Heat Pump Vending Machine Equipped with CO_2 Ejector Refrigerating Cycle

TSURUHA, Takeshi* YAMAGAMI, Yuhei* MATSUBARA, Takeshi ‡

ABSTRACT

Fuji Electric has been utilizing CO_2 refrigerants and hydrofluorocarbon refrigerants in the refrigeration units used in its beverage vending machines. However, compared with hydrofluorocarbon refrigerants, CO_2 refrigerants have a higher operating pressure and thus require a larger amount of power to drive the compressor. To solve this issue, We have adopted an ejector to recover the lost energy by using the high operating pressure, developed a refrigeration unit that optimally control the ejector, and fitted it into our vending machines. Coefficient of performance (COP) improvement in the refrigeration unit has enabled the vending machine to reduce power consumption by 25% compared with conventional ones.

1. Introduction

Fuji Electric has developed a beverage vending machine that utilizes an ejector*1 for its CO_2 refrigerant based refrigeration unit as a non-fluorocarbon based measure to suppress global warming. The unit achieves power savings of 25% compared with previous products. We achieve higher efficiency and reduce the power of the compressor by utilizing the high pressure of the CO_2 refrigerant as a means to recover conventionally lost refrigerant energy.

2. Development Background

Fuji Electric has been working on reducing power consumption of its beverage vending machines, one of the reason for which is that they have been added to the specified equipment based on the “Act on the Rational Use of Energy” (Energy Conservation Act) since 2002. Presently, 80 to 90% of the power consumption of beverage vending machines is used to heat or cool beverages. One of the principle technologies used thus far in reducing power consumption has been heat pump technology, which Fuji Electric developed and adopted for its products in 2008. Refrigerants for beverage vending machines include CO_2 refrigerants and hydrofluorocarbon refrigerants. When comparing both refrigerants, the CO_2 refrigerant has lower global warming potential, but it requires a larger amount of compression work*2 due to its high operating pressure, thus resulting in reduced efficiency.

In general, efficiency improvements for components such as heat exchangers have come close their limit, but in order to enhance efficiency even further, ejectors have been increasingly adopted in vehiclemounted refrigeration units and water heaters. We have successfully developed an ejector based refrigerating cycle for our beverage vending machines, and we are aiming to contribute to the suppression of global warming through the use of non-fluorocarbon refrigerants by making use of the characteristically high pressure of CO_2 refrigerants.

3. Development Goals and Challenges

3.1 Challenge of achieving energy savings under actual use conditions

General-purpose vending machines are designed with 3 partitioned compartments. Depending on the season, these compartments can be utilized for cooling or heating as shown in Fig. 1. Most of the vending machine’s power consumption is used to maintain the temperature of its products.

The method for measuring the energy efficiency of

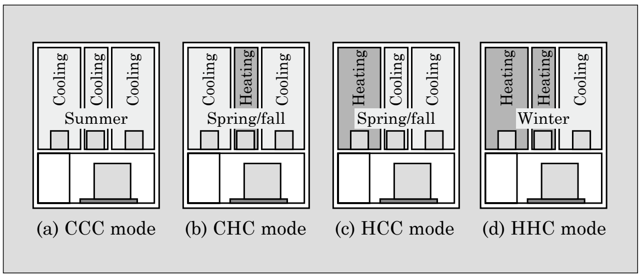

Fig.1 Beverage vending machine seasons and driving modes

*1: Ejector: Refer to “Supplemental explanation 1” on page 207.

*2: Compression work: This refers to the thermodynamic energy required in driving the compressor.

* Food & Beverage Distribution Business Group, Fuji Electric Co., Ltd.

‡ Corporate R&D Headquarters, Fuji Electric Co., Ltd.

beverage vending machines has been set forth in JIS B 8561:2007. The standard defines that power consumption shall be measured based on the spring and autumn cooling and heating mode (HCC mode) in which the left compartment is heated and the center and right compartments are cooled.

