

Review

Application of the Multi-Vane Expanders in ORC Systems—A Review on the Experimental and Modeling Research Activities

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Abstract: This paper reviews the applications of the multi-vane expanders in ORC (organic Rankine cycle) systems. The operating principle and design of the ORC systems are addressed in the introduction. Then, there is a brief review of the expanders applied in small-power and micro-power ORCs, and a discussion of the multi-vane expander design and operating principle as an introduction to a comprehensive review on the applications of the multi-vane expanders in ORC systems. The different features of the multi-vane expanders—i.e., the design of the expander, its geometrical dimensions and operating conditions, durability, applied working fluid, obtained power output, and efficiency—are analyzed in this paper. This review clearly indicates that multi-vane expanders are a promising alternative to the different types of the expanders applied in ORC systems.

Keywords: ORC; multi-vane expander; CFD; working fluid; numerical analysis; experimental analysis

1. Introduction

Over the last decades, the demand for various forms of high-quality energy (i.e., electricity, heat, and cold) has increased significantly mainly due to the increase in the global population and live quality improvement. The energy is traditionally consumed for lighting, heating, and air conditioning. However, the increasing energy consumption that has been observed during the last few decades is caused mainly by the need to power the constantly growing number of home appliances, electrical cars, scooters, computers, mobile phones, etc. Thus, ways of covering this energy demands became one of the most important issues related to the contemporary power industry. Thus, many investments in the power sector that are focused on increasing the installed power, increasing the efficiency of existing power plants, and developing new energy technologies have been observed around the world. Presently, the coverage of energy demands is still largely satisfied by coal or nuclear power plants [1]. In order to limit coal usage, for many years, efforts have been made to increase the usage of alternative energy sources for energy generation including solar energy [2], geothermal energy [3], wind energy [4], hydropower [5], and others (such as e.g., waste energy) [6]. Various energy technologies (such as e.g., photovoltaic panels, solar collectors, heat pumps, wind farms, and others) were developed to enable the efficient harvesting of energy from these sources. These technologies use different physical phenomena to convert the energy from alternative sources into high-quality energy products (i.e., electricity, cold, heat, etc.). The ORC (organic Rankine cycle) system is one of these technologies.

The ORC system operates according to the modified thermodynamic cycle of a classical steam power plant (Clausius–Rankine cycle). The main modification in the cycle is the change of the applied working fluid [7]. Instead of water, a low-boiling working fluid is applied. The methylosiloxanes (e.g., MM, MDM, MD2M), refrigerants (e.g., R123, R134a, R1234yf, R365mfc, and others), mixtures of



refrigerants (e.g., R410A) and other specially designed working fluids (e.g., SES36) can be applied in ORCs [8,9]. Thanks to the application of the low-boiling working fluid, it is possible to harvest the heat from sources featuring significantly lower thermal properties than those of classical steam power plants (such as e.g., solar heat, geothermal heat, or waste heat, which is carried by flue gases or cooling agents in the industry) [10]. The temperature of these sources usually ranges between 150–450 °C [11]. Moreover, the ORC systems differ from classical steam power plants in terms of the system design. The most important differences are: replacement of the steam boiler with a heat exchanger (recuperator or a recovery boiler), replacement of a steam turbine with a Freon turbine (or volumetric expander), and replacement of the condenser with a heat exchanger [12]. However, the operating principle of the ORC system consists of four main components: the evaporator, the expander, the condenser, and the working fluid pump. The basic configuration of the ORC system is presented in Figure 1a, while Figure 1b visualizes the thermodynamic processes of the organic Rankine cycle in a *T-s* diagram.



Figure 1. A scheme and thermodynamic cycle of the simple organic Rankine cycle (ORC) system. (a) Scheme of the ORC system; (b) Organic Rankine cycle visualized in *T-s* diagram.

