1. Abstract

Keywords: Rankine cycle, Working pressure, Working temperature, Boiler, Condenser, Power-vapor cycle.

Some of the barriers presented to the development of low-temperature waste heat recovery are [1]:

1. Long payback periods
2. Material constraints and costs
3. Economies of scale (WHR does not lend itself well to a general solution)
4. Operation and maintenance costs – Corrosion, scaling, and fouling of heat exchange materials lead to higher maintenance costs and lost productivity.

This study will track these features of solutions explored and attempt to make inroads with them where possible.

This project will focus on the development of a smaller (automotive) scale waste heat recovery system. However, it is probably beneficial to the field in general, if the device is able to recover heat from an arbitrary source. This might be accomplished using means similar to the automotive application in which heat is harvested from a coolant stream. The waste heat present in the coolant stream need not have been from an engine.

“Many gaseous waste heat streams are discharged at near-atmospheric pressure (limiting the ability to transport them to and through equipment without additional energy input).” [1] Here, an automotive application really shines. The coolant from which the waste heat is recovered is already being circulated through the engine and through the radiator for the purpose of cooling the engine. It is plausible that WHR system need not impose an additional requirement for energy to circulate this coolant.

“Another key consideration is the interaction between chemicals in the exhaust stream and heat exchanger materials. Fouling is a common problem in heat exchange, and can substantially reduce heat exchanger effectiveness or cause system failure… Deposition of substances on the heat exchanger surface can reduce heat transfer rates as well as inhibit fluid flow in the exchanger.” [1] This is another area in which the proposed project can offer an improvement on current technology. Since the waste heat is harvested from a closed cooling loop, the only fouling potential that exists is from the decomposition of the coolant itself. This is much less than what might be present in an open system where compounds could precipitate from the waste heat stream as it is cooled.

Could a passive air preheater be retrofit to directly harvest energy from fluid motion?

inside the pipe to evaporate. Pressure gradients along the pipe cause the hot vapor to move to the other end of the pipe, where the vapor condenses and transfers heat to the cold gas. The condensate then cycles back to the hot side of the pipe via capillary action.

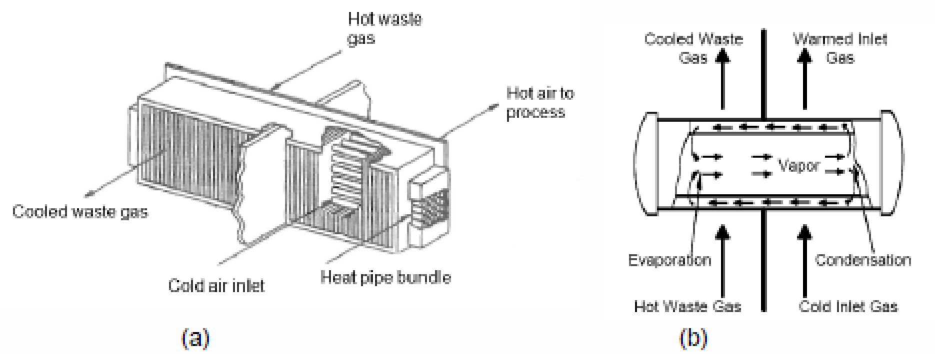

Figure 9 - (a) Heat Pipe Heat Exchanger (Source: Turner, 2006), **(b) Heat Pipe** (Source: PG&E, 1997)

Figure 1: Passive preheater

Thermal Conversion Technology	Temperature Range	Typical Sources of Waste Heat	Capital Cost
Traditional Steam Cycle [a]	M,H	Exhaust from gas turbines, reciprocating engines, incinerators, and furnaces.	\$1100-1,400/kW[f]
Kalina Cycle [d]	L,M,	Gas turbine exhaust, boiler exhaust, cement kilns	\$1100-1,500/kW[f]
Organic Rankine Cycle [c,e]	L,M	Gas turbine exhaust, boiler exhaust, heated water, cement kilns	\$1,500-3,500/kW[f]
Thermoelectric Generation [b]	M-H	Not yet demonstrated in industrial applications	\$20,000-30,0000/kW[b]
Piezoelectric generation [b]	L	Not yet demonstrated in industrial applications	\$10,000,000/kW[b]
Thermal Photovoltaic	M-H	Not yet demonstrated in industrial applications	N/A

Figure 2: Ranking of energy generation cycles.

