Energy and exergy analysis of an efficient organic Rankine cycle for low temperature power generation

S. M. Sami*

SYNOPSIS

This paper presents and discusses the performance of an advanced Organic Rankine Cycle (ORC) using a heated chemical instead of steam as found in the typical Rankine Cycle. Chemicals used are the new quaternary refrigerant mixtures that are environmentally-friendly and have efficient thermodynamic properties at low and medium waste heat temperatures compared to other organic and non-organic fluids.

This mixture boils at extremely low temperatures and is capable of capturing waste heat at temperatures less than 150°F (65°C). The quaternary mixture is formulated from R-125/ R-123/R-124/R-134a and its composition can be varied to best recover heat at temperatures from less than 150°F (65°C) to 900°F (482°C). In this paper energy and exergy analysis have been presented for the behaviour of the quaternary refrigerant mixture in ORC and compared to other fluids.

Results showed that at this temperature range waste heat is recovered and power is produced at efficiencies significantly higher than other fluids. The results also showed that increasing the flue gas temperature increased the thermal energy dissipated at the turbine and converted to kinetic energy.

INTRODUCTION

There is an urgent need for renewable energy sources. The renewable energy industry has experienced dramatic changes over the past few years. Deregulation of the electricity market failed to solve the industry's problems. Also, unanticipated increases in localised electricity demands, and slower than expected growth in generating capacity, have resulted in an urgent need for alternative energy sources; particularly those that are environmentally sound.

Consequently, the renewable energy industry is in a far different situation compared to the period prior to the electricity market deregulation. Instead of struggling to compete in a competitive deregulated electricity market, renewable energy operators suddenly faced requests to accelerate deployment of new renewable energy capacities and restore facilities that had been closed due to poor economics.

Review of a renewable portfolio [1–5] may provide some assurance to long-term funding of renewable energy facilities and lead to a resurgence in new renewable energy facilities. However, a number of factors and issues will require development of these renewable energy facilities both in the short and long-term.

In the short term, there will be increasing pressure to deploy renewable energy facilities to help add generating capacity, improve system reliability, and stabilise electricity prices. However, the strategic installation of these renewable energy facilities will be hindered by a lack of

* Samuel M. Sami, Department of Mechanical Engineering, San Diego State University, 5500 Camponile Drive, San Diego, CA 92182. Professor on leave from University of Moncton, All correspondence be addressed to: ssami@rohan.sdsu.edu

understanding of how the renewable energy facilities integrate into the existing fossil-based generation systems.

In the long term, these renewable electricity generation systems will require development to benefit the current electricity system. These new systems will require an improved services capacity, be more efficient, relatively cheap to run and maintain and utilise ecologically-friendly chemicals. Developing such systems will largely be tied to growth in the renewable energy distributed generation systems and will require an understanding and demonstration of renewable energy distributed generation systems which are used in combination with fossil-based generation.

Recent problems in electricity production emphasise the urgent need for a renewable approach to support the current electricity system, increase its existing capacity, and, equally important, benefit the environment by reducing the need to build more power plants and utilise environmentally-friendly chemicals.

The Organic Rankine Cycle, (ORC), is a non-superheating thermodynamic cycle. An organic Rankine cycle uses a heated chemical instead of steam as found in the Rankine cycle. Chemicals used in this Organic Rankine Cycle include new refrigerant mixtures that are environmentally-friendly (Patent No. 6101813 by Sami, [3]). Organic compounds generally have a higher molecular mass. This gives relatively small volume streams and results in a compact size ORC unit. It also enables high turbine efficiency up to 80% see Klaver [12] and Obernbereger [14].

Another advantage of using organic compounds is that they do not need to be superheated. Unlike steam organic compounds they do not form liquid droplets upon expansion in the turbine. An absence of steam prevents erosion of the turbine blades and enables design flexibility on the heat exchangers, Klaver [12].

From an operational standpoint, the ORC requires little maintenance. Its operation can be automated and unmanned. Its part-load performance is good and start-stop procedures are simple. The efficiency of an ORC is estimated to be between 10 and 20%, depending on the temperature levels of the evaporator and condenser. Increasing the evaporator- and/or decreasing the condenser temperatures results in higher efficiencies Larjola [15].

The energy performance is usually evaluated by the first law of thermodynamics, however, comparing energy analysis to exergy analysis can better project and show areas of inefficiencies. The results of that analysis can also be used to optimise and enhance the performance power cycles. Various energy and exergy analyses, Rosen and Dincer [16], Rosen [17], Ozgener *et al.* [18] and Kanoglu *et al*. [19] of power cycles have been reported.

This research work has been undertaken to enhance our understanding of the Organic Rankine Cycle using a quaternary refrigerant mixture which is considered as a new alternative fluid that enhances the typical ORC performance. Energy and exergy analyses were applied to better understand the benefits of using the said quaternary refrigerant mixture.

