Test Report of
CQM Auto Ball Cleaning System
for Condenser Tubes

Sep. 30, 2000

Korea Institute of Science and Technology

SUBMISSION

This is to submit as a final test report of
CQM Auto Ball Cleaning System
for the condenser tubes

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Principal Researcher : Dr. Yoon Pyo Lee(KIST)

Researcher : Sarng Woo Karng(KIST)

: Min-Cheol Shin(KIST)

Thermal Flow Control Research Center
Korea Institute of Science and Technology

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Summary

We circulate cooling water to cool down the condenser of refrigerators, and "Shell & Tube Type" is widely used. Usually cooling water goes through inside of the tubes. And in the shell, the condensing of refrigerant occurred. Cooling water used to be cooled in cooling tower, but lots of microbes, viruses and dust in the air go into the devices and may cause the formation of fouling which is a kind of deposit inside of the tubes. Fouling can be the thermal resistance of heat transfer of the condenser, so it bring about rising of refrigerant saturation temperature, for inefficiency of the cooling ability caused by fouling.

The rising of refrigerant saturation temperature may cause the rising of refrigerant saturation pressure, and compressor should do more work because of the raised saturation pressure. Thus it needs more electrical power to do more work. The COP(Coefficient of Performance) of the refrigerator could be determined by the works of compressor, eventually fouling makes refrigerator more inefficient.

In this study, we would like to analyse the effectiveness of CQM (Cooling Quality Management) Company's Auto Ball Cleaning System measured for fixed period of time.

Also we are going to calculate all amount of saved electric power and money comparing with before and after installing the “CQM Auto Ball Cleaning System”.

Chapter : Introduction

There are many ways to restrain the fouling, but 'chemical method' and 'brush method' are used ones. Both method has each demerits. While chemical cleaning should stop all systems to clean the fouling, but system of Brush Cleaning is complicated and expensive to maintain the Brush Cleaning System. Moreover the periodical chemical cleaning system which is usually used in the Korea has the weak point that it used to be getting more fouling as time goes even though it has good efficiency just after cleaned up - so the range of fluctuation of ability would be too big. On the other hand, cleaning by circulation ball sponge which keep out formation of fouling has a good point to keep a thermal resistance below the regulation but we should willingly submit stopping all the machine and taking out and washing the sponge ball periodically.

But CQM (Cooling Quality Management) Auto Ball System distributed by Dasan Industries Corp. has the merit that all of sponge balls wash by themselves while compressed air keep circulate the balls periodically so that we need not stop the machine to wash them.

The aim of this study is to analyze the spot investigation of CQM Auto Ball Cleaning System distributed by Dasan Industries Corp..

There were two difficult things in analyzing long-term investigation, one is it takes long time to make experiment on, and another is difficulty that to carry through perfect experiment not in laboratory but in the spot because this system should be installed on now-working refrigerator(on factory, for example). Considering these, we predicted an annual average by fouling formation theory based on 40-days experiment, and we compared the data actually recorded for one year. Being comparing between these - the predict and actual data -, we certificated the experiment.

Chapter : The Installation of
CQM Auto Ball Cleaning System

The Fig. 2-1 is the conception of CQM Auto Ball Cleaning System installed for this study. That is, it is designed that sponge balls are circulated inside of the condenser - heat exchanger - of refrigerator. In this circulation, fouling which formulated inside the condenser tubes are removed by the sponge balls, and then the balls are taken back to the entrance of cooling water which connected to the entry of condenser tube. And in this process, sponge balls are refreshed by themselves.

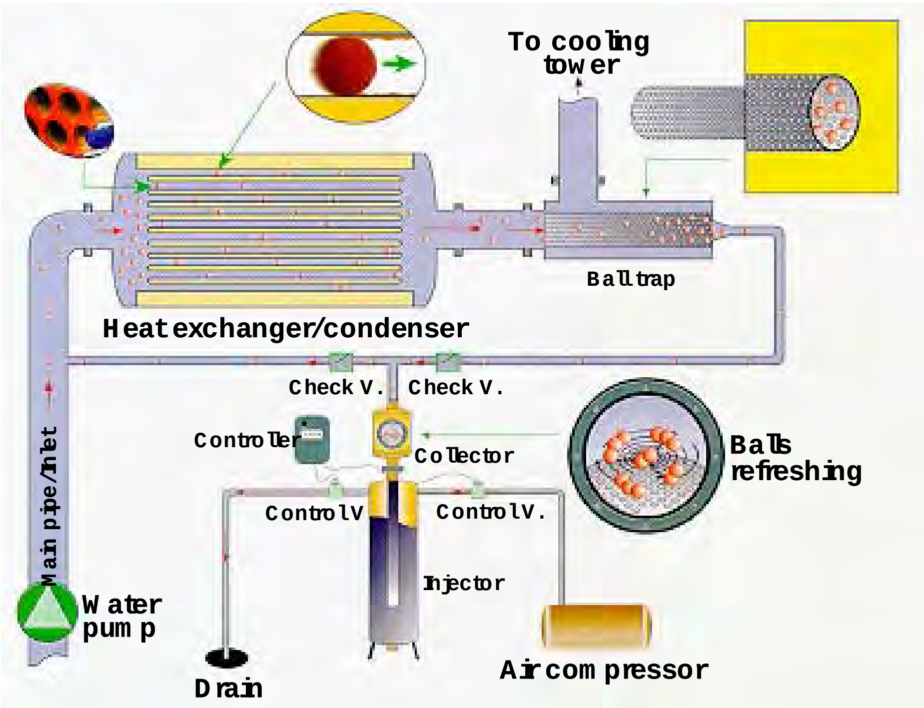


Fig. 2-1 : The conception of CQM Auto Ball Cleaning System

One of CQM Auto Ball Cleaning system was installed on the 550 RT class Turbo refrigerator #3 running on the ORION Electric Co., Ltd factory located in Kumi City, Kyung-buk Province. The date that all tubes were cleaned up was

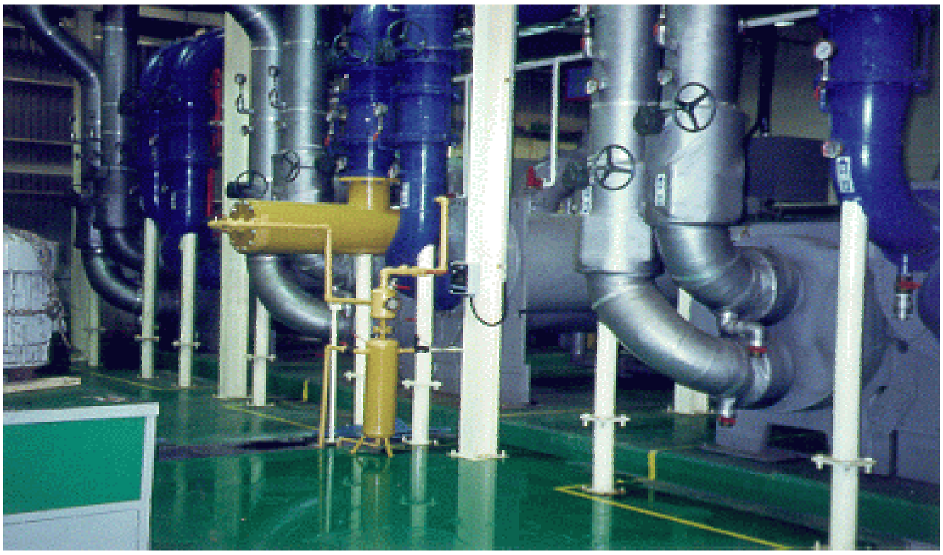
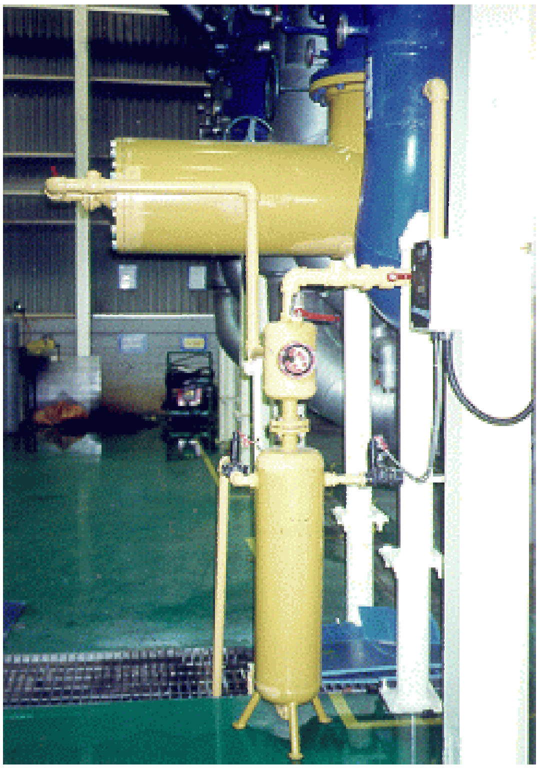
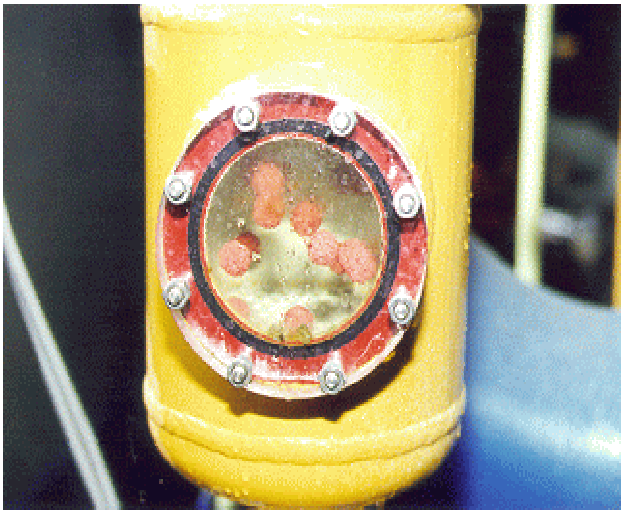


fig. 2-2　CQM Auto ball cleaning system





↑ (b) Auto self cleaning

← a) Sponge ball recirculator, controller and separator

Fig. 2-3　Detail of CQM Auto ball cleaning system(a, b)

And of June, 1999. and this system was started on 9th of June, 1999. CQM Auto Ball System is working up to now(September of 2000 at present). Fig. 2-2 is the whole picture of CQM, and Fig. 2-3 is enlarged CQM picture. Fig. 2-3(a) is the picture of sponge ball collector, controller and divider. And in Fig. 2-3(b), we took a photograph of the sponge balls refreshed by compressed air and whirlpool of water.

The condition of refrigerator and condenser on which installed the CQM is as follows :

- refrigerator capacity	: 550 RT
- type of heat exchanger :	: shell & tube
- inside of shell	: superheated vapor
- inside of tube	: cooling water
- number of tube	: 432
- arrangement	: 8
- number of pass	: 2
- length of tube	: 3752
- material	: copper
- inner diameter of tube	: 15.7
- thickness of tube	: 1.2
- refrigerant	:R-134a
- volume of cooling water	: 400 /h

Chapter : The Basis of Fouling Factor calculation by time

Now we will calculate fouling factor from each case whether CQM system installed or not, and will predict fouling factor by long-terms of time.

1. Formulation of Fouling Factor

We can write overall heat transfer U as follows ;

$$\frac{1}{U} = \frac{1}{h_{cond}} + \frac{A_0}{h_{tube} A_i} + \frac{A_0}{h_f A_i} + R_{metal}$$

(3.1)

$$R_{metal} = \frac{xA_0}{kA_m}$$

(3.2)

where is ;

h_{cond} : heat-transfer constant on condensing

h_{tube} : heat-transfer constant on circulation of cooling water

A_0 : area of tube outside

A_i : area of tube inside

A_m : average area of tube [(A_0+A_i)/2]

R_{meta} : thermal resistant of tube wall

k : thermal conductivity of tube wall

χ : thickness of tube

Subscripts

$_{cl}$: tubes without fouling

$_{d}$: tubes with fouling

sat : refrigerant condition on evaporator and condenser

We can express the calorie 'q' transferred per unit mass to next formula as we put the fouling factor: R_f, Transferred heat: Q, and heat transferred area per tube A.

$$\frac{1}{U_d} = \frac{1}{h_{cond}} + \frac{A_0}{h_{tube}A_i} + R_f + R_{metal} \tag{3.3}$$

$$\frac{1}{U_{cl}} = \frac{1}{h_{cond}} + \frac{A_0}{h_{tube}A_i} + R_{metal} \tag{3.4}$$

$$\frac{1}{U_d} - \frac{1}{U_{cl}} = R_f \tag{3.5}$$

$$\frac{1}{U_d A} - \frac{1}{U_{cl} A} = \frac{R_f}{A} \tag{3.6}$$

$$Q = UA\Delta T_{lm} \tag{3.7}$$

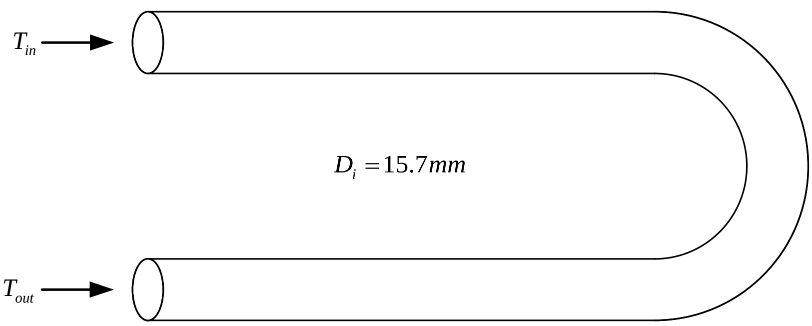
$$\Delta T_{lm} = \frac{(T_{sat} - T_i) - (T_{sat} - T_0)}{\ln\left(\frac{T_{sat} - T_i}{T_{sat} - T_0}\right)} \tag{3.8}$$

$$\frac{\Delta T_{lm}}{Q} = \frac{1}{UA} \tag{3.9}$$

$$\therefore \frac{R_f}{A} = \frac{1}{U_d A} - \frac{1}{U_{cl} A}$$

$$= \left(\frac{\Delta T_{lm}}{Q}\right)_d - \left(\frac{\Delta T_{lm}}{Q}\right)_{cl}$$

$$= \left(\frac{\Delta T_{lm}}{\dot{m}q}\right)_d - \left(\frac{\Delta T_{lm}}{\dot{m}q}\right)_{cl}$$



In this formula, ΔT_{lm} is log mean temperature, q is the transferred calorie per unit length, $\dot{m}$ is the mass current speed of the cooling water passing through one tube.

Supposing that the flux of cooling water inside tubes are same with fouling or not, we can lead one formula as follows :

$$\dot{m}_d = \dot{m}_{cl} = \dot{m} \tag{3.10}$$

$$q = \frac{\dot{Q}}{\dot{m}} = C_p\,(T_{out} - T_{inlet}) \tag{3.11}$$

$$\dot{m}q = \dot{Q} \tag{3.12}$$

$$\frac{\dot{m}}{A} R_f = \left(\frac{\Delta T_{lm}}{\dot{q}}\right)_d - \left(\frac{\Delta T_{lm}}{\dot{q}}\right)_{cl} \tag{3.13}$$

Now we calculate the mass flux of cooling water per 1 tube.

$$\dot{m} = \frac{\dot{M}}{n}$$

N : number of tubes (432)

M : volume of cooling water 400 /hr density of 30 water 995.6 /

So, we can calculate the mass current speed as follows :

$$\dot{m} = \frac{400\,\mathrm{m}^3/\mathrm{hr} \times \dfrac{1\mathrm{hr}}{3600\,\mathrm{sec}} \times 995.6\,\mathrm{kg}/\mathrm{m}^3}{432}$$

$$= 0.256\,\mathrm{kg}/\mathrm{sec}$$

And now we are able to get the fouling factor 'R_f' by putting the heat transfer area and the mass flux we got above into next formula.

$$R_f = \frac{A}{\dot{m}}\left[\left(\frac{\Delta T_{lm}}{q}\right)_d - \left(\frac{\Delta T_{lm}}{q}\right)_{cl}\right]$$

(3.14)

And the unit of fouling factor 'R_f' is as follows :

$$\mathrm{m}^2 \cdot \frac{\mathrm{sec}}{\mathrm{kg}} \cdot \frac{\mathrm{K}}{\mathrm{kJ}} \cdot \mathrm{kg} \Rightarrow \left[\mathrm{K} \cdot \mathrm{m}^2/\mathrm{kW}\right]$$

And it will be arranged as follows :

$$\dot{Q} = \dot{m}q = UA\Delta T_{lm} \tag{3.15}$$

$$\dot{m}q = \dot{m}C_p\left(T_o - T_i\right) \tag{3.16}$$

$$\Delta T_{lm} = \frac{\left(T_{sat} - T_i\right) - \left(T_{sat} - T_o\right)}{\ln\left(\dfrac{T_{sat} - T_i}{T_{sat} - T_o}\right)} \tag{3.8}$$

Auto Ball Cleaning System was installed on the cooling water tube outside of the refrigerator condenser #3. Supposing that there would not be any formation of fouling in this tube, the fouling factor of condenser tube #1 can be calculated owing to the thermal resistant difference between #1 and #3 refrigerator.

$$R_f = \frac{A}{\dot{m}} \frac{1}{C_p\left(T_o - T_i\right)} \left[\left\{ \frac{\left(T_{sat} - T_i\right) - \left(T_{sat} - T_o\right)}{\ln\left(\dfrac{T_{sat} - T_i}{T_{sat} - T_o}\right)} \right\}_1 - \left\{ \frac{\left(T_{sat} - T_i\right) - \left(T_{sat} - T_o\right)}{\ln\left(\dfrac{T_{sat} - T_i}{T_{sat} - T_o}\right)} \right\}_3 \right] \tag{3.17}$$

In the formula above, the 1st term of the braces [ ] is the #1 condenser tube's log mean temperature in case that being polluted, and 2nd term is the #3 condenser tube's unpolluted log mean temperature by circulating the sponge balls of CQM system.

