Recovering and Upgrading Waste Heat of Air-Conditioner by Combining R-123 Vapor Compression Heat Pump

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Abstract:

Experimental study of a vapor compression heat pump to recover waste heat from water-cooled condensers of 2 air-conditioners each of 12,000 BTU/h cooling capacity has been carried out. The waste heat could be upgraded for generating hot water up to 70 $^{\circ}C$. The EER_{AC} of the air-conditions for the water-cooled condenser could be 20% higher than that of the air-cooled units. But when the generating hot water is not used, the cooling water temperature should not be higher 45 $^{\circ}C$, otherwise, the water-cooled unit could not get an advantage in term of EER_{AC}.

A simplified model of the heat pump for recovering the waste heat from water-cooled air-conditioners in a hospital that needs hot water around 815 $litre/d$ at around 45 $^{\circ}C$. The payback is found to be 1.4 y compared with that the electrical heater.

Introduction

Vapor compression heat pump (VCHP) is one method for upgrading low temperature heat to a higher temperature level. In a conventional VCHP, the low temperature heat is absorbed at the evaporator and the heat is delivered at the condenser at a higher temperature. Theoretical and experimental studies of the VCHP have been reported by various literatures. Chaiyat [1] selected suitable working fluid used in a vapor compression heat pump for generating hot water at 90 $^{\circ}C$. The heat source came from hot spring and the evaporating temperature was at 40 $^{\circ}C$. Five working fluids, R-290 (Propane), R-600 (Butane), R-600a (Isobutane), R-1270 (Propylene) and R-717 (Ammonia) were studied. The considered parameters were unit heat transfer, specific volume at the compressor and COP_{hp}. It was found that the most suitable refrigerant was R-290. Techarungpaisan [2] also reported a preliminary mathematical model of a hot water heater generated by waste heat from small split-type air-conditioner. It was found that the total COP of the system was approximately 4.16 for generating hot water temperature at around 50 $^{\circ}C$. However, using discharge temperature for upgrading heat is limited by amount of heat generated and useful hot water temperature. There are some reports on solar-boosted heat pump for hot water production. Heat pump extracts heat from low temperature solar heat of flat-plate solar collector at its evaporator and the high temperature heat is supplied through the condenser for generating hot water. Burapha and Kiatsiriroat [3] reported a 80 kWth unit of the heat pump installed at a building in Maharaj Nakorn Chiang Mai Hospital. The unit consumed one-third of electrical power compared with the electrical water heater and the payback was 3.6 year.

Mathematical model

Figure 1 shows a schematic diagram of a vapor compression heat pump of which the main components are compressor, condenser, evaporator and expansion valve. The working fluid has a low boiling temperature. At state 1, the fluid in vapor phase is compressed in a compressor to state 2 and the vapor condenses in a condenser at a high pressure (P_C) and temperature to be liquid at state 3. The liquid is then throttled to a low pressure (P_E) at state 4 and the temperature drops down thus the fluid could absorbed low temperature heat at an evaporator where the fluid boils at low temperature to be vapor again at state 1 and the new cycle restarts.

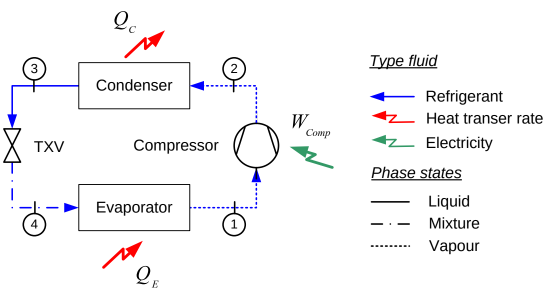


Figure 1. A vapor compression heat pump.