ORGANIC RANKINE CYCLE

An Organic Rankine Cycle, (ORC), engine is a standard steam engine that utilises heated vapour to drive a turbine. Figure 1 illustrates the basic

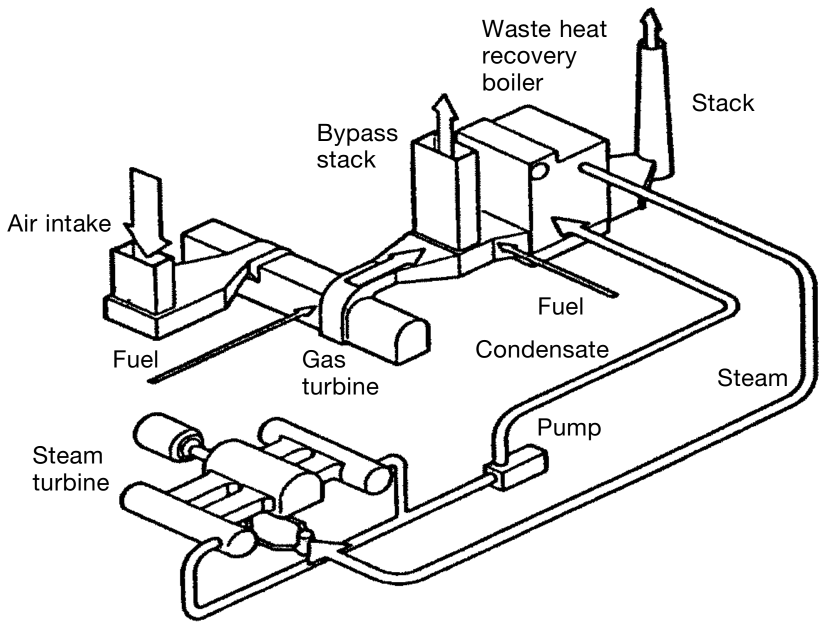

Figure 1
Typical Rankine cycle.

components of an Organic Rankine Cycle. However, this vapour is a heated organic chemical instead of a superheated water steam. The organic chemicals used by an ORC include Freon and most of the other traditional refrigerants, iso-pentane, CFCs, HFCs, butane, propane, and ammonia. The traditional refrigerants require a high temperature heat source.

What differentiates the author's patented quaternary refrigerant mixture (Sami *et al*. [3]) from the traditional refrigerants, is that the patented quaternary refrigerant mixture boils at extremely low temperatures and is capable of capturing heat at temperatures less than 150°F (65°C); thus generating power from low and medium waste heat. Figure 2 presents a typical P-H diagram of the mixture (R125/R123/R124/R134a), where the saturation temperature varies at constant pressure. The degree of variation or gliding temperature depends upon the mixture components and their boiling points as well as thermodynamic and physical properties.

The composition of refrigerant mixture can be adjusted to boil the mixture and generate power at a wide range of temperatures from as low as 150°F (65°C) to 1100°F (593°C). Typical refrigerants require a minimum of 500°F (260°C) to generate power.

Using the patented quaternary refrigerant mixture the system can produce power from captured low and medium heat in applications such as process industries, solar energy and geothermal energy. Using this quaternary refrigerant mixture, the author's patented ORC reduces emissions. Compared with using a typical fossil fuel, using the ORC described reduces NOx by over 4 tons per year and significantly reduces CO_2. Further, the patented quaternary refrigerant mixture has a long life-cycle and requires reduced maintenance and repair costs. These factors result in a relatively short payback period for the initial investment compared to using existing ORC systems. Therefore, the author is able to use ORC technology, ACE [5], to recover what is typically waste heat.

Apart from utilising for environmentally sound power regeneration what is typically an unrecoverable waste heat source from, for example, hot flue gases wasted at smoke stacks at various temperatures, solar energy using different collector geometries, and geothermal energy as well as grey water, a by-product at process industries, the author is able to produce cheaper, more ecologically-friendly power, due to the lower boiling temperature of his patented quaternary refrigerant mixture and its higher latent heat of evaporation.

