INFLUENCE OF THE FLUID-DYNAMIC PROPERTIES OF ORGANIC FLUIDS ON PUMP PERFORMANCE

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ABSTRACT

Pumping systems for ORC applications are generally modelled by assuming constant estimated value for the pump efficiency, without studying in detail the real performance of the machine at different operating conditions. Moreover, even if the different efficiency values are estimated for part-load operation, these estimation are based on the efficiency values reached by commercial pumps designed for the operation with water, without considering any variation due to the operation with fluids having different density and viscosity.

This paper presents an in-depth analysis of the influence of the organic substances fluid-dynamic properties on the pump performance with a particular focus on ORC applications for low-grade heat recovery. The final goal of the analysis was to analyse the reasons of the unexpected drop in hydraulic efficiency, encountered in experimental ORC analyses.

The performance of a multi-stage centrifugal pump, designed to serve with water but suitable for ORC applications, is experimentally and numerically investigated by means of the commercial CFD code Ansys CFX. Flow fields and performance of the pump operating with eight organic fluids typically used in ORC applications (R134a, R141b, R245fa, R152a, R142b, Acetone, Benzene and Toluene) were investigated by properly combining the CFD code with CoolProp. All the fluids are assumed to be sucked by the pump at a condensing temperature of 30°C in pure liquid condition. A negligible heat transfer from the machine to the environment is considered during the numerical simulation.

The analysis highlighted the need of considering, in the prediction of the pump performance with fluids different from water, the general framework of the similarity theory, taking into account the Reynolds number and hence the influence of the flow regime on the viscous friction forces. This findings were particularly important for modelling pumping systems in ORC for low-grade waste heat recovery applications, generally characterized by high head values and low mass flow rate values and hence by flows in the pump not completely turbulent.

1. INTRODUCTION

Industrial processes absorb about a third of the total energy consumed in a country (Brückner et al. 2015) and, due to the absence of internal heat demand, produce significant energy losses in the form of medium, low and ultralow temperature Waste Heat (WH). Therefore, improving the efficiency of these processes by means of Waste Heat Recovery (WHR) technologies can have disruptive implications in our society in terms of additional reduction of energy consumption, chemical pollutants and CO_2 emissions.

To date, several technologies are available to convert high (>650°C), medium (230-650°C), low (<230°C) and ultra-low (<120°C) temperature industrial waste heat into power, but the Organic Rankine Cycles (ORC) technology is able to recover energy from medium to ultralow-grade heat sources. Even if the ORC architecture is extremely simple, its thermodynamic optimization is a very complicated task with several interconnected parameters: organic working fluid selection and expander, pump and heat exchangers design. In such a context, research studies focused their attention on the expander, due to its direct impact on the power output of the system, and mainly on the working fluid selection. Plenty of theoretical and numerical studies proposed criteria, based on the working fluid properties or on optimization procedures, for identifying the most suitable organic fluid depending on the heat source temperature (Lakew en Bolland 2010; Zhao en Bao 2014).

However, as regards the pumping system, the great of the studies, published in literature, fixed a constant estimated value (generally between 65% and 85%) for the pump efficiency, without studying in details the real performance of the machine at different operating conditions and with different properties of the working fluid (Bianchi et al. 2016; Borsukiewicz-Gozdur 2013). Moreover, none considered that the commercial pumps are generally produced for pumping water and hence their performance and operating ranges may be affected by the adoption of organic fluid having different thermo-fluid-dynamic properties (critical temperature, density, viscosity, etc..). These uncertainties explain why, in some experimental analyses on ORC, pumps show unexpected efficiency values lower than the modelled ones (Landelle et al. 2017), causing unexpected decrease in the ORC system global efficiency (Declaye 2015).

