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Comparative analysis of the effects of expander types on thermodynamic performance in low-temperature waste heat recovery systems (ORC)

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Abstract

The growing global demand for energy efficiency has underscored the significance of recovering industrial waste heat. The Organic Rankine Cycle (ORC) stands as the most prevalent method for transforming low-temperature heat sources into electrical energy. This research examines expander technologies, which have a direct impact on the performance of ORC systems. A comparative analysis is conducted between dynamic-type (radial turbine) and volumetric-type (scroll) expanders, focusing on thermodynamic efficiency, operational ranges, and mechanical design limitations. The review concludes that turbines provide efficiency benefits at higher power outputs (exceeding 50 kW), while scroll expanders are more appropriate for small-scale applications (under 10 kW) and fluctuating flow conditions, mainly due to their ability to tolerate liquid presence and their lower cost.

1. Introduction

The consistent escalation in global energy demand, coupled with the severe environmental consequences of fossil fuel dependency, has made the optimization of existing energy resources a critical imperative. In both industrial sectors and internal combustion engines, a substantial portion of primary energy—typically ranging from 50% to 60%—is dissipated into the environment as waste heat [1,2]. To reclaim this unutilized energy, several recovery technologies have been developed, including thermoelectric generators (TEGs), advanced heat exchanger systems, and the Organic Rankine Cycle (ORC) [3]. Specifically, the exhaust systems of heavy-duty vehicles represent a high-potential environment for ORC integration due to the steady supply of high-grade waste heat [4]. Recent research in the Turkish energy sector has further highlighted the importance of these systems through exergoeconomic assessments of solar-assisted ORC configurations [5].

While the conventional Steam Rankine Cycle (SRC) is highly effective for high-temperature and high-pressure utility-scale power plants, it exhibits significant technical and economic limitations when applied to low-temperature heat sources (below 250 °C). At these lower thermal gradients, water requires evaporation under vacuum conditions, leading to excessively large turbine dimensions and reduced economic viability. Conversely, the Organic Rankine Cycle (ORC) utilizes organic working fluids—such as R134a, R245fa, and toluene—which possess lower boiling points and higher molecular weights than water. These thermodynamic properties allow ORC systems to operate with superior efficiency in low-temperature regimes [6,7], making them the premier solution for converting low-grade thermal energy into useful electrical or mechanical work [8].

The critical component determining the overall thermodynamic performance of an ORC system is the expander, which facilitates the conversion of thermal energy into mechanical shaft work. Expanders are generally categorized into dynamic machines (turbines) and positive displacement (volumetric) machines, such as scroll, screw, and piston expanders. Although turbines are the industry standard for megawatt-scale power generation, their efficiency significantly diminishes in small-scale applications and low mass-flow conditions due to exacerbated aerodynamic losses. In contrast, volumetric expanders have emerged as a robust alternative, offering lower manufacturing costs, simplified mechanical configurations, and a higher tolerance for two-phase (wet steam) flow conditions [9].

The objective of the present study is to conduct a comprehensive comparative assessment of various expander types utilized in low-temperature waste heat recovery ORC systems. The analysis focuses on thermodynamic efficiency, mechanical design constraints, and economic feasibility. By synthesizing experimental and theoretical data from the existing literature, this study identifies the optimal power ranges and operational parameters for both turbine-based and volumetric expansion solutions, providing a strategic framework for expander selection in localized energy recovery systems.

2. Thermodynamic Background and Method

2.1. Basic ORC Working Principle

The Organic Rankine Cycle (ORC) operates on the same fundamental principles as the conventional Clausius–Rankine cycle, with the primary distinction being the use of organic compounds as the working fluid in place of water. An ideal ORC system comprises four main components and involves four corresponding thermodynamic state changes, as illustrated in Figure 1.

The ideal ORC consists of the following thermodynamic processes:

(1–2) shows the Isentropic compression: While the organic working fluid is pumped from a low pressure (the pressure in the condenser) to a high pressure (the pressure in the evaporator).

(2–3) exhibits the Isobaric heat addition: The high-pressure liquid absorbs thermal energy from the waste heat source and turns into vapor in the evaporator.

(3–4) is the Expansion: The high-temperature and high-pressure vapor expands within the expander to produce mechanical shaft work. For dry working fluids, the expansion remains entirely in the superheated vapor region, whereas for wet working fluids the expansion may enter the two-phase region.

(4–1) depicts the Isobaric heat rejection: The low-pressure vapor exiting the expander releases heat in the condenser and returns to the liquid phase.

