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Study of Ejector-Vapor Compression Hybrid Air-Conditioning System Using Solar Energy

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ABSTRACT

The ejector cycle has been recognized as a promising cycle for the utilization of solar energy for cooling. However, the conventional ejector cycle suffers from low efficiency owing to a low evaporation temperature. This paper proposes a hybrid ejector-vapor compression heat pump cycle. This hybrid system uses an ejector cycle on the high-temperature side and a conventional vapor compression cycle on the low-temperature side to enhance the cycle performance of a solar-powered air conditioner. A cycle simulation showed that the proposed hybrid ejector cycle could operate during both the heating and cooling seasons and would provide energy savings. In heating mode, the hybrid cycle could reduce energy consumption by up to 50%. In addition, the average energy-saving potential during the cooling season is about 20%, if half of the floor area is covered by the solar collector.

1. INTRODUCTION

Increasing concerns about environmental issues such as global warming and the depletion of fossil fuels have led to the expanding use of renewable energy, which has a negligible environmental impact. Among the different types of renewable energy, solar energy is universally available and has the highest potential, about 67 times the primary energy supply of the entire world. The most well known means of harvesting solar energy is with a photovoltaic system. In Japan, the energy consumption of heating and cooling applications accounts for 10.4% of total energy consumption, therefore, it is important to encourage the use of solar energy directly in heating and cooling.

It is straightforward to use solar energy for heating during the winter, such as for heating rooms or providing hot water. However, the demands of heating during the other seasons are not high, which leads to a long payback time. Because the intensity of solar radiation is highest during the hottest season, the cooling loads and availability of solar radiation are generally in phase. This makes it reasonable to harvest solar energy for cooling purposes. As a result, the facility can operate continuously year-round, thereby reducing the overall energy consumption for heating and cooling and reducing the length of the payback period.

Heat driven absorption or adsorption systems have been well studied and are commercially available. However, the construction, installation, and maintenance of these systems are rather expensive when compared to conventional vapor compression systems. In addition, owing to the inherently intermittent nature of solar energy, systems driven by solar energy cannot stand alone. Additional heat sources, either from waste heat or from the burning of natural gas, are needed to keep the system working continuously. These additional heat sources are not always available. Considering the dominance of the vapor compression system in the air-conditioning and refrigeration market, it is highly promising to combine the solar energy-driven system with the vapor compression system to reduce energy consumption while providing a comfortable environment.

One of the simplest approaches for using thermal energy in cooling is by the use of ejector cycles (e.g., Sun and Eames, 1995). Ejector cycles are very reliable and simple, and they have been commercialized in ice making. However, their energy efficiency is very low, with a typical value of 0.2 or less. It is expected that combining the ejector cycle with other cycles can facilitate higher system performance.

Sun (1997) proposed to combine the ejector cycle with the vapor compression cycle by using the cascade cycle with an ejector cycle working at high temperature and a vapor compression cycle working at low temperature. The ejector cycle was used to reduce the condensation temperature of the vapor compression cycle, thereby reducing the energy consumption. A theoretical study showed that this combined cycle is capable of enhancing the system COP.
by more than 50%. However, the ejector cycle used water, which has a large specific volume and therefore leads to a large piping volume. In addition, the capacity of the combined cycle is determined by the amount of heat collected, which varies with the weather. Therefore, this cycle can work only as an auxiliary system in air-conditioning. In this study, a new hybrid cycle created by combining the ejector cycle with a two-stage vapor compression cycle is proposed. A low GWP refrigerant R1234ze is used in the ejector cycle, whereas R410A is used in the vapor compression cycle. Because a two-stage compression cycle is adopted, the cycle can work even if no solar energy is collected. The proposed cycle can work during both the heating and cooling seasons with a high efficiency.