2. Calculated Fouling Factor from Experimental Data

So now we would like to calculate fouling factor using above formulas by putting into the measured data installed refrigerator in ORION Electric Co., Ltd.

CQM Auto Ball Cleaning System was installed just on the #3 Condenser Tube (after this paragraph, #3 Tube) on 2nd of June 1999. We measured each parts' temperature and pressure of the #1 Tube(Auto Ball System was not installed) and #3 Tube(Auto Ball System was installed) during 40 days(1999.6.9 ~ 1999.7.19). And the data were arranged on the Table 3-1. For example of calculation as follows :

1) 15:00, 15th of July

#3 Tube (Auto Ball System was installed)

$$\Delta T_{lm} = \frac{(T_{sat} - T_i) - (T_{sat} - T_o)}{\ln\left(\frac{T_{sat} - T_i}{T_{sat} - T_o}\right)}$$

cooling water outlet temperature $T_o = 37.4°C$

cooling water inlet temperature $T_i = 34.1°C$

condensation temperature $T_{sat} = 39.5°C$

$$\Delta T_{lm} = \frac{(39.5 - 34.1) - (39.5 - 37.4)}{\ln\left(\frac{39.5 - 34.1}{39.5 - 37.4}\right)}$$
$$= 3.49K$$

$C_P = 4.179\,\mathrm{kJ/kg \cdot K}(30°\mathrm{C}, 40°\mathrm{C})$

Heat outgoing by cooling water, q_b is

$$q_b = \mathrm{C_p}\left(\mathrm{T_0} - \mathrm{T_i}\right)$$

$$q_b = 4.179\,\mathrm{kJ/kg\cdot K} \times \left(37.4 - 34.1\right)\mathrm{K}$$

$$= 13.79\,\mathrm{kJ/kg}$$

$$T_m = \frac{T_o + T_i}{2}$$

$$= \frac{37.4 + 34.1}{2} = 35.8°C$$

$$\frac{\dot{m}}{UA} = \frac{\Delta T_{lm}}{q_b} = \frac{3.49\mathrm{K}}{13.79\,\mathrm{kJ/kg}}$$

$$= 0.253\,\mathrm{K/(kJ/kg)}$$

#1 (Auto Ball System was not installed)

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

cooling water outlet temperature $T_o = 36.4°C$

cooling water inlet temperature $T_i = 34.4°C$

condensation temperature $T_{sat} = 40.8°C$

$$\Delta T_{lm} = \frac{\left(40.8 - 34.4\right) - \left(40.8 - 36.4\right)}{ln\left(\dfrac{40.8 - 34.4}{40.8 - 36.4}\right)}$$

$$= 5.34\mathrm{K}$$

$$\mathrm{C_P} = 4.179\,\mathrm{kJ/kg\cdot K}(30°\mathrm{C}, 40°\mathrm{C})$$

$$\dot{q} = \mathrm{C_p}(\mathrm{T_o} - \mathrm{T_i})$$

$$\dot{q} = 4.179\,\mathrm{kJ/kg\cdot K} \times (39.4 - 34.4)\mathrm{K}$$

$$= 8.358\,\mathrm{kJ/kg}$$

$$T_m = \frac{T_o + T_i}{2}$$

$$= \frac{36.4 + 34.4}{2} = 35.4°C$$

$$\frac{\dot{m}}{UA} = \frac{\Delta T_{lm}}{q} = \frac{5.34\mathrm{K}}{8.358\,\mathrm{kJ/kg}}$$

$$= 0.638\,\mathrm{K/(kJ/kg)}$$

where thermal resistance $\frac{1}{U}$ is

$$\frac{1}{U} = \frac{\Delta T_{lm}}{q} \times \frac{A}{\dot{m}} = \frac{5.34°\mathrm{C}}{8.358\,\mathrm{kJ/kg}} \times \frac{0.1992\mathrm{m}^2}{0.256\,\mathrm{kg/s}}$$

$$= 0.496\mathrm{m}^2\,°\mathrm{C/kW}$$

All of arranged information are shown on the Table 3-1.

On the Table 3-1, the curve of thermal resistant of the #1 (1/*U*) will be drawn like Fig. 3-1. That is, thermal resistant used to be rising up as time goes on account of fouling factor in the cooling water. Fig. 3-2 shows #3 Tube's thermal resistant graph refreshed by Auto Ball Cleaning System. We can recognize that there was no rise of thermal resistant in #3 Tube as time goes by, because tube was washed by sponge ball. For there is no fouling formation in #3 Tube by refreshing, fouling factor can be calculated by taking thermal resistant of #3 from that of #1, as we above-mentioned before, and let's put it to R_{f1} - the fouling factor of #1 Tube. It is arranged on the 2nd lane from bottom of Table 3-1, and a graph can be drawn like Fig. 3-3.

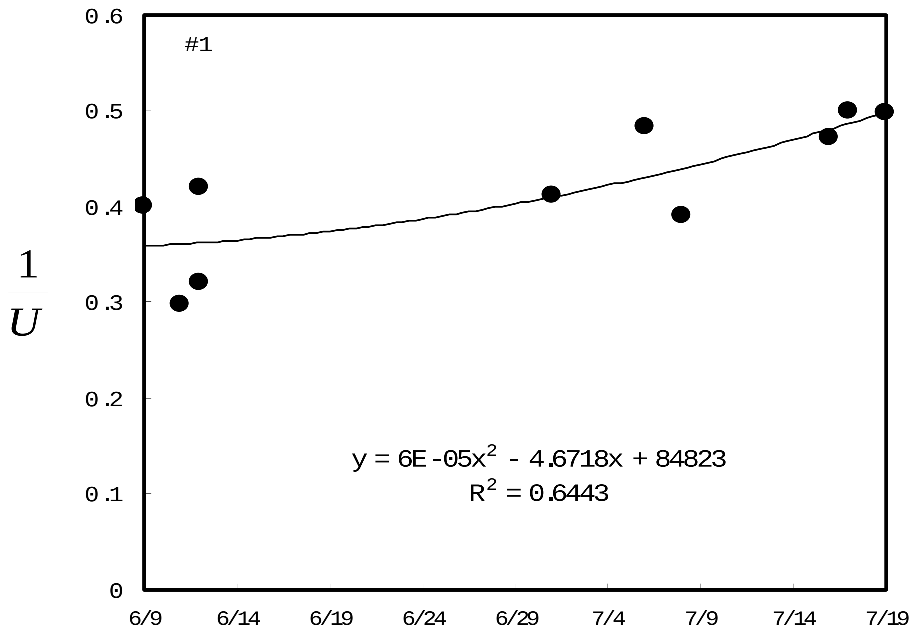


Fig. 3-1 The thermal resistant of #1 Tube

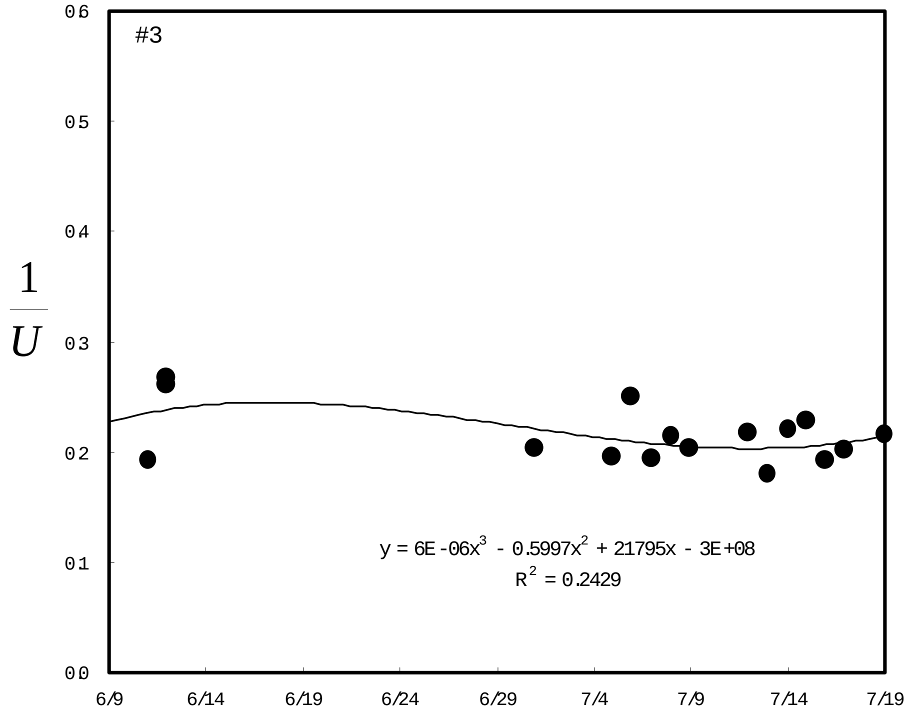


Fig. 3-2 The thermal resistant of #3 Tube

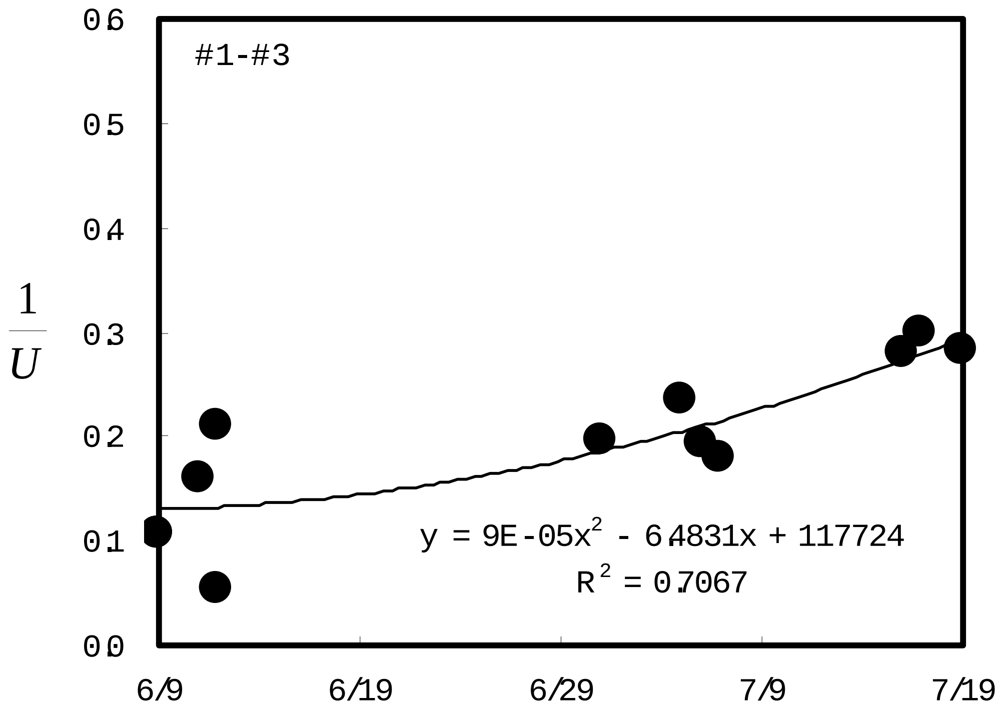


Fig. 3-3 The Fouling Factor of #1 Tube

Table 3-1 Experimental data from heat exchanger

(#1, #2tube; forming fouling(conventional type), #3tube; Auto Ball Cleaning System)

date / item	6/9	6/11	6/12	6/16	7/1	7/5	7/6	7/7	7/8	7/9	7/12	7/13	7/14	7/15	7/16	7/17	7/19
#1	0.514	0.38															0.638
#2	0.388					0.54							0.56				
#3		0.246				0.25							0.28				0.253
#1 T_o	31.8	30.1	31.4	31.7	32.1		31.4		32.5						34.8	35.7	36.4
T_i	29.9	27.3	29.5	28.7	29.0		28.1		28.6						31.9	33.4	34.4
T_{sat}	35.0	33.3	34.8	35.5	37.5		37.6		38.9						40.8	40.8	40.8
ΔT_m	4.08	4.45	4.28	5.16	6.83		8.58		8.20						7.35	6.18	5.34
$\dot{q}$	7.49	11.7	7.94	12.5	12.9		13.8		16.3						12.12	9.61	8.335
$\Delta T_m / \dot{q}$	0.514	0.383	0.539	0.413	0.529		0.622		0.503						0.606	0.643	0.639
$1/U$ [m²℃/kW]	0.400	0.298	0.419	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	32.4	34.1	33.3		35.6	36.2

T_i	29.9					27.7		27.5			28.9	28.1	30.7	29.9		33.2	34.1
T_{sat}	34.9					36.9		37.4			38.1	38.6	40.8	39.7		40.5	40.8
ΔT_m	3.73					7.43		8.08			7.49	8.16	8.28	7.98		6.02	5.58
$\dot{q}$	9.612					13.8		14.2			13.4	17.9	14.2	14.2		10.0	8.77
$\Delta T_m / \dot{q}$	0.388					0.538		0.569			0.559	0.456	0.583	0.562		0.602	0.636
$1/U$ [m^2℃/kW]	0.302					0.419		0.443			0.435	0.355	0.454	0.437		0.468	0.495
#3 T_o		30.5	31.6	32.1	32.5	30.9	31.5	30.9	33.2	30.5	33.0	33.4	34.6	34.0	35.9	33.8	37.4
T_i		27.2	29.3	29.9	29.0	27.7	28.2	27.5	29.3	27.0	29.3	28.3	30.7	30.2	32.1	33.6	34.1
T_{sat}		32.5	33.8	34.3	34.8	32.9	33.8	33.0	36.0	32.8	35.7	36.2	37.5	37.0	38.2	38.9	39.5
ΔT_m		3.39	3.21	3.17	3.78	3.35	4.43	3.53	4.47	3.78	4.29	4.92	4.58	4.64	3.89	3.46	3.34
$\dot{q}$		13.79	9.61	9.19	14.60	13.37	13.80	14.20	16.30	14.60	15.50	21.30	16.30	15.90	15.90	13.40	12.11
$\Delta T_m / \dot{q}$		0.246	0.334	0.334	0.259	0.251	0.321	0.249	0.274	0.259	0.277	0.231	0.281	0.292	0.245	0.258	0.276
$1/U$		0.191	0.260	0.267	0.202	0.195	0.249	0.193	0.213	0.202	0.216	0.179	0.219	0.227	0.191	0.201	0.215
#1- #3 (R_{f1})		0.107	0.159	0.054	0.209		0.234		0.178						0.280	0.299	0.282
#2- #3 (R_{f2})						0.224		0.250			0.219	0.176	0.235	0.210		0.267	0.280

3. Prediction of **Fouling Factor** by Time

Though we carried this experiment for 40 days, but we can predict the remote fouling factor using Kern-Seaton formula.

$$R_f = R^*_f (1 - e^{-t/t_c})$$

(3.18)

We need R^*_f and t_c data (use the result on the Fig. 3-3) to draw Kern-Seaton graph, and the course can be arranged like this :

R^*_f

$$R^*{}_f - R^*{}_f\, e^{-t/t_c} = R_f$$

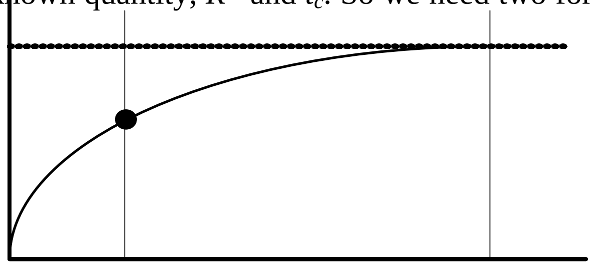
$R^*{}_f$

$$R^*{}_f - R_f = R^*{}_f\, e^{-t/t_c}$$

$$1 - \frac{R_f}{R^*{}_f} = e^{-t/t_c}$$

$$\ln\left(1 - \frac{R_f}{R^*{}_f}\right) = -t/t_c$$

In the above formula, there are two unknown quantity, R^* and t_c. So we need two formula to make them be known. That is :



$$\ln\left(1 - \frac{R_{f1}}{R^*{}_f}\right) = -\frac{t_1}{t_c}$$

$$\ln\left(1 - \frac{R_{f2}}{R^*{}_f}\right) = -\frac{t_2}{t_c}$$

$$t_c = -\frac{t_1}{\ln\left(1 - \frac{R_{f1}}{R^*{}_f}\right)}$$

$$t_c = -\frac{t_2}{\ln\left(1 - \frac{R_{f2}}{R^*{}_f}\right)}$$

If we put the two clause same ;

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

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

There are two unknown quantity as above($R^*{}_f$ and t_c), so we should make two formula like in the below, after reading two groups of data. Doing this, we can calculate $R^*{}_f$ of 29th of June(20 after installation) and 19th of July(40 days after installation), by putting into each of $1/U$, 0.182 and 0.309.

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

$$f(R^*_f) = \frac{\ln\left(1-\frac{0.182}{R^*_f}\right)}{\ln\left(1-\frac{0.309}{R^*_f}\right)} = \frac{20}{40}$$

In the first place, we find R^*_f when $f(R^*_f)$ became 0, using iteration techniques.

