LOW-GWP FLUIDS FOR HIGH TEMPERATURE HEAT PUMPS

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Introduction

High Temperature Heat Pumps (HTHP) represent a viable option for energy efficiency improvement in several industrial sectors, like for instance food production, textile, paper, wood, automotive industries. A study promoted by IEA (IEA, 2014) indicates, with reference to some case studies, that about 16% of the total industry energy consumption in Germany could be supplied by HTHP. Unfortunately, they are still poorly adopted. Therefore, a progressive diffusion of HTHP is expected in the next years and consequently it is fundamental for the next generation of HTHPs to achieve high energetic efficiency and full environmental compatibility. In this framework, the choice of the working fluid plays a key-role.

Nowadays, the most widespread fluid in industrial HTHPs is HFC-245fa. This fluid is not flammable, but it is toxic (classified B1 according to ASHRAE) and has a GWP of around 1000. Consequently, having the lowest possible environmental impact as a target, it is fundamental to select new fluids with ultra-low GWP, no toxicity and no (or at least mild) flammability. When looking for a new substitute refrigerant, the first thermodynamic property to be assessed is the saturation pressure. The new refrigerant should have a pressure-temperature saturation curve in vapour-liquid equilibrium as close as possible to the refrigerant to be replaced. Among the fluids appeared in the market in the last months, HCFO-1233zd(E) and HCFO-1224yd(Z) have saturation pressures and temperatures rather close to R245fa ones (figure 1). Both new molecules are hydrofluoro-olefins with chlorine. Since 2009, at the sunrise of HFO refrigerants in the international scenario, Brown et al. (2009) have been proposing HFO-1234ze(Z) as a replacement of CFC-114 in HTHPs. Since R245fa is a HFC replacement of R114, R1234ze(Z) can be properly considered a suitable alternative to R245fa.

Table 1 reports the main characteristics of the investigated fluids. With reference to figure 1, R1224yd(Z) is the fluid showing the closest saturation pressure to R245fa, especially at temperatures above 90°C.

Table 1. Main thermodynamic properties and environmental characteristics

Fluid	GWP	ODP	P.E.N. (°C)	P_{crit} (MPa)	T_{crit} (°C)	ASHRAE Class.
R245fa	1030	0	15.0	36.51	153.86	B1
R1234ze(Z)	<1	0	9.7	35.31	150.12	A2L (expected)
R1233zd(E)	<5	0.00034	18.3	36.24	166.45	A1
R1224yd(Z)	<1	0.00033	14.6	3.34	155.54	A1

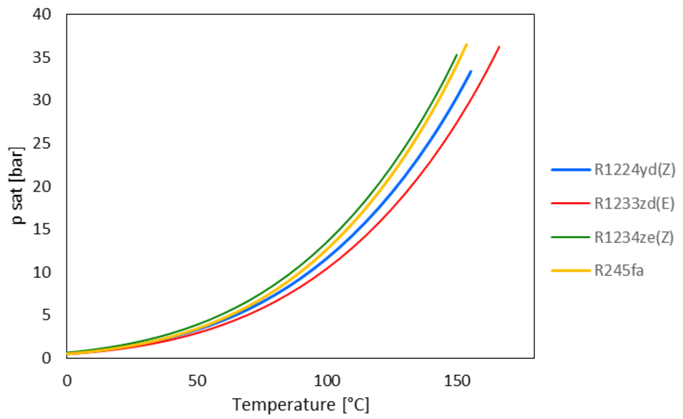

Figure 1. Fluids saturation pressure according to RefProp v.10.0

Figure 2 reports condensation latent heat at different temperatures. In this case, R1224yd(Z) shows the lowest latent heat and consequently the lowest volumetric heating capacity. R1234ze(Z) has a volumetric heating capacity rather close to R245fa one. Hence, it is a candidate for R245fa drop-in replacement when the main goal is to achieve the same heating power, without changing the compressor.

