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A Screening of Low-GWP Refrigerant for Ejector Refrigeration

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Ejector refrigeration is a promising technology to reduce primary energy consumption for building cooling. Unfortunately, a change in the design criteria (i.e., geometry, working fluid, operating conditions) influences the system performance owing to variations in the local fluid dynamic phenomena at the "*local-scale*". For this reason, a general agreement on ejector performance is far from being reached. In addition, a general assessment of ejector performance is even more challenging when considering the recent regulations concerning the working fluids, which are going to phase-out most of the refrigerants commonly used in refrigeration and air conditioning systems. Despite there are different options to replace them, no refrigerant has yet imposed. This paper contributes to the discussion on the screening of working fluids, using a previously-validated lumped parameter model. The modelling approach has been applied to sub-critic ejector refrigeration systems and some alternatives to high GWP refrigerants are considered. The influence of the generator, the evaporator and the condenser temperatures over the ejector performance, for the different working fluids, have been presented and commented. The results are comments in terms of entrainment ratio and coefficient of performance, to provide indications and guidelines for refrigerant selection in prospective ejector refrigeration systems

1. Introduction

The cooling need in the building sector is associated with high primary energy consumption and its reduction, which is very important to achieve the European targets, might be achieved by acting on the demand side and/or on the supply side. Considering the supplies side, thermal energy refrigeration is an interesting technology and, in particular, ejector refrigeration systems seem a promising alternative because of its many advantages (viz. structural simplicity, low capital cost, reliability, little maintenance, low initial and running cost and long lifespan), as reviewed by Besagni et al. (2016). An ejector is able to provide a combined effect of compression, mixing and entrainment with no moving parts and without limitations concerning working fluids. For these reasons, ejector refrigeration systems can be used in buildings, in distributed tri-generation systems and for the waste heat recover from industrial processes. Nevertheless, the ejector refrigeration has not been able to penetrate the market because of the low coefficient of performance: this is because the efficiency of the whole system is highly influenced by ejector performances: a change in the design criteria (i.e., geometry, working fluid, operating conditions) influences the system performance owing to variations in the local fluid dynamic phenomena at the "*local-scale*" (see, for example, Besagni and Inzoli (2017) and Bi et al. (2017)). Furthermore, a general assessment of ejector performance is even more challenging when considering the recent regulations concerning the working fluids: the EU Regulation No 517/2014 (Regulation (EU) No 517/20, 2014) is going to phase-out most of the refrigerants commonly used in refrigeration and air conditioning systems (i.e., R134a, R404A and R410A). Despite there are different options to replace them, no refrigerant has yet imposed (see, for example, the studies proposed by Bao et al., 2017, Chen et al. 2017, Gil and Kasperski, 2018). In a previous study, Besagni et al. (2015), compared and validated five lumped parameter models against experimental data; subsequently, a lumped parameter model was selected and used to perform a preliminary screening of working fluids have bene proposed. This paper contributes to the discussion on working fluid selection in ejector refrigeration systems. In particular, this paper deals with the screening of working fluids, using the previously-

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validated lumped parameter model. The modelling approach has been applied to natural (i.e., R290), HFC (i.e., R32, and R152a – see, for example, ref. Yu et al. (2013) and HFO (i.e., R1234yf – see, for example, Li et al. (2014)) refrigerants (See Table 1); for comparison purposes, R125 has been considered as a high-GWP refrigerant. The influence of the generator, the evaporator and the condenser temperatures over the ejector performance, for the different working fluids, have been presented and commented.