R^*_f

R^*_f	$f(R^*_f)$
0.65	0.000924
0.625	0.0046
0.62	0.0036
0.61	0.00164
0.605	0.000590
0.6025	0.000053

R^*_f

R^*_f	$f(R^*_f)$
0.4	-0.09
0.5	-0.0297
0.6	-0.00049
0.7	0.01703

When R^*_f is R^*_f=0.6021, $f(R^*_f)$ become 0. Thus, we can get t_c from R^*_f as follows :

$$t_c = -\frac{t_2}{\ln\left(1-\frac{R_{f2}}{R^*_f}\right)}$$

$$\therefore t_c = -\frac{40}{\ln\left(1-\frac{0.309}{0.6021}\right)}$$

$$= 55.6\ days$$

So, it took 55.6 days since fouling factor came to 63.2% after long term of the time, and the final fouling factor R_f is :

$$R_f = R^*{}_f \left(1 - e^{-t/t_c}\right)$$
$$\therefore R_f = 0.6021\left(1 - e^{-t/55.6}\right)$$
$$t \to \infty\ ; R_f = 0.6021\ \mathrm{m^2\,°C/kW}$$

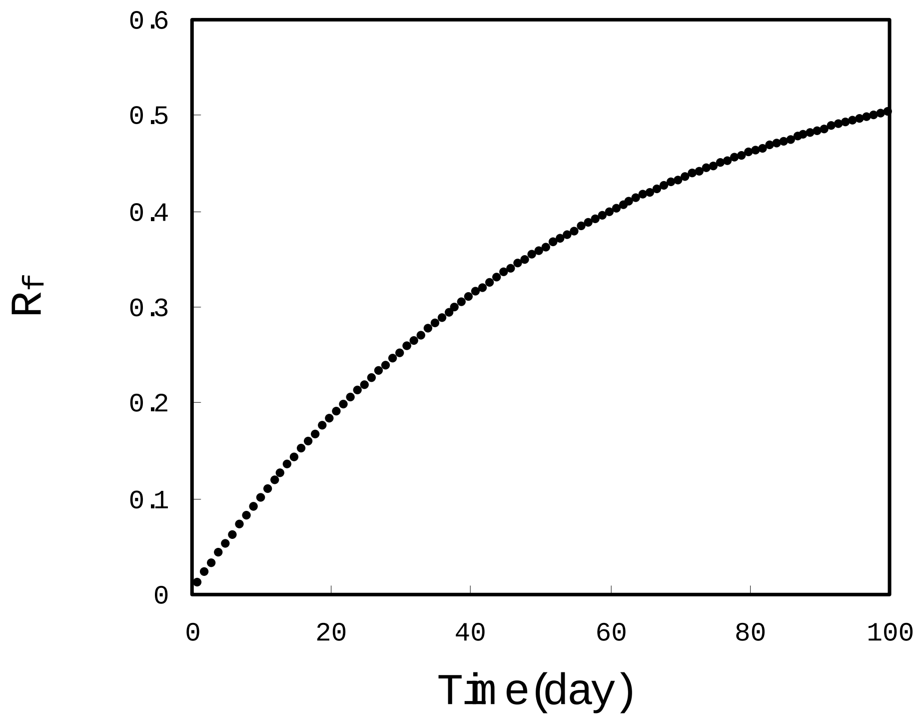


Fig. 3-4　Fouling factor of #1 tube on time [$\mathrm{m^2\,°C/kW}$]

And we should put the letter '*t*' days after beginning of the investigation. In this way, we can get Kern-Seaton graph(Fig. 3-4) showing the change of fouling factor by time, from observed #1 Tube data in this experiment.

Meanwhile, the average fouling factor R_f during a period time T can be calculated as follows :

$$
\begin{aligned}
\overline{R}_f &= \frac{R_f}{T} = \frac{R_f^*}{T}\int_0^T \left(1 - e^{-t/t_c}\,dt\right) \\
&= \frac{R_f^*}{T}\int_0^T dt - \frac{R_f^*}{T}\int_0^T e^{-t/t_c}\,dt \\
&= R_f^* - \frac{R_f^*}{T}\left[t_c\left(1 - e^{-T/t_c}\right)\right] \\
&= R_f^*\left(1 - \frac{t_c}{T} + \frac{e^{-T/t_c}}{T}\right)
\end{aligned}
$$

So, we can predict annual mean thermal resistant like below :

$$
\begin{aligned}
\overline{R_f} &= 0.6021\times 10^{-3}\left(1 - \frac{55.6}{365} + \frac{e^{-365/55.6}}{365}\right) \\
&= 0.6021\times 0.847\times 10^{-3} \\
&= 0.510\times 10^{-3}
\end{aligned}
$$

Chapter : Expectation for the Effect by Time of **CQM Auto Ball Cleaning System**

1. Prediction of Condensing Temperature Rising

It is known that the increasement of fouling factor by cooling water in the tubes could cause the rise of saturation temperature in the condenser because heat transfer in the tube would be interrupted by fouling factor. The condensing temperature of converged fouling factor T_{sat} can be derived using iteration method from eq. (3-17) as follows :

For example, 15:00, 16th of July [ ];

tube	vaporization temperature	condensing temperature	input temperature of the cooling water	output temperature of the cooling water
#1	7.9	40.8	31.9	34.8
#3	7.1	38.2	32.1	35.9
		T_{sat}	T_i	T_o

$A = 0.1992\ \text{m}^2,\quad C_p = 4.182\times 10^3\ \ \text{J/kg°C}$

$\dot{m} = 0.256\ \text{kg/s},\quad R_f = 0.6021\times 10^{-3}\ \text{m}^2\,\text{°C/W}$

And it will be calculated from eq. (3-17) as follows :

$$f(T_{sat}) = 0.6021\times 10^{-3} - \frac{0.1992}{0.256}\times\frac{1}{4.182\times 10^3(35.9-32.1)}\times\left[\frac{(T_{sat}-31.9)-(T_{sat}-34.8)}{ln\left(\dfrac{T_{sat}-31.9}{T_{sat}-34.8}\right)} - \frac{(38.2-32.1)-(38.2-35.9)}{ln\left(\dfrac{38.2-32.1}{38.2-35.9}\right)}\right]$$

T_{sat}	$f(T_{sat})$

40.0	0.000459
45.0	0.0002038
47.0	0.000102
49.0	0.00000456
49.5	-0.00002494
50.0	-0.0000503

$\therefore (T_{sat})_{\tau \to \infty} = 49.2$ °C

So we can predict that after long period of time refrigerant saturation temperature raised up from 40.8 to 49.2 for there was no inefficient heat transfer between cooling water and refrigerant due to tube fouling.

Meanwhile, the annual average saturation temperature of the condenser T_{sat} can be got with same iteration method :

$$f\left(\overline{T_{sat}}\right) = 0.510 \times 10^{-3} - \frac{0.1992}{0.256} \times \frac{1}{4.182 \times 10^{3}(35.9 - 32.1)} \times \left[\frac{(\overline{T_{sat}} - 31.9) - (\overline{T_{sat}} - 34.8)}{\ln\left(\dfrac{\overline{T_{sat}} - 31.9}{\overline{T_{sat}} - 34.8}\right)} - \frac{(38.2 - 32.1) - (38.2 - 35.9)}{\ln\left(\dfrac{38.2 - 32.1}{38.2 - 35.9}\right)} \right]$$

T_{sat}	$f(T_{sat})$
47.0	0.035
47.5	0.0104
47.7	0.00063
47.8	-0.00407

$\therefore (\overline{T_{sat}})_{1yr.\to average} = 47.7°C$

So, we can predict that refrigerant saturation temperature inside the condenser will rise up from 40.8 to 47.7

2. Economical Expectation for the Effect of **CQM Auto Ball Cleaning System**

If the refrigerant(R-134a) saturation temperature on condenser would be 49.2 after long period of time, we can read this saturation temperature from R-134a saturation curve(see attachments). We can arrange this result as follows :

Refrigerant : R-134a

Refrigerator Condition

Date	item / refri-gerator	High Pressure [kPa]	Low Pressure [kPa]	Vaporization Temperature ( )	Condensation Temperature ( )
7/16	#1	938.0	307.3	9.5	40.8
t →	#1	1191.3	307.3	9.5	49.2
7/16	#3	867.8	295.14	8.6	38.2

And Fig. 4-1 shows *P-h* diagram.

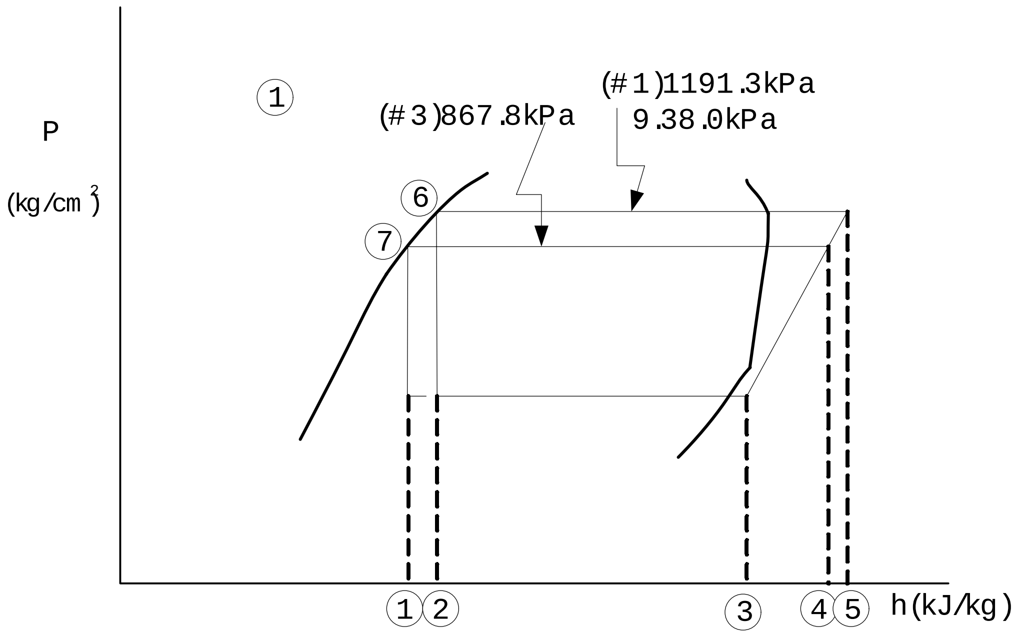


Fig. 4-1 *P-h* diagram of R-134a refrigerator cycle

In the refreshing tube(with Auto Ball Cleaning System, #3), the pressure of condenser was 867.8 kPa. But on the other hand, the condenser pressure was raised up 1191.3 kPa by means of fouling formation inside the tube(without Auto Ball Cleaning System, #1), so the compressor have to do more work to cool them.

Meanwhile, considering to annual average, if the condenser refrigerant saturation temperature would be 47.7 , we could guess refrigerant saturation temperature from R-134 saturation graph. And it could be arranged as follow :

Date	item / refri-gerator	High Pressure [kPa]	Low Pressure [kPa]	Vaporization Temperature ( )	Compression Temperature ( )
7/16	#1	938.0	307.3	9.5	40.8
one year's average	#1 1yr's ave	1142.9	307.3	9.5	47.7
7/16	#3	867.8	295.14	8.6	38.2

That is, if we take an average supposing that fouling is formed, the condenser pressure would be raised up from 867.8 kPa to 1142.9 kPa and make the compressor's work more harder.

We can calculate necessary power of compressor according to fouling as follows. And we need to calculate it, supposing the compression course get through polytropic process.

$$W = \int v dp$$

$$pv^n = C$$

$$v = \left(\frac{C}{p} \right)^{\frac{1}{n}}$$

$$W = C^{\frac{1}{n}} \int p^{-\frac{1}{n}} dp$$

$$= C^{\frac{1}{n}} \frac{n}{n-1} \left[p^{\frac{n-1}{n}} \right]_1^2$$

$$= (pv^n)^{\frac{1}{n}} \frac{n}{n-1} \left[p_2^{\frac{n-1}{n}} - p_1^{\frac{n-1}{n}} \right]$$

$$= \frac{n}{n-1} \left[p_2^{\frac{1}{n}+1-\frac{1}{n}} v_2 - p_1^{\frac{1}{n}+1-\frac{1}{n}} v_1 \right]$$

$$= \frac{n}{n-1} (p_2 v_2 - p_1 v_1)$$

$$= \frac{n}{n-1} RT_1 \left[\frac{p_2}{p_1} \left(\frac{p_1}{p_2} \right)^{\frac{1}{n}} - 1 \right]$$

$$= \frac{n}{n-1} RT_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]$$

$$pv^n = C$$

$$\frac{v_2}{v_1} = \left(\frac{p_1}{p_2} \right)^{\frac{1}{n}}$$

$$p_1 v_1 = RT_1$$

And, considering polytropic efficiency η_p, first we give the letter to the compression work with fouling formation as $W_{comp'}$, with Auto Ball Cleaning System as W_{comp}, and the ratio would be :

$$ratio = \frac{W_{comp'}}{W_{comp}} = \frac{\frac{n}{n-1} RT'_1 \left[\left(\frac{p_2'}{p_1'} \right)^{\frac{n-1}{n}\frac{1}{\eta_p}} - 1 \right]}{\frac{n}{n-1} RT_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}\frac{1}{\eta_p}} - 1 \right]}$$

(4.1)

In this investigation, there is fouling formation inside #1 tube contrary to there is no fouling formation inside #3, so the work ratio can be arranged by this formula :

$$ratio = \frac{W_{comp\ \#1}}{W_{comp\ \#3}}$$

In addition to this, we can get the specific heat ratio by putting into definite number. So to speak, the specific heat ratio when vaporization temperature of R-134a is 5   would be :

$$k = \frac{C_p}{C_v} = \frac{0.825}{0.730} = 1.13$$

And evaporator has no relation to this fouling, so :

$$T_1 = T_1', \quad p_1 = p_1'$$

Supposing that polytropic efficiency η is 0.8, and also supposing polytropic constant $n = k(n = 1.13)$, and put these into formula 4-1, so we can recognize that :

$$\#1\, tube\ ratio = \frac{\left(\frac{938}{307.3}\right)^{\frac{0.13}{1.13}\times\frac{1}{0.8}} - 1}{\left(\frac{867.8}{295.14}\right)^{\frac{0.13}{1.13}\times\frac{1}{0.8}} - 1} = 1.037(3.7\% \quad increasement)$$

the condenser #1 (without Auto Ball Cleaning System) should do 3.7% more work than the condenser #3 (with Auto Ball Cleaning System).

And also we can recognize that if the fouling formation goes on till limit :

$$\#1_{\underset{tube}{\tau\to\infty}}\ ratio = \frac{\left(\frac{1191.3}{307.3}\right)^{\frac{0.13}{1.13}\times\frac{1}{0.8}} - 1}{\left(\frac{867.8}{295.14}\right)^{\frac{0.13}{1.13}\times\frac{1}{0.8}} - 1} = 1.282(28.2\% \quad increasement)$$

The condenser have to do 28.2% more work.

Thinking of annual average, just doing calculation exchanging 1191.3 into 1142.9. The result value would be 1.239, and it shows that the compressor's work have been increased to 23.9%.

Chapter : Analysis for the Effect of **CQM Auto Ball Cleaning System**

1. Calculating of Thermal resistance by Time

In Chapter , we knew the fact that the thermal resistant was decreased by installing Auto Ball Cleaning System and the work of compressor would be decreased because of this. In this chapter, we will effect an inspection of evidence before and after installation of CQM Auto Ball Cleaning System. That is, we will compare with #3 condenser(550 RT) of the OROIN Electric Co., Ltd before & after installation regarding the day tubes were cleaned up on 2nd of June, 1999 as a fiducial point.

The table below(Table 5-1) shows each parts' measuring just before installation of Auto Ball Cleaning System(1st of June, 1999).

Table 5-1, Measuring of #3 Compressor

Date	Entrance of Cold water	Exit of Cold water	Input Temp. Of Cooling water	Output Temp. Of Cooling water	Compression Temp. of Refrigerant	Electrical Current Intensity
1/Jun 1999 PM 3	8.8	6.4	28.5	30.8	35.3	67 A/s
11/Jun 1999	10.2	6.5	27.2	30.5	32.5	63 A/s

PM 3						

Now we are going to calculate thermal resistant using the data of 1st of June, 1999.

Condensation temperature $T_{sat} = 35.3\,°C$

Cooling water inlet temperature $T_{in} = 28.5\,°C$

Cooling water outlet temperature $T_{out} = 30.8\,°C$

The log mean temperature - it's a remainder of refrigerant compression temperature and mean temperature of cooling water - is as follow :

$$\Delta T_{lm} = \frac{(T_{sat} - T_{in}) - (T_{sat} - T_{out})}{\ln\left(\dfrac{T_{sat} - T_{in}}{T_{sat} - T_{out}}\right)}$$

$$= \frac{(35.3 - 28.5) - (35.3 - 30.8)}{\ln\left(\dfrac{35.3 - 28.5}{35.3 - 30.8}\right)}$$

$$= 5.571$$

The amount of calories has taken by cooling water :

$$q = C_p(T_{out} - T_{in})$$

$$C_p = 4.180 \text{ kJ / kg °C}$$

$$q = 4.180 \times (30.8 - 28.5)$$

$$= 9.614 \text{kJ / kg}$$

The thermal resistant formula on the heat transfer from condenser to cooling water is as follow :

$$\frac{\dot{m}}{A}\frac{1}{U} = \frac{\Delta T_{lm}}{q}$$

$$= \frac{5.571}{9.614} = 0.579\ °\mathrm{C}/\mathrm{kJ}/\mathrm{kg}$$

Next, we can calculate thermal resistant $1/U$ as follows :

$$\frac{1}{U} = \frac{\Delta T_{lm}}{q} = \frac{A}{\dot{m}} = \frac{5.571°\mathrm{C}}{9.614\mathrm{kJ}/\mathrm{kg}} \times \frac{0.1992\mathrm{m}^2}{0.259\mathrm{kg}/\mathrm{s}}$$

$$= 0.451\mathrm{m}^2\,°\mathrm{C}/\mathrm{kW}$$

Simply speaking, it needs 0.451 temperature difference of cooling water to deprive 1 kW heat capacity of refrigerator.