In this research field, to the contributors' knowledge, few studies recently tried to analyse more in depth the influence of the fluid properties on the pump performance. Gulich (Gulich 1999a, 1999b) was one of the first to underline the need of adjusting centrifugal pump performance by means of correction factors and losses when it is designed to service with water, but it works with highly viscous fluids. Recently, Buratto et al. (Buratto et al. 2017) proposed a detailed analysis of the analytical methods for predicting the pump performance operating with non-Newtonian fluids. The numerical investigation shows that available models allow to compute the viscosity value used in Hydraulic Institute methods to properly modify the pump head and efficiency curve according to fluids characteristics. In addition, numerical results have shown that centrifugal pumps with greater value of specific speed are much less sensitive to the fluid viscosity. However, they highlighted the need of further investigation to understand real behaviour and performance of centrifugal pumps design for water and operating with non-Newtonian fluids. Other studies analysed the effects of the rotation rate and of the inlet/outlet pressure on the performance of a multi-stage pump for ORC applications (Yang et al. 2018, 2019). The influence of the fluid viscosity gained the attention of the researcher even with reference to the Electric Submersible Pumps (ESP), adopted in the field of oil pumping systems and several theoretical and experimental studies were published to investigate the oil viscosity effects (Vieira et al. 2015; Zhu et al. 2016).

To the authors' knowledge, none of the studies investigated more in-depth the fluid-dynamic reasons beyond the performance variation. This paper will present a CFD numerical analysis carried out on a multi-stage pump designed to serve with water but operated with different organic fluids typically used in ORC applications (R134a, R141b, R245fa, R152a, R142b, Acetone, Benzene and Toluene). The numerical model was validated by comparison with experimental results. Then, the influence of the fluid properties on the performance and cavitating behaviour of the pump was investigated in depth.

The rest of the paper is organized as follows: in Section 2 the numerical model of the centrifugal pump considered in this study is described. The most important results are outlined and discussed in Section 3 while conclusions remarks are given in Section 4.

2. CENTRIFUGAL PUMP NUMERICAL MODEL

The machine considered in the present investigation is a multi-stage centrifugal pump designed to serve with water.

The first two-stages of the multi-stage pump were modelled starting from the real geometry and dimensions provided by the manufacturer. Figure 1 reports the view of the resulting numerical model. The pump intake section is shown in yellow, the two impellers are in green while return channels are illustrated in blue.

The numerical model was validated by comparison with experimental results, acquired with the pump operating with water (Figure 2), showing a general good agreement.

