An Automotive Application of the Organic Rankine Cycle for Power Generation Using
Recovered Waste Heat

Glenn Michael Clapp

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Committee Members:
Dr. Wael Mokhtar
Dr. Mehmet Sozen
Larry Ridge

Contents

1. Abstract

Keywords: Rankine cycle; Working pressure; Working temperature; Boiler; Condenser; Power-vapor cycle; Organic Rankine cycle; Low quality heat; Automotive; Waste heat recovery

The goal of this project is to develop a parametric model of an organic Rankine cycle for the purpose of generating electrical power using waste heat from the coolant system of an automobile. This application requires a small package size, and the utilization of low temperature, low quality waste heat.

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.

A successful solution to this problem will benefit from mass production and therefore mitigate the capital costs of development, utilize materials common to automotive parts in existing electric motors and pumps as well as refrigerants that are used in climate control applications. This project will develop industry knowledge in the area of waste heat recovery and increase the fuel efficiency of all vehicles in which it is implemented.

This project will have tertiary benefits as well, the model will develop methodology for harnessing low quality waste heat in other applications where development was not previously practical due to prohibitive upstart capital requirements and return on investment timing.

The parametric model developed for this project will be verified where applicable with physical prototypes and measurements. Previous work in mathematical modeling and literature on the subjects of waste heat recovery and vapor-power cycles will be reviewed to inform an efficient starting point for this project.

2. Literature review

2.1. Cycle selection

Because of the low temperature and quality of waste heat in automotive applications, the literature on the subject indicates that the optimal cycle for recovering that energy is the Rankine cycle. Specifically, two variations of the Rankine cycle: the Organic Rankine cycle and the Kalina cycle.

There are other options for low quality waste heat recovery such as thermoelectric and piezoelectric generation which both show promise because of their low technical complexity and long service life due to the lack of moving components. Unfortunately, both of those strategies promise very low efficiency and power yield for a small automotive application and require expensive materials for fabrication.

The organic Rankine cycle (ORC), is so named for the hydrocarbons and refrigerants that are typically used in those cycles. ORCs have the same configuration as traditional steam Rankine cycles but make use of hydrochlorofluorocarbons (HCFSs), fossil fuels such as propane and cyclopentane, benzene, cyclohexane and isobutene, and refrigerants such as R134a, R22, R245fa, R236ea, R152a, R123, R600a, R600, R290 and R227ea as working fluids. [2] [3] [4] [3] These working fluids make the ORC particularly well suited to low heat quality applications due to their high molecular weight and low phase transition temperatures.

A single stage turbine is typically used for an ORC [2] which greatly reduces the technical complexity and size of the turbine, both of which are positive features for an automotive application where physical space is crucial.

The Kalina cycle (KC) is a modified form of the Rankine cycle and has a better operating efficiency in certain applications. The use of non-azeotropic[1] working fluid mixtures in an ORC has often been proposed with the aim of reducing thermal irreversibilities; particularly those occurring between the heat source and the evaporating working fluid. The KC is typically implemented with a water/ammonia mixture for a working fluid. The ratio of that mixture is dynamically varied depending on the temperature of the heat source. [5]

Within the temperature range 200°C - 400°C, the Kalina cycle is 20% - 40% more efficient than a standard Rankine cycle. Some studies indicated that the Kalina cycle had better thermodynamic performance than the organic Rankine cycle as well. Because of the ammonia-water mixture used for a working fluid and the industry's long experience with both substances the Kalina cycle is also considered safe and environmentally friendly. This is not the case with some of the fossil fuels and refrigerants used in some organic Rankine cycles. [2] "For low temperature sources,

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[1] Azeotrope: n: A liquid mixture that is characterized by a constant minimum or maximum boiling point which is lower or higher than that of any of the components.

the Kalina is often mentioned as an alternative for the ORC. Although the Kalina cycle is often called to be [sic] superior to the ORC, Dippo (See source in reference material) has shown that an existing Kalina cycle has about the same performance as existing ORCs." [4] "Although the obtained useful powers are actually equal in value, the Kalina cycle requires a very high maximum pressure in order to obtain high thermodynamic performances. So, the adoption of Kalina cycle, at least for low power level and medium-high temperature thermal sources, seems not to be justified because the gain in performance with respect to a properly optimized ORC is very small and must be obtained with a complicated plant scheme, large surface heat exchangers and particular high pressure resistant and no-corrosion materials." [5] In the quoted study, the recovered power calculated from two identical diesel engines was 1615 kW and 1603 kW for the Kalina and ORC cycles respectively.