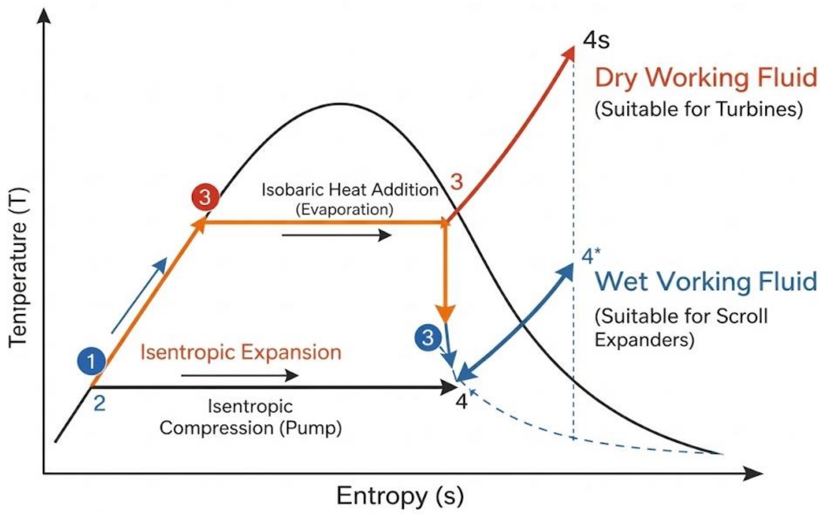

Figure 1. Schematic T–s diagram of an Organic Rankine Cycle (ORC), illustrating a single ORC loop with two alternative expansion paths associated with dry and wet working fluid behaviors.

2.2. Performance Criteria and Governing Equations

The thermodynamic evaluation of the system is governed by the First Law of Thermodynamics, emphasizing the principle of energy conservation in conjunction with mass balance equations. These fundamental frameworks have been extensively utilized to characterize waste heat recovery across diverse thermal applications, including industrial furnaces and internal combustion engines [10-13].

The mathematical formulation of the cycle is predicated on steady-state flow conditions. Furthermore, variations in kinetic and potential energies are considered negligible and are thus excluded from the energy balance calculations. Under these operational assumptions, the energy conservation for each individual system component is defined as follows:

The rate of thermal energy input to the system, $\dot{Q}_{in}$, is quantified based on the enthalpy rise of the organic working fluid as it traverses the evaporator, as expressed in Equation 1:

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

The theoretical power output of the expander under isentropic conditions is determined by the enthalpy gradient between the expander inlet and the corresponding isentropic outlet state, as defined in Equation 2:

$$\dot{W}_{exp,s} = \dot{m}_{wf}(h_3 - h_{4s}) \tag{2}$$

where $\dot{m}$ represents the mass flow rate of the working fluid (kg/s) and h denotes the specific enthalpy (kJ/kg). This quantity signifies the maximum theoretical work extraction achievable through ideal isentropic expansion. In practical operation, however, the actual power output is significantly attenuated by inherent irreversibilities, including mechanical friction, internal leakage, and heat transfer losses. Consequently, the actual power generated by the expander is expressed as follows in Equation 3:

$$\dot{W}_{exp} = \dot{m}_{wf}(h_3 - h_4) \tag{3}$$

To quantify the impact of these irreversibilities and evaluate the mechanical integrity of the expansion process, the isentropic efficiency (η_{is}) is introduced. This dimensionless parameter represents the ratio of the actual enthalpy drop to the isentropic enthalpy drop, as formulated in Equation 4:

$$\eta_{is} = \frac{\dot{W}_{exp}}{\dot{W}_{exp,s}} = \frac{(h_3 - h_4)}{(h_3 - h_{4s})} \tag{4}$$

The isentropic efficiency serves as a critical benchmark for expander selection. While the efficiency of dynamic machines, such as turbines, is primarily dictated by aerodynamic profile optimization, the performance of volumetric expanders (e.g., scroll or screw machines) is predominantly governed by mechanical clearances and sealing characteristics. Finally, the overall thermodynamic efficiency of the Organic Rankine Cycle (ORC) system (η_{th}) is defined as the ratio of the net power output to the total thermal energy input provided to the evaporator. This relationship is quantified in Equation 5:

$$\eta_{th} = \frac{\dot{W}_{net}}{\dot{Q}_{in}} = \frac{\dot{W}_{exp} - \dot{W}_{pump}}{\dot{Q}_{in}} \tag{5}$$

2.3. Influence of Working Fluid Thermodynamics on Expander Selection

The thermodynamic characteristics of the working fluid, specifically the slope of the saturated vapor curve on the Temperature-entropy (T–s) diagram, exert a decisive influence on the selection and structural design of the expansion machine [14]. Working fluids are traditionally classified based on this slope as dry, isentropic, or wet, each imposing distinct operational requirements on the expander.

