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SELECTION OF PROSPECTIVE WORKING FLUID CANDIDATES FOR SUBCRITICAL ORC EVAPORATORS

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ABSTRACT

The trade-off between lower grade waste heat sources and thermal efficiencies of evaporators using refrigerants is an important in subcritical organic Rankine cycles (ORCs). Although the heat transfer performances of many refrigerants have been reported in various studies, there are relatively low amount of studies focusing on temperature and pressure ranges relevant to evaporators for subcritical ORCs. Therefore there is a necessity for new studies that would meet the current needs and fill the gaps in literature. For this purpose, the present study aims to contribute to the revealing and concretizing the lack of information about working fluids for ORC evaporators operating under subcritical conditions. An extensive literature survey is made for deducing the proper working fluids, by means of including both the older and new generation refrigerants. The thermo-hydraulic, environmental, safety and physical properties of 10 refrigerants with zero Ozone Depletion Potentials (ODP) and low Global Warming Potentials (GWP) such as R134a, R245fa, R365mfc, R245ca, R1234ze, R1233zd, Solkatherm® SES36, R1234yf, DR-2 and HDR-14 are discussed, where R134a was taken as reference for evaluation. The best candidates for future research for evaporators for subcritical ORC are proposed, by taking the two-phase heat transfer coefficients and pressure drops into consideration.

INTRODUCTION

Organic Rankine Cycles (ORCs) increasingly receive the attention of many researchers, due to their promising capabilities of reclaiming electrical power from even low grade temperature waste heat sources (even below 100 °C) [1]. ORCs have the same basis as the classical thermodynamic Rankine cycle, but operate an organic fluid as working fluid instead of water or steam. In the last decades, a lot of research has been done on ORCs [2-6].

ORC waste heat recovery can be done through a direct evaporator (e.g. tube bundles) applied on a heat source [7]. The thermodynamic efficiency of an evaporator relies on heat transfer and pressure drops, and thus, the sizing of an evaporator is performed accordingly [8].

Another factor that defines the efficiency and characteristics of an evaporation process in an ORC system is the working fluid. The critical temperature and pressure value of the working fluid is the main criterion for distinguishing the operating conditions (subcritical, transcritical and supercritical) of an ORC.

NOMENCLATURE

Bo		Boiling number
c_p	[m^{3}K/W]	Specific heat
D	[m]	Diameter
E		Two-phase conv. multiplier, Dimensionless parameter
F		Dimensionless parameter
f		Friction factor
Fr_H		Dimensionless parameter
g	[m/s^2]	Gravity of Earth
G	[kg/m^{2}s]	Mass Flux
h	[W/m^{2}K]	Convective heat transfer coefficient
H		Dimensionless parameter
H_{lg}	[J/kg]	Latent heat of vaporization
k	[W/mK]	Thermal conductivity
L	[m]	Tube length
M	[kg/mol]	Molar mass
$\dot{m}$	[kg/s]	Mass flow rate
P	[Pa]	Pressure
Pr		Prandtl number
q	[W/m^2]	Heat flux
Re		Reynolds number
S		Boiling suppression factor
T	[K]	Temperature
t_w	[m]	Tube wall thickness
We		Weber number
x		Vapor quality
X_{tt}		Lockhart-Martinelli parameter

Special characters

φ_{fr}^2		Two-phase pressure drop multiplier
μ	[Pa-s]	Kinematic viscosity
ρ	[kg/m^3]	Density
σ	[N/m^2]	Surface tension

Subscripts

i	In
o	Out
H	Homogenous
L	Liquid
G	Gas

nb	Nucleate boiling
tp	Two-phase
sat	Saturation
ref	Refrigerant
crit	Critical

Although there are studies available in the literature [9-17] the capacities and behaviors of working fluids for subcritical ORC evaporators are not yet fully revealed. Thus, an in-depth study on subcritical ORC evaporator working fluids is necessary.

In that manner, this study aims to propose an extensive literature survey made for deducing the proper working fluids for ORCs, by means of including both the older and new generation refrigerants. The best candidates for future investigation of subcritical ORC evaporator research are proposed, by taking the previously reported desired thermo-hydraulic evaporation properties and selection criteria in subcritical cycles into consideration. Moreover, the thermo-hydraulic, environmental, safety and physical properties 9 zero ODP and low GWP refrigerants are discussed. Also some prospective research topics are discussed.

CHALLENGES OF LOW GRADE WASTE HEAT RECOVERY

The waste heat sources being utilized by ORCs can be listed as waste heat from the condenser of a conventional or a nuclear power plant, waste heat from industrial processes, solar radiation, geothermal energy [18], domestic applications [19] and internal combustion engines [20].

