Modelling of a heating and cooling plant coupled to a hotel using HFC or CO_2 as a working fluid. Comparison of the performances.

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SUMMARY

Since ozone depleting substances were banned, HFCs have become the most common working fluids in refrigeration devices. However, these greenhouse gases are responsible for global warming and are likely to be banned by European directives. Interest is now being turned towards natural fluids such as CO_2. The Heating and Cooling Plant (HCP) is intended to produce domestic hot water (DHW) and to heat and cool residential and smaller office buildings. The HCP presents a special design of the refrigeration circuit and an innovative defrosting system. Two HCPs (CO_2 and HFC) coupled to a hotel have been modelled using TRNSYS software. Simulations show that CO_2 is less efficient. Nevertheless, this working fluid seems to be well suited to the operation of the HCP, because it enables to produce DHW at 55°C and because the high amount of energy recoverable by subcooling increases the efficiency of the defrosting system.

INTRODUCTION

Many buildings have simultaneous needs in heating and cooling. Typically, during summer, they face needs in cooling and in domestic water heating. During in-between seasons, from March to May and from October to November, rooms facing north have to be heated and rooms facing south have to be cooled, especially in buildings with significant glazed surfaces. In winter, only heating is required. The Heating and Cooling Plant (HCP) [1] is intended to satisfy the needs for domestic hot water production, space heating and cooling all year round and uses a special defrosting technique.
This article describes an innovative defrosting system for a Heating and Cooling Plant. This machine is coupled to a hotel whose needs in domestic water heating are quite substantial. It is assumed that the system uses either a hydrofluorocarbon (HFC) or carbon dioxide as a working fluid. As the two machines are quite similar, only the carbon dioxide type is described in this paper. Then annual simulations are run using TRNSYS software [2] for both plants and the results are compared and analyzed.

THE HEATING AND COOLING PLANT

Three heat exchangers

The CO_2 HCP (figure 1) has three heat exchangers: a condenser and an evaporator that heat and cool two water tanks for space heating and cooling and an exchanger that works either as a condenser or as an evaporator on ambient air to adapt production to needs. This last exchanger evacuates any excess cold produced in a heating mode and any excess heat produced in a cooling mode.

Three operating modes

The HCP works in three modes: a heating mode using the water condenser and the air exchanger as an evaporator; a dual mode preparing hot and cold water using the water heat exchangers; and a cooling mode using the water evaporator and the air heat exchanger as a secondary condenser. The cooling mode also integrates the production of domestic hot water by using the top part of the water condenser as a primary condenser.

An innovative defrosting technique

The water condenser is divided into three parts. The top part is used for domestic water preparation, the middle part is dedicated to the production of hot water for space heating and the lower part is connected to the cold water tank. During winter, this feature enables the storage of heat in the cold tank. The HCP alternates between heating mode and dual mode. In heating mode, the heat exchangers involved are the air evaporator and the three parts of the water condenser. The temperature of the cold tank rises to a maximum of 15°C. The fins of the air evaporator become frosted. The HCP then changes mode to operate in the dual mode. In this mode the fan of the air heat exchanger stops. The water evaporator and the top and middle parts of the water condenser are now involved. This allows for better COP by working on water as a source on both sides. A second advantage of the circuit design is that the defrosting system is automatic: after passing through the water condenser for domestic hot water production and space heating, the working fluid enters the air heat exchanger at a temperature around 35°C and is subcooled by exchange with the frosted fins. The cycle finishes on dual mode until the cold tank temperature decreases back to 5°C. Then the HCP switches back to heating mode and so on.

