EXPERIMENTAL COMPARATIVE STUDY OF AN ORC USING PURE FLUID AND ZEOTROPIC MIXTURE FOR WASTE HEAT RECOVERY

Quentin Blondel[1,2]*, Nicolas Tauveron[1], Nadia Caney[2] and Nicolas Voeltzel[1]

[1] Univ. Grenoble Alpes, CEA, LITEN, L2ST
Grenoble, France, F-38000
www.liten.cea.fr

[2] Univ. Grenoble Alpes, CNRS, LEGI
Grenoble, France, F-38000
legi-contact@legi.grenoble-inp.fr

* Corresponding Author: quentin.blondel@cea.fr

ABSTRACT

This study concerns a compact (0.25m^3) Organic Rankine Cycle (ORC) installation using as working fluid a zeotropic mixture composed of 80% Novec^{TM}649 and 20% HFE7000 (mass composition). The purpose of this experimental test bench is to study new generation of fluids potential candidates for existing ORC system. The operation of the system is studied by comparing the experimental results of this mixture with those obtained in pure Novec^{TM}649. A first study (Blondel *et al.*, 2018) demonstrated the good ORC performances with this new generation pure fluid as well as that of the expansion element (axial micro-turbine) used in the installation. The global performances of the installation are increased by 10% thanks to the mixing of fluids. Concerning the turbine, its performances are only slightly affected by the use of the mixture. These preliminary results show that zeotropic mixtures can be used as an adjustment parameter for a given ORC installation and thus allow the best use of the heat source available to produce electricity.

1. INTRODUCTION

The Organic Rankine Cycle, or ORC, has been used since the 19th century to produce mechanical and electrical energy from a thermal energy source. The source of thermal energy can be from various sources such as geothermal (Spadacini *et al.*, 2017), solar (Orosz and Dickes, 2017), biomass combustion (Guercio and Bini, 2017), energy storage (Ayachi *et al.*, 2016), waste heat recovery from industrial processes or internal combustion engines (Mahmoudi *et al.*, 2018). The power production levels of commercial ORCs range from 10 kW to 10 MW for heat sources between 100°C and 300°C. However, these temperatures and power ranges tend to be extended as a result of technological advances in micro CHP and heat recovery in the road transport sector (Quoilin *et al.*, 2013; Colonna *et al.*, 2015; Tauveron *et al.*, 2014). In addition, as a result of current energy and environmental challenges, the intensification of the performance of existing systems and the use of less polluting fluids is tending to increase (Modi and Haglind, 2017; Bobbo *et al.*, 2018).

Interest in waste heat recovery is growing, due to the need for better management of energy production and consumption, particularly for low temperature recovery (ADEME, 2018). Following this trend, small power ORC is proving to be an attractive solution in residential and transportation sectors (Lion *et al.*, 2017; Pereira *et al.*, 2018). Chang *et al.* (2015) and Wu *et al.* (2015) conducted ORC tests with Scroll expander using respectively R-245fa as working fluid for a production of 1.56 kW and R-123 as working fluid for a production of 1.53 kW. Cipollone *et al.* (2015) investigated an ORC using as heat source the energy lost by the exhaust gases of an internal combustion engine, for a calculated power output of 1.36 kW from the database of Landelle *et al.* (2017). Very few experimental studies on new generation-replacement fluids for Organic Rankine Cycles with a low temperature heat source are available. Pu *et al.* (2016) studied a low-power ORC with HFE7100 as the working fluid for a temperature of 100°C and an electrical output of 1 kW. Helvaci and Khan (2016) were interested in HFE7000 with a hot source temperature of 45°C from a solar collector for a production of 0.15 kW. Other fluids such as HFO (Navarro-Esbri *et al.*, 2017) or HCFO (Eyerer *et al.*, 2016) are also studied. These replacement fluids doesn't necessarily leed to higher or equivalent performances for ORC system in comparison to classical HCFC or HFC fluids. To improve replacement fluids performance, the use of zeotropic mixtures is investigated. A zeotropic mixture is a blend of two or more pure fluids, with the specificity to have a non-isothermal phase-change at constant pressure, at evaporation step and condensation step in the ORC; in contrast with pure fluid and azeotropic mixture, whose the change from liquid state to gaseous state, and reciprocally, is performed at constant temperature and constant pressure. This non-isothermal phase-change also called temperature glide could decreased the temperature difference between the working fluids and the heat source and heat sink and thus decreased the irreversibility in exchangers (Bamorovat Abadi and Kim, 2017).

