Technology and Market Development of CO_2 Heat Pump Water Heaters (ECO CUTE) in Japan

Katsumi Hashimoto , Japan

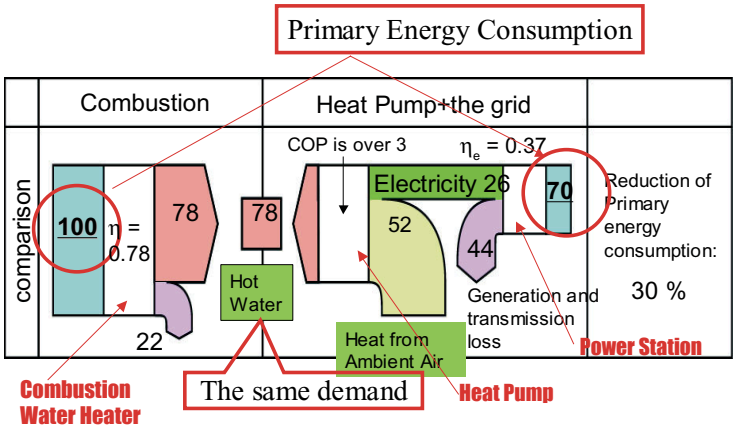
*In Japan, numerous heat pump water heaters for the residential sector have been developed in recent years, and are growing rapidly in popularity. Of these water heaters, the ECO CUTE*1 variety using CO_2 as a refrigerant is attracting attention for its ability to save energy and reduce greenhouse gas emissions. ECO CUTE technology was developed commercially in collaboration between TEPCO, Denso and CRIEPI in 2001. Several other manufacturers have also joined the market, and a government support program has been introduced with a target to increase total ECO CUTE installation to 5.2 million by 2010.*

Introduction

In Japan, energy demand for hot tap water accounts for about 30 % of the total residential final energy consumption, but most of this demand (over 90 %) is met by the direct combustion of fossil fuel. The development of high-performance heat pump water heaters using natural working fluids is thus eagerly anticipated for energy conservation and greenhouse gas reduction. If the COP of a heat pump water heater is 3 or more, the heater uses about 30 % less primary energy than a combustion water heater (Fig. 1).

The Central Research Institute of Electric Power Industry (CRIEPI) has been studying heat pumps using CO_2 as a refrigerant since 1995, and has found by theoretical analysis that the CO_2 cycle has unique characteristics and can achieve a higher COP than conventional refrigerants for domestic hot water production, and by experiments that the CO_2 cycle can be effectively controlled by the combination of an automatic expansion valve and a variable-speed compressor [1].

Figure 1: Comparison of primary energy consumption between heat pump water heater and combustion water heater.



Joint development of a CO_2 heat pump water heater

Using CO_2 heat pump technologies developed independently by CRIEPI and Denso (Denso possessing compressor technologies for car air-conditioning systems), a CO_2 heat pump water heater for residential use was jointly developed by the Tokyo Electric Power Company (TEPCO), Denso Corporation and CRIEPI, starting in 1998. In this collaboration, TEPCO mainly provided the concept for the product, while the main Denso contributions were the research and development of components and methods of improving heater performance. CRIEPI concentrated on evaluation of the prototype and finding ways to improve performance.

Modification of the prototype and improving its performance

Components such as the compressor and heat exchanger were developed and modified, and a prototype built using these components was installed in the test chamber and tested (Fig. 2). As a result, COP improved from 2.1 (first prototype) to 3.4 (final prototype) under winter conditions (heat source air temperature: 8 ^{o}C, tap water temperature: 8 ^{o}C and hot tap water temperature: 65 ^{o}C). Fig. 3 shows test results for both prototypes in a T-s (temperature - specific entropy) diagram. The T-s gradient of the compression stage was higher for the final prototype than for the first prototype (Fig. 3 (1)) and the compression efficiency increased (Figure 4 shows a cutaway model of compressor). The ^{o}C temperature at the outlet of the CO_2 - water heat exchanger was lower than that of the first prototype (Fig. 3(2)). ACO_2 - water heat exchanger with a small temperature difference, a capillary tube (inner diameter 0.5 mm) heat exchanger, was developed for the final prototype (Figure 5 shows the capillary tube heat exchanger) [2].