2. PROPOSED CYCLE

2.1 Hybrid ejector-vapor compression cycle

A schematic drawing of the proposed ejector-vapor compression hybrid cycle is shown in Fig. 1. The cycle consists of a solar energy collection cycle, an ejector cycle, and a two-stage vapor compression heat pump cycle. The system can work in both the cooling mode and in the heating mode, as shown in Fig. 1(a) and (b), respectively. The ejector cycle consists of an ejector, condenser, expansion valve, circular pump, generator, and an internal heat exchanger. The collected solar energy is delivered to the refrigerant in the generator to evaporate the refrigerant into saturated or superheated vapor. The refrigerant vapor then flows into the ejector and is depressurized and accelerated inside the driving nozzle of the ejector. The high-speed, low-pressure driving flow is used to absorb the low-pressure suction flow from the internal heat exchanger. The driving flow and suction flow then mix with each other inside the mixing section of the ejector, and they are pressurized inside the diffuser of the ejector. The mixed flow enters the condenser and is condensed into saturated or subcooled liquid. Finally,
the condensed liquid is divided into two streams: one is pressurized and circulated back to the generator, and the other is depressurized by an expansion valve and delivered to the internal heat exchanger. Inside the internal heat exchanger, the refrigerant of the ejector cycle is used to cool the refrigerant of the vapor compression cycle, reduce the condensation temperature of the vapor compression cycle, and therefore reduce the energy consumption. When the ejector cycle is unable to provide enough cooling ability to the vapor compression cycle, the vapor compression cycle can release heat to the outside air through an auxiliary condenser. When there is no solar energy available, the hybrid cycle may reduce to a simple vapor compression cycle. The P-H diagram of the hybrid cycle is shown in Fig. 2.

When working in heating mode, as shown in Fig. 1(b), the internal heat exchanger works as the evaporator of the vapor compression cycle. The vapor compression cycle absorbs the collected solar energy directly and provides heat to the room or hot water. When there is insufficient heat collected, the vapor compression cycle can absorb heat from an auxiliary evaporator.

2.2 Performance of ejector

Figure 3 shows a schematic of the ejector, which consists of a driving nozzle, suction nozzle, mixing section and diffuser.

The performance of the ejector is determined by solving a one-dimensional governing equation for each component. The following assumptions are applied when calculating the ejector performance, as described by Huang et al. (1999).

(a) The flow is one-dimensional and steady.
(b) Both the driving flow and suction flow are considered ideal gases.
(c) The thermophysical properties, including specific heat \( c_p \) and specific heat ratio \( \gamma \), remain constant.
(d) Chock takes place inside the driving nozzle, suction nozzle, and mixing section.
(e) Entropy losses during the shock wave or mixing are evaluated using different coefficients.
(f) There is no friction loss along the pipe being considered.

For a detailed description of the models used to calculate ejector performance, refer to Huang et al. (1999). The following efficiencies are defined in this research:

\[
\eta_p = 0.95 \quad \eta_s = 0.85 \quad \phi_p = 0.88
\]

The losses in the primary flow in the nozzle and in the suction flow before mixing are taken as \( \eta_p = 0.95 \) and \( \eta_s = 0.85 \). The coefficient of the primary flow leaving the nozzle is taken as \( \phi_p = 0.88 \). The entropy loss in the mixing process is considered as a function of the ejector area ratio \( A_s/A_i \) as

\[
\phi_m = \begin{cases} 
0.94 & (A_s/A_i < 6.9) \\
1.1371 - 0.0286 A_s/A_i & (6.9 \leq A_s/A_i < 8.3) \\
0.9 & (8.3 \leq A_s/A_i) 
\end{cases}
\]

3. PERFORMANCE OF PROPOSED CYCLE

3.1 Cycle simulation

The performance of the proposed hybrid cycle is demonstrated by a cycle simulation for both the heating and cooling modes. For cooling, the cooling capacity of the hybrid cycle is usually insufficient for providing enough cooling ability. Therefore, it is necessary to use a two-stage compressor and an auxiliary condenser or to add an independent vapor compression cooling system. The performances of these two systems are also compared.

In the heating mode, the collected solar heat is used to elevate the evaporation temperature, thereby enhancing the system performance, as shown in Fig. 4. The COP of the system increases with the evaporation temperature. If the hot water from the generator reaches 20–30 °C, the evaporator temperature could increase from -5 °C to 15–20 °C. This would result in an increase in the COP from 4 to 10.

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about 2.5 times that of the conventional cycle, and a reduction of about 50% to 60% in energy consumption for the heating season.

The performance of the proposed cycle in the cooling mode is simulated with a cycle simulation, using the conditions listed in Table 1. For the ejector cycle, the COPERC is calculated by

$$\text{COP}_{\text{ERC}} = \frac{Q_{\text{inj}}}{m_{p} \left( h_{g} - h_{l1} \right)} = \eta \frac{h_{g} - h_{l1}}{h_{g} - h_{l3}}$$

where $\eta$ is the ratio of the suction flow to the driving flow.

The COP of the vapor compression cycle is defined as

$$\text{COP}_{\text{VCC}} = \frac{Q_{\text{evp}}}{W_{p}} = \eta_{\text{cmp}} \frac{h_{g} - h_{l1}}{h_{g} - h_{l0}}$$

where $\eta_{\text{cmp}}$ is the efficiency of the compressor, which is assumed to be 0.7 in the following cycle simulation.

