# Development of reversible residential air conditioners and heat pumps using $CO_2$ as working fluid

*Jakobsen, Skiple, Nekså, Wachenfeldt, Stene & Skaugen, Norway*

*Since 1997, SINTEF Energy Research and The Norwegian University of Science and Technology (NTNU) have been investigating and developing reversible residential air conditioners and heat pumps (RAC split-type units) using carbon dioxide ($CO_2$) as their working fluid. A third-generation prototype $CO_2$ RAC split-type unit has recently been constructed and extensively tested in heating and cooling modes. The test results have been used for calculating the seasonal heating and cooling performance (SPF) for two different climates; Greece (Athens) and Norway (Oslo). The results have been compared with manufacturer's data with verified rating points for the most energy-efficient Japanese R410A split-type unit available on the market.*

*In both the heating mode and the cooling mode, the calculated SPF for the $CO_2$ and R410A units in the Oslo climate were more or less identical. However, in the cooling mode in the Athens climate, the SPF of the $CO_2$ unit was about 17 % lower than that of the R410A unit. Further development and optimization of the $CO_2$ unit, e.g. by utilizing microchannel heat exchanger technology, increasing the isentropic efficiency of the compressor and/or using an ejector or expander for expansion work recovery, will be necessary before the $CO_2$ unit will be able to match or outperform the market-leading R410A unit in terms of energy efficiency. However, since the $CO_2$ unit already matches many of the better R410A units on the market, $CO_2$ must be regarded as a promising working fluid in reversible air-conditioning and heat pump units for residential use.*

## Introduction

The current world market for RAC split-type units is roughly 30 million units per year. Virtually all of them use HCFC-22, R407C or R410A, which are powerful greenhouse gases with relatively high global warming potentials. This is also the main reason why the European Union has introduced legislation regarding better containment of HFCs for all kinds of applications, as well as clear phase-out targets for mobile air conditioning systems.

Carbon dioxide ($CO_2$) is a non-toxic and non-flammable working fluid that does not contribute to ozone depletion (ODP = 0) and has negligible global warming (GWP = 1). Due to its favourable thermophysical properties, $CO_2$ is regarded an interesting alternative to the HCFCs and HFCs in many heat pumping applications, including RAC split-type units.

## Testing of a prototype $CO_2$ RAC split-type unit

A prototype $CO_2$ RAC split-type unit and a state-of-the-art R410A unit have been tested in a two-chamber calorimetric test rig, described by Jakobsen et al. (2004, 2006). According to Eurovent (2005), the selected R410A reference unit had the highest cooling COP at the rating point of all the tested R410A reversible split-type units (Unit 1, Table 1). The measured COP was about 11 % higher than that of the second most energy-efficient unit.

The prototype $CO_2$ RAC split-type unit was equipped with an inverter-

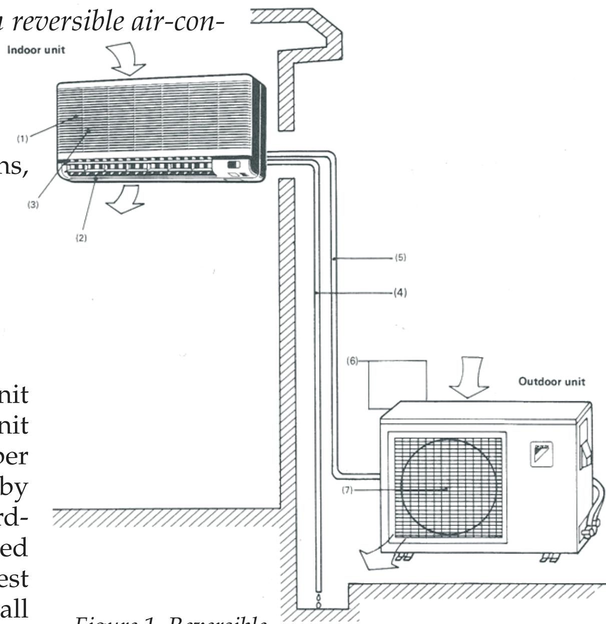


*Figure 1. Reversible residential air conditioner and heat pump unit (RAC split-type unit)*

controlled two-stage rolling piston compressor, finned tube heat exchangers (HX), and a tube-in-tube internal heat exchanger. The compressor was connected to an intercooler to enable cooling of the $CO_2$ gas between the compression stages. In order to simplify the experiments, the heat exchanger was water cooled. However, in a real sys-

