Air-source heat pumps with refrigerant mixtures for cold climates

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Abstract: Heat pumps represent the only end-use heating technology that has coefficient of performance greater than one. However, the efficiency of air-source heat pumps decreases drastically at low cold source temperature which represents a higher barrier to their adoption in cold climates. The use of mixtures of refrigerants with the aim of increasing the COP and heating capacity at lower temperatures by taking advantage of the thermal glide is an option that has been little studied so far. The main goal of the present study is to find a refrigerant mixture properly selected so that it enables good heating performance at low temperatures. This mixture must have desirable thermophysical properties but also it must be non-toxic, non-flammable, oil soluble, and have low GWP. Currently, there is no acceptable pure refrigerant that satisfies all these requirements. In this paper we will present a methodology used for selecting appropriate mixtures, preliminary results, and potential gains for cold climate heat pumps.

Key Words: heat pumps, refrigerant mixtures, cold climate, zeotropic mixtures

1 INTRODUCTION

Heat Pumps are a technology that can make a significant contribution to energy conservation. However, unlike fuel boilers or electric heaters, the efficiency of air-source heat pumps varies significantly with ambient temperature levels. When there is a high temperature difference between the cold source and the heat sink, the capacity and the Coefficient of Performance (COP) of the heat pumps fall drastically. This is a major problem for air-source heat pump applications in cold climates.

Refrigerants as a means of transferring heat between heat sources and heat sinks have been widely used since Jacob Perkins in 1834 invented the first vapor-compression cycle. Until the 1930s, the primary refrigerants used were ammonia, methyl chloride, and sulphur dioxide. Pictet, 1885 applied a volatile liquid which could split-up into two or more volatile liquids; this can be considered as a first use of mixtures as a refrigerant. A more detailed literature review on refrigerants is presented by Calm and Didion, 1898.

The use of mixtures of refrigerants with the aim of increasing the COP and heating capacity at lower temperatures by taking advantage of the thermal glide is an option that has been little studied so far. Higher heat pump performance can be achieved by approaching the conventional heat pump cycle to the Lorenz cycle. More exactly, a performance improvement is obtained by having a temperature variation during the constant pressure condensation and evaporation, rather than a constant temperature in conventional cycles. This improvement is mainly achieved by decreasing heat transfer irreversibilities in the heat exchangers, as a result of reducing the thermal pinch.

The main goal of the present study is to find a zeotropic refrigerant mixture properly selected so that it enables good heating performance (capacity, COP) at low temperatures for heating applications. This mixture must require minimum changes in the system components of

conventional residential heat pumps. Besides having desirable thermophysical properties, it must be non-toxic, non-flammable, oil soluble, and have low GWP. Currently, there is no acceptable pure refrigerant that satisfies all these requirements. In this paper, a methodology used for selecting appropriate mixtures, preliminary results and potential gains for cold climate heat pumps are presented.

Over the past 20 years, developments in the field of refrigerants have been limited to finding suitable substitutes for CFCs and HCFCs in response to the Montreal Protocol and re-introducing natural refrigerants (hydrocarbons, ammonia, CO_2) in response to the Kyoto Protocol.

McLinden, 1987 presented a simplified model to provide performance ratings of refrigerants and refrigerant mixtures operating in vapor compression cycle called Cycle 7. His model consists of seven cycle state points. This cycle was subsequently improved by adding more states through a suction-line heat exchanger and a change of the compressor model. This new model was called Cycle 11 (Domanski P.A. and McLinden M.O., 1992). Pannock J. and Didion D.A., 1992 applied Cycle 11 to investigate the best possible binary zeotropic refrigerant mixture as a replacement of R-22 for residential heat pump applications. They found that the mixtures of R-32/R-134A and R-32/R-152A perform better than R-22 with respect to COP and volumetric capacity for a certain composition range and using a counter-flow heat exchanger.

