TEWI ANALYSIS OF HIGH-TEMPERATURE RESIDENTIAL HEAT PUMPS

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ABSTRACT

Heat pump for residential heating constitutes a key technology to lower CO_2 emissions associated with building heating. The heat pump system capable to replace the current fuel or gas burner heating system needs to provide heat at a high condensing temperature (around 55°C) in order not to change the hydronic network. The heat pump system needs also to provide 100% of heating capacity even for low outside temperature, for Europe typically –15°C.

The paper presents a new design of a variable capacity heat pump capable to provide heat at such a high level of temperature by using variable composition blends, and a two-stage system.
The seasonal energy efficiency is calculated and a comparison is performed with the current heating system using fuel or gas in order to forecast the gains in terms of CO_2 emissions for European climatic conditions and different generation mixes.

Key Words: ***heat pumps, high temperature, residential, seasonal energy efficiency.***

1 INTRODUCTION

Heating floor heat pumps is the usual technology installed for new systems in the residential sector. This technology delivers heat at low temperature due to large heat exchange surface; the maximum condensing temperature is of 35 °C. Taking into account the CO_2 emissions coming from gas-fired or fuel boilers a new technical option of interest consists in replacing old boilers by high-temperature heat pump (HTHP). The condensing temperature level depends on the radiator technology and may vary from 55 up to 75 °C. One of the challenges is also to provide 100% of the heating needs at the lowest outdoor temperature and to provide service hot water (SHW) all along the year. One technical option is to develop reversible heat pump for cooling in summer and heating in the cold season. Currently in France the share between electrical, gas, and fuel heating is roughly one third each. The total number of individual houses is approximately around 11 million. This paper aims to evaluate the gain in CO_2 emissions by switching from boilers to HTHP.

2 HEAT PUMP DESIGN AND HEATING NEEDS ACCORDING TO OUTDOOR TEMPERATURE

For weather conditions in France, the lower outside temperature is taken at – 15°C meaning an evaporating temperature of about –20°C. The larger difference of temperatures between source and sink is so of 80 K leading to a new design for residential heat pump.

Fig. 1 shows one of the possible design of a two-stage system where a fraction m_2 of the total mass flow rate m_1 is evaporated in a sub-cooler in order to sub-cool the complementary mass flow rate m_3. The vapour formed in the sub-cooler is reintegrated between the two compressors at the intermediate pressure. This design has been chosen in order to make an easy switch from the 2 staged system to a single stage one.

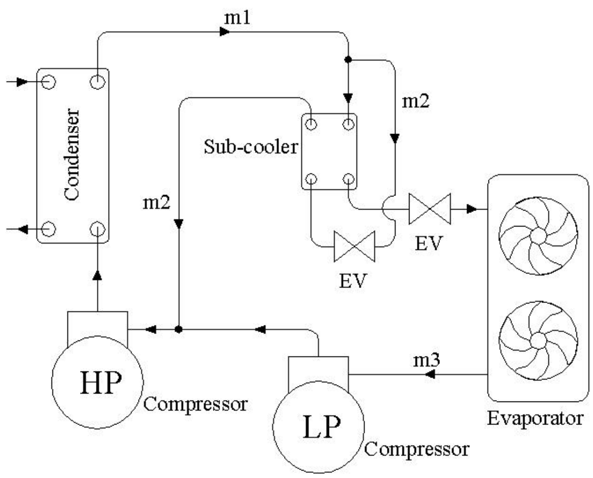

Fig. 1. Two-stage compressor system.

The hourly repartition of temperatures for one of the coldest region in France, Nancy is shown in Fig. 2. It can be seen from this figure that the occurrence of outdoor temperature lower than –12°C represents only 0.1 %. Nevertheless, this lowest temperature represents a design point for the maximum heating capacity and the maximum temperature difference between source and sink. Complementary analysis shows that 50 % of the heating needs are met between –0 and +6°C.