One of the major challenges of exploiting low grade temperature heat source is the temperature instability, which may especially lead to problems regarding to the fact that subcritical evaporation is an isothermal two-phase process. The thermodynamic efficiency of an evaporator working under subcritical conditions can change significantly with the changing source temperature [13, 21]. For overcoming that problem, mass flux of the working fluid or hot source should be controlled for keeping the pinch point temperature difference constant, which is significant for reliable calculations [22]. Moreover, components such as economizers or preheaters are being widely used for mitigating the heat transfer inconsistency by means of maintaining a steady state inlet temperature of the heat source. By those means, the thermal efficiency of a system through the heat exchanger can be increased up to 82%. [23]

Furthermore, from the aspect of surface where the heat transfer occurs, the low temperature difference between the waste heat source and working fluid necessitates larger heat transfer surfaces due to smaller temperature gradients between two fluid streams [24]. A too small sized evaporator will not be capable of evaporating the refrigerant completely at the evaporator outlet, which might cause turbine damage in some cases. On the other hand, a rather large evaporator yields working fluid superheating, which may lead to a negative impact on system performance and a high heat exchanger cost [25].

Despite its generally approved efficiency, the waste heat recovery done by means of direct heat transfer between heat source and working fluid may lead to chemical problems. Especially at high temperatures (e.g. during start-up and transients), the working fluid can deteriorate when its chemical stability potential is exceeded or when hot spots occur in the heat exchanger [26].

WORKING FLUIDS UNDER SUBCRITICAL CONDITIONS

When the related literature is investigated [3, 9-12, 16, 27-29], it can be deduced that subcritical ORC conditions and corresponding working fluid performances are affected by various system configuration parameters, operating conditions and thermo-physical properties of working fluids. Thus, it is a challenging task to come up with an optimal combination of all parameters. Each parameter should be particularly investigated and the working fluid should be chosen in accordance with the desired work output, operating conditions and system optimality.

In the Table 1, a parametric summary of the a priori literature about subcritical heat transfer working conditions and applications of various common and novel refrigerants which can be related to ORCs are provided. It should be noted that the parameters differ due to the large diversity of study conditions and application geometries.

Table 1: A priori studies of some refrigerants at subcritical region

Refrigerant	Pressure range (bar)	Hot Source Temp (K)	Tube Dia (mm)	Mass Flow (kg/s)	References
R123	1-6	300-443,15	0,8 -10	6,5	[3, 9-10, 12, 30]
R600	2-15	358,15–423,15	6-22	17,746	[2, 9-10, 12]
R245fa	1-12,5	358,15 – 460,15	10-15	3-33	[2, 9-10, 12-15, 31]
R600a	4-19	358,15 – 423,15	6-22	20,423	[2, 9-10,12]
R236ea	2-16	373,15-400	10	41,361	[2-3, 9, 13]
R114	12	358,15 – 423,15	16	37	[10, 12-13]
n-pentane	0,8-6	358,15 – 423,15	15	16,331	[2, 10, 12-13]
R141b	1-7	443,15-358,15	~0,8	4,86	[3, 10, 12, 30]
R365mfc	24	443,15-413,15	~0,8	~4	[16, 30]
R717	10-52	300 – 423,15	21	0,93	[2, 10,12]
R410a	<49	<345	6-14	~1	[15, 17]
SES36	8,7-25,07	379 - 443,15	~10	0,129 – 3,3	[30, 32-35]
R1234yf	4-28	333-393	7,9 - 20	0,03-0,08	[36-43]
R1234ze(E)	14-48	343-375	9	<0,01	[39, 44-47]

In the numerical study of He et al. [12], best working fluids were reported to be R114, R245fa, R123, R601a, n-pentane, R141b, and R113, from the aspect of total heat transfer capacity. These results are coming from the fact that larger net power output will be produced when the critical temperature of working fluid approaches the temperature of the waste heat source. Shengjun et al. [9] investigated the optimality of working fluids for subcritical ORCs. Fluids favored by the thermal efficiency and exergy efficiency are R123, R600, R245fa, R245ca and R600a. From the aspect of Carnot efficiency, the high thermal efficiency was obtained by increasing evaporating temperature and with fluids having high boiling point. Liu et al. [10] stated that the thermal efficiency for various working fluids is a weak function of the critical temperature, regardless of the fact that the working fluids with lower critical temperature demonstrate lower thermal efficiencies. Moreover, in general, the maximum value of total heat-recovery efficiency can be attained at an appropriate evaporating temperature between the inlet temperature of waste heat and the condensing temperature. In addition to that, the efficiency increases with the increase of the heat source inlet temperature and decreases when working fluids with lower critical temperatures are used. Chen et al. [28] performed an extensive review of working fluids and their potentials of usage in this group of fluids, by means of thermodynamic comparison between subcritical and supercritical ORC conditions. According to the study, isentropic fluids such as R141b, R123, R21, R245ca, R245fa, R236ea and R142b, which have critical temperatures above 400 K, are more favorable for subcritical ORCs. Moreover, working fluids having high density and high latent heat yield higher system efficiencies. On the other hand, Borsukiewicz-Gozdur and Nowak [29] have studied the performances of working fluids for a low temperature Rankine cycle. They reported that the working fluids having a critical temperature point close to the heat source temperature and a low evaporation enthalpy are prone to reach the critical point more rapidly. This leads to a faster replacement with more working fluid, thus, more waste heat removal. Moreover, they have stated that propylene and R245fa showed best efficiency in low temperature operations.