One challenge has been to reduce peak power consumption during the summer while also improving the amount of yearly power consumption as measures to respond to social demands following the Great East Japan Earthquake.

We have decided to tackle the latter item, reduction of yearly power consumption, by balancing the coefficients of performance (COP) of refrigerator cooling operation (CCC mode) and heat pump operation (HCC mode) so that both COPs are maximized.

3.2 Points regarding energy consumption reduction

As shown in Fig. 2, the use of refrigerants in beverage vending machines requires heat to be emitted to the outside air. In this respect, the radiator refrigerant temperature must be approximately 10 K higher than the installation environment temperature, corresponding to a range between approximately 30 °C and 50 °C. General fluorocarbon refrigerants have a pressure of approximately 1 to 3 MPa. On the other hand, CO_2 refrigerants are characterized by critical points at a pressure of 7.4 MPa and temperature of 31 °C, and as a result, pressure needs to be in a supercritical state between 8 and 10 MPa to raise a temperature higher than the outside air temperature required in heat radiation. This, in turn, generates a high pressure difference for the compressor's refrigerant compressor component. As a result, the power energy for refrigerant compression increases, and this results in decreased energy efficiency.

Conventionally, countermeasures have been taken, which include the installation of a larger radiator or internal heat exchanger, or the adoption of a 2-stage compression circuit. However, this resulted in a reduction in COP to about 60% of that of refrigeration units utilizing hydrofluorocarbon refrigerants. As a means of rectifying this, we have utilized an ejector to achieve COP improvements.

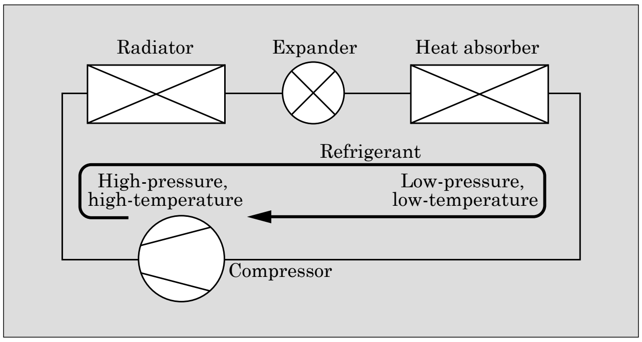

Fig.2 Basic principles of refrigeration unit

4. Configuration and Newly Adopted Technology for the Ejector Mounted Heat Pump Refrigeration Unit

4.1 Development tasks

The purpose of our development work this time has been to maximize COP for heating and cooling operations. To achieve this, we established the following development tasks.

(a) Theoretical value for ejector effectiveness when utilizing a CO_2 refrigerant

(b) Application of the ejector in the refrigeration circuit of beverage vending machines that utilize 3 evaporators in parallel

(c) Application of ejectors used in water heaters to beverage vending machines

(d) Securing reliability for the installation environment of beverage vending machines

4.2 Theoretical value for ejector effectiveness when Utilizing a CO_2 Refrigerant

Figure 3 shows the internal configuration of the developed ejector. The refrigerant flowing into the ejector as driving flow increases in flow velocity when passing through a nozzle with a narrow diameter. Since pressure decreases as flow velocity increases, a force for drawing fluid from the suction flow side is generated. Two fluids converge in the mixing component, and then the diffuser reduces the velocity and increases the pressure. Design was made so as to minimize turbulence in the passage, and this has enabled us to maximize the effects shown below.

Figure 4 shows the refrigeration cycle diagram of conventional CO_2 refrigerant based beverage vending machines. The horizontal axis represents enthalpy, and the vertical axis represents pressure. The expansion process of the refrigeration cycle changes from isenthalpic expansion to ideal isentropic expansion, that is, expansion with no fluid turbulence to reduce energy loss. The figure shows that the cycle recoveries the energy loss caused by turbulence and reduces compressor driving power.