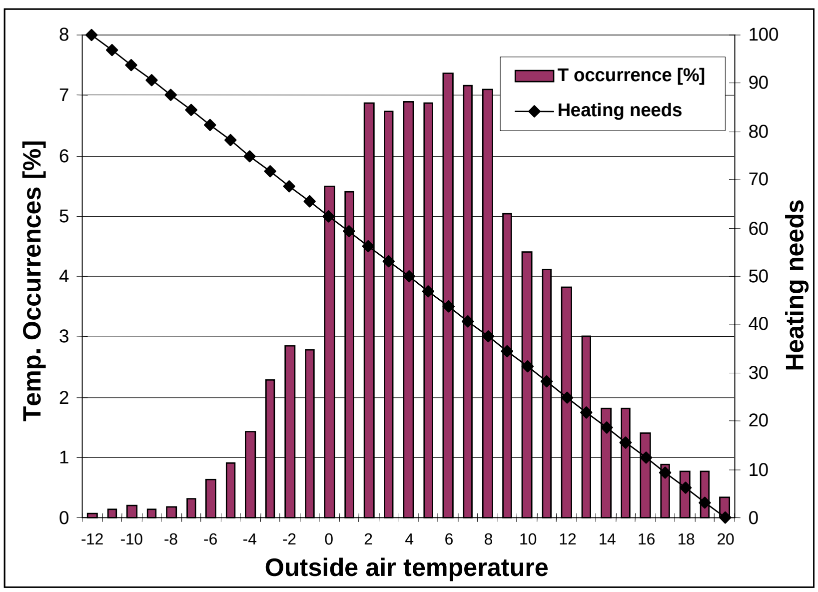

Fig. 2. Heating needs and temperature occurrences in Nancy (France).

Two different constraints have to be taken into account: variation of heating capacity depending on outdoor temperature and variation of energy efficiency depending on the difference of temperature between source and sink. In order to provide the heating capacity at the lowest temperature a two-stage architecture system is needed, and for the most frequent temperature occurrences the efficiency of the system needs to be carefully studied in order to reach a high seasonal energy efficiency. Calculations and tests are needed to analyse when a two-stage systems is less efficient than the single-stage one.

3 SYSTEM EFFICIENCY DEPENDING ON THE OUTDOOR TEMPERATURE

A first design consideration is to vary the temperature of the hydronic network at the outlet of the condenser heat pump. The so-called "water law" makes a direct relationship between the outdoor air temperature and the water delivery temperature. An example of such a law is given in Fig. 3 where the water delivery temperature at the condenser outlet is of 62°C for an outdoor temperature of –20°C, and for an outdoor temperature of 10°C, the water delivery temperature is of 35°C.

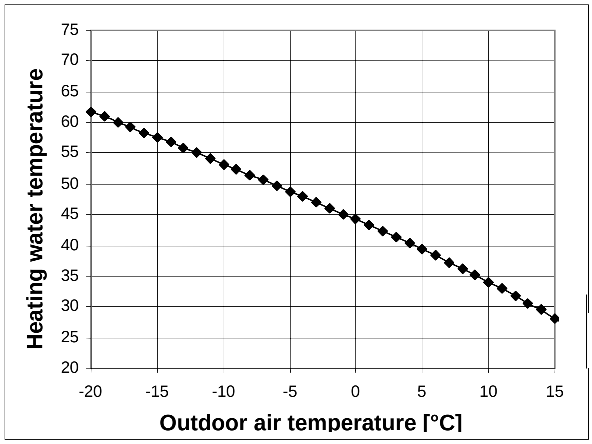

Fig. 3. Variation of water delivery temperature as a function of outdoor air temperature.

The control of the water delivery temperature allows significant energy savings due to the COP improvement when the condensing temperature is lowered when the heating needs are also decreasing. Based on this control system, a detailed study has been performed in order to define when the two-stage system has a higher COP compared to a single-stage system.

4 COMPRESSOR AND REFRIGERANT CHOICES

Taking into account an average condensing temperature of 60°C, the condensing pressure with R-410A is of 3.8 MPa, and the availability of R-410A compressors is currently low in Europe, whereas for R-407C the condensing temperature is about 2.65 MPa and the compressor availability in term of type and swept volume is large. The choice that has been made is R-407C, choice which is also related to the possibility of composition variation.