But the other side, thermal resistant of on the same refrigerator will be changed after installation of CQM Auto Ball Cleaning System. In case that 11th of June 1999 - after installation :

Like same way :

condesation temperature	$T_{sat} = 32.5°C$
Cooling water inlet temperature	$T_{in} = 27.2°C$
Cooling water outlet temperature	$T_{out} = 30.5°C$

Log mean temperature can be calculated as follow :

$$\Delta T_{lm} = \frac{(T_{sat} - T_{in}) - (T_{sat} - T_{out})}{ln\left(\dfrac{T_{sat} - T_{in}}{T_{sat} - T_{out}}\right)}$$

$$= \frac{(32.5 - 27.2) - (32.5 - 30.5)}{ln\left(\dfrac{32.5 - 27.2}{32.5 - 30.5}\right)}$$

$$= 3.386$$

$$q = C_p(T_{out} - T_{in})$$

$$C_p = 4.18\text{kJ/kg°C}$$

$$q = 4.18 \times (30.5 - 27.2)$$
$$= 13.794\text{kJ/kg}$$

And we can calculate thermal resistant as follows :

$$\frac{1}{U} = \frac{\Delta T_{lm}}{q} \times \frac{A}{\dot{m}} = \frac{3.386\text{°C}}{13.794\text{kJ/kg}} \times \frac{0.1992\text{m}^2}{0.256\text{kg/s}}$$
$$= 0.191\ \text{m}^2\text{°C/kW}$$

We know, it needs 0.451 temperature difference of cooling water to deprive 1 kW heat capacity of refrigerator - 1st of June 1999 - before installation of Auto Ball Cleaning System, but after installation it needs just 0.191 . That is, we recognize that just low difference of temperature could be possible to transfer same amount of calories if Auto Ball Cleaning System removes the fouling inside tube. If all conditions of cooling tower are same, the condensing temperature of refrigerant T_{sat} could be more lower than before installation of Auto Ball Cleaning System. Actually, the condensing temperature of refrigerant on 11th of June 1999 became lower than 1st of June 1999, before installation, from 35.3 to 32.5 . Being the vaporization temperature same, we recognize that the amount of compressor's work have been decreased by installing Auto Ball Cleaning System.

Also one could guess that the improvement of efficiency is due to cleaning up the tubes as well as Auto Ball Cleaning System, because we cleaned up insides of tubes on installing. But Auto

Ball Cleaning System keep up the state improved, and we can verify it from the measured data after June at the Section 4 in this chapter.

2. Improving the Effects of **Coefficient of Performance(COP)**

And now we will examine what kind of efficiency would the decrease of thermal resistant by Auto Ball Cleaning System installation give.

Firstly let us calculate refrigeration ability before installation on the data from 1st of June.

The condition of the cool water formed by #3,

cooling water inlet temperature $T_i = 8.8$

cooling water outlet temperature $T_0 = 6.4$

That is, cool water come in at 8.8 degree, and after freezing, it will be cooled to 6.4 degree. If the amount of circulation would be like this :

Cooling water flow rate $= 333 \text{ m}^3/\text{hr}$

$= 0.0925 \text{ m}^3/\text{s}$

$= 999.8 \text{ kg}/\text{m}^3$

ρ

The specific heat of cool water is like this :

$C_p = 4.196 \ \ \text{kJ}/\text{kg}\cdot\text{K}$

And the producted amount of cooling heat Q_L can be derived like below :

$$Q_l = \dot{m} C_p (T_i - T_o)$$

$$= 0.0925 \times 999.8 \times 4.196 \times (8.8 - 6.4)$$

$$= 931.3 \text{ kW}$$

And the used electrical current measured is like this :

Used Electric Current $\quad I = 67 A/s$

So we can calculate all amount of used electrical power W.

$$W = I \times 3.3kV \times \sqrt{3} \times \Phi$$
$$= 67 A/s \times 3.3kV \times \sqrt{3} \times 1.0$$
$$= 383\text{kW}$$

In above, Φ means torque efficiency. Eventually we can calculate Coefficient of Performance(COP$_d$) before installation like below :

$$COP_d = \frac{Q_L}{W} = \frac{931.3}{383} = 2.43$$

In the other hands, we can calculate COP$_d$ at 11th of June 1999 after installation like below. That is :

cooling water inlet temperature $\quad T_i = 10.2\ °C$

cooling water oulet temperature $\quad T_o = 6.5°C$

The amount of cool water circulation is same on the two refrigerator.

Cooling water flow rate $\quad = 333 \text{ m}^3/\text{hr}$

$$= 0.0925 \text{ m}^3/\text{s}$$

$$= 999.8 \text{ kg} / \text{m}^3$$

ρ

$$C_p = 4.196 \text{ kJ} / \text{kg} \cdot \text{K}$$

And we can calculate the producted amount of cool heat as samely we did above like below :

$$Q_L = \dot{m} C_p (T_i - T_o)$$
$$= 0.0925 \times 999.8 \times 4.198 \times (10.2 - 6.5)$$
$$= 1435.8 \text{kW}$$

And measured electrical currency is :

$$I = 63A / s$$

Thus, used all amount of electrical power is :

$$W = I \times 3.3kV \times \sqrt{3} \times \phi$$
$$= 63A / s \times 3.3kV \times \sqrt{3} \times 1.0$$
$$= 360 \text{kW}$$

So COP_d on 6th June after installation of Auto Ball Cleaning System is like this :

$$COP_{cl} = \frac{Q_L}{W} = \frac{1435.8}{360} = 3.987$$

We can recognize that the COP of refrigerator had been risen up to 3.987 after installation of Auto Ball Cleaning System at 3:00 pm of 11th June, while COP had been 2.43 at 3:00 pm of 1st June before installation. And it is the evidence that Auto Ball Cleaning System had refreshed the fouling inside the path of cooling water.

3. Mathematical Formulation of Power Reducing Rate by **COP**

As we certificated by the results of experiment, the condensing temperature of refrigerant T_{sat} could be set more lower than the case fouling formed, if Auto Ball Cleaning System would have removed fouling inside tubes. And it shows that the efficiency of the whole refrigerator had been raised for whole work the compressor should do to make same condition of cool water could be even less than before installation.

And the increase of the refrigerating efficiency can also save input power in case that formation of cool heat condition is same. Next, we are going to derive a formula just by measured COP.

It needs 383 kW work to product cool heat $Q_L = 931.3kW$ at #3 refrigerator on 1st of June 1999 before installation of Auto Ball Cleaning System - and the refrigerator has fouling formation inside tube. On the other hand, it needs 360 kW work to product cool heat $Q_L = 1435.8kW$ at #3 refrigerator on 11th of June 1999 after installation, being removed fouling by Auto Ball Cleaning System. If this system is installed on 1st of June and produces same amount of cool heat $Q_L = 1435.8kW$ without fouling, it needs below amount of electrical power :

$$\frac{(Q_L)_{cl}}{(Q_L)_d} = W_d = \frac{1435.8}{931.3} \times 383$$

$$= 590.5\text{kW}$$

It needs different amount of work to produce same amount of cool heat 1435.8 kW, that is, it needs 360 kW work after installation without fouling on 11th of June, while 590.5 kW work should be needed before installation of Auto Ball Cleaning System.

Differently speaking, refrigerator on 11th of June - after installation of Auto Ball Cleaning System - saved (590.5 kW - 360 kW =) 230.5 kW of work than before installation, for being refreshed by this cleaning system. Expressed on formula :

$$\frac{590.5 - 360}{590.5} = 0.395$$

So, we can save 39.5 %'s power by installing Auto Ball Cleaning System. And we can arrange this fact generalized formula :

$$590.5\text{kW} \quad = \frac{(Q_L)_{cl}}{(Q_L)d} W_d$$

For we can put 360 kW = W_{cl}, the derived formula saved 39.5 %'s work can be expressed like this :

$$\frac{\frac{(Q_L)_{cl}}{(Q_L)_d} W_d - W_{cl}}{\frac{(Q_L)_{cl}}{(Q_L)_d} W_d}$$

Dividing $(Q_L)_{cl}$ a denominator numerator of this formula, next putting COP in this formula :

$$\frac{\frac{W_d}{(Q_L)_d} - \frac{W_{cl}}{(Q_L)_{cl}}}{\frac{W_d}{(Q_L)_d}} = \frac{\left(\frac{1}{COP}\right)_d - \left(\frac{1}{COP}\right)_{cl}}{\left(\frac{1}{COP}\right)_d}$$

(5-1)

And putting each COP value into above formula :

$$\frac{\frac{1}{2.432} - \frac{1}{3.987}}{\frac{1}{2.432}} = 0.395$$

We can calculate saved rate of electrical power after installation of Auto Ball Cleaning System if we just put the COP value before(COP_d) and after(COP_{cl}) installation of Auto Ball Cleaning System into formula 5-1.

4. Calculation of Electrical Power Saving Rate

Table 5-2 shows that measured basic data on the #3 refrigerator at ORION Electric Co., Ltd. Actually, chemical or physical cleaning tend to making COP rising up for a while, but it gathered fouling inside again and make it down as before. Therefore, we should be careful to compare two conditions - before and after installation of Auto Ball Cleaning System - also be careful make one(before installation) a data point some time passed after chemical of physical cleaning with some fouling formed.

Looking at Table 5-2, and we can recognize that COP on 28th, 31st of May and 1st of June had been slowly down to 2.978, 2.628 and 2.432. Therefore considering measurement error, it is proper to put the average COP before installation 2.678, average of them. And we think this value as a data point COP_d - the right condition after some time had passed and there wasn't almost any effect of chemical or physical cleaning, so lots of fouling had formed already. Next, as against this data point COP_d, put the value COP after installation of Auto Ball Cleaning System into formula (5-1), and we calculate electrical power saving rate. For example, for COP on the 11th of June is 3.987, we can calculate risen degree of all electrical power saving rate by installing this system as follows :

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

$$\frac{\frac{1}{2.678} - \frac{1}{3.987}}{\frac{1}{2.678}} \times 100 = 32.81$$

Fig. 5-1 shows the thermal resistant graph based on the Table 5-2. Before 1st of June 1999, the thermal resistant value was high - maximum 0.774 on 6th of February 1999, for instance. What is noticeable is that the thermal resistant is changeable very rapidly according to cleaning, just comparing just before and after cleaning. For example, on 6th of March 1999, - just before cleaning - the thermal resistant was a high value 0.663, but it went rapidly down just after cleaning to 0.269 just after cleaning on 8th of March 1999.

But thermal resistant has been constant between 0.2 0.3 after installing Auto Ball Cleaning System 2nd of June 1999. Fig. 5-2 shows the monthly average of thermal resistant value. Before 2nd of June 1999 - installation day - thermal resistant according to cleaning or not, was rapidly variable from 0.34 to 0.64 and its value was very large. But after installation in June, we can recognize that the monthly average thermal resistant value is constant around 0.22. Fig. 5-3 shows standard deviation of thermal resistant. Before installation of Auto Ball Cleaning System on 2nd of June 1999, the range of fluctuation - the standard deviation - went up to a high value, but after cleaning in March, we can catch that the thermal resistant range of fluctuation went down rapidly. However, after installation of Auto Ball Cleaning System in June, the range of fluctuation - the standard deviation - became constantly around 0.03.

Fig. 5-4 shows the amount of cold heat producted per unit electrical power - ability coefficient COP - as time goes by. As we predicted above paragraph, the COP went up very rapidly to 4.074 just after cleaning on 9th of March than 2.809 on 6th of March just before cleaning. But after installation of Auto Ball Cleaning System on 2nd of June, COP went up to 3.583 and keep constantly above 3 degree. Fig. 5-5 shows the monthly average of saved amount of energy calculated from COP. Better than data point, maximum 36.9 % energy was saved in Oct 1999, and annual average of saved energy is 26.36 %.

And this is a little bit higher than maximum saved energy 28.2 % and annual average saved energy 23.9 % theoretically predicted in Chapter , but it is approximately close to real value.

Fig. 5-6 shows the normal state of tubes in which general condensing heat exchanger before cleaning. Although it is cleaned up periodically, we can recognize that some scale stick to the tubes.

Fig. 5-7 shows the state of tubes which CQM Auto Ball Cleaning System was installed with. By circulation of sponge ball inside, so fouling or scale didn't formed almost.

Table 5-2 Pressure and temperature at the components of the #3 refrigerator (ORION Electronics Co, Ltd, Gumi, R.O.Korea)- attachment ;

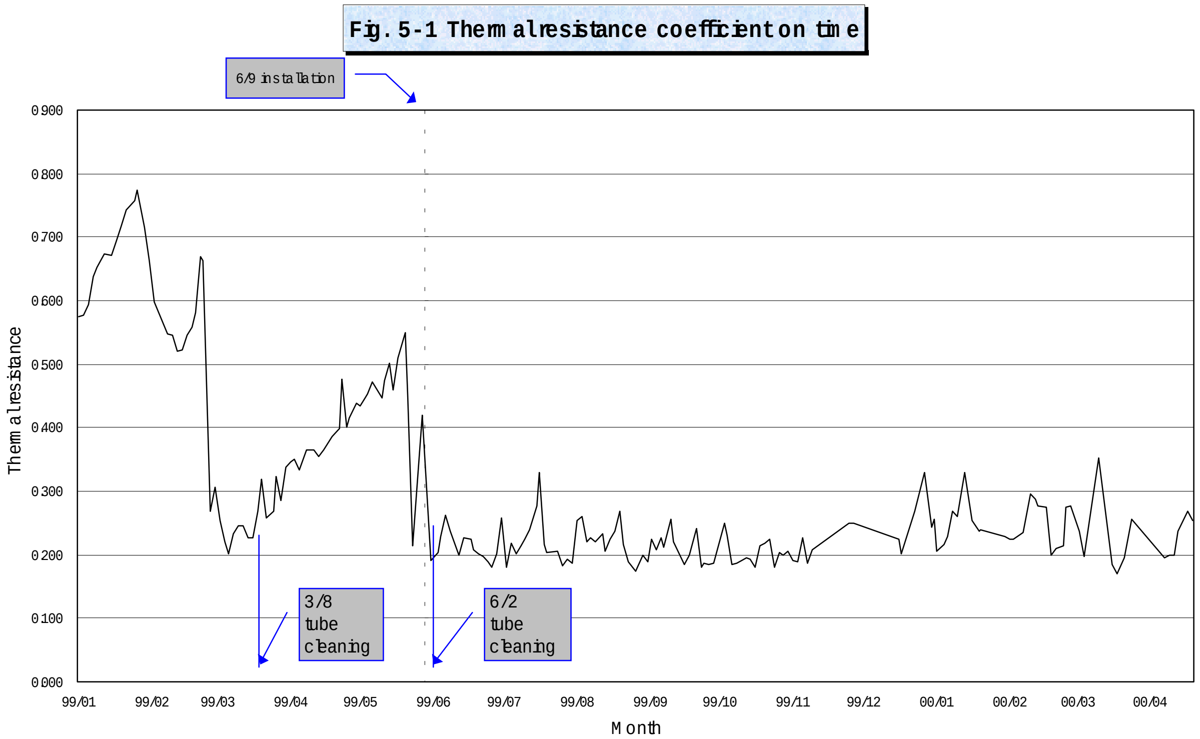


Fig. 5-1 Thermal resistance coefficient on time
6/9 installation
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
Thermal resistance
3/8
tube
cleaning
6/2
tube
cleaning
99/01
99/02
99/03
99/04
99/05
99/06
99/07
99/08
99/09
99/10
99/11
99/12
00/01
00/02
00/03
00/04
Month

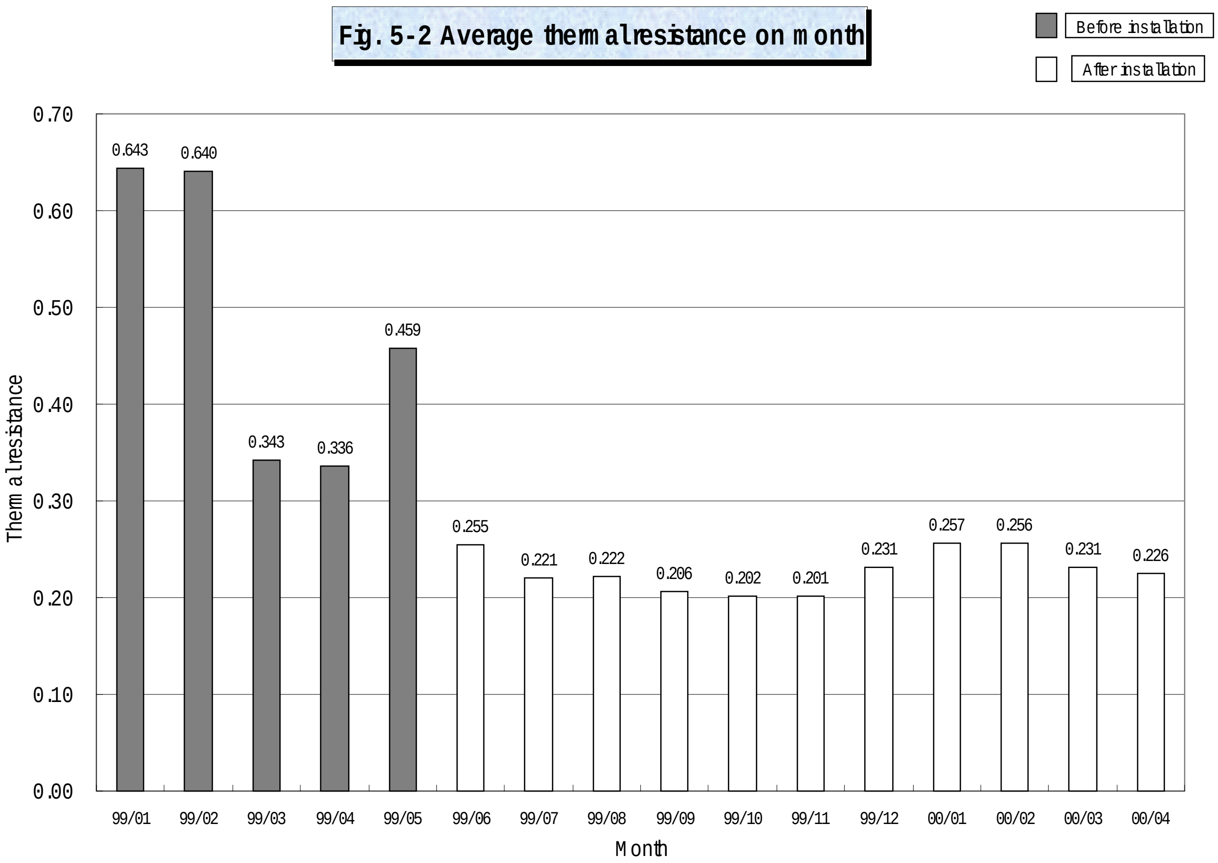


Fig. 5-2 Average thermal resistance on month
Before installation
After installation
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Thermal resistance
0.643
0.640
0.343
0.336
0.459
0.255
0.221
0.222
0.206
0.202
0.201
0.231
0.257
0.256
0.231
0.226
99/01
99/02
99/03
99/04
99/05
99/06
99/07
99/08
99/09
99/10
99/11
99/12
00/01
00/02
00/03
00/04
Month

