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ASSESSMENT OF C6F AS WORKING FLUID FOR ORGANIC RANKINE CYCLE APPLICATIONS

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ABSTRACT

This paper makes an assessment of C6F as a working fluid for Organic Rankine Cycle applications by comparing it with HFC245fa, an ORC working fluid with a similar critical temperature. The smaller slope of the saturated liquid line of C6F on the temperature-entropy diagram relative to hydrofluorocarbon working fluids can be an advantage for certain ORC applications. This smaller slope reduces the pinch-point problem in the evaporator allowing better utilization of sensible heat sources. On the other hand, the corresponding smaller slope of the saturated vapor line of C6F on the temperature-entropy diagram limits the specific isentropic enthalpy drop over the turbine. This results in larger mass flow rates for identical turbine power output at equal evaporator and condenser saturation temperatures, which for systems with pump efficiencies less than turbine efficiencies would result in a cycle efficiency penalty. The highly leaned-over saturation dome of C6F also increases the de-superheat loss in the condenser, hurting ORC cycle efficiency. A recuperator would be required to minimize these losses.

1. INTRODUCTION

Ketone C6F, which has the chemical formula: $CF_3CF_2C(O)CF(CF_3)_2$, has been introduced recently as a zero-ODP, zero-GWP fire extinguishing fluid [1,2]. Its non-flammability and non-toxicity combined with its excellent environmental properties make it an attractive working fluid for either vapor compression HVAC or Organic Rankine Cycle power generation applications.

Earlier studies on its potential use for HVAC applications have concluded that the low vapor density of C6F limits its use to water-cooled chiller applications using centrifugal compressors [3]. It was also found that the slope of the saturation dome on the temperature-entropy diagram forces the use of a suction line heat exchanger to prevent wet compression and reduce the throttling losses. With a zero-pressure drop suction line heat exchanger, centrifugal chiller cycle efficiencies similar to those of R245fa are obtainable. The low speed of sound of the fluid allows direct drive single stage compressor operation at relatively small tonnages. The sub-atmospheric evaporator (0.162 bar) and condenser (0.604 bar) pressures necessitate the use of a purge but eliminate the need for pressure vessel code certification.

Recently, Organic Rankine Cycle (ORC) power plants derived from existing HVAC hardware have been introduced commercially to convert low-temperature heat into electricity [4,5]. The availability of a moderate temperature heat source, such as a geothermal fluid, and an ambient temperature heat sink allows a reversal of the vapor compression cycle, used in the HVAC industry, into a power producing ORC system by replacing the throttle valve with a pump and reversing the direction of fluid flow as illustrated in Figure 1.

Organic Rankine Cycles using geothermal heat are zero emission power plants. Power generated by ORC systems replaces conventionally generated power and will have a positive effect on air quality in general and global warming in particular. The absence of fuel consumption leaves the potential loss of working fluid as the only emission to be evaluated in an environmental assessment. The total equivalent warming impact (TEWI) concept used in the air conditioning and refrigeration industry has been adopted for ORC systems and used to assess the environmental impact of various potential HFC working fluids. That assessment shows that accidental complete loss of charge can occur many times before the global warming benefit of ORC power plants is negated [6]. Nevertheless, a working fluid without any direct global warming effect, such as ketone C6F, would be a still better solution if thermal efficiency and heat resource utilization are not negatively affected. The properties of ketone C6F even indicate a

potential benefit for low temperature sensible heat resource applications such as encountered in the geothermal industry.