However, there are no studies conducted on zeotropic mixtures from only new generation fluids. The objective of the present work is to test an ORC cycle with a mixture of Novec^{TM}649 and HFE7000 and to investigate system performances with this zeotropic mixture of new generation fluids.

2. MATERIALS AND METHODS

2.1 ORC system

The Process Flow Diagram (PFD) of the installation is shown in Figure 1. Within it, the working fluid, in its liquid state, passes to the upper pressure level thanks to the volumetric pump. The fluid is then heated, evaporated and superheated in contact with the hot source through the preheater and evaporator. It is expanded in the turbine, producing mechanical work. At low pressure, the fluid is cooled, condensed and sub-cooled by the cold source within the condenser and then pumped again to close the cycle. In order to dissipate the electricity produced at the generator, two elements are used: lamps with a total power of 50 W and a heat sink.

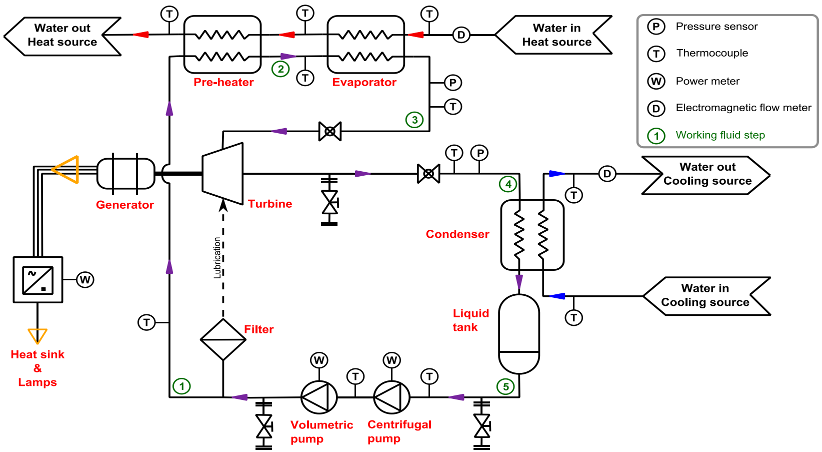

Figure 1: PFD of the experimental ORC

The system includes a 1 kW micro axial single stage impulse turbine, specifically designed for the installation by Enogia Company. The lubrication of the bearing system is carried out with the working fluid. An external circuit specific to the generator ensures its cooling to allow its proper operation. Two pumps ensure the circulation and pressurization of the working fluid in the ORC circuit. The main pump is a diaphragm positive displacement pump with an electrical consumption of 74 W, the second is a small centrifugal pump, with an electrical consumption of 29 W, to avoid any risk of cavitation within the main pump. Two plate heat exchangers, a preheater and an evaporator, are placed in series to allow the energy transfer from the heat source. A third plate heat exchanger, a condenser, allows the cooling of the working fluid within the cycle. Placed between the condenser and the centrifugal pump, a tank ensures a sufficient level of liquid at the inlet of the centrifugal pump.

2.2 Heating and cooling loops

Waste heat is simulated by an electric boiler in which water is pumped and pressurized to achieve a temperature up to 110°C in the liquid state at the evaporator inlet. A proportional integral derivative (PID) controller is integrated into the boiler to keep the water at a constant temperature at the evaporator inlet. The water flow rate of the heat loop is fixed manually by means of a valve on the boiler bypass circuit.

The cold source corresponds to the laboratory's industrial water network, which is at a constant temperature close to 13°C. A manual valve is used to regulate the water flow within the cold loop.

A specific circuit for the generator ensures its cooling to allow the internal temperature level of the element to be regulated during operation of the installation. This circuit consists of a small centrifugal pump, a liquid tank and a fan cooler.