For dry fluids (e.g., R245fa, pentane), the working medium remains in the superheated vapor phase throughout the expansion trajectory. This characteristic is particularly advantageous for dynamic expanders, such as turbines, as it precludes the formation of liquid droplets. By ensuring a single-phase gaseous flow, dry fluids effectively mitigate the risk of blade erosion and prevent the degradation of aerodynamic efficiency associated with moisture content.

Conversely, wet fluids tend to enter the two-phase (liquid-gas) region during the expansion process, leading to partial condensation at the expander outlet. The presence of liquid droplets within high-speed dynamic machines can cause severe mechanical impingement and structural failure. Under these operating regimes, volumetric machines—specifically scroll expanders—demonstrate a significant mechanical advantage. Due to their inherent robustness and high tolerance for two-phase flow conditions, volumetric expanders can accommodate liquid fractions without compromising the integrity of the system, making them the preferred choice for cycles utilizing wet working fluids.

3. Mechanical Investigation of Expander Technologies

The architectural selection of expansion units within Organic Rankine Cycle (ORC) frameworks is fundamentally dictated by the system's rated power capacity, operational pressure ratios, and economic constraints. In established literature, expansion machines are systematically classified into two primary categories: dynamic machines (turbomachinery) and volumetric machines (positive displacement).

3.1. Dynamic Expanders (Turbines)

Turbines facilitate continuous power generation by converting the kinetic energy and enthalpy drop of a working fluid into a momentum change across rotor blades.1 Within the context of small-to-mid-scale ORC applications, radial-inflow turbines have emerged as the preferred configuration.2 These machines offer distinct advantages over axial architectures, specifically regarding their compact geometry and the capacity to accommodate significant enthalpy gradients across a single expansion stage [15,16]. Conversely, axial turbines are typically reserved for utility-scale power plants characterized by high mass flow rates and multi-stage architectures, often operating at the megawatt (MW) level.

Despite their performance advantages, turbines face significant operational constraints. Their exceptionally high rotational velocities—typically ranging between $10,000$ and $100,000$ rpm—necessitate rigorous dynamic balancing and the integration of high-precision reduction gearboxes to synchronize with electrical generators. These additional components can introduce parasitic mechanical losses to the system. Furthermore, the structural integrity of turbine blades is highly susceptible to moisture; high-velocity liquid impingement can lead to rapid erosion and catastrophic failure. Consequently, maintaining a strictly superheated vapor state at the expander inlet is a critical operational requirement.

3.2. Volumetric (Positive Displacement) Expanders

Volumetric expanders extract work by isolating a discrete mass of the working medium within a sealed chamber and allowing it to expand by increasing the chamber's volume. Their operational methodology is frequently conceptualized as the reverse application of conventional industrial compressor cycles.

3.2.1. Scroll Expanders

Scroll-type machines represent the predominant solution for micro-scale ORC systems, generally optimized for power outputs ranging from 1 to 10 kW [17]. The architecture comprises two interleaved spiral geometries: one remains stationary while the other executes an orbital trajectory.

This design features a minimal number of moving components, which effectively reduces vibrational signatures and acoustic emissions. Crucially, scroll expanders demonstrate a high tolerance for two-phase (wet) flow conditions. The presence of a liquid fraction does not result in structural damage; instead, the liquid phase serves to bridge internal sealing gaps, thereby mitigating leakage and enhancing mechanical efficiency [18, 19]. However, their performance is highly sensitive to the operating pressure ratio. Experimental investigations have indicated that exceeding the design pressure ratio leads to increased leakage through internal sealing gaps, resulting in a marked decline in volumetric efficiency [20].

3.2.2. Screw and Piston Expanders

Screw expanders are optimally suited for medium-scale power recovery, generally categorized within the 20 to 200 kW range. These machines utilize the rotation of two intermeshing helical rotors to facilitate the expansion of the working fluid. While screw expanders are characterized by robust mechanical construction, they are subject to significant internal leakage at elevated pressure ratios, which can substantially compromise their overall efficiency.

4. Comparative Analysis and Literature Synthesis

This section provides a rigorous comparative analysis of dynamic (turbine) and volumetric (scroll) expanders, focusing on their respective power capacities, isentropic efficiencies, and mechanical design constraints. This synthesis is predicated on an extensive review of both empirical and numerical studies documented in the current literature.