For a two-stage system, it is well known that the equality of the pressure ratios of the low and high compression stages corresponds to the optimal efficiency zone. Taking into account this selection criterion and making the related calculations, it appears also that the swept volume V_{HP} of the high-pressure compressor has a fixed ratio with the swept volume of the low-pressure compressor V_{BP}:

$$\frac{\dot{V}_{HP}}{\dot{V}_{BP}} = 0.5$$

Based on the available compressors on the European market, the following two swept volumes have been chosen, 8 m^3/h for the high-pressure compressor, and 17 m^3/h for the low-pressure one. Fig. 4 shows the variation of volumetric and global efficiencies of these two compressors as a function of the pressure ratio. These figures indicate that the compressors have been optimized for a pressure ratio in the range of 3, and that the LP compressor (17 m^3/h) is significantly more energy efficient than the HP compressor (8m^3/h).

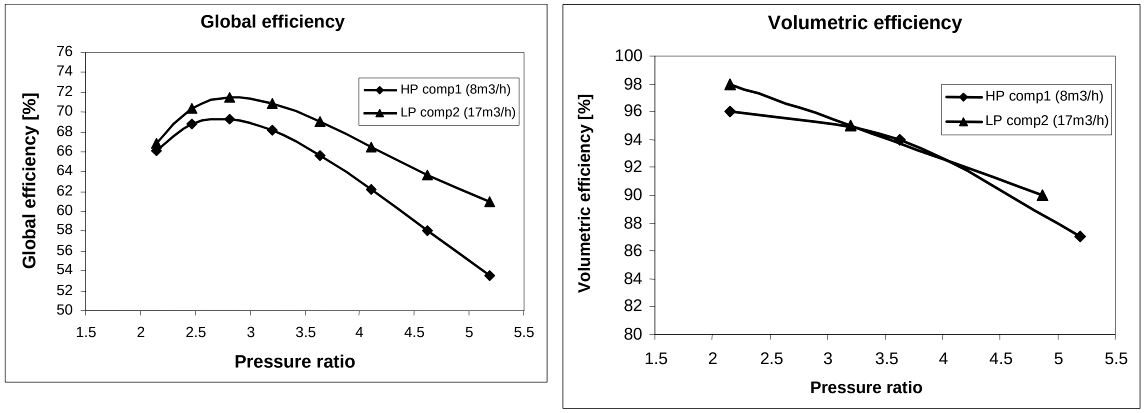

Fig. 4. Global and volumetric efficiencies of the two compressors.

Taking into account these efficiencies of the chosen compressors in single-stage or two-stage operation, simulations and extensive tests on a prototype have permitted to analyze both the heating capacity of the single-stage and two-stage systems as well as the energy efficiency. With a constant delivery water temperature of 55°C at the condenser outlet, Fig. 5 show that with a constant temperature water supply the global efficiency is varying between 2 and 3, which is no satisfactory.