**1:"ECO CUTE" is a name used by electric power companies and water heater manufacturers, and refers only to heat pump water heaters using CO2 as a refrigerant.*

Evaluation of the annual average COP of the final prototype

The annual average COP was evaluated using performance test results for the final prototype (Table 1). The evaluated system COP, which includes the power input to the air fan and water pump, was 3.4. This value was better than the targeted value of 3.0. In addition, it was confirmed that the final prototype could produce hot water at 90 ^{o}C at an ambient air temperature of -15 ^{o}C [2].

Putting ECO CUTE on the market

From May 2001, Corona, Sekisui Chemical, Mitsubishi Electric, Shihen Technical, Kyuhen and other companies started selling ECO CUTE water heaters (Fig. 6), with Denso as the original equipment manufacturer. This was the world's first CO_2 heat pump water heater on the market.

ECO CUTE can reduce primary energy consumption by about 30 % and CO_2 emissions by about 50 % in comparison with combustion water heaters (Fig. 7). These features were recognized and ECO CUTE technology was awarded various prizes, including the Energy Conservation Grand Prize awarded by the Minister of Economy, Trade and Industry (Jan. 2002), and the US EPA Climate Protection Award (Mar. 2002). In addition, ECO CUTE water heaters usually operate during the night and the hot water produced is stored in a hot water storage tank. The system can use cheap night rate electricity, saving on running costs drastically (Fig 7). Note, however, that the actual running cost of the water heater may vary, depending on the amount of hot water consumed, family composition and season of the year.

Market development and new development

Market development of heat pump water heaters

Fig 8 shows the trend in shipments of ECO CUTE water heaters, indicating that the market for ECO CUTE has been growing rapidly. In fiscal year

Figure 2: Photograph of the test chamber and the prototype.

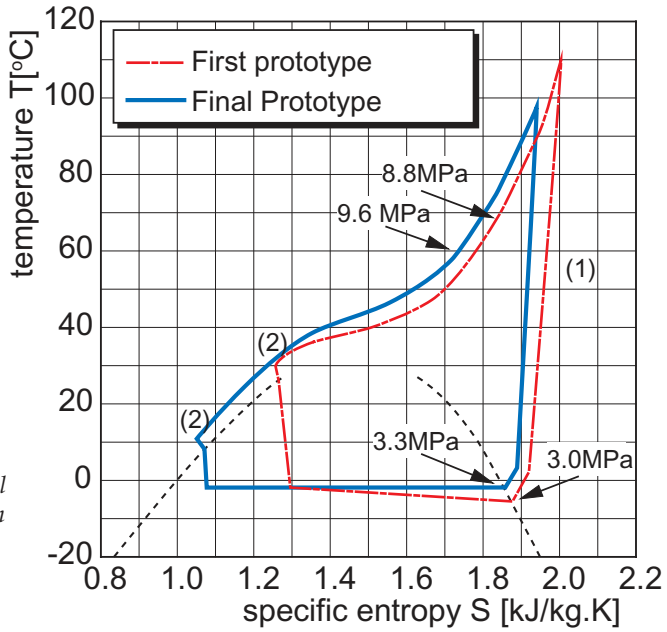
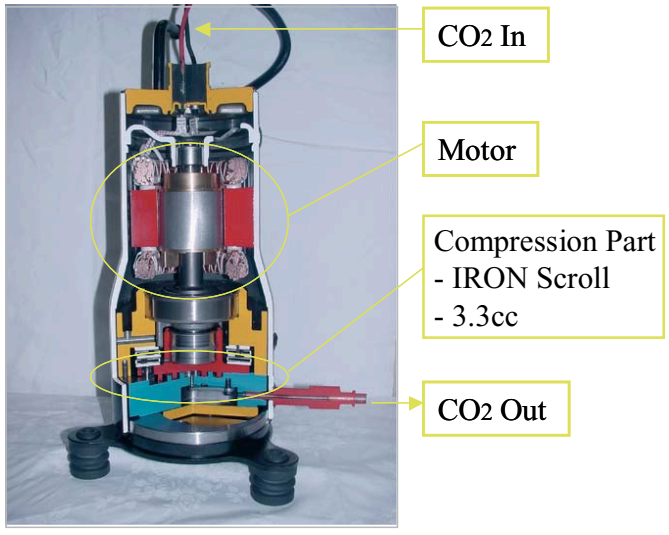


Figure 3: Performance improvement of the final prototype in comparison with the first one

Figure 4: Photograph of compressor.



2005 alone, about 225 000 units were shipped [4]. Although this is far less than total water heater shipments (4.2 million per year), it is an excellent result.