Mikielewicz et al. [11] reported a subcritical cycle for micro-CHP, where ethanol, R141b and R123 demonstrate the best cycle efficiency, as R365mfc demonstrates the least. According to the authors, heat transfer to vapor yields smaller values of heat transfer coefficient than the case of heat transfer during boiling of vapor. Therefore, the size of heat exchangers is influenced accordingly. Dai et al. [3] compared 9 working fluids and water for ORC applications. They reported that the ORC system operating with R236EA has higher exergy efficiency under the same given waste heat condition. Results show that R236EA has the highest exergy efficiency due to the lowest exhaust temperature in comparison to all the working fluids, including water. Marion et al. [16] studied a subcritical ORC solar collector. They reported that the mass flow rate of the working fluid significantly affects the efficiency. R365mfc was observed as having the highest heat storage performance, especially with the increasing mass flux. R365mfc is also reported as having optimal operating pressure at the evaporator, as the other investigated fluids (R134a and R227ea) necessitated higher pressure values which may increase the system cost.

Jarall [48] compared the refrigeration performance of R1234yf and R134a. They observed that R1234yf has less values of pressure ratio, discharge temperature, COP and Carnot efficiency and higher values of evaporation and convection heat transfer coefficients in comparison to R134a. R1234yf also yielded less evaporator overall heat transfer coefficient and by 3-27%. Park et al. [44] performed an experimental heat transfer study with R1234ze(E), R134a and R236fa. The results showed that R134a had higher experimental heat transfer coefficients (about 15-25%) than two other refrigerants. The experimental heat transfer coefficients of R236fa are slightly higher than R1234ze(E) (about 5%). Mikielewicz [30] conducted heat transfer experiments with R141b, R123, R134a, Ethanol and SES36. They stated that the critical temperature of the working fluid has a significant influence on the effectiveness of ORC and heat exchanger dimensions. According to the results, SES36 is found to be the best refrigerant for their particular case, by means of testing at an evaporation temperature as close to the critical temperature as possible. Tartière et al. [49] included R1233zd(E) in their study about subcritical and transcritical ORCs. They concluded that R1233zd(E) is a good working fluid candidate for subcritical and transcritical ORCs, despite the fact of relatively high specific investment cost. Moreover, Zyhowski et al. [50] mentioned in their patent application that R1233zd(E) can be very advantageous for subcritical ORCs operating especially between 90°C-165°C. According to the results, R1233zd(E) has the best cycle thermal efficiency in comparison to the R245fa, R365mfc, HFE-7100 and HFC-4310mee.

The research regarding DR-2 and HDR-14 is still at its infancy. Kontomaris [51] investigated DR-2 as a replacement for R123 in chiller applications. Results show that DR-2 could be a reasonable replacement, due to its low vapor pressures and high energy efficiency in comparison to R123 and R134a. Datla and Brasz [52] compared DR-2 with various refrigerants for their cycle thermal efficiencies. Especially R245fa was considered to be replaced. They stated that DR-2 has cycle efficiency comparable to R245fa; however it requires more heat transfer surface. Moreover, preliminary studies [53-55] regarding HDR-14 show that it could be a reasonable replacement for R245fa for usage in low grade temperature application. HDR-14 is reported to have lower vapor pressure, higher boiling point and critical temperature, and higher cycle thermal efficiency in comparison to R245fa.

From the perspective of thermal and chemical stability, organic fluids are usually prone to chemical deterioration and decomposition when working at high temperatures, unlike water. Therefore, the chemical stability of the working fluid is a significant constraint in determining the operation temperature ranges. Moreover, the working fluid is expected to be noncorrosive and compatible with the components used in the cycle. Calderazzi and Paliano [56] investigated the thermal stability of R-134a, R-141b, R-13I1, R-7146 and R-125, where stainless steel was used as the container material. Moreover, Andersen and Bruno [57] presented a method to assess the chemical and thermal stability of *n*-pentane, 2-methylbutane, 2,2-dimethylpropane, toluene and benzene by ampule testing techniques. The method is used to attain the decomposition reaction rate constant of fluids at custom temperatures and pressures. They reported that although the half-lives of all studied pure fluids are in the order of years, small concentrations of decomposition reaction products were found in all of the heated fluids after as few as 2 days.

When the mentioned studies are considered from the aspects of subcritical ORCs and performance evaluation of new refrigerants, the need for more extended scientific knowledge becomes observable. The aforementioned studies mostly focus on micro/mini scale evaporators and very low saturation temperatures. Therefore, especially there is no or very little amount of studies done for evaporators utilizing low-grade waste heat and having relatively larger diameters, which are common in ORCs.