"In comparison with water vapor, the fluids used in ORCs have a higher molecular mass, enabling compact designs, higher mass flow, and higher turbine efficiencies (as high as 80%-85%). However, since the cycle functions at lower temperatures, the overall efficiency is only around 10%-20%, depending on the temperature of the condenser and evaporator.

In addition to evaluating the quantity of waste heat, the work potential was also estimated. The work potential is the maximum work that could be obtained by using the waste heat to drive a heat engine. The work potential is given by:

$$WP = \eta \dot{E} = \left(1 - \frac{T_o}{T_H}\right)\dot{E} \qquad \text{Equation (7)}$$

where T_H is the waste heat temperature, and T_O is the atmospheric temperature (assumed here to be 77°F, [25°C]). An overview of industry-specific recovery practices and estimated heat losses is contained in the sections below.

Figure 3: Work potential calculation

2. Literature review

This goal of this project is to design a mathematical model of an organic Rankine cycle with parameters such that an automotive scale generator can be designed and built. This system will use a refrigerant working fluid because of the low quality of waste heat in the cooling system. This system must be small so that it can fit in the limited available space in an automotive application. The system must also have sensors throughout the four major components for the purpose of comparing a prototype to a simulation of the system done prior to build.

While the system is being designed with the goal of fitting in an automotive package, this first prototype will not be constrained to any vehicle package in particular, and may require size optimization in order to fit a specific application in future projects.

Study	Type			Cycle studied						Heat recovery			
	Sim./Model	Analytical	Meta	Rankine	Organic Rankine	ORC with internal heat exchanger	Regenerative ORC	Supercritical Rankine	Kalina	Steam generation	Heating	Absorption cooling	Cascading to lower temp processes
A review of WHR technologies for maritime applications			✓	✓	✓			✓	✓				
Waste heat reduction and recovery options for metals industry			✓	✓	✓					✓	✓	✓	✓
A numerical analysis of a composition-adjustable KC power plant for power generation from low-temperature geothermal	✓	✓							✓				
Power generation using waste heat recovery by organic Rankine cycle in oil and gas sector in Egypt: A case study	✓				✓								
A comparative exergoeconomic analysis of different ORC configurations for binary geothermal power plants	✓	✓	✓	✓	✓	✓	✓						
A review of Organic Rankine cycles (ORCs) for the recovery of low-grade waste heat	✓		✓		✓								
Application of waste heat powered absorption refrigeration system to the LNG recovery process	✓											✓	
BCS I Waste heat recovery technology and opportunities in US industry			✓	✓	✓				✓	✓	✓	✓	✓

3. Feasibility

According to Singh and Pedersen's work, a heat balance for a typical maritime application might look like the following diagram.

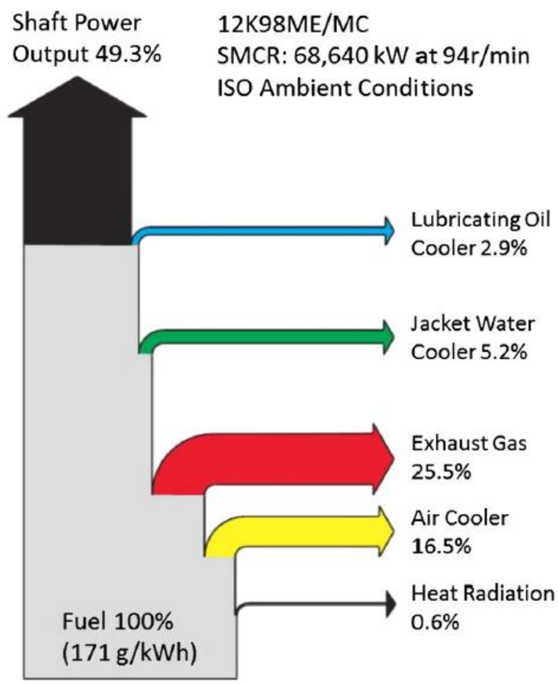

Figure 4: Heat balance diagram for MAN 12K98ME/MC marine diesel engine operating at 100 SMCR under ISO conditions [2]