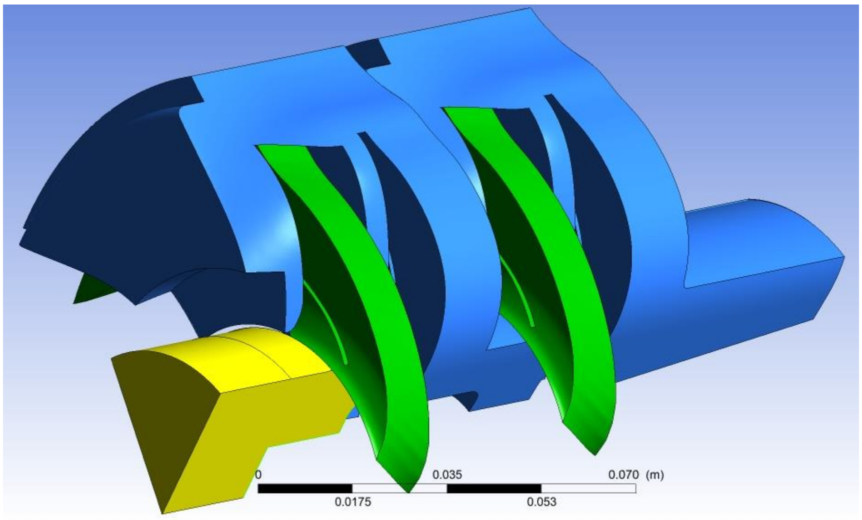

Figure 1: Numerical model of the double-stage centrifugal pump

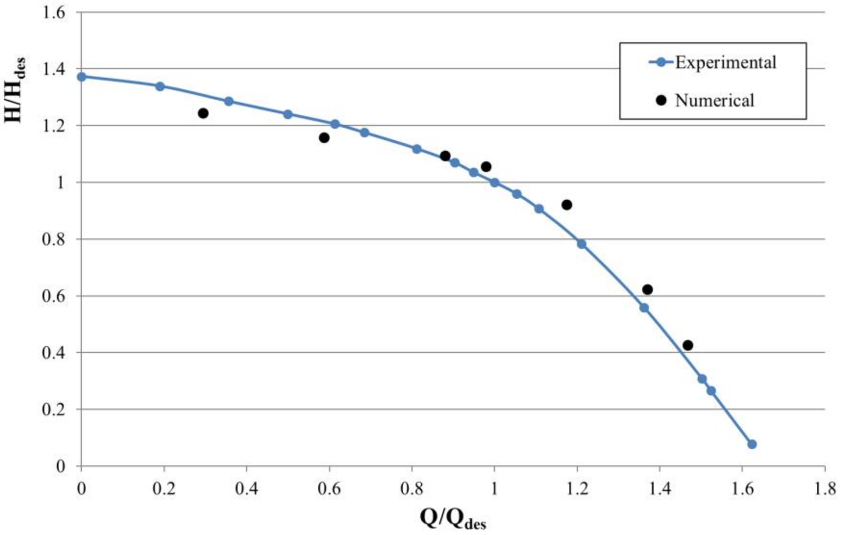

Figure 2: Performance comparison between experimental and numerical results with the pump operating with water: H/H_{des} vs. Q/Q_{des}

To analyse the influence of the fluid properties on the pump performance, eight organic fluids, typically used in ORC applications, were considered: R134a, R141b, R245fa, R152a, R142b, Acetone, Benzene and Toluene. The performance of the pump operating with these fluids were numerically analysed by means of the commercial CFD code Ansys CFX.

Since the considered fluids are characterized by different critical temperatures and pressures, to carry out a fair comparison among them, it was assumed that the pump sucked all the fluids at a fixed temperature of 30°C. Since the great part of these fluids were not available in the Ansys fluid libraries, their properties were acquired from the CoolProp database (Bell et al. 2014) (Table 1). Moreover, the heat transfer during the pumping process was assumed negligible and hence no heat transfer model was considered during the numerical simulations.

Therefore, in ANSYS-CFX, the Reynolds-averaged Navier-Stokes equations (or RANS equations) for momentum and mass conservation in fluid flow were solved. A Shear Stress Transport (SST) model was selected as turbulence model. The pump behaviour was evaluated, for each fluid and flow rate, in steady-state condition, using a Frozen-Rotor interface between stationary and rotating components.

Table 1: Properties of the considered organic fluids

Fluid	**Molecular Mass**	**Temperature**	**Pressure**	**Density**	**Specific Heat**	**Dynamic Viscosity**	**Kinetic Viscosity**
	$\frac{g}{mol}$	$°C$	kPa	$\frac{kg}{m^3}$	$\frac{J}{kg\,K}$	$Pa\,s$	$\frac{m^2}{s}$
Water	18,0	30	4,25	995,6	4180	7,97E-04	8,01E-07
R245fa	134	30	178	1325	1329	3,72E-04	2,81E-07
R134a	102	30	770	1188	1447	1,83E-04	1,54E-07
R152a	66,1	30	690	886,6	1826	1,52E-04	1,72E-07
R141b	117	30	94,2	1224	1161	3,85E-04	3,15E-07
Benzene	78,1	30	15,9	868,1	1749	5,62E-04	6,47E-07
Toluene	92,1	30	4,89	857,5	1717	5,20E-04	6,06E-07
Acetone	58,1	30	38,0	779,0	2156	2,92E-04	3,75E-07
R142b	101	30	393	1098	1328	2,18E-04	1,99E-07

As regards the boundary conditions, the surfaces were supposed as adiabatic walls with a no-slip condition. An automatic near-wall treatment smoothly switched from a low-Reynolds number formulation to a wall function formulation. At the inlet, a static pressure equal to the pressure that each fluid assumes at 30°C in the saturated liquid condition (Table 1) was assumed, whereas at the pump outlet the mass flow rate was fixed.
Regarding solver settings, in the present work, the Authors adopted a High Resolution Scheme in the Advection Scheme section of the Solver Control Panel with a tolerance of 10^{-4}.

