1998

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A TRANSCRITICAL REFRIGERATION CYCLE WITH CARBON DIOXIDE FOR BUS AIR CONDITIONING AND TRANSPORT REFRIGERATION

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ABSTRACT

The first part of this paper presents carbon dioxide air conditioning units which were installed in two city buses. The two buses were tested "on-the-road" during summer 1997 in Bad Hersfeld, Germany. By the end of 1997, the air condition systems of the two buses had been running together for more than 860 hours proving that CO_2 systems fulfill important on-the-road requirements. In the second part of this paper a laboratory prototype is discussed which used carbon dioxide as refrigerant for transport refrigeration. An internal heat exchanger improves the cooling capacity but has no significant effect on the COP for ambient air temperatures of 30 °C (86 F). The last part of the paper describes the design steps of the compressor used for both bus air conditioning and transport refrigeration. The comparison of compressor versions 1 and 2 show significant improvements differences in the measured indicator diagrams mainly due to the modified discharge valves.

INTRODUCTION

Carbon dioxide is an environmentally benign refrigerant. Unlike synthetically produced HFC-134a, carbon dioxide has a negligible global warming potential and it has no harmful breakdown products. Carbon dioxide is a natural substance and does not have to be produced especially as refrigerant. It is available from natural wells or as a by-product from industrial processes. Hence, recycling of carbon dioxide is not necessary. That makes service and maintenance for CO_2 systems easier than for conventional systems, which use synthetically produced refrigerants. This is an important advantage of carbon dioxide compared to HFC's.

ON-THE-ROAD TESTS WITH CARBON DIOXIDE AIR CONDITIONING SYSTEMS

In August 1996 the first carbon dioxide air conditioning system was installed in a bus (Bus A in Fig. 1, O 405). This bus, a five year old city bus is owned and operated by the public transportation company in Bad Hersfeld, Germany. A detailed description of the carbon dioxide air conditioning system was given by Sonnekalb and Köhler [1]. In May 1997 two new buses (O 405 N) were bought by the same public transportation company in Bad Hersfeld. These two buses are totally similar, except that one bus (Bus C in Fig. 1) is equipped with a standard HFC-134a air conditioning system, whereas the second bus (Bus B in Fig. 1) is air-conditioned by a CO_2 air conditioning system. The carbon dioxide system is identical with the HFC-134a system with respect to weight, overall size, blowers and fans, and (air-side) dimensions of the heat exchangers. The CO_2 compressor is smaller than the HFC-134a compressor. Fig. 2 shows the CO_2 air conditioning system of Bus B. With the help of the Buses B and C the "on-the-road"-behavior of the CO_2 system and the standard HFC-134a system can be ideally compared. All three buses (Buses A, B, and C) are used for public transportation in Bad Hersfeld, Germany, all year round. By the end of 1997 the air conditioning system of Bus A had been running for more than 550 hours. At the same time the air conditioning system of Bus B had been operating for more than 310 hours. Both CO_2 air conditioning systems operated during summer 1997 without significant problems.

The carbon dioxide air conditioning systems were equipped with commercially available electronic expansion valves (see Fig. 3). These expansion valves were modified for the special carbon dioxide bus air conditioning application. Measurement data collected during 1997 showed that this type of expansion valve is able to maintain an almost constant evaporator superheat in spite of the significant variation of the compressor speed, and of the suction and discharge pressure. The expansion valve is well suited for highly transient operating conditions.