The basic equations for the behavior of each component in the vapor compression cycle are as follows:

- Evaporator

$$Q_E = \dot{m}_{ref}(h_1 - h_4) \quad ; (kW) \qquad (1)$$

$$\dot{m}_{ref} = \dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}_4 \; ; (kg/s) \qquad (2)$$

- Compressor

$$W_{Comp} = \dot{m}_{ref}(h_2 - h_1) \quad ; (kW) \qquad (3)$$

$$s_1 = s_2 \text{ (Isentropic process)} \quad ; (kJ/kg \cdot K) \qquad (4)$$

$$\eta_{Comp} = \frac{h'_2 - h_1}{h_2 - h_1} \quad ; (\%) \qquad (5)$$

- Condenser

$$Q_C = \dot{m}_{ref}(h_2 - h_3) \quad ; (kW) \qquad (6)$$

- Expansion valve

$$h_3 = h_4 \text{ (Throttling process)} \quad ; (kJ/kg) \qquad (7)$$

- The overall coefficient of performance of the air-conditioner

$$EER_{AC} = \frac{Q_E}{W_{Comp}} \quad ; (BTU/h \cdot W) \qquad (8)$$

- The overall coefficient of performance of the heat pump

$$EER_{HP} = \frac{Q_C}{W_{Comp}} \quad ; (BTU/h \cdot W) \qquad (9)$$

Selection Working Fluids of the VCHP as Heat Recovery Unit

The schematic sketch of a vapor compression heat pump for recovering waste heat of an air-conditioners is shown in Figure 1. There are two air-conditioned rooms each has its own water-cooled air-conditioner. Heat rejected at the water-cooled condensers of the air-conditioners will be absorbed by an evaporator of a heat pump which will be transferred and upgraded to its condenser for generating hot water. The cooling water temperatures at the water-cooled condensers then drop down and the water could be back to the condensers for recooling. When the heat pump does not work, the air-cooled condensers are taken in stead of the water-cooled units.

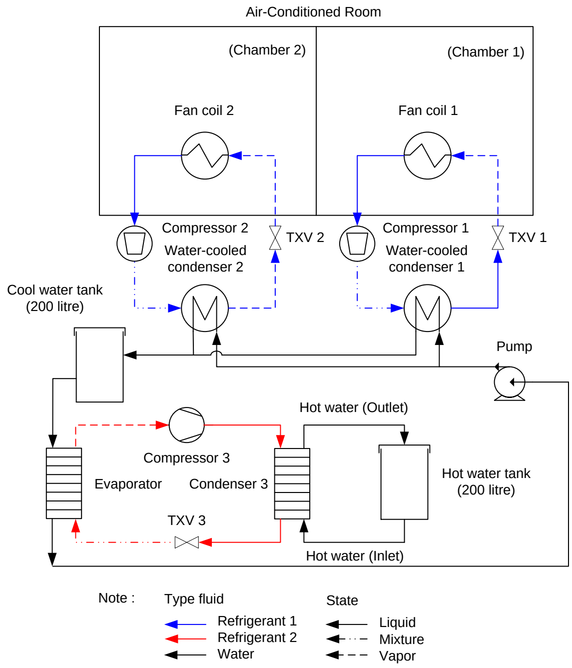


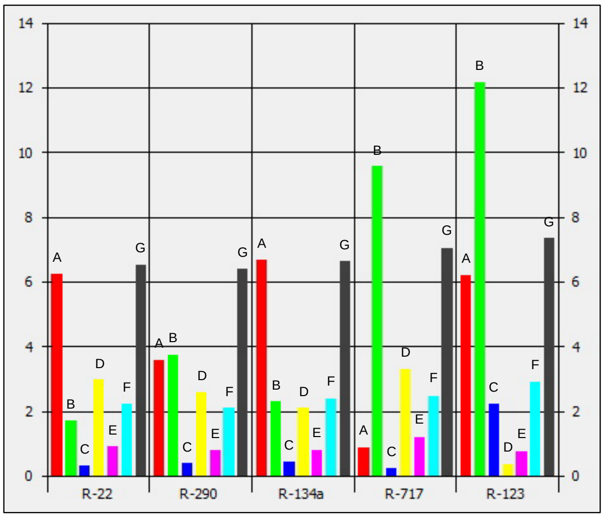
Figure 1. Diagram of a vapor compression heat pump for recovering waste heat of air-conditioners.

