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## Prospects of the use of nanofluids as working fluids for organic Rankine cycle power systems

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### Abstract

The search of novel working fluids for organic Rankine cycle power systems is driven by the recent regulations imposing additional phase-out schedules for substances with adverse environmental characteristics. Recently, nanofluids (i.e. colloidal suspensions of nanoparticles in fluids) have been suggested as potential working fluids for organic Rankine cycle power systems due to their enhanced thermal properties, potentially giving advantages with respect to the design of the components and the cycle performance. Nevertheless, a number of challenges concerning the use of nanofluids must be investigated prior to their practical use. Among other things, the trade-off between enhanced heat transfer and increased pressure drop in heat exchangers, and the impact of the nanoparticles on the working fluid thermophysical properties, must be carefully analyzed. This paper is aimed at evaluating the prospects of using nanofluids as working fluids for organic Rankine cycle power systems. As a preliminary study, nanofluids consisting of a homogenous and stable mixture of different nanoparticles types and a selected organic fluid are simulated on a case study organic Rankine cycle unit for waste heat recovery. The impact of the nanoparticle type and concentration on the heat exchangers size, with respect to the reference case, is analyzed. The results indicate that the heat exchanger area requirements in the boiler decrease around 4 % for a nanoparticle volume concentration of 1 %, without significant differences among nanoparticle types. The pressure drop in the boiler increases up to 18 % for the same nanoparticle concentration, but this is not found to impact negatively the pump power consumption.

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*Keywords:* organic Rankine cycle; working fluids; nanofluids.

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**Nomenclature**

$\rho$	density, kg/m <sup>3</sup>	PG	propylene glycol
$\mu$	dynamic viscosity, Pa s	PHE	plate heat exchanger
$k$	thermal conductivity, W/mK	$p_{\text{sat}}$	saturation pressure
$h_t$	heat transfer coefficient, Wm <sup>-2</sup> K <sup>-1</sup>	STHE	shell and tube heat exchanger
$c_p$	isobaric heat capacity, kJ/kgK		
$\Delta p$	pressure drop	<b>Subscripts</b>	
EG	ethylene glycol	nf	nanofluid
HTO	heat transfer oil	bf	base fluid
ORC	organic Rankine cycle	np	nanoparticle

**1. Introduction**

The search of novel working fluids for organic Rankine cycle (ORC) power systems is driven by the recent regulations imposing additional phase-out schedules for substances with adverse environmental characteristics. Researchers have recently suggested the great potential of nanofluids as working fluids for ORCs [1] due to their enhanced thermal properties, potentially giving advantages with respect to the design of the components and the cycle performance. However, the research on the practical use of nanofluids as working fluids is at a very early stage, mostly based on simulations, and currently the research efforts are focused on understanding the changes introduced in the thermophysical properties and heat transfer characteristics of the fluid by the addition of nanoparticles. Saadatfar et al. [2, 3] suggested the use of a nanofluid, consisting of pentane and silver nanoparticles, as a working fluid for an ORC unit operating in a system of concentrated solar thermal polygeneration. The authors concluded that the use of the nanofluid allowed for smaller heat exchangers and increased efficiencies, compared to the base fluid. Other works simulate the use of nanofluids as heat transfer fluids of solar collectors or intermediate loops for the heat source or sink, but to the best of our knowledge, no other studies have evaluated the performance of nanofluids as working fluids of ORC power systems.

Although there are a number of challenges concerning the practical use of nanofluids that need further investigations (e.g. nanofluid stability, migration of nanoparticles to the gas phase, performance in expanders, settling in heat exchangers), the level of knowledge presently available allows performing a first evaluation of the potential benefits that nanofluids could bring to ORC units. In this sense, a sensitivity analysis that relates the size of heat exchangers with the change in the working fluid heat transfer and thermophysical properties due to the addition of nanoparticles, can provide initial insight on the prospects of nanofluids in this field.

This paper aims at evaluating the effects of the use of nanofluids as working fluids for ORC power systems on the heat exchanger's size, the pressure drops, and the pump power consumption. For a given application case, a preliminary sensitivity analysis of the heat exchanger's size is carried out for a series of base fluid and nanoparticle combinations. The paper presents first a brief literature review of the available publications on experimental studies on thermophysical properties and heat transfer of nanofluids. Next, general trends of these properties as a function of the volume concentration of nanoparticles are derived. Then, the calculated ranges of the properties are used as inputs on a Monte Carlo simulation of a case study ORC unit, and their impact on the boiler size, boiler pressure drop, and pump power consumption is discussed.