Fig. 4 shows the variation of the interior air temperatures of the two identical buses (Bus B and Bus C) for a typical summer day (August 5, 1997) in Bad Hersfeld, Germany. In addition, the variation of the ambient air temperature is also depicted in Fig. 4. At that day the maximum ambient air temperature reached about 28-30 °C (85 F). The particular design aim in Germany for the (comparatively low) cooling capacity of city bus air conditioning units is to maintain an interior air temperature that is only 2 to 3 K below the ambient air temperature. Hence, on hot summer days the control system does not influence the comparison of the two buses, because for high ambient air temperatures the air conditioning units run with 100 % cooling capacity all the time. It can be clearly seen in Fig. 4 that for most of the time there is no significant difference between the interior air temperatures of the two buses. It is interesting that the interior air temperature of Bus C exceeds the ambient air temperature between 2:00 p.m. and 3:30 p.m., probably due to an open hatch or door. A more detailed discussion of the data collected during summer 1997 is given in Köhler et al. [2]. This data show that the on-the-road behavior of the carbon dioxide air conditioning system is comparable to that of a standard HFC-134a-system.

LABORATORY PROTOTYPE FOR TRANSPORT REFRIGERATION

The laboratory prototype presented in this paper was designed as an independent truck refrigeration unit of about 4000 Watts cooling capacity in the electric mode. The unit has a separate Diesel engine with a generator. If electric power is available at the parking place the unit can be operated with an electric motor in order to reduce noise emission. The truck unit is a so called "split unit", which means that evaporator and expansion valve are installed in an insulated box, the cargo compartment. All other parts are placed usually outside in front of the box and above the truck driver's compartment. A more detailed description of the laboratory prototype can be found in Sonnekalb and Köhler [3]. Refrigerant and air temperatures were measured by thermocouples, and refrigerant pressures by transducers with semiconductor diaphragm pressure sensors. The cooling capacity was measured in a calorimeter test cell with a procedure based on the regulations of German Industrial Standard for testing cooling equipment for insulated means of transportation [4]. The evaporator and expansion valve were installed in an indoor simulation box. All other parts were placed in a room where ambient conditions were maintained. The insulated box was heated by electrical resistance heaters. All test data were recorded by a logging and processing system during a steady-state test period of about three hours. The indoor temperatures varied between -20 °C (-4 F) and 12 °C (54 F). The ambient temperature was set to 30 °C (86 F). The first data set was measured with a CO_2 system which was not equipped with an internal heat exchanger. The internal heat exchanger was installed in the CO_2 system for the second data set. Fig. 5 displays the measured cooling capacity and the COP of data set 2 compared to data set 1 which was set to 100 %. It can be clearly seen that the internal heat exchanger improves the cooling capacity considerably. On the other hand, the internal heat exchanger has no clear effect on the COP of the system. Additional measurements with ambient air temperatures of 38 °C (100 F) and 46 °C (115 F) indicated that for these conditions the internal heat exchanger also improves the COP of the system. These measurement data points are not shown in Fig. 5.

COMPRESSOR DESIGN

In order to achieve the necessary cooling capacity for a bus or coach using CO_2 instead of HFC-134a, extensive preliminary tests indicate that a compressor can be rated for approximately 60 to 100 cc displacement capacity, instead of approximately 400 to 650 cc for HFC-134a.

This results in a relative small compressor when the two-cylinder version is selected, in spite of the high operating pressures of less or equal 150 bar occurring in operation with CO_2. The only installation problems with this model in engine compartments of buses could occur with respect to its height. The compressor was developed as part of a research project. The whole design of this compressor (which is nearly ready for series production) takes particular account of the adverse operating conditions encountered in mobile air conditioning.

The development of the new compressor for refrigerant CO_2 is based on the test compressors used hitherto in various research projects and made up to now in two versions (version 1 and version 2 in Fig. 6, see Kaiser [5]). Due to the low pressure ratio and the high pressure difference with CO_2 as refrigerant the experiments showed in particular that

- a relative small piston diameter is required (the forces on the connecting rod bearing increase with increasing piston diameter),
- a longer stroke is of advantage (see Süß and Kruse [6]),

- several (4) piston rings are advisable (improved efficiency),and
- the chosen suction and discharge valve cross sections should be large enough.