Table 1: Properties of the selected refrigerants

Month	M [g/mol]	NBP [°C]	T_{crit} [°C]	p_{crit} [MPa]	ODP	GWP [100 y]
R125	120.0	-48.1	66.0	3.62	0	3,450
R152a	66.1	-24.02	113.26	4.517	0	133
R1234yf	114.0	-29.5	94.7	3.38	0	<1
R290	44.1	-42.1	96.7	4.25	0	0
R32	52.0	-52.0	78.4	5.82	0	675

2. Material and methods

A subcritical cycle operating has been considered for the analysis, due to the ability of the selected models to describe only subcritical ejection cycles (Besagni et al., 2015). The system considered is shown in Figure 1 and consists of a generator, a condenser, an evaporator, an ejector, a circulation pump and a throttle valve. The low-grade heat energy is delivered to the generator for the working fluid vaporization. The high-pressure vapor (the primary flow) flows out from the generator enters into ejector nozzle and draws low-pressure vapor from the evaporator (the secondary flow). The two flows mix, the pressure is raised in the ejector diffuser and the flow reaches the condenser where it changes phases from vapor to liquid rejecting heat.

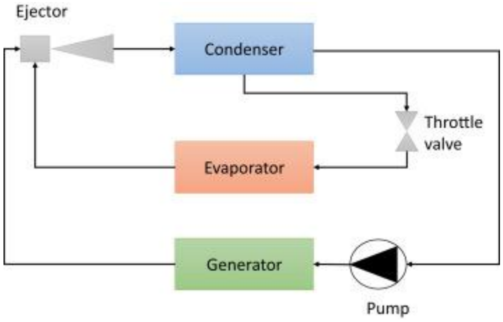


Figure 1: Ejector refrigeration system

Table 2: Cases studied

Code name	T_g [°C]	T_e [°C]	T_c [°C]	Results
Baseline	Varied	5	25	Figure 2
Evaporator#1	Varied	0	25	Figure 3
Evaporator#2	Varied	10	25	Figure 4
Condenser#1	Varied	5	20	Figure 5
Condenser#2	Varied	5	30	Figure 6

The model of Chen et al. (2014) have been applied, following the conclusions of Besagni et al. (2015). This model has been implemented in the MATLAB® R2015a framework and the thermodynamic properties have been evaluated by using the thermophysical property library CoolProp (v 6.1.0) (Bell et al., 2014). The performance of the ejector refrigeration systems has been evaluated in terms of the coefficient of performance (COP) and the entrainment ratio (viz. the ratio between the secondary and the primary mass flow rates). The range of operating conditions considered in the following of this paper and the cycle configuration is the one typically employed for the case of solar energy sources or water heat. In particular, starting from a baseline case, the evaporator (T_{eva}) and condenser (T_{cond}) temperature are varied, to study the influence of the ejector boundary conditions on the system performances (Table 2). It is worth noting that ejector component efficiencies have a large influence on the results; the ejector component efficiencies in the cases listed in Table 1 are as follows for the motive nozzle, mixing chamber and diffuser respectively: η_n = 0.9, η_m = 0.85, η_d = 0.9. Sensitivity analyses on these values have been performed as well (Section 3.3).

3. Results and discussion

Herein, the modelling results are commented and discussed in terms of the entrainment ratio and the coefficient of performance, to provide indications and guidelines for refrigerant selection in prospective ejector refrigeration systems. For comparison purposes, it is worth noting that the coefficient of performance for similar refrigeration systems ranges between 0.05 and 0.85 (Besagni et al., 2016).