"Engine cooling water temperatures of 80-90 ^{o}C are fairly standard for most engines." [2] While exhaust gas appears to be the most lucrative source of waste heat energy, there are several complications which, though not as important for the Pederson and Singh study, would prevent it's being as lucrative in an automotive application. Some of these factors are the increase in exhaust back pressure on the engine, the cooling of exhaust gases below the dew point of steam which could result in liquid water in the exhaust system causing corrosion, and reduced efficacy of reactions in the catalytic converter due to sub-optimal temperatures and high pressures caused by the heat harvesting system.

For waste heat streams with a temperature of 95 ^{o}C – 260 ^{o}C it was recommended that an ORC be used for power generation. It was also noted that the least efficient form of energy recovery from waste heat at this time is electrical generation. [3]

The Kalina Cycle (KC) is another variation on the RC that utilizes low temperature heat sources. The KC uses a variable composition working fluid mixture, typically water and ammonia to track with the heat sink temperature available. The efficiency of a KC can be increased due to a close temperature match with heat transfer fluids in the evaporator and condenser. "For instance, a KC system using an ammonia-water mixture as the working fluid to generate power from waste heat of a gas turbine achieved a thermal efficiency of 32.8%." [4] "Some studies showed that a KC can achieve a better thermal efficiency than ORC systems." [4] "In practice, the expansion ratio of the turbine for KCS-34 is relatively high and a multi-stage turbine is required." [4] This may be the drawback of the KC that makes ORC somewhat more attractive for an automotive application due to the extreme space requirements though it might be marginally less efficient. The KC also requires a significant amount of control in order to adjust the mass-fraction of ammonia including density sensors and real-time monitoring of working fluid composition in some implementations making this cycle significantly more complicated to implement. KC is also generally used as a method of improving a conventional (steam) RC. Therefore, the system architecture tends to be similar. It also appears that the working temperatures are slightly higher than some refrigerant based ORCs. "When the ammonia mass fraction is 0.8, the bubble and dew temperatures are around 60.3 and 147.3 ^{o}C respectively." [4]

The ORC is a promising cycle for recovery of energy from low heat sources. However, it has been shown that for certain working fluids, benzene or cyclohexane, the most suitable conditions were an expander inlet pressure of 4.1 MPa and temperature of 290 ^{o}C – 300^{o}C. [5]

R134a appeared to be the most suitable for small scale solar applications, though R152a, R600a, R600 and R290 were promising though they required handling precautions due to their flammability. Isobutene also showed improved system performance when compared to R123 and R245fa. [5] Reading through the literature review in M.A. Khatita et al. did not show consensus on the best working fluid for ORC, however. With most fluids the use of a regenerative ORC instead of the basic cycle reduced the irreversibility of a solar ORC. Additionally, at the two temperature ranges studied fluids with higher molecular complexity resulted in more effective regenerative cycles with the exception of cyclo-hydrocarbons. [5] This was primarily due to higher turbine efficiency and increased mass flow rates.

"Unlike water, most organic fluids suffer chemical decomposition and deterioration at high temperatures and pressures." [6] ORC systems showed efficiency gains with higher turbine inlet pressures, and efficiency losses for higher condenser outlet temperatures. This suggests that operating conditions, primarily temperature, could have a significant effect on the efficiency of a given system. [6]

4. Preliminary results

A simple Rankine vapor power cycle was modelled similar to the diagram shown in Figure 5. The model was produced in Python as shown in Appendix C – Source Code.

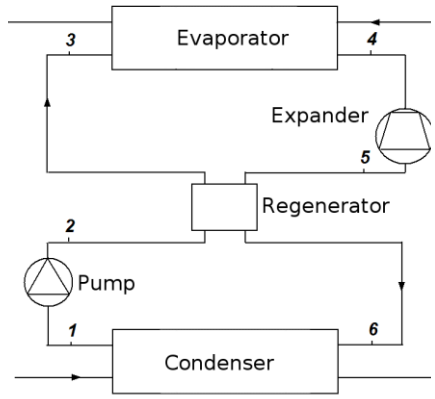

Figure 5: Typical Rankine cycle

The results from this model are shown in the following figures, which, if valid will inform a more nuanced model of a design space in which to start:

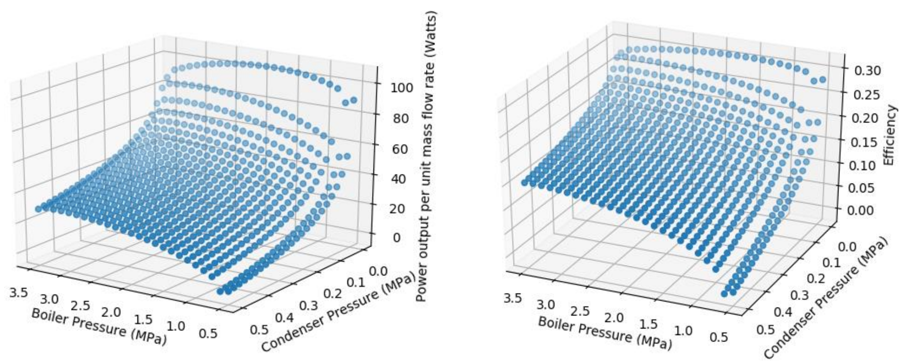

Figure 6: Power output per unit mass flow rate and efficiency by boiler and condenser working pressures

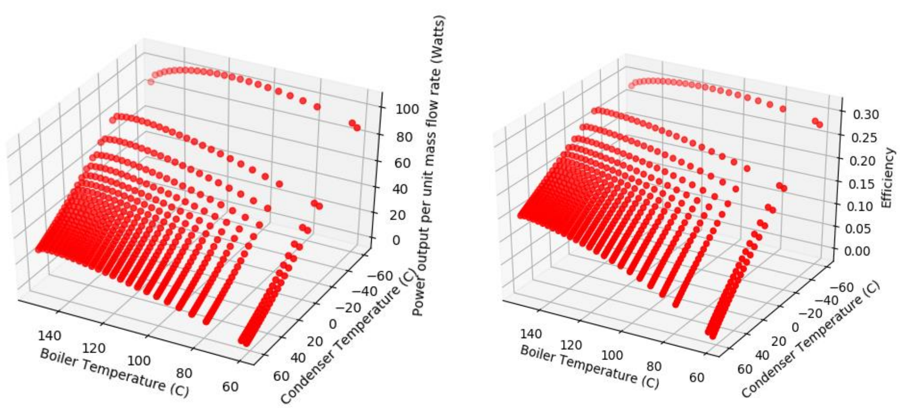

Figure 7: Power output per unit mass flow rate and efficiency by boiler and condenser working temperatures

5. Appendix A – Acronyms

C – Celsius
CHP – Combined cooling heating and power
F – Fahrenheit
LNG – Liquefied natural gas
ORC – Organic rankine cycle
RC – Rankine cycle
SCRC – Super-critical Rankine cycle
SRC – Steam Rankine cycle
WHR – Waste heat recovery
WHRS – Waste heat recovery system

