13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

Study on Aging of Heat Pump based on Long-term Assessment

Nobuhiro TAKAHASHI[a,c,*], Masashi MOMOTA[a], Masahiko KUMAGAI[c],

Tadahiko IBAMOTO[a], Takashi INOUE[b]

[a]Tokyo Denki University, 5, SenjuAsahiCho Adachi-ku, Tokyo 120-8551, Japan
[b]Tokyo University Of Science, 2641 Yamazaki, Noda, Chiba 278-0022, Japan
[c]JAPAN FACILITY SOLUTIONS,Inc, 6-4, Osaki 1-Chome, Shinagawa-ku, Tokyo 141-0032, Japan

Abstract

In this study, we focused on the aging degradation of heat pumps and developed an efficiency evaluation method. From the analysis result of the COP fluctuation factor by the typical CR, it was confirmed that the partial load and the cooling water temperature affected the fluctuation of COP. We developed a method to create a multiple regression equation using these variables as explanatory variables, and analyzed 72 centrifugal refrigerators. As a result, we confirmed the possibility of the efficiency evaluation with this method. Also, it was found that more than 5,000 hours of operation data was necessary to ensure the accuracy of the correction method using the multiple regression equation. In addition, our analysis showed that little aging was observed in CRs under proper maintenance.

Keywords: Long-term Assessment; centrifugal refrigerators; COP;

1. Introduction

1.1. Background of the study

The efficiency of heat pumps for air-conditioning applications, which occupies a large proportion of energy consumption in buildings, should be maintained properly. Therefore, regular inspection and proper maintenance are needed to maintain their initial efficiency. The aging of common equipment is generally represented by a schematic diagram shown in Figure 1. This figure is well known in many fields, however actual investigation on heat pumps are very few. Because, evaluating the changes of actual operation efficiency is not easy. In actual operation, every parameters such as cooling water temperature or partial load change from moment to moment. Complicating things further, seasonal changes also affects to efficiency. According to this background, the evaluation method of heat pumps for stakeholders are demanded.

1.2. Outline of the study

Evaluating efficiency change is worthful for compressing the maintaining cost which to the life cycle management. Considering this issue, the efficiency evaluation method for heat pumps is developed in this study. In particular, focusing correcting the coefficient of performance (COP) of heat pumps against the efficiency fluctuation during operation, long term assessment by maintenance was examined.

* Corresponding author. Tel.: +81-363-712-555; fax: +81-363-712-561.
E-mail address: n.takahashi@j-facility.com.

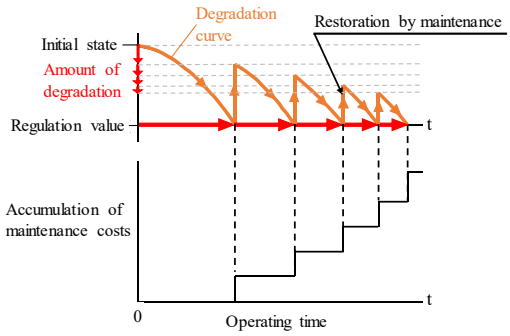


Fig. 1. Schematic diagram of maintenance and costs of recovery from deterioration

1.3. Property of analyzed centrifugal refrigerators

The data of actual operation result used in this study was provided by an energy service company (ESCO) that collaborated in this study and was collected from 73 centrifugal refrigerators (CRs) installed at 30 locations as an ESCO service utilizing thermal energy storage systems. The data was stored on a building automation and control system (BACS) every hour from April 2000 to March 2019. Figures 2 - 5 show outline of the CRs. Many of them have been in operation for more than 10 years. The ESCO includes a maintenance contract for most CRs with the CRs' manufacturers to ensure a supply of chilled water to the users, and it performs satisfactory manufacturer-recommended maintenance at recommended intervals. Since the data contained a large amount of data that was unnecessary for the COP assessment, we had to select the appropriate data before starting the analysis. Table 1 shows the requirement of COP analysis. For this study, not only calculating COP but also functional analysis was main issue, this requirement includes such as the cooling water temperature. In practice, most CRs met this requirement and as a result 72 of CR data was remained.