Five working fluids, R-22 (Chlorodifluoromethane), R-290 (Propane), R-134a (1,1,1,2-Tetrafluoroethane), R-717 (Ammonia) and R-123 (2,2-Dichloro-1,1,1-trifluoroethane) for heat pump have been considered. The working conditions for the evaluation are:

1. Designed room temperature is at 25 $^{\circ}C$.
2. Total cooling capacity is 2 TR .
3. Required hot water temperature is at 60-70 $^{\circ}C$
4. No pressure drops at the condenser, the fancoil and the evaporator.
5. Isentropic efficiency of compressor is 80%
6. Degree of superheating is 5 $^{\circ}C$
7. Degree of subcooling is 5 $^{\circ}C$
8. The properties are based upon REFPROP [4].

The indicators used to identify the appropriate working fluid are mass of refrigerant per unit heat output, volume flow rate of refrigerant, refrigerant high-side pressure, refrigerant temperature at the compressor outlet, pressure ratio and heating COP.

The simulation results are shown in Figure 2. It could be seen that R-123 seem to be the most suitable refrigerants for the heat pump for generating hot water at about 60-70 $^{\circ}C$. R-123 is selected due to its lower high-side pressure and gives the highest COP.



A) Mass of refrigerant per unit heat output, (g/kJ)

B) Vapor volume flow rate, $(10^{-2} \cdot m^3/kg)$

C) Displacement volume, $(10 \cdot m^3/h)$

D) Discharge pressure, $(10 \cdot bar)$

E) Discharge temperature, $(10^2 \cdot {}^\circ C)$

F) Pressure ratio, (-)

G) COP_{HP}, (-)

Figure 2. The results of selection working fluids.

Results

Performance curves of the two air-conditioners each at cooling capacity of 12,000 BTU/h when it used air-cooled condensers and water-cooled condensers are shown in Figure 3. For water-cooled condensers, the waste heat is recovered by the heat pump and supplied for hot water generation. Two cases of hot water utilization are considered. The first case is to accumulate heat in the hot water tank without any use and the second case the hot water in the storage tank is consumed by keeping the water temperature in the tank be constant.

From Figure 3, it could be seen that when the difference between the ambient temperature and the inside room temperature increases, the air-conditioning EER_{AC} decreases. The water-cooled operation gives higher EER_{AC} due to higher heat transfer of water cooling. However, for non-use of hot water, there is a limit on the energy advantage are the air-cooled condensers due to a higher temperature of the water coolant, It is not recommended to use water-cooled condensers (non-use of hot water) when $Ta - Tr$ is over around 12 $^\circ C$ of which the coolant temperature is around 45 $^\circ C$.

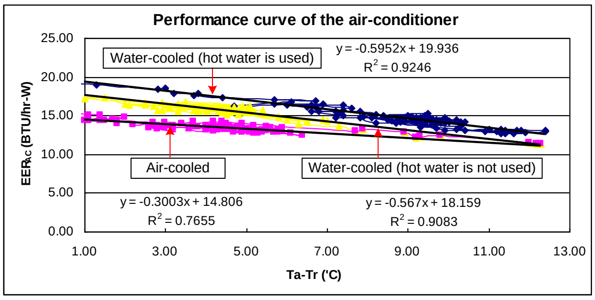


Figure 3. Effect of $Ta - Tr$ on EER_{AC} of the air-conditioners with air-cooled and water-cooled.

Figure 4 shows the performance curve of the R-123 VCHP at heating capacity which is used to recover the heat rejection from 2 water-cooled air-conditioners. It could be seen that increasing the temperature difference between useful hot water and supplied cooling water ($T_{HW} - T_{CW}$) decreases the energy efficiency ratio (EER_{HP}) .

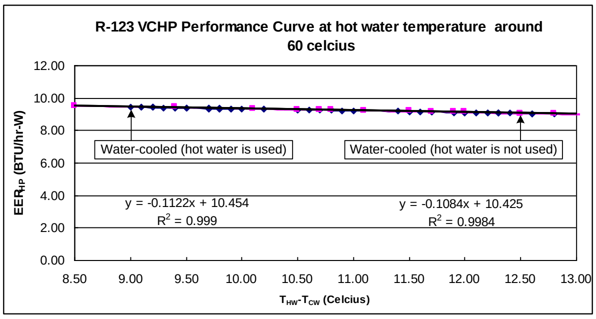


Figure 4. Effect of $T_{HW} - T_{CW}$ on EER_{HP} of the R-123 VCHP.