The cycle begins when the pump pushes high-pressure working fluid into the evaporator (see, process 3–4 in Figure 1b). In the evaporator, the low-boiling working fluid evaporates thanks to the heat supplied from the heat carrier e.g., flue gas or geothermal brine (see process 4–1 in Figure 1b). Then, the vapor flows through pipelines to the inlet of the expander in which, by the expansion, the thermal energy of the vapor is converted into mechanical power (see process 1–2 in Figure 1b). The shaft of the expander can be coupled through a clutch with different machines (e.g., compressors, pumps, and generators). If the shaft of the expender is coupled with the shaft of the generator, the mechanical energy is converted into electricity. After the expansion in the expander, the vapor reduces its thermal properties (i.e., pressure and temperature) and flows through the pipeline to the condenser, in which it liquefies due to the heat rejection to the cooling agent (see, process 2–3 in Figure 1b). Then, the condensate is pumped again by the pump to the evaporator. At this point, the cycle closes.

ORC systems can be applied in various technical configurations including power plants, combined heat and power plants (CHPs), and multigeneration systems (providing the simultaneous generation of electricity, heat, and cold). The ORC system power can be different and usually ranges from a few kW (domestic ORCs) up to few MW in the case of large industrial systems [13].

In the following part of the article, the author focuses the attention on the expanders that can be applied in ORC systems, with special attention paid to ORCs with integrated multi-vane expanders.

2. Expanders Applied in ORC Systems

ORC systems can be classified using different criteria, such as e.g., system power, the type of the applied expander, or the type of the applied working fluid. By the type of the applied expander, ORCs can be classified into two categories: systems adopting turbines and systems adopting volumetric expanders. Turbines are mainly applied in high-power ORC systems that utilize the heat sources of high thermal power, which feature a high-temperature heat carrier (i.e., industrial waste heat, heat obtained from biomass combustion, or geothermal heat) [14]. Medium-power ORCs utilize the heat sources of medium thermal power, which feature a medium-temperature heat carrier. In these systems, both turbines and volumetric expanders (mainly screw expanders) are applied. Small-power and micro-power ORC systems are designed mainly for domestic agricultural or automotive usage, and are driven by the heat sources of low thermal power, which feature the low temperature of the heat carrier. The temperature and output characteristics of these heat sources are often floating, which directly translates into the floating conditions of the heat supply and thus the floating operating conditions of the ORC system. Domestic ORC systems should be simple, cheap, safe to operate, and easy to use. Small-power and micro-power ORCs should feature a low flow rate of the working fluid and low operating pressure. The above-mentioned properties of the heat source result in difficulties related to the design and manufacture of domestic ORCs and system regulation. Therefore, many of the small-power and micro-power ORC systems are currently at the level of experimentally tested prototypes. The applicability of turbines in these systems is very limited due to the limitations of the required operating conditions of the turbine. In order to provide the optimal operating conditions and high efficiency of the turbine, the working fluid flow rate through the machine should be kept at a high and fixed level. To provide such conditions of the working fluid flow rate, the high-output and

high power consuming pumps should be applied, which is not possible in the case of small-power or micro-power ORCs. Moreover, in order to minimize the dimensions of the system, the external dimensions of the turbine that were designed for application in small-power and micro-power ORCs should not be large. Small turbines feature very high rotational speeds (several hundred thousand revolutions per minute); in turn this leads to difficulties in balancing the rotor and a complicated bearings and clutch design, which connects the turbine shaft with the generator. What is more, the turbine efficiency decreases with decreasing power. In the case of the small turbines, a very precise workmanship is necessary, which translates into very large production costs. In spite of these difficulties, few attempts have been made to adopt micro-turbines to small-power ORC systems [15].

Compared to turbines, volumetric expanders feature lower range of operating pressure and lower working fluid flows. Thus, a volumetric expander seems to be a good alternative to the turbine in the case of small-power and micro-power ORCs.

Further advantages of volumetric machines resulting from their comparison to turbines are [16]:

- Lower cycle frequency,
- Lower rotational speed,
- The possibility of obtaining larger expansion ratios in one stage, and
- Ease of hermetic sealing.

The following main disadvantages of the volumetric machines can be mentioned:

- Internal friction, which reduces the efficiency of machine operation and its reliability,
- Need for lubrication (in majority of the designs),
- Large weight in relation to the power,
- Internal and external leakages reducing the efficiency of the machine.