3. RESULTS

The pump numerical model was initially validated by comparing the results achieved with the water model implemented in ANSYS-CFX with the experimental measurements (Figure 2). However, as mentioned above, in the ANSYS-CFX library some organic fluids like Benzene, R245fa, etc. were not implemented and, for this reason, the different approach, based on the CoolProp library, was adopted in order to acquire the fluid properties (Table 1).

Therefore, to verify the accuracy of this approach, a comparison of pump performance curve between the case with the ANSYS water model and the one based on the CoolProp water properties was firstly performed. The comparison in terms of pump head and efficiency between the two approaches showed a very good agreement (Figure 3), validating the approach based on the CoolProp properties.

The performance of the pump operating with the eight selected organic fluid were then numerically analysed. Figures 4 and 5 report the obtained performance in terms of head coefficient ψ and efficiency η as a function of the capacity coefficient φ.

As expected, the representation of the pump performance in the dimensionless form brings the comparison between the different fluids into the framework of the similarity theory, allowing to identify a general trend of pump performance, apparently irrespective of the different fluid properties. However, a closer look to the results highlights that the results are more spread than expected around the mean pump behavior. For example, at the design operating condition (φ_{des}=0.159), the fluid R134a is characterized by the greatest pump efficiency (about 76%) whereas the water by the lowest one (about 74%) (Figure 5).

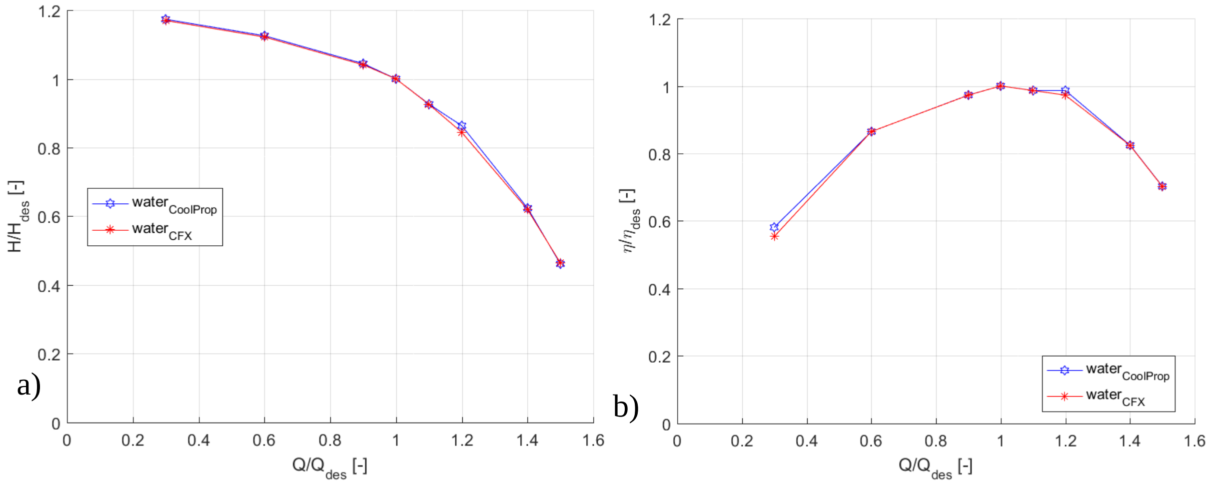

Figure 3: Comparison of the pump performance in the case of water simulated with ANSYS-CFX model and the CoolProp one: a) H/H$_{des}$ vs. Q/Q$_{des}$; a) η/ η $_{des}$ vs. Q/Q$_{des}$;