**2. Thermophysical properties of nanofluids***2.1. Literature review*

The addition of nanoparticles to improve the thermophysical properties of fluids has been studied since the mid-1990s [4], but it was only in the early 2000s the first experimental study on nanofluids heat transfer was published [3]. Since then, around 2000 publications on experimental studies with nanofluids have been presented, of which nearly 50% belong to the last 3 years.

The compilation of data which is presented here, is based on an under-development database which collects experimental data of several thermophysical properties (density  $\rho$ , isobaric heat capacity  $c_p$ , thermal conductivity  $k$ , and dynamic viscosity  $\mu$ ) for a number of nanofluids consisting of a pure fluid or binary mixture, and a single type of nanoparticles. Figure 1 shows the distribution of the currently available data in the database, as a function of the studied property (1.a), nanoparticle (1.b), and base fluid (1.c). As it can be observed, the number of studies on aqueous nanofluids exceeds the rest, in the same way that the most studied nanoparticles are  $Al_2O_3$  and  $CuO$ , which could be a consequence of their lower cost. In the same way, density data are the most available in the literature, while thermal conductivity data are scarcer (most likely due to the ease or complexity, respectively, of their measuring procedure). Due to the lack of enough experimental data on vapor pressure of nanofluids, this property will be neglected in the following analysis.

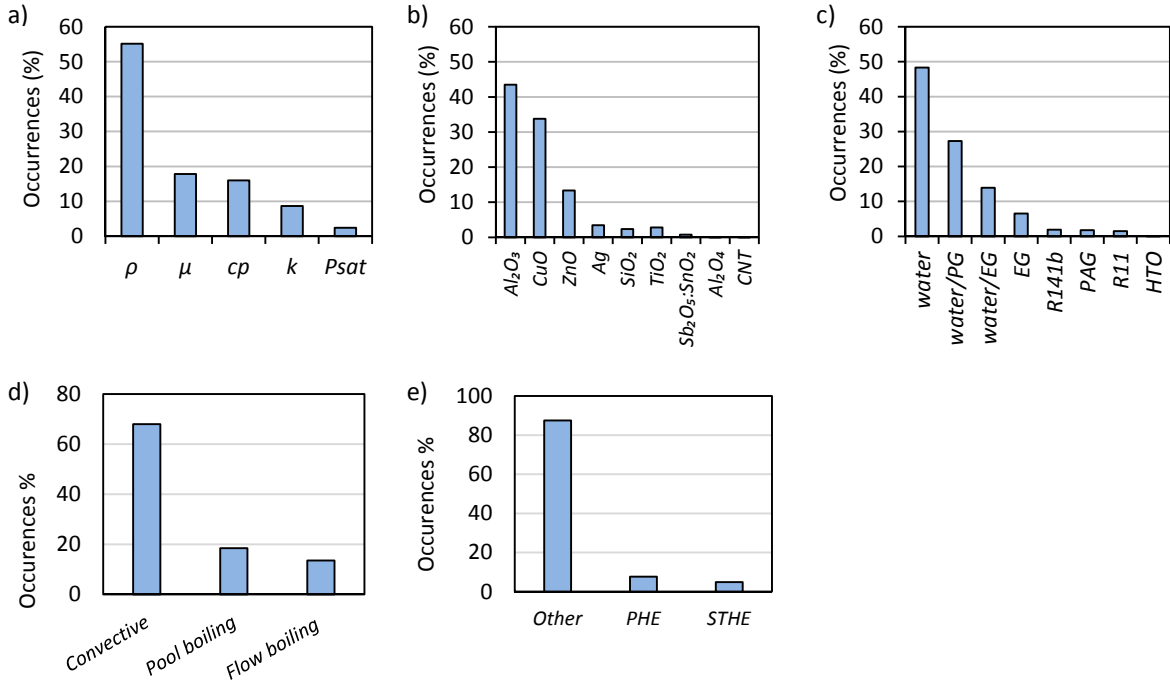


Fig. 1. Distribution of the available experimental data for thermophysical and heat transfer properties of nanofluids based on: a) thermophysical property, b) nanoparticle, c) base fluid, d) heat transfer process, and e) type of heat exchanger (d) and e) are based on a keywords search on Scopus).