There are many reasons for the rapid uptake of ECO CUTE water heaters, such as:

- Good concept and good performance
- Many manufacturers and suppliers in the market (Fig. 9 [3]). There are six manufacturers: Denso, Daikin, Sanyo, Matsushita Electric Industrial, Hitachi Appliances and Mitsubishi Electric. These may increase in future.
- Government subsidy program
- Electric power companies have been promoting all-electric homes (IH cooking heater for cooking and ECO CUTE for hot water supply)
- The government has set a specific target for installation (5.2 million units by 2010).

Technical progress of heat pump water heaters

Manufacturers have been competing to be the market leader of ECO CUTE water heaters, and therefore have made the following improvements independently.

- Size reduction
  The unit footprint has been reduced in order to install ECO CUTE water heaters in confined spaces, such as housing complexes in urban areas.
- For cold regions
  In order to encourage installation of ECO CUTE water heaters in cold climate regions of Japan (Hokkaido, Tohoku and Hokuriku areas), a certain heating capacity and efficiency must be available at a very low ambient temperature, and steps taken to prevent freezing in pipes etc. Some manufacturers are already marketing ECO CUTE water heaters for cold regions, and others are developing such heaters.
- Multiple functions
  New features (floor heating and bathroom heating) have been added.
- Silent operation
  Because ECO CUTE water heaters run during the night, quietness is very important. The noise level has now been reduced to 37 dB from 45 dB in 2001.
- High efficiency
  Efficiency is a very important factor in the success of ECO CUTE technology. The highest COP is now 4.9 (latest model in 2006), an increase from 3.5 (first model in 2001) under intermediate conditions. Each manufacturer is developing technology independently, using compressors and heat exchangers with different designs. Measures used to improve efficiency are different too. For example, Denso's ECO CUTE water heater is equipped with an ejector to recover the expansion energy.
- Optimum operation control
  When stored hot water is not used up, cooled remaining hot water (not so hot, about 40 ^{o}C) must be reheated to over 65 ^{o}C. This is a loss. Moreover, the COP is reduced when inlet water temperature rises higher than the usual water temperature. This is also a loss. An optimum operating control method (studying daily demand and controlling the optimum hot water amount) needs to be developed as soon as possible.

Figure 5: Photograph of capillary tube heat exchanger.

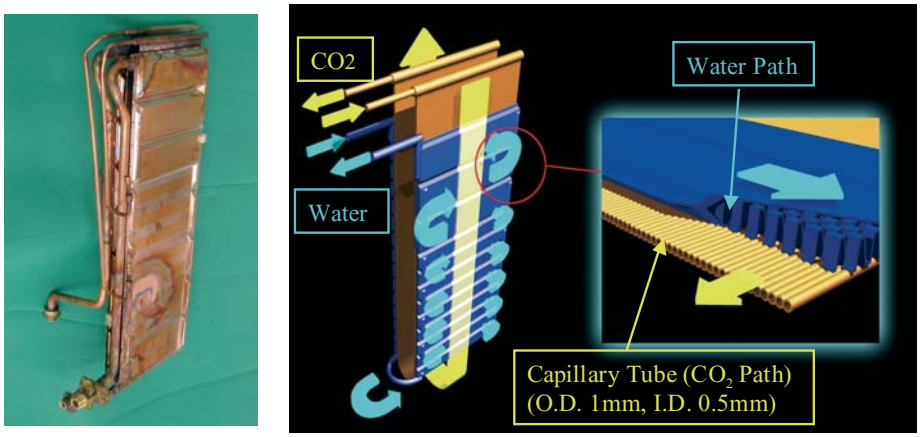
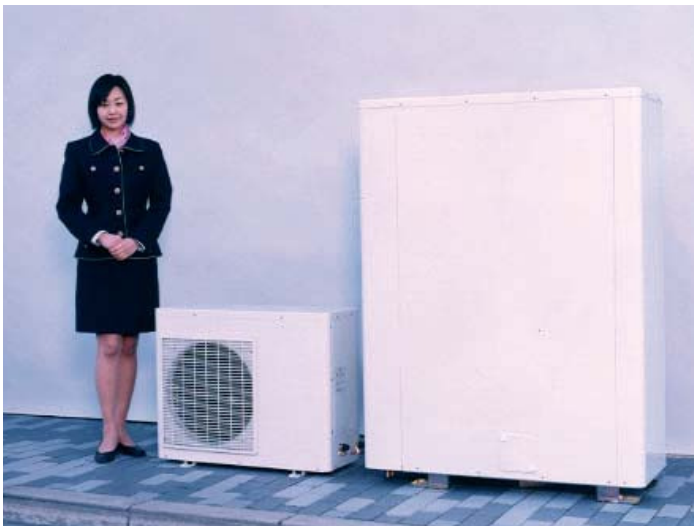
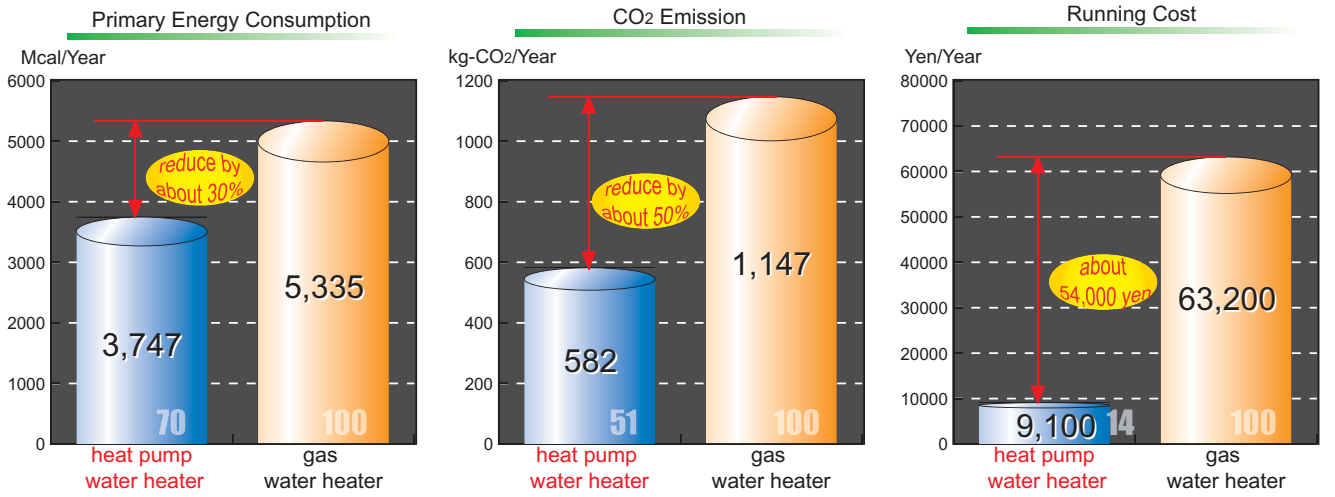