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%." [6] "Some studies showed that a KC can achieve a better thermal efficiency than ORC systems." [6] "In practice, the expansion ratio of the turbine for KCS-34 is relatively high and a multi-stage turbine is required." [6] This may be the drawback of the KC that makes ORC somewhat more attractive for an automotive application.

The KC also requires a substantial 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 more complicated to implement. KC is generally used as a method of improving a conventional (steam) RC. In some of these cases, the KC is the only real choice for waste heat recovery. It also appears that the working temperatures are slightly higher than some refrigerant based ORCs. This makes the KC less appropriate for an automotive application where the heat source is less than 100°C.

For the reasons outlined above, the ORC and the KC are the two leading competitors, and from those two, the ORC was selected for further study due to its comparable power output and efficiency that come without the draw backs of system complexity and corrosion that are common in implementations of the Kalina cycle.

The goal of this project is to design a parameterized mathematical model of an ORC such that an automotive scale generator can be designed and built. This model will use one of several hydrocarbons or refrigerants as a working fluid because the low quality of waste heat in the cooling system requires a working fluid with a low phase transition temperature. This model must also take as arguments the space available for the simulated system, though the project will not strictly limit the size of the application.

2.2. Working fluid selection

There are several viable working fluids for the organic Rankine cycle. The usage of each depends on a number of factors. Foremost among those factors are the working temperatures and pressures of the desired system.

In a traditional Rankine cycle, the working fluid used is water. That is not an appropriate selection for an automotive application due to the comparatively low temperature of the waste heat utilized. The Organic Rankine cycle uses organic compounds as a working fluid. These include hydrocarbons and refrigerants.

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. [7] 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. [7] 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." [8] These working fluids eventually foul the heat exchanger passages through which they pass, inhibiting heat transfer from the that source to the working fluid and from the working fluid to the heat sink. This is often referred to as a fouling factor and is an inefficiency that will be considered in the proposed model. 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 subsequent fouling of the heat exchangers and the efficiency of a given system. [8] [1]

In addition to the fouling on the working fluid side of the heat exchangers, the heat source side of the heat exchangers can also experience detrimental fouling if the exhaust stream from the vehicle is used as a heat source. This is the reason why, when considering which heat source to model, the cooling loop that exists in the engine compartment was chosen. 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. The system architecture being considered for this project assumes that there will be a heat exchanger through which the heat source (engine coolant) and the working fluid of the simulated cycle will

pass without directly interacting with one another. There is another benefit to this type of heat exchange. Because of the flammable nature of many organic compounds, separating the working fluid from the heat source also reduces fire hazards that might otherwise arise in a system of this kind. Because of the lack of oxygen in a closed loop of working fluid there is no possibility of fire without some sort of leak. There is further advantage to using the cooling loop of the vehicle as a heat source with respect to this design consideration in that there is no oxygen present in either system, and therefore reduced risk even in the case of a leak between the coolant system and the waste heat recovery system.

An analysis of a much more exhaustive list of working fluids used in an ORC is contained in the paper Exergetic and economic comparison of ORC and KC for low temperature enhanced geothermal system in Brasil. [9] This analysis includes several fluids that are not commonly considered in the literature and may be worth consideration.