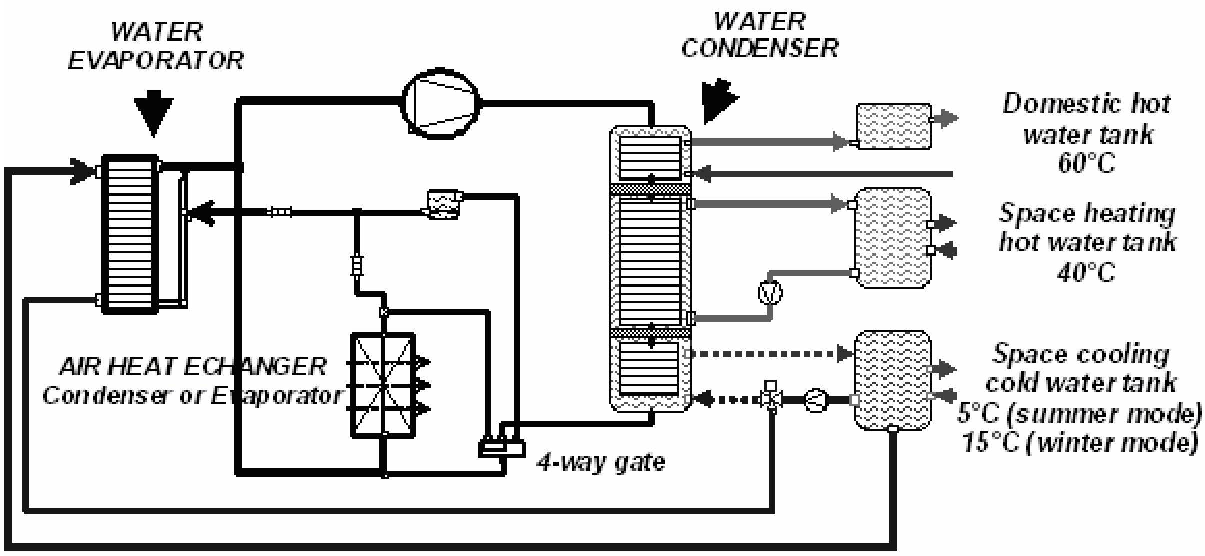

Figure 1. The Heating and Cooling Plant working with CO_2 as a working fluid

THE REFRIGERANTS

R407C

The choice of the refrigerant is linked to three criteria: performance, cost and security and environmental regulations.

Table 1. Characteristics and properties of some refrigerants

Fluid	CFC-12	HCFC-22	HFC-134a	NH_3 R-717	C_3H_8 R-290	CO_2 R-744
Natural substance	No	No	No	Yes	Yes	Yes
Molar mass (g/mol)	120,92	86,48	102,03	17,03	44,10	44,01
Volumic refrigerating capacity at 0°C (kJ/m^3)	2740	4344	2860	4360	3870	22600
ODP	1	0.05	0	0	0	0
GWP (100 years)	7100	1500	1200	0	0	1
Flammable?	No	No	No	Feebly	Yes	No
Toxic?	Feebly	Feebly	Feebly	Yes	No	No

Table 1 shows the most common fluids used until now in refrigeration. R12 is a chlorofluorocarbon (CFC) and R22 is a hydrochlorofluorocarbon (HCFC). Because of their impact on the ozone layer (Ozone Depletion Potential ODP $\neq$ 0), the sale of devices using these substances was banned in Europe in 2000 for CFCs and in 2004 for HCFCs [3] [4]. Widely used in mobile air-conditionning systems, R134a is one of the best performing HFCs however it has a high Global Warming Potential (GWP = 1200). Therefore these refrigerants are also likely to be banned in future by the European directive on F-gases. R407C is a HFC mostly used in heat pumps and air-conditionning for residential applications. Its GWP is 1503.

Carbon dioxide

According to Gustav Lorentzen, author of "Revival of carbon dioxide as a refrigerant" [5], CO_2 is today's best natural refrigerant as a substitute for HFCs. CO_2 is quite performant when used in transcritical cycles (Fig. 2). In such cycles the major problem is dealing with high pressures. Indeed for CO_2, low pressures are around 40 bars and high pressures can reach 120 bars. During heat rejection, the pressure of the refrigerant is above its critical value (73.8 bar for CO_2). This implies that there is no drastic change of phase at heat rejection. When the temperature decreases, supercritical gas progressively turns to supercritical liquid. The temperature of the fluid at the compressor outlet is between 70 and 100°C. The gliding temperature obtained at the heat rejection side enables the production of hot water at different temperatures as required for the HCP (Dosmestic hot water at 60°C and space heating water at 40°C). Producing DHW with a HCP R-134a would have required an auxiliary heater. The CO_2 transcritical cycle seems to suit residential and office applications selected for the HCP. Besides, the defrosting technique can also benefit from the good thermodynamic properties of supercritical carbon dioxide because of the high amount of energy created by subcooling.