Figure 6: Photograph of the first CO_2 heat pump water heater for residential use.



Left: Heat Pump Unit (81 x 32 x 65cm), Heating Capacity: 4.5 kW
Right: Hot Water Tank(109 x 45 x 152cm), Capacity: 300 liters

Figure 7: Energy conservation, greenhouse gas reduction and cost saving performance.



1. The equivalent hot water amount at the temperature of 43 °C on the L mode of IBEC*1 is used for the standard water heater load.
2. The ambient air temperature and the tap water temperature are based on JRA4050:2005*2.
3. The primary energy intensity for electricity is 2.3 Mcal/kWh(night), one for city gas is 11 Mcal/m^3.
4. COP is assumed to be 3. Defrosting and boiling out loss are included.

1. The equivalent hot water amount at the temperature of 43 °C on the L mode of IBEC*1 is used for the standard water heater load.
2. The ambient air temperature and the tap water temperature are based on JRA4050:2005*2.
3. The CO_2 emission intensity for electricity is 0.357 kg-CO2/kWh, one for city gas is 2.364 kg-CO2/m^3.
4. COP is assumed to be 3. Defrosting and boiling out loss are included.

1. The equivalent hot water amount at the temperature of 43 °C on the L mode of IBEC*1 is used for the standard water heater load.
2. The ambient air temperature and the tap water temperature are based on JRA4050:2005*2.
3. COP is assumed to be 3. Defrosting and boiling out loss are included.
4. The electricy rate: TEPCO's "Season and Time-Specific Lighting (Denka-Jozyu)" (the discount for fully-electrified homes and the discount for energization-controlled nighttime thermal storage type appliances are applied. In this case, an amount due to the fuel cost adjustment is not applied) [3]. The electricity cost required for heat retension of bathtub water is not included.
The gas rate: Tokyo gas's cost table B (In this case, an amount due to the fuel cost adjustment is not applied.)

*1: Institute for Building Environment and Energy Conservation
*2: the standard of The Japan Refrigeration and Air conditioning Industry Association

New moves surrounding ECO CUTE

The government has a strong interest in ECO CUTE because of its potential to save energy and reduce greenhouse gas emissions. The government announced a target of 5.2 million units to be installed by 2010, and has been providing subsidies to purchasers of ECO CUTE heaters since fiscal year 2002.