SELECTION CRITERIA OF WORKING FLUIDS

As mentioned above, working fluid selection is a very important process for an efficiently operating ORC evaporator. Conventionally, working fluid investigation and selection are done by taking their legal status, environmental, chemical, thermal and physical properties into consideration.

Montreal and Kyoto protocols caused a strict phase-out of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs). Although the HFCs are still legislatively available, the working fluids having a GWP higher than 1000 are not regarded as reasonable topics for further research. Current chemical research on the related field is mainly focused on producing refrigerants having zero ODPs and low GWPs. As HFCs are to be phased-out completely in the future, new chemical compositions such as hydrofluoroolefins (HFOs) and hydrochlorofluoroolefins (HCFOs) are being proposed. Although there is an increasing number of numerical and simulation studies recently, the extent of research is still at its infancy stage for new generation working fluids in ORCs [37, 48]. Especially, empirical data is necessary for contributing to the void of scientific knowledge regarding HFOs and HCFOs.

Although it is not possible to distinguish the best working fluid for ORCs, several generally accepted criteria can be expressed. With the light of knowledge provided by various studies [5, 8, 28, 59-62], three main indicators (safety/environmental, thermo-hydraulic and economic) should be taken into account, alongside the following list of sub-criteria of working fluid selection for a subcritical ORC evaporator. The preferred environmental and safety criteria for prospective ORC research can be listed as:

- High safety factor according to ASHRAE criteria (low flammability and toxicity),
- Low ODP due to progressive phase-out of refrigerants having high ODP with Montreal Protocol,
- Low GWP for causing less carbon footprint in the environment,

The thermo-hydraulic and economic selection criteria can be listed as:

- High heat transfer coefficients for overcoming the design limitations of significantly dominant flue gas side overall heat transfer coefficient in flue gas cooled/heated heat exchangers. In other words, refrigerants with high heat transfer coefficients might allow designing evaporators with smaller size,
- Critical temperature slightly higher than heat source fluid's temperature due to thermal efficiency advantage of the increase in total heat capacity at higher evaporation temperatures,
- High boiling point (lower than heat source temperature) since it leads to higher thermal efficiencies,
- High liquid and vapor density, which would allow the mass flux to be higher at the same evaporator geometry. Also, high liquid and vapor density allows the usage of smaller heat exchangers, due to less pressure drop of system,
- High latent heat which increases the thermal efficiency and reduces the required mass flux for attaining same amount of heat removal,
- Relatively lower saturation pressure values so that the system operation cost can be maintained lower,
- Low liquid and vapor viscosity, which results in higher heat transfer coefficients and low friction losses,
- High thermal conductivity, which improves the heat transfer coefficient,
- High temperature stability for avoiding chemical decompositions,
- Lower melting point than lowest ambient temperature to avoid freezing,
- Low purchase cost.

Moreover, in accordance with the previous discussions, system efficiency of an ORC strongly correlates with the working fluid's boiling point, critical pressure and molecular weight [35].

EVALUATION OF WORKING FLUIDS FOR AN ORC EVAPORATOR

To evaluate the aforementioned criteria, HFCs R245fa, R365mfc, R245ca; and novel refrigerants such as R1234ze, R1233zd, Solkatherm® SES36 and R1234yf were investigated and compared to R134a as reference fluid. The properties of DR-2 and HDR-14 are also mentioned. However, these two refrigerants are not included in the simulations due to the lack of thermo-physical and experimental data. They are all pure fluids (except SES36, which is a pseudo-pure fluid) and have zero ODP. The ASHRAE criteria (according to the ANSI/ASHRAE Standard 34) represent the designation and safety classification of refrigerants. The letters "A" and "B" denote low and high toxicity, respectively; whereas the numbers 1 to 3 denote the flammability index (1 means no flammability and 3 means high flammability) and the letter "L" denotes "lower flammable than mentioned criteria". The Table 2 represents the main properties of refrigerants.

Table 2: Working fluids selected for investigation

Working Fluids	GWP	ASHRAE Criteria	M. Mass ($g.mol^{-1}$)	Normal Boiling Point (K)	T_{crit} (K)	P_{crit} (MPa)
R134a	1430	A1	102,03	246,6	374,1	4,06
R245fa	950	B1	134,05	288,05	427,2	3,640
R365mfc	794	N/A	147,8	313,3	460	3,266
SES36	N/A	Non-Flammable	184,53	308,75	450,7	2,849

R245ca	693	A/B2	134,05	298,41	447,57	3,94
DR-2	9,4	A1*	164,05	306,55	444,45	2,903
HDR-14	7	A1*	N/A	293,15	>427,15	N/A
R1234ze	6	A2L	114	254,15	384,35	3,576
R1233zd	5	A1	130,5	292,15	438,75	3,570
R1234yf	4	A2L	114	245,15	369,25	3,435

*Expected criteria

In order to clarify the capabilities of the fluids in Table 2 in fulfilling the desired working fluid criteria, some boundary condition assumptions were made and exemplary tubular evaporator geometry was used for the working fluid property simulations related to a subcritical ORC evaporator. Table 3 represents the assumptions and considered evaporator geometry.

