

# Organic Rankine Cycles with Dry Fluids for Small Engine Exhaust Waste Heat Recovery

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## ABSTRACT

Engine manufacturers are considering the implementation of thermodynamic cycles for Waste Heat Recovery (WHR) in order to increase Internal Combustion Engine (ICE) system thermal efficiency. For these secondary cycles, the literature illustrates the preference of Organic Rankine Cycles (ORC's) due to its simplicity and efficient recovery of the medium grade waste heat found in engine exhaust. This paper simulates the heat recovery capacity of eight dry fluids (butane, pentane, hexane, cyclopentane, benzene, toluene, R245fa, and R123) for an ORC based on the exhaust from a single-cylinder diesel engine-generator operating under five different loading conditions. The model, developed using REFPROP and the Matlab Optimization Toolbox, represents the physical components using isentropic pump and expander efficiencies, along with two-zone heat exchangers. All fluids present cycle efficiencies between 10-15%, with the heaviest hydrocarbons generating the largest amount of work. Of these fluids, pentane is the ideal candidate for an ORC. This fluid illustrates an approximate 10% improvement to the engine-generator efficiency across all conditions. Moreover, the simulation predicts low peak pressures and expansion ratios that are compatible with available displacement expanders. In addition, this effort compares evaporator flow configurations (counter vs. parallel), along with condenser air flow rates. For the evaporator, results illustrate that a parallel flow evaporator arrangement can transfer more heat in phase change applications by setting the high temperature difference in the area of low heat transfer coefficients. Different air flow rates across the condenser show little variation in cycle efficiency with the consumption of fan power at high rates reducing the overall power generated.

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## INTRODUCTION

A traditional Rankine cycle uses four components to transform waste heat into a more usable form of energy, such as mechanical or electrical. As [Figure 1](#) presents, this system includes repeated circulation of the working fluid. If the working fluid is organic in nature, the system is known as an Organic Rankine Cycle (ORC).

The four components in the cycle are the pump, evaporator, expander, and condenser. Accordingly, the cyclic nature of the ORC allows for arbitrary choice of the numerical identifiers for the thermodynamic states (1 through 4 on [Figure 1](#)). In addition to the schematic representation, [Figure 2](#) provides another view of the Rankine cycle using a temperature versus specific entropy ( $T$ - $s$ ) diagram.

In order to illustrate the Waste Heat Recovery (WHR), or conversion of waste heat to useful work, description of the ORC processes will begin with state 2. In the evaporator, the circulating working fluid captures waste heat from the source, raising its temperature (process 2-3 in [Figure 2](#)). Next, an

expansion device generates mechanical or electrical power (process 3-4 in [Figure 2](#)); this device can be either a reciprocating expander or turbomachine. Following expansion of the working fluid, low grade thermal energy discharges to the atmosphere through a condenser, by either natural or forced convection (process 4-1 in [Figure 2](#)). Finally, a pump compresses the working fluid using external power input, returning the fluid back to its original state (process 1-2 in [Figure 2](#)).

Performing simulations of an ORC requires a number of basic design choices. For the current study, exhaust gas from an Internal Combustion Engine (ICE) is the waste heat source ( $\dot{Q}_{in}$ ). This is because the high exergy content of engine exhaust yields more efficient WHR than engine coolant [1]. In addition, only dry fluids are being studied. As opposed to the wet fluid indicated in [Figure 2](#), dry fluids have positive saturated-vapor curve slopes. This characteristic prevents wet expander-exit conditions, which decreases the lifespan of turbine expanders [2]. Also, many hydrocarbons are dry

fluids and offer an environmentally-friendly alternative to common refrigerants. Lastly, the decision to use a traditional Rankine cycle (no reheat or regeneration) minimizes system complexity and initial cost of eventual implementation in the authors' laboratory for validation of model predictions.

After a brief introduction on ORC-WHR in the Background section, the Methods section of this paper describes the creation of a component-based ORC model using Matlab in order to solve the non-linear governing equations. Cycle simulation results across five engine loading conditions are then presented for subsequent evaluation of eight candidate working fluids from a practical and performance perspective. Specifically, parametric studies of pressure ratio and condenser air flow rate are described. Finally, this effort compares both parallel and counter-flow evaporator configurations.

## ORC BACKGROUND

In the 1970's, increasingly stringent emissions regulations and high fuel prices motivate the research of alternative power plants to traditional ICE's. However, other power cycles fail to match the high power density and low cost of ICE's, preventing a substantial change in vehicle propulsion [3]. Instead, efforts shift toward supplementing the engine's power through WHR.