2.3 Working fluid selection

The choice of the working fluid is an important parameter in the design of an ORC. Several studies have examined the determining criteria for selecting the most suitable fluid for an ORC installation (Quoilin *et al.*, 2013; Chen *et al.*, 2010). Theoretical efficiency, price, availability, human and environmental constraints are recurring parameters taken into account to select the most suitable fluid.

In this study, the system uses a zeotropic mixture of Novec^{TM}649 and HFE7000 as working fluid with a mass proportion of 80% and 20% respectively.

This mixture is non-toxic, non-flammable, has a low environmental impact with a null Ozone Depletion Potential (ODP = 0) and a low Global Warming Potential (GWP = 107) as greenhouse gas. These two fluids are suggested as possible substitutes for HCFC and HFC (3M, 2009; 3M, 2014). The mixture obtained is a dry fluid, which provides two significant advantages for the installation: it is not necessary to overheat the steam to avoid the formation of droplets within the turbine, the mixture being in the dry steam state throughout the expansion stage; this results in a lower minimum hot source temperature compared to the case requiring overheating. Due to the low operating pressures, less than 6 bar, the addition of specific and expensive high pressure protections is not necessary.

2.4 Instrumentation

All sensors used for measurements and data acquisitions are present on the PFD of the installation in Figure 1. The characteristics of the measurement devices are listed in Table 1. The working fluid, heat source and cooling source loops are equipped with Type-K thermocouples to measure temperatures between the various components. The working fluid circuit is equipped with absolute pressure sensors (APS) at the turbine inlet and outlet to measure the two pressure stages within the installation. Volumetric flow rate measurements of hot and cold circuits are performed using electromagnetic flow meters (EFM). The mass flow rate of the working fluid is determined by the energy balance at the condenser of the experimental installation. The electrical power produced at the turbine is measured by means of a wattmeter.

Table 1: Measurement devices characteristics

Variable	Device	Range	Uncertainty
Electrical power	Wattmeter	0 – 3250 W	± 0.3 % $_{range}$
Volumetric flow rate (heat source)	EFM	0 – 3500 l/h	± 0.23 % $_{range}$
Volumetric flow rate (cooling source)	EFM	0 – 2500 l/h	± 0.33 % $_{range}$
Temperature	Type-K thermocouples	0 – 1100 °C	± 0.1 °C $_{value}$
Pressure	APS	0 – 7 bar	± 1 % $_{range}$

3. DATA PROCESSING

3.1 Experimental investigation

During the tests, various experimental parameters can be modified, such as the temperature of the heat source, the volumetric flow rates of the hot and cold circuits or the working fluid flow rate inside the ORC loop, in order to study their impacts on the installation and its performance.

In a first comparative approach of this ORC installation in pure and mixture fluid, this study focuses on the impacts of the change in working fluid on the overall performances of the ORC and turbine.

The main installation parameters and their range of variation imposed on the system during the experimental tests are presented in Table 2.

Table 2: Main parameters settings

$T_{in,hf,evap}$	$T_{in,cf,cond}$	$q_{v,hf}$	$q_{v,cf}$	$\dot{m}_{wf}$
°C	°C	l/h	l/h	kg/s
109.5 – 110.5	12.5 – 14	300 – 3500	250 – 2500	0.055 – 0.069

3.2 Thermodynamic investigation

The study of the ORC installation, based on experimental data, is carried out using a 0D model, by solving energy balances on components and the global system, developed on the EES software (Klein, 2018). A coupling is carried out with the REFPROP software (Lemmon *et al.*, 2013) to allow the implementation of thermodynamic properties in mixture and pure fluid. These properties result from Helmholtz's model adapted for the considered fluids (McLinden *et al.*, 2015; Outcalt *et al.*, 2013).

