HFC-245fa Working Fluid in Organic Rankine Cycle - A Safe and Economic Way to Generate Electricity from Waste Heat

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Abstract: Climate change, environmental legislation and binding targets for renewable energy, alongside an increased focus on the economic benefits of energy and fuel conservation, are driving the adoption of new technologies as sources of energy. With these dynamics, it is evident that waste heat recovery technologies can play a key role in reducing the dependency on fossil fuels and in meeting future energy needs. These technologies can be important in reducing the CO_2 footprint of existing fossil power generation and achievement of renewable energy targets. Since the recovered heat is effectively 'free of charge', there is a direct positive impact on the energy costs to the end user. There has been considerable focus on the recovery of high temperature waste heat but less attention has been paid to the extensive opportunities that exist to recover lower grade heat. This paper focuses on the Organic Rankine Cycle (ORC) as an effective technology for low to medium temperature heat recovery. Recovery of low to medium temperature waste heat from installations such as power plants, diesel & gas generators, and industrial plants using ORC technology can provide additional electrical output, thus boosting overall efficiency and reducing the ratio of emissions/kWe produced. When available process heat cannot be readily utilized to satisfy a thermal requirement, Organic Rankine Cycle offers flexibility since the additional electrical output can be used in many ways, eliminating the associated expense and engineering required to use this heat in methods that require site-specific design. The availability of a non-flammable working fluid with appropriate thermophysical properties is an important aspect affecting the efficiency of the Organic Rankine Cycle. This paper describes the properties of HFC-245fa and discusses its potential application in power generation systems. The commercially available Refrigeration Grade HFC-245fa meeting Air-Conditioning and Refrigeration Institute Standard 700 has provided a viable option for safe, flexible, and economically efficient conversion of waste heat to electric power using Organic Rankine Cycle technology.

Keywords: HFC-245fa, Organic Rankine cycle, geothermal energy, bottoming cycle.

1. Introduction

Predictions of the growth in energy consumption around the world offer a clear picture that fossil fuel energy resources alone will not be capable of meeting future energy requirements. Additionally, climate change, environmental legislation and binding targets for renewable energy, alongside an increased focus across the manufacturing sector on the economic benefits of energy and fuel conservation, are driving the adoption of alternative technologies as sources of both thermal and electrical energy. On the basis of these dynamics it is evident that heat recovery and waste heat recovery technologies can be important in reducing the dependency on fossil fuel power. To date, both the industrial world and the power generation sector have predominantly focused on the utilization and recovery of high temperature heat and waste heat, but less attention has been paid to the large number of opportunities that exist to recover and use lower temperature heat.

In terms of off-setting current fossil fuel power generation, it is clear that a mix of both renewable and cleaner energy technologies will be necessary to meet future demand. Geothermal power, for example, will be part of this energy mix. In Europe, 2030 targets are for the geothermal sector to contribute to 5% of the total electricity production, and 3.5 % of the total heat generation [1]. In North America, geothermal sources hold huge theoretical potential for power generation. In the US alone it is assumed to be as high as ~350 GW. The targeted growth in geothermal electricity production will require the development of lower temperature geothermal heat sources utilizing binary ORC cycles. Quite a number of examples of this are already in existence, for example Raser Technologies power plant in Utah, and a number of other projects are under development, for example in Germany, New Mexico, Nevada and Mozambique.

While ORC has become recognized as an established technology to recovery lower temperature geothermal heat, its implementation to recovery low temperature waste heat from installations such as power plants, diesel & gas generators, and industrial plants is in its relative infancy. The opportunity is a substantial one. Energetic, Inc has estimated that there may be as much as 10 Quads of industrial waste heat energy available in the United States [2]. (This equates to 10^{16}BTUs or approximately $1.06x10^{13}$ megajoules). However, historically neither the economic or regulatory drivers have been in place to stimulate a significant focus on this opportunity. The lansdscape is changing however, and as energy prices increase, and environmental regulations tighten, e.g. anticipated developments come 2013 in CO_2 emissions legislation, commercial companies are increasingly being required to take additional steps to offset their power costs and reduce their environmental footprint. Low temperature waste heat recovery using Organic Rankine Cycle technology can provide the dual benefit of additional electrical output that reduces cost by offsetting existing power consumption, and the reduction of the CO_2 footprint. For example, recovery of waste heat streams from a coal fired power plant using Organic Rankine cycle Technology, provides the opportunity to achieve the same electrical power output, but with a lower fuel consumption, thus offering a net reduction in CO_2 emissions.