Thermodynamic and thermo physical properties

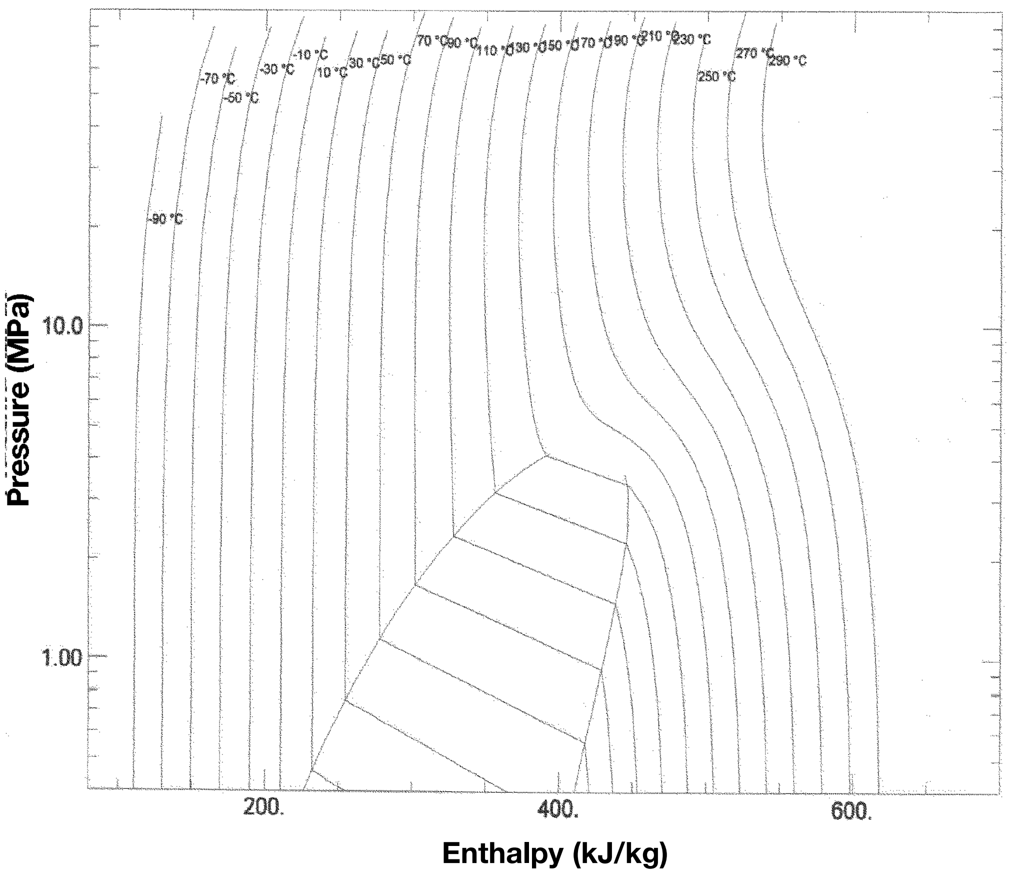

Figure 2
Typical Pressure-Enthalpy diagram of the refrigerant mixture.

are determined using the well known NIST REPROP.8 program, Mc Linden [10]. In addition to these properties the conservation is solved for each control volume to obtain the thermal behaviour for each component. Each component was represented by a finite control volume.

THEORTICAL CONSIDERATIONS

There are four processes in the Organic Rankine Cycle similar to the steam cycle, each changing the state of the working fluid. These states are identified by number in the diagram (c.f. Figure 3). First: The working fluid is pumped from low to high pressure by a pump. Pumping requires a power input, (for example mechanical or electrical). Second: The high pressure liquid enters a boiler where it is heated at a constant pressure by an external heat source to become a superheated vapour. Common heat sources for power plant systems are coal, natural gas, or nuclear power. Third: The superheated vapour expands through a turbine to generate power output. Ideally, this expansion is isentropic. This decreases the temperature and pressure of the vapour. Fourth: The vapour then enters a condenser where it is cooled to become a saturated liquid. This liquid then re-enters the pump and the cycle repeats.

SYSTEM EQUATIONS

Energy analysis. Each of the first four equations is easily derived from the energy and mass balance for a control volume. The fifth equation defines the thermodynamic efficiency of the cycle

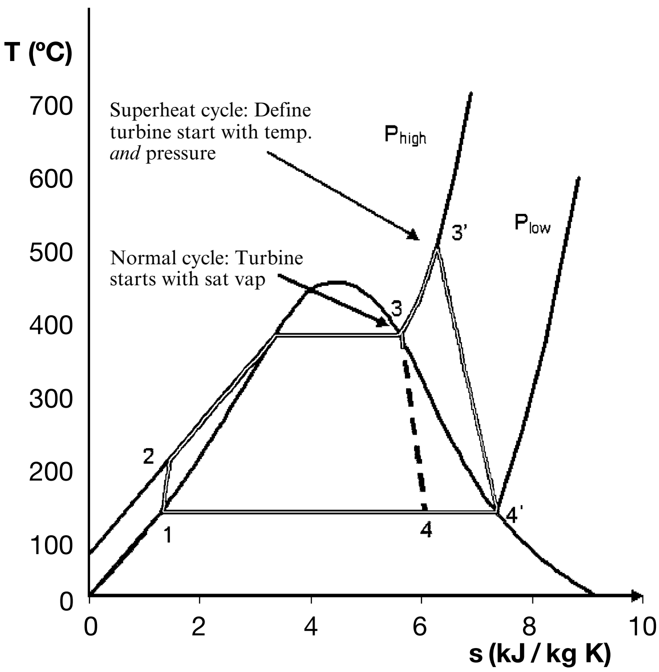

Figure 3 Typical Rankine Cycle; T-S diagram for steam.

as the ratio of net power output to heat input.

$$\frac{\dot{Q}_{in}}{\dot{m}} = h_3 - h_2 \tag{1}$$

$$\frac{\dot{Q}_{out}}{\dot{m}} = h_4 - h_1 \tag{2}$$

$$\frac{\dot{W}_{turbine}}{\dot{m}} = h_3 - h_4 = (h_3 - h_{4s}) \times \eta_{turb} \tag{3}$$

$$\frac{\dot{W}_{pump}}{\dot{m}} = h_2 - h_1 \quad \frac{v_1\, \Delta p}{\eta_{pump}} \quad \frac{v_1\,(p_2 - p_1)}{\eta_{pump}} \tag{4}$$

$$\eta_{therm} = \frac{\dot{W}_{turbine} - \dot{W}_{pump}}{\dot{Q}_{in}} \quad \frac{\dot{W}_{turbine}}{\dot{Q}_{in}} \tag{5}$$

$$NHR = Q_{in} / W_{turbine} \tag{6}$$

In a real Organic Rankine Cycle, the compression by the pump and the expansion in the turbine are not isentropic. In other words, these processes are non-reversible and entropy is increased during the two processes. This increases the power required by the pump and decreases the power generated by the turbine. It also makes calculations more involved and difficult. Two main variations of the basic Organic Rankine Cycle are used in modern practice and are implemented in our proposed; reheat and regenerative cycles. In this cycle, two turbines work in series.

The first accepts vapour from the boiler at high pressure. After the vapour has passed through the first turbine, it re-enters the boiler and is reheated before passing through a second lower pressure turbine. Among other benefits this prevents the vapour from condensing during its expansion. Condensation at this stage can seriously damage the turbine blades.

In the regenerative Organic Rankine Cycle the working fluid is heated by steam tapped from the hot portion of the cycle. This increases the average temperature of heat addition, which in turn increases the cycle efficiency. Both the reheat and regenerative options will be implemented in our proposed system.

