Honeywell Refrigerants Improving the Uptake of Heat Recovery Technologies

By Gary J. Zyhowski

I. Introduction

When developing a business strategy, it may seem odd to take into account the geologic time scale. However, in making the case to adopt heat recovery and thermal energy conversion technology now, it is meaningful to do so. Most of us would agree that we are consuming fossil fuels at a rate that exceeds the rate of manufacture, and that the limited fossil fuel resources alone will not be capable of meeting future energy requirements. Fossil fuel consumption can be tempered by improving the efficiency of the systems where the fuel is used. However, it is clear that the current supply-demand balance is a key factor that is driving the adoption of alternative sources of energy, for example, solar, geothermal, wind, and wave power. Additionally, climate change, environmental legislation and binding targets for renewable energy, alongside an increased focus on the economic benefits of energy and fuel conservation, are also driving the adoption of new technologies as sources of energy. It is clear on the basis of these dynamics that both heat and waste heat recovery technologies will play a key role in reducing the dependency on fossil fuels and in meeting future energy needs. They will make a significant contribution to the reduction of CO2 emissions, achievement of renewable energy targets, and, since the heat recovered is effectively 'free of charge', will have a major positive impact on the energy costs for commercial entities as well as home owners.

Energetic, Inc has estimated that there may be as much as 10 Quads of industrial waste heat energy available in the United States[1]. (This equates to 1016BTUs or approximately 1.06x1013 megajoules.) Honeywell's refrigerants business, recognizing the growth potential associated with energy efficiency, has endorsed an R&D effort to promote the use of refrigerants in high-temperature heat pumps, organic Rankine cycle systems, and in thermally-driven adsorption refrigeration. Fig. 1 illustrates that high-temperature heat pumps typically utilize source temperatures of 30-40 °C and deliver heat to applications approaching 90 °C. Thermally activated technologies such as adsorption cooling utilize source temperatures of 50-100 °C. Organic Rankine cycle systems generally require source temperatures of 80 °C or greater in order to have viable efficiencies.

An Organic Rankine cycle is a variation on the theme of the Rankine or steam cycle. In the Rankine cycle, water is the working fluid. The Rankine cycle is commonly used in fossil fuel-fired electric power plants, where fuel is combusted to liberate heat. The heat is applied to water, converting it to steam which is expanded through a turbine. This causes the turbine shaft to rotate. This mechanical shaft power is used to drive an electric generator. In general terms, a thermal energy conversion system has just been described. When lower temperatures are encountered, water as the working fluid does not look as attractive thermodynamically. With lower quality heat, substitution of water with an organic working fluid, typically with a lower boiling point/higher vapor pressure and thus, higher gas densities, will improve the thermal efficiency of the cycle and decrease the size of the equipment required.

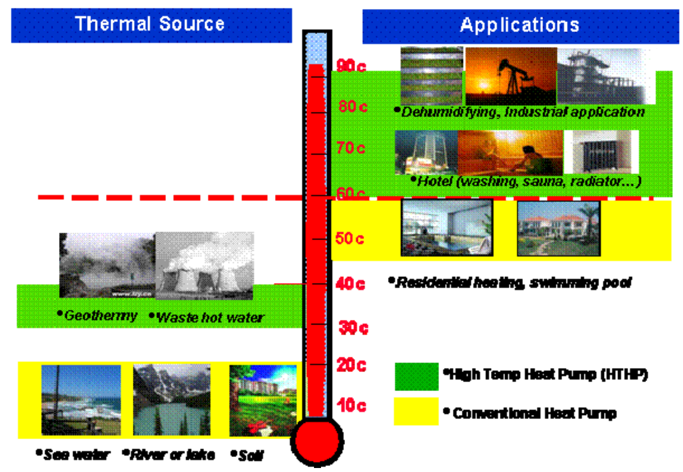

Fig. 1. High-Temperature Heat Pump Applications

This paper focuses on the Organic Rankine cycle as an effective technology for heat recovery and illustrates this through a number of applications. Honeywell's Refrigerants business, part of the Fluorine Products Division, has been working to develop the use of HFC-245fa refrigerant as a working fluid for Organic Rankine cycle (ORC) systems. A schematic of a simple ORC system appears in fig. 2. Heat is applied to the vapor generator (boiler) to generate working fluid vapor. The vapor passes to an expander where work is extracted. Typically, the work is extracted as mechanical shaft power and is used to run an electric generator. The vapor exiting the expander is condensed to liquid. A pump is used to elevate the pressure of the liquid for entry to the boiler.