2.3. Heat exchange

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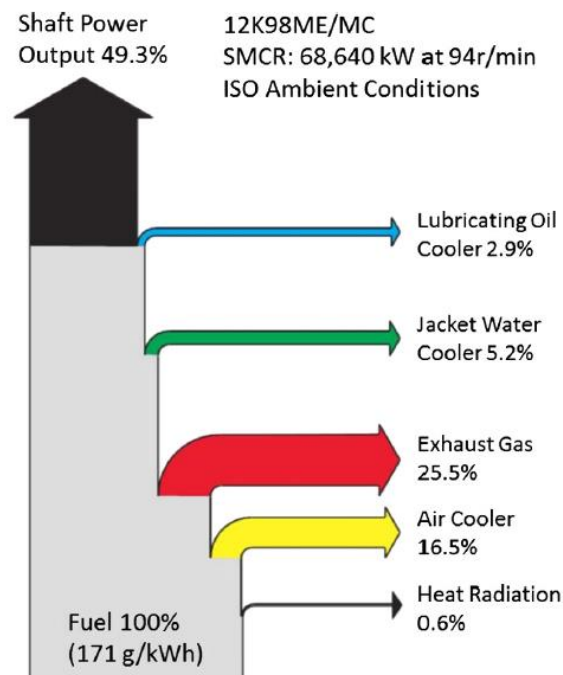

Figure 1: Heat balance diagram for MAN 12K98ME/MC marine diesel engine operating at 100 SMCR under ISO conditions [2]

While this application is not the subject of the proposed study, the breakdown of energy availability is likely to be very similar, though the quantities, temperature, and quality of those heat sources diverge from the diagram above.

"Engine cooling water temperatures of 80-90 $^{\circ}$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.

"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 will be 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 heat source. Because of the increased density, heat exchange occurs more efficiently if the two working fluids passing through a heat exchanger are each in a liquid state. Therefore, it should be a design consideration that the heat echanger pipes are always submerged in the liquid working fluid.

There is further, related upside to using organic compounds as a working fluid. One of the features of organic molecules is their relatively high molecular mass. In comparison with water vapor, the fluids used in ORCs have a higher molecular mass, enabling more compact designs, a higher mass flow rate, and higher turbine efficiencies. However, since the cycle functions at lower working temperatures, the overall efficiency is only around 10%-20%, depending on the precise temperature of the condenser and of the evaporator.

2.4. Cycle evaluation

There are many ways to evaluate the efficacy of an Organic Rankine cycle and across the literature many of these are employed. It is also not uncommon for the authors of a given paper to develop their own fitness criteria and use that to evaluate competing system designs. One common way in which waste heat recovery systems are compared is by comparing work potential. The work potential is the maximum work that can be obtained using a given heat source to drive a heat engine such as one using the Rankine cycle. That maximum work potential is given by the following equation.

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

Equation 1: Maximum work potential

Other methods of comparison include parameters such as system cost, research and development time and cost, system complexity and maintenance, and other recurring factors that may offset, in some cases entirely, the benefit of adding a waste heat recovery system to the process under consideration. This study will define an evaluation algorithm. The purpose of this is to iteratively evaluate parameters which are continuous over a user-defined range for the purpose of optimization.

Study	Type			Cycle studied						Steam generation	Heating	Absorption cooling	Heat recovery	
	Sim./Model	Analytical	Meta	Rankine	Organic Rankine	ORC with internal heat exchanger	Regenerative ORC	Supercritical Rankine	Kalina				Kinetic energy recovery (Turbo)	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	Waste heat recovery technology and opportunities in US industry			✓	✓	✓				✓	✓	✓	✓		✓
New Turbo Compound Systems in Automotive Industry for Internal Combustion Engine to Recover Energy		✓											✓	
Comparison of Thermodynamic Cycles for Power Production from Low-temperature Geothermal Heat Sources	✓	✓			✓	✓	✓	✓	✓	✓				
Design and Preliminary Tests of ORC (Organic Rankine Cycle) with Two-Stage Radial Turbine	✓				✓					✓				
Electricity from industrial waste heat using high-speed organic rankine cycle (ORC)			✓		✓					✓			✓	
Energetic and exergetic analysis of waste heat recovery systems in the cement industry	✓	✓		✓	✓					✓				
Heat recovery from Diesel engines A thermodynamic comparison between Kalina and ORC cycles	✓				✓				✓	✓				
Exergetic and economic comparison of ORC and KC for low temperature enhanced geothermal system in Brazil	✓	✓			✓				✓	✓				
ICMEAS_2017_paper_86 Waste heat recovery systems for internal combustion engines A review		✓	✓	✓	✓					✓	✓		✓	
Integration of low-level waste heat recovery and liquefied nature gas cold energy utilization	✓	✓	✓		✓				✓	✓				✓
Multi-criteria evaluation of several million working fluids for waste heat recovery by means of organic rankine cycle in passenger cars and heavy duty trucks	✓				✓			✓		✓				
19														

3. Plan of study

3.1. Objectives and outcomes

There are professional, academic, and personal objectives for this course of study. They are summarized in this section and expounded upon in the following sections. The industry objectives for this study are to design a tool with which to develop design specifications for an automotive waste heat recovery system that can be utilized on a light truck or similar platform. The tool will allow for the manipulation of various parameters of a Rankine cycle and estimate the power output of a system conforming to those parameters. The parameters chosen for manipulation are justified in the following sections and supported by the literature review. The parameters which will be studied for this application are shown in the table below.