Piston, screw, scroll, multi-vane, and rolling piston expanders can potentially be applied in ORCs. In most of the cases, these expanders are at the level of lab prototypes, or are under research. There are no commercial solutions currently available. Scroll and screw expanders are mainly applied in micro-power and small-power ORC systems. A number of papers report the modeling and experimental results related to these expanders see, e.g., [17–23]. Some screw and scroll expanders are made in oil-free versions, and screw expanders can operate in moist gas conditions. Despite the mentioned advantages, the design of the screw and scroll expanders is complicated; the manufacturing process is difficult, and requires the application of advanced machine facilities in order to maintain a high quality of screw rotors and scrolls. Thus, their price is high compared to the other types of volumetric expanders. Compared to scroll expanders, piston expanders have a simpler design, but they require lubrication, valve timing, and vibrations are generated during their operation. Multi-vane expanders, in turn, have a very simple design, which directly translates into low production costs and a promising ratio of machine power to external dimensions. Multi-vane machines are applied in many industrial applications (e.g., food processing, chemical plants, mining, refrigerating systems, pneumatic systems, air conditioners, etc.) as pumps (for water, fuels, and other fluids pumping), compressors, expanders (e.g., for pneumatic tools driving) and vacuum pumps; thus, their design principles are well known [24,25]. If special construction materials are applied, it is possible to eliminate the need for lubrication. The multi-vane expander features lower vapor consumption and a smaller range of operating pressures compared to the other types of volumetric machines and turbines. At the same time, multi-vane expanders can be easily hermetically sealed, which is one of the key design issues in ORC systems. The multi-vane expander can operate in moist gas conditions, which (in the case of powering the ORC system by a heat source with variable thermal characteristics) is its big advantage. However, the positive slope of the saturation curve decreases the moisture problems (if a dry working fluid is applied). Multi-vane expanders feature power ranging from a few hundred W up to 10 kW and shaft rotational speeds of 1000–4000 rpm, while the maximum value of the pressure at the inlet to the multi-vane expander is about 10 bar [26].

3. Multi-Vane Expander Features and Operating Principle

The multi-vane machine (compressor) was invented and patented in 1908 by Karl Wittig [27]. Figure 2 shows a simplified scheme of the multi-vane expander. Assembly of the expander can be described on the basis of this figure.



Figure 2. A simplified scheme of the multi-vane expander. 1—cylinder, 2—rotor, 3—vane, 4—vane slot.

The main machine elements are the cylinder (1) and the rotor (2). The diameters of the rotors and cylinders may vary, depending mostly on the machine power. The rotor is mounted eccentrically in the cylinder on bearings (rolling or slide). Eccentricity can also vary, depending on the machine design. Vanes (3) are placed in perpendicular or inclined slots (4) milled in the rotor. The vanes remain in close contact with the cylinder as a result of centrifugal force, or are pressed to the cylinder surface with the help of other elements e.g., springs or rings. The number of vanes may vary, depending on the machine design and power. The inlet and outlet port edges (A, B, C, and D in Figure 2) are referred to as the machine "steering edges". The proper arrangement of these edges has a significant influence on the expander operation. This issue is comprehensively described in [16]. The ideal vane expander working cycle is formed by four ideal thermodynamic processes [16]: isobaric filling, polytropic expansion, isobaric evacuation, and polytropic compression. The real working cycle is influenced by the following energy dissipation phenomena: underexpansion and overexpansion, pressure losses during filling and evacuation, friction, internal leakages, and heat transfer from the machine surface to the surroundings. The internal leakages proceed between the adjacent working chambers (through the gap between the tip of the vane and the cylinder) and between the rotor and side covers. The external leakages proceed through bearings and seals. A more detailed description of the working principle of a multi-vane expander is presented in [16,26].