A critical element in the design of an Organic Rankine Cycle is the selection of the working fluid. Thermodynamic properties of a working fluid are not the only criteria to be taken into account during this selection. The impact of the working fluid on total system cost and safety in the end-user environment are also key criteria as they directly impact the economic fit, acceptability and ultimately market growth of Organic Rankine Cycle systems. This paper examines the suitability of one such fluid HFC-245fa or 1,1,1,3,3-pentafluoropropane, which is a non-flammable, single-component hydrofluorocarbon working fluid.

2. HFC-245fa organic Rankine cycle applications

2.1 Organic rankine cycle system characteristics

Figure 1 is a basic ORC system diagram. ORC systems convert thermal energy to mechanical shaft power. Typically, the mechanical shaft power is then used to drive an electric generator.

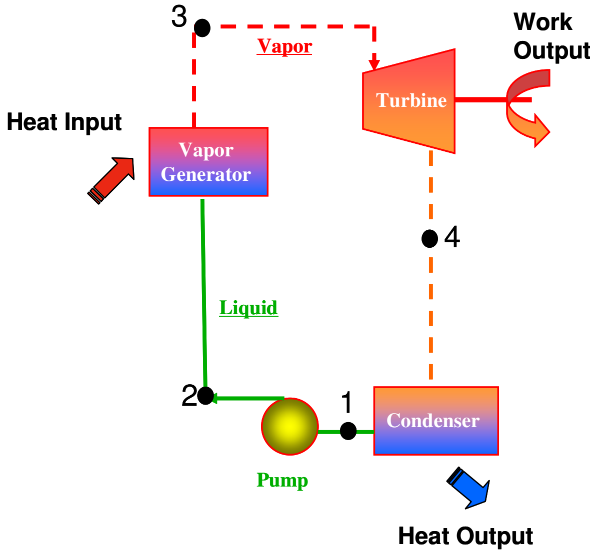

Fig. 1. Simple organic Rankine cycle system diagram.

ORC can be used for waste heat recovery from industrial plants, efficiency improvement in power stations, and utilization of geothermal and solar heat. The efficiency of an ORC is typically between 10 and 20%, depending on temperature levels and availability of a suitably matched fluid. ORC is an attractive option for heat recovery in the range of 90 ºC to 200ºC, particularly if no other use for the waste heat is available on site. At temperatures of 650-980 ºC, water is a very cost-effective working fluid, whereas; when source temperatures drop low enough that a steam cycle is no longer thermodynamically efficient, organic fluids are more suitable. One such fluid is HFC-

245fa or 1,1,1, 3, 3-pentafluoropropane. Cycle performance and heat exchanger limitations relating to the use of water, isopentane, and HFC-245fa as working fluids are discussed later in this paper. In the section that follows is a comparison of HFC-245fa and water as working fluids in a bottoming cycle application.

2.2 Bottoming cycle

Coal-fired thermal power plants consume vast amount of fossil fuel. Interest in efficiency improvement is currently high. With some systems, it is possible to utilize the low-grade heat that might otherwise be abandoned. Often, not quite 40% of the heat imparted to the steam is converted to mechanical work, with the rest being abandoned to a "cold reservoir". Consider a simple example where a steam boiler feeds a primary turbine (or 1st stage) and then effluent is reheated and routed to a secondary turbine operating at lower pressure (or 2nd stage). In Table 1 below is an example with conditions chosen such that condensation does not occur in the turbines. At the conditions given in Table 1, the theoretical cycle efficiency is 36.3%. Thermodynamic data used to develop the examples and illustrations in this paper were taken from NIST Refprop 7.0 [3].

In this example, if HFC-245fa is used in a bottoming cycle arrangement, the overall thermal energy efficiency can be improved 25%. Table 2 lists example conditions/quantities for the HFC-245fa cycle. The energy efficiency improvement attainable for a given plant will depend on the particular operating conditions.

Table 3 includes a cursory payback assessment which illustrates that for this example, the ORC system payback is less than 3 years.