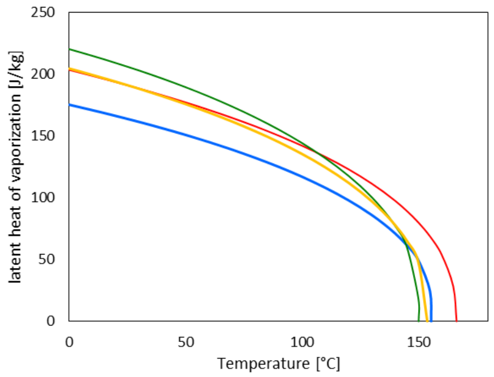

Figure 2. Condensation latent heat

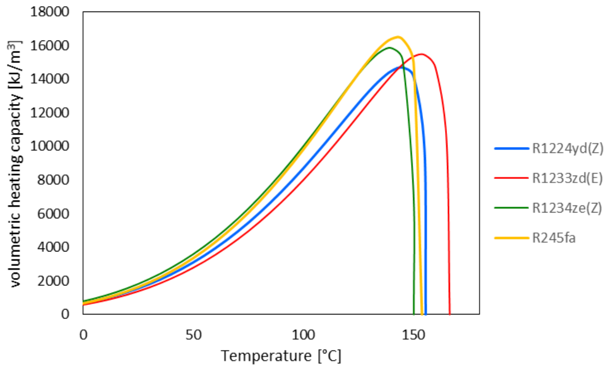

Figure 3. Volumetric heating capacity

Case study

In IEA report (IEA, 2014) several case studies are referred to real industrial plants in Europe. For the scope of the present paper, among the IEA report case studies, the following one is considered. A single stage heat pump working with R245fa used for heat recovery. The refrigerant reference condensation temperature is 92 °C with 5°C condensate subcooling. The evaporation occurs at 38°C, with 5 °C vapour superheating. The global compression efficiency is 0.7 (assumed constant for all the fluids, for simplicity). Table 2 reports the main parameters during the condensation of the four fluids under investigation.

Table 2. Main parameters according to Refprop v. 10.0 (condensation temp. 92 °C)

Fluido	p	p.red	COP	VHC	λ_L	$c_{p,L}$	ρ_L	ρ_V	μ_L
	[bar]	[-]	[-]	[kJ/m^3]	[mW/m K]	[J/kgK]	[kg/m^3]	[kg/m^3]	[μPa s]
R245fa	10.54	0.289	2.48	2554	66.88	1546.3	1126.0	59.27	172.69
R1234ze(Z)	11.33	0.321	2.40	2982	67.99	1551.2	1012.9	56.89	119.34
R1233zd(E)	8.72	0.241	2.47	2260	63.88	1378.0	1076.9	46.56	148.94
R1224yd(Z)	9.74	0.292	2.45	2410	57.98	1320.8	1143.8	61.24	136.94

According to Table 2, COP values for the fluids are very close, indicating that the energy efficiencies of the HTHP are expected to be very similar. It should be noted that these COP values have been obtained with the hypothesis of constant imposed condensation and evaporation temperatures. A more comprehensive approach should include also the effects of heat transfer performances. For given heat exchangers and set conditions of the secondary fluids, a better heat transfer efficiency would lead to a lower temperature approach between the secondary fluid and the refrigerant. Hence, the evaporation would increase and/or the condensation temperature would decrease causing a reduction of the compression work that, as an outcome, would increase the thermodynamic efficiency of the whole cycle.

It is possible to observe from Table 2 that R1234ze(Z) has liquid thermal conductivity (λ_L), liquid heat capacity ($c_{p,L}$) and reduced pressure higher that the other fluids ones. These properties are positive for the heat transfer coefficient. The relatively low liquid dynamic viscosity of R1234ze(Z), with respect to the other fluids, together with an higher reduced pressure indicates lower frictional pressure drops.

As an example, figure 4 reports the condensation heat transfer coefficients inside a smooth tube with 10 mm inner diameter at 92°C, vapour quality 0.5, estimated according to Cavallini et al. (2006) model. The frictional pressure drops at the same conditions estimated with Friedel (1979) are reported in figure 5.

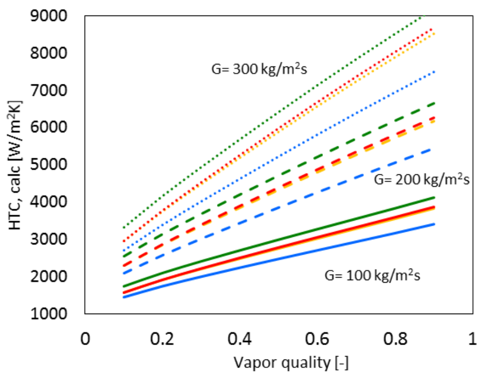

Figure 4. Condensation heat transfer coefficient at 92°C, x=0.5, according to Cavallini et al. (2006)