Table 1: Study parameters

Parameter	Cases
Working fluid	R245fa, R236ea, R227ea, isopentane
Boiler working pressure	0.5 MPa - 3.5 MPa
Condenser working pressure	0.0 MPa - 0.5 MPa
Pump mass flow rate	350 L/min – 570 L/min

The academic objectives for this course of study are to expand my knowledge of vapor power cycles to the end of developing a useful automotive application. Further to complete my degree at GVSU in order to open up avenues for further study on this and related subjects. It is also an objective of this work to contribute to the body of knowledge in this field for the benefit of the engineering profession at large and for the environmental and commercial benefits of improving energy utilization.

The personal objectives for this project include satisfying a personal interest I have in the field of alternative energy, and novel technical projects.

The ultimate research objective of this study is to produce a model that can be manipulated to evaluate arbitrary attributes of an Organic Rankine cycle. That model will be used in future work to develop prototypes and eventually commercially viable products for my employer.

3.1.1. Develop a mathematical model for iterative design of an organic Rankine cycle

A model will be developed using Python to simulate a Rankine cycle with the parameters specified by the user. This model will be used to iteratively evaluate cycles with parameters over a specified range. The squares in the figure below represent the various subcomponents of that mathematical model as well as the key components of this project.
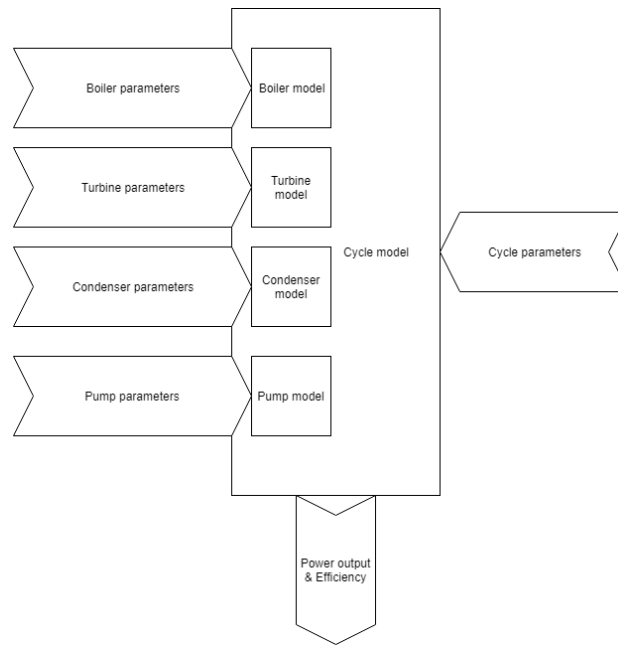
Figure 2: Proposed study components diagram

3.1.2. Design an organic Rankine cycle to recover heat from an automotive cooling system

Using the model described under the previous heading, ideal parameters will be developed for a specific automotive application. The purpose of the model is to develop design specifications for an actual application and eventually as part of a future project to build a working prototype.

4. Preliminary results

4.1. Working fluid

The most common working fluids used in ORC are R134a, R245fa, R22, isobutene, pentane, propane and PFCs. In the past, CFCs and HCFC were commonly used but are being phased out of current applications, and avoided for new applications due to environmental and safety concerns. Any leaks that may occur in the system additionally pose a fire safety hazard if the working fluid selected is flammable. If a hydro-carbon were selected, heat exchangers in which the working fluid does not come into direct contact with the heat source become necessary and the flash point of the working fluid must be considered as a boiler maximum temperature.