The most common WHR method, particularly for diesel engines, is turbocharging. Here, a turbocharger utilizes the elevated pressure of engine exhaust to boost the air into the engine. This approach enhances engine performance by improving volumetric efficiency; however, engine exhaust at the turbocharger exit still contains significant amounts of thermal energy. For more complete WHR, the primary candidates for ICE WHR are ORC's, steam Rankine cycles, Brayton cycles, Stirling cycles, thermoelectrics, Kalina cycles, and carbon dioxide transcritical cycles. While publications are available on each concept, most small-scale WHR efforts prefer the Rankine cycle due to its standard components and efficient operation between small to moderate temperature differences [4]. Along with these advantages, a brief comparison of the WHR methods above with additional references is found in a publication by the authors [5].

One of the pioneering ORC-WHR research efforts comes from Patel and Doyle in 1979 [6]. Their system generates power through the recovery of exhaust heat from a Mack 676 diesel engine on a long haul truck, a suitable candidate for WHR due to long periods of near constant engine operation. Using Fluorinol-50 as the cycle working fluid, the system provides a 15% improvement in fuel economy over the NAPCA control route. While Doyle et al. describe plans for an expansion of the program to ten trucks in FY1981-1982, no further information is available [7].

During the 1980's and 1990's, numerous efforts address working fluid and expander selection. These design choices are known to significantly influence cycle efficiency [8]. Of interest, low power applications are shown to favor reciprocating expanders (e.g., Badr [4]). Advantages of reciprocating expanders include decreased sensitivity to wet expander-exit conditions and engine speed fluctuations, low cost, potential hermetic power generation, and rotational speeds similar to an ICE. Alternatively, turbines offer slightly higher efficiencies and large expansion ratios.

The initial choice of working fluid considers water and organic fluids. Hung notes in 1997 that increasing waste heat source temperatures (above 370°C) favor water, while low temperature applications justify the use of organic fluids [9]. Water tends to provide the highest cycle efficiencies; however, low condensing pressures, high expansion ratios, potential freezing, and wet expander-exit conditions must be addressed. Large amounts of superheat added combats water droplet formation, but transient engine operation makes dry expander-exit conditions difficult to maintain. When using an

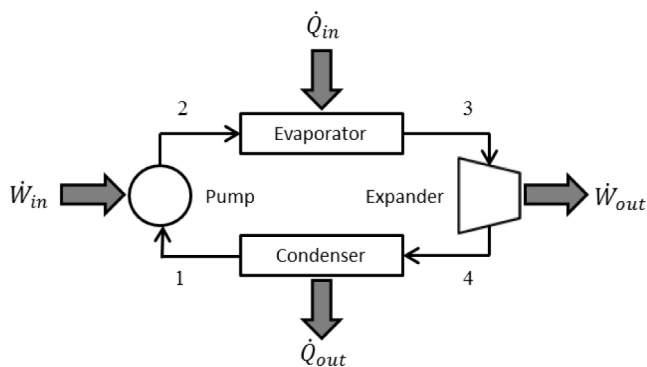


**Figure 1. Rankine cycle system illustrating the different locations of analysis as a function of cycle location.**

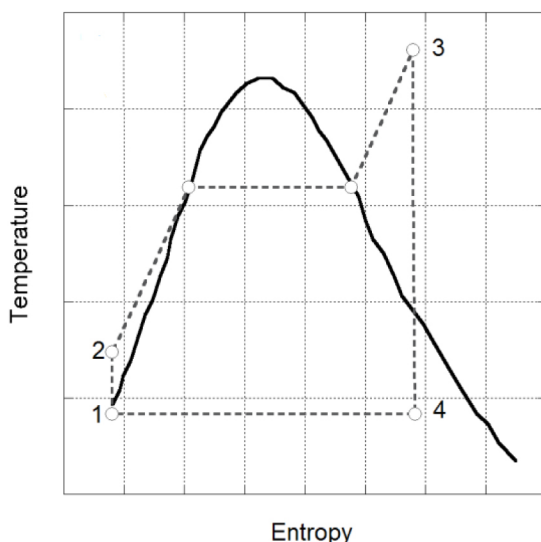


**Figure 2. Rankine cycle temperature versus specific entropy diagram indicating the thermodynamic states of Figure 1.**

organic fluid, a later effort by Teng et al. concludes isentropic (vertical saturated-vapor curve slope) or nearly-isentropic fluids are generally most suitable for ORC-WHR systems [10].

More recent developments in working fluid selection include identification of a weak connection between critical temperature of the fluid and cycle efficiency [11]. In other words, more efficient heat recovery is expected from high critical temperature fluids. A 2005 study by El Chammas and Clodic finds a discrepancy in cycle performance with superheat between wet fluids and dry or isentropic fluids [12]. Increasing superheat yields higher cycle efficiencies for wet fluids, while performance is constant or hindered when superheating the other classes of fluids.