Rice C.K., 1993 developed a simplified model called BICYCLE for simulation of the pure and mixed refrigerants in order to evaluate R-22 alternatives. Four different refrigerant mixtures from small to large temperature glide were selected for evaluation. He assumed the same air flow rate, UA values and sensible heat ratios as for R-22 in his simulations, and only the compressor displacement was adjusted to obtain the same design capacity. He concluded that the potential of COP gains are 1.5 to 2 times larger in cooling mode than in heating.
Haselden G.G. and Chen J., 1994 developed a simulation program for mixed refrigerant air conditioning. They stated they were the first to develop a complete mixed-refrigerant simulation model. They neglected the pressure drop in the superheated vapor and subcooled liquid flow. Moreover, they did not consider the volumetric efficiency of the compressor in their simulations. The volumetric efficiency is an important factor in determining the refrigerant mass flow rate and accordingly the system performance at different working conditions.

Ragazzi F. and Pederen C.O., 1995 studied the thermodynamic optimization of various evaporator designs with zeotropic refrigerant mixtures using an irreversibility-based function. Their main goal was to find a replacement for R-22. They showed that the zeotropic mixtures are less irreversible than the pure refrigerants with cross-counter-flow heat exchanger.
Bensafi A. et al., 1997 developed a computational model for the detailed design of plate-fin-and-tube heat exchangers using pure and mixed refrigerants. They predicted the pressure drop with the error of the order of 30%, and heat transfer rates were predicted with discrepancies less than 3%.

Maczek K. et al., 1997 investigated ternary zeotropic mixture of CO_2/R-32/R-134A as a possible alternative to R-22. They found that the mixture with mass fraction of 7/31/62 increases both the COP and capacity by 2.5% and 18.6% respectively. A comprehensive review on recent developments in new refrigerant mixtures for heating and cooling applications is presented by Mohanraj et al., 2011.

This paper represents a part of a larger research project, regarding application of refrigerant mixtures in cold climate residential heat pumps. In this study, a detailed screening heat pump model previously developed (Hakkaki-Fard A. et al., 2014) is applied to investigate the performance of a group of selected refrigerant mixtures in different working conditions in

order to find a suitable refrigerant mixture for residential cold climate applications. The current paper compares different refrigerant mixtures in the current-current flow and cross flow heat exchangers to find a suitable refrigerant for residential applications. Moreover, the selected refrigerant from the first part is compared to a refrigerant with higher temperature glide in colder working conditions, in a heat pump cycle with internal heat exchanger to assess their performance in such a condition.

2 Simulation model

A numerical model for detailed simulations of air-source heat pumps compatible with both pure and mixed refrigerants is applied. In order to make the calculations simple, the following assumptions are made:

- Steady-state flow conditions.
- One-dimensional flow for the refrigerant inside tubes and air across the coils.
- Negligible heat losses to the environment.
- The flow across the expansion valve is isenthalpic.

The scroll compressor is considered in simulations. Both cross and counter-flow heat exchange are compared. Each component is divided in a number of control volume elements. Fundamental conservation equations of mass, momentum and energy, based on the corresponding correlations (Hakkaki-Fard A. et al., 2014), are applied to each control volume element. The system of the equations obtained, is non-linear and parameters are strongly linked; therefore, an iterative method is applied. A separate subroutine is developed for each component calculations. The code is developed in the FORTRAN language. The REFPROP program subroutines, version 9.0 (Lemmon E.W., 2013) are linked to the present code to calculate the thermodynamic properties of the refrigerants and the air. More details regarding the model and the code are given in Ref. (Hakkaki-Fard A. et al., 2014).

The required input data of the program are:

- Pure refrigerant or refrigerant mixture type and its composition.
- Evaporator and condenser inlet air temperatures and their flow rates.
- Evaporator and condenser specifications (type, size, number of rows, sub-cooling, super-heating …).
- The compressor specifications (efficiency, speed, clearance volume ratio …).
- Number of computational sections for each component.