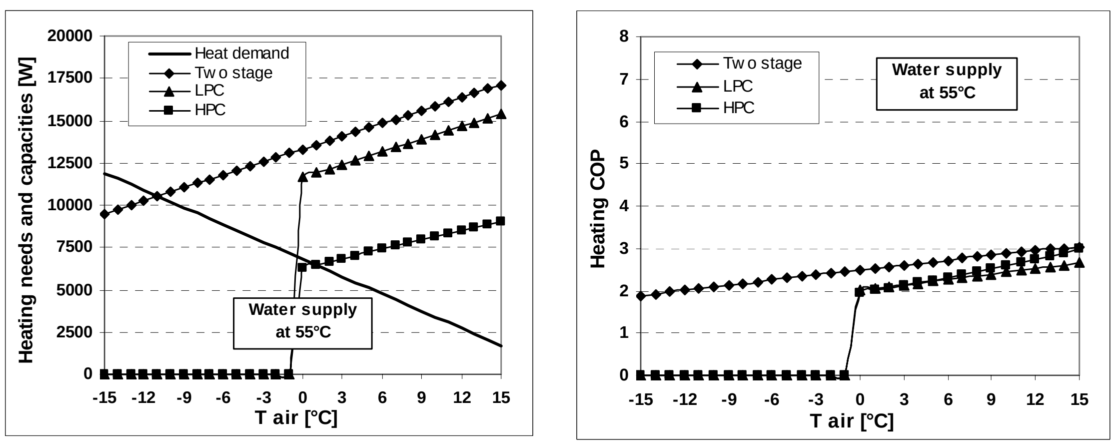

Fig. 5. Variation of heating capacity and COP at a constant 55°C water temperature supply.

When using the variation of water delivery temperature depending on the outdoor temperature, the COP improvement is quite significant varying from 2 to 6.3 (Fig. 6).

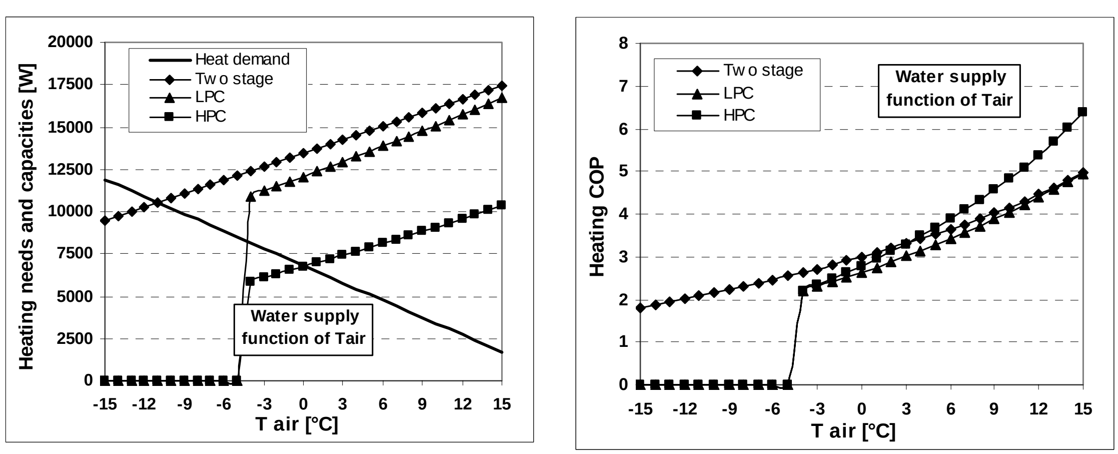

Fig. 6. Variation of heating capacity and COP with a water temperature supply depending on the outdoor temperature.

Fig. 6 shows that even if the larger compressor (LPC) is more efficient than the small one (HPC) when running as a single compressor, the efficiency is slightly higher with the small compressor. This behavior is related to the increase of efficiency of heat exchangers when working with a smaller mass flow rate (i.e. the smaller compressor).

Fig. 6 shows also that for an outdoor temperature varying

- from –11 to –5°C the two-stage system is necessary
- from – 5 to 0°C, the larger compressor (LPC) will run alone, and then
- from 0 to 14°C, the smaller compressor (HPC) will run alone.

Nevertheless at a temperature lower than –11°C, the heating needs are higher than the heating capacity and so a complementary solution needs to be developed.

As it will be shown in the next paragraph, it is possible to keep the same compressor choice by controlling the circulating composition of R-407C.

5 COMPOSITION VARIATION OF R-407

A number of possible technical options exist for composition control of refrigerant blends as R-407 where the normal boiling point of one of the components is significantly different from the others [Kuz00, Mas94].

Table 1. Normal boiling points of the three components of R-407.

Fluid	R-32	R-125	R-134a
Normal boiling point (°C)	-51.7	-48.1	-26

Note: R-407 means the series of blends that can be realized based on the three components R-32, R-125, R-134a with any types of concentration.