Table 3: Exemplary tubular heated section conditions

D_o (m)	t_w (m)	L (m)	T_{crit} - T_{sat} (K) (ΔT_{sat})	G (kg/m^{2}s)	Material
0,0254	0,00277	2	10°C to 70°C	200	Copper

In the light of the application range information provided in Table 1 and the fluid properties from Table 2, a range of fluid saturation temperature (ΔT_{sat}) from 10°C to 70°C lower than each fluid's critical temperature ($\Delta T_{sat} = T_{crit}$ -70°C to 10°C) was taken into account for each particular refrigerant, for the sake of a reasonable comparison between thermodynamic properties and thermo-hydraulic performances. For calculating the mean convective heat transfer coefficients, Gungor-Winterton correlation [63] was used. Frictional pressure drops were calculated through Friedel's correlation [64]. In the literature, performance prediction and evaluation studies exist for both correlations [38, 65-67]. Those correlations have a reasonable application range for subcritical ORCs as shown in Table 4.

Table 4: Application ranges of used correlations

Correlation	q (W/m^2)	D_i (mm)	P_{sat} (kPa)	G (kg/m^{2}s)
Gungor-Winterton [63]	350 - 70000	2,95 - 32	35 - 1030	12 – 2863
Friedel [64]	No limit	No limit	No limit	<2000

Gungor and Winterton [63] correlation for two-phase heat transfer is expressed as following:

$$h_{tp} = Eh_L + Sh_{nb} \tag{1}$$

where liquid-phase convective heat tr ansfer coefficient $\propto_L$ is expressed through Dittus-Boelter (1930) correlation as:

$$h_L = 0{,}023 Re_L^{0,8} Pr_L^{0,4} (\frac{k_L}{D_i}) \tag{2}$$

where liquid Reynolds number Re_L and Prandtl number Pr_L are defined as:

$$Re_L = \frac{\dot{m}(1-x)D_i}{\mu_L} \tag{3}$$

$$Pr_L = \frac{c_{pL}\mu_L}{k_L} \tag{4}$$

where the nucleate boiling coefficient is calculated through Cooper (1984b) correlation as:

$$h_{nb} = 55 p_r^{0,12} (-0{,}4343 \ln p_r)^{-0,55} M^{-0,5} q^{0,67} \tag{5}$$

Two-phase convection multiplier E is expressed as:

$$E = 1 + 24000 Bo^{1,16} + 1{,}37 \frac{1}{X_{tt}}^{0,86} \tag{6}$$

where Boiling number Bo is:

$$Bo = \frac{q}{\dot{m}H_{lg}} \tag{7}$$

and Lockhart-Martinelli parameter X_{tt} is:

$$X_{tt} = (\frac{1-x}{x})^{0,9} (\frac{\rho_G}{\rho_L})^{0,5} (\frac{\mu_L}{\mu_G})^{0,1} \tag{8}$$

The boiling suppression factor S is expressed as:

$$S = \left[1 + 0{,}00000115 E^2 Re_L^{1,17}\right]^{-1} \tag{9}$$

Moreover, the Friedel [64] correlation for two-phase pressure drop is implemented through introducing a two-phase multiplier φ_{fr}^2 to the liquid pressure drop ΔP_L as:

$$\Delta P_{frict} = \Delta P_L \varphi_{fr}^2 \tag{10}$$

$$\Delta P_L = 4 f_L (\frac{L}{D_i}) \dot{m}_{total}^2 (\frac{1}{2\rho_L}) \tag{11}$$

The liquid friction factor $\boldsymbol{f_L}$ is expressed as:

$$f_L = \frac{0{,}079}{Re^{0,25}} \tag{12}$$

Two-phase multiplier is defined as:

$$\varphi_{fr}^2 = E + \frac{3{,}24 FH}{Fr_H^{0,045} We_L^{0,035}} \tag{13}$$

Dimensionless factors are as follows:

$$Fr_H = \frac{\dot{m}_{total}^2}{g D_i \rho_H^2} \tag{14}$$

$$E = (1-x)^2 + x^2 \frac{\rho_L f_G}{\rho_G f_L} \tag{15}$$

$$F = x^{0,78} (1-x)^{0,224} \tag{16}$$

$$H = (\frac{\rho_L}{\rho_G})^{0,91}(\frac{\mu_G}{\mu_L})^{0,19}(1-\frac{\mu_G}{\mu_L})^{0,7} \quad (17)$$