The outputs of the simulation program would be:

- The pinch values of the heat exchangers.
- Refrigerant and air states at any point in the cycle.
- The thermophysical performance of the system in terms of Coefficient of Performance (COP), capacity…

A gradient based optimization method is used to update the iterations in order to speed up the convergence of the program. The heat transfer coefficients predicted by the model are validated in Ref. (Hakkaki-Fard A. et al., 2014) with available data in the literature.

The coefficient of performance (COP) of a heat pump is the ratio of the heat delivered to the overall power consumption of the cycle, and is defined as follows:

$$COP = \frac{QH}{W_{COMP} + W_{F_{EVAP}} + W_{F_{CND}}} \quad (1)$$

where *QH* represents the heat derived by the condenser, W_{comp} represents the compressor work, and W_{Fevap}, and W_{Fcnd} represent the air fan work of the evaporator and condenser, respectively.

2 Results and discussion

A group of pure refrigerants are selected according to their thermophysical properties, availability, toxicity and environmental issues as potential components of the refrigerant mixtures. In total fifteen pure refrigerants are selected. Then their binary/ternary mixture combinations are studied and compared. In this study, R-410A is used as a reference refrigerant. The cycle components are designed for the best performance of R-410A. In all the comparisons, the size of the compressor, evaporator and condenser are kept the same as the R-410A cycle. This type of comparison is fair to find the best replacement of R-410A without any changes, or with minimum changes, in the components of the conventional residential air-source heat pump.

The properties of the group of selected refrigerants investigated in this study are presented in Table 1 (the properties of new refrigerants are obtained by REFPROP (Lemmon E.W., 2013)).

Table 1: Properties of a group of selected refrigerants

Refrigerant	GWP	Safety group	Critical temp. (ºC)	Critical pressure (MPa)
R-410A	2088	A1	70.17	4.77
Propane	20	A3	96.74	4.25
R-32/CO_2 (80/20)	540	-	70.83	6.61
Propane/R-32 (95/5)	52	-	94.69	4.47
Propane/R-32 (10/90)	610	-	70.69	5.43
Propane/CO_2 (95/5)	20	-	95.40	4.63
Butane/R-32/R-125 (10/45/45)	1880	-	77.88	5.26
Propane/R-32/CO_2 (10/80/10)	542	-	69.77	6.08
Propane/R-32/R-125 (20/50/30)	1391	-	65.76	4.99

These selected refrigerants are compared in a heat pump with counter flow heat exchangers in Sec. 2.1. The results of the simulations with cross flow heat exchangers are presented in Sec. 2.2. Next, the most suitable refrigerant for residential applications is selected form the obtained simulations. This selected refrigerant is then compared with a refrigerant with higher temperature glide in a cycle with an internal heat exchanger in Sec. 2.3.

2.1 Counter flow heat exchanger

The inputs used for the simulations are given in Table 2; moreover, heat exchanger tubes and fins are assumed to be made of copper and aluminum, respectively. Four different evaporator inlet air temperatures are considered: 8.3℃, 0℃, -8.3℃ and -16.6℃; the last two temperatures represent the cold climate conditions.

Table 2: Simulation input values (counter flow)

Condenser input air temperature, (°C)	*W, compressor speed* (rpm)	V_{cp}, compressor displacement (m^3)	Evaporator fan blow rate (L/s)	Condenser fan blow rate (L/s)	No. of evaporator circuits	No. of condenser circuits
22	50	4.95×10^{-5}	300	200	10	8

Figures 1 and 2 present respectively the COP and heating capacity of a selected group of refrigerants/refrigerant mixtures studied as a function of the outside air temperature (evaporator inlet air temperature). Figures 1 and 2 legends are sorted by the highest COP and heating capacity, respectively. Each mixture has its own thermal behavior and this behavior might be of interest for a specific application. Since in this study the main goal is to find an efficient environmentally friendly refrigerant for cold climate applications, the main characteristic would be the heating capacity. It is also important that such a refrigerant has a reasonable COP.