Fig. 7 is a diagram allowing the study of the variation of capacity, COP, and flammability of different blends using the three basic refrigerants R-32, R-125, R-134a. The parallel lines drawn in front of each top of the triangle means iso-composition of the given component in the blend.

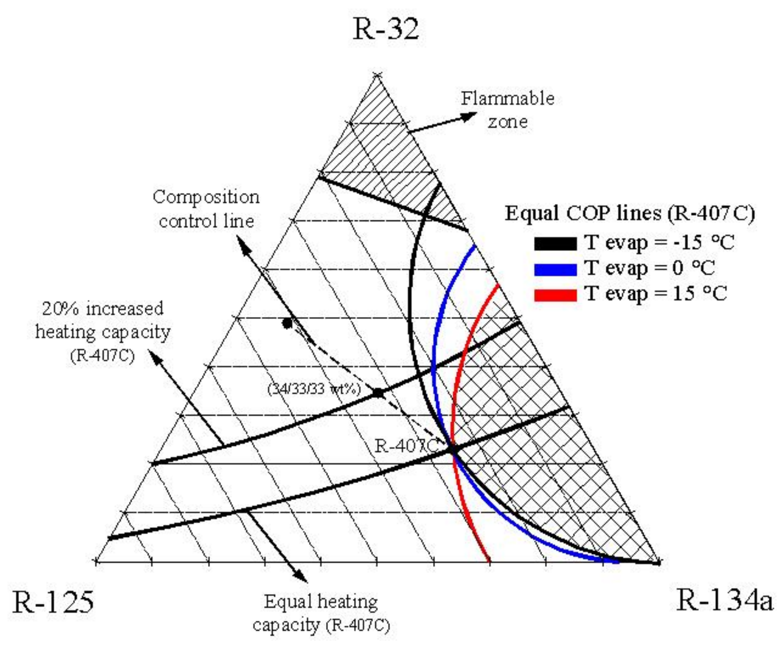

Fig. 7. Variation of heating capacity and COP within a ternary blend composition diagram.

A first line (equal heating capacity) shows blend compositions of R-407 with heating capacity equal to the one of R-407C. A second line has been calculated in order to increase the heating capacity of 20 %, which is needed to fulfil the heating needs at –15°C. One of the possible composition is R-32/R-125/R-134a (0.34/0.33/033 w%). The enriched composition in low NBP components (R-32/R-125) increases the heating capacity but also the evaporating and condensing pressures.

For this composition the COP is decreased of about 2 to 3.5 % (depending on evaporation temperature) compared to R-407C.

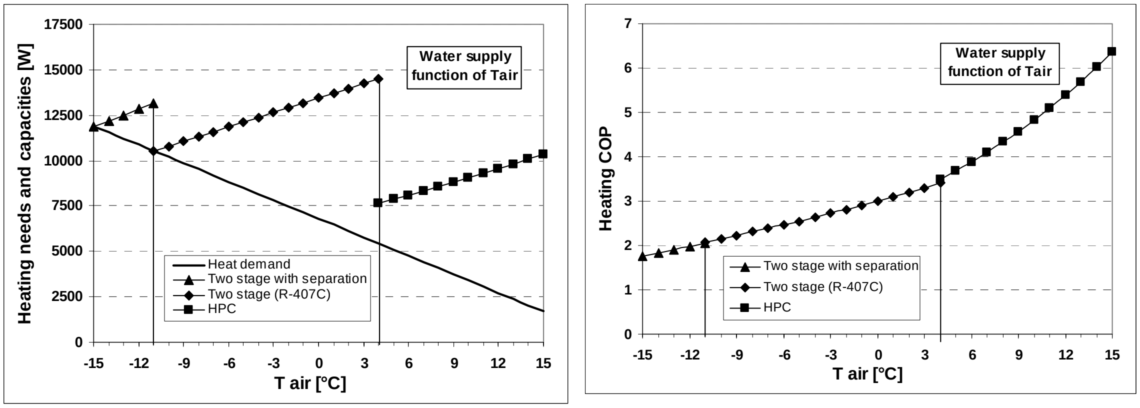

Fig. 8. Variation of the heating capacity and COP as a function of composition variation at low temperature (-11 to –15°C).