3.1 Influence of generator temperature (T_g)

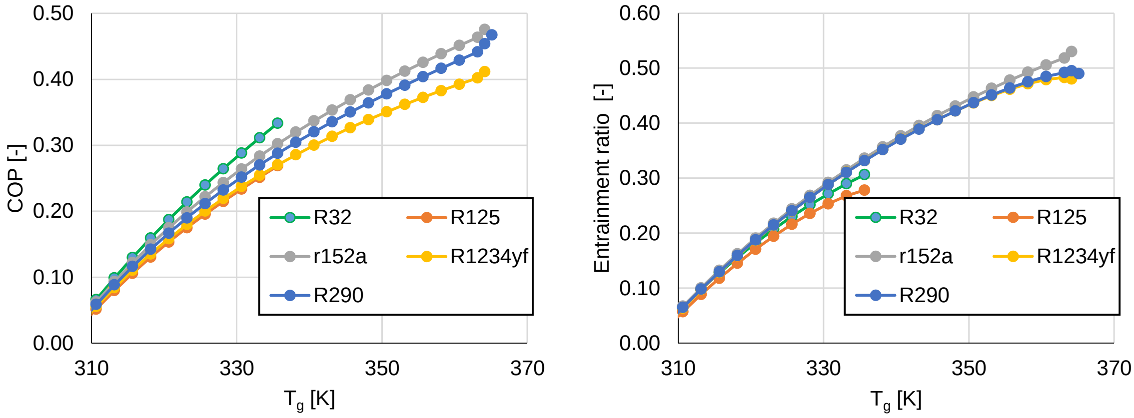
Figures 2-6 display the influence of T_g on the system performance: both the entrainment ratio and COP increase with increasing T_g (in agreement with the literature, i.e., Yapici et al (2008) and Besagni et al. (2016)), regardless of the refrigerant considered. Indeed, when T_{gen} is increased, the pressure and the enthalpy of the primary flow increase and, as T_e and T_c are both constant, the entrainment ratio increases. Of course, the refrigerant used affects this trend according to the nature of the refrigerant (viz. its physical properties and its p-h properties) and to the operating condition in which the ejector works. This is the reason of the maximum value of the entrainment ratio is observed for R290 and R1234yf. It should not escape notice that these results have been obtained by using the model of Chen et al. (2014), which predicts the performances of a variable-area ejector operating at the optimum area ratio (viz. the ratio between the mixing chamber area and the nozzle throat area); this condition is obtained through an adjustment of the area ratio and, of course, these performances differs from the ones of which are different from a fixed-geometry ejector working under the same boundary conditions. Generally, the area ratio increases with T_g as a result of the increase of the entrainment ratio (Besagni et al., 2016); the interested reader may refer to the results obtained by Besagni et al. (2015) for a discussion concerning the relationship between the area ratio and T_g. For a fixed-geometry ejector, instead, each ejector with a specific area ratio has its own optimum Tg, at where the maximum COP could be obtained (Selvaraju and Mani, 2006). As a result, R290, R152a and R1243yf show a broad range of operating conditions (owing to the value of the critical temperature); conversely, the other refrigerants have a limited range of operating conditions due to the low critical temperature. In the low- T_g operating conditions, R32 represents an interesting opportunity, having higher COP and entrainment ratio compared with the other refrigerants; at higher generator temperature, R152a has shown higher performances compared with R290 and, finally, R1234yf has the lower COP and entrainment ratios. However, it is worth noting that (a) R1234yf is less flammable than 152a and has a lower GWP and (b) R290 has several limitations in terms of the refrigerant charge (owing to safety reasons). It is worth noting that these results have been obtained by neglecting the influence of the refrigerant charge and under the assumption that T_g, T_e and T_c are independent from each other: this situation can be hardly observed in practical applications as, in real systems, the controlled parameter is the superheat at evaporator outlet (which depends on the refrigerant charge) rather than T_e. For this reason, in practical cases, T_e depends on ejector suction capacity, the cooling load and the operating conditions (i.e., T_g and T_c). Nevertheless, the reader should take into account that this study aims in providing a map of ejector system performances in steady-state operating conditions, rather than proposing a study concerning the control system of an ejector-based system.

3.2 Influence of condenser (T_c) and evaporator temperature (T_e)

Figures 3-6 display the influence of T_c and T_e on the system performance: (a) as expected, when increasing T_e, COP and the entrainment ratio increases; (b) when decreasing T_c COP and the entrainment ratio increases. When considering these data, the reader should take into account that they refer to the performances of a variable-area ejector operating at the optimum area ratio; in the case of a fixed-geometry ejector, it is known that a critical condenser pressure exists. At this condition, the entrainment ratio is independent of the condenser temperature T_c when the condensing pressure is lower than the critical value; conversely, when the condensing pressure increases above the critical value, the performances of the system decreases (Besagni et al., 2016). Conversely, in the case of a variable-geometry ejector, when increasing T_c, both COP and the entrainment ratio decrease. It is worth noting that the T_c has higher influence on the system performances compared with the T_e and, both T_c and T_e have n higher effect compared with T_g. For this reason, it would be interesting to develop a more detailed off-design model to predict the performance of the system at variable system operating conditions (i.e., at variable cooling loads and/or generator loads).