Figure 1: Comparison of COP of a group of refrigerant mixtures as a function of outside air temperature (counter flow heat exchangers)

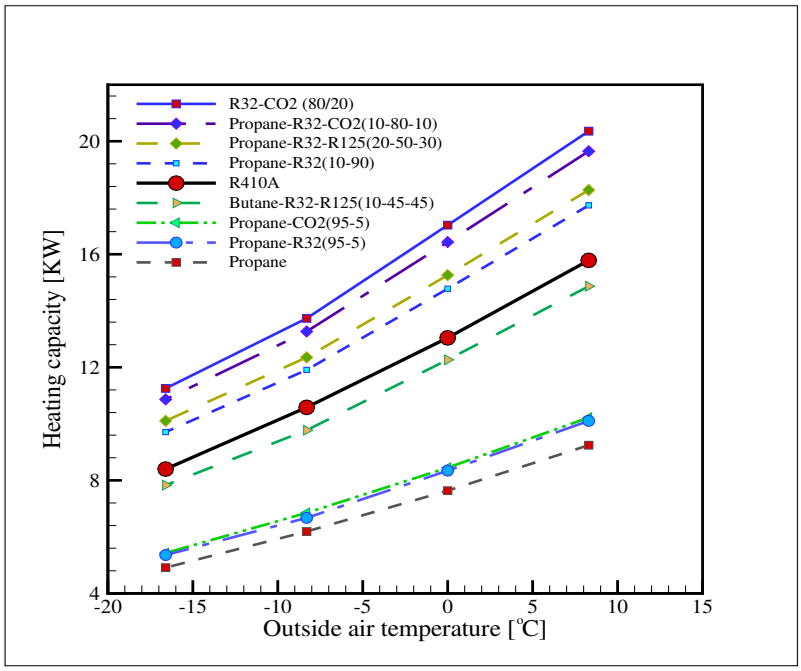


Figure 2: Comparison of heating capacity of a group of refrigerant mixtures as a function of outside air temperature (counter flow heat exchangers)

As it is shown, propane and its mixtures (when propane is the dominant component of the mixture) have highest COP but on the other hand they have the lowest heating capacity; therefore, they are not of interest of this study. On the other hand among all the mixtures studied, the mixture of R-32/CO_2 (80/20) has the highest heating capacity, which is approximately 30% better than R-410A. The COP of this mixture is slightly smaller (less than 2%) than that of R-410A. The main component of this mixture, R-32 is a good refrigerant; but it is categorized as a flammable gas (group A2). Therefore, it cannot be used alone as a refrigerant in residential applications. On the other hand, the other component of this mixture, CO_2, is a very attractive refrigerant, and is non-flammable, but its low critical temperature and high pressure limit its residential application in conventional systems. However, by mixing these two refrigerants, not only will the flammability effect of R-32 be reduced, but also the high pressure effect of CO_2 will be minimized. This mixture is non-toxic with a GWP of approximately 540 which is 25% of the GWP of R-410A. Moreover, it is a zeotropic mixture with approximate temperature glides of 6ºC and 8.5ºC in evaporator and condenser respectively. Therefore, among all the mixtures studied, R-32/CO_2 (80/20) mixture presents better performance potential for the purpose of this study.

2.2 Cross flow heat exchanger

The inputs used for the simulations are given in Table 3. Four different evaporator inlet air temperatures are considered: 8.3℃, 0℃, -8.3℃ and -16.6℃; the last two temperatures represent the cold climate conditions.

Table 3: Simulation input values (cross flow)

Condenser input air temperature, (℃)	*W, compressor speed* (rpm)	V_{cp}, compressor displacement (m^3)	Evaporator fan blow rate (L/s)	Condenser fan blow rate (L/s)	No. of evaporator circuits	No. of condenser circuits
22	50	4.95×10^{-5}	120	120	6	6

Figures 3 and 4 present, respectively, the COP and heating capacity of a selected group of refrigerants/refrigerant mixtures studied as a function of the outside air temperature. Figures 3 and 4 legends are sorted by the highest COP and heating capacity, respectively.