6. Appendix C – Source Code

```
import csv
import math
from mpl_toolkits.mplot3d import axes3d
import matplotlib.pyplot as plt
import numpy as np

def interpolate(x1,y1,x2,y2,x):
    try:
        y = ((y2-y1)/(x2-x1))*(x-x1) + y1
    except TypeError:
        y = y1

    return(y)

def vlookup(rfile, index, search_col, result_col):
    # The file is where the data is stored.
    # index is the item to search rows for.
    # search_col is the column in which the index should be searched for.
    # result_col should be the column from which the result should be extracted.

    index = float(index)
    search_col = int(search_col)
    result_col = int(result_col)

    RDR = csv.reader(rfile, dialect = 'excel')
    pos_diff = 1000
    neg_diff = -1000

    x1 = None
    y1 = None
    x2 = None
    y2 = None

    for row in RDR:
        # Search for the rows just smaller and just larger than the search
        # term. Calculate the difference between the x value in a given row
        # and the search term. Keep the rows that result in the smallest
        # positive difference and the smallest negative difference.
        try:
```

```
            diff = index - float(row[search_col])

        except ValueError:
            if row[search_col] == "Inf":
                diff = math.inf

            #print("Header?")
            continue

        if diff < pos_diff and diff > 0:
            x1 = float(row[search_col])
            y1 = float(row[result_col])
            pos_diff = diff

        elif diff > neg_diff and diff < 0:
            x2 = float(row[search_col])
            y2 = float(row[result_col])
            neg_diff = diff

        elif diff == 0:
            x1 = float(row[search_col])
            y1 = float(row[result_col])
            x2 = None
            y2 = None

    return (x1, y1, x2, y2)
    # Return the x,y pairs of the search column and result column just
    # above and below the desired x value.

#----------Main----------#
fig = plt.figure()
fig1 = plt.figure()
fig2 = plt.figure()
fig3 = plt.figure()

ax = fig.add_subplot(111, projection='3d')
ax1 = fig1.add_subplot(111, projection='3d')
ax2 = fig2.add_subplot(111, projection='3d')
ax3 = fig3.add_subplot(111, projection='3d')
```

```
#b_press = np.arange(30,154.01,10)
#c_press = np.arange(0.00127,30, 1)
c_press = np.linspace(0.1225, 0.5, 25)
b_press = np.linspace(0.5,1,25)

X = []
X2 = []
Y = []
Y2 = []
Z = []
Z2 = []

for xs in c_press:
    for ys in b_press:
        boiler_pressure = ys
        condenser_pressure = xs
        #print("Boiler pressure: ", boiler_pressure,"\nCondenser pressure: ",condenser_pressure)

        ##boiler_pressure = 1
        ##condenser_pressure = 0.25

        temp_col = 0 # Degrees Celsius
        press_col = 1 # MPa
        v_col = 3 # Specific volume of vapor m3/kg
        hl_col = 4 # Enthalpy of saturated liquid kJ/kg
        hv_col = 5 # Enthalpy of saturated vapor kJ/kg
        sl_col = 6 # Entropy of saturated liquid kJ/(kgK)
        sv_col = 7 # Entropy of saturated vapor kJ/(kgK)

        R245fa_db = 'R245fa Saturated properties temperature table.csv'
        db_path = 'H:\\WIP\\12343 - Research & Development\\Issue #251 - Rankine cycle research\\Additional references'

        # Fix states with specified pressures
        p1 = boiler_pressure
        p4 = boiler_pressure

        file = open("%s/%s" %(db_path, R245fa_db), mode = 'r', newline='')
        x1, y1, x2, y2 = vlookup(file, p1, press_col, temp_col)
        boiler_temp = interpolate(x1, y1, x2, y2, p1)
```

```
file.close()

p2 = condenser_pressure
p3 = condenser_pressure

file = open("%s/%s" %(db_path, R245fa_db), mode = 'r', newline='')
x1, y1, x2, y2 = vlookup(file, p2, press_col, temp_col)
condenser_temp = interpolate(x1, y1, x2, y2, p2)
file.close()

file = open("%s/%s" %(db_path, R245fa_db), mode = 'r', newline='')
x1, y1, x2, y2 = vlookup(file, p1, press_col, hv_col)
h1 = interpolate(x1, y1, x2, y2, p1)