Due to the constraints of the architecture of the ORC installation (prototype), the fluid flow rate, not directly accessible, is calculated using the energy balance carried out at the condenser, as defined by Equation 1. A distribution of the heat losses between the hot and cold sources was therefore determined when the ORC installation was commissioned. This losses distribution, statistically adjusted during the experimental tests, made it possible to complete the simulation system 0D model.

$$\dot{m}_{wf} = \frac{\dot{m}_{cf} \cdot (h_{out,cf,cond} - h_{in,cf,cond}) + \dot{Q}_{losses,cond}}{(h_{in,wf,cond} - h_{out,wf,cond})} \tag{1}$$

The turbine performance, analyzed according to the variation in the pressure ratio as defined by Equation 2, is studied according to two different approaches: firstly with a dimensionless parameter of the turbine as defined by Equation 3, and secondly with the electrical isentropic efficiency of the turbine, which includes the expansion element and the generator as defined by Equation 4.

$$\pi_{tur} = \frac{P_{in,wf,tur}}{P_{out,wf,tur}} \tag{2}$$

$$\bar{A} = \frac{\dot{m}_{wf}}{S_{in,tur} \cdot \rho_{0,in,tur} \cdot c_{0,in,tur} \cdot \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2\cdot(\gamma-1)}}} \tag{3}$$

$$\eta_{tur} = \frac{\dot{W}_{el,tur}}{\dot{W}_{is,tur}} \tag{4}$$

$$\eta_{th,net} = \frac{\dot{W}_{el,tur} - \dot{W}_{el,ps}}{\dot{Q}_{heat}} \tag{5}$$

To analyze the overall performance of the installation, the thermal efficiency of the ORC, as defined by Equation 5, is studied according to the electricity production. Two comparisons of the tests conducted in pure fluid and mixture are presented. The first one covers all the tests, the second one compares the pure fluid tests with the mixture tests with the same operating parameters. The influence of the variation in the upper pressure of the cycle is also studied.

Error bars given in the result section ensue from the uncertainties presented in the Table 1; and are calculated according to the uncertainty propagation, using the root-sum-square method.

4. RESULTS AND DISCUSSION

4.1 Turbine performances

The axial micro-turbine is designed to work with pure Novec^{TM}649 fluid. In order to study the impact generated by the use of the mixture Novec^{TM}649/HFE7000 on the operation of the expansion element, the dimensionless parameter Ā is calculated in both cases (mixture and pure fluid) as a function of the pressure ratio. This value corresponds to the normalized blade throat area (A^*/A_0), which represents an intrinsic value of the expansion component (see Nederstigt (2017) for theoretical developments of compressible and isentropic flows of real gases).

Shown in Figure 2 on the left ordinate, the value of Ā is uniform and identical in the case of mixture as for pure fluid. This result therefore experimentally confirms that the operation of the turbine is not affected by the change in working fluid, provided that the physical dimensionless parameter (Ā) is considered relevant and generalized to real gases.

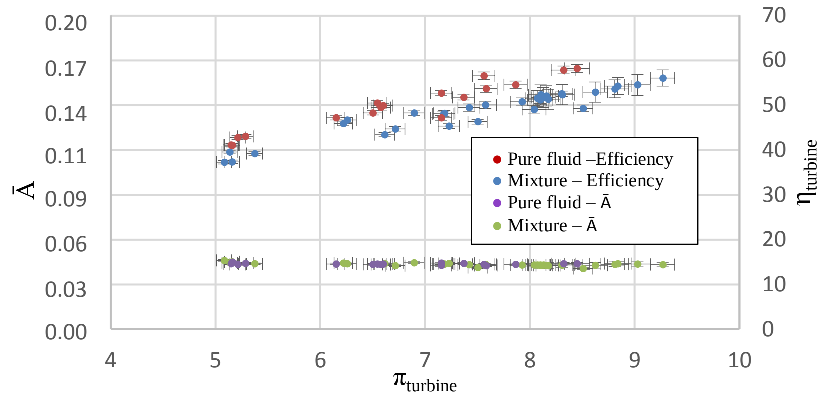

Figure 2: Turbine performances according to pressure ratio,
left ordinate: Dimensionless parameter Ā; right ordinate: Turbine electrical isentropic efficiency

The electrical isentropic efficiency of the turbine, shown in Figure 2 on the right ordinate, varies in the same way with the mixture and with the pure fluid, confirming the suitable operation of the expansion component with the mixture. There is a slight decrease in the value of the efficiency, in the order of 10%, in the case of zeotropic mixture: this is due to the different thermodynamic properties at the turbine inlet compared to those in pure fluid. However, the mixture efficiency values classify this turbine in the high range of this type of small size technology which is comparable to the more conventional scroll technology used (Blondel *et al.*, 2018).