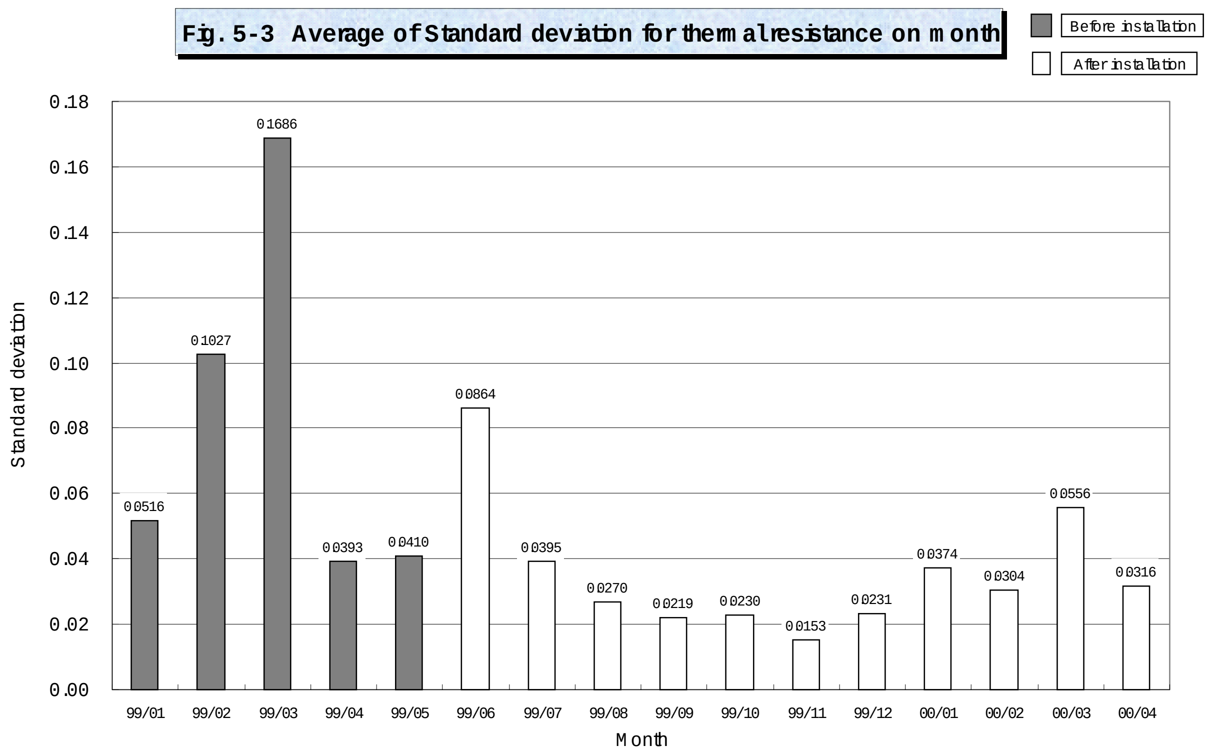


Fig. 5-3 Average of Standard deviation for thermal resistance on month
Before installation
After installation
Standard deviation
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0.0516
0.1027
0.1686
0.0393
0.0410
0.0864
0.0395
0.0270
0.0219
0.0230
0.0153
0.0231
0.0374
0.0304
0.0556
0.0316
99/01
99/02
99/03
99/04
99/05
99/06
99/07
99/08
99/09
99/10
99/11
99/12
00/01
00/02
00/03
00/04
Month

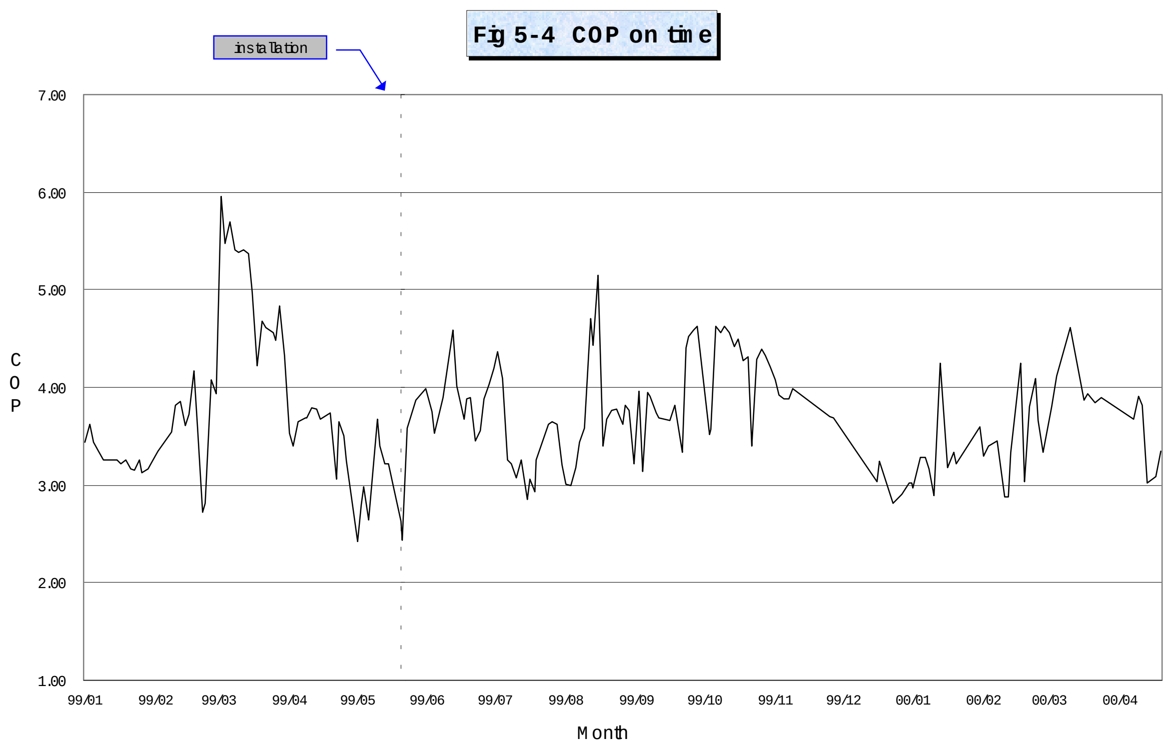
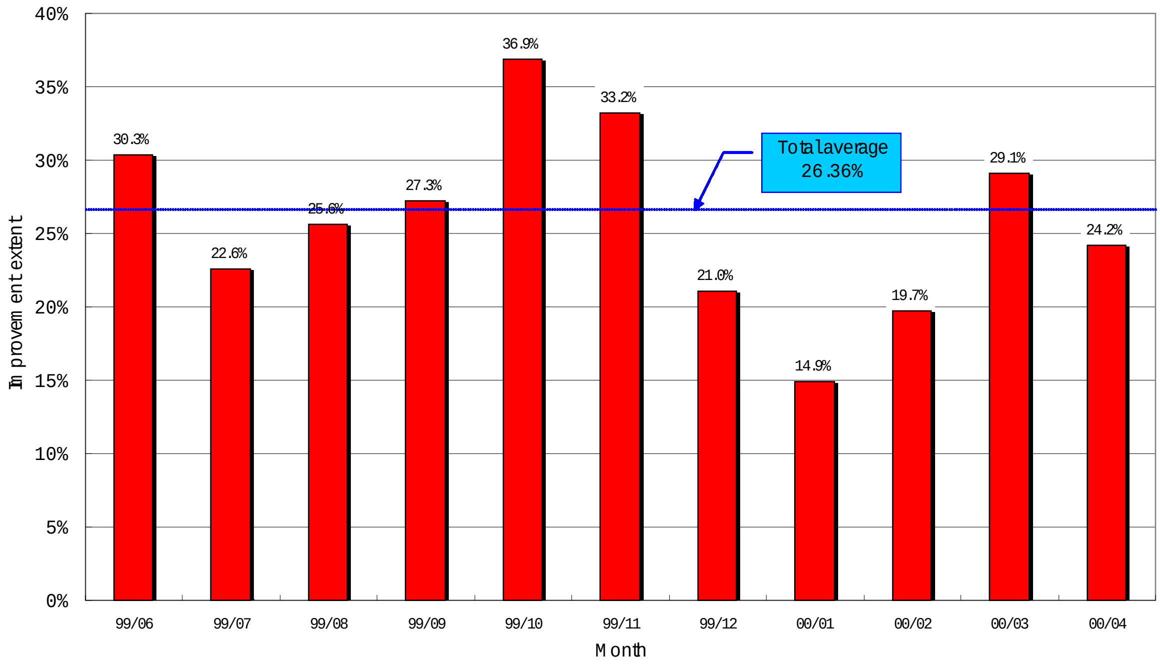


Fig 5-4 COP on time
installation
COP
7.00
6.00
5.00
4.00
3.00
2.00
1.00
99/01
99/02
99/03
99/04
99/05
99/06
99/07
99/08
99/09
99/10
99/11
99/12
00/01
00/02
00/03
00/04
Month

Fig. 5-5 Average of energy saving amount on month



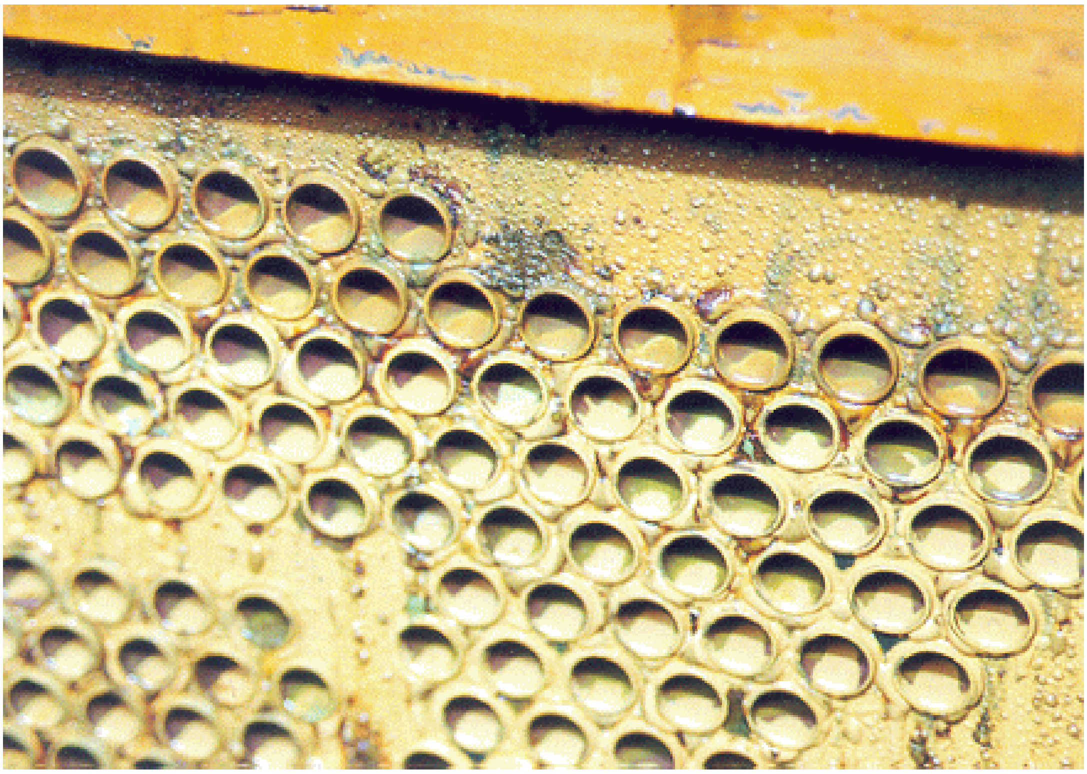


Fig. 5-6 Tube before cleaning

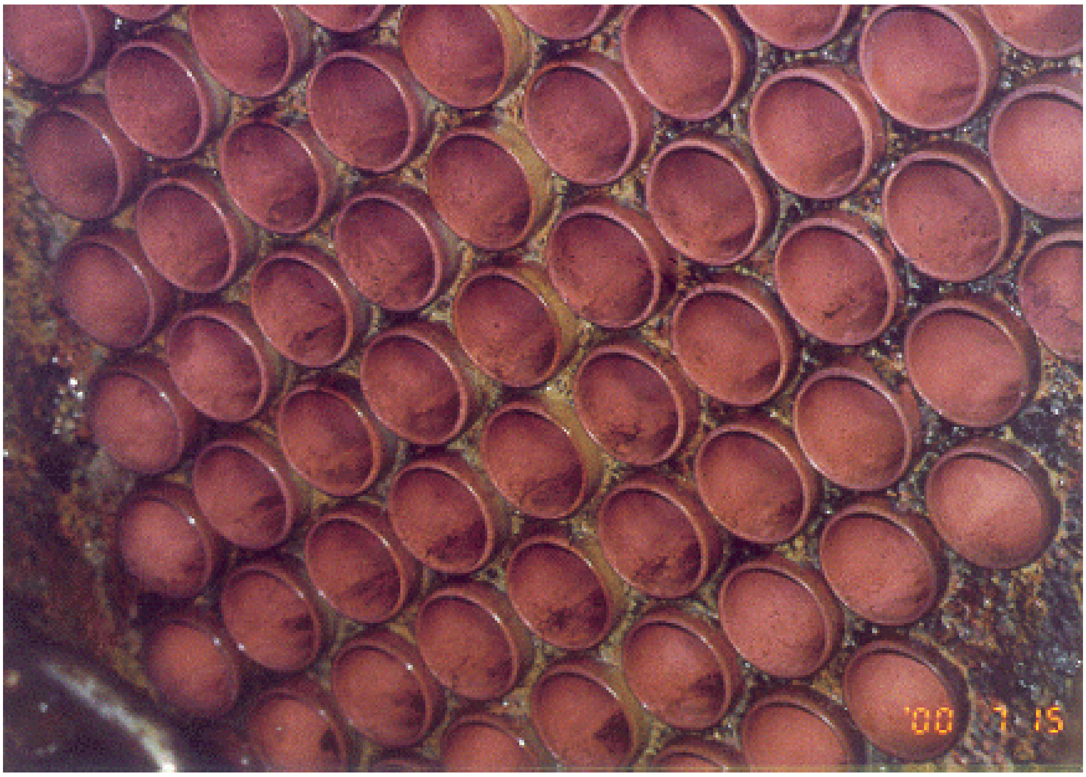


Fig. 5-7 Tube after installation of CQM Auto ball cleaning system

Chapter : Analysis of Economical Efficiency

Now we'd like to calculate all amount of saved money based on the data theoretically calculated and practically measured.

Capacity of Refrigerator	:550 USRT
Necessary Power	:432 kWh
Running Time in a year	:3600 hours
Electric Charge	:54 /kWh (0.0423$/kWh, 1260 =1$ at Dec. 2000)
Efficiency of the Machine	:0.8

The table below shows saved all amount of electric charges predicted previously and measured actually.

550 RT Class Refrigerator :

Method	Saved Energy [%]	Based on :	Saved amount of electric charges
Predicted	23.9	432 kWh ×0.239 ×0.8 ×3,600 hr/year × 54 /kWh = 16,057,128 /year	16,057,128 /year 12743.752$
Measured	26.4	432 kWh ×0.264 ×0.8 ×3,600 hr/year × 54 /kWh = 17,736,744 /year	17,736,744 /year 14076.781$

Chapter : A Case Study on Korean Company "S"

The same kind of Auto Ball Cleaning System as ORION Electric Co., Ltd has were installed on the Korean "S" Company on 19th of June 2000. It was installed on the TRAIN 1200 RT class refrigerator and functioning refrigerant was R-123. To certify the Auto Ball Cleaning System's fouling removing effect, we measured each 1 month's data before installation(at 15:00) on 19th of June in 1999 and after installation(at 15:00) on 19th of June in 2000. Comparing with two months' data before and after installation, we analyzed the Auto Ball Cleaning System effect. Concrete informations are arranged on the Table 7-1.

1. Calculation of **COP**

Auto Ball Cleaning System may repress fouling or scale formation inside the cooling water path, located outside of the condenser. Therefore, we can expect that COP - Coefficient of Performance, producted cool heat per unit electrical power - will rise up because thermal resistant of the condenser will be restricted to the minimum in the cooling tubes. So we will verify this effects by comparing before and after installation based on measured data at 15:00 in 1999 and 2000.

To show an example of freezing ability calculation, firstly let us calculate this on 19th of July, 1999, at 15:00 from arranged data on Table 7-1.