The calculated COPERC and COPVCC versus the internal heat exchanger temperature are shown in Fig. 5. Although different refrigerants are adopted for both the ejector and vapor compression cycles, the differences between refrigerants are small. For the ejector cycle, the COPERC increases steadily as the internal heat exchanger temperature rises. When the ejector cycle is being used directly in cooling, the COPERC is usually lower than 10%; therefore, a huge amount of collection area is needed to provide sufficient driving energy. However, if the ejector cycle works at an evaporation temperature of 25 °C, the COPERC may increase to about 0.7. At the same time, the COPVCC decreases from 24 to 4 as the condensation temperature of vapor compression cycle (evaporation temperature of ejector cycle + 5°C) increases from 16 °C to 40 °C.

The COP of the hybrid cycle is the product of the COPERC and COPVCC. However, for a given cooling load, the collected amount of solar heat may be higher or lower than that needed to provide sufficient cooling capacity for the internal heat exchanger. Usually, an auxiliary condenser is needed to release excessive heat to the environment. Considering the inherently variableness of solar energy, such an auxiliary condenser is essential for a hybrid ejector-vapor compression system.

The performance of the hybrid ejector-vapor compression system is compared with that of a conventional ejector
cycle equipped with an independent vapor compression cycle to provide additional cooling capacity, as shown in Fig. 6.

Cycle simulations were conducted for both the independent cycle and the hybrid cycle using the conditions shown in Table 1, and the simulation results of the COP versus solar heat are shown in Fig. 7.

The COP of the hybrid cycle is defined as

$$\text{COP}_{\text{hybrid}} = \frac{Q_e}{W_1 + W_2} = \frac{Q_e}{\text{COP}_{\text{R1234ze}} + \text{COP}_{\text{R410A}} + \text{COP}_{\text{hybrid}}} = \frac{1}{\text{COP}_{\text{R1234ze}} + \text{COP}_{\text{R410A}} + \text{COP}_{\text{hybrid}}}$$

where

$$W_1 = \frac{Q_e}{\text{COP}_{\text{R1234ze}}}$$

$$W_2 = \frac{Q_e}{\text{COP}_{\text{R410A}}}$$

The COP of the independent cycle is calculated by

$$\text{COP}_{\text{independent}} = \frac{Q_e}{W_e} = \frac{Q_e}{\text{COP}_{\text{R1234ze}}} + \text{COP}_{\text{hybrid}}$$

Figure 7 shows that the COP of both the independent cycle and the hybrid cycle increases with an increase in collected heat. When there is no heat input, the two cycles take the same COP. For the independent cycle with higher solar heat, the cooling capacity provided by the ejector cycle increases, resulting in lower energy being consumed for the vapor compression cycle. Therefore, the COP increases steadily with the input heat. For the hybrid cycle, a similar increase in the COP versus the input heat can be seen. However, by increasing the evaporation temperature of the ejector cycle while decreasing the condensation temperature of the vapor compression cycle, the COPs of both cycles are enhanced, resulting in a higher system COP than that in the independent cycle.

### Table 1 Simulation conditions (cooling)

| Working fluid (ejector cycle) | R1234ze |
| Working fluid (vapor compression cycle) | R410A |
| Generation temperature | 80 °C |
| Condensation temperature | 40 °C |
| Evaporation temperature | 8 °C |
| Temperature difference inside internal heat exchanger | 5 °C |
| Compressor efficiency | 0.7 |
| Cooling capacity | 2 kW |

#### 3.2 Effect of internal heat exchanger temperature

As shown in Fig. 7, the higher the solar heat input, the higher the system COP obtained. However, in practice, the cycle usually works with limited available solar heat. The temperature at the internal heat exchanger should be adjusted to obtain the maximum system performance according to the solar heat and required cooling capacity.

The effect of the internal heat exchanger temperature on the system COP is shown in Fig. 8. At a lower internal heat exchanger temperature, the COP of the vapor compressor cycle increases. However, the cooling capability provided by the ejector cycle decreases, and the energy consumption by the auxiliary cycle increases. In contrast, at a higher internal heat exchanger temperature, the lower COP of the vapor compression cycle leads to a decrease in system performance. Therefore, an optimum internal heat exchanger temperature exists where the system COP has a maximum value. As shown in Figs. 8 and 9, the optimum internal heat exchanger temperature decreases with an increase in the ratio of available solar heat to the required cooling capability. At a heat ratio lower than 1.5, the auxiliary cycle works, which results in a low system COP. However, when the heat ratio is higher than 1.5, the combined ejector-vapor compression cycle alone can provide sufficient cooling ability. The COP increases with increases in the heat ratio, whereas the optimum internal heat exchanger temperature decreases.
4. ENERGY-SAVING POTENTIAL OF PROPOSED CYCLE

The previous section demonstrated that the proposed hybrid cycle can provide a higher energy efficiency than can a conventional cycle, thereby reducing the energy consumption. Based on the performance of the ejector-vapor compression hybrid cycle, a cycle simulation work is conducted to investigate the energy-saving potential of the proposed cycle, as applied to an office building. This was done by considering the climate and sequential environmental temperature change of the Tokyo area during a cooling season.