*Table 1. Relative rating point COPs for different R410A RAC split-type units (Eurovent, 2005)*

| Unit | **1** | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| COP [%] | **100** | 89 | 83 | 73 | 69 | 62 | 64 | 79 | 77 | 83 | 92 | 78 | 75 | 71 |

tem, the heat exchanger would have been an integral part of the outdoor heat exchanger and would be cooled with ambient air. The $CO_2$ pressure in the gas cooler was controlled and optimised by means of a manual expansion valve and a low-pressure receiver (Shecco Cycle, http://www.shecco.com). Figure 2 shows a schematic diagram of the prototype $CO_2$ unit.

The maximum compressor power consumptions of the $CO_2$ unit and the R410A unit were about 2.0 kW and 1.7 kW respectively. Microchannel (MPE) heat exchangers for $CO_2$ in, for example, mobile air conditioning applications have shown excellent performance. However, round tube heat exchangers were selected for the $CO_2$ prototype unit due to the limited availability of MPE heat exchangers, and concern about water retention and frosting issues.

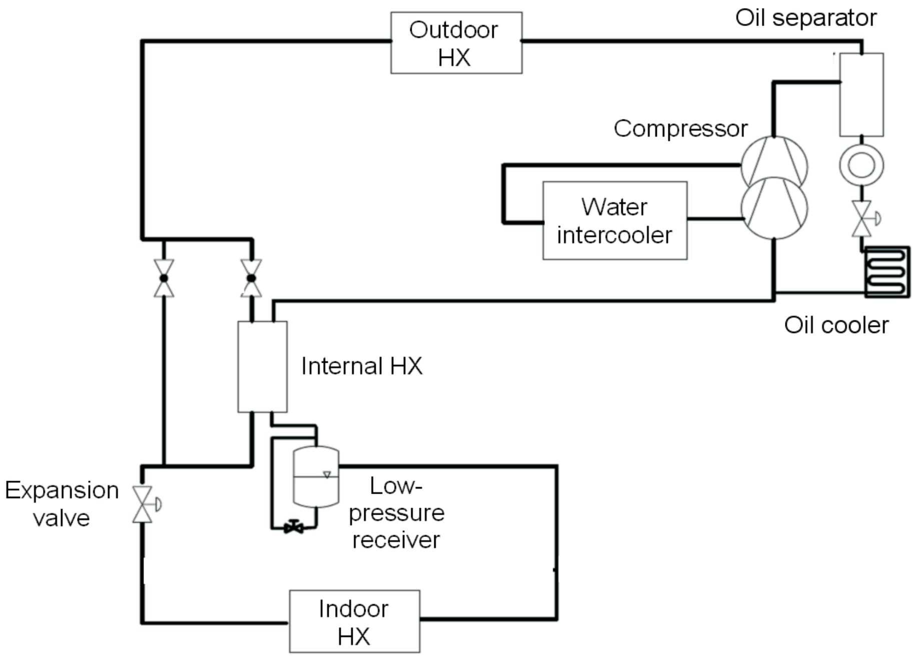


*Figure 2. Schematic diagram of the prototype CO2 RAC split-type unit, AC operation*

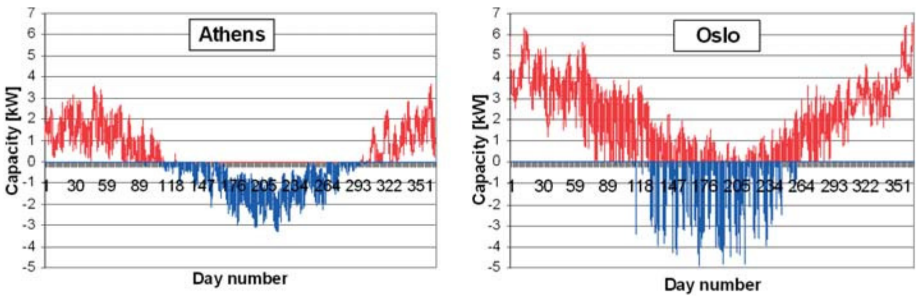


*Figure 3. Predicted heating and cooling loads in the Norwegian and Greek dwellings*