In addition, the preliminary tests also indicated that when used for air conditioning purposes, CO_2 caused extreme erosion on the valve seats. To counteract this, the valve system in particular was modified from conventional one-sided (lamella) reed valves to concentric ring (annular) valves on both the suction and pressure side. This resulted in considerable improvement in the inner losses, as shown in the two measured indicator diagrams in Fig. 7 (see also Köhler et al. [2]).

In contrast to the first two versions (which had a piston diameter of 28 mm and a stroke of 49 mm) version 3 is designed for a piston diameter of up to 38 mm. A reinforced oil pump is better able to cope with the specific properties (high solubility because of high pressures) of various oils (e.g. mixtures of ester and alkyl benzol) and the refrigerant CO_2. The structure is rounded off by flat seals suitable for high-pressure compressors, together with a shaft seal specially rated for CO_2. The housing consists initially of globular cast (GGG), to be made of aluminum later. It is also important to mention that the CO_2 compressor in its final version will be considerably smaller than a comparable HFC-134a compressor (see also Sonnekalb and Köhler [1]).

CONCLUSIONS

On-the-road tests of two city buses equipped with transcritical refrigeration cycles using carbon dioxide as refrigerant showed no significant differences to buses equipped with conventional HFC-134a air conditioning systems. The total on-the-road running time of the two CO_2 air conditioning systems in 1997 exceeded 860 hours without any problems. Measurements with a laboratory prototype designed for transport refrigeration indicated that an internal heat exchanger improves the cooling capacity but has no significant effect on the COP for ambient air temperatures of 30 °C (86 F). In addition to that, the steps of the compressor design and optimization were presented. The CO_2 compressor in its final version will be considerably smaller than a comparable HFC-134a compressor.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support for parts of this work provided by "Deutsche Bundesstiftung Umwelt, Osnabrück".

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Fig.1: Three Public Transportation Buses in Bad Hersfeld, Germany (bus type, refrigerant, date of a/c installation, operating hours)