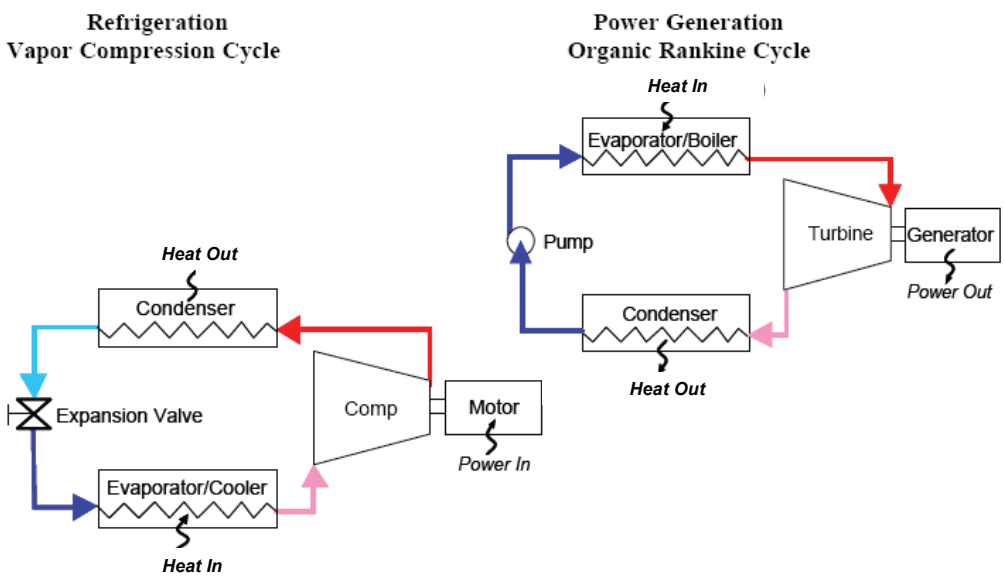


Figure 1. Comparison of the refrigeration vapor compression cycle and the power generation organic Rankine cycle

Electricity production from geothermal resources is at the moment the main application area of ORC technology. Existing ORC power plants use more conventional power plant technology and require relatively high geothermal resource temperatures in order for the power plant to be cost effective. This limits the application of existing ORC technology to geothermal fields with higher resource temperatures. Lower cost heat exchanger and turbine technology is required to overcome the inherently lower thermal efficiency of systems using lower temperature heat sources. The utilization of high volume existing HVAC hardware for ORC power plants enables economic power generation at resource temperature levels that were previously considered too low for power production.

2. THE PINCH POINT PROBLEM OF SENSIBLE HEAT DRIVEN BOILERS

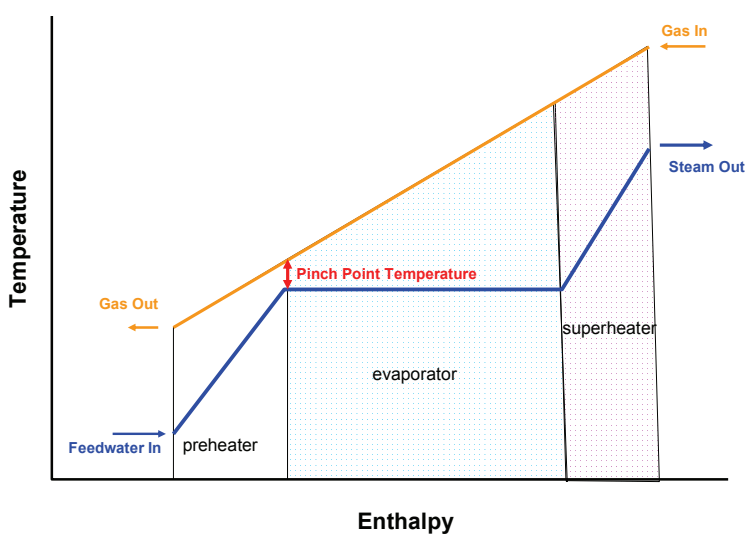


Figure 2. The pinch point temperature in a gas turbine exhaust heat recovery steam generator

If a sensible heat source such as high temperature gas or liquid, is used to preheat and boil and superheat a Rankine cycle working fluid the maximum saturation temperature in the evaporator section of the boiler is controlled by the pinch point of the heat exchanger. This pinch point is the smallest temperature difference between the sensible heat source and the working fluid encountered in a counter-flow heat exchanger arrangement as shown in Figure 2 for a Gas Turbine Exhaust Heat Recovery Steam Generator (HRSG). The pinch point temperature has to be positive to assure heat transfer from the sensible heat source to the working fluid. Its value should be large enough to maintaining reasonable heat flux rates at the end of the preheater and the beginning of the evaporator section of the boiler. The steam boiling pressure in HRSG's is affected by this phenomenon [7].