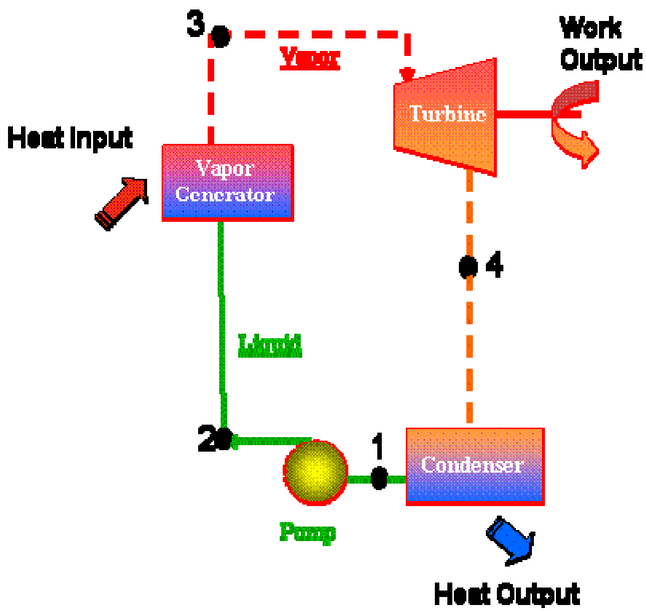

Fig. 2. Simple schematic of ORC system

ORC systems may utilize a variety of working fluids depending on the source temperature and system design. Fig. 3, although not all-inclusive, illustrates how a number of commercial working fluids are applied in ORC systems. Thermal sources and working fluid applicability typically have a temperature range associated with them. Ranges have been illustrated for industrial processes, solar, and fuel cells. Ranges for the other source types listed were not included in order to simplify the figure. The shaded triangles to the left of several of the working fluids illustrate that the fluids can be used to address a range of source temperatures. Practical ranges for working fluids are influenced by thermophysical properties and characteristics such as flammability and thermal stability. For non-flammable fluids such as HFC-245fa, higher source temperatures can be addressed by using direct heat exchange provided the evaporator (boiler) is properly designed to avoid reaching the thermal decomposition temperature of the fluid. The autoignition temperature of flammable hydrocarbons typically precludes their use in direct heat exchange with high temperature exhaust gases that contain oxygen or other oxidizers. As an alternative, a thermal oil loop can be placed between the source and ORC system evaporator. This approach is used for flammable fluids and non-flammable fluids as well, managing flammability risk or thermal decomposition risk, respectively. For example, by choosing heat exchange components advantageously, the red-shaded triangle next to HFC-245fa in fig. 3 can be extended upward to address applications such as engine heat sources and combustion exhausts.

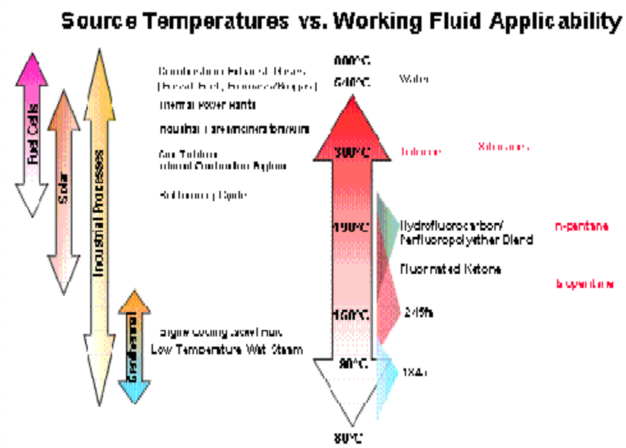

Fig. 3. Working Fluid Applications

HFC-245fa is the hydrofluorocarbon 1,1,1,3,3-pentafluoropropane. It is a non-flammable, single-component working fluid with favorable heat transfer properties, high latent heats (within its class of working fluids), good thermal stability, hydrolytic stability and materials compatibility which collectively contribute to attractive cycle efficiencies, the ability to use common construction materials, and ease of maintenance.

Honeywell's level of activity has recently increased as ORC system manufacturers around the world have stepped up efforts to develop systems to meet downstream market needs to implement renewable energies and reduce energy costs and carbon emissions. Future increases in fuel costs and electric power costs will only serve to make ORC systems more economically attractive. Honeywell's HFC-245fa has already been adopted by a number of ORC system manufacturers, with a number of commercial applications to be found, for example in geothermal power plants, commercial and residential buildings, remote power engines, e.g. gas generators, and industrial installations. ORC systems tend to be robust and relatively easy to maintain, and an upside to these systems is that they can be driven by a wide variety of heat sources. Systems being offered currently are driven by waste heat from gas turbines, internal combustion engines, and industrial processes and also by heat from renewable energy sources such as geothermal, solar, and biomass/biogas.