The effectiveness of using the ejector was calculat-

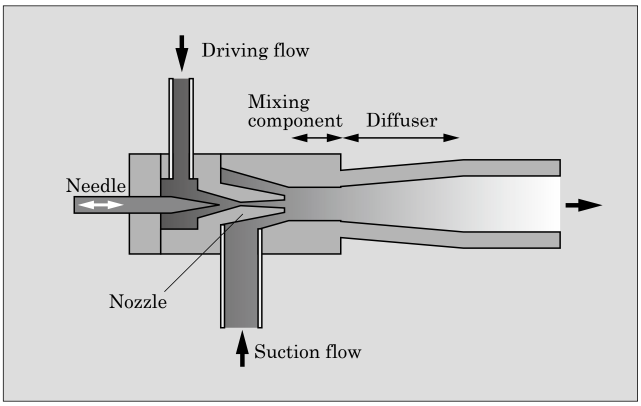

Fig.3 Internal configuration of ejector

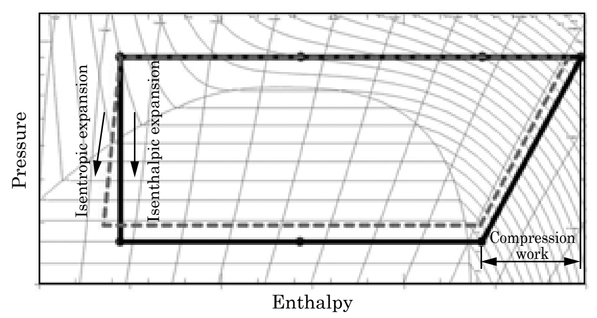

Fig.4 Refrigeration cycle diagram of CO_2 refrigerant based beverage vending machines

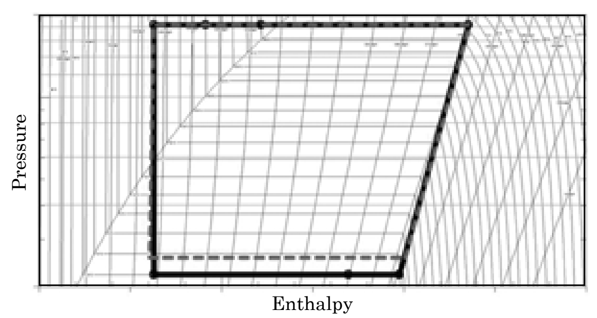

Fig.5 Refrigeration cycle diagram of hydrofluorocarbon refrigerant based beverage vending machines

ed with regard to energy loss. When there is no turbulence in the pressure reducing expansion process, isentropic change occurs, and the reduction in compression work, corresponding only to the pressure difference after expansion, is lower than the isenthalpic change. When the evaporation temperature is at −10 °C, high pressure at 9.0 MPa, gas cooler outlet temperature at 40 °C, internal heat exchanger high-pressure outlet temperature at 20 °C and compressor suction overheat temperature at 5 K, the difference due to the presence of the ejector results in a 3.1 kJ/kg reduction in theoretical compression work and a 10.3% improvement in COP.

On the other hand, Fig. 5 shows the same effectiveness calculation using a hydrofluorocarbon refrigerant. The rise in the compression work reducing effect was 4.2%, which is lower than that of the CO_2 refrigerant. The ejector has demonstrated its increased effectiveness for reducing compression work for CO_2 refrigerants.