## 2.2. Prediction of nanofluids' properties

Several correlations have been developed during the last few years in order to predict the thermophysical properties of nanofluids. Linear correlations using the volume concentration and the properties of the nanoparticles are commonly used for density and specific heat capacity, giving satisfactory results especially at low temperatures and low volume concentrations. However, we have observed high relative deviations for viscosity and thermal conductivity, for which more complex correlations, both theoretical and empirical, have been proposed by different authors. These more complex correlations consider additional parameters for the prediction, such as the particle average diameter, the molecular weight, or the thermal diffusivity. Furthermore, it must be pointed out that some of the analyzed experimental data show high discrepancies with similar studies, which could indicate the presence of outliers in the database and should be considered carefully.

In order to analyze, in a general way, to what extent thermophysical properties are enhanced by the addition of nanoparticles, a new parameter, the *impact factor*, was defined as  $F_{\chi} = \chi_{nf} / \chi_{bf}$ , where  $\chi$  refers to each of the mentioned properties, *nf* refers to nanofluid, and *bf* to base fluid. This parameter has been used by a number of authors to evaluate the influence of nanoparticles on the heat transfer coefficient and pressure drops [5], and for

consistency, we use it also here for the evaluation of the change in thermophysical properties. Figure 2 shows the experimental impact factor for each of the considered thermophysical properties (i.e. density, heat capacity, dynamic viscosity, and thermal conductivity) as a function of the nanoparticles volume ratio. Nanofluids with the same base fluid are represented in the same color, while the type of nanoparticles is represented with the same symbol.

The plots of Figure 2 show that all properties but the isobaric heat capacity increase with the volume fraction of nanoparticles, irrespectively of the nature of particles or base fluid. However, this relative increase with respect to the base fluid properties shows a significant scatter, not only among nanofluids of different composition, but also within the same nanofluid studied in different publications. In order to obtain a simplified trend of these data, we calculated the 25% and 75% quartiles of the data for each interval of volume concentration. In this way, the impact of outliers in the database is also minimized. The trend lines of the quartiles, which were fitted by the least squares method, are represented in Figure 2 by dashed lines, so that it can be considered that for a certain volume concentration of nanoparticles, the impact factor would be between the two lines for at least 50% of the cases (no matter the base fluid or nanoparticle type).