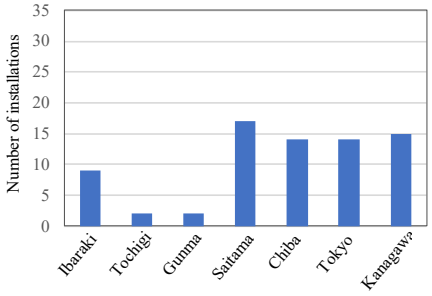


Fig. 2. Number of units installed by prefecture

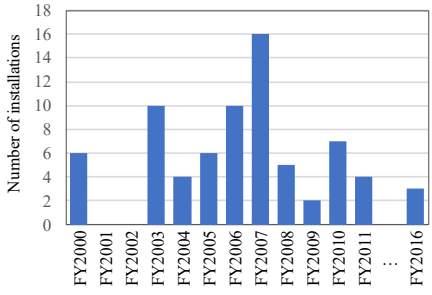


Fig. 3. Number of units installed by year from April

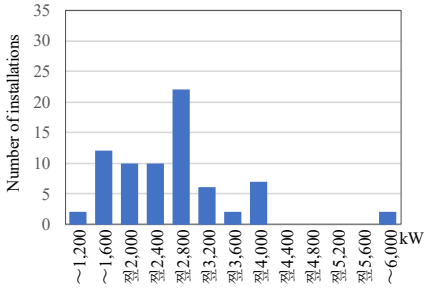


Fig. 4. Number of units installed by capacity (kW)

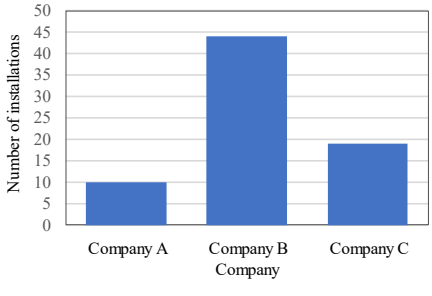


Fig. 5. Number of units installed by supply company

Table 1. Requirement of COP analysis on BACS data

Measurement item
Chilled water inlet and outlet temperature
Chilled water flow
Cooling water inlet and outlet temperature
Power consumption
Heat production
* Hourly data stored in the BACS

2. Analysis on COP fluctuation and factors

2.1. Confirmation of the operation trend

Before the development of the correction of COP, the operation result of all the CRs was analyzed to confirm the trend. Figure 6 shows the operation result of NO.19-01 as a typical example. This CR which installed in FY2006, capacity of 2,700kW, had a decade operation data. This time series COP fluctuation plots are distinguished into colour which indicates the cooling water temperature. Focusing on these colors, it was confirmed that COP fluctuation has a strong relationship along to fluctuation of the cooling water inlet temperature (here in after, "cooling water temperature") which depending on a change of season, same as a theoretical behavior. On the other side, COP was enhanced at the point of 3,000 hour after the operation started. Through the other detailed analysis, it was confirmed that this behavior was caused by the set point change of the chilled water outlet temperature. Considering above, the correlation of the COP with factors which selected in Table 1 was investigated.

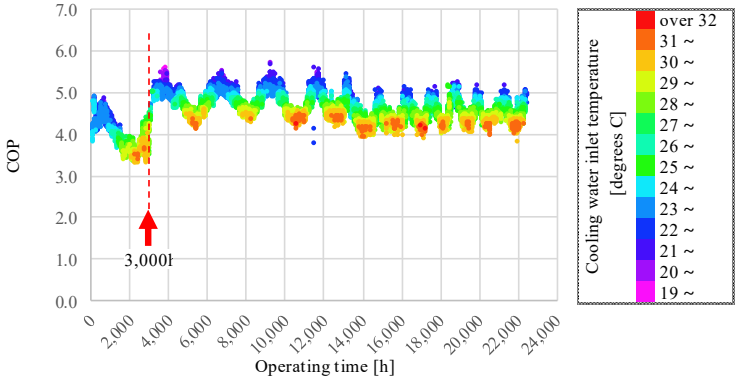


Fig. 6. Operation result of NO.19-01 as a typical example.