The most popular use of ORC systems is for the conversion of thermal energy to electric power. An example of such a system appears in fig. 4. In this case, an ORC system is appended to an existing biogas-fired internal combustion engine that serves as the prime mover for a 1000 kW electric power generator. The first benefit is the use of a fuel that is not a fossil fuel. The second benefit comes from the ORC system. The ORC system, driven by waste heat from the engine exhaust gas (high temperature loop) and engine coolant (low temperature loop) generates an additional 150 kW electric power (15% increase) without any increase in CO2 emissions.

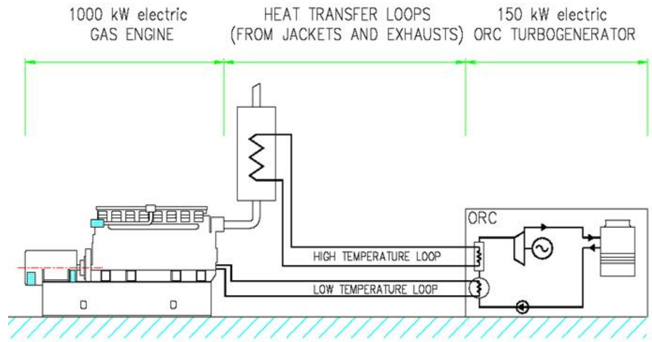

Fig. 4. Biogas ORC Application

CO2 emissions, alternative fuel utilization, and potential global warming impact of direct chemical emissions are taken into account when evaluating the environmental benefits of thermal energy conversion systems such as this. Leaking a high global warming potential fluid into the environment is not desirable. Consider that R-134a (tetrafluoroethane) is being phased out of automotive air-conditioning applications in Europe due to its global warming potential (1300 GWP on a 100-yr. time horizon). The GWP of HFC-245fa is 950.2 However, the operation of the ORC system, when displacing conventional grid power, avoids the CO2 emissions associated with that source. Therefore, we can conclude that there is a substantial net global warming benefit to using HFC-245fa as a working fluid in an ORC heat recovery system. This is determined on the basis of the CO2 emissions that are avoided during the typical 15-20 year operational lifetime of the ORC as a result of the non-CO2 emitting electricity that is generated. The benefit is on the order of 118 times the (potential) equivalent CO2 emissions that might be expected to occur due to direct chemical emissions from system leaks. The previous figure is determined based on 1999 estimated US power plant emissions and a leak rate of 2% of charge per year3. Since different working fluids have different global warming potentials, the concomitant risk of global warming in the event of ORC system leaks differs accordingly.

In addition to environmental factors, other factors influence the selection of ORC system working fluids. Thermal cycle efficiency, thermal stability, and safety are also important considerations. The theoretical thermodynamic cycle efficiency derives from the thermodynamic properties of the fluid. In general, high values for critical temperature, latent heat, and heat capacities are desirable. System efficiencies are also improved by having favorable transport properties. Fig. 5 charts temperature-entropy of several fluorinated fluids. The saturated liquid-vapor lines for the fluids define domes having varying areas beneath them. The area swept out by a given ORC cycle, and fundamentally, the area of a given dome provides an indication of the potential for work extraction and the associated cycle efficiencies that can be attained. A broad, tall dome would be preferred. To save space, the individual graphical cycle analyses for the fluids of fig. 5 have not been included here. In Tables 1 and 2, cycle conditions and results appear, respectively. The fluids in fig. 5 can be ranked in decreasing order of theoretical thermal cycle efficiency as HFC-365mfc > HFC-245fa > HFC 43-10mee > HFE-7100*. Note that the height of the 245fa dome (lower critical temperature) is lower than the other fluids but efficiency is still quite high as the 245fa dome is rather broad. Ranking fluids by theoretical thermal cycle efficiency is useful but it does not provide a complete picture. If the same fluids are ranked on a relative basis according to the amount of work output for a fixed equipment size, HFC-365mfc would produce 50% less output than HFC-245fa for the same size equipment.