Research on the use of multi-vane expanders in ORC systems originated in multi-vane compressors. Intensive research on the use of multi-vane compressors in pneumatic, refrigeration, and air-conditioning systems was conducted in many research centers in the 1970s and 1980s. During this period, the mathematical models of these machines were developed, and many experiments were carried out. Some of the results were published in [28–32]. The influence of different design parameters such as eccentricity (e), diameter of the rotor (d), diameter of the cylinder (D), length of the cylinder (L), thickness of the vane (g), height of the vane (h), and number of vanes (z) on the machine efficiency and internal friction was also investigated. Many new designs were also invented [33–37]. Analytical modeling also proceeded on the optimum compression and expansion ratios and its influence on the machine efficiency and power. The results were presented in many works [38–42]. The modeling and experimental results gave a number of construction guidelines for selecting the optimal dimensions of the machine. These guidelines are presented in [24,25]. Research on multi-vane expanders application in ORC systems began in the 1970s. The design problems related to the multi-vane expanders applied in ORC systems are more complex than those in the case of the multi-vane refrigeration compressors or pneumatic expanders. Regarding the latter, the larger thermal load on the expander caused the design problems, which results from the high thermal parameters of the working fluid at the inlet to the expander. Large thermal load influences the choice of the lubricant and lubrication method and the design of the hermetic gas-tight sealing.

4. Review of the Experimental and Modeling Works and the Applications of Multi-Vane Expanders in ORC Systems

In the following part of the paper, a review on the research activities related to the application of multi-vane expanders in ORCs is presented. The review indicates that the research on this topic has been conducted at the following industrial and scientific centers:

- 1. General Electric Company (USA),
- 2. Cranfield Institute of Technology (England),
- 3. Wrocław University of Science and Technology (Poland),
- 4. Czech Technical University in Prague (Czech Republic),
- 5. University of L'Aquila (Italy),
- 6. Brunel University London (England),
- 7. City University London (England),
- 8. Politecnico di Milano (Italy),

- 9. Enea Mattei Spa (Italy),
- 10. University of Rome "Sapienza" (Italy),
- 11. Thammasat University (Thailand),
- 12. Phranakhon Rajabhat University (Thailand),
- 13. Bournemouth University (England),
- 14. Ferdowsi University of Mashhad (Iran),
- 15. RMIT University (Australia),
- 16. Magna Powertain (Austria),
- 17. University of Nottingham (England),
- 18. Jilin University (China),
- 19. Normandie University in Saint-Lô (France).

4.1. Early Works (1977–1994)

In 1981, Curran [43] reviewed 2150 ORCs implemented by 20 manufacturers that adopted 16 different working fluids. This article provides the technical data of three ORC systems with integrated multi-vane expanders, which were tested by the General Electric Company (USA) within the NASA research program titled "Prototpe solar heating and combined heating and cooling systems" between 1977–1979 [44]. The technical data of these expanders are summarized in Table 1. One of the tested expanders was the two-stage multi-vane expander; a general view is presented in Figure 3 (adapted from [44]). The power output of the tested expanders ranged from 2.3 to 7.9 kW. The expanders were used to drive the generator, dynamometer, and compressor [43,44]. These research studies were also described by Badr et al. [45] in 1984. The following advantages resulting from the application of multi-vane expanders in ORC systems were listed in [45]: simple construction, low level of noise and vibration, high brake efficiency, high torque at low or zero speeds, high volumetric expansion ratios, high tolerance for floating operating conditions, and the quality of the expanded gas. The following challenges and research problems concerned with multi-vane expanders were indicated [45]: the selection of the optimal working fluid, the reduction of breathing losses and the proper arrangement of the steering edges, reduction of the high internal leakages and friction, and the reduction of heat transfer losses related to oil injection.

Working Fluid	Engine	Expander		Driven	No. of	Total	tuun
	Energy Source	Power kW	Speed rpm	Equipment	Operating Engines	Operating Time	°C
R11	Electric (b)	2.3	1200-1800	Vapor compressor, dynamometer (b)	-	1200 h (b)	105
FC88	Solar, Electric (b)	2.3 7.9	1625 1625	Vapor compressor, dynamometer (b)	1 2	1000 h (b)	175 175
Alcohol/water	Gasoline	7.5	1800	Generator, dynamometer	-	16,000 h	340

Table 1. Technical data of the multi-vane expanders tested by General Electric in 1977–1979 [43].

Curran [43] reported that during the experiments with R11, a rapid decomposition of the working fluid above 105 °C was observed in the presence of oil (lubricant). Similarly, the decomposition was observed in the case of using of alcohol and water during the experiment. In addition to the decomposition, corrosion was also observed in this case.