4.2 ORC performances

<u>4.2.1 First law efficiency:</u> The optimal operation of the ORC with the zeotropic mixture resulted in a net thermal efficiency value of 5.6%. The corresponding value of gross thermal efficiency (6.5%) placed in the available literature (Blondel *et al.*, 2018) makes it possible to rank this installation with mixture working fluid among the 20% of the most efficient small power ORC installations.

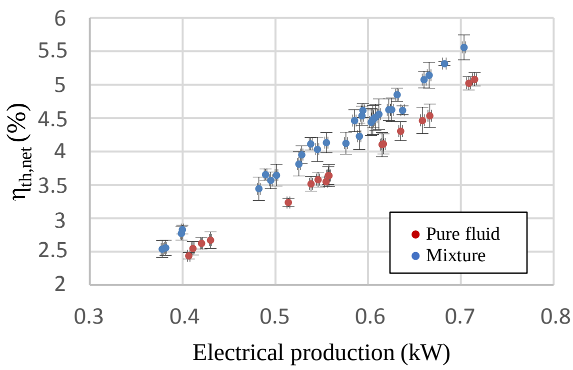

Figure 3a: ORC performance according to electrical production in pure fluid and mixture

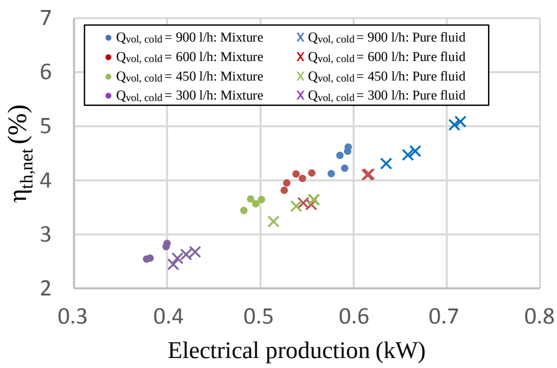

Figure 3b: ORC performance according to electrical production in pure fluid and mixture – isoparameters –

During the experimental tests conducted in mixture on the ORC and compared with the pure fluid tests, for the range of parameters variation as defined in subsection 3.1, an increase in the net thermal efficiency of the overall system is observed as shown in Figure 3a. This increase in performance is in the order of 10% for an equivalent production of electricity.

In the case of a comparison with complete isoparameters, i. e. identical temperatures and flows of hot and cold sources for both pure fluid and mixture, the net thermal efficiency is identical and the power produced in the case of the mixture is reduced by 10% (see Figure 3b).

The two previous analyses of the results obtained in the experimental tests seem to be contradictory as to the interest of using a mixture as a working fluid within an ORC. However, when using an Organic Rankine Cycle, the aim is to transform thermal energy, called degraded energy, from the heat source, into electrical energy, called noble energy. This type of technology therefore seeks to make the best use of the available thermal energy source, and therefore to obtain the highest possible thermal efficiency, to produce the greatest amount of electricity. The results presented in Figure 3a confirm the interest of using fluid mixtures to increase the performances of an ORC installation. The results presented in Figure 3b highlight some of the limitations that can be achieved when using mixtures. Indeed, at isoparameters, the mixture is more efficient than the pure fluid for a given range of parameters and electricity production. In this defined range, the zeotropic mixture will therefore allow a better use of the heat source.

<u>4.2.2 Upper pressure:</u> The upper pressure of the cycle, an important parameter of an ORC installation, is also impacted when using a zeotropic mixture compared to pure fluid. For the experimental tests conducted in mixture Novec^{TM}649 and HFE7000 with respective mass proportions of 80% and 20% and compared to the pure fluid Novec^{TM}649, there is a reduction of about 7.5% in the high-pressure value for equivalent turbine power generation, as shown in Figure 4.