* 3MTM NovecTM Engineered Fluid HFE-7100, a blend of hydrofluoroethers

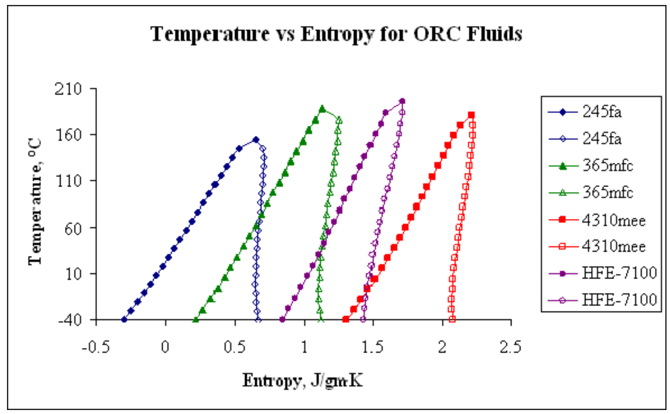

Fig. 5. Temperature-Entropy Domes for Fluorinated Working Fluids

TABLE 1- CYCLE CONDITIONS

Cycle Conditions		
Pump Efficiency	75	%
Expander Efficiency	80	%
Boiler Temp	130	°C
Condenser Temp	45	°C
Heat to Boiler	1000	W

TABLE 2 – THERMAL EFFICIENCY

Cycle Results					
	Units	245fa	365mfc	HFE-7100	4310mee
Boiler Press	psia	338.67	146.7	93.63	114.56
Condenser Press	psia	42.9	16.7	8.7	7.6
Superheat in Boiler	°C	0.0	0.0	0.0	0.0
Fluid Flow	g/s	4.37	4.10	5.41	5.07
Pump Work	J/g	2.12	0.99	0.53	0.66
Expander Work	J/g	-30.22	-32.22	-22.00	-24.21
Net Work	J/g	-28.10	-31.23	-21.47	-23.54
Net Work	W	-122.74	-127.91	-116.21	-119.33
Q Boiler	J/g	228.94	244.13	184.78	197.30
Thermal Efficiency		0.123	0.128	0.116	0.119

In addition to factors such as thermal cycle efficiency and equipment size, other factors such as safety need to be taken into account. For example, among the fluids in fig. 5, HFC-365mfc is flammable. To counter this, a current commercial product blends a perfluoropolyether with HFC-365mfc which renders the blend non-flammable; however, the resulting theoretical cycle efficiency is lower than HFC-245fa. To use flammable fluids “as is”,

special permitting is typically required, alongside incorporation of design components necessary to meet code requirements for use of a flammable fluid in the application, and safety precautions in the end use operating environment. The additional cost of these measures can make the cost of electricity generated from ORC systems that use flammable fluids less economically attractive than from those systems that use non-flammable fluids such as HFC-245fa. Highly flammable hydrocarbons are also used in ORC systems. For example, in some geothermal installations, there may be more than 40,000 lbs of flammable working fluid in a system. However, commissioning of installations such as these is usually only considered viable in remote un-inhabited locations. In general, while flammable fluids such as hydrocarbons have been commonly used in the early days of ORC technology, ORC system developers are now steering away from the use of flammable fluids in future ORC technologies due to the additional risks and costs that are now associated with their use.

ORC cycle efficiency is maximized by having the greatest temperature difference between the boiler temperature and the condenser temperature. So, higher temperature sources have the best potential for thermal energy conversion provided the working fluid has the necessary thermodynamic properties and thermal stability. Angelino and Invernizzi reported no signs of thermal decomposition in HFC-245fa in 50-100 hour exposures at 300 °C.4 Honeywell conducted 2-week (336-hour) thermal stability tests at 204 °C, 232 °C, and 260 °C. At 260 °C, there was no significant thermal breakdown. Since time, temperature, moisture, metals, and lubricant additives (if a lubricant is required) can affect stability, these factors must be taken into account when establishing an upper limit for system operating temperature.

Once a source has been selected, efficiencies are maximized by minimizing the magnitude of the irreversibilities in the system. For example, minimizing the temperature difference between the evaporating condition (boiler) and source, and likewise, between the condensing condition and sink serve to improve system efficiency.

Finally, throughout the paper, the discussion of cycle efficiency, environmental benefits, and stability lead one to conclude that HFC-245fa properties make it a very suitable ORC working fluid. Yet, there is a desire to utilize a fluid with a higher critical temperature and lower global warming potential, and therefore the search for improved ORC working fluids will continue to be a part of Honeywell's Refrigerants R&D effort in the future.

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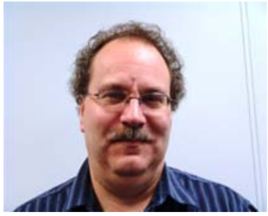
ABOUT THE AUTHOR



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