Exergy and energy efficiency. The use of exergy in assessing the power cycles such as ORC is highly beneficial. The efficiency of the ORC based upon exergy, as the ratio of total exergy output to to exergy input:

$$\eta_{ex} = Ex_{out} / Ex_{input} = (W_{net} + Ex_{heat}) / Ex_{input} \tag{7}$$

and can be equal:

$$Ex_{heat} = -\Delta Ex_{heat\text{-}hot}$$

?

$$= \dot{m}\,[h_i - h_e - T_o\,(s_e - s_i)] \qquad (9)$$

$$= 1 - Ex_{dest} / Ex_{input} \qquad (8)$$

where Ex_{heat} represents the rate of exergy transfer associated with transfer of heat, Ex_{dest} is the rate of exergy destruction and W_{net} represents the net work.

In this paper the thermal exergy rate is expressed in terms of the decrease of the hot fluid:

$$Ex_{heat} = -\Delta Ex_{heat\text{-}hot}$$

$$= \dot{m}\,[h_i - h_e - T_o\,T_o\,(s_e - s_i)]\,(s_i - s_e)] \qquad (9)$$

The subscripts, i, and e, refer to the inlet and exit states of the fluid in the heat exchanger and $\dot{m}$ is the mass flow rate of the fluid circulating in the ORC.

Finally the ORC efficiency based upon the rate of exergy destruction is:

$$\eta_{ex} = (W_{net,out} + \dot{m}\,[h_i - h_e - T_o\,(s_i - s_e)] / Ex_{input} \qquad (10)$$

and the rate of exergy input is:

$$Ex_{input} = \dot{m}\,[h_e - h_i - T_o\,(s_e - s_i)\,] \qquad (11)$$

In the particular case of heat recovery across a waste heat boiler:

$$Ex_{input} = \dot{m}\,[C_p\,(T_e - T_i - T_o\,(s_e - s_i)\,] \qquad (12)$$

and the entropy change of flue gases is:

$$(s_e - s_i) = C_p\,Ln\,(T_e / T_i) \qquad (13)$$

Furthermore, the second law efficiency can be given as follows:

$$\eta_{II} = Ex_{output} / Ex_{input} \qquad (14)$$

$$Ex_{output} = (\Delta h - T_o\,(\Delta s)\,)_{turbine,\ net} \qquad (15)$$

DISCUSSION AND ANALYSIS

In order to analyse the ORC cycle using our quaternary refrigerant mixture the aforementioned equations have been programmed and coupled with the REFPROP program, Mc Linden [10] to obtain the thermodynamic and thermophysical properties of the mixture in question. The use of the mixture offers the following benefits: operates at low pressure under 200 psi (1379 kPa) and low temperatures, low source heat temperatures under 100ºF (37ºC), environmentally sound, non toxic, non flammable and low maintenance and repair costs. It is scalable utilising mass-produced off the shelf components and has high efficiency 20% – 30%.

A comparative study has been made between the behaviour of our mixture and other refrigerants reported in the literature of similar applications. The system simulation of the various refrigerants: R-11, R-114, R-54fa and our mixture R-125, R-134a,R-123,R-124 under operating conditions; 235ºF (112ºC) and 230 psi (1585 kPa) at the waste heat boiler exit and 85ºF (29ºC) and 10 psi (68 kPa) at the condenser inlet. System capacity is 125 kW. The schematic diagram of the system simulated is shown in Figure 4, where our ORC is retrofitted to a CHP system. The CHP system is a gas turbine system with a steam generator. Typically the temperature of the flue gases at the gas turbine

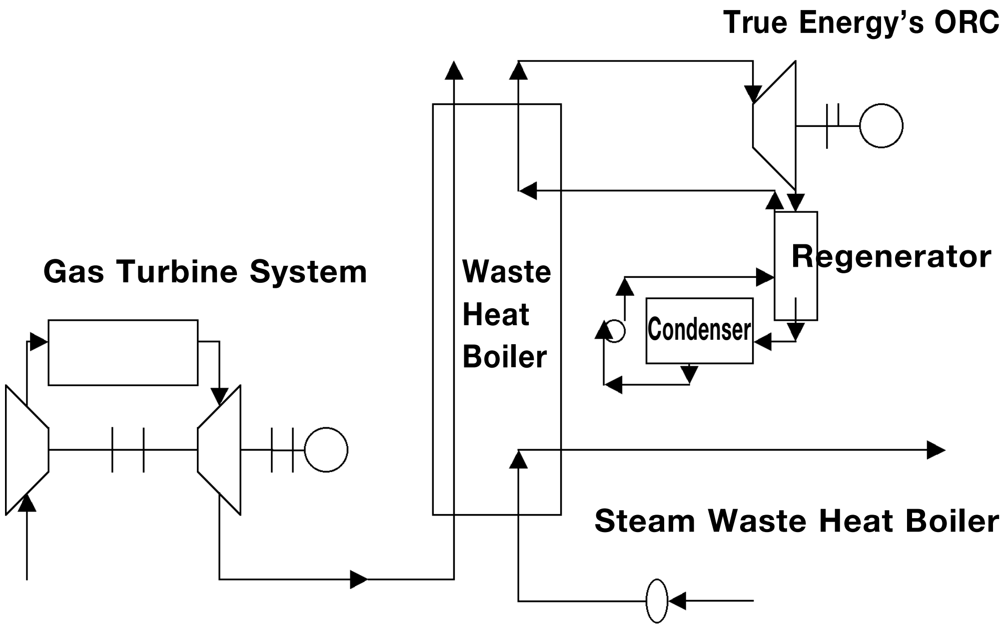

Figure 4
Schematic diagram for ORC retrofitted with Gas Turbine/ CHP System.

exit varies between 800°F (426°C) to 1000°F (537°C). In addition the flue gas temperature after the steam generator is around 300°F (148°C) to 400°F (204°C). At this temperature range we can recover heat and produce power at significantly higher efficiency than other fluids.