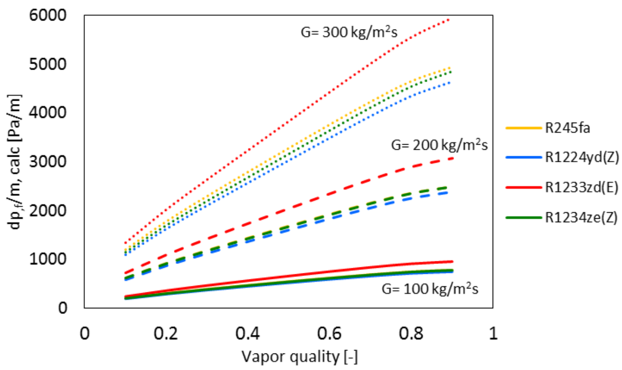

Figure 5. Frictional pressure drops during condensation at 92°C, x=0.5, according to Friedel (1979)

R1234ze(Z) shows condensation heat transfer coefficients higher than the other fluids and frictional pressure drops lower than R245fa ones. It emerges that R1234ze(Z) should have condensation heat transfer efficiency higher than R245fa one. R1224yd(Z) has condensation heat transfer coefficients lower than the other fluids ones, but also pressure drops lower than that of R245fa and R1233zd(E). Basing on this latter observation it is possible to speculate that the lower saturation temperature drop, thanks to lower pressure drops, should at least partially compensate the possible penalization caused by lower heat transfer coefficients. It worth to underline that the considerations proposed above should be considered only preliminary, also considering that R1224yd(Z) thermodynamic and thermophysical properties are not fully defined and the present authors are involved in an international cooperation for the development of reliable correlation for the prediction of thermodynamic and thermophysical properties (Fedele et al., 2019).

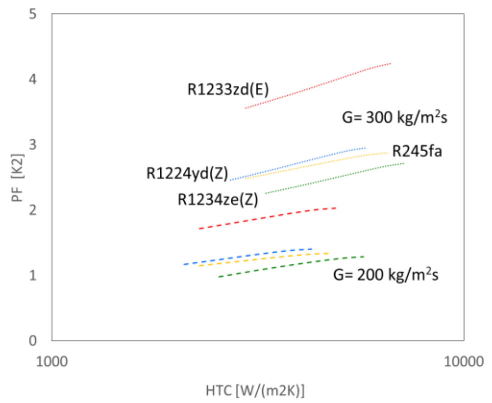

Figure 6. Penalty Factor (Cavallini et al. 2006)

Cavallini et al. (2010) proposed the Penalty Factor (PF) approach to compare on thermodynamic basis the heat transfer performance of different refrigerants. The PF of the analyzed fluids are compared in figure 6, under the same working conditions of figures 4 and 5: the lowest the PF, the best the heat transfer performance.

R1224yd(Z) seems to have the best heat transfer potential, while R1234ze(Z) is in line with R245fa.

Conclusions

On the basis of the thermodynamic analysis here proposed, the new fluids with ultra-low GWP, HFO1234ze(Z), HCFO1224yd(Z), HCFO1233zd(E) can be considered viable options for HFC245fa replacement.

References

Brown J.S., Zilio C., Cavallini A. (2009). The fluorinated olefin R-1234ze(Z) as a high-temperature heat pumping refrigerant. *Int. J. of Refrigeration*, 32, 1412-1422

Cavallini A., Del Col D., Doretti L., Matkovic M., Rossetto L., Zilio C., (2006). Condensation in horizontal smooth tubes: a new heat transfer model for heat exchanger design. *Heat Transfer Engineering* 27, 31–38.

Fedele L., Bobbo S., Scattolini M., Zilio C., Akasaka R. (2019), Compressed liquid density measurements and correlation for cis-1-chloro-2,3,3,3 tetrafluoropropene (R1224yd(Z)), to be presented at ICR 2019, Montreal

Friedel L., (1979). Improved Friction Pressure Drop Correlations for Horizontal and Vertical Two-phase Pipe flow, European Two-Phase Group Meeting, Ispra, Italy, Paper E2, 1979.

IEA Heat Pump Programme, (2014) Applications of industrial heat pumps, part I and II, Annex 35.

Cavallini A., Brown J.S., Del Col D., Zilio C., (2010), In-tube condensation performance of refrigerants considering penalization terms (exergy losses) for heat transfer and pressure drop, *Int. Journal of Heat and Mass Transfer*, 53, 2885-2896

Lemmon E.W., Bell I.H., Huber M.L., McLinden M.O. (2018). NIST Standard Reference Database 23: REFPROP, Version 10.0, National Institute of Standards and Technology.