Figures 7 - 11 show the correlation of the COP of the CR NO.19-01 over the measurement period for each parameter. The partial load in Figure 8 indicates the ratio of the actual generated heat to the rated capacity of the CR. As shown in Figures 7 - 11, a strong correlation was confirmed between the COP and the partial load as well as the cooling water temperature. On the other side, considering the thermal energy storage system, it is able to be thought that the chilled water temperature is stable in operation except the set point change. Therefore, as the first step of this study, factors which are the partial load and the cooling water temperature were picked up for the correction of COP fluctuation.

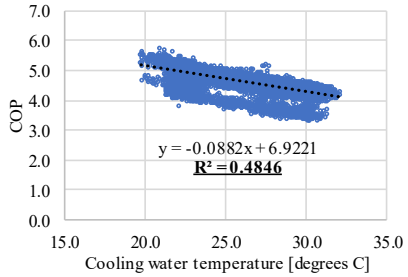


Fig. 7. Correlation between cooling water temperature and COP

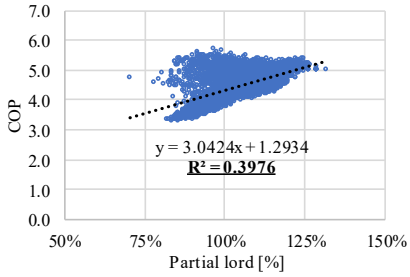


Fig. 8. Correlation between partial lord and COP

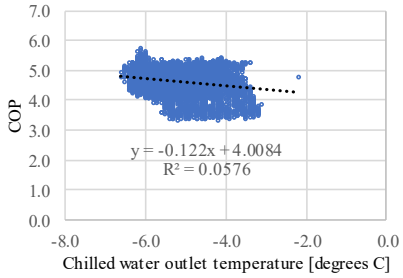


Fig. 9. Correlation between chilled water outlet temperature and COP

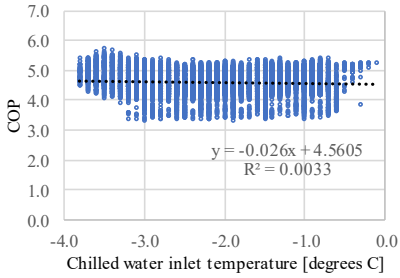


Fig. 10. Correlation between chilled water inlet temperature and COP

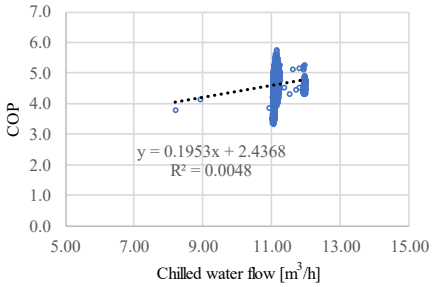


Fig. 11. Correlation between chilled water flow and COP

3. Correction of the COP

3.1. Method of correcting the COP

Table 2 shows the procedure of COP correction. Conception of this method is based on the performance curve generated from an actual operation data. Basically, utilizing the generated curve, the cancellation against fluctuation of factors is realized by correcting the COP of a certain operation state to the data of the reference state. Concrete process utilizing a multiple regression equation is following.

First, to derive a multiple regression equation, a regression analysis of the data for the baseline period is conducted using the partial load and the cooling water temperature as explanatory variables.

The COP obtained by substituting the partial load and the cooling water temperature into the multiple regression equation is defined as the "COP on the performance curve". At this step, we defined the baseline period as three years from the initial fiscal year. If the fluctuation on the cooling water temperature during the

three years is fine degree, another three years with a larger degree of fluctuation were selected to improve the accuracy of the multiple regression equation.