Figure 3. A general view of the two-stage multi-vane expander, which was tested by the General Electric Company in the late 1970s [44]. This figure is taken from Prototype Solar Heating and Combined Heating and Cooling Systems; DOE/NASA Contractor Report No. DOE/NASA CR-161340 and used with permission of NASA.

The above-described advantages of the multi-vane expanders pushed the authors of [45] to conduct the research project known as the "King Tut Project", which was conducted by a consortium of the Cranfield Institute of Technology (England), the Egyptian government, and two English companies: Denco Air Ltd. And GEC. The aim of the research was to develop an ORC system utilizing solar heat and adopting a multi-vane reversed compressor featuring a power output of 5 kW and driving irrigation pumps in Egypt. As a part of the project, the prototype test stand was implemented, and a large number of experiments were carried out using the test stand. Detailed information about these experiments and the test stand are presented in [46]. The applied expander was an oil-lubricated eight-vane machine, and the working fluid was R113 [46]. The tests were carried out for various temperatures and pressures of the working medium at the inlet to the expander, and various rotational speeds of the expander shaft. The pressure of the working fluid at the inlet to the expander was varied in the range from 4.45 to 6.39 bar, and the temperature was in the range of 110 to 120 °C. The rotational speed of the expanders' shaft was in the range from 1750 to 3750 rpm. For such values of experimental conditions, an expander power from 1.0–2.0 kW and isentropic efficiency of 35–55% were achieved. As a part of the conducted research, the issues related to the working fluid selection to ORC systems and their thermodynamic properties were also analyzed. The results of these works were reported in [47,48]. The thermal stability of the working fluids in the presence of lubricants was studied in [49]. The influence of the expanders' efficiency on the efficiency of the ORC system was reported in [50]. The dynamics of the vane and friction losses were modeled in [51], while internal leakage losses were analyzed in [52]. The hydraulic losses on the inlet of the multi-vane expanders were comprehensively studied in [53]. The geometry and kinematics of vanes were presented in [54]. In [55], the results of a comparative analysis of the performance of ORC systems adopting R11, R113, and R114 as working fluids were presented.

In the mid-1990s, the research project on the applicability of the low-grade waste heat for powering the micro-power ORC systems was conducted at the Department of Thermodynamics of the Institute of Heat Engineering and Fluid Mechanics at the Wrocław University of Technology (Poland). This project implemented a prototype micro-power ORC test stand in the laboratory and adopted the multi-vane air motor as the expander in this setup. A general view of this test stand is presented in Figure 4a (adapted from [56]).

The test stand consisted of the following main components: a vapor generator (designed as a tank with an internal coil made of copper, see Figure 4b adapted from [56]), a multi-vane pump driven by an electric motor (see Figure 4c adapted from [56]), a multi-vane expander coupled with a generator (car alternator) (see Figure 4d adapted from [56]), a shell-and-tube condenser (grey element visible in Figures 4a and 5 adapted from [56]), a reservoir of the liquid working fluid (blue element visible in Figures 4a and 5 adapted from [56]), and a control and measurement system (components visible on Figure 4a adapted from [56]). R11 was used as the working fluid in this test stand. The liquid working fluid was flowing from the reservoir through the multi-vane pump, and then was directed to the coil of the vapor generator. Water was initially used as a heating medium in the vapor generator (in a further experimental series, water was replaced with thermal oil in order to increase the heat source temperature). The heat was supplied to the heating medium using a set of electric heaters. The obtained vapor was flowing through the pipelines to the inlet of the multi-vane expander coupled with the DC alternator. After expansion in the expander, the working fluid was flowing to a shell-and-tube condenser cooled by cold water. Obtained condensate was flowing to the liquid reservoir. Generated electricity was used for supplying electric receivers connected with a set of measuring devices. A specially adapted multi-vane pneumatic motor featuring a maximum power of about 600 W was used as an expander device. The geometrical properties of the applied expander were as follows: cylinder radius R = 22.5 mm, rotor radius r = 19 mm, cylinder length L = 60 mm, eccentricity e = 3.5 mm, vane thickness g = 3.0 mm, vane height h = 13 mm, number of vanes z = 4(vanes were inclined to the rotor radius), and number of revolutions under load n = 3000 rpm [56]. The vapor consumption of the expander was equal to 127 kg/h. Many sets of the experimental data were obtained using the test stand. The research results were presented in reports [56], a PhD thesis [57], and publications [58].



