Thermodynamic Analysis of Heat Pump Cycle for Hot Water Supply
－ Definition of Ideal Cycle and Evaluation of Hopeful Refrigerant －

Background

The reverse Carnot cycle, the high and low heat sources of which are constant temperatures, decides the theoretical limit of COP [*1] of conventional heat pumps used as air conditioners etc. (Fig.1), but the cycle which decides the theoretical limit of COP of a heat pump used as tap water heater isn't the simple reverse Carnot cycle because tap water heating with high temperature rise is needed. So the definition of the ideal cycle for tap water heating and its COP is necessary. Furthermore, it is necessary to clarify the refrigerant which has the highest COP for tap water heating.

Objectives

The ideal cycle for tap water heating and its COP are clarified. Upper limit COP of heat pump cycle with various refrigerants for tap water heating is studied and finally the refrigerant which achieves the highest COP for supplying hot water is clarified.

Principal Results

1. Definition of the ideal cycle for tap water heating and its COP

The ideal cycle for water heating can be defined as the cycle whose high heat source varies temperature with constant specific heat, because the specific heat of tap water is constant and tap water heating with high temperature rise is needed. Other processes of the cycle are same as the reverse Carnot cycle. Fig1. shows the T-S diagram of the cycle and its COP in comparison with those of the reverse Carnot cycle. It is clarified that like COP of the reverse Carnot cycle, COP of the cycle is expressed for a function of the absolute temperature.

2. Evaluation of upper limit COP of heat pump cycle for hot water supply of various refrigerants

Fig.2 shows the evaluation results of the upper limit COP of various refrigerants in comparison with the COP of the ideal cycle. The upper limit COP means the COP of each refrigerant cycle without the loss. The evaluation condition is heat source temperature 16˚C, water temperature 17˚C and hot water temperature 65˚C. This is the rating condition of JRA4050 [*2]. In the figure, COP of the ideal cycle is also shown. No refrigerant can be beyond this value. Among the refrigerants, COP of CO_2 is the highest.

Fig.3 shows T-S diagrams of CO_2 and R410A. The critical temperature of CO_2 is very low. The high pressure of its cycle becomes super critical and there is no condensation. Because the shape of its cycle is almost the same as that of the ideal cycle, COP of CO_2 is the highest. On the other hand, there is a condensation process in R410A cycle and the shape of its cycle is similar to the reverse Carnot cycle. So COP of its cycle is lower than that of CO_2. COP of other refrigerants are almost the same as that of R410A because there is condensation process in those refrigerants.

3. Evaluation of the feasible COP of CO_2 heat pump cycle for water heating

About CO_2 refrigerant which achieves the highest upper limit COP among various refrigerants, the feasible COP considering the efficiency of element machinery of heat pump, is evaluated in the rating condition of JRA 4050. The feasible COP of around 6 is provided assumed that the temperature difference of evaporator is 5˚C, the minimum temperature difference of hot water supply heat exchanger is 3˚C, adiabatic compression efficiency is 0.75 and adiabatic expansion efficiency is 0.5.

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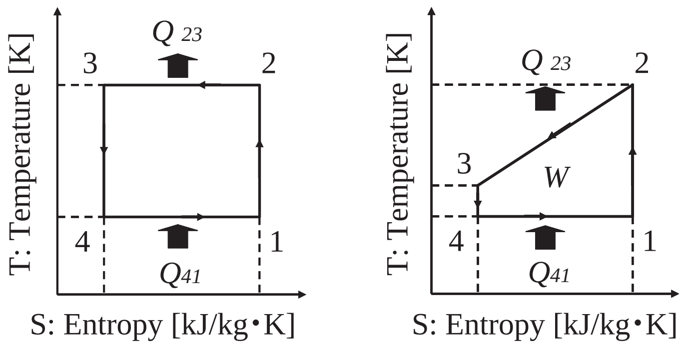
Reference

M. Saikawa, 2006, "Thermodynamic Analysis of Heat Pump Cycle for Hot Water Supply - Derivation of Ideal Cycle and Evaluation of Hopeful Refrigerant," CRIEPI Report M06002 (in Japanese)

＊1：Coefficient of Performance (= heat output / compression power)
＊2：JRAIA, Residential heat pump water heaters, JRA4050:F2005

1→2	Isentropic Compression
2→3	Reversible Isothermal Compression (Reverse Carnot cycle)
	Reversible Constant Specific Heat Change (Ideal cycle for water heating)
3→4	Isentropic Expansion, 4→1 : Reversible Isothermal Expansion
Q_{23}	Heat Output, Q_{41} : Heat Input, W : Work Input ($=Q_{23}-Q_{41}$)
COP	Coefficient of Performance ($=Q_{23}/W=Q_{23}/(Q_{23}-Q_{41})=1/(1-Q_{41}/Q_{23})$)

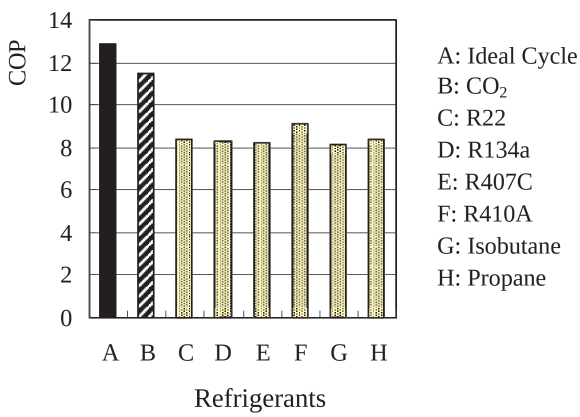


The ideal cycle for water heating is defined as the cycle whose high heat source varies temperature with constant specific heat and other processes of which are same as the reverse Carnot cycle

$\boxed{COP=1/(1-T_1/T_2)}$ $\boxed{COP=1/(1-T_1\ln(T_2/T_3)/(T_2-T_3))}$

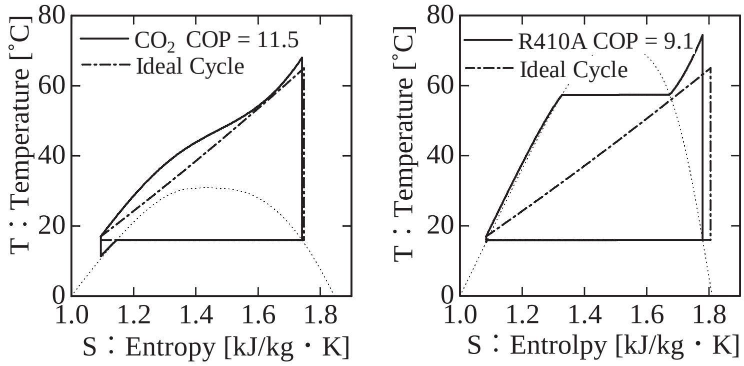
(a) Reverse Carnot cycle (b) Idea cycle for water heating

Fig.1 T-S diagram and COP of ideal cycle for water heating (comparison with reverse Carnot cycle)



COP of the ideal cycle is 12.9 (A). No refrigerant can be beyond this value. COP of CO_2 is 11.5 (B) and the highest among the refrigerants.

Fig.2 Upper limit COP of each refrigerant, JRA condition



The shape of CO_2 cycle is similar to that of the ideal cycle (dash line in the figure) in comparison with R410A cycle. So COP of CO_2 is the highest. The shapes of other refrigerants are almost the same as that of R410A because of condensation process.

Fig.3 T-S diagram of CO_2 and R410A, JRA condition