The variability ratio of COP is the value obtained by dividing the actual COP by the COP on the performance curve and subtracting 1 from the resultant value. The multiple regression equation produced in previous step is summarized in the form of equation (1). The coefficients for each variable differ for each CRs. Table 3 shows the coefficients for typical CR.

Figure 12 shows a comparison between the performance curve obtained by the multiple regression equation and the actual operation COP. A few outliers are seen at lower cooling water temperatures, but they are generally similar.

Table 2. COP correction procedure

Step	Contents (Implementation / calculation)
Step.1	Create a correlation diagram between partial lord and COP for each cooling water temperature in the base year
Step.2	Create a multiple regression equation with the partial lord and cooling water temperature as explanatory variables
Step.3	Calculate the COP at each time by substituting the actual cooling water temperature and partial lord every 100 hours into the multiple regression equation * The COP calculated here is defined as COP on the performance curve.
Step.4	The actual COP divided by COP on the performance curve and subtracted 1 is the variability ratio of COP

$$f(x,y) = (C_{11}x^3 + C_{12}x^2 + C_{13}x + C_{14})y^3 + (C_{21}x^3 + C_{22}x^2 + C_{23}x + C_{24})y^2 + (C_{31}x^3 + C_{32}x^2 + C_{33}x + C_{34})y + (C_{41}x^3 + C_{42}x^2 + C_{43}x + C_{44}) \quad (1)$$

$f(x,y)$: COP on the performance curve
x : Cooling water temperature [degrees C]
C_{nm}: Constants
y : Partial lord [%]

Table 3. Coefficient list of typical CR

		m			
		C_{n1}	C_{n2}	C_{n3}	C_{n4}
n	C_{1m}	-8.69283E-02	6.88748E+00	-1.80476E+02	1.56145E+03
	C_{2m}	1.99511E-01	-1.58588E+01	4.17038E+02	-3.62289E+03
	C_{3m}	-1.15261E-01	9.19175E+00	-2.42631E+02	2.12142E+03
	C_{4m}	1.89280E-04	-1.50236E-02	3.92556E-01	-3.36224E+00

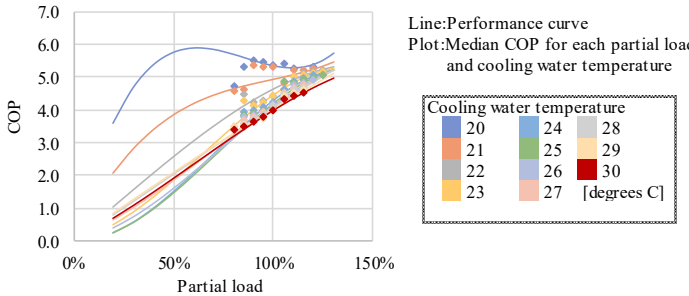


Fig. 12. Comparison of performance curve and actual operation COP

Figure 13 shows the variability ratio of COP for the typical CR (No.19-01). The fluctuation of efficiency concerned with the cooling water temperature and the partial lord was suppressed, effectiveness of this correcting method is confirmed.

On the other side, the variability ratio of COP became a positive value after 6,000 hours. From the point of view of theory, as shown in Figure 13 positive value is not suitable. However, this trend might be caused by the set point change of the chilled water outlet temperature. Also, this trend is able to guess from the correlation of Figure 9. Considering the ordinary circumstances, the chilled water outlet temperature should be involved into the factor of a multiple regression equation. However, all of CRs which picked up in this study are connected to thermal energy storage system, is able to maintain the temperature in stable state, the exclusion effect of the chilled water outlet temperature was estimated not strong issue to evaluate the overview of the trend. Therefore, here in after, two factors which are the cooling water temperature and the partial load were adopted for the correction considering as a first step of this study.

