Over the last years there has been a growing interest in air conditioning (AC) systems which apply the natural working fluid carbon dioxide (CO$_2$) as the refrigerant (R744). Experiments on prototype systems have demonstrated the competitiveness of R744 systems, and the automotive industry is now doing a commercial introduction.

There is an increasing interest for different AC systems that can be reversed for heat pump (HP) operation. There are two possible ways of reversing the mode of such units, either the refrigerant flow is redirected or the air flow is reversed. The second choice will be the focus of this work.

The performance of a small capacity prototype unit was measured in the climate chamber / HVAC test facility at SINTEF/NTNU Refrigeration and AC laboratories.

Focus of the study is the system performance of the unit, including extreme operating conditions, i.e. from -20 °C to +52 °C ambient temperature.

The system design and components is presented along with experimental results applied in a Life Cycle Climate Performance (LCCP) analysis; this analysis has been performed for different climate regions of the world.

1. INTRODUCTION

On a global base there are many living areas where buildings require heating during the cold season and cooling during the hot season to achieve comfort inside. Traditional HFC residential split air conditioning (RAC) units are able to deliver both heating and cooling, nevertheless, the system layout and its components are mainly a compromise or partly optimized for only one mode. Since HFC’s are on the phase out list of the Kyoto Protocol, due their high Global Warming Potential (HFC-134a = 1410 kg CO$_2$equiv.; HFC-410A = 2060 kg CO$_2$equiv., IPCC 2005), R744 represents a sustainable global alternative refrigerant. If the AC industry is taking the GHG emissions serious, development focus should be given to sustainable refrigerants, i.e. well known substances, which do not harm the environment today and in the future.

Split RAC designs are possible with R744, however, switching valves are challenging components and the most compact R744 heat exchanger concepts differ from conventional HFC units. A high degree of heat exchanger compactness can be achieved when Multi-Port-Extruded (MPE) tube heat exchangers are utilised. The cost of these efficient aluminium heat exchangers can be reduced when they are produced in large numbers, similar to concepts of mobile Air Conditioning units. (RIEGEL 2007, WIESCHOLLEK & HECKT 2007)

Refrigerant distribution inside the evaporator header manifolds of MPE heat exchangers is challenging, due to the large number of tube ports, which ideally have to be charged equally with liquid and vapour. Applying an ejector instead of an ordinary expansion device can reduce the degree of mal-distribution, since the vapour fraction at the evaporator inlet is low, i.e. mainly liquid enters the heat exchanger tubes.

Low temperature approaches$^1$ can be achieved with compact MPE tube gascooler designs when the heat rejection takes place in the preferred flow configuration of cross counter flow. The gliding temperatures

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$^1$ Gascooler refrigerant outlet temperature - air inlet temperature
inside the gascooler at transcritical conditions require the internal conduction be avoided (HAFNER 2003). Additionally, uniform air side distribution is important to achieve a high system performance, i.e. the overall efficiency depends on optimized air flow arrangements.

There are two possible ways of reversing the operation mode of AC units, either the refrigerant flow is redirected or the air flow is in a way reversed. Figure 1 shows the system circuit of a refrigerant side reversing unit which requires several additional valves and fittings, which adds extra costs, possible leakage and pressure drop to the system. Such a system has the benefit that there is no need to change the airside installations, when reversing the operation mode.

![Figure 1 System circuit, reversible R744 system](image)

![Figure 2 Example from a HFC system, MER-AIR 2006](image)

Figure 2 shows an example of an air reversing concept where ducts are connected to the unit.

The independently developed R744 small capacity ECU (Environmental Control Unit), as described in this work, with its novel way of reversing the operating modes, was investigated thoroughly applying different kind of simulation tools.

2. SYSTEM DESIGN

The principle system layout for the air reversing concept presented here is a turning table ECU with a tangential placement of the heat exchangers as shown in Figure 3. Stationary fans are located in every corner of the ECU.

$Csim^2$ was applied to analyze the behaviour of this transcritical R744 heat pumping unit. $Csim$ was used for steady-state simulations with all operating parameters and the component geometry fixed. In addition optimization routines for R744 systems were applied to investigate different gas cooler (high-side) pressures, component sizes, and fan speeds that provide the desired capacity at maximum coefficient of performance (COP).

**System operation**

The rpm of the compressor is not variable, however, the rpm of the heat exchanger blowers can be controlled, and thereby it is possible to adjust the air flow rates manually or automatically to realize high energy efficiencies (Eco-mode)

If the evaporator has to be defrosted, mainly during heating mode at temperatures around 0 °C, a valve bypassing the gascooler, IHX and the expansion devices (as shown in Figure 9) is opened for a short time. During this time, the blowers should be operated at their lowest rpm or switched off.

