Comparing R1233zd And R245fa For Low Temperature ORC Applications

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ABSTRACT

The majority of recently introduced Organic Rankine Cycle systems use R245fa as working fluid. The lower saturation pressures of R245fa versus R134a allowed the use of existing Heating Ventilation and Air Conditioning electric motors, compressors, evaporators and condensers after minor modifications as ORC electric generators, turbines/expanders, boilers and condensers. At elevated saturation temperatures R245fa turbine/expander equipment matches the power density of R134a HVAC compressors equipment. Refrigerants with still lower saturation pressures such as R123 and the newly developed low Global Warming Potential fluid DR2 are excellent ORC working fluids but lack the synergy that exists in terms of power density between existing R134a compressors and their R245fa turbine derivatives. The use of these fluids in ORC applications prevents the use of existing HVAC compressor/motor hardware.

Recently, a new refrigerant R1233zd has been introduced as a low GWP alternative for R245fa. This paper analyses the effect of this new fluid as a drop-in for R245fa into an existing 75 kW variable-speed, oil-free low temperature ORC system. The somewhat lower saturation pressure and vapor density of R1233zd allows a somewhat higher boiling temperature at maximum operating pressure, resulting in 8.7% higher cycle efficiency at equal capacity.

1. INTRODUCTION

The use of refrigeration equipment in Organic Rankine Cycle systems helps transfer cost benefits realized through economics of scale from Heating Ventilation and Air Conditioning equipment manufacturing. The majority of recently introduced small capacity < 250 kW electric power output ORC systems using heat source temperatures in the range of 200 ^{0}C to 120 ^{0}C use R245fa as working fluid to be able to take advantage of these cost benefits by adapting existing HVAC electric motors, compressors, evaporators and condensers after minor modifications as ORC electric generators, turbines/expanders, boilers and condensers. The lower cost realized through manufacturing scale of HVAC equipment allows for small capacity installation of ORC systems to be price attractive to customers as pointed out by Brasz and Holdmann (2005).

When using HVAC equipment for an ORC system, the rated pressure and temperature of the equipment dictates the ORC turbine inlet temperatures and pressures, as such for turbines/expanders derived from a medium pressure R134a based compressors, an ORC working fluid should have lower critical pressure and higher temperatures to be able to operate at higher evaporation temperatures and realize a higher thermal efficiency out of the system. In addition the working fluid should have a similar power density to R134a to be able to use the compressor hardware with minor modifications. Most of the ORC systems introduced using this hardware have R245fa as the working fluid, with a moderate Global Warming Potential of 950, matching power density, while its lower critical pressure at higher temperature allows for reasonable system thermal efficiency. Recently lower GWP fluids like R1233zd, DR-2 with thermo physical properties close to R245fa have been introduced.

ORC systems have low thermal efficiency due to use of low-grade, low temperature heat for power generation. And any improvement in efficiency by changing the working fluid without major modifications to the existing system would directly correlate to a lower cost per kW and shorter investment return times. In addition the capability of using a low GWP fluid in an existing ORC system provides additional environmental and regulatory benefits.

In this paper we evaluate the feasibility of one such low GWP fluid R1233zd as a drop in replacement working fluid for an existing R245fa based ORC system. We evaluate the cycle performance of each fluid with exiting turbine hardware and later make a comparison of both the fluids being used. Table 1 compares the properties of R1233zd with R245fa.

Fluid Property	**Units**	**R1233zd**	**R245fa**
Molar Mass	[kg/kmol]	130.5	134.1
Critical Pressure	[kPa]	3570.9	3651.2
Critical Temperature	[C]	165.6	950.0
GWP	[-]	6	950
Boiling Point @ 1 atm	[C]	18.7	15.1

Table 1: Fluid properties of R1233zd and R1233zd

2. R245fa BASED ORC SYSTEM OVERVIEW

The R245fa system was derived from R134a variable-speed compressor. The compressor housing had a rated pressure of 2200 kPa (a). A design pressure of 2000 kPa (a) was selected for the R245fa based ORC system which corresponds to a turbine inlet saturation temperature of 121.9 °C. And a condenser saturation temperature of 30 °C was selected for design. At these conditions the turbine was designed to produce 75 kW output at the shaft. Figure 1 and 2 show pictures of the rotor and nozzle.