The working fluid used for the preliminary study was R245fa, a popular choice for similar applications with medium to low grade waste heat. The phase transition diagram is shown below. A table from the same source was used in the Python model used to produce the results shown in the following section.
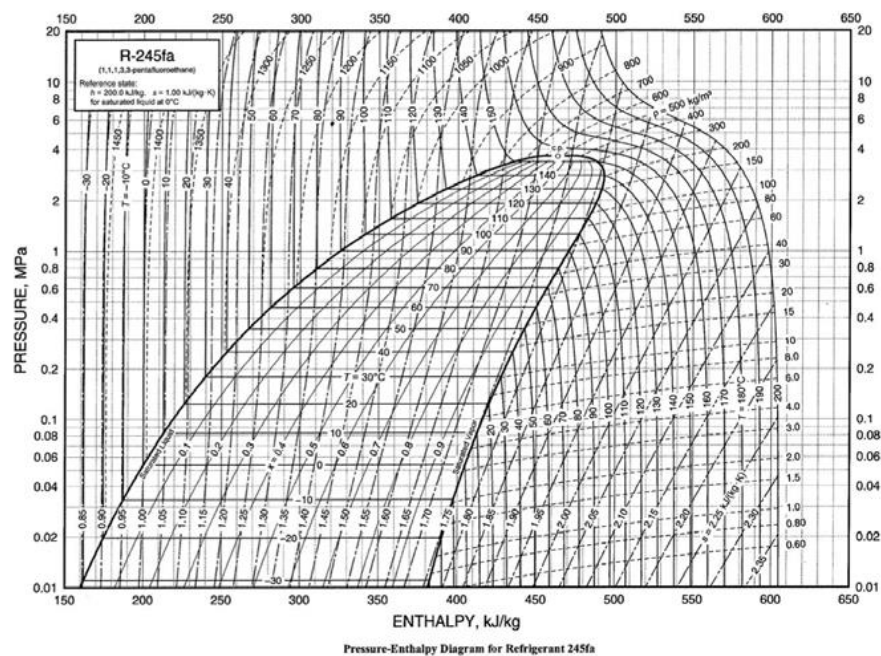

Figure 3: R245fa Pressure/Enthalpy diagram [10]

The proposed study will explore other common working fluids as one of the parameters in the ORC model.

4.2. Working pressures and temperatures

A simple Rankine vapor power cycle was modelled like the diagram shown in Figure 4. The model was produced in Python as shown in Appendix C – Source Code.
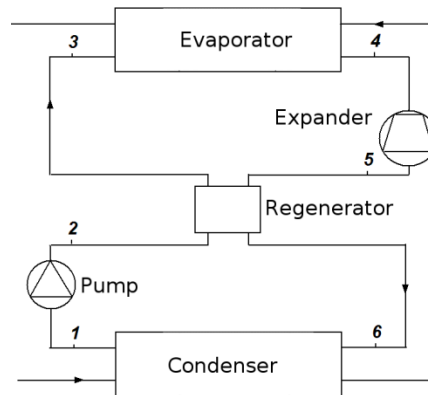
Figure 4: Typical Rankine cycle

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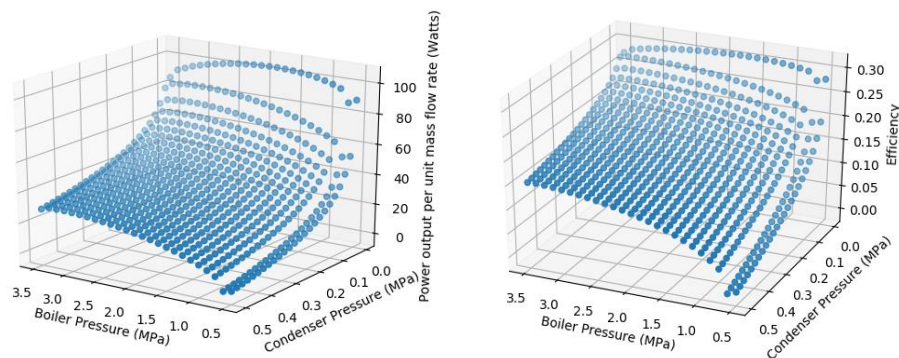