3.3 Sensitivity analysis on ejector component efficiencies

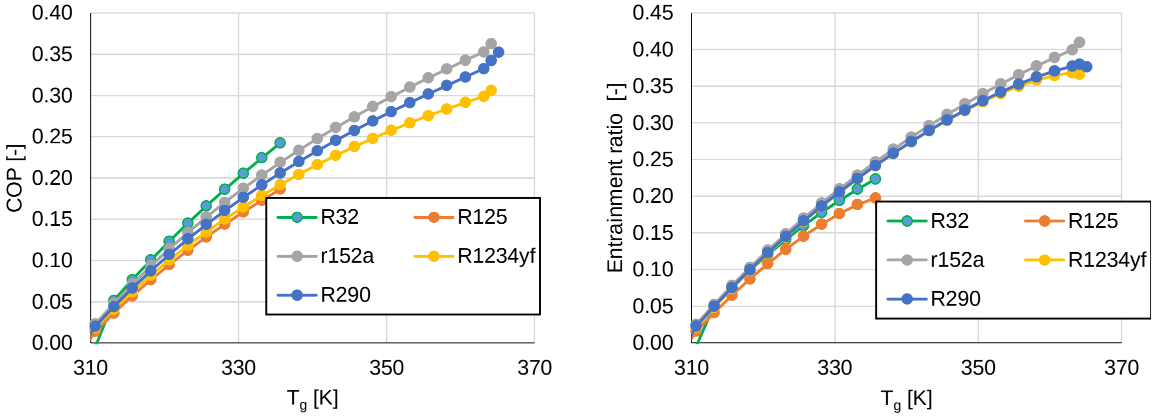
It is known that ejector component efficiencies have a large influence on the ejector performances. For this reason, a sensitivity analysis has been conducted to determine the influence of the mixing chamber efficiency (η_m) and the diffuser efficiencies (η_d) on the results. The results are presented in Figure 7: as expected, a change on the ejector component efficiencies has a large effect on the ejector performance. A decrease in the ejector component efficiencies lead to a large decrease of ejector performance and, possibly, a malfunction operation mode. In this respect, future studies should formulate variable ejector component efficiencies when describing the role of refrigerants over ejector performance. Indeed, a present, the relationship between operating conditions and refrigerants on the efficiencies is far from being understood and limited to some cases (i.e., vapor ejectors and R744 ejectors, Besagni et al., 2016).



(a) COP

(b) Entrainment ratio

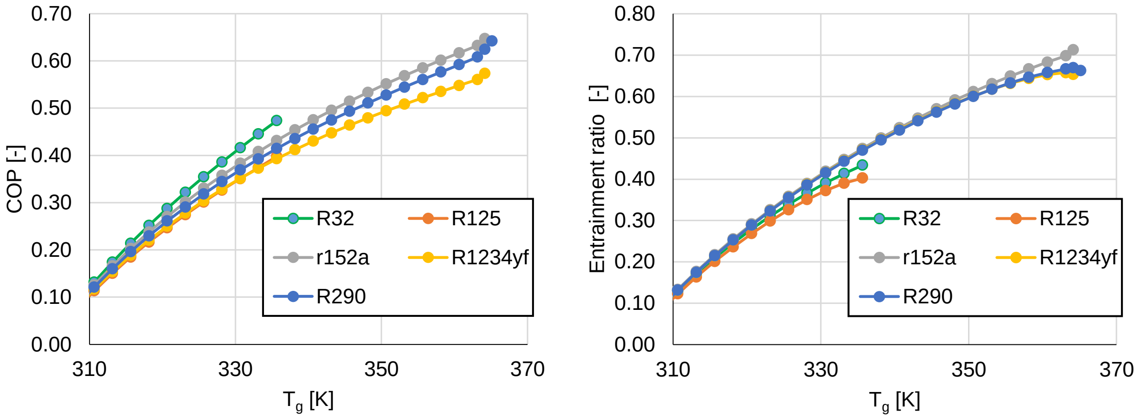
Figure 2: COP and entrainment ratio: baseline case (T_e = 5°C; T_c = 25°C) - η_n = 0.9, η_m = 0.85, η_d = 0.9