4.3 Application of the ejector in the refrigeration circuit of beverage vending machines that utilize 3 evaporators in parallel

Figure 6 shows the refrigeration circuit of the CO_2 refrigerant heat pump (HCC mode). Figure 6(b) shows a circuit that utilizes an ejector. In addition to adding an ejector and gas-liquid separator, it also

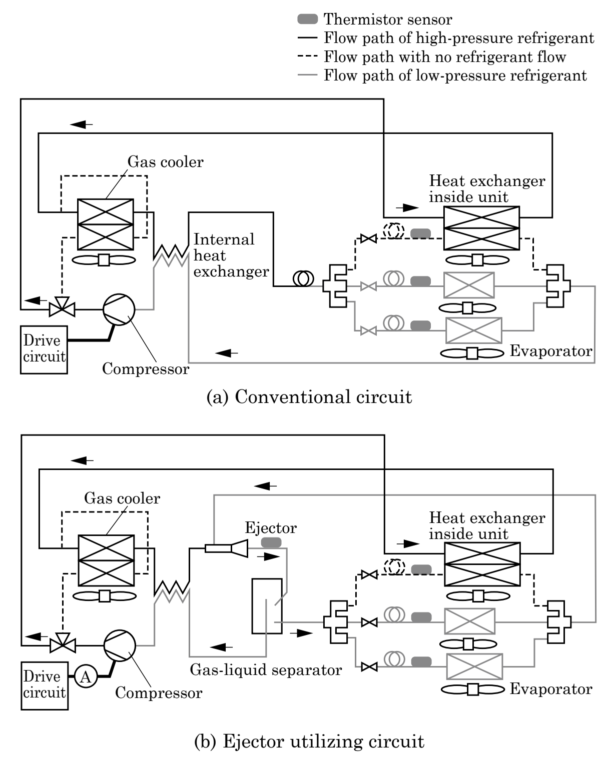

Fig.6 Circuit of CO_2 refrigerant based heat pump refrigeration unit (HCC Mode)

equips the ejector outlet with a thermistor sensor and the compressor drive circuit with an ammeter. The gas-liquid separator is designed to return the liquid phase portion of the low-pressure refrigerant ejected from the ejector to the evaporator, and the remaining portion to the compressor. When this happens, the refrigerator oil, which outflows to the evaporator side with the liquid phase refrigerant, must be returned to the compressor side. To achieve this, we designed the unit with several special features such as an oil return mechanism.

4.4 Application of ejectors used in water heaters to beverage vending machines

Beverage vending machines adopt variable needle ejectors developed for use in beverage vending machines based on the ejectors used in water heaters. Table 1 shows the difference in specifications between

Table 1 The Difference in specifications between water heater and beverage vending machine refrigeration units

Item	Water heater	Beverage vending machine
Refrigerant circulation rate	50 kg/h	7 kg/h
Application	Heating	Heating and cooling
No. of evaporators	1	3
No. of stops per day	Several times	Several tens times

water heater and beverage vending machine refrigeration units.

The refrigerant circulation rate in the vending machine is only about one-seventh of that of water heaters, and hence it is necessary to almost completely close the valve opening of the variable needle. Furthermore, the vending machine was designed with 3 evaporators installed in parallel as shown in Fig. 6. In order to properly maintain the refrigerant circulation rate corresponding to rapid changes resulting from compartment heating and cooling switchover operations, the unit is required to have highly responsive control at a low flow rate.

Therefore, we designed the unit to implement feedback control as it measures the physical quantity for quickly responding to the control rate of the ejector. The physical quantity has been configured so as to use the input current of the compressor and the temperature of the ejector outlet.

4.5 Cooling & heating capacity and COP maximization

As mentioned in the development goals stated in Chapter 3, there is a need to strike a balance between the COPs of refrigerator cooling operation (CCC mode) and heat pump operation (HCC mode) so that both COPs are maximized. However, there is only one circuit, and since the refrigeration filling amount cannot be changed according to season, changes in the refrigerant circulation rate, required as a result of these load differences, were accommodated by adjusting the rotational speed of the compressor and the valve opening of the ejector.

Figure 7 shows an example of the results of measuring the heating COP and cooling COP in HCC mode. This example shows the COP at the time of adjusting the valve opening of the ejector in HCC mode when both heating and cooling are required at the same time. Adding the heating COP and the cooling COP gives a total COP that is more than 124% of previous products. We also found that it is possible to control valve opening corresponding to load fluctuation to adjust the cooling capacity and heating capacity.