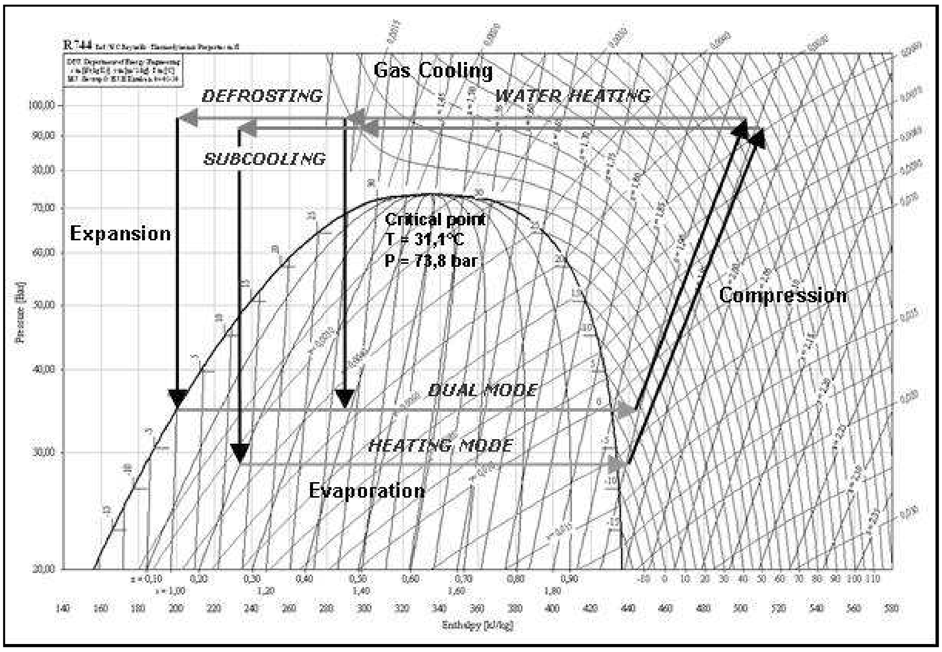

Figure 2. Transcritical cycles of carbon dioxide on the Mollier diagram

MODELLING HYPOTHESES

Building model

The building model is a hotel of 45 rooms where domestic hot water consumption is quite significant. Thermal zones, wall compositions, glazings, solar protections, ventilation et occupancy and light schedules are defined using the building module of TRNSYS so as to calculate the hotel's daily needs in heating and cooling. The simulations are run using a weather data file from Paris.

Heating and cooling plant model

The components of the system are also modelled using TRNSYS software. Simulations calculate the heating and cooling capacities and the coefficients of performance for the three operating modes (heating, cooling and dual mode) according to the ambiant temperature. The HCP is supposed to have a heating capacity of 100 kW in the heating mode for the base temperature of Rennes (-6°C). This capacity corresponds to a maximum operating time of 10 hours during the coldest day the year.

Operating strategy

The HCP is designed to work mainly in the dual mode as this is the most efficient. Then it works in the heating or the cooling mode depending on the needs of the building. When heating, the HCP alternates between the heating and dual mode. The cold tank temperature increases in the heating mode and decreases in the dual mode between 5 and 15°C. Time ratios were previously calculated in order to take into account the alternation of the two modes in the heating sequence with and without frosting (Equations 1 and 2). These ratios were supposed constant and are reported in Table 2. The ratios are different with and without frosting because when appearing the defrosting capacity is added to the heating capacity. To balance the higher heating capacity, the cooling capacity increases as well. Therefore the cold tank temperature decreases more quickly from 15 to 5°C.

$$r_{DM-noF} = \frac{dual\ mode\ time\ without\ frosting}{time\ of\ the\ heating\ sequence} \quad (1)$$

$$r_{DM-F} = \frac{dual\ mode\ time\ with\ frosting}{time\ of\ the\ heating\ sequence} \quad (2)$$

Table 2. Time ratios in heating sequences

Time ratio	CO_2	R407C
r_{DM-noF}	0.28	0.15
r_{DM-F}	0.25	0.12

A third time ratio was calculated to estimate the time of frosting conditions during each day of the year (Equation 3).t is assumed that frost appears when the ambient temperature is beyond 7°C.