(a) COP

(b) Entrainment ratio

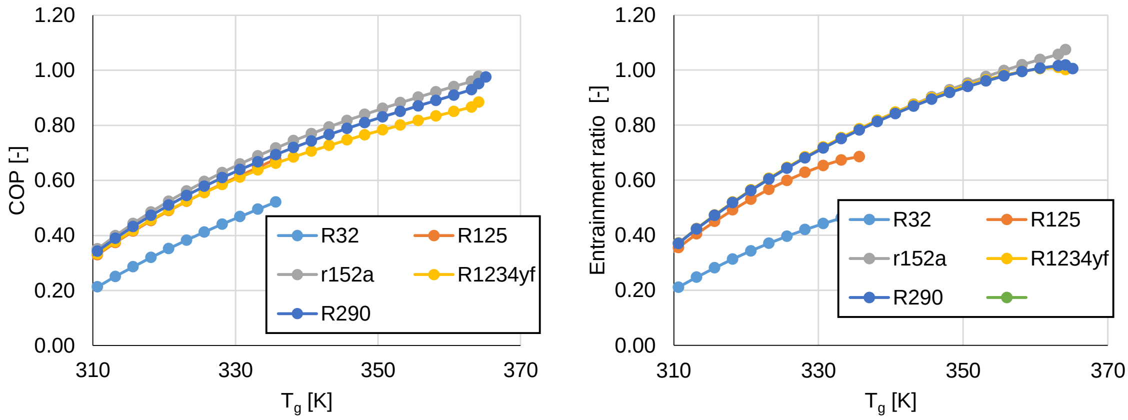
Figure 3: COP and entrainment ratio: case evaporator#1 (T_e = 0°C; T_c = 25°C) - η_n = 0.9, η_m = 0.85, η_d = 0.9



(a) COP

(b) Entrainment ratio

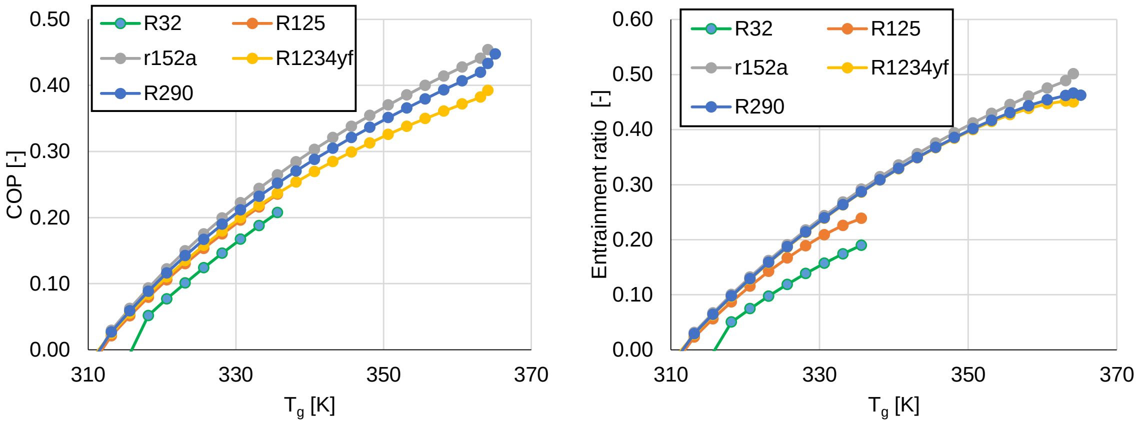
Figure 4: COP and entrainment ratio: case evaporator#2 (T_e = 10°C; T_c = 25°C) - η_n = 0.9, η_m = 0.85, η_d = 0.9