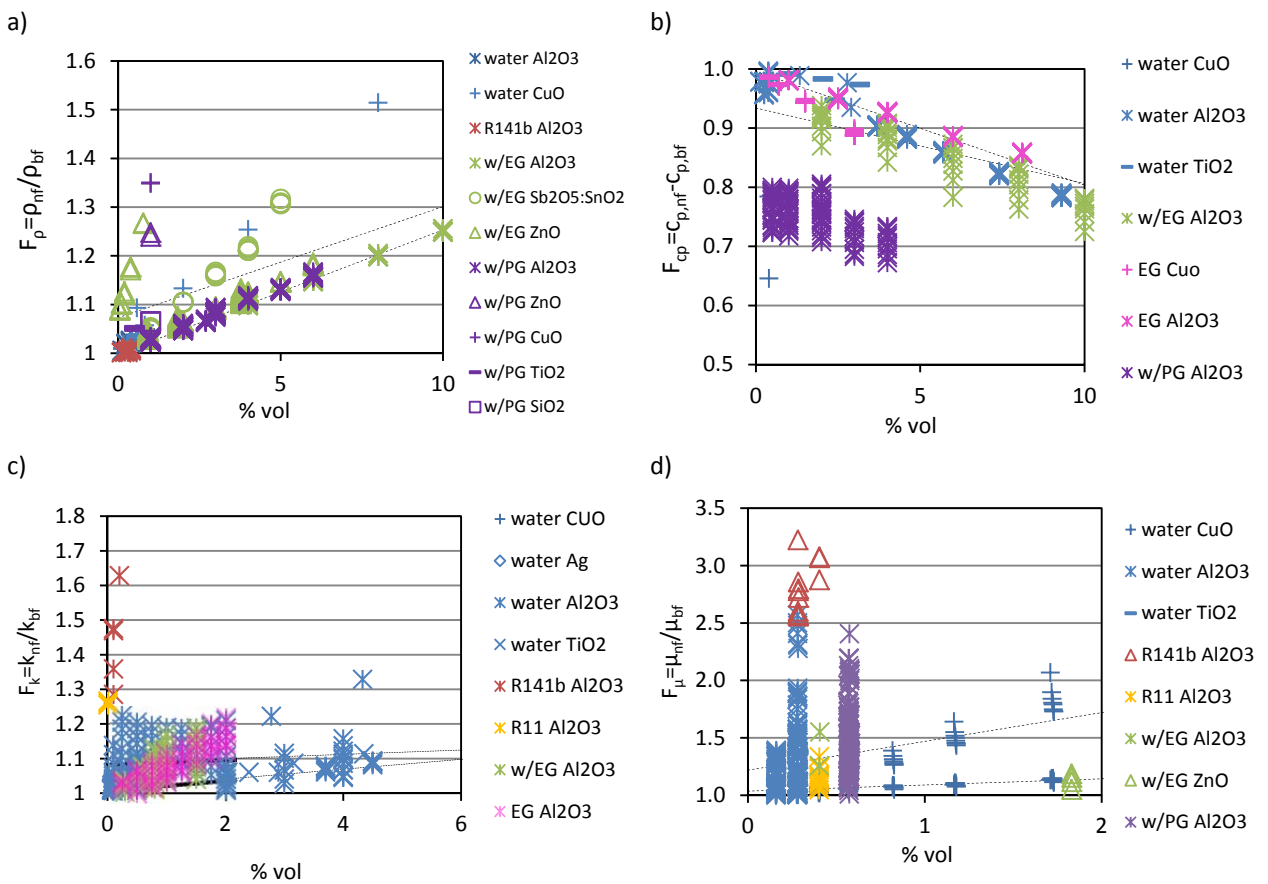


Fig. 2. Impact factor versus volume fraction for a) density ( $F_\rho$ ), b) heat capacity ( $F_{cp}$ ), c) thermal conductivity ( $F_k$ ), and d) viscosity ( $F_\mu$ ). The dashed lines represent the trend lines of the 25% and 75% quartiles calculated for each interval of volume concentration (w/EG: water – ethylene glycol mixtures; w/PG: water – propylene glycol mixtures).

### 3. Heat transfer of nanofluids

#### 3.1. Literature review

The enhancement of heat transfer of nanofluids has been pointed out since two decades ago [6], and it has been explained by the intensification of the flow turbulence due to the interaction between the nanoparticles and the base fluid, the suppression of the thermal boundary layer, and a substantial augmentation of the surface area and the effective thermal conductivity of the fluid [7].

Figures 1.d and 1.e show the distribution of the available experimental works on heat transfer of nanofluids depending on the heat transfer process and the type of heat exchanger, respectively. As it can be seen, most of the studies are carried out in single pipes, while only a few studies use plate heat exchangers (PHE) or shell and tube heat exchangers (STHE). The majority of these studies refer to convective heat transfer, followed by pool boiling of water based nanofluids, although the study of flow boiling could have more interest in order to assess the performance of nanofluids in practical applications, such as refrigeration or power cycles. Moreover, it should be pointed out that, to the best of our knowledge, no publication on the study of heat transfer of nanofluids in condensation is available today. Because of this, the effect of nanofluids on the heat transfer coefficient in the condenser is not explicitly accounted in this work, and only the thermophysical properties enhancement will apply.