The liquid Weber number We_L is defined as:

$$We_L = \frac{\dot{m}_{total}^2 D_i}{\sigma \rho_H} \quad (18)$$

Homogeneous density based on vapor quality is as follows:

$$\rho_H = (\frac{x}{\rho_G} - \frac{1-x}{\rho_L})^{-1} \quad (19)$$

RESULTS AND DISCUSSION

A performance screening is made by means of observing the influence of P_{sat}, H_{lg}, ρ_l, ρ_g, μ_l, μ_g on h_{tp} and ΔP_{ref} for each refrigerant at the ΔT_{sat} ranges mentioned in Table 3. Figures 1 to 6 show the investigated parameters for R134a, R245fa, R245ca, R1234yf, R1234ze, R1233zd(E), SES36 and R365mfc. The values at X axis' of figures are sorted from left to right with respect to decreasing ΔT_{sat}.

Figure 1 shows the influence of saturation pressure P_{sat} to h_{tp} to ΔP_{ref}. Fluids with higher P_{sat} ranges such as R1234ze, R134a and R245ca have higher heat transfer coefficients at low and high saturation pressures. At saturation pressures lower than 2,23 MPa, R134a has the highest heat transfer coefficients, and followed by R1234ze and R245ca. The line-up changes as the saturation pressure gets higher. R1234ze, R245ca and R1234yf have higher h_{tp} at higher P_{sat} ranges. R1233zd has the lowest h_{tp} continuously. The h_{tp} difference among all fluids gets less significant as ΔT_{sat} gets lower. On the other hand, P_{sat} range of a fluid is observed to be an insignificant indicator of expected ΔP_{ref}, yet the line-up is in accordance with h_{tp} case. Fluids having larger P_{sat} values cause more pressure drops. SES36 deviates significantly (>20%) among others as the fluid with lowest pressure drop. The deviation of all pressure drops slightly increase as ΔT_{sat} gets lower.

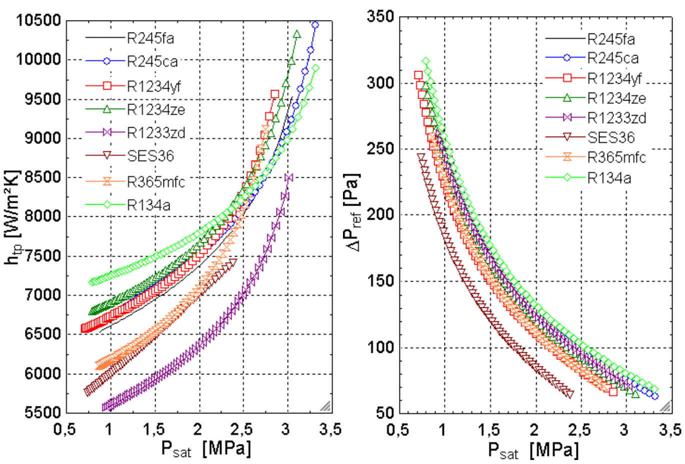

Figure 1: h_{tp} (left) and ΔP_{ref} (right) vs P_{sat} for all fluids

Figure 2 shows the influence of latent heat H_{lg} of vaporization on h_{tp} and ΔP_{ref}. Fluids with higher H_{lg} tend to have higher h_{tp} in general, whereas SES36 with lowest H_{lg} has the lowest h_{tp} accordingly. This relation is probably related to the amount of heat flux, which changes according to total heat removal for same evaporator geometry. The H_{lg} values reduce as ΔT_{sat} gets lower, whereas the h_{tp} deviation among fluids get gets slightly less significant as well. R245ca, R134a and R1234ze have the highest H_{lg} values, whereas SES36 has the lowest. Generally, high H_{lg} seems to be a strong indicator of expected high h_{tp}, which can make a difference up to 50%. On the other hand, fluids having high H_{lg} cause less pressure drops. ΔP_{ref} decreases as ΔT_{sat} gets lower, whereas R134a and SES36 have the lowest and highest ΔP_{ref} values, respectively.