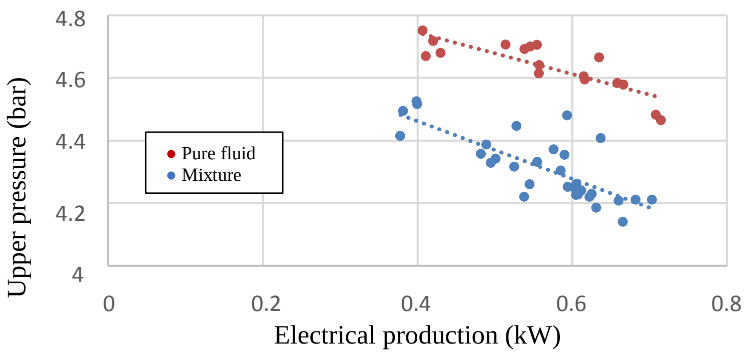

Figure 4: ORC performances according to electrical production in pure fluid and mixture

This pressure drop between the pure fluid and the mixture can also be a selection criterion in the choice of a mixture to be used in an ORC with an equivalent power generation range. Indeed, in an ORC, criteria such as the type of materials used for the components, the thickness of the pipes or the safety devices are directly related to the pressure levels of the system and generate additional costs in the case of higher pressures.

4.3 Mass flow rate validation and reconciliation

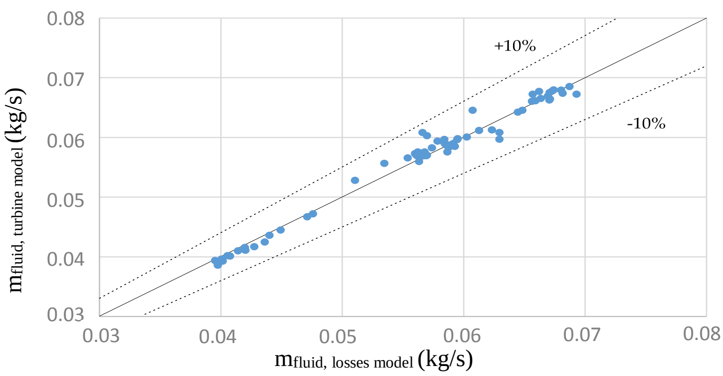

Figure 5: The working fluid’s mass flow rate reconciliation between the losses model and the turbine model.

Recent results, obtained thanks to mixture experimental test, had let us to calculate an accurate value of the working fluid's mass flow rate based on the turbine specific parameter Ā. The mass flow rate reconciliation is show in the above Figure 5. This second calculation, using a deterministic method of the flow rate of the working fluid that ensues from the dimensionless parameter of the turbine Ā, made it possible to verify the confidence interval of the results obtained with the previous calculation method. The relative error between the two methods is less than 7% for all of the tests and less than 5% for 95% of the tests.

5. CONCLUSION

In this paper, a compact experimental ORC installation (0.25m3), of low power, has been studied with a zeotropic mixture composed of Novec^{TM}649 and HFE7000 in respective mass proportions of 80% and 20%, in order to valorize a low temperature heat source. The working fluid used is a mixture of new generation fluids and a potential candidate to replace the traditionally fluids used in ORCs, such as R-134a and R-245fa. This study presents the results of comparative experimental tests in mixture and pure fluid for the same installation.

The analyses highlighted that the expansion element, a micro-turbine, was functioning properly with a zeotropic mixture, a fluid for which this turbine was not initially designed. The performances of this installation, in its optimal operating point, classifies this ORC using a zeotropic mixture as a high performance low power installation, compared to the literature available for low temperature heat recovery. Moreover, the use of a zeotropic mixture as working fluid within an ORC can be a very useful parameter for the system adjustment. Indeed, it is possible to improve the overall efficiency of the installation, according to the electricity needs sought, by optimizing the use of the heat source.

Tests are currently underway on the ORC facility to complete the experimental study of this zeotropic mixture for other fluid mass proportions.