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$Csim$: In-house advanced circuit simulator, developed by SINTEF/NTNU (Skaugen 2002)
The tangential arrangement of the heat exchangers guarantees a uniform air side distribution by drawing the air through the heat exchangers. Figure 4 shows a result example from CFD investigations regarding air distribution of local temperatures.

**2.1 Component specification**

**Evaporator**

The evaporator is required to have the same cross sectional air flow area as the gas cooler because of the turn-table concept. The evaporator is a four row heat exchanger which, unlike the gas cooler, does not require counter-flow configuration because the refrigerant operates in the two-phase regime.
**Gascooler**

The gascooler was designed as a four row cross counter flow heat exchanger. A typical temperature profile obtained during the design process is shown in Figure 5. A four row heat exchanger design represented the optimum between performance, size, and cost.

![Gascooler temperature profile](image)

*Figure 5 Typical gas cooler (GC) temperature profile and view of header arrangement*

**Expansion devices**

A combination of two expansion devices was implemented in the R744 ECU.

- A thermal back pressure valve (TBR) was selected to adjust the high side pressure to an optimum level at all times. The refrigerant side gas cooler exit temperature is used as the control feedback signal.
- A manual back pressure valve (MBR) was then connected in parallel to ensure that the system would start up properly, especially at elevated ambient temperatures.

**Internal Heat Exchanger (IHX)**

The IHX design consists of two MPE tubes brazed together, as shown in Figure 6. This concept replaces some of the connecting lines between the gascooler and the expansion device on the high pressure side and between the receiver and the compressor on the low pressure side.

![Conceptual IHX drawing](image)

*Figure 6 Conceptual IHX drawing*

**Receiver**

An accumulator, designed for automotive R744 Air Conditioning systems was applied downstream of the evaporator.

**Compressor**

The displacement of the hermetic type piston compressor was 3 cm³. There is no capacity control of the compressor, *i.e.* manual on–off operation only. However, the rpm of the heat exchanger blowers can controlled, thereby it is possible to adjust the system performance, *i.e.* power saving by adjusting the air flow rate across the heat exchangers.

![Applied R744 compressor](image)

*Figure 7 Applied R744 compressor*
3. EXPERIMENTAL SETUP & RESULTS

The compact ECU, as shown in Figure 8 was equipped with pressure and temperature sensors, as shown in Figure 9. Upstream of the expansion devices a mass flow meter was installed to be able to measure the performance of the different components.

![Figure 8 View of the Prototype unit, seen from the evaporator side.](image)

![Figure 9 System circuiting, including location of measurement equipment](image)

**Extreme Ambient conditions**

The ECU has to be able to operate at ambient temperature from -20°C to over 50°C. Figure 10 shows the operation conditions in ph-diagrams, respectively for heating and cooling at these conditions.

A) Cooling at 50°C ambient temperature

B) Heating at -20°C ambient temperature

![Figure 10 Measured system performance at extreme ambient temperatures.](image)

To be able to calculate the annual emissions related to the power consumption of the ECU, a wide range of experiments was performed at various ambient temperatures and interior temperatures, according to common comfort measures, as shown in Figure 11. However, due to technical challenges with the prototype unit, only

![Figure 11 Initial simulation results, applied in the LCCP analysis. (assumed isentropic efficiency of the compressor: 60 %)](image)
initial simulation data are available at the deadline for the pre-prints, the final paper in the proceedings will contain results based on measured performance data.

**Input to LCCP**

The main input value to the Life Cycle Climate Performance analysis in case of R744 AC units are the emissions related to the power production, i.e. the electrical power which is required to run the unit is the major source for GHG emissions. If the LCCP is compared to current HFC units, the HFC leak rates (production and transport of refrigerant, during normal operation, service and end of life) have to be considered as well, due to the high GWP values of such refrigerants.

In this case various power (plant) sources for electricity are considered, i.e. the CO$_2$ equivalent emission per kWh at different locations, as shown in Table 1.