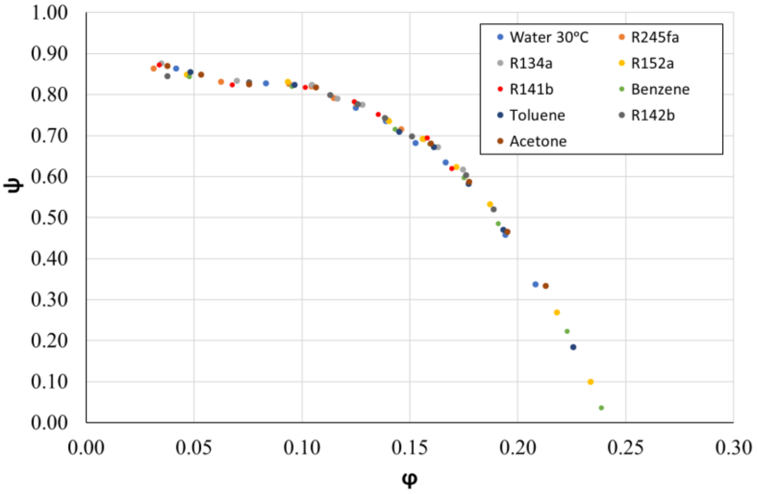

Figure 4: Comparison of pump performance between water and organic fluids: head coefficient vs. capacity coefficient

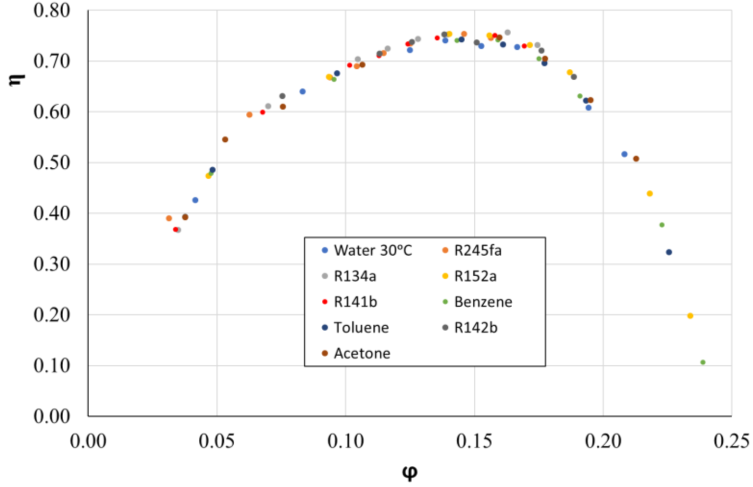

Figure 5: Comparison of pump performance between water and organic fluids: efficiency vs. capacity coefficient

This result is in agreement with the evidence of several experimental and numerical analyses carried out on working fluids having different properties (Declaye 2015).

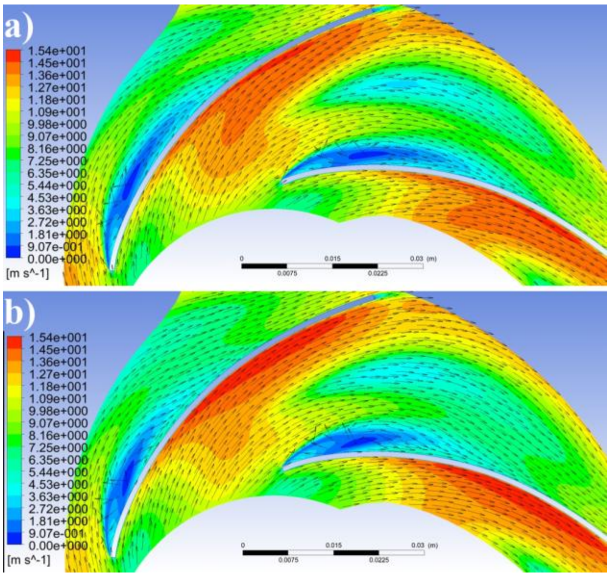

Figure 6: Velocity vectors and contour plots at mid-span of the second-stage impeller. Water (a) vs. 152a (b)

The only way to explain this discrepancy in efficiency without questioning the similarity laws, which include the fluid properties in their formulation (Stepanoff 1957), is to verify all the hypotheses at their basis.