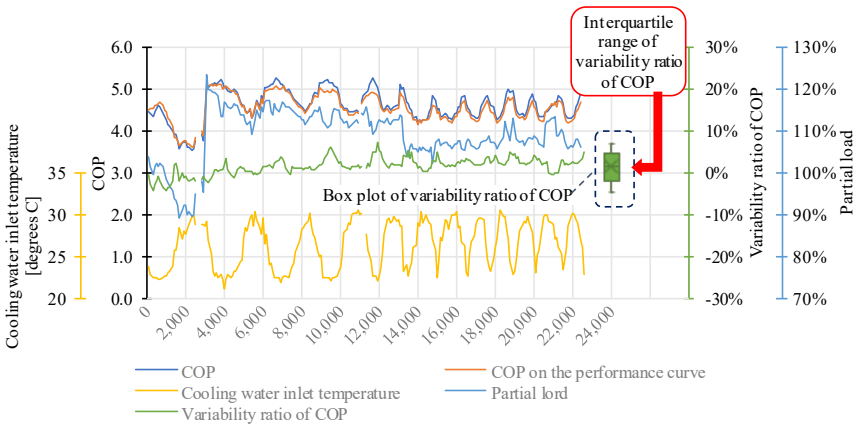


Fig. 13. No.19-01 Changes in variability ratio of COP and COP, etc.

3.2. Correction results of all the COP

Before the evaluation for all the variability ratio of COP, for each CR, it was calculated the interquartile range (the height of the boxplot) of the variability ratio of COP as shown in Figure 13 in previous. This is for the confirmation of the factors that cause a significant fluctuation on the variability ratio of COP.

Figure 14 shows the correlation between the operating (cumulative) time of each CR and the interquartile range of the variability ratio of COP. As shown in the figure, the interquartile range converges after 5,000 hours of the operating time. In other words, a minimum operating time should be decided to maintain the accuracy of the multiple regression equation. Therefore, from point of view of this, these 4 of CRs which are less than 5,000 hours were excluded from the next evaluation.

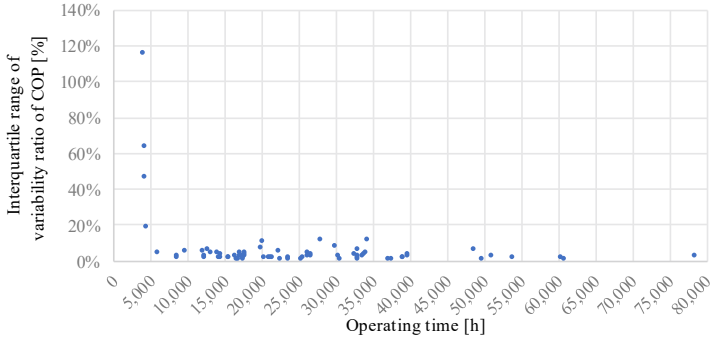


Fig. 14. Correlation diagram of Interquartile range of variability ratio of COP and operation time

Figure 15 shows the variability ratio of COP which averaged in 100 hours for 68 CRs in total, excluding the four CRs mentioned above. Since grasping the overview of the trend was difficult from this figure, statistical processed result was shown in Figure 16. This is boxplot for each 1,000 hours average. Concretely, the evaluation on the variability ratio of COP was performed in the interquartile range to quantitatively determine whether the correction was effective. The range was within roughly ± 5%, indicating that the fluctuation due to the partial load and the cooling water temperature has suppressed by the correction.

Figure 17 shows a comparison between the interquartile range of change in the actual COP for each CR (Red plot) and that of the variability ratio of COP (Blue bar chart). Except for three CRs, the interquartile range is smaller for the variability ratio of COP, it was confirmed that correction method to be effective to almost CRs.