The performance curves as shown in Figure 3 and Figure 4 are used to develop a simple model of the R-123 VCHP for simulating the energy efficiency ratio and the hot water temperature. Figure 5 and Figure 6 show the simulation results compared with the measured data for storage (200 $litre$) when the stored is not used and used hot water respectively. It could be seen that the simulation results agree well with those of the measured data. The maximum upgrading hot water temperature of the R-123 VCHP could be up 70 $^\circ C$ from the water-cooled condensers at about 40 $^\circ C$ and high pressures of each air-conditioner was less than 300 $psig$.

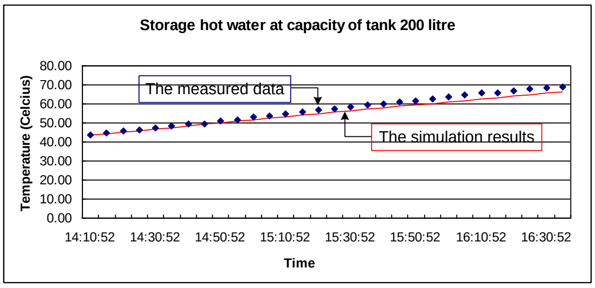


Figure 5. The measured data and the simulation results comparison of the R-123 VCHP for storage hot water.

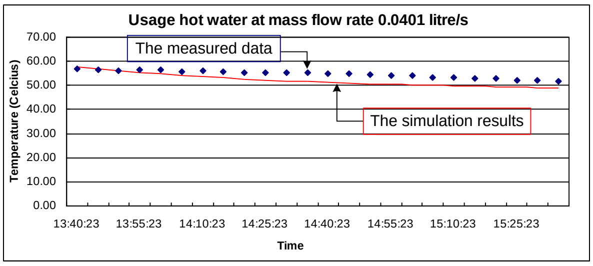


Figure 6. The measured data and the simulation results comparison of the R-123 VCHP for usage hot water.

Economics evaluation is also carried out when using the R-123 VCHP to generate hot water from a set water-cooled air conditioners of a hospital. The hot water consumption is 815 $litre/d$. It could be seen that the electricity cost of the heat pump is about 62,581.51 $Bath/year$ which saves cost about 80,000 $Bath/year$ and it has payback period around 1 year 4 months compared with electric heater for generating hot water.

Conclusions

From this study, the conclusions are as follow:

1. The suitable working fluid of the VCHP is R-123, its give the temperature for generating hot water at around 60-70 $^{\circ}C$.
2. The R-123 VCHP could be upgraded hot water temperature to around 70 $^{\circ}C$ from supplied water temperature which is around 40 $^{\circ}C$ from the water-cooled condensers.
3. The water-cooled air-conditioners combining with the R-123 VCHP can increase EER_{AC} by approximately 20% over that of the air-cooled air-conditioners.
4. Payback period of the R-123 VCHP is around 1 year 4 months compared with using electric heater to generate hot water of 815 $litre/d$ at 45 $^{\circ}C$ in a hospital.

Acknowledgement

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Nomenclature

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EER	Energy Efficiency Ratio, $(BTU/hr \cdot W)$
h	Enthalpy, (kJ/kg)
m	Mass flow rate, (kg/s)
P	Pressure, (Bar)
Q	Heat rate, (kW)
s	Entropy, $(kJ/kg \cdot K)$
T	Temperature, $(^{\circ}C)$
W	Work, (kW)

Greek symbol

η	Compressor efficiency, $(\%)$

Subscript

AC	Air-conditioner
C	Condenser
$Comp$	Compressor
CW	Cooling water
E	Evaporator
HP	Heat pump
HW	Hot water
P	Pump
ref	Refrigerant