Figure 1: Radial inflow rotor

Figure 2: Fixed vane nozzle for 75 kW

The turbine has a radial inflow rotor with a fixed vane nozzle designed for chocked flow at the throat. The nozzle throat area corresponds to a chocked flow capable of producing 75 kW at the turbine design inlet and exit conditions. The turbine specific speed is 0.71 with rotor speed of 35000 rpm. The turbine has an isentropic efficiency of 80 %.

Being a variable speed machine the turbine is capable of maintaining peak aero efficiencies at off design conditions by keeping the rotor tip speed to spouting velocity ratio in the optimum range of 0.65 to 0.70 as shown by Whitfield and Baines (1990).

The heat input heat exchangers (evaporator), heat rejection heat exchangers (air cooled condenser) and a working fluid pump complete the ORC system. For the cycle analysis a combined pump and drive efficiency of 55 % was used. Figure 3 below shows the basic schematic for an ORC system and the Figures 4 and 5 represent the R245fa based organic Rankine cycle in Temperature-Entropy (T-s) and Pressure-Enthalpy (P-h) diagrams respectively. The state point 1 corresponds to evaporator exit/turbine inlet, state point 2 corresponds to turbine exit/condenser inlet, state point 3 is condenser exit/pump inlet and state point 4 corresponds to pump exit/evaporator inlet. Heat source temperatures above 140 ° C would be required to produce the required R245fa temperature and pressure at the turbine inlet, while allowing for a reasonable ΔT across the heat exchanger. Temperatures below 140 ° C would have a negative effect on the heat exchanger prices as the required surface area keeps increasing with lowering source temperature.