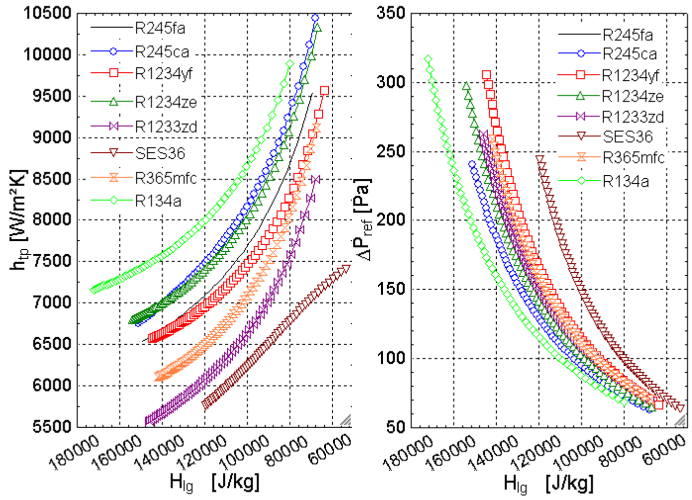

Figure 2: h_{tp} (left) and ΔP_{ref} (right) vs H_{lg} for all fluids

Figure 3 and 4 shows the influence of ρ_l and ρ_g on h_{tp} and ΔP_{ref}. Figure 3 indicates that liquid phase density is a strong indicator of h_{tp} and ΔP_{ref}. Fluids having low liquid densities such as R365mfc and R1233zd have lower h_{tp}, whereas the high h_{tp} values of R245ca, R245fa and R134a are in accordance with their higher densities. ΔP_{ref} values are high for the fluids with lowest ρ_l. In that manner, R365mfc seems to be the most disadvantageous fluid for heat transfer and pressure drop concerns due to its low ρ_l.

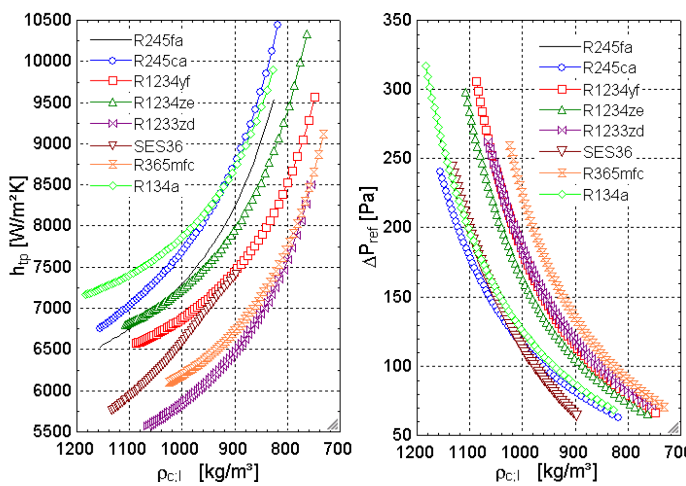

Figure 3: h_{tp} (left) and ΔP_{ref} (right) vs ρ_l for all fluids

Figure 4 implies that the vapor density is quite the same in all fluids. However, the vapor heat transfer performance of R365mfc, R1233zd and SES36 seems to be relatively low. SES36's h_{tp} rise slows down as ΔT_{sat} gets lower. On the other hand, the effect of ρ_g for ΔP_{ref} is insignificant and a negligible relation in between is observed.

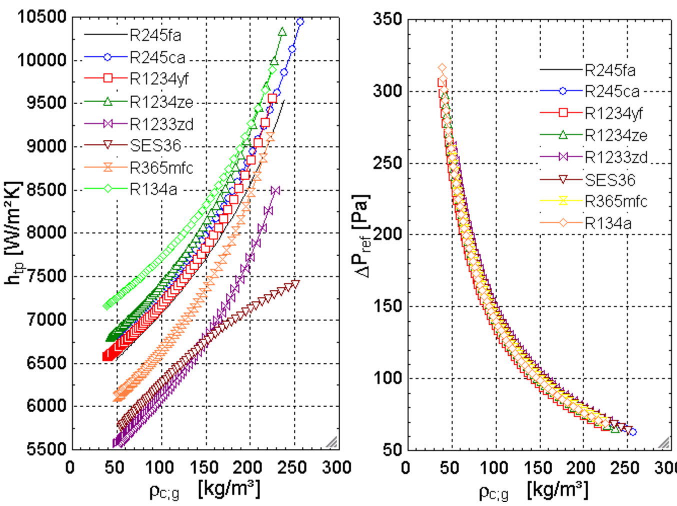

Figure 4: h_{tp} (left) and ΔP_{ref} (right) vs ρ_g for all fluids

Figure 5 shows the influence of liquid phase dynamic viscosity μ_l on h_{tp} and ΔP_{ref}. As discussed before, low viscosity fluids like R1234yf, 1234ze, R134a and R365mfc have high h_{tp} as saturation temperature approaches T_{crit} (i.e. as ΔT_{sat} gets lower). Especially R1234yf and R1234ze allow attaining high heat transfer coefficients due to their low viscosities at lowest values of ΔT_{sat}. Similarly, R1234yf and R1234ze have higher ΔP_{ref}, but have similar ΔP_{ref} values with others at relatively lower viscosities.