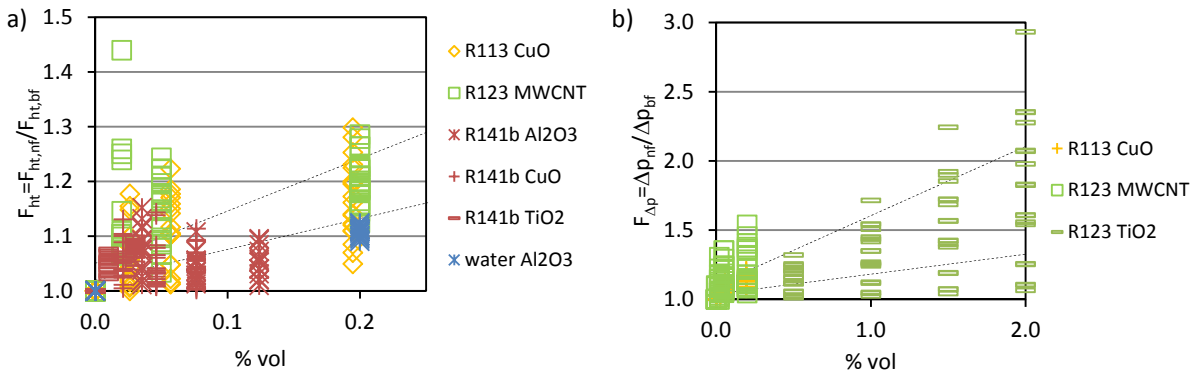


Fig. 3. Impact factor versus volume fraction for a) heat transfer coefficient ( $F_{ht}$ ), and b) pressure drop ( $F_{Dp}$ ). The dashed lines represent the trend lines of the 25% and 75% quartiles calculated for each interval of volume concentration.

#### 3.2. Prediction of nanofluids' heat transfer

In order to predict the heat transfer behavior of a nanofluid, previous works suggest that the nanofluid can be treated as a pure fluid, so that the equations of continuity, motion and energy can be utilized. Therefore, the dimensionless correlations of pure fluid heat transfer can be applied as well to nanofluids, by using the nanofluids thermophysical properties instead. In the case of single phase heat transfer, Xuan and Roetzel [8] suggested that this approach is applicable for nanofluids if their effective thermophysical properties are used. This was followed in the present work, where the heat transfer of the nanofluid in the single phase heat transfer was estimated by using the standard heat transfer correlations with the nanofluid thermophysical properties.

However, this approach has been found not to be applicable for two-phase heat transfer. In this regard, and similarly to the previous section, an under-development database collecting the data of all published experiments on the thermal-hydraulic performance of nanofluids, has been used to analyze the two-phase heat transfer enhancement of different nanofluids. The main evaluated variables are the heat transfer coefficient and the pressure drop. Here, two impact factors are also defined, as in section 2.2., for each of them ( $F_{ht}$  and  $F_{Dp}$ ). As a general observation, the experimental heat transfer coefficient (or Nusselt number) increases with the nanoparticle volume fraction and the Reynolds number. However, the magnitude of the enhancement depends significantly on the heat transfer process, the nanofluid type, and the experimental conditions. Although two main correlations were used by researchers to

correlate their experimental data [5, 9], we have observed high deviations from experimental data, especially at high nanoparticle volume concentrations. Figure 3 represents the impact factors of the heat transfer coefficient ( $F_{ht}$ ) and pressure drop ( $F_{\Delta p}$ ) for different volume concentrations and nanofluids. Despite the scatter of data, especially at low volume concentrations, a general positive trend can be obtained by calculating the 25% and 75% quartiles, as before, which is represented by dashed lines.

#### 4. Impact of nanofluids in an ORC unit operation

Since it was observed that the developed predictive correlations are not accurate for all nanofluids, or for a wide temperature range, the effects of nanofluids were evaluated by imposing variations to the properties within specific ranges. A Monte Carlo method [10] was employed, using the already defined quartile trend lines to determine the maximum and minimum limits for each property range. In this way, the impact of the nanoparticles is evaluated through the relative variation of the boiler area, the pressure drops, and the pump power consumption with respect to a base case study. Such approach provides preliminary insights on the potential benefit that the use of nanofluids could have in ORC power systems. Future work will include the development of more accurate correlations for the prediction of the thermophysical properties and heat transfer of nanofluids, with the aim of evaluating more accurately the benefit of using them in ORC units.