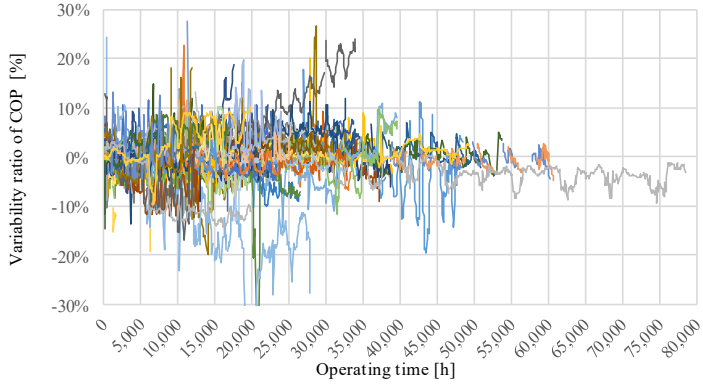


Fig. 15. Trend of variability ratio of COP of 68 units every 100 hours

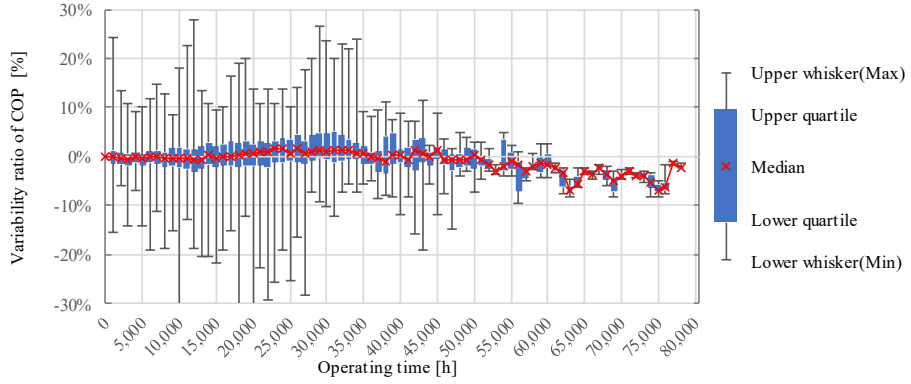


Fig. 16. Box plot for each 1,000 hours

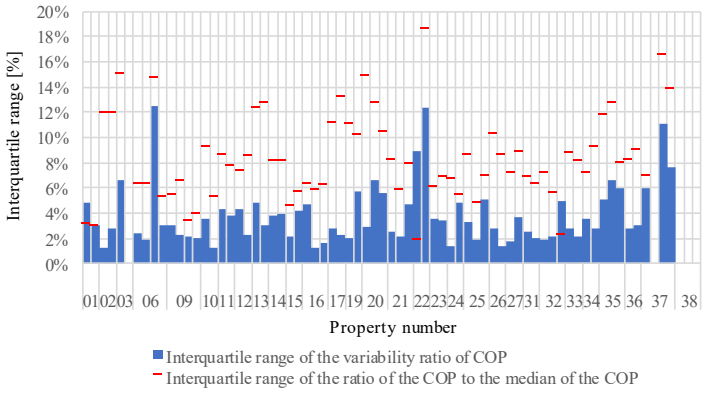


Fig. 17. Interquartile range of the ratio of the COP to the median of the COP and the interquartile range of the variability ratio of COP

4. Conclusions

Focusing on the aging of heat pumps, the efficiency evaluation method is developed in this study. In particular, the correcting COP method against the efficiency fluctuation during operation, long term (longest is 10 years) assessment for centrifugal refrigerators was examined. As a result, following was shown.

- Possibility was confirmed to correct the COP to evaluate the variability COP utilizing developed method which with a multiple regression equation.
- The partial load and the cooling water temperature was explicable factors for the correcting. On the other side, considering other type of refrigerator or HVAC system, it was estimated that the chilled water temperature is one of the effective factor.
- Only in the scope of this study, but more than 5000 hours of operation data is required to ensure the accuracy of the multiple regression equation for the correction method. In addition, from our analysis, almost no aging was observed on CRs under the proper maintenance.

References

[1] Akira Tkakusagi Study on maintenance cost for restoring physical degradation of air−conditioning system. j.Archit. Plann. Environ.Eng.,AIJ, No.459,27-36,May,1994(Japanese paper)