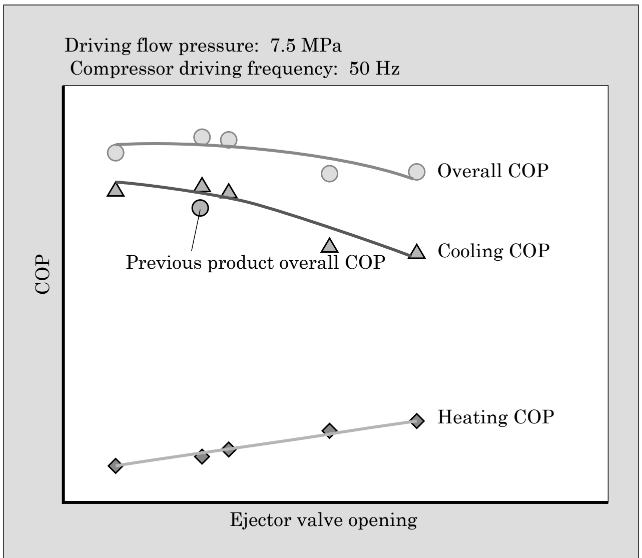

Fig.7 Example of results of measuring heating COP and cooling COP in HCC mode

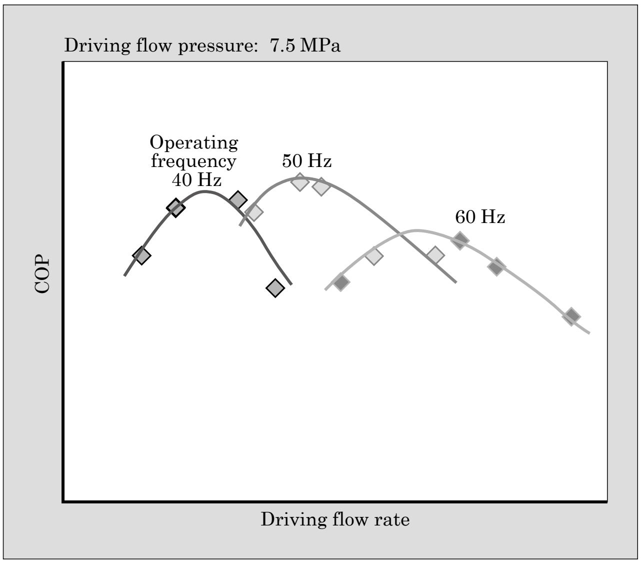

Fig.8 Example of COP measurement for each compressor drive frequency

Figure 8 shows an example of the results of measuring COP when there are changes in the valve opening of the ejector and operating frequency of the compressor. These characteristics showed that by properly controlling the valve opening and operating frequency of the compressor and by optimizing driving flow, it is possible to maximize COP while also maximizing ejector capacity.

Therefore, we determined the optimal evaporation temperature and compressor operating frequency as parameters for heating loads measured from the ambient temperature and internal temperature of the unit. Following this, we implemented control by performing micro adjustment of the valve opening of the ejector so as to obtain the designated evaporation temperature. When there is large load fluctuation such as changes in the number of cooling compartments, feedback control is performed while detecting the ejector outlet temperature and evaporator inlet temperature. In addition, further correction is made while detecting the input current of the compressor used for monitoring pressure, and control is made so as to maintain the cooling cycle at maximum efficiency.