2.3 Geothermal hot water

Geothermal power can address growing demand for power without consuming more fossil fuel. With Rankine cycle systems that obtain heat from a liquid source, it is important to consider the implications of latent heat of vaporization and heat capacity as they bear on boiling and sensible heating. Looking to the previous example where water was one of the working fluids, it brings this to light. Since water and HFC-245fa differ significantly with regard to latent heat of vaporization, it makes the example illustrative. A comparison of HFC-245fa and a second organic fluid, isopentane, are discussed in Section 3.2. Heat exchange limitations associated with water relate to the high ratio of latent heat of vaporization to heat capacity. In Figure 2, point A represents the condition for transfer of heat from flowing source fluid to the working fluid (10°C temperature difference in heat exchanger) in order to supply the heat required to vaporize the working fluid. This determines the maximum flow rate for the working fluid. At those flow rates, the heat required to raise the temperature of the liquid working fluid from the condensing condition to the evaporating condition can then be determined. In Figure 2, the sensible heat required is the thermal power difference between points A and B (water) or points A and B' (HFC-245fa). The temperature of the flowing source is lowered to a greater extent with HFC-245fa (point b') than with water (point b). Thus, more heat can be extracted from the source with HFC-245fa. Overall efficiency, defined as the cycle efficiency times the ratio of thermal power extracted to the total thermal power available, is influenced by heat exchange limitations. In the example of Figure 2, the higher cycle efficiency of water is offset by a heat exchange limitation and results in a lower overall efficiency versus HFC-245fa.

3.0 HFC-245fa as a Rankine cycle working fluid

3.1 Fluid properties and equipment configuration

ORC cycle fundamentals establish that the greater the temperature difference between the source and sink, the more work that is available. However, the properties of a particular working fluid will dictate the practical extraction points. When HFC-245fa is subjected to isentropic expansion, the exiting gas is more superheated than at the outset of expansion. The thermal energy associated with this exit superheat provides no benefit if it is only to be rejected at the condenser. A recuperator (heat exchanger) located between the turbine exhaust and the condenser can be employed to recover the superheat into the condensate return thus improving cycle efficiency.

Table 4 lists the enthalpy drop associated with expansion and the enthalpy difference between superheated and saturated conditions at the expander outlet. The data show that increasing expander inlet temperature reflects increasing expander inlet superheat and that the enthalpy drop associated with the expansion (work extraction) step increases with increasing expander inlet superheat and with decreasing condensing temperature. Table 4 shows the enthalpy difference between the exit superheat and saturated condition can be of comparable magnitude to the expander enthalpy drop. Thus the benefit of a recuperator becomes clear.

3.2 Comparison of HFC-245fa and Isopentane

When selecting a working fluid for a particular application, it is important to match the working fluid to the source temperature. Typically, the boiler must operate at a temperature such that the corresponding thermodynamic state is sufficiently below the fluid critical point so that the latent heat of vaporization is not so small as to dictate an unrealistically high mass flow rate. As noted in Section 2.3, in the comparison of HFC-245fa and water, it is also important to

Table 1. Steam Conditions for Simple Turbine Arrangement.

Outlet Location	Temperature, ºC	Pressure, kPa	Enthalpy,liq. kJ/kg	Enthalpy,vap. kJ/kg	Entropy,vap. kJ/kg K
From Boiler	537.8	8274		3486.7	6.8229
From 1st turbine	152.0	500.0	640.0	2748.8	6.8299
From Reheater	482.2	413.7		3446.3	8.1256
From 2nd turbine	135.0	29.2	552.0	2676.3	8.1274
From condenser	55.0	19.3	223.9		
From Pump	58.0	8619	243.1		
Net Heat Output	1389.2 kJ/kg steam				
Heat Input	3822.1 kJ/kg steam				
Theoretical cycle efficiency	0.363				

Enthalpy, entropy values use ASHRAE thermodynamic reference state.

Table 2. HFC-245fa Rankine Cycle.