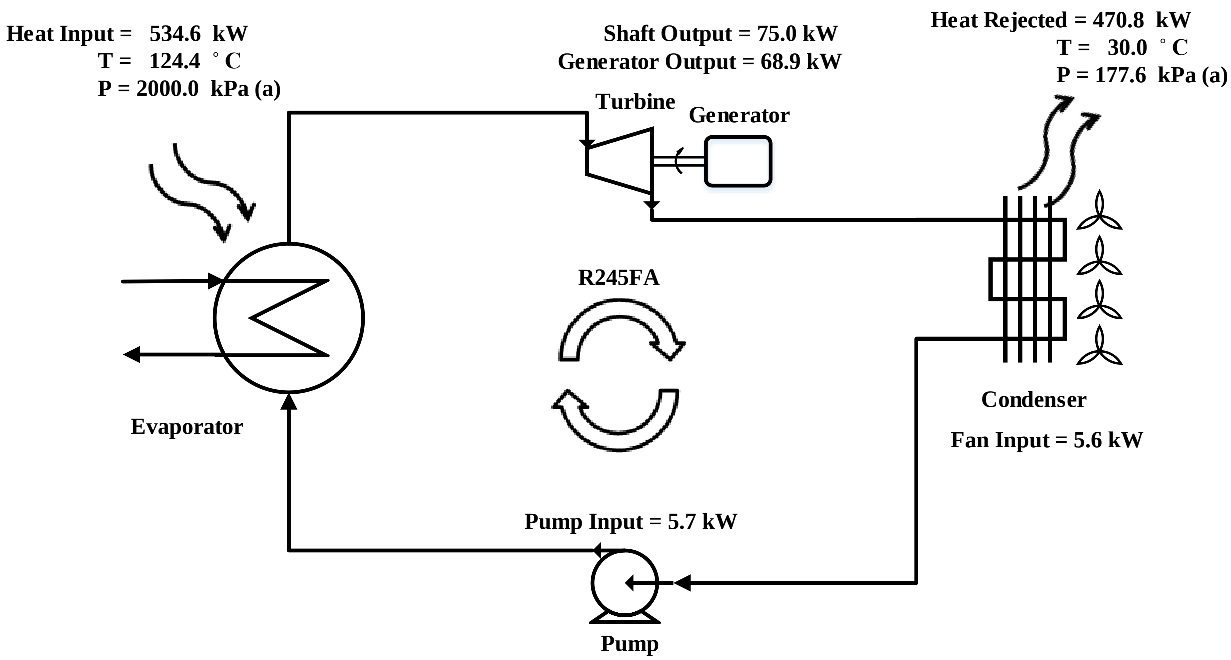

Figure 3: Schematic of an organic Rankine cycle system with R245fa as working fluid

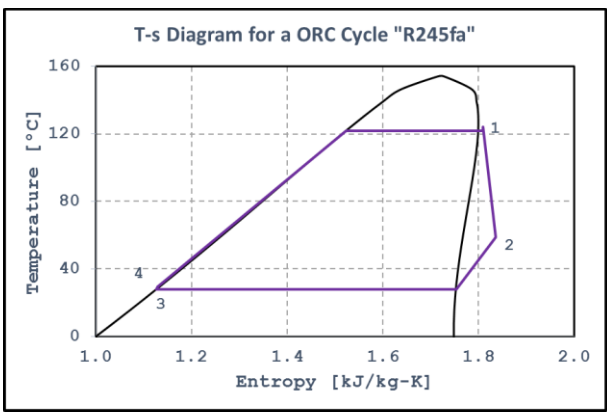

Figure 4: T-s diagram for R245fa ORC cycle

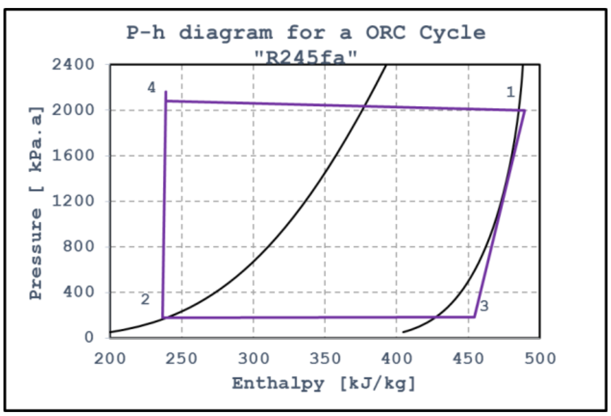

Figure 5: P-h diagram for R245fa ORC cycle

The R245fa ORC system needs a heat input of 534.6 kW to produce 75 kW of power out at turbine shaft, with R245fa mass flow rate of 2.13 kg/sec through the turbine and a pressure ratio of 10.45 across the turbine. After taking into account all the system related parasitic losses the power available for export to the grid is around 57.5 kW. The system Carnot efficiency is 23.74 %. While the thermal efficiency based on shaft power is 14.0 %, the efficiency of the system drops by 23% after taking into account the parasitic losses from pump, condenser fans and generator electrical conversion. This results in a net system heat to power output conversion of 10.8 %.

3. R1233zd AS DROP IN FOR R245fa

R1233zd being a lower pressure fluid compared to R245fa, helps in using a higher saturation temperature at design pressure. While using the same design condenser saturation temperature used for the R245fa based system, results in a higher Carnot efficiency compared to a R245fa system. This could indicate a higher net thermal efficiency of an R1233zd system compared to R245fa if the parasitic pump losses and system irreversibility's are comparable to the R245fa based ORC system. Figure 6 below shows the basic schematic for an ORC system and the Figures 7 and 8 represent the R245fa based organic Rankine cycle in a Temperature-Entropy (T-s) and Pressure-Enthalpy (P-h) diagrams respectively