<table>
<thead>
<tr>
<th>Source of Electricity</th>
<th>CO$_2$ emission [kg CO$_2$ eq. / kWh]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel power generator</td>
<td>1.12 - 0.769</td>
<td>US-Army</td>
</tr>
<tr>
<td>Coal power plant</td>
<td>0.94</td>
<td><a href="http://www.klima.ph/ghg_calculator/primer/primer.html">http://www.klima.ph/ghg_calculator/primer/primer.html</a></td>
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<td>Energy mix China*</td>
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</tr>
<tr>
<td>Energy mix India</td>
<td>0.84</td>
<td><a href="http://www.klima.ph/ghg_calculator/primer/primer.html">http://www.klima.ph/ghg_calculator/primer/primer.html</a></td>
</tr>
</tbody>
</table>

*(75% coal, 15% hydro, 8% gas 2% nuclear, National Bureau of Statistics, 2005)

The reference regions of the LCCP analysis in this study are Beijing, Baghdad and New Delhi. Figure 12 shows the number of temperature-hours for the different locations.

![Figure 12: Number of annual hours within a 5 K temperature bin of different locations. (METEONORM)](image)

The total Energy consumption of the unit depends on the number of operating hours during a year. Figure 13 shows two examples: A) Using the unit during the daytime, from 8 a.m. until 4 p.m. and B) during the rest of the day. I.e. the sum of both tables is the annual power consumption and related GHG emissions when running the unit 24h a day.

While the fraction between energy applied for heating and cooling is 0.17 to 0.83 (0.1/0.9 if only daytime operation) for New Delhi, in Beijing 59% (52%) of the energy is used for heating. In Baghdad 62% (71%) of the energy is spent for cooling.
The total annual power consumption during daytime operation varies between 2111 and 2379 kWh. If the unit is on duty 24h/a the energy consumption is 5569 kWh in Beijing, 5909 kWh in Baghdad and 6098 kWh in New Delhi.

A) Operation between 8 a.m. and 4 p.m. 
B) Operation between 4 p.m. and 8a.m.

Figure 13  Annual energy consumption and corresponding CO₂ equivalent emissions.

Depending on the primary source for electricity production the total annual GHG emission may reach 5732 kg CO₂eqv if a coal fired power plant in New Delhi delivers the electricity, however, due to the Indian energy mix, the total GHG emission of one unit in New Delhi is about 5122 kg CO₂eqv.

4. DISCUSSION

This concept study showed that a turn-table residential AC-unit, applying R744 as working fluid, is a viable option for many global areas, where both heating and cooling is required during a year. The ‘one-way’ refrigerant circuit, without switching valves, seems to be a cost efficient solution for all markets. The degree of automatization of the turning mechanism can be from a simple manual handle to an electrical motor.

Such a system arrangement keeps the refrigerant side relatively simple, and no sophisticated high pressure switching devices are required, i.e. heat conduction and additional pressure losses common in such components can be avoided. The function of the air to refrigerant heat exchanges is independent of the operation mode, therefore no design compromises have to be made and the efficiency of the heat exchangers are higher than in conventional split units, reversing the refrigerant flow.

This concept, developed among other alternatives, was preferred because no negative effects were expected related to air side mal-distribution. The undisturbed air flow upstream of the heat exchangers minimizes issues related to the air side mal distribution as mainly seen with current applications.

The turn-table concept is especially favourable for portable applications since the refrigerant circuit is compact and located in the centre of a unit. Since the air is drawn through the heat exchangers from ambient, special emphasis has to be given to be able to remove the condensed water drained out of the evaporator, since the absolute pressure inside the ECU is lower than outside.

The investigated ECU reconfirmed that R744 RAC systems are able to perform even at extreme ambient conditions. At global locations with rather hot seasons living, without AC is more and more impossible. As the living standard in developing counties is increasing, sustainable working fluids have to be applied in RAC systems to avoid unexpected surprises to the environment, as seen in the past.
5. SUMMARY & CONCLUSION

An air reversing, turn-table ECU was designed and experimentally investigated. The refrigerant circuit can be unchanged, when directing the air through the designated heat exchanger by rotating the entire refrigeration unit. Therefore the function of the heat exchanger does not change, i.e. the gascooler can be optimized for a low temperature approaches. Refrigerant charge problems can be handled since no ‘dead’ lines are present.

This concept study showed that a turn-table residential AC-unit, applying R744 as working fluid, is a viable option for many global areas, where both heating and cooling is required during a year.

Further work to enhance the system efficiency:

- Investigation of different means to improve the refrigerant distribution inside the evaporator.
- Adjustment of the optimal length of the IHX.
- Adjustment of the thermal back pressure expansion device.
- Evaluate and investigate the use of an ejector, replacing the TBR.

ACKNOWLEDGEMENT

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REFERENCES


METEONROM, climate date base, version 5.1, www.meteonorm.com