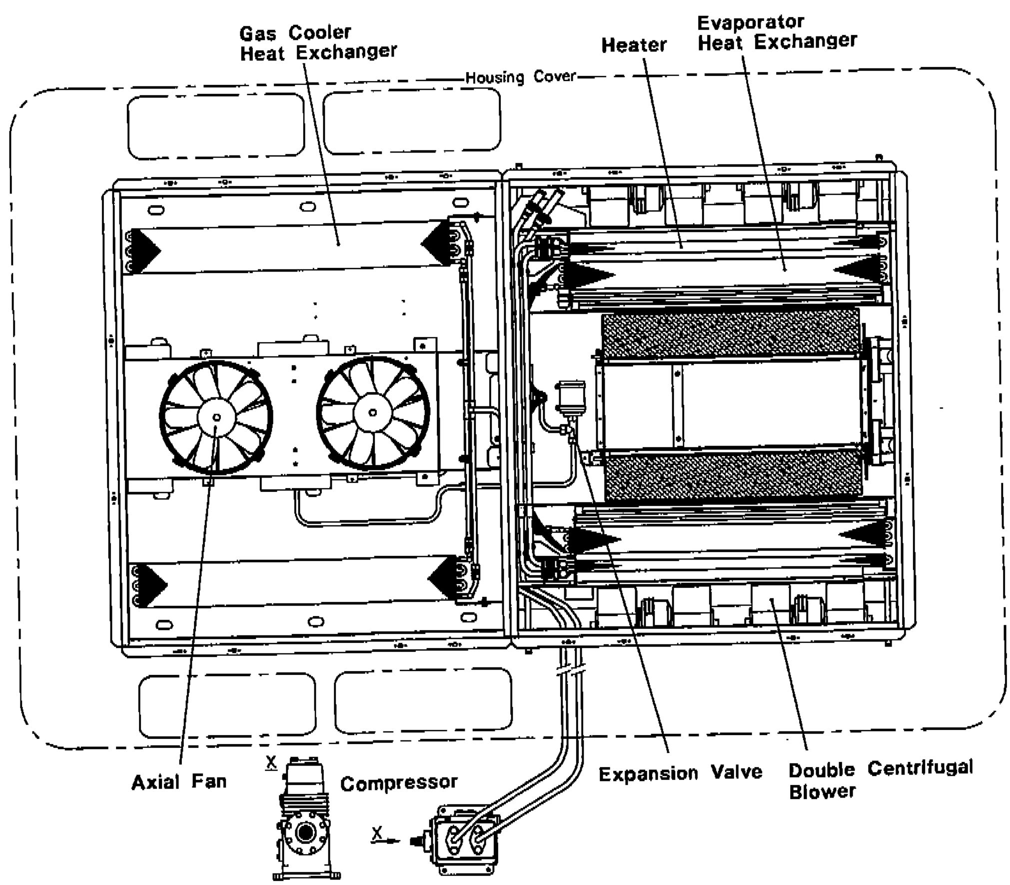

Fig.2: Plan View without housing cover of the Prototype Roof-Mount Bus A/C Unit

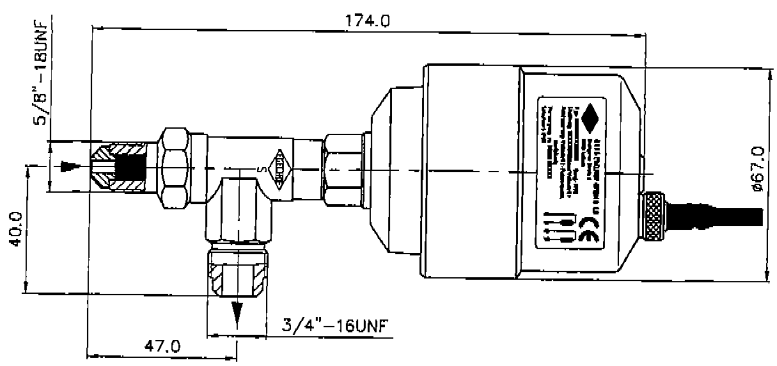

Fig. 3: Electronic Expansion Valve

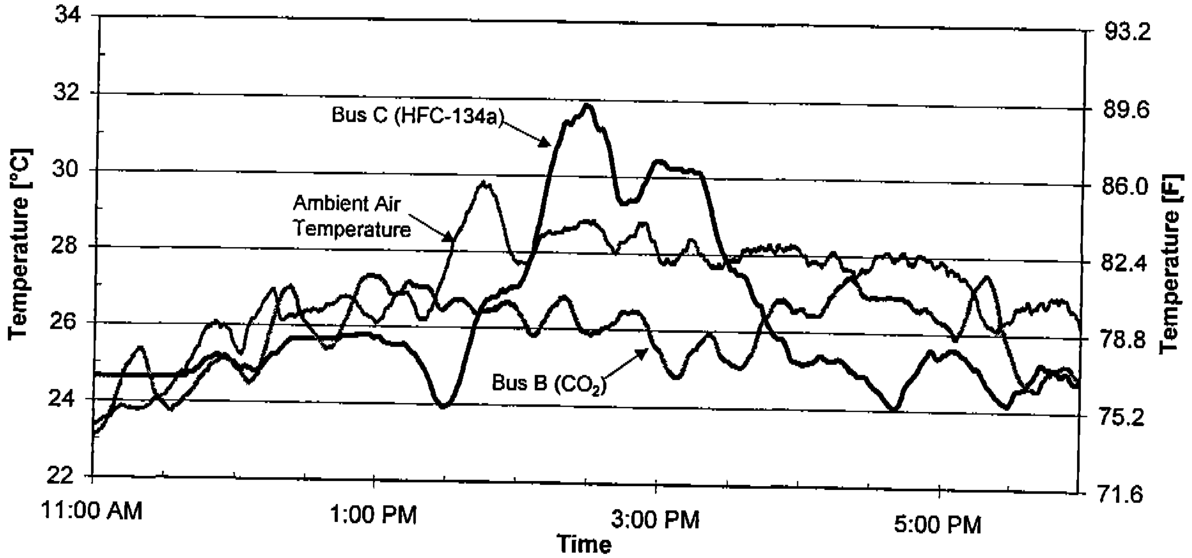

Fig. 4: Variation of the Interior Air Temperature of Bus B (Carbon Dioxide A/C System) and Bus C (Standard HFC-134a A/C System). Bad Hersfeld, August 05, 1997.