1. Increase formula of electric power : (On Table 7-1)
2. $\mathrm{W} = \text{eledtric current}\left(\mathrm{A/s}\right)\times 3.3\mathrm{kV}\times\sqrt{3}\times 0.979$

Refrigerator before Auto Ball Cleaning System Installation

The condition of cool water producted by refrigerator :

Cooling Water inlet Temperature : T_i = 8.4

Cooling Water outlet Temperature : T_o = 5.0

That is, it is the fact that the cool water cooled down to 5.0 from 8.4 after being frozen by refrigerator. But the volume of cool water circulation is same on 600 /hr (standardized on 12 inch pipe) for there's no relation to scale between year 1999 and 2000.

cooling water flow rate : 600 /hr

0.166 /sec

ρ = 999.8 /

The specific heat of cool water is : C_p = 4.196 kJ/ ·K

And the amount heat produced by refrigerator Q_L is :

$$Q_L = \dot{m} C_p (T_i - T_o)$$

$$= 0.166 \times 999.8 \times 4.196$$

$$\times (8.4 - 5.0)$$

$$= 2368 \text{ kW}$$

And the measured value of necessity electric current is :

As consumed electric currency I = 130 *A/s*,

so consumed electric power could be calculated :

$$\begin{aligned} W &= \mathrm{I} \times 3.3\mathrm{kV} \times \sqrt{3} \times \varphi \\ &= 130\mathrm{A/s} \times 3.3\mathrm{kV} \times \sqrt{3} \times 0.979 \\ &= 727\ \mathrm{kW} \end{aligned}$$

Eventually we can calculate Coefficient of Performance(COP) as follows :

$$COP = \frac{Q_L}{W} = \frac{2368}{727} = 3.26$$

On the other hand, if Auto Ball Cleaning System were installed, the scale that is formed by cooling water would be removed, and heat-transferring from condenser to cooling water path would be better because of this.

Being same condition of cooling water, heat-transferring would be better, and it need not high condensing pressure. That is, the necessity power of compressor can be saved as much.

To prove this effect, we will calculate COP - Coefficient of Performance, producted cool heat per unit electrical power - based on the data ay 15:00, 19th of June 2000, just after installation of Auto Ball Cleaning System.

And the condition of INPUT & OUTPUT of cool water is as follows :

Cooling Water inlet Temperature : $T_i = 10.8°C$

Cooling Water outlet Temperature : $T_o = 6.0°C$

For both amount of cool water circulation is same :

cooling water flow rate : 600 /hr

0.166 /sec

ρ = 999.8 /

$C_p = 4.196 \text{ kJ / kg°C}$

And the amount heat produced by refrigerator Q_L is as above :

$$Q_L = \dot{m} C_p (T_i - T_o)$$

$$= 0.166 \times 999.8 \times 4.196 \times (10.8 - 6.0)$$

$$= 3343 \text{ kW}$$

And the measured value of necessity electric current is :

Consumed electric currency I = 158 *A/s*

So consumed electric power is :

$$W = I \times 3.3kV \times \sqrt{3} \times$$

$$= 158\text{A / s} \times 3.3\text{kV} \times \sqrt{3} \times 0.979$$

$$= 884 \text{ kW}$$

The COP in the year 2000 when the Auto Ball Cleaning System was installed is as follows :

$$COP_2 = \frac{Q_L}{W} = \frac{3343}{884} = 3.80$$

And we can recognize that the COP was risen after Auto Ball Cleaning System restricted the formation of fouling or scale inside the cooling water tubes, the COP was up to 3.8 on the 19th of June 2000(at 15:00), while COP was 3.26 just one year before - without Auto Ball Cleaning System.

Generally the lower input temperature of cooling water from cooling tower into refrigerator is, the higher the COP value will be. But, for the annual air temperature of June & July 2000 was higher than 1999, the input temperature of cooling water in 2000 was also higher than 1999(19th of June 1999, 15:00, input Temperature was 26.2 ; 19th of June 2000, 15:00, input Temperature was 29.9). So if the condition was same, the COP in year 2000 can be estimated lower than 1999. But in year 2000, there were no scales and fouling inside of the tubes being removed by Auto Ball Cleaning System, so COP went up more even though the input temperature in year 2000 was higher than that of 1999.

2. Calculation of Electrical Power Saving

Next, let us do calculation of all amount of saved electrical power considering that same basic cool heat was producted owing to rise of COP.

The average of COP, June & July in 1999, at 15:00 : $\overline{COP_N} = 3.14$

The average of COP, June & July in 1999, at 15:00 : $\overline{COP} = 4.15$

So, we can calculate saved electrical power rate as follows :

$$\frac{\frac{1}{\overline{COP_N}} - \frac{1}{\overline{COP}}}{\frac{1}{\overline{COP_N}}} = \frac{\frac{1}{3.14} - \frac{1}{4.15}}{\frac{1}{3.14}} = 0.243$$

Therefore, we can save 24.3 % of electrical power.

3. Expectation for Condensation Pressure of Compressor

As we saw above, the input temperature of cool water in 2000 was higher than that in 1999 because weather outside was hotter, and refrigerating load was heavier than 1 year before. So, although COP went up by Auto Ball Cleaning System, the input electrical power and condensing pressure will be raised because more refrigerating load were given. Therefore, for the correct compare to 1999, firstly we assume that the refrigerating load was same in the year 1999 and 2000, next we calculate the condensing pressure by Auto Ball Cleaning System.

As the each year's COP is 3.26(1999/6/19, at 15:00) and 3.8(2000/6/19, at 15:00), we calculate condensing pressure by next formula which is related to compression ratio and pressure.

Considering polytropic efficiency η_p , let the compression work with fouling formation inside(without Auto Ball Cleaning System) be $W_{comp'}$, let this with Auto Ball Cleaning System be W_{comp}, and this ratio can be expressed to following formula :

$$ratio = \frac{W_{comp'}}{W_{comp}} = \frac{\frac{n}{n-1} RT_1' \left[\left(\frac{p_2'}{p_1'} \right)^{\frac{n-1}{n}\frac{1}{\eta_p}} - 1 \right]}{\frac{n}{n-1} RT_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}\frac{1}{\eta_p}} - 1 \right]}$$

In the above equation, the subscripts 1 and 2 mean evaporation condition and compression condition, respectively.

Let the denominator and numerator of ratio be divided same value Q_L, supposing that same amount of cool heat was producted in 1999 and 2000.

$$ratio = \frac{\frac{W_{comp'}}{Q_L}}{\frac{W_{comp}}{Q_L}} = \frac{\frac{1}{COP}}{\frac{1}{COP_N}}$$

In the formula above, the subscript N means Auto Ball Cleaning System was not installed. And putting the data into this formula, the results are arranged below. At 5 of evaporation temperature of R-123, isentropic constant, specific heat is

$$k = \frac{C_p}{C_v} = 1.1$$

For evaporator doesn't relate to fouling, so :

$$T_1 = T_1' \,,\ p_1 = p_1'$$

Supposing that polytropic efficiency η= 0.8, and also supposing polytropic constant n = k(n = 1.1), and the result will be like below. And the pressure units were changed into MPa.

$$ratio = \frac{\left(\frac{P_{con}}{0.0405}\right)^{\frac{0.1}{1.1}\times\frac{1}{0.8}} - 1}{\left(\frac{0.216}{0.0405}\right)^{\frac{0.1}{1.1}\times\frac{1}{0.8}} - 1} = \frac{\frac{1}{3.8}}{\frac{1}{3.26}}$$

From above, we can calculate the pressure in year 2000 when Auto Ball Cleaning System was installed :

$$\mathrm{P_{con}} = 0.173\mathrm{MPa}$$

And if it would be changed into psig unit, it would become 7.056 psig. Consequently, we can recognize that the condensing pressure in year 2000 had been down than the condensing pressure in 1999, from 15.4 psig to 7.506 Psig. But if the refrigerating load had been same in two years(1999 and 2000), the input electrical power should have been decreased as COP increased. But in the truth, the weather(so to speak, the temperature of outer air) and refrigerating load in year 2000 was hotter and heavier than these in 1999. Therefore, even though COP had been increased, input electrical power and condensing pressure had not been decreased.

4. Calculation of Saving Amount of Money

Necessary Power of 1200 R/T refrigerator : 755 kWh (on 133 A/s)

Total Running Time : 4160 hours

Efficiency of the Machine : 0.8

Electric Charges : 50 /kWh (The charge presented by Korean "S" Company)

From the data above, supposing that 24.3 % of electrical power can be saved for one year in average, the saved amount of money is :

Necessary Power ×Saved rate ×Running Time in a year × Charge per kWh

= Saved amount of money

755 kWh×0.243×0.8×4160 hour/year×50 /kWh = 30,528,576 /year

So 30,528,576($ 24,229.03, $ 1= 1,260) can be saved in one year.

Now let us summarize above :

Auto Ball Cleaning System make the efficiency of refrigerator more better by restricting fouling/scale formation.

It was natural that the COP in 2000 should had been lower than COP in 1999 for the weather in June & July of 2000 was hotter than this of 1999. But in case of Auto Ball Cleaning System, the COP in year 2000 rather increased because this system refreshed scale/fouling inside the condenser's tube as follows :

Average COP in June & July, 1999, at 15:00

$\overline{COP_N} = 3.14$

Average COP in June & July, 2000, at 15:00

$\overline{COP} = 4.15$

From this, it is clear that Auto Ball Cleaning System can save 24.3% electrical power, and all amount saved money would be 30,528,576($ 24,229.03, $ 1 = 1,260).

Chapter : Conclusion

In general refrigerating equipments, cooling water used to be cooled in cooling tower, but lots of microbes, viruses and dust in the air go into the devices and may cause the fouling which is a kind of piled deposit inside of the tubes. Condenser might not be cooled enough because of fouling. And this cause the refrigerant saturation temperature being raised.

The rising of refrigerant saturation temperature may cause the rising of refrigerant saturation pressure, and compressor should do more work because of the raised saturation pressure. Thus it needs more electrical power to do more work.

On the other hands, after installation of Auto Ball Cleaning System, it does not need more rising pressure because this system removed fouling inside. That is, it means that the compressor may work less than before. As we saw in Chapter , this system can save 23.9 % energy theoretically. But actually measured saved energy was 26.4 % for one year.

This value is somewhat higher than the value theoretically predicted, but approximately close to each other. And this result means that objective prove had been assured by comparing theoretically predicted to practically analyzed.

And all amount of saved money on 550 RT refrigerator is :

Method	Saved Energy [%]	Based on :	Saved amount of electric charges
Predicted	23.9	432 kWh ×0.239 ×0.8 ×3,600 hr/year × 54 /kWh = 16,057,128 /year	16,057,128 /year 12,743.752$/year
Measured	26.4	432 kWh ×0.264 ×0.8 ×3,600 hr/year × 54 /kWh = 17,736,744 /year	17,736,744 /year 14,076.781$/year

And we can save the chemical charge to restrict erosion and scale, and saved tube cleaning cost that should pay periodically.

And the prediction of saving cost about another refrigerators or another companies could be calculated by just putting measured values(total running hours, electric charges, etc.) into above formula.

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elf atochem

ATO

ELF ATOCHEM (AUSTRALIA)

Forane® 134a PRESSURE / TEMPERATURE CHART

°C	°F	kPa	PSIG
-50	-58	-70.50	-10.22
-49	-56.2	-68.80	-9.98
-48	-54.4	-66.90	-9.70
-47	-52.6	-65.00	-9.43
-46	-50.8	-63.00	-9.14
-45	-49	-60.90	-8.83
-44	-47.2	-58.70	-8.51
-43	-45.4	-56.30	-8.17
-42	-43.6	-53.90	-7.82
-41	-41.8	-51.40	-7.45
-40	-40	-48.80	-7.08
-39	-38.2	-46.00	-6.67
-38	-36.4	-43.20	-6.27
-37	-34.6	-40.20	-5.83
-36	-32.8	-37.10	-5.38
-35	-31	-33.90	-4.92
-34	-29.2	-30.50	-4.42
-33	-27.4	-27.00	-3.92
-32	-25.6	-23.40	-3.39
-31	-23.8	-19.60	-2.84
-30	-22	-15.60	-2.26
-29	-20.2	-11.60	-1.68
-28	-18.4	-7.30	-1.06
-27	-16.6	-2.90	-0.42
-26	-14.8	1.60	0.23
-25	-13	6.40	0.93
-24	-11.2	11.30	1.64
-23	-9.4	16.30	2.36
-22	-7.6	21.60	3.13
-21	-5.8	27.00	3.92
-20	-4	32.70	4.74
-19	-2.2	38.50	5.58
-18	-0.4	44.50	6.45
-17	1.4	50.70	7.35
-16	3.2	57.20	8.30
-15	5	63.80	9.25
-14	6.8	70.70	10.25
-13	8.6	77.80	11.28
-12	10.4	85.10	12.34

°C	°F	kPa	PSIG
-11	12.2	92.60	13.43
-10	14	100.40	14.56
-9	15.8	108.40	15.72
-8	17.6	116.70	16.93
-7	19.4	125.20	18.16
-6	21.2	134.00	19.43
-5	23	143.10	20.75
-4	24.8	152.40	22.10
-3	26.6	162.00	23.50
-2	28.4	171.90	24.93
-1	30.2	182.00	26.40
0	32	192.50	27.92
1	33.8	203.20	29.47
2	35.6	214.30	31.08
3	37.4	225.60	32.72
4	39.2	237.30	34.42
5	41	249.20	36.14
6	42.8	261.50	37.93
7	44.6	274.20	39.77
8	46.4	287.10	41.64
9	48.2	300.50	43.58
10	50	314.10	45.55
11	51.8	328.10	47.59
12	53.6	342.50	49.67
13	55.4	357.20	51.81
14	57.2	372.30	54.00
15	59	387.80	56.24
16	60.8	403.70	58.55
17	62.6	419.90	60.90
18	64.4	436.50	63.31
19	66.2	453.60	65.79
20	68	471.00	68.31
21	69.8	488.90	70.91
22	71.6	507.20	73.56
23	73.4	525.90	76.27
24	75.2	545.10	79.06
25	77	564.70	81.90
26	78.8	584.70	84.80
27	80.6	605.20	87.77

°C	°F	kPa	PSIG
28	82.4	626.10	90.80
29	84.2	647.60	93.92
30	86	669.50	97.10
31	87.8	691.80	100.33
32	89.6	714.70	103.65
33	91.4	738.00	107.03
34	93.2	761.90	110.50
35	95	786.30	114.04
36	96.8	811.10	117.64
37	98.6	836.50	121.32
38	100.4	862.50	125.09
39	102.2	888.90	128.92
40	104	915.90	132.84
41	105.8	943.50	136.84
42	107.6	971.60	140.91
43	109.4	1000.30	145.08
44	111.2	1029.60	149.33
45	113	1059.40	153.65
46	114.8	1089.80	158.06
47	116.6	1120.80	162.55
48	118.4	1152.50	167.15
49	120.2	1184.70	171.82
50	122	1217.60	176.59
51	123.8	1251.10	181.45
52	125.6	1285.20	186.40
53	127.4	1319.90	191.43
54	129.2	1355.40	196.58
55	131	1391.40	201.80
56	132.8	1428.20	207.14
57	134.6	1465.60	212.56
58	136.4	1503.70	218.09
59	138.2	1542.50	223.71
60	140	1582.00	229.44
61	141.8	1622.20	235.27
62	143.6	1663.20	241.22
63	145.4	1704.80	247.25
64	147.2	1747.20	253.40
65	149	1790.40	259.67

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Table A-9 Properties of saturated liquid water

T, °C	ρ, kg/m³	μ, Pa · s		ν, m²/s		c_p, kJ/(kg · K)	k, W/(m · K)	Pr
.01	999.8	17.91	−04	17.91	−07	4.217	0.562	13.44
10	999.8	13.08	−04	13.08	−07	4.193	0.582	9.42
20	998.2	10.03	−04	10.05	−07	4.182	0.600	6.99
30	995.6	79.77	−05	80.01	−08	4.179	0.615	5.42
40	992.2	65.31	−05	65.80	−08	4.179	0.629	4.34
50	988.0	54.71	−05	55.37	−08	4.181	0.640	3.57
60	983.2	46.68	−05	47.48	−08	4.185	0.651	3.00
70	977.7	40.44	−05	41.36	−08	4.190	0.659	2.57
80	971.8	35.49	−05	36.52	−08	4.197	0.667	2.23
90	965.3	31.50	−05	32.63	−08	4.205	0.673	1.97
100	958.3	28.22	−05	29.45	−08	4.216	0.677	1.76
140	926.1	19.61	−05	21.17	−08	4.285	0.685	1.23
180	886.9	14.94	−05	16.85	−08	4.408	0.674	0.98
220	840.3	12.10	−05	14.40	−08	4.613	0.648	0.86
260	784.0	10.15	−05	12.95	−08	4.983	0.606	0.83

The properties of saturated liquid oxygen (Table A-11), were obtained from NASA SP-3071,[12] and similar properties for liquid parahydrogen (Table A-12), were obtained from NASA SP-3089.[13]

The liquid-metal properties in Table A-13 were obtained primarily from *Liquid Metals Handbook*[14, 15] and supplemented from Ref. 16.

The properties of some typical hydrocarbon fuels and oils (Tables A-14 to A-16) were adapted from data presented in *SAE Aerospace Allied Thermodynamics Manual.*[16]

Table A-17 contains properties of the atmosphere, taken from the 1976 U.S. Standard Atmosphere published by NOAA.[17]

Table A-10 Properties of saturated liquid ammonia

T, °C	ρ, kg/m³	μ, Pa · s		ν, m²/s		c_p, kJ/(kg · K)	k, W/(m · K)	Pr
−30	677	26.3	−05	38.9	−08	4.447	0.609	1.92
−20	665	23.7	−05	35.6	−08	4.501	0.586	1.82
−10	652	21.2	−05	32.4	−08	4.556	0.562	1.72
0	639	19.0	−05	29.7	−08	4.618	0.539	1.63
10	625	17.0	−05	27.2	−08	4.683	0.516	1.54
20	610	15.2	−05	24.9	−08	4.758	0.493	1.47
30	595	13.6	−05	22.9	−08	4.843	0.470	1.40
40	580	12.2	−05	21.0	−08	4.943	0.447	1.35
50	563	11.0	−05	19.5	−08	5.066	0.423	1.32
60	545	98.7	−06	15.7	−08	5.225	0.400	1.29

Appendix A : Fouling of Heat Exchanger

1. Introduction

"Fouling" is undesirable piled deposit formed inside heat exchanger, and also means a kind of thermal resistant on the heat path in the heat exchanger. On the way the heat goes inside the heat exchanger, the thermal resistant proportionates to the thickness of the deposit, and is in inverse proportion to the thermal conduction of this deposit. At first we can ignore fouling resistant for this thermal conductivity of the thin deposit is very low actually, but as time goes on, the deposit is getting more thicker, it would become the most high thermal resistant of the heat path, so it could make the whole system inefficient rapidly.