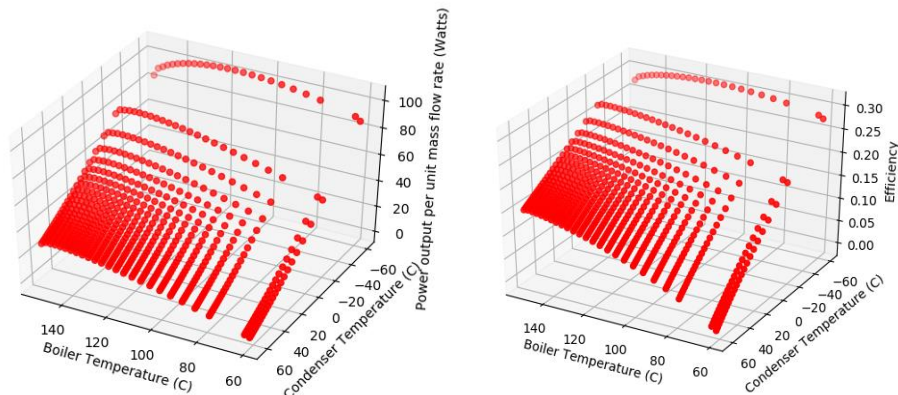*Figure 5: Power output per unit mass flow rate and efficiency by boiler and condenser working pressures*

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

As can be seen from these figures, increased mass flow rate increases power output and efficiency. There are two aspects of the cycle that can be manipulated to achieve faster mass flow rate: A pump design that has a faster volumetric flow rate, and a working fluid of higher density.

4.3. Increased energy efficiency

One must be able to justify the addition of any waste heat recovery system with respect to several factors. The first is that the system must increase energy efficiency of the process onto which it is added by a quantity meeting or exceeding the energy cost to the system which includes it. In an automotive application the most obvious way an added system taxes the automobile is with increased mass which the system is now responsible for accelerating. Put another way, the WHR system must generate at least enough energy to accelerate its own mass; otherwise it does not contribute in a positive way to the energy balance of the vehicle. Another way in which the system must pay for itself, though not always a requirement for a consumer, is that the system should recover enough energy to offset its own manufacture.

This is of specific concern to GHSP and will therefore be considered during the iterative cycle optimizations a significant contributor to the fitness function used to evaluate a given set of cycle parameters.

5. Experimental design

Some of the parameters of the system cannot be independent for each of the subsystems. The parameter that is necessarily shared by all subsystems is the working fluid and the mass flow rate of the working fluid.

A preliminary investigation of working fluids was performed and the working fluid used to obtain the preliminary results was R245fa. However, this investigation was far from exhaustive and the literature review yielded several more working fluids of interest that this study will investigate. Some of the working fluids of particular interest are isopentane and R236ea which at least one study cited as the best working fluid for a heat source of 145°C. [4] Another source used R227ea as a working fluid which was observed to have an electric efficiency of 4.88% [3]

There are also efficiency improving features of a Rankine cycle which could be explored. Boiler temperatures super, trans, and sub critical are all discussed in the literature; recuperators, secondary turbine stages, turbine bleeds, heated feed-water and many others are discussed. Most of these will be beyond the scope of this study, but will likely be included among the recommendations for further study as the literature seems to indicate that marginal gains in efficiency and power output can be achieved by the integration of some or all of these features.

5.1. Boiler factors

In addition to the working pressure and temperature of the boiler, mass flow rates of the heat source, the working fluid from the automobile's cooling system, and of the vapor power system can be manipulated to increase the rate of heat transfer. The interaction surface area of the heat exchanger can also be manipulated. Some of these factors are much easier to manipulate than others. So, while the model will be developed such that any relevant parameter can be manipulated, this study will focus on the results of changing those that make the most practical and economic sense.

For the boiler, because this application requires a very small size with respect to traditional power generation layouts, the surface area of the heat exchanger is not a parameter that can be manipulated easily in practice. The temperature is also difficult to manipulate as the application is going to be integrated into an existing vehicle system which will have waste heat at a given temperature over which designers have very little control.

The factor that does make sense to manipulate is the operating pressure. And to that end, preliminary results have been included to demonstrate the design space that exists for this application.