Current practical working fluid considerations include the selection of fluids with low Ozone Depletion Potential (ODP) and Global Warming Potential (GWP), which decreases environmental harm upon discharge from the system [13]. Thermodynamically, exceedingly large evaporation pressures return greater thermal efficiencies; however, this adds expense to the system in order to handle these pressures [14]. Thus, no Rankine cycle configuration or working fluid is optimal for every waste heat source, which requires a thermodynamic analysis targeting the specific source.

## VEHICLE INTEGRATION

Oomori and Ogino show a resurgent interest on the part of vehicle manufacturers regarding integration with the vehicle in 1993 with an incorporated ORC using the HCFC (hydrochlorofluorocarbon) R123 as the working fluid while recovering heat from the engine coolant only [15]. While the coolant has similar energy content as compared to the exhaust, a fuel economy improvement of only 3% is achieved due to its low exergy levels. In this passenger car application, the complexity of system control during fluctuating engine speeds causes the authors to decide against exhaust WHR.

At the large end of the application spectrum is a marine application described by Schmid in 2004, where waste heat from a 68,040kW Sulzer 12RTA96C engine provides a 12% efficiency gain above the standard 50% engine efficiency [16]. Due to the short four year payback period of the heat recovery plant, Wartsila went ahead and installed the steam Rankine system on several other ships [17].

Three years later, Endo et al. study engine exhaust WHR on a Honda Stream hybrid vehicle [1]. The prototype Rankine cycle system uses an innovative catalyzed evaporation device and swash plate axial piston type expander. As a benefit of the hybrid drivetrain's battery pack, a generator is connected to the expander, allowing periods of storage and outflow of recovered energy. Subsequent testing reveals a 13.2% thermal efficiency improvement relative to the base vehicle and demonstrates transient control capabilities through dramatic variations in engine operation.

A recent publication by Ringler et al. investigates the use of a Rankine cycle on a four-cylinder engine for WHR,

providing a comparison of exhaust only and exhaust+coolant heat recovery [18]. The authors find an engine performance increase in the range of 10%, with slightly better performance from the exhaust+coolant ORC-WHR system at typical driving conditions. One year later, Espinosa claims 10-15% system efficiency for Rankine cycles in a Volvo study of commercial truck WHR [19].

When considering a Rankine cycle for vehicle implementation, fuel economy improvements must account for slightly reduced engine performance caused by the additional exhaust backpressure imposed by the evaporator. In previous efforts, horsepower losses of 1.5-2.5% at high loads and 0.2-0.5% at low loads have been observed [12]. For a thorough review of the aforementioned studies and additional literature efforts on ICE WHR with ORC's, the reader is referred to a recent publication of the authors [5].

## METHODS

The simplest ORC modeling approach uses steady-state reversible processes, resulting in the idealized  $T$ - $s$  diagram of Figure 2. However, performance predictions are improved by permitting entropy generation, which includes isentropic and actual thermodynamic states (see Figure 3). Here, isentropic processes result in states designated by 's' and actual processes are identified with 'a'.

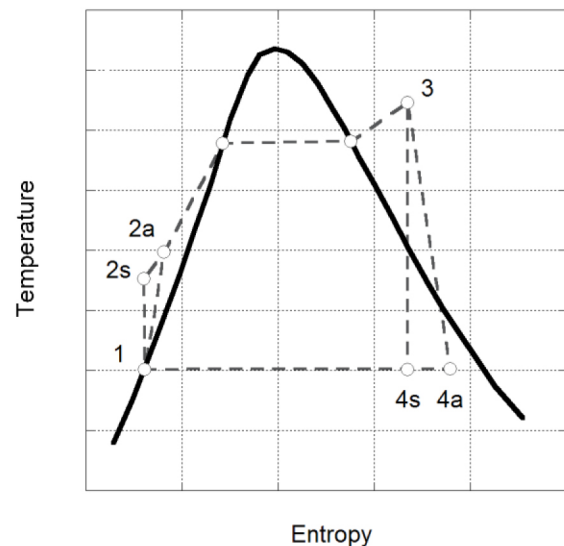


**Figure 3. Actual Rankine cycle including both isentropic 's' and actual 'a' thermodynamic states.**

For the current study, a zero-dimensional steady-state ORC model with entropy generation is simulated within Matlab. An additional attribute of the model is the use of a component-based formulation instead of using performance-based attributes. This allows specification of heat transfer areas and is valuable for evaluating the WHR of an ORC in a mobile application, where space limitations are common. Since the heat recovery from a single-cylinder Yanmar L100V diesel engine-generator is under evaluation, the