A number of technical development projects have also been launched since 2005 on the initiative of NEDO. Development items in the projects include downsizing and improving performance in cold regions. Denso, Daikin, Sanyo and Matsushita have been working to reduce the size of the units. Hitachi, Mitsubishi Electric and Corona meanwhile have been working to improve COP in cold climate regions. The results of these projects will be published by NEDO.

Figure 8: Shipment of ECO CUTE.

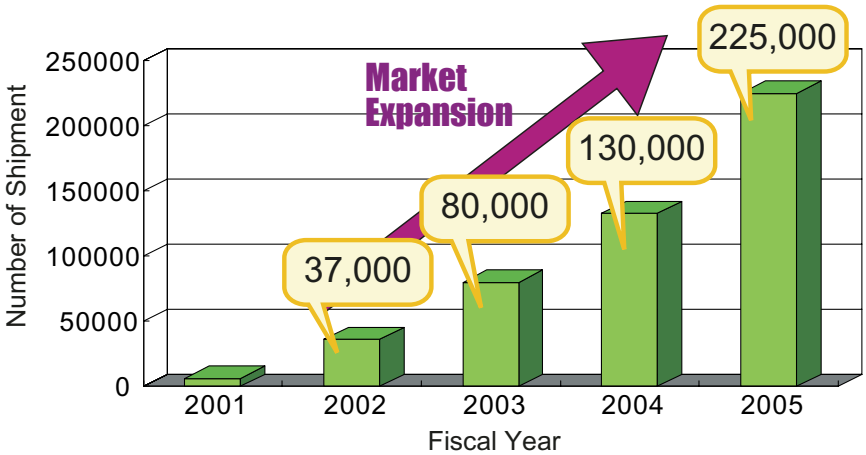


Figure 9: Photographs of various ECO CUTEs.

Conclusions

There are high expectations of technological developments by the NEDO projects and manufacturers. Once these technologies are incorporated in new ECO CUTE models, shipments are expected to grow. Further widespread use of ECO CUTE water heaters may reveal new problems. It is hoped that all the interested parties will cooperate to address any such problems and facilitate further uptake of the technology.

Finally, CRIEPI will cooperate with electric power companies on these issues and offer positive support. We also intend to conduct our own basic research on heat transfer phenomena in the evaporating and gas cooling processes, and methods for evaluating CO2 heat pump water heater technology.

	Winter (Dec.-Mar.)	Intermediary (Others)	Summer (Jun.-Sep.)	Yearly
Ambient air temperature (°C)*1	4.6	13.8	22.5	-
Tap water temperature (°C)	8.3	15.9	23.2	-
Hot tap water temperature (°C)*2	65	65	65	-
Estimated system COP (-)*3	3.1	3.5	3.9	-
Hot tap water demand (MJ)	7369	5828	4291	17488
Energy consumption (MJ)	2378	1679	1115	5172
Estimated yearly average COP				3.4

*1 Temperatures are the average for each season.
*2 Heating capacity / power input to inverter of compressor motor
*3 Heating capacity / power input to heat pump unit (including input to air fan and water pump)

Table 1: Estimation of yearly average COP of the final prototype for a family living in Tokyo

References

[1] Saikawa, M. and Hashimoto, K, 1998, "Evaluating the potential of CO2 as a working fluid for heat pumps", IEA Heat Pump News Letter, No.3, Vol.16

[2] Saikawa, M., Hashimoto, K., Kobayakawa, T., Kusakari, M., Ito, M., Sakakibara, H., 2000, "Development of Prototype of CO2 Heat Pump Water Heater for Residential Use", Proceedings of 4th IIR Commission B1, B2, E1, and E2, Purdue Univ., USA

[3] Manufacturers' brochures (Corona, Daikin, Mitsubishi, Matsushita, Hitachi, Sanyo)

[4] Kusakari, K., 2006, "The Spread Situation and the Future View of the CO2 Refrigerant Heat Pump Water Heater in Japan", Proceedings of 7th IIR Gustav-Lorentzen Conf. on Natural Working Fluid, Trondheim, Norway

Katsumi Hashimoto
Central Research Institute of Electric Power Industry
2-6-1 Nagasaka, Yokosuka-shi, Kanagawa-ken, 240-0196, Japan
hashimo@criepi.denken.or.jp
+81-46-856-2121
+81-46-856-3346