In many cases, mechanical designer used to make the area of heat exchanger more larger than theoretically planned. But fouling formation is very changeable and rapid according to temperature increase. The enlargement of area of heat exchanger cause temperature rise, so it may cause more excessive fouling finally.

The study about fouling had been tried since long time ago, but it is very surprising that there had not been big progress on this field. At the latest opinion, fouling is peculiar and unavoidable one on given condition, and there is no particular way to design technique to remove or restrict fouling.

2. Fouling as a Thermal resistance

Fig. A-1 shows the heat transferring course from warm to cold materials. Fig. A-1(a) is clean heat exchanger, and Fig. A-1(b) means fouling have been formed on the surface of the heat exchanger. Total transferred heat constant can be derived as follows :

$$\frac{1}{U_{cl}} = R_1 + R_w + R_2 \tag{A.1}$$

$$\frac{1}{U_d} = R_1 + R_{f1} + R_w + R_{f2} + R_2 \tag{A.2}$$

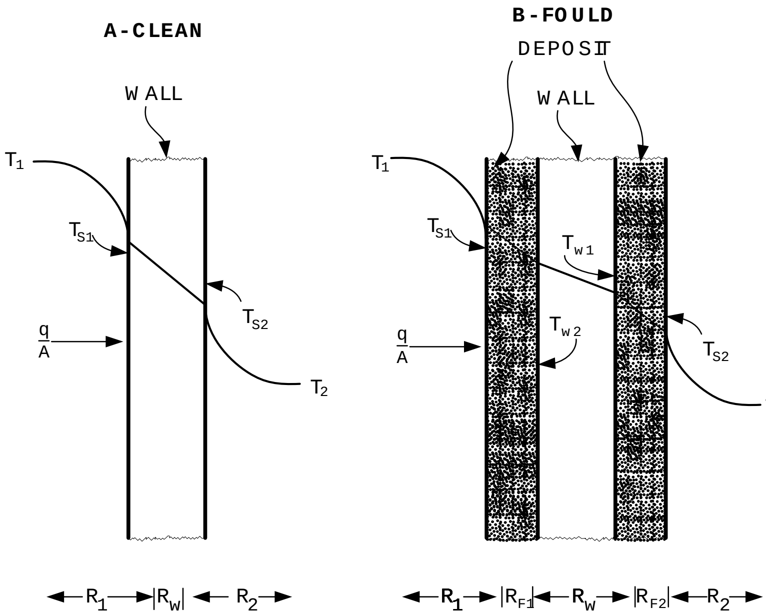

Fig. A-1 : The heat transferring course from warm to cold materials

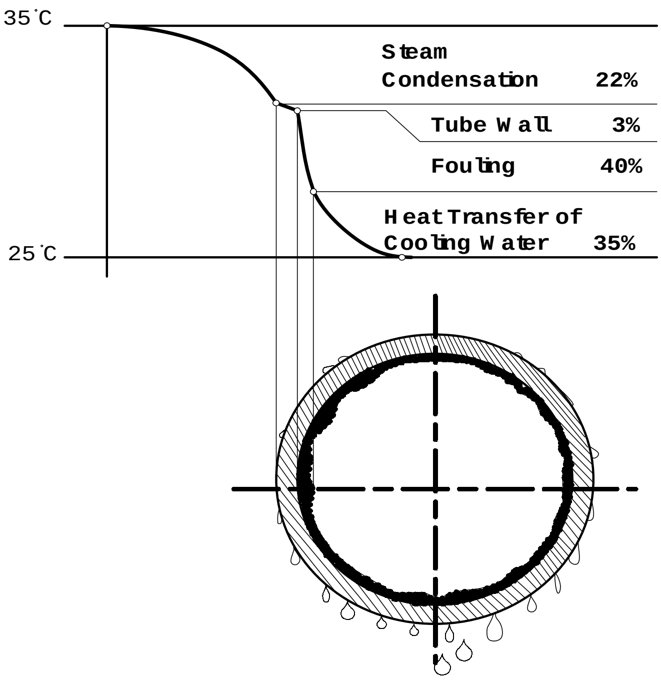

Fig. A-2 : Decrease of temperature inside the heat exchanger tubes

So, we can calculate fouling resistant as follows :

$$R_f = R_{f1} + R_{f2} = \frac{1}{U_d} - \frac{1}{U_{cl}}$$ (A.3)

The unit of fouling constant on this surface is [/W].

Fig. A-2 shows that decrease of temperature by thermal resistant rate in the multi-stage flash heat exchanger tubes. As we see above, about 40% of thermal resistant is due to fouling. It means that the thermal resistant constant on fouling condition U_f have been decreased to 30~65% degree than the constant on the clean condition U_{cl}.

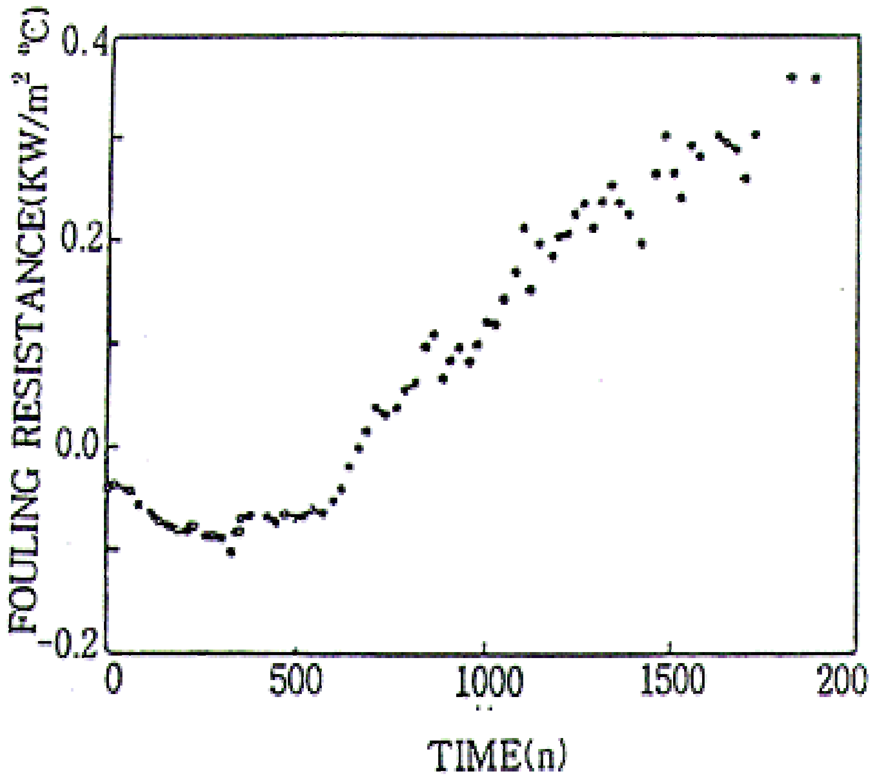

Fig. A-3 : The change of fouling resistant by Silica

Fig. A-3 is Silica fouling resistant value, which is measured on experiment, and it shows that the resistant value rises up rapidly as time goes by. That is, fouling resistant can be most important factor to affect the amount of heat transfer getting more fouling on the surface as time goes.

And let us explain the reason why the fouling resistant value was minus at first of the graph : we calculated the total heat transferred constant U_{cl} supposing that the tube is perfectly smooth, but it is not perfectly smooth actually, so it rather increase. Therefore, the surface area of U_f which is measured value is an tolerance because it was risen up than smooth tube.

3. A Common Type of Fouling

Fouling formed in driving of the refrigerator, so fouling formation subordinate to driven time. Fig. A-4 is fouling curve measured on experiment, and we can recognize that the fouling resistant close to regular value after passing some period of time. And the model being curve-fitting to this curve from the experiment is Kern-Seaton equation :

$$\frac{dm}{dt} = \frac{dm_d}{dt} - \frac{m}{t_c}$$

(A.4)

In this equation, m_d is the mass of deposit, and m/t_c means the mass which sticked to or took away for unit time. And d_m can be expressed multiple of p_f (Density of the fouling) and x(Thickness of the fouling) like below :

$$dm = \rho_f \cdot dx = \rho_f \cdot k_f \cdot dR_f$$

And let us do integral calculate to above formula :

$$m = \rho_f \cdot x = \rho_f \cdot k_f \cdot R_f$$

In this formula, each letter x, p_f, k_f, R_f means the thickness of deposit, the density of deposit, thermal conductivity, and thermal resistant. Supposing that density and thermal conductivity is a constant, next let us put these into above formula, and we can derive famous formula, Kern-Seaton formula.

<Kern, D.Q. and Seaton, R.E. 1959, A Theoretical Analysis of Thermal Surface fouling, Brit. Chem. Eng. 4(5): 258~262>

$$R_f(t) = R_f^*\left[1 - e^{-t/t_c}\right]$$
(A.5)

R^*_f means a gradual approach of fouling resistant, and t_c is time constant.

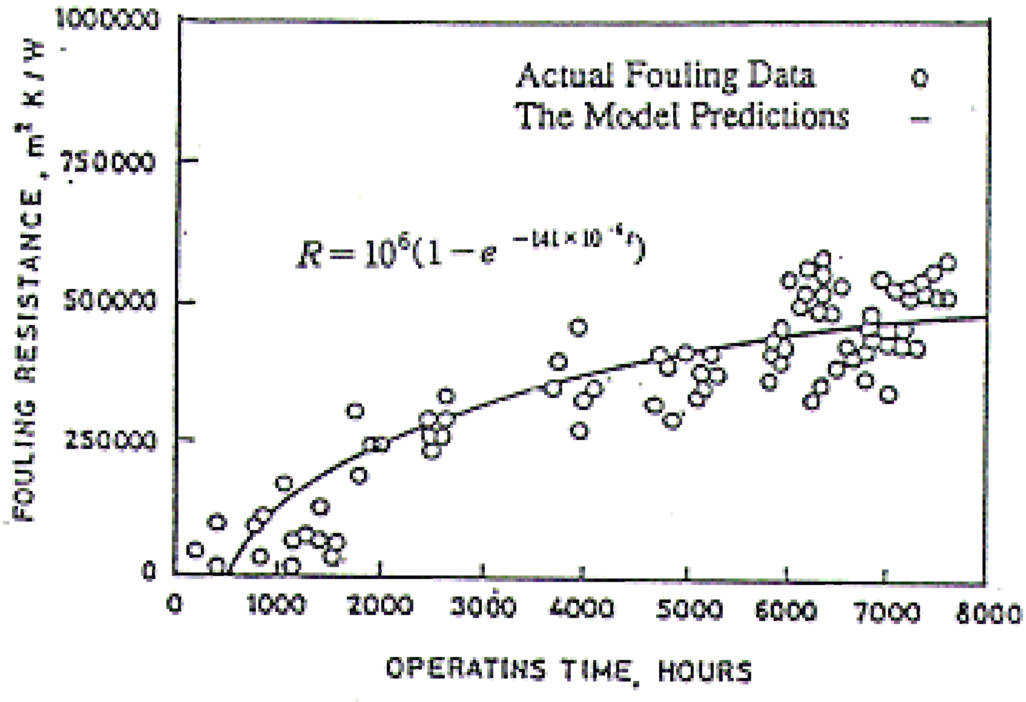

Fig. A-4 : The relation between model formula and experimental data

4. How to Control or Remove the Fouling

The most effective way to prevent fouling formation is to analyze the fact of fouling and so to design heat-exchange machine. But it is very difficult to remove fouling thoroughly by design.

Therefore, periodical cleaning should be needed. Table A-1 shows that many kinds of cleaning method, and this methods can be divided to off-line method and on-line method, whether the refrigerator should be operated or not when clean the tube. On-line technique make it possible to clean inside of the tube with the machine turned on, so it's more profitable.

Table A-1 : The way to Remove fouling

On-line Technique	Off-line Technique
Additioner (chemical)	Disassembling and Hand-wash
Restrainer (chemical)	Liquid injection
Scale preventer	Steam injection
Acid	Air injection
On-line washer	Mechanical cleaning
Sponge ball	Drilling
Brush style	Scraper
Microwave method	Chemical cleaning
Chain and scraper	
Heat shock	

Appendix B : Fouling in Refrigerator Caused by Cooling Water

1. Introduction

Fig. B-1 shows the general diagram of refrigerating equipments, and Fig. B-2 shows the cycle graph of refrigerating. Refrigerating course is the cycle that goes round from the evaporation of refrigerant to compressing, to condensation, and to expansion of the pressure through throttle valve and to evaporate again. Compressed refrigerant goes through condensing course, when the heat-transferring to outside is occurred. In case that this refrigerator is cooled down by water-cooling system, the cooling water is cooled at cooling tower and takes heat away from condenser on this transferring.

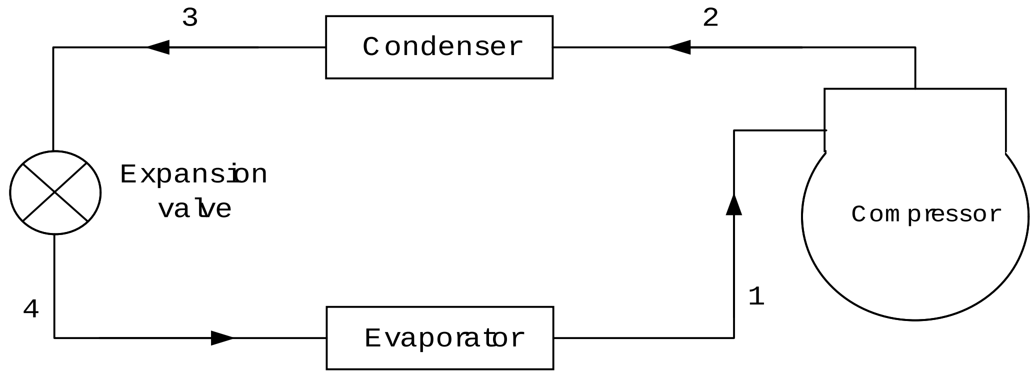

Fig. B-1 : The general evaporating refrigerator equipments

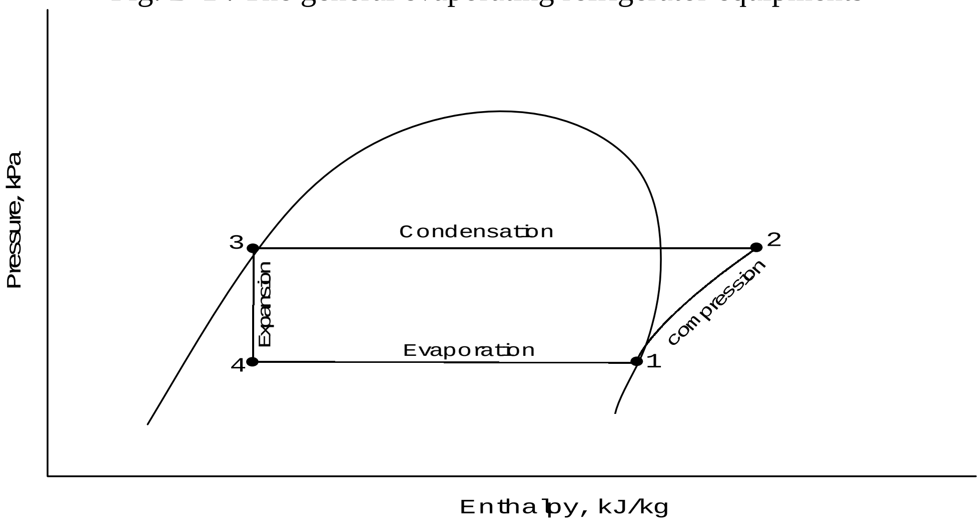

Fig. B-2 : The refrigerating cycle of evaporating refrigerator

The Shell & Tube condenser type is generally used one, and it is designed to flow cooling water inside the tube to make it more easier to clean fouling.

2. Relations between Thickness of Scales, Suction Temperature, Condensing Temperature and Horsepower

Table B-1 shows that fouling resistant according to scale thickness. In the Table B-1, 'cooler' means the object being cooled as a refrigerator, and 'overall heat transfer coefficient' means that total heat-transferring constant on the part from evaporation of refrigerant to production of cool water outside evaporator. So, 'cooler fouling' means fouling that formed at the part that cool water producted.

On the other side, 'condenser fouling' is the fouling formed by cool water, on circulating cool water to radiate heat from condensed refrigerant of refrigerator.

Table B-1a (BI Unit) Heat Transfer Surface required to offset fouling

Fouling thermal Resistance [hr·ft²·°F/BTU]	Overall Heat Transfer Coefficient BTU/[hr·ft²·°F]		Thickness of Scale Approx. [in]	Increase of required Heat Transfer Area (%)	
	cooler	condenser		cooler	condenser
clean tubes	400	850	0.000	0	0
0.0005	333	595	0.006	20	45
0.001	286	460	0.012	40	85
0.002	222	315	0.024	80	170
0.003	182	240	0.036	120	250

Assumption) Thermal Conductivity of Scale: . /[· ·°]

Table B-1b (SI Unit) Heat Transfer Surface required to offset fouling

Fouling thermal Resistance [m²℃/W]	Overall Heat Transfer Coefficient [W/m²℃]		Thickness of Scale Approx. [mm]	Increase of required Heat Transfer Area (%)	
	cooler	condenser		cooler	condenser
clean tubes	2271	4827	0.00	0	0
0.08805×10^{-3}	1891	3379	0.15	20	45
0.176×10^{-3}	1624	2612	0.31	40	85
0.352×10^{-3}	1260	1789	0.61	80	170
0.528×10^{-3}	1034	1363	0.91	120	250

Assumption) Thermal Conductivity of Scale: . [/ °]

On seeing Table B-1b, we can recognize that the thermal resistant is linearly proportionate to the scale thickness.