As it can be seen by changing the heat exchangers from counter flow to cross flow no change is obtained in the order of the refrigerants performance. Therefore, it can be concluded that the heat exchangers type does not play a crucial role in the performance of the refrigerant mixtures. In other words, a refrigerant which has a good performance in one type should have a good performance in other types of heat exchangers as well. Henceforth, the mixture of R-32/CO_2 (80/20), so far has shown to have a desirable performance, as a substitute for residential heat pumps at low temperatures.

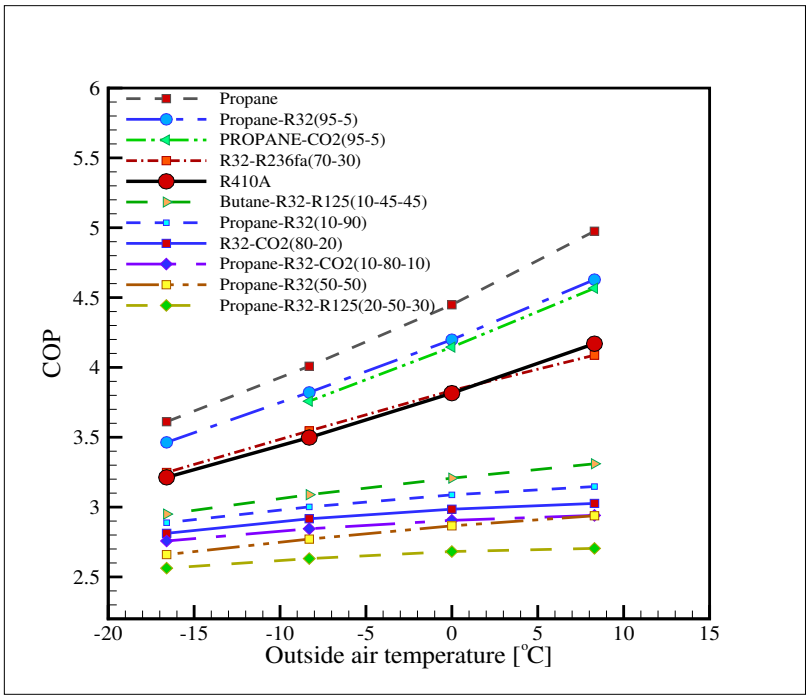


Figure 3: Comparison of COP of a group of refrigerant mixtures as a function of outside air temperature (cross flow heat exchangers)