Since only small differences can be seen in the main flow of the pump impellers operating with different fluids (Figure 6), a particular attention should be paid to the dynamic similarity, represented by the head coefficient (which is verified) and by the Reynolds number Re. In standard design procedure, the flow is assumed to be completely turbulent and for this reason the influence of the Reynolds number is disregarded. However, in this case, at the best efficiency point, all the considered fluids seems to operated in the transition zone between laminar and turbulent flow with Reynolds number at the pump inlet between 2e5 and 1.6e6, depending on the value of fluid density and viscosity (**Figure 7**).

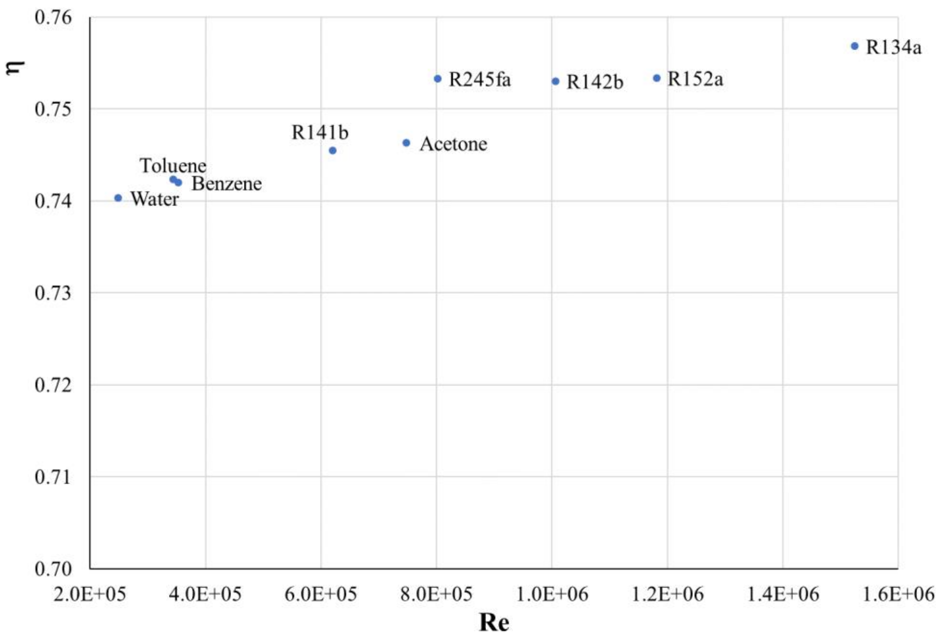

Figure 7: Pump efficiency at the best efficiency point for all the considered fluids vs. Reynolds number

In this condition of flow, the viscous losses are related to the Reynolds number via the friction factor and increase with decreasing Reynolds number, justifying the difference in efficiency among the different operating fluids. In particular, the water, having the highest kinetic viscosity ν ($\nu=\mu/\rho$), is penalized in terms of the viscous losses and presents the lowest efficiency value.

To further confirm the influence of the fluid properties on the pump efficiency, numerical analyses at different Reynolds numbers were carried out on the pump operating with the most performing fluid, the R134a. To modify the Reynolds number, different dummy values of the rotation rate of the pump were assumed up to 9000 rpm in order to reach a complete turbulent flow (Figure 8).

As can be seen in Figure 8, the pump efficiency increases with the Reynolds number until the complete turbulent flow is reached.