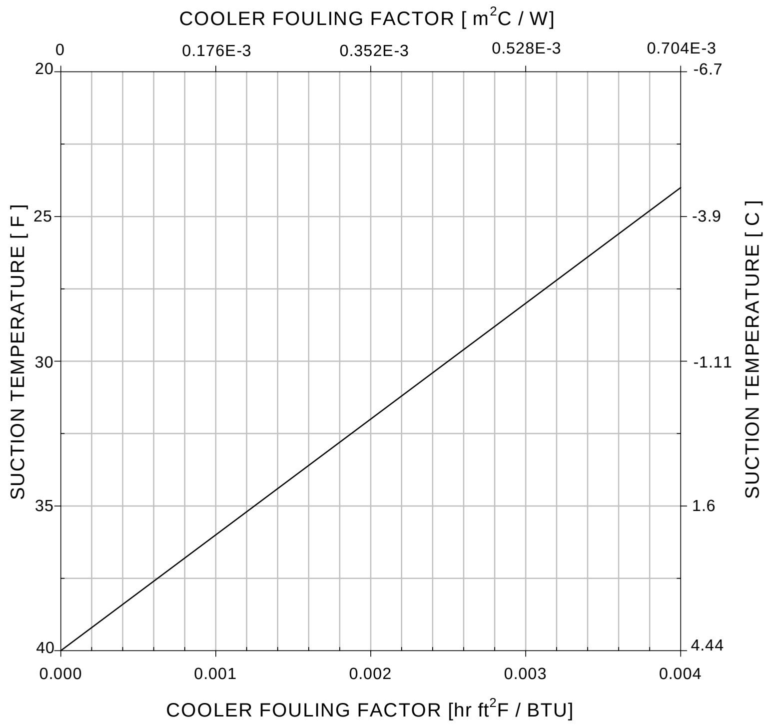

Fig. B-3 The effect of various thickness of scale
(expressed as fouling factors)
on the suction temperature of a typical flooded cooler

Fig. 3-3 shows the change of compressor entrance condition according to fouling factor of cooler. For the compressor entrance comes under the evaporator in the cooling cycle, so suction temperature - as an evaporation temperature of refrigerant - decreases proportionally according to increase of fouling factor.

And it can be explained as follows :

Let the all amount of calorie which evaporator should take from inflow water Q, and this formula can be made :

$$\dot{Q} = \frac{\left(T_m - T_{evap1}\right)}{\left(R_{conv} + R_w + R_{evap}\right)} \tag{B.1}$$

But on the other side, the all amount of calorie which evaporator should take from inflow water if fouling would have been formed :

$$\dot{Q} = \frac{\left(T_m - T_{evap2}\right)}{\left(R_{conv} + R_f + R_w + R_{evap}\right)} \tag{B.2}$$

On this formula, T_m means the average temperature of cool water which goes through outside of the evaporator, and T_{evap} means the evaporation temperature of refrigerant inside of the evaporator. And the letter R means resistant - each R_{conv}, R_f, R_w, R_{evap} comes under the thermal resistant by compulsion convection current(R_{conv}), fouling resistant(R_f), the thermal resistant by conduction on surface of the cooler's wall(R_w), the thermal resistant related to evaporation in the evaporator(R_{evap}).

We have to rotate same amount of calorie Q to get the same temperature of cool water T_m, if fouling was formed, the denominator of (B.2) could be bigger than that of (B.1) because of the increase of thermal resistant. Also the T_{evap2} of (B.2) should be smaller than T_{evap1} of (B.1) because the numerator of (B.2) must be bigger than that of (B.1) to make same amount of calories.

Arranging these, we can get the fact that the more fouling factor is, the lower the suction temperature - the input condition of compressor - should be, when we want to make same amount of cool water : Because of the increase of fouling resistant. Therefore, the value(the suction temperature) will decrease linearly according to increase of fouling factor like Fig. B-3.

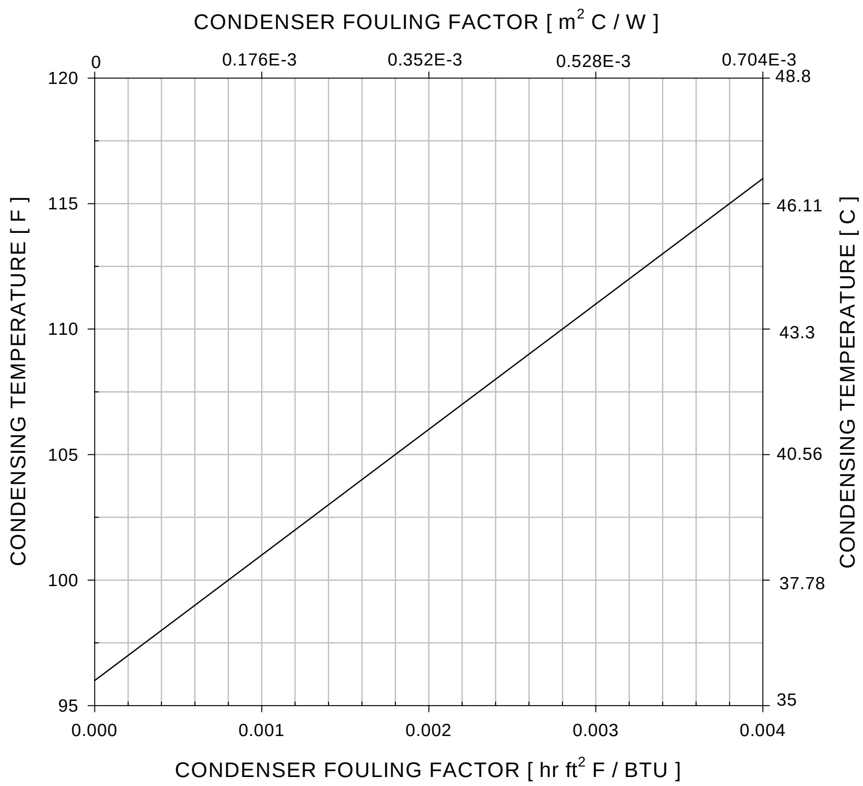

Fig. B-4 Effect of scale on the condensing temperature of a typical water-cooled condenser

Fig. B-4 shows that how the condensing temperature changes according to increase of fouling factor on the outsurface of the condenser, and we can recognize that condensing temperature increase linearly according to decrease of fouling factor.

And it can be explained like cooler's case above :

Let the calories that should be radiated from condenser is Q, and we can derive one formula as follows :

$$\dot{Q} = \frac{\left(T_{condens1} - T_c\right)}{\left(R_{condens} + R_w + R_c\right)} \tag{B.3}$$

But on the other hand, the calories that should be radiated from cooling water to condenser with fouling outsurface of condenser is as follows :

$$\dot{Q} = \frac{T_{condens2} - T_c}{R_{condens} + R_w + R_f + R_c} \tag{B.4}$$

In this formula, T_c is average temperature, $T_{condens}$ is refrigerant condensing temperature inside of condenser. And let the letter R be resistant inside of condenser - each $R_{condens}$, R_w, R_f, R_c comes under the thermal resistant by refrigerant condensing($R_{condens}$), the thermal resistant by conduction on surface of the cooler's wall(R_w), the fouling resistant(R_f), the thermal resistant by compulsion convection current(R_{conv}).

Being same condition of cooling water, same amount of calorie should be radiated : so if fouling was formed, the denominator of (B.4) could be bigger than that of (B.3) because of the increase of fouling resistant. Also the $T_{condens2}$ of (B.4) should be smaller than $T_{condens1}$ of (B.3) because the numerator of (B.4) must be bigger than that of (B.3) to make same amount of calories. Therefore, as fouling is piled up - as fouling factor increases - the condensing temperature in freezing cycle will be increased, and it increases linearly as we see Fig. B-3 and (B.4).

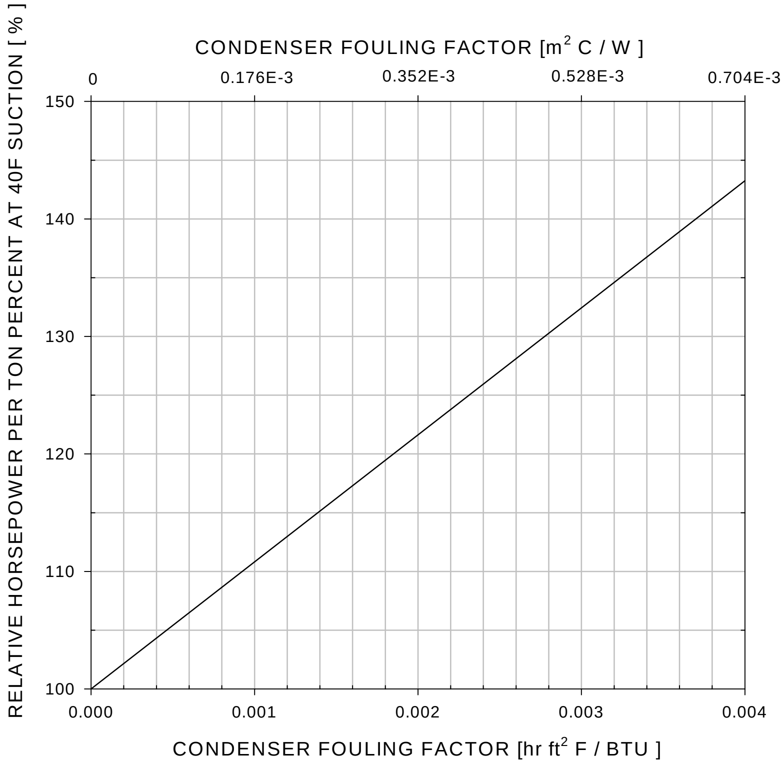

Fig. B-5 Effect of sacle on compressor Horsepower

Fig. B-5 shows the effect of scale on compressor horsepower being fixed condensing fouling factor(outsurface fouling) and suction temperature(input condition) at 40F. As fouling factor increase, refrigerant condensing temperature will also increase linearly as we saw on Fig. B-3. And finally compressor horsepower will increase linearly because refrigerant condensing pressure increased linearly as refrigerant condensing temperature increased. That is, if fouling factor become 0.002 [hr ft^2 F / BTU], we can recognize that the compressor horsepower will increase up to 122%.

Arranging this : the increase of fouling resistant on the outsurface of evaporator will cause the decrease of suction temperature - the input condition of compressor - and the fouling inside of the cooling water path can cause the increase of condensing temperature. Because of these, the all amount of work(horsepower) that the compressor should do will be increased more than without fouling inside.

Also we can recognize that fouling increase, suction temperature, condensing temperature and horse power is linearly related to each other.

3. Relations between Condensing Temperature and Refrigerative Effect

On the above, we explained that the scale which formed by cooling water can cause the increase of fouling factor and refrigerant condensing temperature. But in the previous paragraph, we assumed that same amount of calorie was transferred - so the freezing efficiency is same. Yet, in actually, the increase of fouling factor can make the freezing more inefficient in itself. From now, we will explain what kinds of effect would scale formation cause to freezing efficiency.

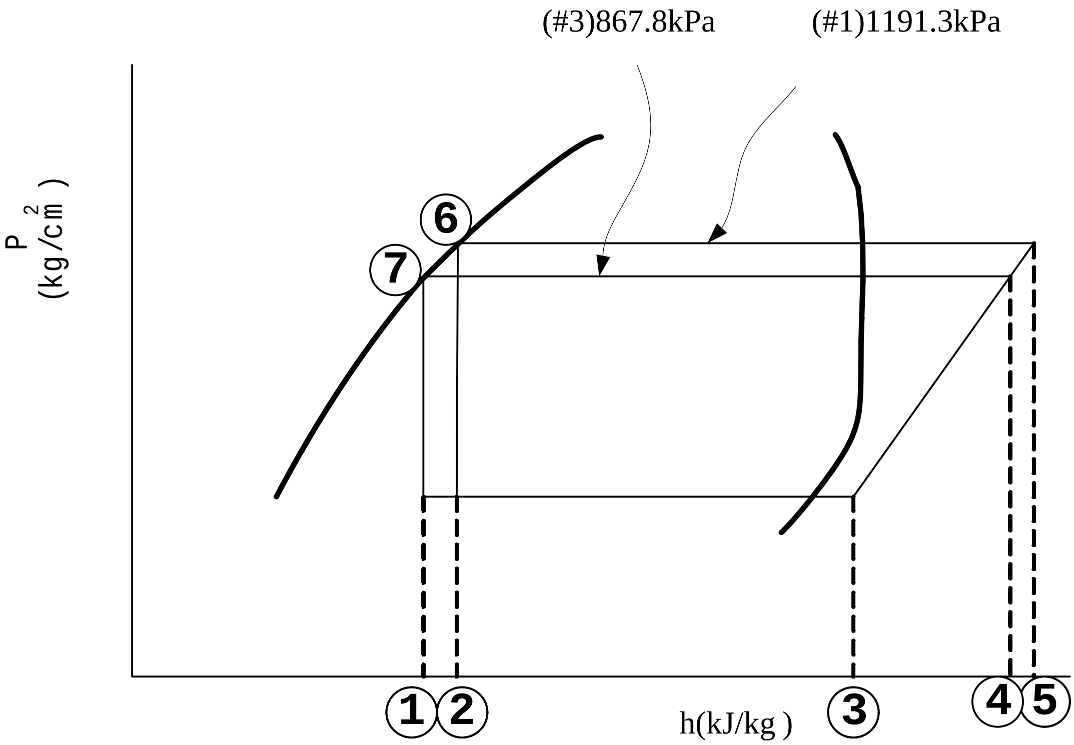

Fig. B-6 p-h diagram

Fig. B-6 shows the relation between refrigerant condensing temperature and freezing effects. First of all, without fouling, the refrigerating cycle degree could be displayed 1-3-4-7-1, and the all amount of frozen calorie at evaporator can be expressed by enthalpy as follows :

$$q_{evap} = h_3 - h_1 \tag{B.5}$$

On this moment, the compressing work at compressor would be :

$$w_{comp} = h_4 - h_3 \tag{B.6}$$

Thus, the COP on this refrigerating cycle can be calculated :

$$COP = \frac{q_{evap}}{w_{comp}} = \frac{h_3 - h_1}{h_4 - h_3} \tag{B.7}$$

On the other hand, with fouling outside of the surface of the condenser, the refrigerating cycle degree is 2-3-5-6-2. And as previous explanation, the refrigerant condensing temperature would be increased owing to fouling. On this moment, all amount of frozen calorie at evaporator can be expressed by enthalpy as follows :

$$q_{evap\ f} = h_3 - h_2$$

And, the compressing work at compressor would be :

$$w_{comp\ f} = h_5 - h_3$$

(B.9)

On the above, we explained that fouling which was formed outside of the surface of the condenser make just the compressor work more higher, but actually as we see the graph, it is decreased not the compressor work but also the amount of frozen calorie. And we can calculate COP as follows :

$$COP_f = \frac{q_{evap\ f}}{w_{comp\ f}} = \frac{h_3 - h_2}{h_5 - h_3}$$

(B. 10)

Thus, on this formula, if the denominator increased and the numerator decreased, the brought value COP should be more decreased.

4. How to Remove the Fouling Caused by Cooling Water

As above explanation, we must clean refrigerator periodically because fouling formation may make the ability of refrigerator more inefficient.

And there are many methods to remove obstacles of the refrigerator as follows :

Table B-3 : Fouling Remove Methods by Cooling Water

Methods	Problems
1. Periodical Cleaning using Acid or Brush (Hand cleaning)	- Simple cleaning method that cleaning several times per year manually.
2. Hard water softner injection	- Generally used methods by lots of salt injecting : it may occur pollution by drain water. - It needs manual hand cleaning once a year.
3. Magnetic handling equipment	- Scale handling method using magnet, but it needs a lot of engineering information : a quality, flow, temperature of water, pH etc. - And the scales made by silica cannot be removed
4. Chemical treatment	- Periodical softening chemical injecting method : it is cheaper than 'Hard water softner injection method', but it needs manual hand cleaning once a year.
5. Brush System	- Inserting brushes into condenser tubes, but it interrupt the flow of the cooling water moving into inverse, and it costs high when inserting or changing brushes.
6. Sponge Ball Circulation	- Circulate sponge ball a little bit bigger than the tube size, and it is most clear methods but it needs separate sponge circulating machine.

Table B-4 : Comparison of Cleaning Methods

Features of the Clean Methods	Sponge Balls	Chemical Cleaning	Nozzle	Brushes
Clean pipes for a long time	positive	negative	negative	positive
Prevents pipe wear in the cleaning process	positive	negative	negative	positive
Simple and reliable	positive	positive	positive	negative
Increases the life of span of the exchanger	positive	negative	negative	positive
Preserves the performance coefficient of the exchanger	positive	negative	negative	positive
Preserves environmental quality	positive	negative	positive	positive

Table B-3 and B-4 shows that the most proper way to remove fouling by cooling water is 'Sponge ball circulation method'. But this method need separate equipments to circulate sponge ball, and also needs cleaning equipments to wash sponge balls themselves, so the considering problems about this method is :

1. How much reliable and simple this method is?
2. How much simple the self-cleaning sponge ball equipments?
3. Are there any damages on the sponge balls circulating sponge ball by pump or something?
4. What is most proper period to circulate sponge balls?
5. Is the cost not expensive to run and is it convenient to install?