The results of the comparative study have been plotted in Figures 5, 6 and 7. It is evident from Figure 5 that using our refrigerant mixture results in lower values of NHR and more power production at the same heat input at the waste heat boiler. This is mainly due to the lower boiling temperature of the mixture and higher latent heat of evaporation compared to the refrigerants under investigation.

Figure 7 displays the system efficiency using our refrigerant mixture compared to the other refrigerants under investigation. It is apparent that our refrigerant mixture has the maximum cycle efficiency. This is due to the increase in work produced at the same waste heat recovery at the waste heat boiler as shown in Figure.7. This comparison is significant since it compares the refrigerant mixture efficiency to that of R-245fa which is considered as alternative to the CFCs R-11 and R-114 in chillers and ORCs applications. The enhancement of efficiency is significant due to the use of the mixture. This is due to the high heat transfer ratio between the thermal energy and kinetic energy at the turbine side as well as the pressure ratio.

The impact of integrating the ORC using the proposed mixture on a typical gas turbine system using a steam Organic Rankine Cycle is shown in

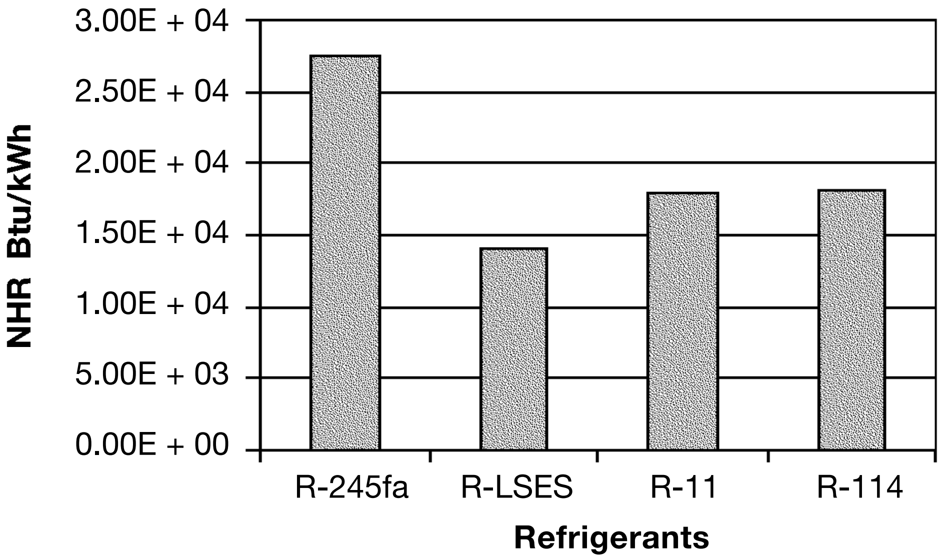

Figure 5
NHR for various refrigerants.

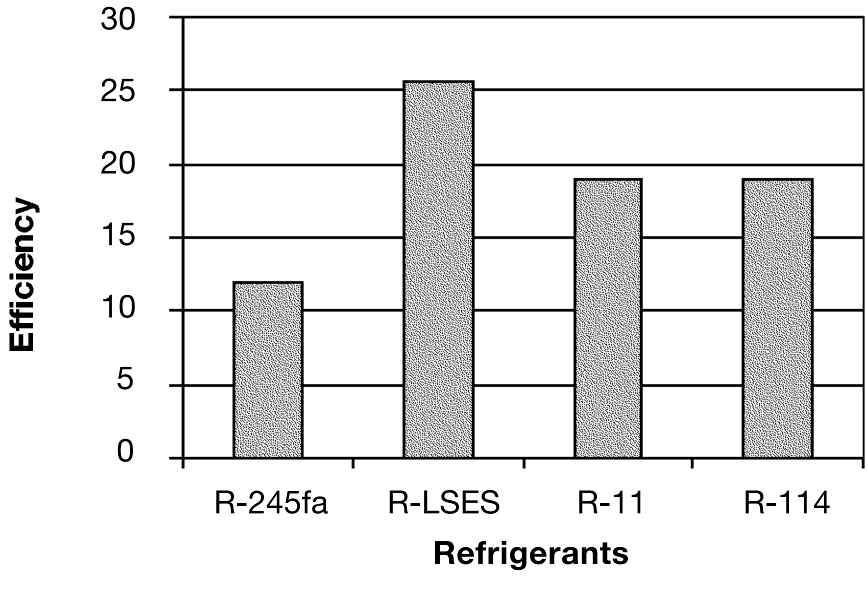

Figure 6
Efficiency for different refrigerants.