Outlet Location	Temperature,ºC	Pressure, kPa	Enthalpy, liq. kJ/kg	Enthalpy, vap. kJ/kg	Entropy, vap. kJ/kg K
From Boiler	125.0	2113		490.1	1.811
From turbine	51.9	213		447.5	1.811
From condenser	95	213	246.5		
From pump	97.7	2113	249.1		
Work done on 245fa - pump		2.53 kJ/kg			
Net mechanical energy/unit mass		39.95 kJ/kg			
Thermal input to 245fa/cycle		241.0 kJ/kg			
Mass ratio		9.07 kg 245fa per kg steam condensed			
Net ORC Work/unit mass steam		362.7 kJ/kg			
Combined cycle work output		1792.5 kJ/kg			
Combined cycle efficiency		0.456			
% Increase in efficiency		25.6 (compared to Table 1 case)			

(Enthalpy, entropy values use ASHRAE thermodynamic reference state.)

Table 3. High Level Payback Analysis.

Mechanical Power (W) = Power in load circuit (We)/commercial efficiency	1.39 x 10^9 W or 5.0 kJ/hr
Steam mass flow (kg/hr) = mechanical power (kJ/hr)/heat input with reheat (kJ/kg)	1.27 x 10^6 kg/hr steam
ORC work = Mass Flow Steam (kg/hr) x Net Work Out/Unit mass steam (kJ/kg)	4.6x10^8 kJ/hr or 128MW
Plant electric output increase, %	25
ORC System Cost ($1500 to $2000/KW)	$192M to $256M
Value of Power produced in ORC ($0.085/kWhr)	$95M
Payback (assumes operating cost is small)	2 to 3 years

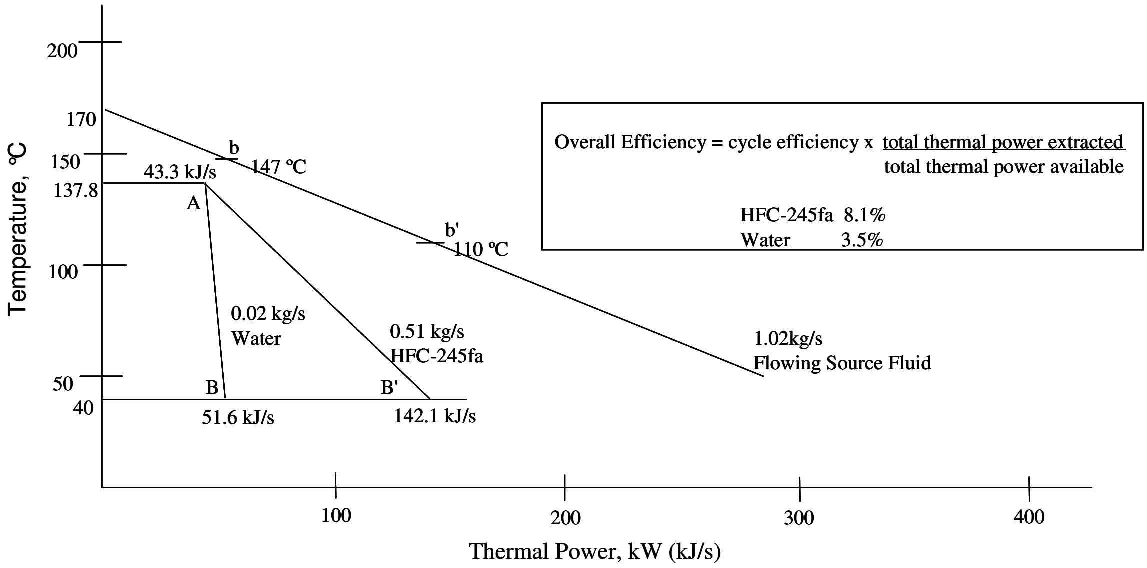

Fig. 2. Comparison of boiling and sensible heating contributions to overall efficiency.

Table 4. Enthalpy drop and superheat enthalpy of HFC-245fa (isentropic expansion).