The properties of the working fluid, water/steam in case of the HRSG, dictate the location of the pinch point and therefore the boiling pressure in the evaporator. For Organic Rankine Cycles, with the properties of organic working fluids being different, the evaporator saturation temperature for identical pinch point temperatures will be different. Obviously, the higher the evaporator saturation temperature the better the cycle efficiency will be.

3. THERMAL EFFICIENCY VERSUS RESOURCE UTILIZATION

The thermal energy supplied to the system is the sensible heat of the hot water delivered by the geothermal well. With a sensible heat source the amount of power produced per unit volume flow of hot water (the resource utilization of the system) is a more meaningful performance measurement than the thermal efficiency (the electrical power output divided by the thermal heat input). The highest thermal efficiency IS achieved by extracting a limited amount of heat from the resource, allowing the highest possible boiling saturating temperature in the ORC evaporator. However, since the amount of heat absorbed is limited, the total power being produced by the ORC at a relatively high thermal efficiency is limited as well. In other words, the utilization of the geothermal resource is limited.

Increasing the amount of heat being extracted from the geothermal resource will typically reduce the saturation temperature in the evaporator and therefore the thermal efficiency of the cycle. However, more power will be produced by such a system and the utilization effectiveness of the cycle improves. Figure 3 shows the difference between maximum thermal efficiency and maximum resource utilization for a low temperature geothermal resource of 105 ^{0}C pressurized water assuming a condenser saturation temperature of 30 ^{0}C.

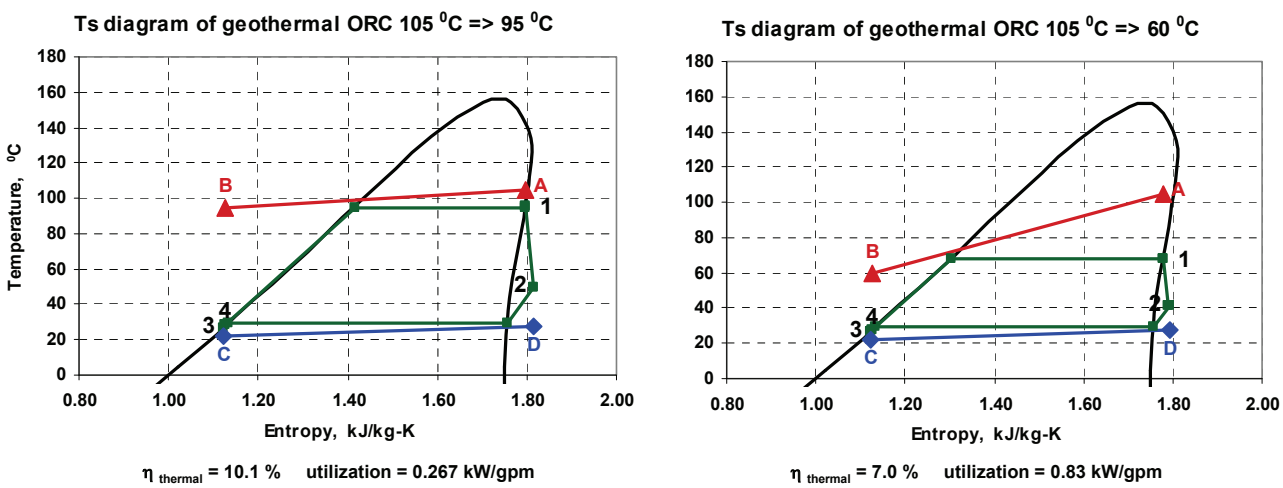


Figure 3. The difference between thermal efficiency and resource utilization

It can also be seen from Figure 2 that the properties of the working fluid affect the thermal efficiency as well as the resource utilization of an ORC system. An earlier study assessing the relative performance of a number of refrigerants for various ORC applications indicated different preferred working fluids dependent on resource temperature and whether a latent or sensible heat source was available [6].