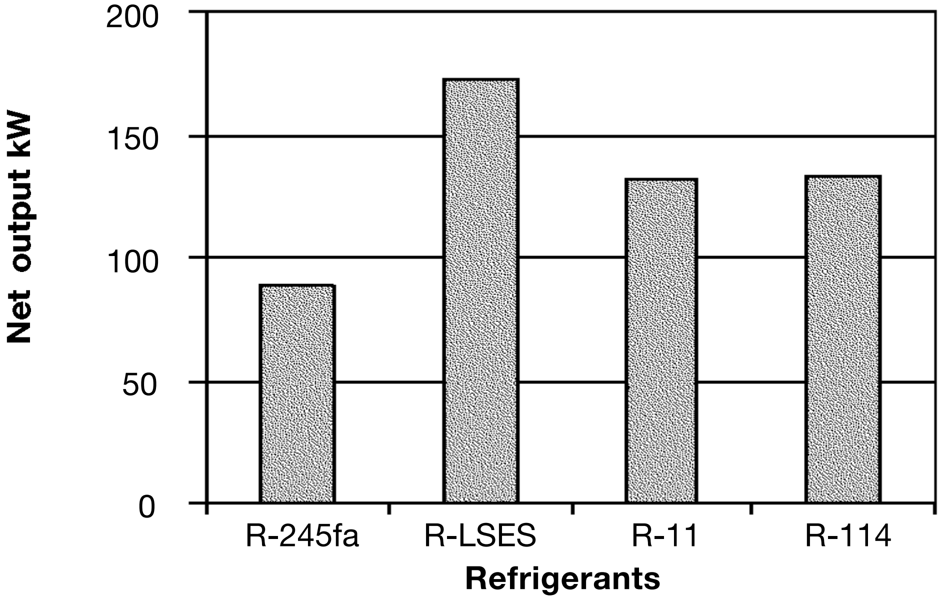

Figure 7
Net output work for various refrigerants (kW).

Figure 8, where the Net Heat Rate NHR (Btu/kWh) is plotted for a typical Gas turbine, steam turbine and ORC. The Net Heat Rate is defined as the thermal energy used in Btu to produce 1.0 kWh of power. The data displayed in this Figure clearly show that retrofitting our proposed ORC will significantly enhance the efficiency and reduce the NHR and will also have a positive effect on the environment by cooling down the flue gases.

The impact of the flue gases temperatures on the performance of the ORC is displayed in Figure 9, where under flow of constant flue gases, the temperature has been varied from 350°°F (176°C) to 600°F (315°C). The data clearly shows the higher the flue gas temperature the more power produced at the turbine side. This result is expected since increasing the flue gas temperature increases the thermal energy and is dissipated at the turbine and converted to kinetic energy.

Figure 10 has been constructed to demonstrate the effect of waste heat boiler source temperature T(WHB) on the cycle efficiency η.

Furthermore the data presented in Figure 10 also demonstrate that the proposed ORC is very efficient in recovering waste heat at temperatures above 200°F (93°C). This can be achieved by changing the formulation of the mixture to reduce the boiling point of the mixture.

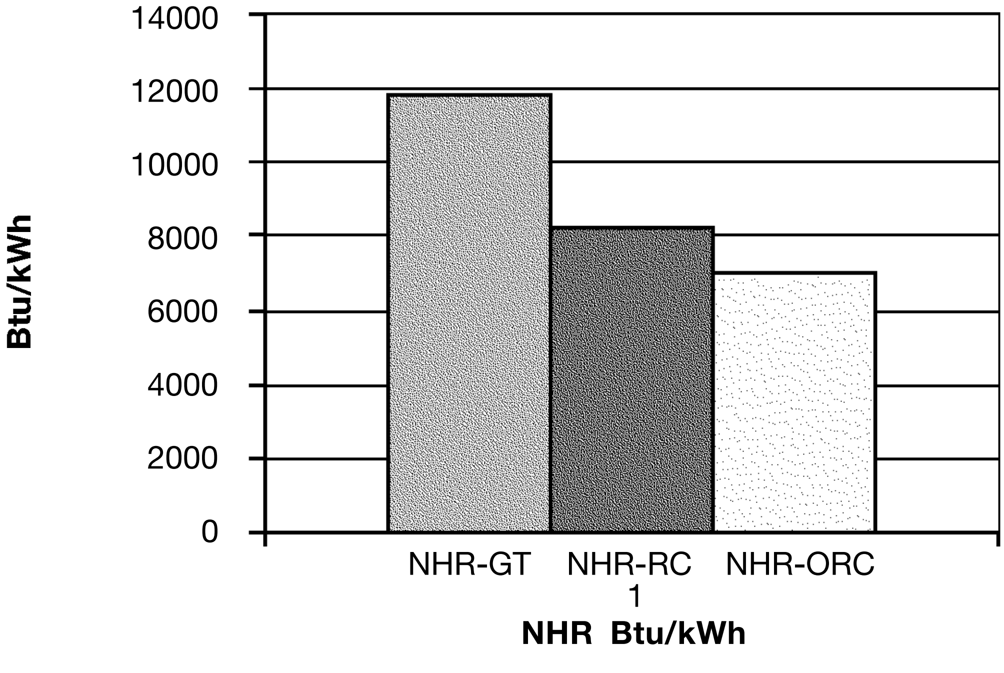

Figure 8
NHR for gas turbine cycle.