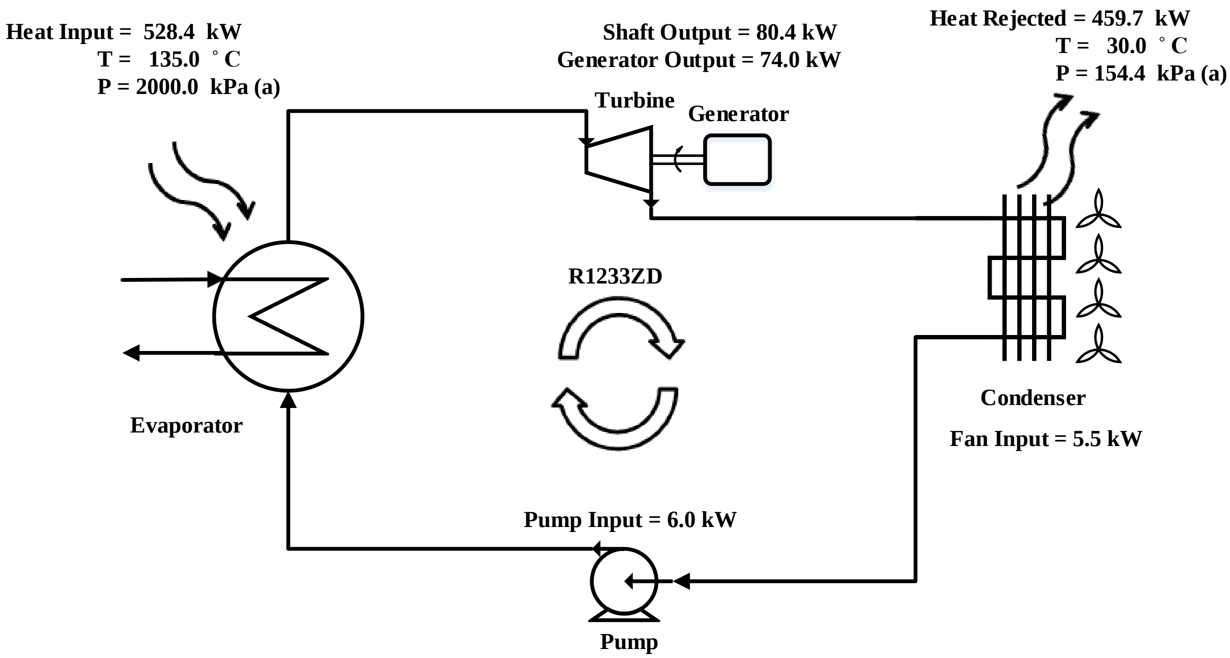

Figure 6: Schematic of the R1233zd based ORC system

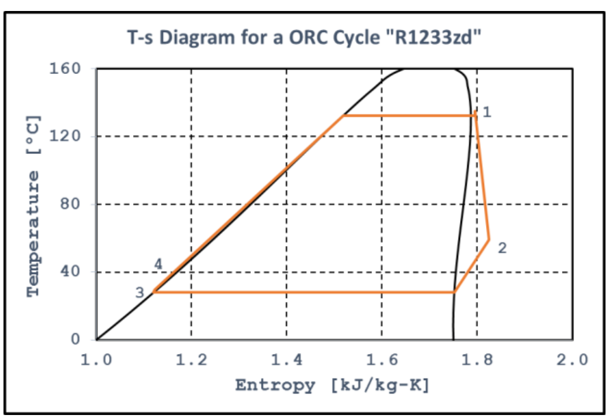

Figure 7: T-s diagram for R1233zd ORC cycle

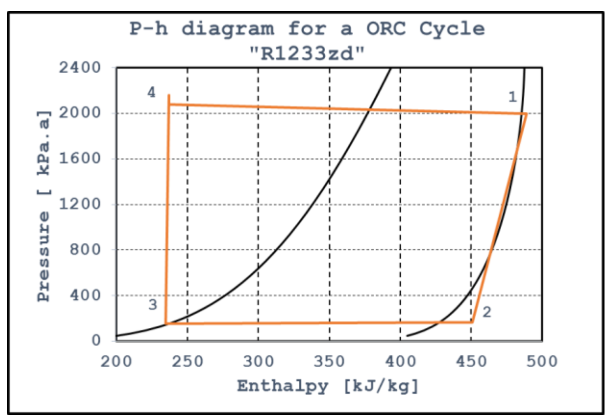

Figure 8: P-h diagram for R1233zd ORC cycle

R1233zd cycle analysis was done by using the same nozzle used in the 75.0 kW R245fa system and the same system component efficiencies. This results in an identical mass flow rate of 2.10 kg/sec through the turbine, at higher pressure ratio of 11.93 across the turbine inlet and exit, resulting in a power output of 80.4 kW at the shaft. Taking into account all the system parasitic losses the power available for use out of the system is 62.5 kW. The Carnot efficiency of this system is 25.73%. The efficiency based on power output at the shaft is 15.2%. Taking into account all the parasitic losses from the system components the efficiency drops by 22 % resulting in a net thermal efficiency of 11.8% out of the system.

4. COMPARISSION OF R1233ZD ORC SYSTEM WITH R245FA