(a) COP

(b) Entrainment ratio

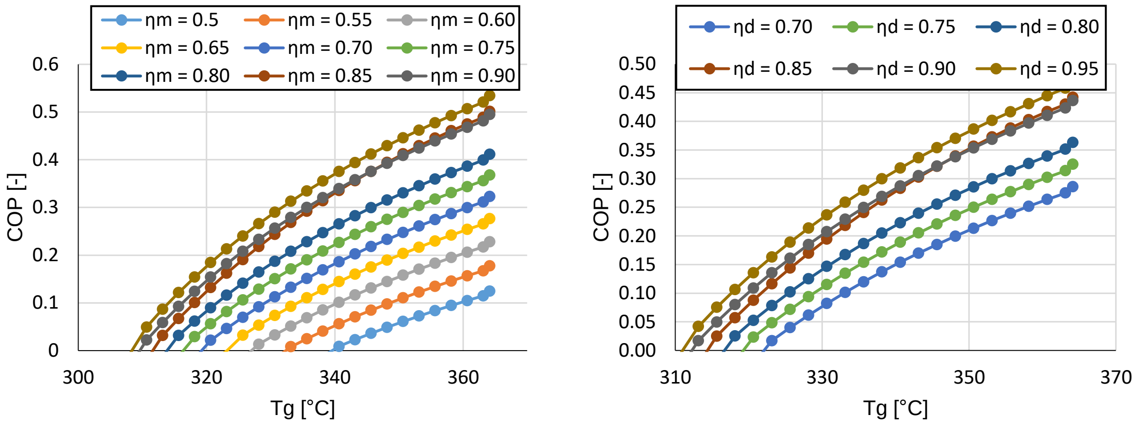
Figure 5: COP and entrainment ratio: case condenser#1 (T_e = 5°C; T_c = 20°C) - η_n = 0.9, η_m = 0.85, η_d = 0.9



(a) COP

(b) Entrainment ratio

Figure 6: COP and entrainment ratio: case condenser#1 (T_e = 5°C; T_c = 30°C) - η_n = 0.9, η_m = 0.85, η_d = 0.9



(a) Influence of mixing chamber efficiency (η_n = 0.9, η_d = 0.9)

(b) Influence of diffuser efficiency (η_n = 0.9, η_m = 0.85)

Figure 7: Influence of ejector component efficiencies on the coefficient of performance (R152a, T_e = 5°C; T_c = 25°C)

4. Conclusions

This paper contributes to the discussion on the screening of working fluids, using a previously-validated lumped parameter model. In particular, a model to predict the performances of variable-area ejectors is used. The main results are as follows:

1. R32 represents an interesting opportunity, in the low-temperature application, having higher COP and entrainment ratio compared with the other refrigerants;
2. R290, R152a and R1243yf show a broad range of operating conditions; in this range, R152a has shown higher performances compared with R290 and R1234yf;
3. R1234yf is an interesting refrigerant, owing to the performances, quite comparable with the other refrigerants, and is properties (i.e., it is less flammable compared to 152a and R290, and it has lower GWP compared to 152a);
4. regardless of the working fluid, the entrainment ratio and the COP increase with increasing of generator temperature and evaporator temperature, while an increasing condenser temperature leads a decrease in the ejector performance;
5. a decrease in the ejector component efficiencies lead to a large decrease of ejector performance; thus, variable efficiency models should be considered.

Future studies should apply CFD approach to study the local flow phenomena, obtain ejector component efficiencies and develop an integrated lumped parameter-CFD approaches.

Acknowledgments

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