#print("h1 = ", h1)
file.close()

file = open("%s/%s" %(db_path, R245fa_db), mode = 'r', newline='')
x1, y1, x2, y2 = vlookup(file, p1, press_col, sv_col)
s1 = interpolate(x1, y1, x2, y2, p1)
s2 = s1
#print("s1 = ", s1,"\ns2 = ", s2)
file.close()

# Calculate the quality of state 2
# First find the liquid and vapor entropy at the condenser pressure
file = open("%s/%s" %(db_path, R245fa_db), mode = 'r', newline='')
x1, y1, x2, y2 = vlookup(file, p2, press_col, sl_col)
s2L = interpolate(x1, y1, x2, y2, p2)
file.close()

file = open("%s/%s" %(db_path, R245fa_db), mode = 'r', newline='')
x1, y1, x2, y2 = vlookup(file, p2, press_col, sv_col)
s2v = interpolate(x1, y1, x2, y2, p2)
file.close()

#print("sL = ",s2L,"\nsv = ", s2v)
try:
   qual_2 = (s2 - s2L)/(s2v - s2L)
except ZeroDivisionError:
   qual_2 = 0
```

```
except RuntimeWarning:
    qual_2 = 0

#print("x2 = ", x2)

# Note that evaporating enthalpy is equal to the difference between the enthalpy
# of a saturated vapor and the enthalpy of a saturated liquid at a given
# temperature or pressure.
file = open("%s/%s" %(db_path, R245fa_db), mode = 'r', newline='')
x1, y1, x2, y2 = vlookup(file, p2, press_col, hl_col)
h2L = interpolate(x1, y1, x2, y2, p2)
#print("h2L = ", h2L)
file.close()

file = open("%s/%s" %(db_path, R245fa_db), mode = 'r', newline='')
x1, y1, x2, y2 = vlookup(file, p2, press_col, hv_col)
h2v = interpolate(x1, y1, x2, y2, p2)
#print("h2v = ", h2v)

hLv = h2v - h2L
#print("hLv = ", hLv)
file.close()

h2 = h2L + (qual_2*hLv)
#print("h2 = ", h2)

file = open("%s/%s" %(db_path, R245fa_db), mode = 'r', newline='')
x1, y1, x2, y2 = vlookup(file, p2, press_col, hl_col)
h3 = interpolate(x1, y1, x2, y2, p2)
file.close()
#print("h3 = ", h3)

file = open("%s/%s" %(db_path, R245fa_db), mode = 'r', newline='')
x1, y1, x2, y2 = vlookup(file, p2, press_col, v_col)
v3 = interpolate(x1, y1, x2, y2, p2)
file.close()
#print("v3 = ", v3)

h4 = h3 + v3*(p4-p3)
#print("h4 = ", h4)
```

```
    W_m = h1-h2-h4+h3 # Watts of power per kg/s of mass flow rate
    #print("Watts per kg/s of mass flow rate = ", W_m)

    efficiency = ((h1-h2) - (h4-h3))/(h1 - h4)

    X.append(boiler_pressure)
    X2.append(boiler_temp)

    Y.append(condenser_pressure)
    Y2.append(condenser_temp)

    Z.append(W_m)
    Z2.append(efficiency)

ax.set_xlabel("Boiler Pressure (MPa)")
ax.set_ylabel("Condenser Pressure (MPa)")
ax.set_zlabel("Power output per unit mass flow rate (Watts)")
ax.scatter(X, Y, Z)

ax1.set_xlabel("Boiler Pressure (MPa)")
ax1.set_ylabel("Condenser Pressure (MPa)")
ax1.set_zlabel("Efficiency")
ax1.scatter(X, Y, Z2)

ax2.set_xlabel("Boiler Temperature (C)")
ax2.set_ylabel("Condenser Temperature (C)")
ax2.set_zlabel("Power output per unit mass flow rate (Watts)")
ax2.scatter(X2, Y2, Z, color='r')

ax3.set_xlabel("Boiler Temperature (C)")
ax3.set_ylabel("Condenser Temperature (C)")
ax3.set_zlabel("Efficiency")
ax3.scatter(X2, Y2, Z2, color='r')

plt.show()
```

7. References

[1] BCS, Incorporated, "Waste Heat Recovery: Technology and Opportunities in U.S. Industry," *U.S. Department of Energy Industrial Technologies Program,* p. 112, 2008.

[2] E. P. Dig Vijay Singh, "A review of waste heat recovery technologies for maritime applications," *Energy Conversion and Management,* no. 111, pp. 315-328, 2016.

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[4] Z. Y. Enhua Wang, "A numerical analysis of a composition-adjustable Kalina cycle power plant for power generation from low-temperature geothermal sources," *Applied Energy,* vol. 180, pp. 834-848, 2016.

[5] T. S. A. F. H. A. I. M. I. Mohammed A. Khatita, "Power generation using waste heat recovery by organic Rankine cycle in oil and gas sector in Egypt: A case study," *Energy,* vol. 64, pp. 462-472, 2013.

[6] T. C. Hung, T. Shai and S. K. Wang, "A Review of Organic Rankine Cycles (ORCs) for the Recovery of Low-Grade Waste Heat," *Energy,* vol. 22, no. 7, pp. 661-667, 1997.