kept in the range 0.2～0.3 m^2℃/kW.

Acknowledgement

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