4.1. Comparison by Power Capacity

The thermal capacity of the available waste heat source remains the primary variable in the expander selection matrix. An analysis of the literature reveals that specific expander technologies are dominant within well-defined power regimes, as graphically represented in Figure 2.

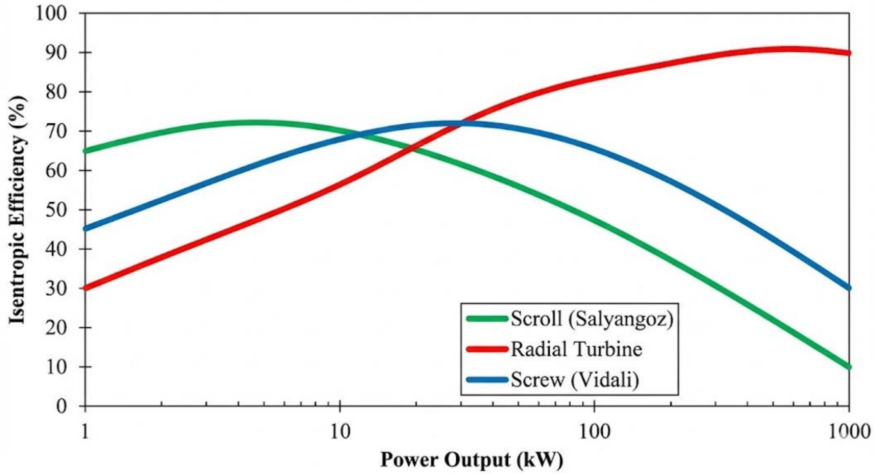

Figure 2. Variation of isentropic efficiency as a function of power output for various expander configurations, including scroll, radial turbine, and screw machines (Synthesized from comprehensive experimental and analytical studies documented in the literature).

4.2. Comparative Analysis of Performance Trends

As delineated in Figure 2, distinct performance characteristics are evident across the evaluated expander technologies. Within the low-power regime (below 10 kW), scroll expanders—represented by the green curve—demonstrate a relatively stable isentropic efficiency, thereby providing a clear thermodynamic advantage over radial turbines. However, as the power capacity increases, volumetric machines are subjected to heightened internal leakage and mechanical frictional losses, which result in a progressive attenuation of their isentropic efficiency.

In contrast, at power levels of 50 kW and above, radial turbines benefit from streamlined aerodynamic optimization and achieve isentropic efficiencies surpassing 80%, establishing them as the dominant technology in this range. The intersection point of the performance curves underscores the critical role of power scale as a decisive parameter in expander selection. The suitability of these technologies can be categorized into three distinct power ranges:

- Low Power (0.1 kW – 10 kW): In this range, scroll expanders are the preferred architectural choice. They are extensively utilized in waste heat recovery systems, such as heavy-duty vehicle exhausts and residential solar-thermal installations, owing to their high efficiency at low mass-flow rates and superior cost-effectiveness [21, 22].
- Medium Power (10 kW – 200 kW): Screw expanders are frequently implemented within this interval; however, they face direct competition from small-scale radial turbine designs. The selection between these two technologies typically depends on specific system requirements, such as the working fluid type and economic constraints.
- High Power (>200 kW): Radial and axial turbines represent the only feasible options for large-scale industrial waste heat recovery. These machines are essential for high-capacity sectors, including cement, iron, and steel production.

4.3. Isentropic Efficiency Comparison: Scroll vs. Turbine

A comprehensive summary of the fundamental comparative characteristics between radial turbines and scroll expanders, synthesized from existing literature and experimental data [23], is presented in Table 1.

Table 1. Comparative analysis of radial turbine and scroll expanders.

Comparison Criteria	Radial Turbine (Dynamic)	Scroll Expander (Volumetric)
Power Range	> 50 kW (typically tens of kW to MW scale)	1 - 10 kW
Isentropic Efficiency (η_{is})	High (80% - 90%)	Medium (60% - 75%)
Rotational Speed (RPM)	Very High (10,000 - 60,000)	Low (1,500 – 3,600)
Mechanical Complexity	High (Requires precise balance, gearbox)	Low (Simple bearing, direct coupling)
Liquid Tolerance	None (Risk of blade erosion)	Yes (Resistant to liquid slugs)
Cost	High (Custom production)	Low (Convertible from HVAC compressors)

4.4. Cost and Manufacturing Complexity Analysis

An analysis of Table 1 reveals that radial turbines demonstrate a distinct advantage in thermodynamic performance, as evidenced by their elevated isentropic efficiency (η_{is}). Nevertheless, this efficiency benefit is predominantly observed at the designated operating point. When there are fluctuations in the temperature or mass flow rate of the waste heat source—such as during stop-and-go driving in urban environments—the efficiency of the turbines experiences a significant decline due to heightened aerodynamic losses.