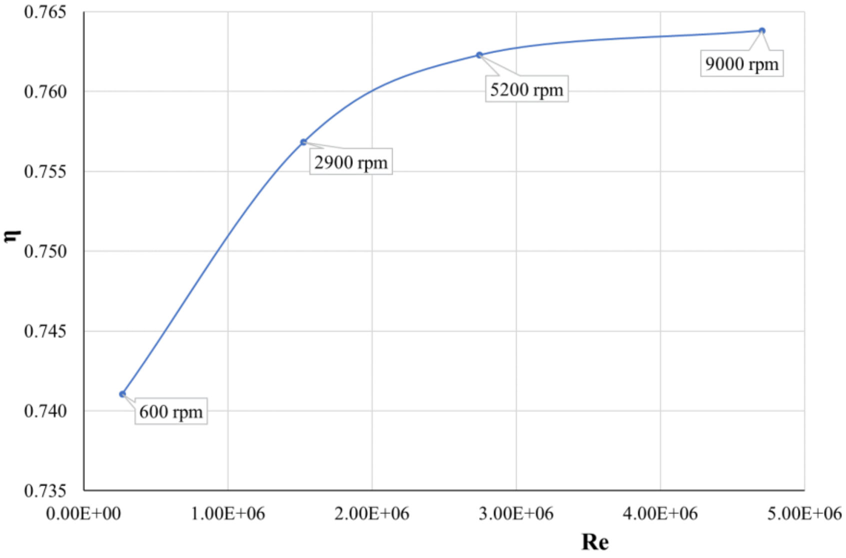

Figure 8: Maximum pump efficiency values for the fluid R134a vs. Reynolds number

As a consequence, the analysis and performance prediction of pumps operating with fluids different from water require to consider the general framework of the similarity theory, taking into account the Reynolds number and hence the influence of the flow regime on the viscous friction forces. This is particularly true in ORC for low-grade waste heat recovery applications, generally characterized by high head values and low mass flow rate values. In these cases, the difference in fluid properties (mainly density and dynamic viscosity) between water and organic fluids does not allow to neglect the influence of the Reynolds number and requires in-depth analyses for an accurate prediction of the pump performance in the ORC system.

4. CONCLUSIONS

This paper presents an analysis of the influence of the fluid properties on the resulting performance of a centrifugal pump with a closer look on ORC applications for low-grade heat recovery systems. The final goal of this analysis is to overcome the limits related to the general modelling approach in ORC studies, assuming for the pumping system constant estimated efficiency values, irrespective of the different operating conditions and of the different properties of the organic fluids.

A numerical model of the double-stage centrifugal pump, designed for operation with water, was built and validated by comparison with experimental results. Numerical analyses of the pump operating with eight common organic fluids (R134a, R141b, R245fa, R152a, R142b, Acetone, Benzene and Toluene) were carried out by means of the commercial CFD software Ansys CFX. Since the organic fluid were not all available in the Ansys CFX library, a different approach based on the CoolProp database was developed and validated.

The comparison between the dimensionless performance with the water and those with the other organic fluids showed a general trend, apparently irrespective of the different fluid properties.

However, a closer look to the results highlighted performance differences depending on the working fluid and in particular a difference of about 2% of efficiency at the best efficiency point between the worst and the best fluid.

This different behavior resulted to be due to the Reynolds number of the fluids, as a consequence of the different densities and viscosities. For all the fluids, the pump operated in the transition zone with an uncomplete turbulent flow with consequent different values of the friction factor and hence of the viscous losses. The dynamic similarity was not satisfied and the performance of the pump were affected by the fluid properties.

As a consequence, the analysis and performance prediction of pumps operating with fluids different from water require to consider the general framework of the similarity theory, taking into account the Reynolds number and hence the influence of the flow regime on the viscous friction forces. This is particularly true in ORC for low-grade waste heat recovery applications, generally characterized by high head values and low mass flow rate values.

NOMENCLATURE

c	Absolute velocity	(m/s)
g	Gravity acceleration	(m/s^2)
H	Head	(m)
Q	Flow Rate	(m^3/s)
n	Rotation rate	(rpm)
R	Radius	(m)
$Re = \frac{\rho c D}{\mu}$	Reynolds number	(-)
$u = \omega R$	Peripheral velocity	(m/s)
η	Pump efficiency	(-)
μ	Dynamic viscosity	(Pa s)
ρ	Fluid density	(kg/ m^3)
$\varphi = \frac{c_{m2}}{u_2}$	Capacity coefficient	(-)
$\psi = \frac{gH}{u_2^2}$	Head coefficient	(-)
ω	Rotation rate	(rad/s)

Subscripts

des	referred to the design operating conditions
m	meridional
2	referred to the impeller outlet

Acronyms

CFD	Computational Fluid Dynamics
ORC	Organic Rankine Cycle
RANS	Reynolds-Averaged Navier-Stokes
WF	working fluid
WH	waste heat
WHR	waste heat recovery

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