Temperature Expander Inlet °C	Temperature Condensing °C	Enthalpy Drop Expansion kJ/kg	Superheat Enthalpy kJ/kg
148.9	21.1	56.0	29.3
162.8	21.1	61.1	48.1
176.7	21.1	64.9	65.1
148.9	15.4	60.1	29.8
162.8	15.4	65.5	48.4
176.7	15.4	69.9	64.7

understand the impact of the sensible heating component. One application where sensible heating is of particular interest is geothermal energy conversion. In geothermal ORC applications, it is desirable to maximize per pass heat removal from the source; that is, to lower the temperature of the source effectively as this impacts overall efficiency. Both HFC-245fa and isopentane may both be considered for use as ORC system working fluids for geothermal hot water sources. Examining a hypothetical case of a 245fa ORC system and an isopentane ORC system each sized so that 5000kJ/s goes to the boiler, the following data was derived for a 90ºC source and a 120ºC source. A specific diameter of 4 was assumed (taken from a Balje diagram) [4]. To determine the diameter, the equation

$$D= d_s Q^{0.5} / H^{0.25} , \quad (1)$$

was used where

Q is the volumetric flow rate (m^3/s),
H is head (m^2/s^2) and
d_s is specific diameter (dimensionless).

Head is determined from the equation

$$PR=[1+(\gamma-1) H/ a^2]^{\gamma/\gamma-1} , \quad (2)$$

where

PR is the turbine pressure ratio (dimensionless),

γ is the isentropic exponent (dimensionless, for an ideal gas the term is the ratio of heat capacity at constant pressure to heat capacity at constant volume, Cp/Cv), and

a is the speed of sound in the particular working fluid (m/s).

The term H was introduced previously.

Table 5. Geothermal hot water: HFC-245fa and isopentane comparison.

90ºC source*	Mass flow, kg/s	Turbine Exit flow, m^3/s	Turbine Diameter, m	Theoretical electrical output, kWe
HFC-245fa	22.4	2.34	0.474	473.5
Isopentane	11.9	3.94	0.526	476
120C source**				
HFC-245fa	20.6	2.30	0.418	646.5
Isopentane	10.6	4.06	0.470	531

*30ºC condensing (fluid temperature)

** exit condition governed by 9:1 pressure ratio

Analysis of the data in Table 5 reveals that the isopentane turbine diameter would be approximately 11% larger than the 245fa turbine diameter for the case of a 90ºC and about 12% larger for the 120ºC source. This would, of course, result in an equipment cost increase. The electrical output, without de-rating for efficiency of the generator, is about 0.5% more for isopentane with the 90°C source and about 4.0 % more with the 120°C source. The turbine and generator efficiency are ignored in this comparison. It is reasonable to conclude that the achievable optimized turbine efficiency would be comparable for the two fluids. Bearing in mind that equipment is often built at a fixed size, it is more realistic to compare the output for a given turbine size using the two fluids, HFC-245fa and isopentane.

A comparison of electrical output for a 245fa system versus an isopentane system for the same size turbine is summarized in Table 6. One may think it as “dropping-in” isopentane in place of HFC-245fa; essentially replacing HFC-245fa with isopentane on a 1:1 volume basis. Equation (1) can be rearranged to determine the volumetric flow rate from the known turbine diameter. Equation (2) can be rearranged to determine head at the given conditions. From the volumetric flow rate and density at the given conditions, the mass flow rate is found. Knowing the mass flow rate and the latent heat of vaporization at the conditions of the cycle, the corresponding thermal input is derived. Finally, the product of the thermal input and the theoretical thermodynamic cycle efficiency provides an estimate of the electrical output. Theoretical thermodynamic efficiencies used were 0.0952 and 0.1344 for isopentane at 90°C and 120°C, respectively. Corresponding efficiencies for HFC-245fa were 0.0947 and 0.1293, respectively. For the conditions in Table 5, using isopentane instead of HFC-245fa would result in an estimated 19% reduction in electrical output for a 90°C source and nearly an 18% reduction for a 120°C source.

An analysis of piping sizing was also conducted; however, for the sake of brevity, a detailed discussion has been omitted. Looking at the 90°C source condition, if the piping diameters determined for HFC-245fa are used for isopentane at the corresponding isopentane mass flow, velocities for the expander outlet and

Table 6. "Drop-in" of isopentane in a turbine initially sized for HFC-245fa.

90°C Source	Turbine Diameter, m	Volumetric flow rate (turbine exit), m^3/s	Mass flow, kg/s	Electrical Output, kWe	% Change kWe vs. HFC-245fa
Isopentane	0.474	3.20	9.6	383	(19.0)
HFC-245fa	0.474	2.34	22.4	473.5	
120°C Source					
Isopentane	0.418	3.22	8.4	531	(17.9)
HFC-245fa	0.418	2.30	20.6	646.5	

liquid line are outside the acceptable range by about 1% and 15%, respectively. The isopentane expander inlet velocity was within acceptable parameters.