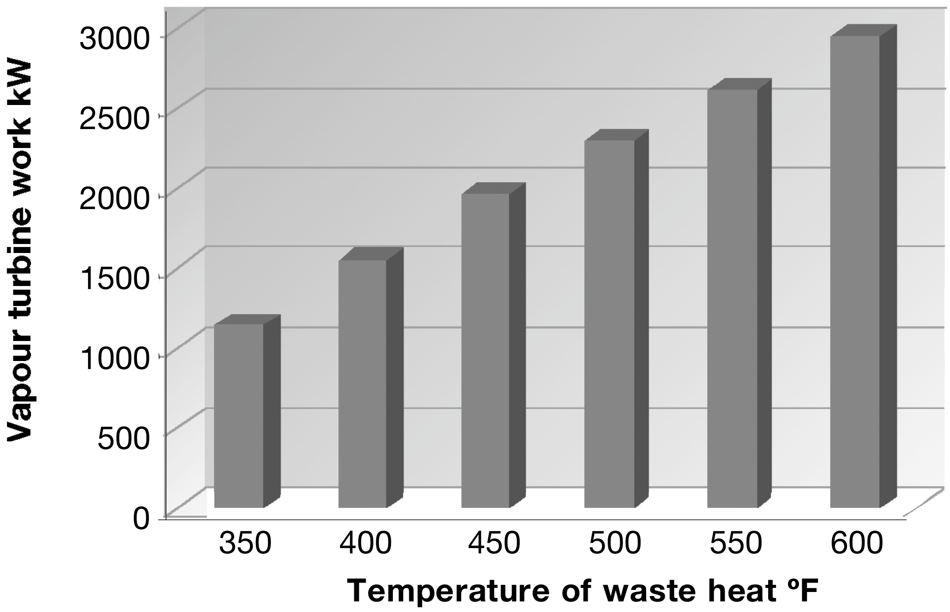

Figure 9
Output power produced is displayed for temperature of flue gases.

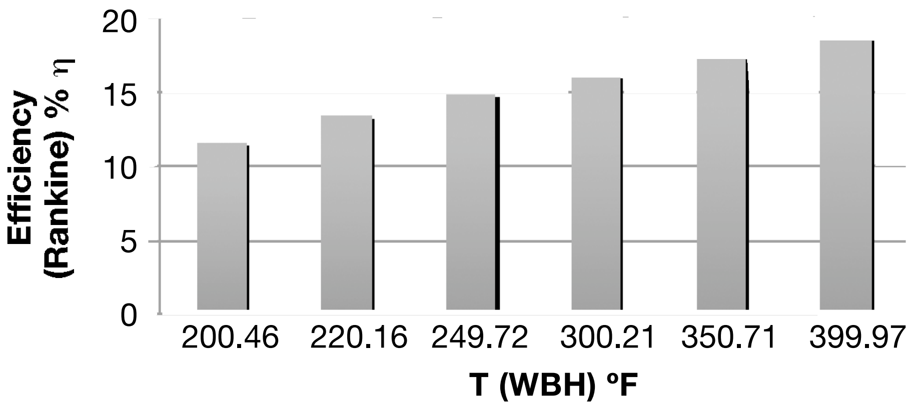

Figure 10
ORC output at low temperatures.

Figure 11 has been constructed to show the impact of increasing the flue gas flow rate on the power produced (kWe) after waste heat recovery. These results were generated at a flue gas temperature of 400ºF (204ºC). The data displayed in this figure clearly show that higher flows will result in increased power production. This suggests that systems with higher thermal capacities would produce more power. However, it is important to assess the impact of the various parameters involved during the waste heat recovery process; such as heat losses, stack backup pressure, dew point and heat loss in the chimney and in order to select the optimised size and number of units and circuits of waste heat recovery boiler for a particular application.

Figures 12 and 13 have been constructed to present the energy and the second law thermal efficiencies and exergy performance results of the various fluids used in this study; namely R245fa, R-114, R-11 and the quaternary refrigerant mixture. To facilitate the comparisons of the refrigerants under question, the same heat source and sink conditions were used; 4.5 MW, 235ºF (112ºC) and 85ºF (29ºC) respectively. Operating parameters were selected to yield the same flow rate in each case.

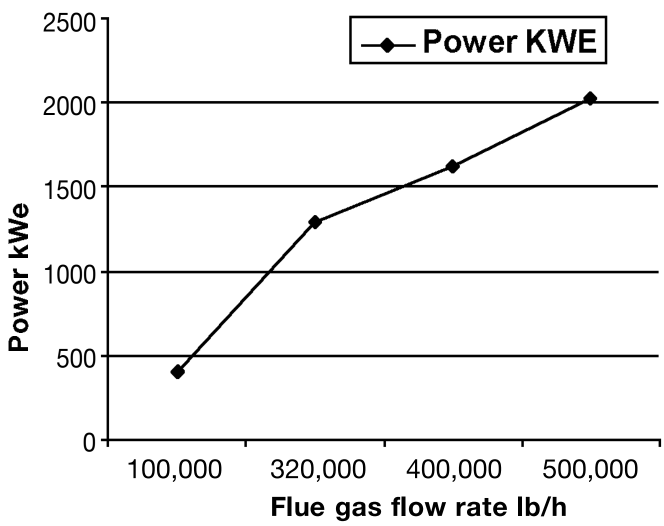

Figure 11 Power produced at various gas flue rate.

Clearly ORC operating with the quaternary refrigerant mixture has the highest energy efficiency compared to the others. Examining the exergy efficiencies displayed in Figures 12 and 13 shows that the quaternary refrigerant mixture has the higher thermal efficiency compared to the other refrigerants under study. R-245fa has the lowest thermal efficiency because of its low boiling point compared to the quaternary refrigerant mixture as well as others.

Similar results can be observed from Figure 13 when examining the second law efficiencies. Furthermore, the results presented in Figure 14 clearly showed that the exergy destruction is much lower in conditions where the quaternary refrigerant mixture is used compared to other refrigerants. In addition the results displayed in this figure show that R-245fa has the highest exergy destruction among the refrigerants presented in this study. This is because of its low boiling point.