$$r_{T<7°C} = \frac{Number\ of\ hours\ with\ T_{amb} < 7°C}{24} \quad (3)$$

Operating times per mode

Dual mode is the first mode until the minimum need is satisfied (Equation 4). The right-hand member is due to the alternation between dual and heating mode during a heating functioning.

$$t_{DM} = \min\left(\frac{q_h}{Q_{hDM}}, \frac{q_c}{Q_{cDM}}\right) + \left[r_{T<7°C}.r_{DM-F} + \left(1 - r_{T<7°C}\right).r_{DM-noF}\right] \times \left[\frac{q_h}{Q_{hHM}} - \min\left(\frac{q_h}{Q_{hDM}}, \frac{q_c}{Q_{cDM}}\right)\right] \quad (4)$$

where q_h is the daily need in heating, q_c, the daily need in cooling, Q_{hDM}, the heating capacity in dual mode and $_{HM}$ stands for heating mode.

In heating mode, the real operating time is the time needed to cover all the heating needs minus the dual mode time (Equation 5).

$$t_{HM} = \frac{q_h}{Q_{hHM}} - t_{DM} \quad (5)$$

In cooling mode, the real operating time is the time needed to cover all the cooling needs minus the time dedicated to cooling of the dual mode (Equation 6).

$$t_{CM} = \frac{q_c}{Q_{cCM}} - \min\left(\frac{q_h}{Q_{hDM}}, \frac{q_c}{Q_{cDM}}\right) \quad (6)$$

where $_{CM}$ stands for cooling mode.

Coefficients of performance

The daily and annual coefficients of performance are calculated in proportion to the operating times.

RESULTS AND DISCUSSION

Building simulation

The annual simulation of the 45-room hotel (Figure 3) shows the evolution of heating and cooling needs all year round. Annual needs amount to 25322 kWh in DHW production, 68640 kWh in space heating and 30146 kWh in cooling. Paris is situated in a temperate climate where heating needs are higher than cooling needs. It can also be pointed out that during in-between seasons heating and cooling needs appear simultaneously. During summer the plateau in the heating curve corresponds to the hot water production that is nearly constant. From the end of April to the end of October hot and cold productions are simultaneous during at least a few hours day.

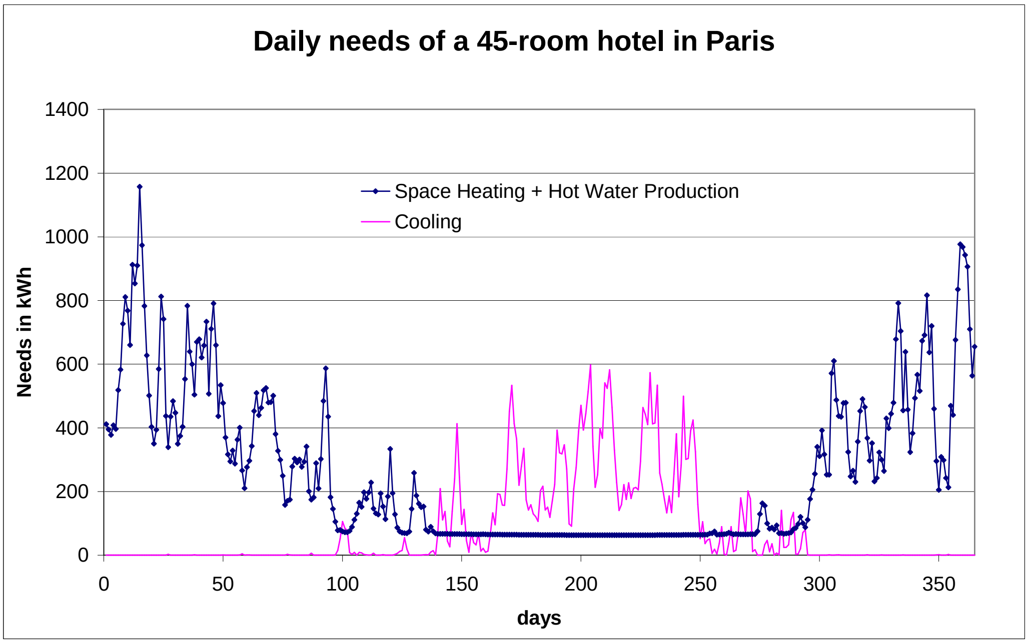

Figure 3. Evolution of daily needs in heating and cooling of a 45-room hotel in Paris

Operation times

Operation times per mode to satisfy the needs of the building are calculated and reported in table 3. Performances of carbon dioxide being lower the total operation time is greater. The weaker cooling capacity of CO_2 implies an increase in the cooling mode time whereas in heating mode the weaker performances are balanced by an increase in the dual mode. This is due to the better time ratio between dual and heating mode during winter. These values show that in spite of its poorer performance CO_2 as a working fluid better suits the modal operation technique of the heating and cooling plant.