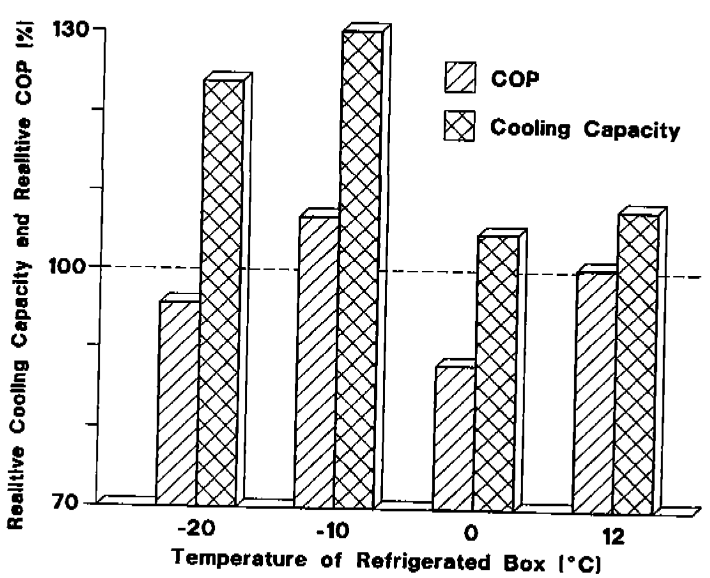

Fig. 5: Realitive COP and Realitive Cooling Capacity of the CO_2-System with Internal Heat Exchanger (Ambient Air Temperature t_{amb}=30 °C (86F), 100%=Cooling Capacity of System without Internal Heat Exchanger)