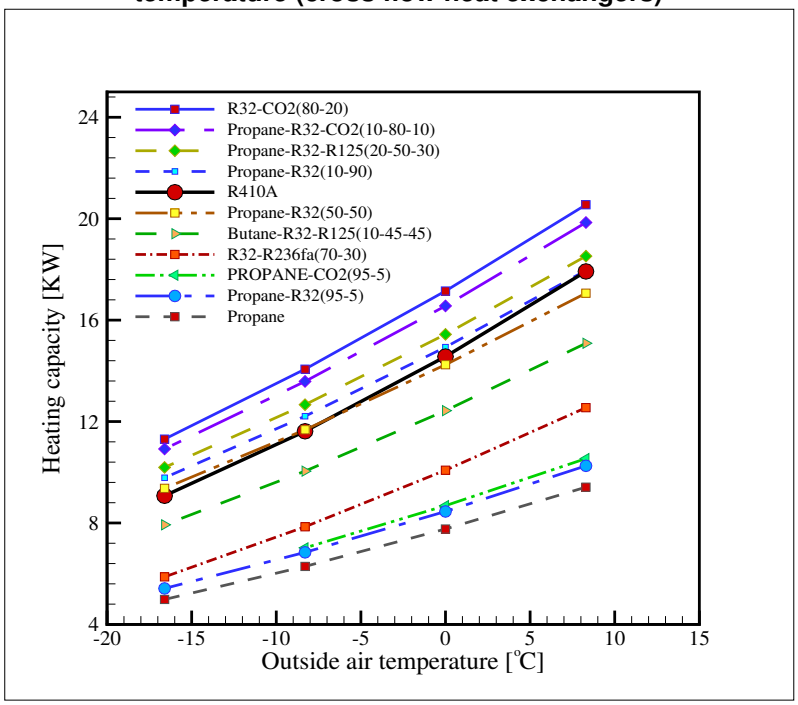
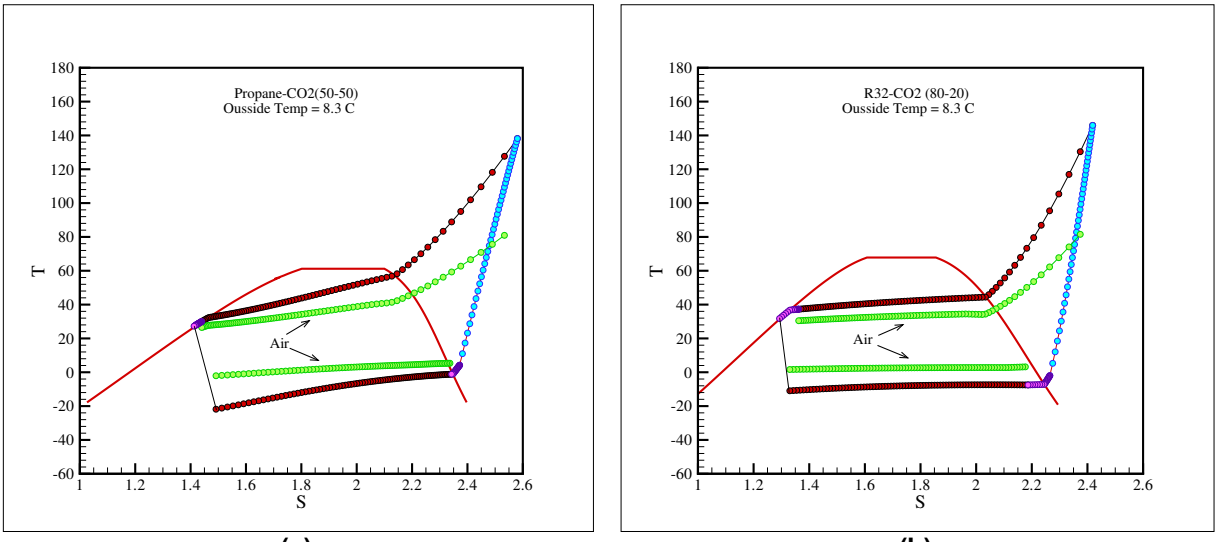


Figure 4: Comparison of heating capacity of a group of refrigerant mixtures as a function of outside air temperature (cross flow heat exchangers)

2.3 Implication of internal heat exchanger

Since the mixture of R-32/CO_2 (80/20) has shown good performance, it would be interesting to compare its performance with a mixture with higher glide such as Propane/CO_2 (50/50). In these simulations an internal heat exchanger is also added to the heat pump cycle. The same conditions as given in Table 4 with cross flow heat exchangers are used for both refrigerants. Moreover, 5°C of superheat and 5°C of subcooling are also considered for both cases. For such a range of working conditions Propane/CO_2 (50/50) has approximately 20°C and R-32/CO_2 (80/20) has approximately 4°C of temperature glide at the evaporator. In these simulations lower temperatures down to -33.2°C are reached.