Table 3. Comparison of the operation times per mode

Operation times	R407C	CO2
Dual mode	134.7 h	244.4 h
Heating mode	543.5 h	513.0 h
Cooling mode	127.2 h	291.1 h
Total	805.4 h	1048.6 h

Coefficients of performance

These graphs on figure 4 show clearly that CO_2 has a lower COP for space heating and cooling than any HFC. The curves record a serious increase during in-between seasons, and summer especially for R407C. For carbon dioxide the performances in cooling are not as good as in heating. So when cooling demands are important, the average COP goes down. Annual COPs are near their value in winter because the operation times are higher in the heating period for the climate of Paris.

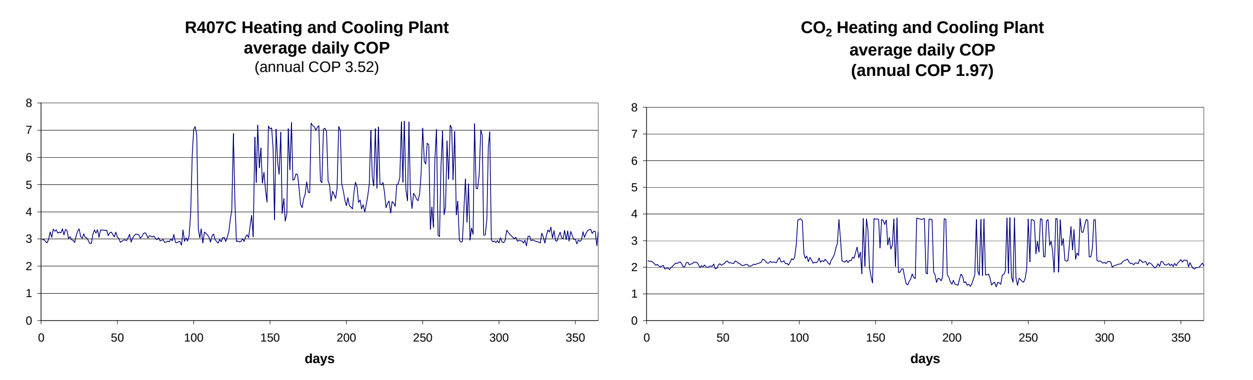

Figure 4. Comparison of daily coefficients of performance between R407C and CO_2

In addition the results of the HCP can be compared to the ones of a classic reversible heat pump (Table 4). The decrease of the performances due to carbon dioxide is less for the HCP than for the reversible heat pump. By another way, replacement of a standard heat pump by a HCP leads a better increase with carbon dioxide than with a HFC.

Table 4. Comparison of annual COPs of HCPs and reversible heat pumps

Fluid	R407C	CO2	Decrease
Reversible Heat Pump	3.18	1.58	-50.4%
Heating and Cooling Plant	3.52	1.97	-43.9%
Increase	10.7%	25.1%	

CONCLUSIONS

Today, HFCs are the most efficient “secure” fluids on the market. Unlike these greenhouse gases, carbon dioxide is environmentally friendly but is about 50% less efficient. CO_2 technology needs more development to be competitive in space heating and cooling applications. Nevertheless its thermodynamical properties allow domestic hot water production. It is an option to explore for the CO_2 HCP. The new defrosting technique for heat pumps noticeably increases average performance in heating mode, and increases more with high subcooling capacity.

The model presented here show how this Heating and Cooling Plant can satisfy the needs in heating, cooling and domestic hot water production of a hotel of 45 rooms situated in Paris. The HCP records better annual performances by between 10 and 25% and could even be improved with carbon dioxide for lower cooling needs obtainable in Northern countries such as Finland.

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