NOMENCLATURE

Symbols

$\bar{A}$	dimensionless turbine parameter	(–)
c_0	upstream turbine soundspeed	(m/s)
h	specific enthalpy	(kJ/kg)
$\dot{m}$	mass flow	(kg/s)
P	pressure	(bar)
$\dot{Q}$	thermal power	(kW)
q_v	volumetric flow	(l/h)
S	section de passage	(m²)
T	temperature	(°C)
$\dot{W}$	power	(kW)

Greek symbols

η	efficiency	(%)
π	pressure ratio	(–)
γ	polytropic coefficient	(–)
ρ_0	upstream turbine density	(kg/m^3)

Subscripts

cond	condenser
cf	cooling fluid
el	electric
evap	evaporator
heat	heat source
hf	heat fluid
in	inlet
is	isentropic
net	net
out	outlet
losses	losses
ps	pumps
th	thermal
tur	turbine
wf	working fluid

Acronyms

APS	Absolute Pressure Sensor
GWP	Global Warming Potential
ORC	Organic Rankine Cycle
EFM	Electromagnetic Flow Meter
ODP	Ozone Depletion Potential
PFD	Process Flow Diagram
PID	Proportional Integral Derivative

REFERENCES

ADEME, 2018, Excess heat, *ADEME,* Available: https://www.ademe.fr/excess-heat.

Ayachi, F., Tauveron, N., Tartière, T., Colasson, S., Nguyen, D., 2016, Thermo-Electric Energy Storage involving CO2 transcritical cycles and ground heat storage, *Applied Thermal Engineering*, 108, pp. 1418–1428.

Bamorovat Abadi, G., Kim, K.C., 2017, Investigation of organic Rankine cycles with zeotropic mixtures as a working fluid: Advantages and issues, *Renew. Sustain. Energy Rev.*, 73, 1000–1013.

Blondel, Q., Tauveron, N., Caney, N., Bentivoglio, J., 2018, Experimental study of a compact ORC for low grade heat conversion to electricity, *EORCC*, Lyon, France.

Bobbo, S., Nicola, G. D., Zilio, C., Brown, J. S., Fedele, L., 2018, Low GWP halocarbon refrigerants: A review of thermophysical properties, *International Journal of Refrigeration*, 90, pp. 181–201.

Chang, J.-C., Hung, T.-C., He, Y.-L., Zhang, W., 2015, Experimental study on low-temperature organic Rankine cycle utilizing scroll type expander, *Applied Energy*, 155, pp. 150–159.

Chen, H., Goswami, D. Y., Stefanakos, E. K., 2010, A review of thermodynamic cycles and working fluids for the conversion of low-grade heat," *Renewable and Sustainable Energy Reviews,* 14(9), pp. 3059–3067.

Cipollone, R., Bianchi, G., Gualtieri, A., Battista, D. D., Mauriello, M. et al., 2015, Development of an Organic Rankine Cycle system for exhaust energy recovery in internal combustion engines, *J. Phys.: Conf. Ser.*, 655(1), p. 012015.

Colonna, P., Casati, E., Trapp, C. *et al.*, 2015, Organic Rankine Cycle Power Systems: From the Concept to Current Technology, Applications, and an Outlook to the Future, *J. Eng. Gas Turbines Power*, 137(10), pp. 100801–19.

Eyerer, S., Wieland, C. *et al.*, 2016, Experimental study of an ORC […] low temperature heat utilization, *Energy*, 103, pp. 660–671.

Guercio, A., Bini, R., 2017, Biomass-fired Organic Rankine Cycle combined heat and power systems, *In:* Macchi, E., Astolfi, M., *Organic Rankine Cycle (ORC) Power Systems*, Woodhead Publishing, pp. 527–567.

Helvaci, H. U., Khan, Z. A., 2016, Experimental study of thermodynamic assessment of a small scale solar thermal system, *Energy Conversion and Management*, 117, pp. 567–576.