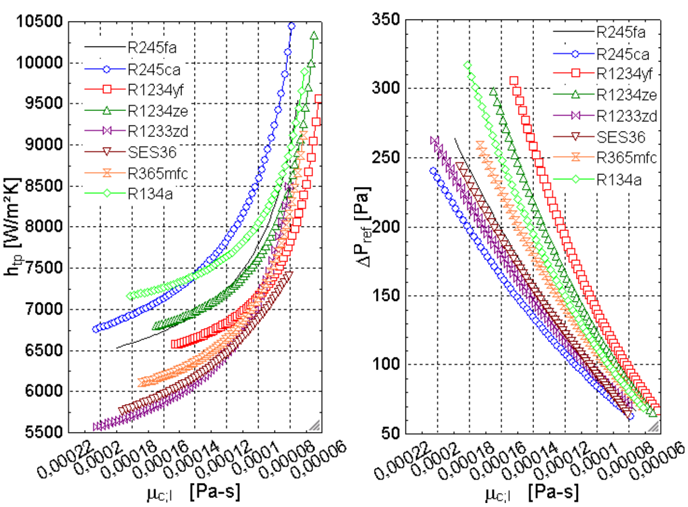

Figure 5: h_{tp} (left) and ΔP_{ref} (right) vs μ_l for all fluids

Figure 6 shows the influence of μ_g on h_{tp} and ΔP_{ref}. Fluids having low vapor viscosities like R1234yf and R134a have high h_{tp} values. R1233zd and SES36 yield the lowest h_{tp} with higher viscosity values. Similar to liquid behaviors, R1234yf and R134a has the lowest vapor viscosity and pressure drop in comparison to others. However the influence of vapor viscosity on ΔP_{ref} decreases greatly as the influence of liquid viscosity gets dominant especially at lower ΔT_{sat} values.

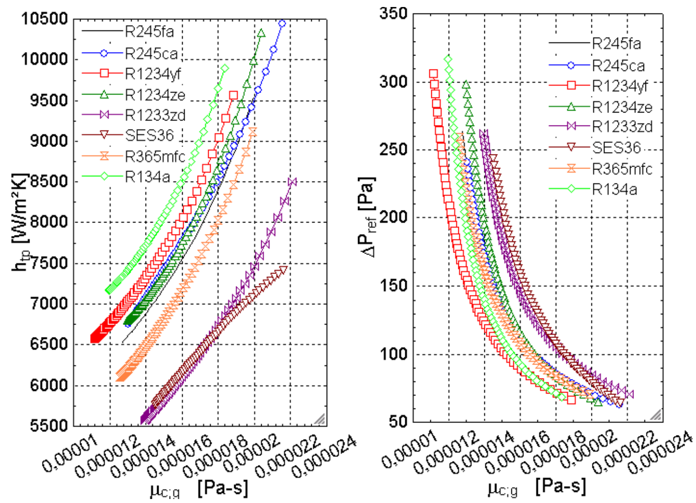

Figure 6: h_{tp} (left) and ΔP_{ref} (right) vs μ_g for all fluids

CONCLUSION

The thermo-hydraulic performance predictions of R134a, R245fa, R245ca, R1234yf, R1234ze, R1233zd(E), SES36 and R365mfc are performed for an exemplary tubular subcritical ORC evaporator. For a subcritical range of T_{crit} – 10°C to 70°C, influence of saturation pressures, latent heats, liquid and vapor viscosities and densities on two-phase heat transfer coefficients and pressure drops for each refrigerant are evaluated. Gungor and Winterton correlation was used for two-phase heat transfer coefficient, whereas Friedel's correlation for the two-phase pressure drop. According to the results, following conclusions are made:

- Choice of a reasonable working fluid highly depends on heat source profile, evaporator geometry and desired operation conditions.
- At low-temperature heat sources, fluids having lowest critical points should be implemented in the subcritical ORCs.
- SES36 is not recommended for larger scale evaporators, since it is prone to high frictional pressure drops due to high vapor and liquid viscosities. Moreover, low latent heat necessitates higher mass flow rates.
- R1234ze and R245ca are promising working fluids as replacement for R134a, and may have high thermal efficiencies especially for ORC applications with small or middle size evaporators that are subject to relatively low-temperature heat sources. They might allow operating with smaller heat exchangers. However, their high purchase price is a disadvantage.
- R1234yf comprises many of the desired thermo-physical working fluid criteria alongside good heat transfer coefficients and low pressure drops. Only disadvantages are the low density, which can be overcome through

increasing the mass flow rate if necessary, and the high price.
- Predictions regarding R1233zd(E) imply that it may not be suitable for most of the subcritical ORC applications, yet more empirical studies are necessary for investigating it's thermo-hydraulic capabilities.
- R245fa and R365mfc have moderate results and properties in comparison to other fluids.
- As a replacement for R134a, R245fa is the most recommended fluid for subcritical ORC evaporators, due to acceptable heat transfer and pressure drop values, existence of more knowledge in literature and low cost.
- Before making a choice, desired work output, operating conditions and system optimality should be evaluated in detail.
- For contributing to the knowledge about subcritical ORCs, an extensive set of experiments is necessary for a complete understanding of the capabilities of new working fluids (especially of HDR-14 and DR-2) for evaporators with relatively larger diameters.

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