In Section 2.3, it was mentioned in broad terms that the temperature drop of a flowing source is an indicator of how effectively heat is being delivered to the organic Rankine cycle system. If follows that a greater temperature drop is more desirable since it has a positive impact on overall efficiency. An organic Rankine cycle system sized to deliver 5000kJ/s (from a 90°C source) to the boiler will have contributions from the latent heat of vaporization of HFC-245fa at 80°C and the sensible heating from 30°C to 80°C totalling about 224 kJ/kg. The product of the corresponding mass flow rate from Table 6 and the total heat delivered to the working fluid can be set equal to the heat given up by the flowing source water, which is, in this instance, 5000kJ/s. From the relationship

$$q=m C_p \Delta T, \quad (3)$$

where

q is the heat removed (kJ/s),

m is mass flow (kg/s),

Cp is heat capacity at constant pressure (kJ/kg K), and

ΔT is the temperature difference (°C),

the latter can be determined. Assuming a source flow rate of 100kg/s and using the heat capacity of water at 90°C, the estimated drop in the source temperature would be 12°C. As a check, the total latent and sensible heat delivered to isopentane, 419kJ/kg times the corresponding mass flow rate in Table 5 results in expectedly 5000kJ/s. Since both systems are sized to 5000kJ/s heat input, the temperature drop in the source water would be the same 12°C.

Finally, the most obvious difference between HFC-245fa and isopentane is that the former is non-flammable while the latter is flammable. The use of a flammable working fluid typically means that significant additional costs are incurred relating to the end-user site and the equipment. A 5MWe geothermal power plant utilizing an organic Rankine cycle system containing a flammable working fluid could require on the order of an additional $500,000 for flammability and site safety-related costs [5]. Additional factors such as site permitting, which is also more involved when a flammable fluid is used and impact on insurance premiums also should be taken into account when making a choice between flammable and non-flammable working fluids. Flammability risk would also be a concern with transportation, storage, handling, and during system operation.

4. Benefits to the environment

Increasing the use of solar, geothermal, biomass and waste heat energy to produce electricity curbs the use of fossil fuels and thereby helps reduce air emissions. The additional power output from ORC systems appended to power generation systems can help meet growing demand for power while offering a more attractive emissions profile since there is a gain in output without additional fuel consumption. Optionally, integrated ORC/distributed generation equipment can be downsized relative to unmodified distributed generation equipment, potentially using less fuel and producing fewer emissions while providing the same power output. Equation (3) can be used to reasonably estimate the electric power that can be derived using organic Rankine cycle to convert thermal energy from a flowing fluid source [6]. A notable example of a flowing liquid source would be geothermal hot water.

$$NEP = [(0.18T - 10)\,ATP]/278\,, \qquad (4)$$

In (4),

T is the inlet temperature of the flowing source fluid (ºC),

NEP is the net electric power (kW) and

ATP is the available thermal power (kW).

The available thermal power is the heat available from the flowing source fluid and is typically determined using a temperature 10ºC above the bottom cycle temperature. With liquid sources such as diesel genset engine coolant, organic Rankine cycle systems can produce on the order of 10% to 15% additional electric power from the waste heat. In addition to the increased electric power output without consumption of additional fuel, there is the concomitant benefit of no additional emissions.

5.0 CONCLUSIONS

HFC-245fa thermophysical properties make it a suitable working fluid for organic Rankine cycle applications. The high heat capacity of HFC-245fa results in improved theoretical cycle efficiency and heat exchanger performance that translates into improved overall efficiency. In a bottoming cycle, the advantages of HFC-245fa as compared to water include higher cycle efficiencies, lower latent heat-to-heat capacity ratio (heat exchange pinch point for water), and higher gas densities (lower volumes). Geothermal, solar, and industrial waste heat sources can be used to drive HFC-245fa as the working fluid in organic Rankine cycle systems in order to achieve useful thermal energy utilization via thermal energy conversion to electric power. When coupled with fossil fuel-driven distributed power generation systems, improved air emissions profiles and fuel consumption profiles can be realized.

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