An image of the cooling simulation scenario is shown in Fig. 10. The office has a total floor area of 144 m², and the collector area is assumed to be 1/2, 1/3, or 1/6 of the floor area. The solar collector is a vacuum tube-type solar collector. Standard annual climate data for Tokyo during the period 1991–2000 are used. The cooling load of the office building is calculated following JIS B 8616, using the main parameters listed in Table 2.

<table>
<thead>
<tr>
<th>Table 2 Office simulation conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor area</td>
</tr>
<tr>
<td>Perimeter area</td>
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<tr>
<td>Interior area</td>
</tr>
<tr>
<td>Height</td>
</tr>
<tr>
<td>Window area</td>
</tr>
<tr>
<td>Number of occupants</td>
</tr>
<tr>
<td>Fluorescent lamps</td>
</tr>
<tr>
<td>Personal computers</td>
</tr>
<tr>
<td>Amount of fresh air intake</td>
</tr>
<tr>
<td>Overall heat transfer coefficient</td>
</tr>
<tr>
<td>Indoor temperature</td>
</tr>
<tr>
<td>Rated cooling capacity</td>
</tr>
<tr>
<td>Daytime operation period</td>
</tr>
</tbody>
</table>

The collected heat is calculated by:

\[ q = A(n_oG - a_1dT - a_2dT^2) \]

where \( A \) is the solar collector area, \( G \) is the solar radiation intensity, \( dT \) is the temperature difference between the hot water and the ambientair, and \( n_o, a_1, a_2 \) are coefficients.

Figure 11 shows the heat load and collected solar heat over a 24-h period. The heat load increases with time and reaches a maximum value at about 14:00, whereas the solar radiation reaches a maximum value at about 12:00. The collected heat amount increases proportionally with an increase in the collector area.
Figure 12 shows the change in heat load of the building over time, and the change in cooling capacity of the hybrid ejector cycle and the auxiliary cycle. With the installation of the solar collector, the heat load decreases with an increase in the collector area, as shown in Fig. 12(a). When the installation area is half of the floor area (72 m²), as shown in Fig. 12(b), the hybrid ejector cycle can provide sufficient cooling capacity at noon when the solar radiation intensity is high. The auxiliary cycle does not work under this condition. However, at earlier times or in the afternoon, the ejector cycle is unable to provide sufficient cooling capacity, and the auxiliary cycle must be operated. Figures 12(c) and (d) show the simulation results for collector areas of 48 m² and 24 m², respectively. Because the hybrid ejector cycle cannot provide sufficient cooling capacity, the auxiliary cycle works continuously and provides the major part of the cooling capacity.

Figure 12 Change in heat load of the building and cooling capacities for the month of July.
Figure 13 Energy-saving potential of ejector cycle

Figure 13 shows the energy-saving potential of introducing the hybrid ejector cycle into the office building. The energy consumption decreases with the increase in solar collector area. For a collector area of 72 m², the energy savings reach 23%, 20%, and 19% in July, August, and September, respectively. The average energy savings for the collector areas of 24, 48, and 72 m² reaches 7%, 14%, and 21%, respectively.

5. FUTURE WORK

The efficiency of the proposed hybrid ejector-vapor compression cycle is highly dependent on the ejector performance. To evaluate the validity of the simulation results, a performance study of the ejector is being carried out. This ongoing study includes the measurement of the entrainment ratio and pressure recovery of the ejector under different geometric conditions, together with a detailed numerical simulation of the mixing process inside the ejector.

6. CONCLUSIONS

A hybrid ejector-vapor compression cooling cycle is proposed for the utilization of solar energy in air-conditioning. Cycle simulations were conducted; the results showed that the proposed cycle could work in both the heating and cooling seasons and could reduce the overall annual energy consumption. The main findings of this study are summarized as follows:
1. An optimum temperature exists for the internal heat exchanger; this temperature decreases with an increase in solar heat input.
2. In the heating season, the proposed cycle could reduce energy consumption by 50%.
3. Based on a simulation in which the proposed cycle was applied to an office building, the cooling season energy consumption can be reduced by about 20% with a solar heat collector area corresponding to 1/2 of the total floor area. The reduction in energy consumption is proportional to the collector area.

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REFERENCES