## Calculation of Seasonal Heating and Cooling Performance

In order to estimate the heating and cooling demands in typical residential dwellings, simulation models representing conditions for a dwelling in Athens, Greece (hot, dry climate) and one in Oslo, Norway (cold, dry climate) were created using the integrated ESP-r (ESRU, 1999) building simulation tool. The models were based on a reference dwelling established through the IEA District Heating and Cooling project. The reference two-floor dwelling was located in a terrace block with four similar dwellings of 112 m2. Identical dimensions were assumed for the Greek and the Norwegian dwellings, and the mass of the structure was chosen to reflect thermo-physical qualities in accordance with building traditions in the two countries. The windows of the Greek dwelling were assumed to be equipped with external shading systems. Ventilation of the dwellings was assumed to be solely by exhaust fans placed in the laundry and the bathroom.

Simulations for a whole year were carried out for one hour time steps, using climate data for a reference year. Figure 3 shows the predicted heating and cooling loads during the year.

The set-point for the indoor air temperature was 25 ºC in cooling mode, and 21 ºC in heating mode. The indoor relative humidity was calculated using the same absolute humidity as in the ambient. Cooling in Athens and Oslo started at 23 °C and 18 °C respectively. The difference was mainly due to different practice in the application of solar shading systems and exposure of thermal mass, as a result of different building traditions in the two countries.

The measured COPs for the $CO_2$ unit, and the manufacturer's data with verified rating point for the R410A unit, together with the heating and cooling loads at different ambient temperatures, were used for calculating the seasonal performance factors (SPF) in the heating and cooling modes in the two different climates. Table 2 shows the results. The SPF in heating mode included the electric peak load (bivalent heating system), while the SPF for the $CO_2$ unit in cooling mode included intercooling between the compressor stages, which increased the SPF by 5 to 7 %.

*Table 2. The calculated seasonal performance factors (SPF) for the RAC split-type units based on measured data in heating and cooling mode in two different climates*

| RAC unit | Heating Mode | | Cooling Mode | |
|---|---|---|---|---|
| | Athens | Oslo | Athens | Oslo |
| CO2 prototype – measured data | 4.3 | 2.7 | 4.4 | 6.7 |
| R410A-unit – manufacturer data | 4.0 | 2.6 | 5.3 | 6.7 |

The calculated SPF in heating mode for the $CO_2$ unit was about 7 % higher than that of the R410A unit in the Athens climate, and about 3 % higher in the Oslo climate. In cooling mode, the $CO_2$ unit achieved the same SPF as the R410A unit in the Oslo climate, but about 17 % lower SPF in the Athens climate. The results demonstrate that it is possible for a $CO_2$ RAC split-type unit to match the energy efficiency of the best R410A unit on the market in heating mode and in cooling mode in colder climates, but that further development is required in order to achieve the same energy efficiency in cooling mode in warmer climates.

Sakamoto (2001) indicated that the overall isentropic efficiency for hermetic R410A compressors for RAC split-type units is up to 0.65. The measured isentropic efficiency of the $CO_2$ compressor was about 0.54 (Jakobsen et al., 2006), with the relatively low efficiency probably being due to the fact that the compressor was from an early stage of development. Owing to the favourable charac¬teristics of the $CO_2$ compression process, a $CO_2$ compressor should be able to reach at least the same efficiency level (Fagerli, 1997). Postulating an isentropic efficiency of 0.65 for the $CO_2$ compressor, and using intercooling, the SPF for the $CO_2$ unit in cooling mode in the Athens climate would have equalled the SPF of the R410A unit.

## Conclusions

Extensive testing of a prototype $CO_2$ RAC split-type unit has shown promising results when comparing the unit with the most energy-efficient R410A unit on the market. However, the $CO_2$ system is still at an early stage of the development process, and improvements are required to achieve the same energy efficiency as the best R410A units under certain operating conditions. The next development steps for the $CO_2$unit will be to optimize the heat exchangers, use a compressor with higher isentropic efficiency and possibly use an ejector or expander for expansion work recovery.

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***Jakobsen, A.[1], Skiple, T.[1], Nekså, P.[1], Wachenfeldt, B.[2], Stene, J.[1], Skaugen, G.[1]***

[1]*SINTEF Energy Research, Trondheim – Norway*

[2]*The Norwegian University of Science and Technology, NTNU*