5.2. Turbine factors

The number of stages, and turbine blade size, shape, and angle can all be manipulated to affect the efficiency of the turbine. The type of cycle in this case, the organic Rankine cycle, also has a large effect on the efficiency of this component of the system.

The literature review indicates that the turbine design selected for an organic Rankine cycle is usually a single stage turbine. This greatly simplifies the design space for the turbine. Blade size, shape and angle can be optimized for a given application and therefore are not parameters that are transparent to the user of the mathematical model as these parameters will be determined by the selection of other parameters.

These reasons make the turbine design an area in which there is not a lot of interesting work to be done in this project. Because of this, it will not be a subject that receives much specific attention in this study.

5.3. Condenser factors

In addition to the working pressure and temperature of the condenser, the mass flow rate of the heat sink can be manipulated; though the mass flow rate of the heat sink, in this case the ambient air, is harder to manipulate. The interaction surface area of the heat exchanger can also be manipulated.

The condenser also represents a potential design challenge in an automotive application because the environment in which the system will be placed, the engine compartment, can be expected to have a highly variable temperature. It will also not be practically feasible to manipulate that temperature in any meaningful way.

The condenser factors face many of the same limitations as those of the boiler. Primarily that space in this application is a premium and therefore will likely be fixed. The condenser temperature is fixed to the ambient temperature which, in addition to being largely out of the control of this device, is somewhat variable depending on other heat sources and sinks in the engine compartment as well as operating conditions of the vehicle and the weather in which the vehicle is operating.

As a result the parameter that is of interest to this study is primarily that of working pressure of the condenser and to that end the preliminary results contain the likely design space for this application.

5.4. Pump factors

The pump working pressure can be manipulated, and it may be possible to drive the pump directly with mechanical energy from the turbine shaft rather than electrically which could

represent some efficiency gains. This area is also of particular interest to GHSP as they design and manufacture pumps currently and can be considered experts in this area.

Mass flow rate of the working fluid and the pressure of the boiler, which is the output pressure of the pump, are parameters of interest to this study. The pressure is explored in the preliminary results, but the mass flow rate is represented in the results as a variable quantity and will be one of the primary foci of the proposed study.

6. 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.

[3] S. H. Kang, "Design and Preliminary Tests of ORC (Organic Rankine Cycle) with Two-Stage Radial Turbine," *Energy,* no. 96, pp. 142-154, 2016.

[4] B. L. W. D. Daniel Walraven, "Comparison of Thermodynamic cycles for Power Production from Low-temperature Geothermal Heat Sources," *Energy Conversion and Management,* no. 66, p. 14, 2012.

[5] C. M. I. C. P. Paola Bombarda, "Heat Recovery from Diesel Engines: A Thermodynamic Comparison Between Kalina and ORC cycles," *Applied Thermal Engineering,* no. 30, pp. 212-219, 2010.

[6] 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.

[7] 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.

[8] 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.

[9] J. C. E. P. O. J. V. E. E. S. L. V. M. C. D. M. d. S. F. R. L. D. V. G. Carlos Eymel Campos Rodriguez, "Exergetic and economic comparison of ORC and KC for low temperature enhanced geothermal system in Brazil," *Applied Thermal Engineering,* no. 52, pp. 109-119, 2013.

[10] American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., "Chapter 30 - Thermophysical Properties of Refrigerants," in *2009 ASHRAE Handbook*, Atlanta, https://app.knovel.com/hotlink/toc/id:kpASHRAE37/ashrae-handbook-fundamentals/ashrae-handbook-fundamentals, 2009, p. 75.

[11] C. B. Arvind Thekdi, "Waste Heat Reduction and Recovery Options for Metals Industry," *Energy Technology. John Wiley & Sons, Inc.,* pp. 17-24, 2011.

[12] BCS, Incorporated, "Waste Heat Recovery: - Technology and Opportunities in U.S. Industry -," 2008.

[13] 15 December 2017. [Online]. Available: https://en.wikipedia.org/wiki/Carnot_cycle.

[14] 28 December 2017. [Online]. Available: https://hellafunctional.com/?p=629.

[15] J. P. Holman, "Heat Transfer," in *Heat Transfer*, New York, McGraw-Hill, 2010, p. 713.

7. 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

8. 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:
```

```python
            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')
```

```python
#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()
```