The base case study that was considered in this work was presented by Andreasen et al. [11], and consists of an ORC unit without regeneration used for waste heat recovery (WHR) of a water stream at 90 °C, and using R32 (difluoromethane) as working fluid. The main simulation parameters (e.g. turbine and pump efficiencies, sink temperature, etc...) can be found in Ref. [11]. The values of the decision variables (e.g. diameter, baffling, and number of tubes in the heat exchangers, pinch point in heat exchangers, evaporator pressure, superheating degree) were optimized for maximum net power output of the proposed case, for a fixed total cost of 800 k\$ [11]. The simulation model used to perform this study is a modification of a previous model, presented by Andreasen et al. [12]. The impact of the nanoparticles on the working fluid has been accounted for in the following way: I) the considered thermophysical properties of the working fluid were multiplied by their corresponding impact factors, which were functions of the nanoparticle volume concentration; II) for the heat transfer in the boiler, the impact factor of the heat transfer coefficient was considered; III) while in the evaporation the heat transfer impact factor was considered, only the changes of the properties were considered in both the single phase heat transfer (i.e. preheating) and condensation (due to the lack of experimental data on the impact of nanoparticles on the latter heat transfer process); IV) the pressure drops in the evaporation in the boiler were affected by the defined impact factor for pressure drops; V) the pump efficiency is affected by the increase in viscosity of the nanofluid, according to the correlation proposed by Gülich [13] for viscous fluids. Other assumptions made in this work include the following: heat exchangers were considered of the shell and tube type (where the working fluid flows inside the tubes), and surfactants are not considered. It is unclear, from the available literature [14], whether nanoparticles can migrate to the gas phase of the working fluid, and therefore, flow through the expander. Because of this, the effect of nanoparticles on the expansion is not considered, and their impact is studied here only from the point of view of the reduction of the heat transfer area, and the increase of the pressure drops and pump power consumption (assuming that further modifications on the cycle configuration would be needed, possibly including a turbine by-pass of a nanoparticle-enriched stream). This simulation process was carried out, for the nanoparticles shown in Table 1, for a set of 1000 samples of input variables for the Monte Carlo method, which were generated aleatory considering a normal distribution of each variable.

Table 1. Thermophysical properties of the nanoparticles studied in this work (at ambient temperature).

Property / Nanoparticle	Al <sub>2</sub> O <sub>3</sub>	CuO	ZnO	Ag	SiO <sub>2</sub>	TiO <sub>2</sub>	SWCNT
Density, $\rho$ (kg/m <sup>3</sup> )	3950	6320	5610	10490	2650	4230	2170
Thermal conductivity, $k$ (W/mK)	25	33	13	407	1.4	8.4	3000
Heat capacity, $c_p$ (kJ/kgK)	0.85	0.55	0.43	0.24	0.93	0.68	2.1

The simulation results were analyzed in terms of the variation of the boiler heat exchanger area and pressure drop, and the pump power consumption, in relation to those of the reference case. Due to the fact that no explicit heat transfer enhancement was considered in the condenser, the change in the condenser size was negligible, and is, therefore, not presented here. Figures 4.a, 4.b and 4.c depict the relative change of the boiler heat transfer area, the pump power consumption, and the pressure drop in the boiler as a function of the nanoparticle volume concentration, for the nanoparticle types given in Table 1. The error bars represent the standard deviation of the property obtained from the Monte Carlo simulation (considering that the output variable follows a normal distribution).

The results indicate that the boiler area decreases with the volume concentration, while the pressure drops in the boiler increase significantly. The pump power consumption does not increase significantly, and it remains within the bar of uncertainty, so it can be concluded that, based on the correlation by Gülich, the nanoparticle impact on the pump performance will not be important. The increase in pressure drops is expected and follows the notable increase of the fluid viscosity with the addition of nanoparticles. The decrease in the required boiler area results from the increase of the overall heat transfer coefficient, which reduces the amount of heat exchange area needed for the same heat transfer rate.