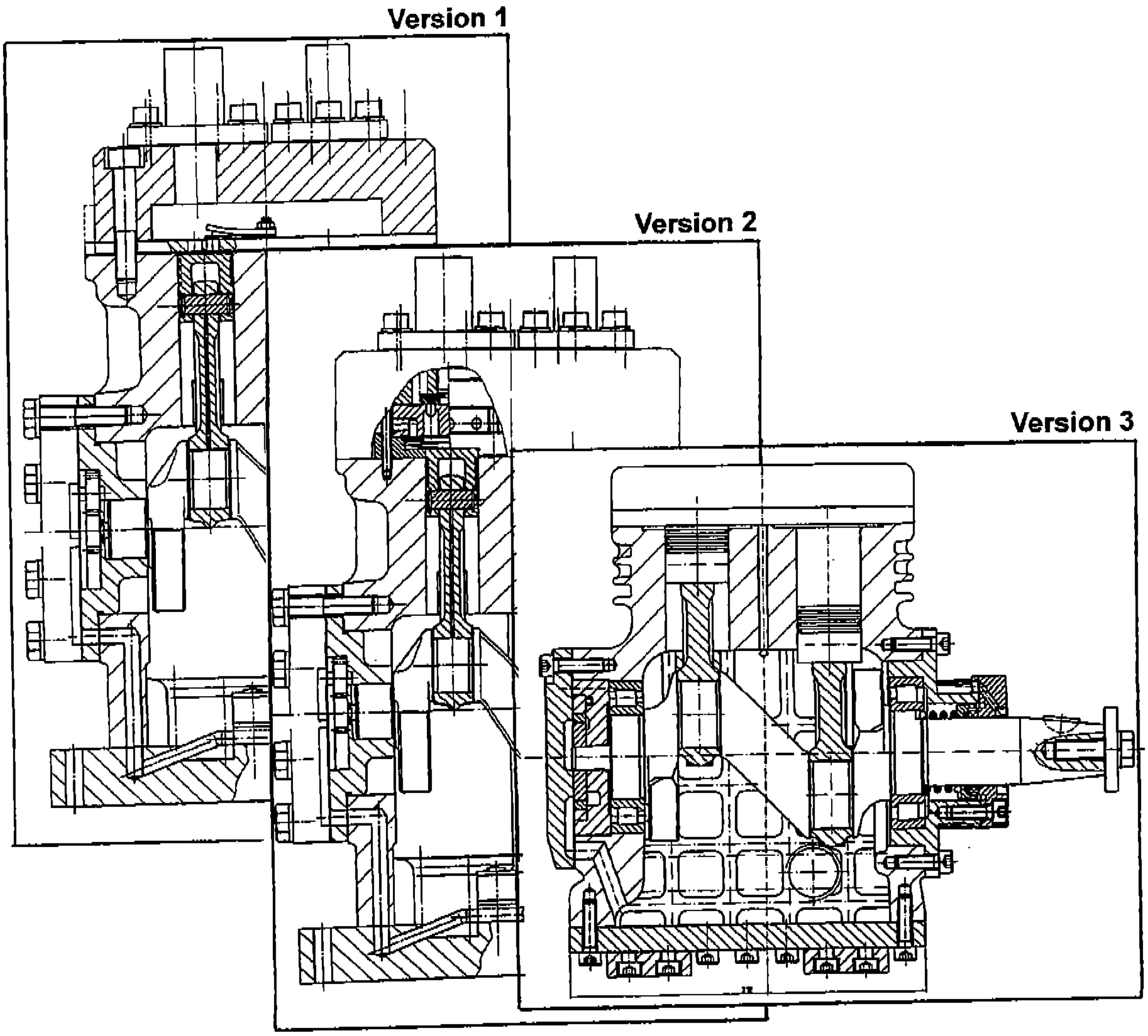

Fig. 6: Design Steps of Bock CO_2-Compressor.

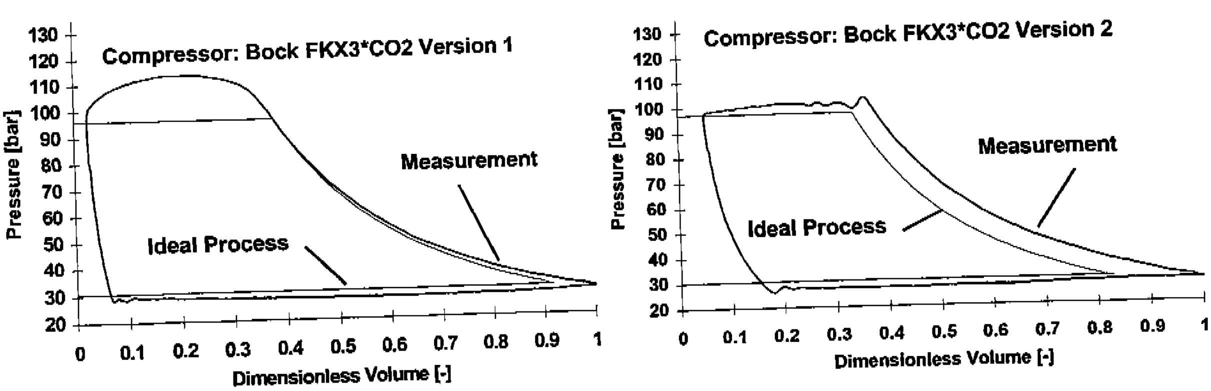

Fig. 7: Measured Indicator Diagrams.
Comparison between Version 1 and Version 2 of the Compressor BOCK FKX3*CO_2.
(Version 2 shows improvement in valve design.)