Study of a heat pump cycle for application to the condenser of a nuclear power plant

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1. Introduction

In accordance with the declaration of carbon neutrality in advanced countries around the world, technology development is being carried out to reduce carbon emission and improve efficiency of various systems. A heat pump is the most promoted technology because it can make high-temperature water with high efficiency by using a low-temperature heat source.

In general, the used steam in a PWR(Pressurized Water Reactors) is condensed through heat exchange with seawater in the steam condenser. However, it causes an increase in temperature of seawater and changes in the surrounding natural environment. The problem is that rising temperature of seawater usually has an adverse effect on ecosystems[1,2]. For this reason, the heat pump system can be seen as one of the most realistic technologies for carbon neutrality because it can supply high-temperature water to surrounding industries at a low cost while preventing seawater temperature change. In the present study, a heat pump cycle was suggested for application to the steam condenser of a nuclear power plant.

2. Methods and results

In order to examine the applicability of the heat pump to the steam condenser of PWR, the performance of the heat pump cycle was analyzed through thermodynamic analysis. Thermophysical properties of refrigerants were used in database of REFPROP V10. The theoretical calculations were performed using Matlab 2022a.

2.1 A heat pump cycle and refrigerants

First of all, we suggested the following heat pump cycle(Fig. 1) that is a two-stage compression cycle with a flash tank. For efficient compression, two compressors were considered in this cycle. The flash tank also contributed to improving the performance of the heat pump by reducing the power requirement of the compressor in the first stage.

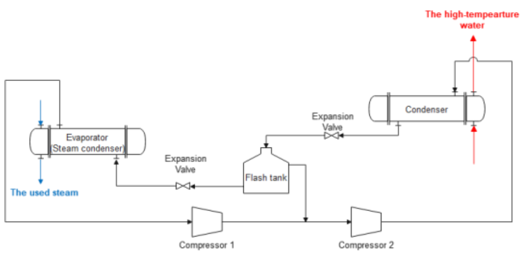

Fig. 1. A schematic of a two-stage compression cycle with a flash tank.

In the suggested heat pump cycle, temperatures at the evaporator and the condenser(it is not the steam condenser in PWR) are important parameters. Also, it is necessary to carefully select a suitable refrigerant in consideration of the characteristics of the refrigerant.

The saturated temperature of the steam condenser is about 33℃ based on the report for APR1000[3]. Then, the temperature of the evaporator in the heat pump cycle should be lower than 33℃. In the present study, the saturated temperature of a refrigerant was assumed to be 25℃. In addition, the saturated temperature at the condenser was also assumed to be in the range of 80 to 120℃.

With consideration of the temperature range of the heat pump cycle, we selected four available refrigerants as shown in Table I. These refrigerants have the critical temperature higher than 120℃ which is the maximum saturated temperature at the condenser in this re. It means that the heat pump cycle can normally operate in a subcritical state using these refrigerants.

Also, the refrigerants are eco-friendly refrigerants that have GWP(Global Warming Potential) lower than 1 and zero ODP(Ozone Depletion Potential). On the other hand, all four refrigerants are non-toxic, but R1234ze(Z) has disadvantage because it is mildly flammable unlike other refrigerants that are nonflammable.

Table I: Characteristics of the examined refrigerants

Refrigerant	$T_{critical}$ (℃)	$P_{critical}$ (kPa)	GWP (-)	ODP (-)	Class. (-)
R1224yd(Z)	156	3337	1	0	A1
R1233zd(E)	166	3624	1	0	A1
R1234ze(Z)	150	3531	1	0	A2L
R1336mzz(Z)	171	2903	7	0	A1

2.2 Result and discussion

The performance of the heat pump can be represented as COP(Coefficient of Performance) that is shown in the following equation. $\dot{Q}_{HP}$ is heat transfer rate of the condenser in the heat pump cycle, and $\dot{W}_{comp}$ is work of the compressors.

$$COP = \frac{\dot{Q}_{HP}}{\dot{W}_{comp}}$$

For comparison of COP in accordance with the saturated temperature at the condenser, other parameters were fixed as shown in Table II. $P_{m,ratio}$ represents the factor for the saturated pressure of the flash tank. For example, $P_{m,ratio}$ is one when the compression ratios of the first-stage compressor and the second-stage compressor are the same. For simple comparison of COP, $P_{m,ratio}$ was fixed at one. Additionally, the isentropic efficiencies of the first-stage compressor and the second-stage compressor were both assumed to be 0.8.

Table II: Value for design parameters

Parameter	T_{eva} (°C)	$P_{m,ratio}$ (-)	$\eta_{comp,1}$ (-)	$\eta_{comp,2}$ (-)
Value	25	1.0	0.8	0.8

Fig. 2 shows COP at the given conditions for each refrigerant. It can be seen that the lower the saturated temperature at the condenser is, the higher the COP is.