A drop in of R1233zd into R245fa based ORC systems would help realize a performance gain of 10 percent over the existing system, accomplished with little or no changes changes to the existing ORC system. In addition R1233zd has a low GWP of 6 when compared to R245fa with a moderate GWP of 950. Environmentally R1233zd would be a step forward towards low GWP low temperature ORC systems. This performance gain of 8.7 % could translate to reduction in $/kW and Return of Investment times by 8.7 % when looking at machines using similar amount of heat. The summary of the system performance with no changes in the turbine geometry is compared in Table 2. The cycle comparisons on T-s and P-h diagram are shown in Figure 9 & 10 respectively

System Performance Comparison	Units	R1233zd	R245fa
Mechanical Shaft Power Output	[kW]	80.4	74.8
Gross Electric Power Out from Generator	[kW.e]	74.0	68.9
Total Heat Input	[kW.th]	528.4	534.6
Total Heat Rejected	[kW.th]	459.7	470.8
Pump Power	[kW.e]	6.0	5.7
Energy Balance	[kW]	0.00	-0.07
Condenser Fan Power based on 0.012 kW.e/kW.th	[kW.e]	5.5	5.6
Net Power Out of Air Cooled System	[kW.e]	60.3	55.4
Thermal Efficiency based on Shaft Power	[%]	15.2%	14.0%
Thermal Efficiency based on Generator Power	[%]	14.0%	12.9%
Thermal Efficiency based on Air Cooled Net Power	[%]	11.4%	10.4%