When we look at scroll expanders, they really stand out with their consistent efficiency. Typically, their isentropic efficiency hits its sweet spot at around 70%, but they shine even more when it comes to flexibility in off-design situations. Plus, if we take automotive air-conditioning compressors and flip them to work as expanders, we could see cost savings of about 50–70% for scroll systems compared to turbine-based options [9].

5. Conclusion

The sustained increase in global energy demand, together with the need to limit environmental impacts, underscores the necessity of utilizing waste heat sources more efficiently. The Organic Rankine Cycle (ORC) has consequently become the most widely implemented and technically mature solution for converting low-temperature waste heat into electrical power.

In ORC systems, the expander is pivotal in influencing overall efficiency, as it is responsible for converting thermal energy into mechanical shaft work. This research provides an extensive comparative analysis of the two primary types of expanders—dynamic (such as radial turbines) and volumetric (like scroll expanders)—with an emphasis on their thermodynamic efficiency, mechanical design limitations, and economic considerations. The conclusions are derived from a meticulous review of both experimental and theoretical studies documented in the literature.

Within ORC systems, the expander is the component that most significantly affects overall efficiency, given its role in transforming thermal energy into mechanical shaft work. Consequently, this study offers a thorough comparative evaluation of the two main classes of expanders—dynamic (radial turbine) and volumetric (scroll)—focusing on thermodynamic efficiency, mechanical design constraints, and techno-economic factors. The analysis is grounded in a systematic review of experimental and theoretical research available in the literature. Based on this, the following key conclusions regarding optimal expander selection are presented.:

1. Scale Effect: Power capacity plays a crucial role in selecting the appropriate expander. In industrial settings characterized by stable conditions and power requirements surpassing 50 kW, radial turbines emerge as the optimal option. These turbines frequently attain remarkable isentropic efficiencies—often exceeding 85%—due to their sophisticated aerodynamic design. Conversely, the geometric and aerodynamic losses associated with miniaturization hinder turbines from achieving satisfactory efficiency in smaller applications, especially those below 10 kW.

2. Operational Flexibility: For waste heat sources characterized by frequent variations in mass flow rate and temperature, such as heavy-duty vehicle exhaust systems, operational flexibility becomes more critical than peak efficiency. Turbines experience a pronounced decline in performance under off-design conditions as a result of increased aerodynamic losses, whereas volumetric scroll expanders exhibit a flatter efficiency characteristic and adapt more effectively to transient operating regimes.

3. Liquid Tolerance and Cost: One of the main differences lies in how well the expander can handle two-phase flow. In turbines, when liquid droplets hit the fast-moving blades, it can cause serious mechanical wear and tear. This means they have to operate with the working fluid only in a superheated vapor state. On the other hand, scroll expanders are naturally more forgiving when it comes to liquid slugs. This ability allows for the removal of the superheater from the ORC setup, which simplifies the system, cuts down on costs, and makes control easier..

4. General Assessment: While radial turbines exhibit the highest theoretical efficiency, this benefit is offset by significant mechanical intricacies, which include the necessity for precise dynamic balancing and expensive gearboxes due to their extremely high rotational speeds. Conversely, scroll expanders can be produced by modifying existing low-cost HVAC compressors and generally utilize simpler drive configurations that allow for direct coupling to the generator. These features make scroll expanders a more cost-effective and mechanically resilient option for small-scale applications.

5. Future Research Directions: Despite the considerable benefits that scroll expanders present for small-scale waste heat recovery applications, forthcoming research should focus on enhancing their lubrication systems and sealing technologies. Furthermore, experimental studies carried out under realistic transient operating conditions, such as typical driving cycles, are crucial for evaluating long-term durability and dynamic performance.

6. Environmental Implications: Picking the right expander technology is crucial not only for maximizing thermodynamic efficiency but also for cutting down the carbon footprint of industrial processes and transportation systems. The broader use of cost-effective scroll expanders in heavy-duty vehicles could significantly contribute to achieving global emission reduction targets.

Author contributions
Alperen Yazıcı: Conceptualization, Methodology, Data curation, Software, Writing-Reviewing and Editing.

Conflicts of interest
The author declares no conflicts of interest.

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