(a) **(b)**

Figure 5: T-S diagram of two refrigerant mixtures for outside air temperature of 8.3ºC

Table 4: Simulation input values

Condenser input air temperature, (°C)	*W, compressor speed* (rpm)	V_{cp}, compressor displacement (m^3)	Evaporator fan blow rate (L/s)	Condenser fan blow rate (L/s)	No. of evaporator circuits	No. of condenser circuits
22	50	4.95×10^{-5}	100	65	3	4

Figures 5(a) and (b) show the T-S diagrams of Propane/CO_2 (50/50) and R-32/CO_2 (80/20) respectively. It should be noted that the air temperature shown in these diagrams represents the local output air temperature in the heat exchanger; therefore, the actual output air temperature of the heat exchanger would be the average of the temperatures shown. The high air local temperatures result from the combination of the gliding effect and the amount of superheat produced by the compression, which extend the range over which air is being heated. Figures 6 and 7 present, respectively, the COP and heating capacity of these refrigerant mixtures as a function of the outside air temperature for a wide range of outside air temperatures. As shown in Fig. 5(a) the mixture of R-32/CO_2 (80/20) has a much better COP, which is approximately 17% better than Propane/CO_2 (50/50). However, the heating capacity of Propane/CO_2 (50/50) as shown in Fig. 5(b) is only slightly better (4.5%) than R-32/CO_2 (80/20). Therefore, it can be concluded for residential purposes R-32/CO_2 (80/20) has a better performance than most of the other refrigerants studied.

Figure 6: Comparison of COP of a group of refrigerant mixtures as a function of outside air temperature

3 CONCLUSION

In this paper, detailed numerical simulation of the air-source residential heat pump is used for assessment of refrigerant mixtures performance in cold climates. A group of pure refrigerants is selected as potential mixture components, and their corresponding refrigerant mixtures are compared. It is shown that the mixture of R-32/CO_2 (80/20) has the best performance among the mixtures studied. This mixture has both advantages of the CO_2 and R-32; while, the flammability effect of R-32 and high pressure effect of CO_2 are minimized. This mixture can increase the heating capacity of a conventional heat pump that runs on R-410A by 30%. Moreover, the GWP of this mixture is 25% of that of R-410A. This paper demonstrates the potential of zeotropic refrigerant mixtures in conventional heat pumps with no changes in the cycle components that will allow for substantial performance improvements under cold climate conditions.

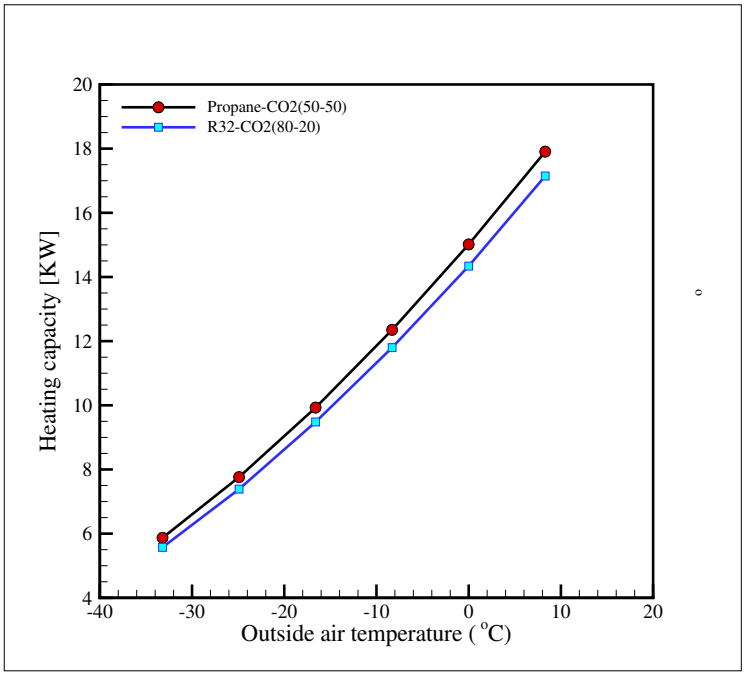


Figure 7: Comparison of heating capacity of a group of refrigerant mixtures with internal heat exchanger as a function of outside air temperature

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