4.6 Securing reliability for installation environment of beverage vending machines

As shown in Table 1, beverage vending machines start and stop 10 times more often per day than water heaters. The ejector outlet temperature in beverage vending machines is constantly below the freezing point. During operation, atmospheric moisture freezes, but thaws when the unit stops. If there is bonding fail-

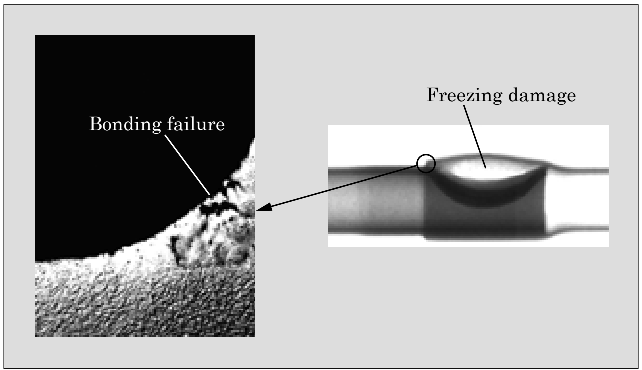

Fig.9 Example of brazing portion bonding failure and freezing damage

ure, such as void or shrinkage cavities, on the brazing portion of parts, moisture deposits in such areas will repeatedly expand and contract in volume due to freezing and thawing, and it is well known that this can lead to freezing damage as shown in Fig. 9.

Therefore, we implemented final quality assurance by carrying out repeated process verification and actual machine verification utilizing methods such as detailed cross-sectional observation.

5. Performance of Beverage Vending Machines

5.1 Energy savings performance

Table 2 shows the performance of a beverage vending machine mounted with the new technology based device. Although it was considered difficult to further increase efficiency in CO_2 refrigerant based refrigeration units, we achieve a COP improvement of 124% in HCC mode and 140% in CCC mode. Furthermore, with regard to heat pump type vending machines that utilize an internal heat exchange system, we significantly reduce disparities with hydrofluorocarbon refrigerant based refrigeration units. This development results in the following achievements: annual power consumption of 440 kWh/y based on the measuring method set forth in JIS B 8561:2007; an achievement rate of 242% compared with the Energy Conservation Act's top runner standard value of 1,068 kWh/y; and the highest level of energy savings for vending machines even when compared with low-pressure refrigerants having the same internal capacity.

Table 2 Performance of beverage vending machine mounted with a CO_2 refrigerant based refrigeration unit

Item	Developed unit	CO_2 heat pump 2	CO_2 heat pump 1
Refrigerant	CO_2		
Compressor drive system	Variable speed	Variable speed	Constant speed
Heat pump circuit	Yes	Yes	Yes
Ejector	Yes	No	No
Cooling/heating COP ratio	1.57	1.25	1
Cooling COP ratio	1.41	0.97	1
Launch time	Apr. 2015	Dec. 2014	Nov. 2011
JIS display value*	440 kWh/y	585 kWh/y	895 kWh/y
Top-runner standard value	1,068 kWh/y	1,081 kWh/y	1,086 kWh/y
Top-runner achievement rate	242%	184%	121%

*JIS display value: A value based on the measurement method provided in JIS B 8561:2007 classification III

5.2 Future developments

We have achieved extensive COP improvements for refrigeration units utilizing ejectors. However, as shown in the refrigeration cycle diagram in Fig. 4, in order to make optimal use of this effect, the units should be operated during the expansion process at an even higher enthalpy point. In the future, we would like to utilize our applicable technologies in water heaters to achieve heating-only operation of the CO_2 refrigerant based refrigeration units in vending machines, a feat that up until now has been considered very difficult to do.

6. Postscript

The use of an ejector mounted to the refrigeration unit of beverage vending machines utilizing environmentally friendly and natural CO_2 refrigerants makes it possible to further expand the energy savings of CO_2 refrigerants. We believe that this current development contributes to suppressing global warming by improving the COP of the refrigeration unit. As mentioned in the Future Developments section, however, we believe that there is still room for improving the performance of the heating component of vending machines. Applying this cycle to the heating component will help to overcome the weaknesses of current heat pumps, and as a result, further contribute to suppressing global warming.

Finally, we would like to express our appreciation to DENSO Corporation for their efforts and support in developing this device.

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