CONCLUSIONS

In this analytical study the performance of the Organic Rankine Cycle (ORC) has been analysed and discussed. Our proposed ORC uses a new quaternary refrigerant mixture that is environmentally sound and thermodynamically very efficient using low and medium waste heat. The mixture composition can be formulated to effectively capture heat at a wider range of temperatures than is currently available.

Various comparative studies have been presented using energy, exergy analysis to demonstrate the superior performance of the proposed refrigerant mixture compared to alternative proposed fluids. The data presented clearly shows that the proposed quaternary refrigerant mixture has the capability to produce power from low and medium waste heat with significant thermodynamic efficiency and less exergy destruction.

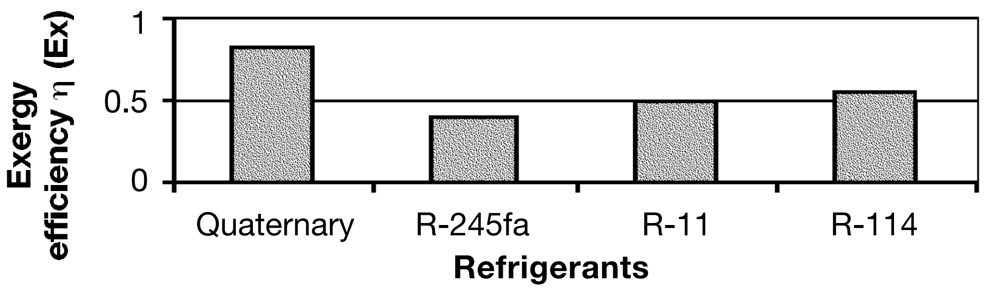

Figure 12
Exergy comparison of refrigerants.

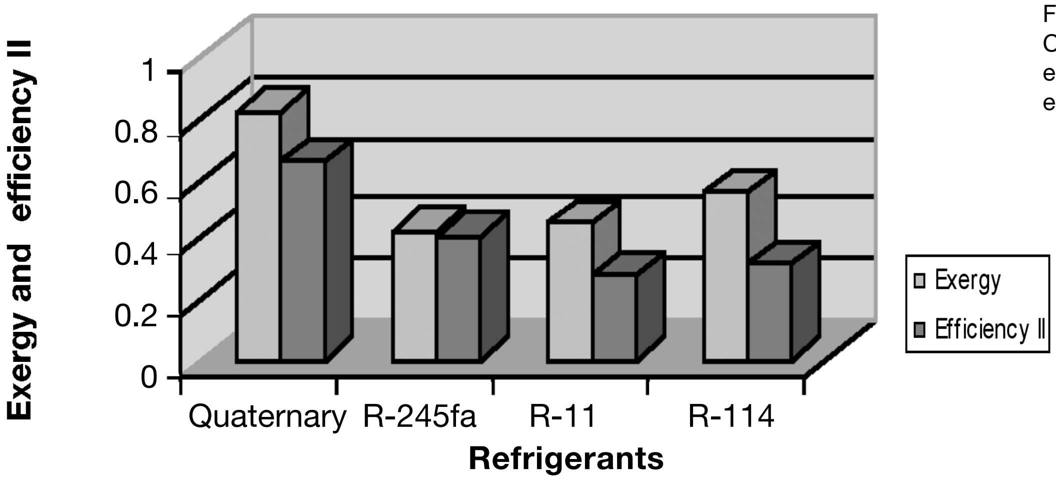

Figure 13
Comparisons between exergy and second law efficiencies.

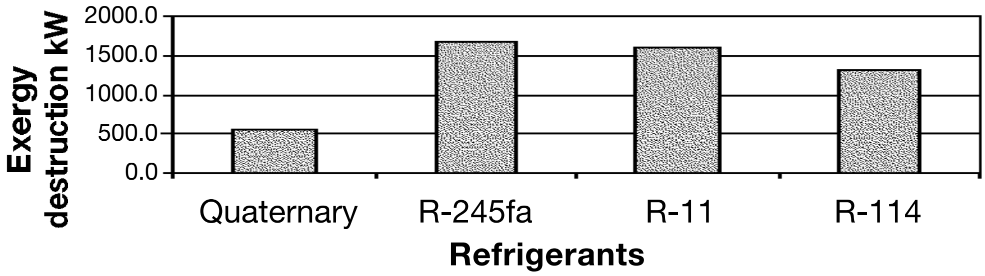

Figure 14
Exergy destruction.

NOMENCLATURE

C_p Specific heat (kJ/kg K)
Ex Exergy rate (kJ/kg/sec)
η_{ex} Exergy efficiency
η_{pump} Pump efficiency
η_{turb} Turbine efficiency
η Cycle efficiency
$\dot{Q}_{in}$ Heat input rate (kJ/sec)
Q Heat transfer (kJ/kg)
$\dot{m}$ Mass flow rate (kg/sec)
$\dot{W}$ Mechanical power used by or provided to the system (kJ/sec)
NHR Thermodynamic efficiency of the process (power used for turbine per heat input, Net Heat Rate (Btu/kWh)
h_1,h_2,h_3,h_4 These are the specific enthalpies at indicated points on the T-S diagram (kJ/kg)
ΔP Pressure drop (kPa)
S Entropy (kJ/kg K)
T Temperature (K)
v Specific volume (m^3/kg)
W Work (kJ/kg)

Subscripts

3 Turbine inlet and saturated vapour
3′ Turbine inlet superheated vapour
4 Turbine outlet and wet vapour
4′ Condenser inlet and saturated vapour
2 Waste heat boiler inlet
1 Inlet to the pump
in Input to waste heat boiler
i input
e output
des destruction
o ambient

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