4. PREHEATING VERSUS EVAPORATION HFC134a and HFC245fa

For low temperature sensible heat source applications where resource utilization is more important than thermal efficiency, working fluids that have a larger portion of their heat absorption through sensible heat transfer in the preheater section of the boiler and a smaller portion in the evaporator section of the boiler tend to maximize the utilization of the geothermal resource. That is why theoretically HFC134a results in better resource utilization than HFC245fa for the temperatures as shown in Figure 3. The theoretical results shown in Figure 3 assumed reversible expansion and pumping action and zero frictional losses in the interconnecting piping. It should be noticed that using actual component efficiencies assuming e.g. a turbine efficiency of 80% and a pump efficiency of 50% reverses the previous findings due to larger work ratio ($W_{turbine}/W_{pump}$) of HFC245fa compared to HFC134a. For the conditions analyzed in this study the 8% resource utilization advantage of HFC134a from an ideal cycle perspective changes into a 5% disadvantage with actual component efficiencies.

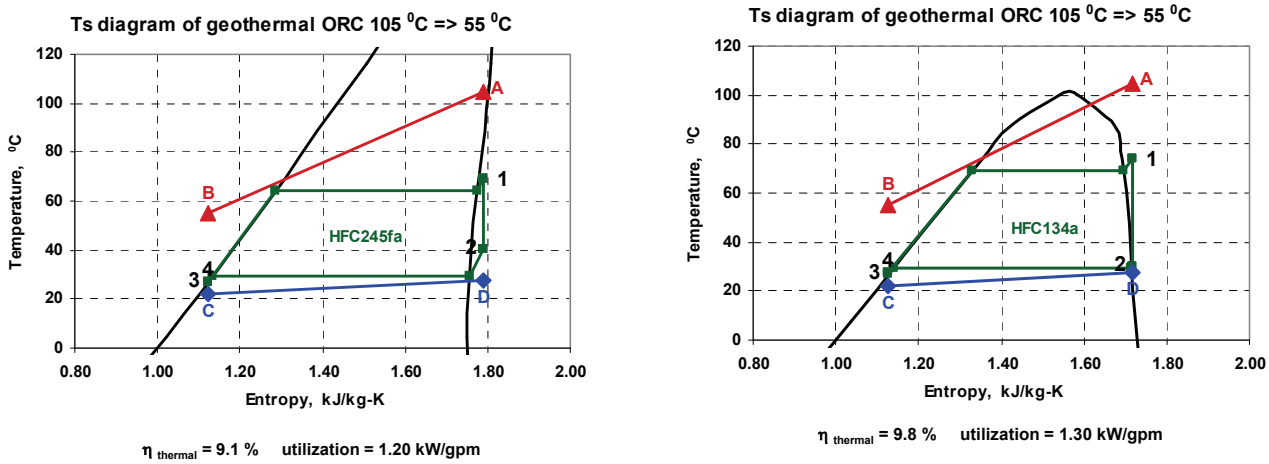


Figure 4. Resource utilization comparison between HFC134a and HFC245fa

5. PREHEATING VERSUS EVAPORATION HFC245fa and C6F

We now want to study the potential of C6F ORC working fluid for low temperature sensible heat geothermal applications. From looking at the Ts diagrams of HFC245fa and C6F as shown in Figure 5, C6F seems be a very efficient fluid for sensible heat source ORC applications thanks to the small slope of the liquid saturation line on the Ts diagram. This will allow a higher evaporation saturation temperature in the boiler, increasing overall thermal efficiency.