Klein, S. A., 2018, EES – Engineering Equation Solver (Professional V10.417–3D), F-Chart Software, from http://www.fchart.com/ees/

Landelle, A., Tauveron, N., 2017, Experimental ORC database. Retrieved 11,22,2017, from https://zenodo.org/record/400556#.W hUzgVXia70

Lemmon, E. W. et al., 2013, REFPOP – Reference Fluid Thermodynamic and Transport Properties (version number 9.1), NIST Software, from https://www.nist.gov/srd/refprop

Lion, S., Michos, C. N. *et al.*, 2017, A review of waste heat recovery and Organic Rankine Cycles (ORC) in on-off highway vehicle Heavy Duty Diesel Engine applications, *Renewable and Sustainable Energy Reviews*, 79, pp. 691–708.

Mahmoudi, A., Fazli, M., Morad, M. R., 2018, A recent review of waste heat recovery by Organic Rankine Cycle, *Applied Thermal Engineering*, 143, pp. 660–675.

McLinden, M. O. *et al.*, 2015, Thermodynamic Properties of 1,1,1,2,2,4,5,5,5-[…]-pentanone: Vapor Pressure, (p, ρ, T) Behavior, and Speed of Sound Measurements, and an Equation of State, *J. Chem. Eng. Data*, 60, pp. 3646-3659.

Modi, A., Haglind, F., 2017, A review of recent research on the use of zeotropic mixtures in power generation systems, *Energy Conversion and Management*, 138(Supplement C), pp. 603–626.

Navarro-Esbrí, J., Molés, F. *et al.*, 2017, Experimental study of an Organic Rankine Cycle with HFO-1336mzz-Z […] for micro-scale low temperature applications, *Energy*, 133, pp. 79–89.

Nederstigt, P., 2017, Real Gas Thermodynamics and the Isentropic Behavior of Substances, Delft University of Technology, Netherland.

Outcalt, S. L. *et al.*, 2013, Bubble-Point Measurements of Eight Binary Mixtures for Organic Rankine Cycle Applications", *J. Chem. Eng. Data*, 58, pp. 1853-1860.

Orosz, M., Dickes, R., 2017, Solar thermal powered Organic Rankine Cycles, In: Macchi, E., Astolfi, M., Organic Rankine Cycle (ORC) Power Systems, Woodhead Publishing, pp. 569–612.

Pereira, J. S., Ribeiro, J. B., Mendes, R. *et al.*, 2018, ORC based micro-cogeneration […] – A state of the art review and current challenges, *Renewable and Sustainable Energy Reviews*, 92, pp. 728–743.

Pu, W., Yue, C., Han, D., He, W., Liu, X. *et al.*, 2016, Experimental study on Organic Rankine cycle for low grade thermal energy recovery, *Applied Thermal Engineering*, 94, pp. 221–227.

Quoilin, S., Broek, M. V. D., Declaye, S., Dewallef, P., Lemort, V., 2013,Techno-economic survey of Organic Rankine Cycle (ORC) systems, *Renewable and Sustainable Energy Reviews,* 22, pp. 168–186.

Spadacini, C., Xodo, L. G., Quaia, M., 2017, Geothermal energy exploitation with Organic Rankine Cycle technologies, *In:* Macchi, E., Astolfi, M., *Organic Rankine Cycle (ORC) Power Systems,* Woodhead Publishing, pp. 473–525.

Tauveron, N., Colasson, S., Gruss, J.-A., 2014, Available systems for the conversion of waste heat to electricity, *Proceedings of ASME International Mechanical Engineering Congress and Exposition*, 6A.

Wu, Z., Pan, D., Gao, N., Zhu, T., Xie, F., 2015, Experimental testing and numerical simulation of scroll expander in a small scale organic Rankine cycle system, *Applied Thermal Engineering*, 87, pp. 529–537.

3M, 2009, 3M^{TM} Novec^{TM}649 Engineered Fluid, *3M*, Available: https://multimedia.3m.com/mws/media/569865O/3mtm-novectm-649-engineered-fluid.pdf.

3M, 2014, 3M^{TM} Novec^{TM}7000 Engineered Fluid, *3M*, Available: https://multimedia.3m.com/mws/media/121372O/3m-novec-7000-engineered-fluid-tds.pdf.

ACKNOWLEDGEMENT

The authors would like to express their gratitude to the Office of the Commissioner for Atomic Energy and Alternative Energies and the Carnot Energies of the Future Institute.