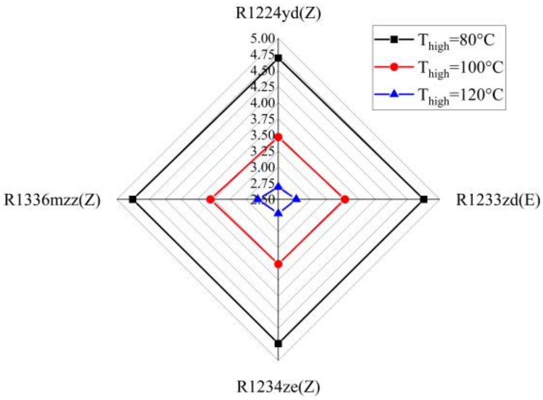

Fig. 2. COP with changing refrigerant for each high-temperature water condition.

In order to compare COP according to the refrigerant in detail, the value of COP was compared when the temperature at the condenser was 100℃. As shown in Fig. 3, R1336mzz(Z) shows the highest COP, but R1224yd(Z) shows the lowest COP.

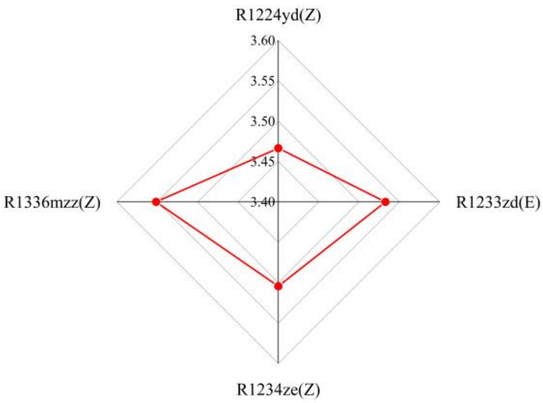

Fig. 3. COP with changing refrigerant T_{high}=100℃.

Fig. 4 shows wall superheat at the evaporator in the heat pump cycle. If a high degree of superheat is required in the evaporator, the size of the evaporator must be increased. Since the evaporator in the heat pump cycle means the steam condenser in PWR, R1224yd(Z) and R1336mzz(Z) are considered to be difficult to utilize in this heat pump cycle.

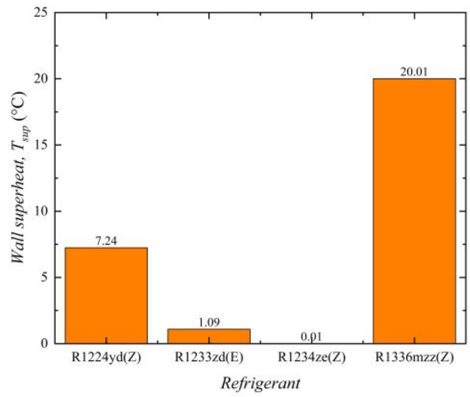

Fig. 4. The wall superheat of the refrigerants in the condenser.

2.3 Optimization

Considering COP, wall superheat and flammability, R1233zd(E) was determined as the most suitable refrigerant for the given heat pump cycle. To optimize the heat pump cycle, RSM(Response Surface Method) was used as an optimization technique using Design Expert V13.

Fig. 5 is the main effect plot of COP versus $P_{m,ratio}$. Although the COP increases as the pressure at the flash tank increases, it has been shown to have a very small effect on the COP of the heat pump.

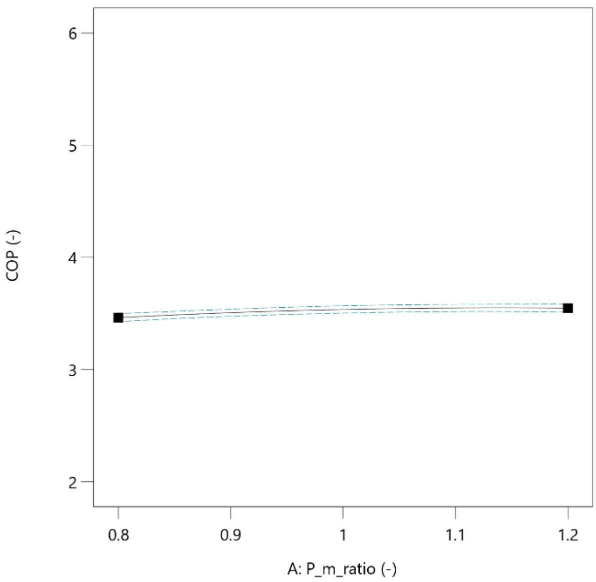

Fig. 5. Main effect of $P_{m,ratio}$ on COP.

Fig. 6 also shows the main effect plot of the temperature at the condenser on COP. As T_{high} increases, COP decreases significantly. This is because the pressure ratio increases as the saturation pressure at the condenser increases. This leads to an increase the power required of the compressor causing decrease of COP.