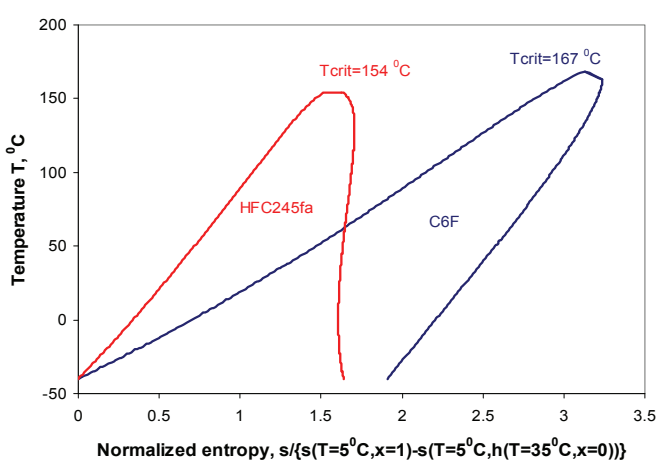
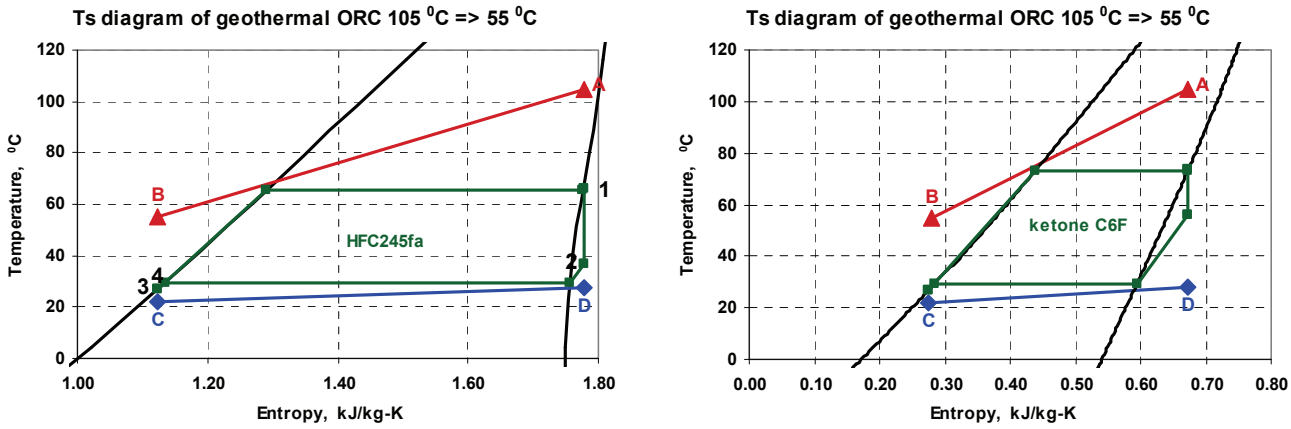