Fig. 8 show that the heating needs can be fulfilled with 3 successive strategies using composition variation for low temperature, then using a two-stage compression, and then using a single-stage compression. This design permits to fulfill both the heating capacity requirements and high seasonal efficiency.

6 IMPACT IN TERMS OF CO_2 EMISSIONS

Table 2 summarizes the key parameters of heating needs and the electrical consumption of the HTHP including the auxiliary consumption. Globally for the Nancy region the seasonal energy efficiency is 3.1. For other French regions the seasonal efficiency varies from 3 to 4.2.

Table 2. Heating needs and electrical consumption of High temperature heat pump (HTHP).

Annual heating time (hours)	6136
Heating needs (kWh)	30057
Electrical consumption of compressor along the season (kWh)	8926
Electrical consumption of fans (kWh)	581
Stand-by electrical consumption (kWh)	158
Total electrical consumption (kWh)	9664
Operation time (%)	47.9
Seasonal COP	3.11

Table 3 summarizes the fuel and gas CO_2 emissions of boilers depending on the boiler efficiency.

Table 3. Fuel consumption of boilers depending on the boiler efficiency.

Boiler efficiency	1	0.8
Seasonal CO_2 emissions for fuel (kg CO_2)	9318	11647
Seasonal CO_2 emissions for gas (kg CO_2)	8416	10520

Taking into account an annual emission of R-407C refrigerant of 10 %, which is a realistic value (Toc02), Fig. 9 shows that the strong dependence of CO_2 emissions related to the electricity generation mix. Calculations have been successfully performed for a CO_2 emissions per kWh varying from 50 g/kWh up to 800 g/kWh. The winter generation mix in France is of about 200 kg of CO_2/kWh.

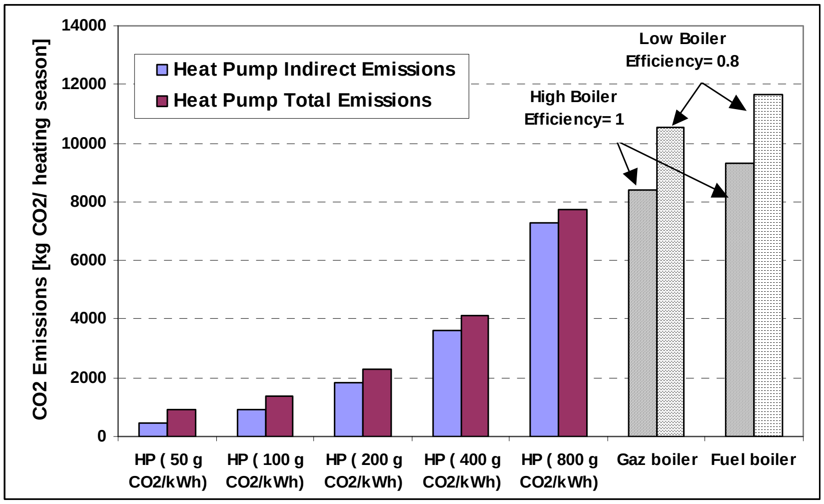

Fig. 9. TEWI of heat pump and boiler depending on the CO_2 emissions of the energy mix.

Fig. 9 shows that for countries where renewal energy or nuclear energy has a significant sharing, the impact of the replacement of old boilers by efficient heat pumps permits to avoid very significant CO_2 emissions.

6 CONCLUSIONS

Possible new designs of residential heat pumps using a concept of two-stage compression for low temperature switching to a single-stage compression when the outdoor temperature is above +4°C permits to develop high efficiency heat pump even with an average condensing temperature of 60°C.

Moreover, the use of refrigerant blends such as R-407C allows a concentration variation that increases the heating capacity at low outdoor temperature. Significant research work is still needed to improve the seasonal energy efficiency of this promising new concept of residential high temperature heat pump.

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