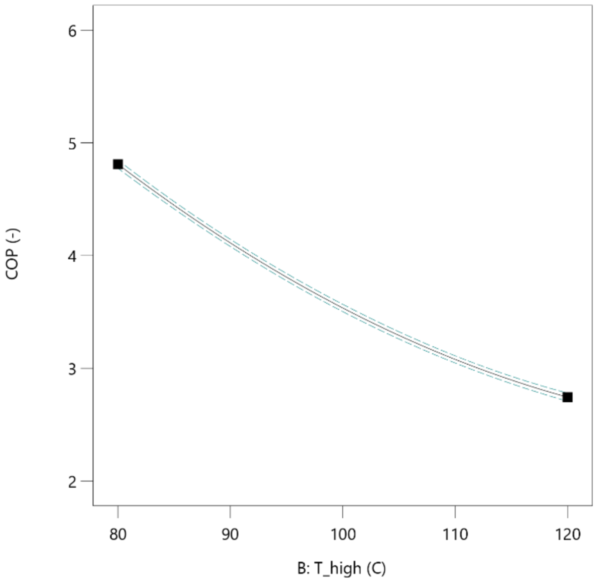

Fig. 6. Main effect of T_{high} on COP.

Finally, the change of COP with respect to $P_{m,ratio}$ and T_{high} is shown in Fig. 7. As $P_{m,ratio}$ gradually increased, although the effect was insignificant, COP showed a tendency to increase. Above all, it was found that even at a condenser temperature of 120℃, the COP was greater than 2.5. Furthermore, it can be seen as a highly competitive technology for carbon neutrality since it does not emit carbon dioxide. As a result, it seems meaningful to apply a heat pump to the steam condenser in PWR for making the hot water of 120℃.

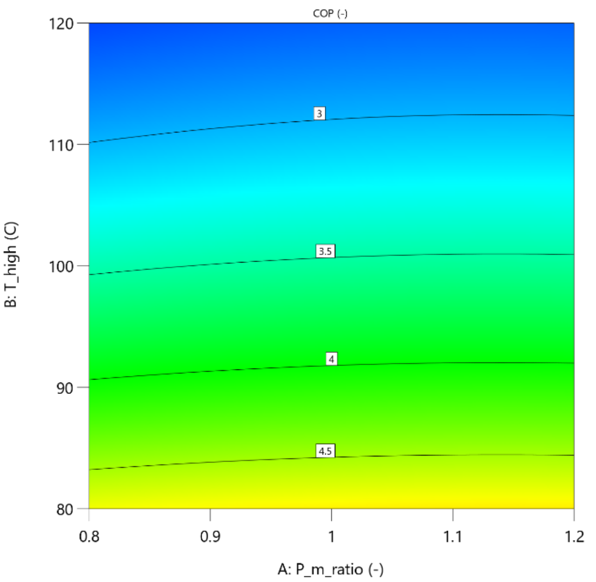

Fig. 7. Contour plot of COP with changing $P_{m,ratio}$ and T_{high}.

Based on the result of RSM, we recalculated and summarized COP, $P_{r,1}$(pressure ratio for the first stage) and $P_{r,2}$(pressure ratio for the second stage) in Table III. In this result, even when the condenser temperature is 120℃, the COP is 2.8.

However, when the temperature at the condenser was 110℃ and 120℃, the compression ratio of the first-stage compressor was 3.6 and 4.0, respectively. If a centrifugal compressor is used, these values are a fairly high compression ratios, so it is judged to be difficult to implement in reality. In other words, considering the compression ratio in the cycle presented in this study, the temperature at the condenser can realistically be raised to 100℃, and the COP at this condition is 3.55. Alternatively, considering the compression ratio, it is thought that optimization studies on pressure are necessary.

Table III: Optimized condition for each T_{high}

T_{eva} (℃)	T_{high} (℃)	P_{eva} (kPa)	P_{flash} (kPa)	P_{con} (kPa)	$P_{r,1}$ (-)	$P_{r,2}$ (-)	COP (-)
25	80	130	334	658	2.6	2.0	4.75
25	90	130	376	833	2.9	2.2	4.06
25	100	130	420	1042	3.2	2.5	3.55
25	110	130	467	1288	3.6	2.8	3.14
25	120	130	516	1575	4.0	3.1	2.80

3. Conclusions

In the present study, a two-stage compression cycle with a flash tank was proposed as a heat pump cycle in order to make high-temperature water in surrounding industries from the heat of the used steam in the steam condenser in PWR. From the analysis, we concluded the followings.

1) It was analyzed that COP increased when $P_{m,ratio}$ increased and T_{high} decreased. And even if the temperature at the condenser reached 120℃, it was confirmed that the COP was higher than 2.5 based on the calculation.
2) Considering COP, wall superheat, and flammability, R1233zd(E) was determined as the most suitable refrigerant among the four selected refrigerants.
3) However, considering the compression ratio, the practical maximum saturation temperature at the condenser was 100℃. In order to increase it, it is necessary to study the optimization of the system pressure.

ACKNOWLEDGEMENT

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[3] F. Name, R. Type, N. Spectrum, T. Capacity, G.E. Capacity, D. Status, L. Update, A.P. Reactor, L. Water, L. Water, T. Neutrons, I. Operation, Status Report 103 – Advanced Power Reactor (APR1000), (2011).