Figure 5. The Ts diagrams of HFC245fa and C6F

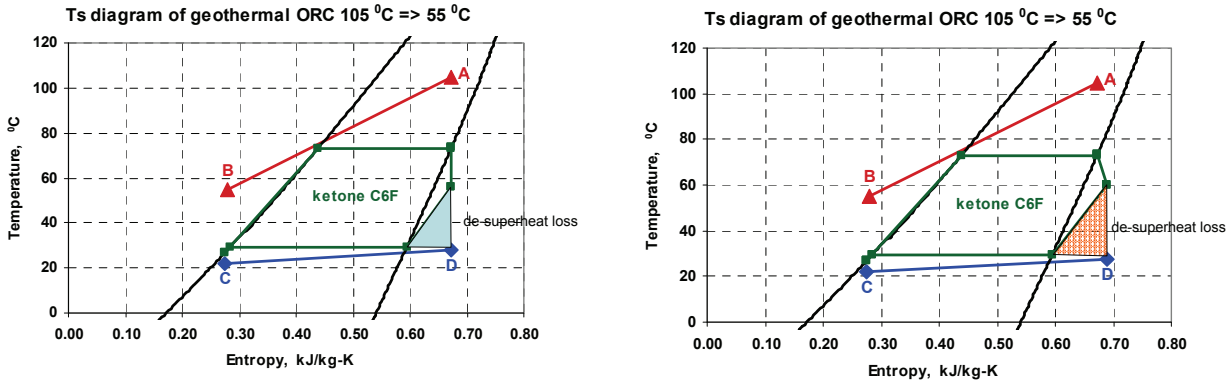


As can be seen from Figure 6, for the same hot water resource temperatures (105 ^{0}C entering the boiler) and the same utilization (55 ^{0}C leaving the boiler) C6F has a larger portion of heat absorption occur in the preheating section allowing a higher boiling temperature and therefore a higher thermal efficiency. In other words, C6F enables heat transfer with less irreversibility in the boiler. On the other hand, the smaller slope of the saturated vapor line of C6F in the Ts diagram causes a larger heat transfer irreversibility in the condenser on the heat rejection side compared to HFC245fa. For ideal conditions ketone C6F has a slightly better thermal efficiency (0.096 for C6F versus 0.091 for HFC245fa under the given conditions).

6. THE DE-SUPERHEAT CONDENSER LOSS OF C6F

However, using actual component efficiencies in the cycle calculations reverses the advantage of C6F. The additional de-superheat loss in the condenser increases with lower turbine efficiency as shown in Figure 7. The left picture in Figure 7 shows the de-superheat loss for ideal conditions while the right picture shows the increase in the desuperheat loss due to turbine inefficiency.

HFC245fa had a very small de-superheat loss under ideal conditions. The increase in the desuperheat loss with actual turbine efficiency numbers is therefore relatively small.



.Figure 7 Ts diagram of ketone C6F for ideal and actual component efficiencies.

CONCLUSIONS

1. Ketone C6F has very attractive environmental properties.
2. Under ideal conditions its performance is superior to that of HFC245fa, currently the best zero ODP low temperature working fluid for ORC applications where maximum resource utilization is required.
3. With actual turbine efficiencies the advantage of C6F over HFC245fa disapprears for this application due to its relatively large desuperheat loss.
4. C6F is inferior to HFC245fa as low temperature ORC working fluid for almost constant temperature hot resource applications such as jacket water cooling of reciprocating engines, due to its large de-superheat loss. Adding a recuperator to the cycle would overcome that problem.
5. C6F would require larger and therefore more costly equipment (turbine, pump, piping and heat exchangers) than HFC245fa due to its lower density.
6. The lower speed of sound of C6F relative the HFC's results in slower running larger turbomachinery.
7. The properties of C6F do not allow the power density similarity that exists for HFC245fa ORC equipment with HFC134a water-cooled chiller equipment that allowed utilization of low-cost mass-produced existing HVAC hardware to be used for ORC duty.

REFERENCES

1. Owens, J.G., *Physical and Environmental Properties of a Next Generation Extinguishing Agent, NIST SP 984; June 2002,* Halon Options Technical Working Conference, 12th. Proceedings. HOTWC 2002. April 30-May 2, 2002, Albuquerque, NM
2. Owens, J.G., *Understanding the Stability and Environmental Characteristics of a Sustainable Halon Alternative*, NIST special publication 984-1, 2003
3. Biederman, B.P., Mulugeta, J., Zhang, L, Chen, Y, Brasz, J.J., *Cycle Analysis and Turbo Compressor Sizing with Ketone C6F as Working Fluid for Water-Cooled Chiller Applications***,** International Refrigeration and Air Conditioning Conference at Purdue, July 12-15, 2004
4. www.utcpower.com/fs/com/bin/fs_com_Page/0,5672,0167,00.html
5. Brasz, J.J., Holdmann G., Power Production from a Moderate Temperature Geothermal Resource, GRC Transactions Vol. 29, pp 729-733, 2005
6. Brasz, L.J., Bilbow, W.M., *Ranking of Working Fluids for Organic Rankine Cycle Applications*, International Refrigeration and Air Conditioning Conference at Purdue, July 12-15, 2004
7. Ragland, A., Stenzel, W., *Combined Cycle Heat Recovery Optimization,* Paper IJPGC2000-15031, presented at the ASME International Joint Power Generation Conference, Miami Beach, Florida, July 23-26, 2000
8. Brasz, J.J., Zyhowski, G.J., *The Total Equivalent Warming Impact of Organic Rankine Bottoming Cycles*, IASME Transactions, Issue 5, Volume 2, pp 780 – 785, 2005