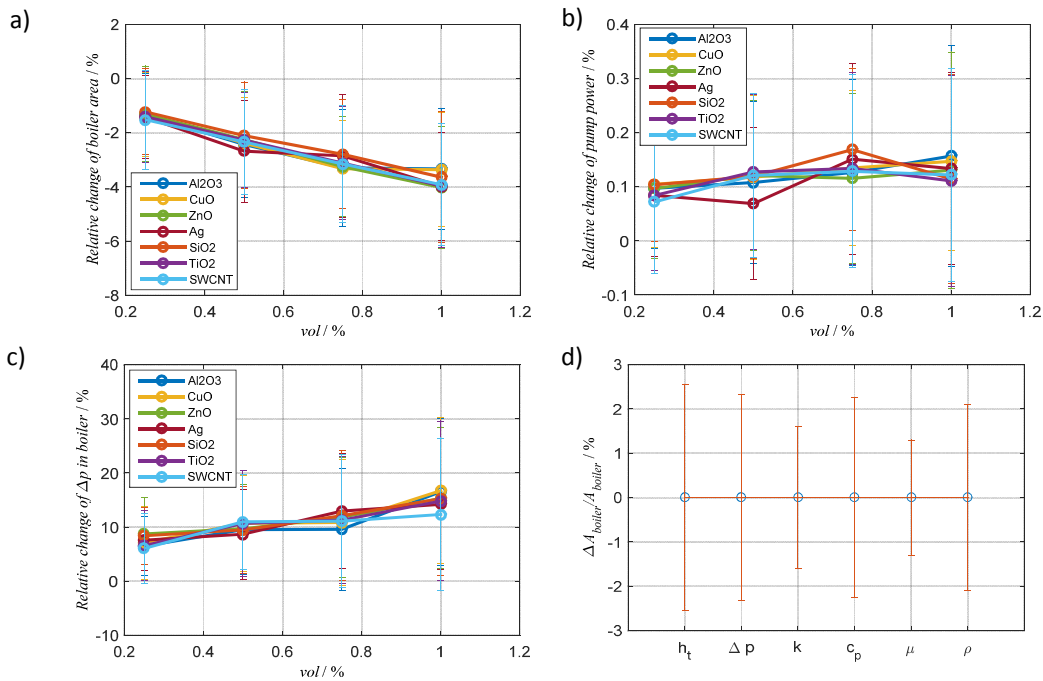


Fig. 4. Relative change of a) the boiler area, b) the pump power consumption, and c) the boiler pressure drop. d) Relative variation of the boiler area corresponding to an individual variation of each of the properties considered in the model of  $\pm 10\%$ .

Based on the depicted mean values, the reduction of the boiler area could be as high as 4 % for a nanoparticle volume concentration of 1 %, which suggests that the use of nanofluids could benefit the ORC unit by reducing the heat exchanger size. The relative differences among the different nanoparticles are very small. Moreover, the reduction of boiler area could be questionable for volume concentrations of nanoparticles of less than 0.5 %. However, a number of aspects must be also considered in this analysis. As mentioned in section 3.2., the single phase heat transfer was accounted for by using the standard heat transfer correlations with the nanofluid thermophysical properties. We have observed that with this approach, the heat transfer coefficient in the single phase both increases and decreases during our simulations, due to the aleatory variation of the properties. This can have a negative impact in the total boiler area reduction. Since the available literature on single phase heat transfer of nanofluids suggests a general enhancement of the heat transfer coefficient, there could be a higher potential for boiler area reduction than that shown in Figure 4.a. Moreover, a comparable comment could be applied to the



condenser, where a potentially beneficial effect of the nanofluid in the heat transfer coefficient could have been disregarded as well in this study.

As a final remark, Figure 4.d. presents the relative variation of the boiler area corresponding to an individual  $\pm 10\%$  variation for each of the properties considered in the model. This figure intends to show the sensitivity of the boiler heat exchange area to each property, although it should be considered that both the heat transfer coefficient and the pressure drop are, in turn, functions of the rest of the properties. As it can be seen, the two phase heat transfer coefficient and the density have the highest impact, which seems obvious since the dominating heat transfer process in the boiler has been influenced by the nanoparticles' impact factor. However, the sensitivity of the area to the thermal conductivity and heat capacity indicates that a more detailed consideration of the influence of nanoparticles in the single phase heat transfer processes could further improve the expected boiler area reduction.

## 5. Conclusions

This work presented a preliminary evaluation of the potential benefit of the use of nanofluids as working fluids for ORC power systems. The effects of adding nanoparticles to the working fluid on heat exchanger area requirement, pressure drop, and pump power consumption were evaluated using a Monte Carlo approach. The results suggest that the heat exchanger area requirements decrease. The relative reduction in heat exchanger area is around 4 % for a nanoparticle volume concentration of 1 %. The increase in pressure drop for the same concentration of nanoparticles can be expected to be around 18 %, but no negative impact on the pump power consumption is appreciated.

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