Table 2: Fluid properties of R1233zd and R1233zd

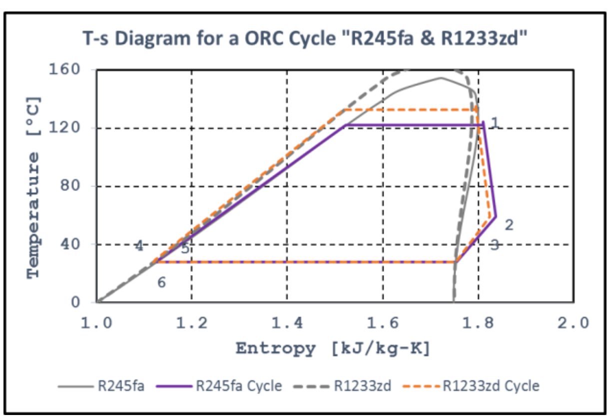

Figure 7: T-s diagram for R1233zd ORC cycle

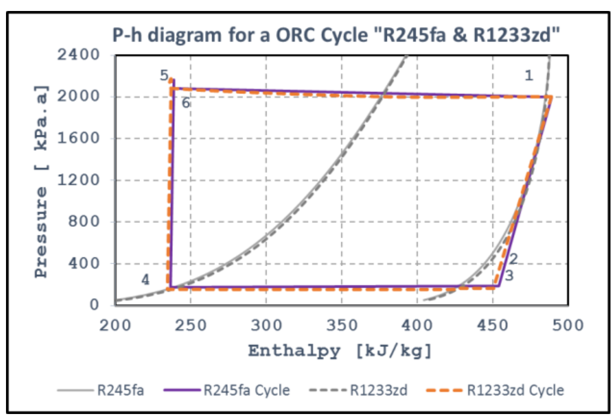

Figure 8: P-h diagram for R1233zd ORC cycle

Table 4 shows the comparison of the turbine parameters for the two fluid. The spouting velocity in an R1233zd based turbine is higher compared to R245fa which would require the rotor to run at a higher rpm compared to the R245fa rotor to achieve a similar peak aero efficiency. A variable speed machine should be able to match the speed for peak efficiencies. With the difference in R245fa and R1233zd rotor speed for maximum efficiency being relatively small, even a fixed speed machine should be capable of extracting energy in the rotor at peak efficiency as the tip speed by spouting velocity ratio for maximum aero efficiency has a flat dome in the velocity ratios of 0.6 to 0.7. The shaft power out of the R1233zd machine is 80.4 kW compared to the original R245fa machine with 75 kW power output at the shaft at design conditions. If there is a shaft power limitation of 75 kW for the machine, then with minor modifications in the nozzle, reducing the throat area by the % of over capacity, in this case around 7% would give the required R1233zd turbine capable of 75 kW at the shaft. This can be easily achieved with changing the nozzle vane angles in case of machine having variable nozzle vanes or even for the fizzed vane nozzle new vanes can be designed to achieve the required throat area reduction without any external dimensional modifications to the turbine assembly components. Alternatively the throat area could also be reduced by decreasing the nozzle throat depth using machining/ grinding of the nozzle vane face by the required % area reduction, this would result in changed nozzle assembly dimensions, but generally without any major impact on the complete turbine assembly.

When using a new working fluid in this case R1233zd, care should be taken to check the compatibility of all materials, especially sealing gaskets which come in contact with the working fluid.

Turbine Parameters	Units	R1233zd	R245fa
Inlet Temperature	[°C]	135.0	124.4
Inlet Pressure	[kPa]	2000	2000
Outlet Temperature	[°C]	59.1	59.0
Outlet Pressure	[kPa]	167.7	191.3
Pressure Ratio	[-]	11.93	10.45
Spouting Velocity	[m/s]	309.5	295.9
Mass Flow Rate	[kg/s]	2.10	2.13
Exit Volume Flow Rate	[m^3/s]	0.253	0.218
Rotor Speed	[rpm]	36628	35000
Shaft Power	[kW]	80.4	75.0

Table 4: R1233zd and R245fa turbine parameters comparison.

5. CONCLUSIONS

- R1233zd can be used in existing R245fa based ORC turbine with little or no modifications. While care should be taken for components in contact with the working fluid and be checked for material compatibility.
- With the a reasonably close spouting velocity of R1233zd compared to R245fa at design conditions, a fixed speed machine would have a comparable turbine efficiency to that of variable speed machine when R1233zd is used as the drop in fluid.
- The use of low GWP R1233zd for low temperature ORC system shows promising 8.7% higher cycle efficiency when compared to an equivalent R245fa based system.
- This gain in performance of R1233zd when compared to R245fa system should help realize proportional reduction in cost/kW and ROI time over existing R245fa machines.
- R1233zd with its low GWP and high cycle efficiency when compared to R245fa could make it a great candidate for low GWP, low temperature ORC systems.

NOMENCLATURE

GWP	global warming potential
ORC	organic Rankine cycle
P	pressure
ROI	return on investment
T	temperature

Subscripts

1	turbine Inlet/evaporator exit
2	turbine outlet/condenser inlet
3	condenser outlet/pump inlet
4	pump outlet/evaporator inlet

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