Figure 4. A view of a micro-power ORC test stand implemented in the mid-1990s at the Wrocław University of Technology. (a) A general view of the test stand; (b) A detailed view of the vapor generator; (c) A detailed view of the multi-vane pump with an electric motor; and (d) A detailed view of the multi-vane expander and generator.



Figure 5. A detailed view of a micro-power ORC test stand implemented in the mid-1990s at the Wrocław University of Technology.

Experiments on the efficiency of the ORC system and the efficiency of the multi-vane expander were carried out for varied temperatures of the heat source (i.e., 160 °C, 190 °C, and 220 °C) [57]. In these experimental conditions, the determined internal efficiency of the expander was 0.31, 0.3, and 0.28, respectively. It was observed that the efficiency decreases with the increasing temperature of oil contained in the vapor generator and increasing temperature of the working fluid. In [57], the reason for such a low expander efficiency was reported: the wrong selection of construction materials (seals) for the operating conditions of the expander and the applied working fluid increased the internal leakages in the expander due to the high temperature of the working fluid. The internal efficiency of the expander was comparable to the efficiency of cryogenic expanders. The analysis of the expanders' design with the application of the method introduced in [41] showed that the internal expansion ratio for the analyzed expander was close to 1.3, which was smaller than the external expansion ratio. Thus, expansion proceeded partially outside the working chamber, which is disadvantageous from the machine performance point of view. Based on the experimental results, the following guidelines for optimizing the expander design and thus improving its efficiency were stated: necessity of application of rotor and blade seals in order to minimize the internal leakage of the working fluid, necessity of the reduction of friction forces by the selection of different materials for vanes, cylinders, and rotors, as well as the necessity of the appropriate selection of steering edges in order to improve the level of the internal expansion ratio. Despite the low efficiency achieved, the experimental research results confirmed the conclusions presented in [45–55] i.e., the multi-vane expanders can be successfully applied in ORC systems. Gnutek used the results of this experimental research in his further analyses regarding the optimization of the design of multi-vane compressors, expanders, and vacuum pumps. The most important results of his works were presented in [39]. In this book, it was analytically proven that the optimal expansion ratio of the multi-vane expanders ranges between 2.8–3.2.

4.2. Present Research (Since 2000)

4.2.1. Wrocław University of Technology (Poland)

Since 2006, the research on ORC systems using multi-vane expanders has been continued at the Department of Thermodynamics of the Institute of Heat Engineering and Fluid Mechanics at the Wrocław University of Technology (Poland). Between 2009–2016 two more test stands were implemented in the laboratory. These test stands were applied for experimentally analyzing the different problems related to the ORC systems i.e., investigating the influence of a variable amount of working fluid on the system operating conditions, testing the different multi-vane expanders and other system components, and studying the applicability of heat storage devices for ORC system powering. The first of the above-mentioned test stands was finished in 2009. A general view of this system is presented in Figure 6. The basic elements of the system are a shell-and-tube evaporator, two multi-vane expanders, a plate condenser, a multi-vane pump coupled with an electric motor, and a measuring and control system. The applied working fluid is R123. The heat source for the system is hot water, which is heated by a gas-fired central heating boiler. The application of this heat source gave the opportunity to control the water temperature in the range of 45 to 90 °C, thus easily simulating various alternative heat sources. The condenser of the system is cooled by cold water. Two types of multi-vane expanders were applied in the system.



Figure 6. A general view of a micro-power ORC test stand implemented in 2009 at the Wrocław University of Technology.

Initially, two five-vane pneumatic motors (each featuring a power of about 1.5 kW) were applied. In these expanders, vanes were pressed to the cylinder surface as a result of the centrifugal force resulting from the rotor rotation. A view of these expanders is presented in Figure 7a. These expanders were especially adapted for the low-boiling working fluid conditions. Special bearings were applied instead of the standard ball bearings, standard vanes were replaced with vanes made of cured silicone (in order to reduce the internal friction), and standard rubber seals were replaced with seals made of cured silicone. Finally, magnetic clutches made in-house were applied on the shafts of the expanders. Experiments were performed under varied heat supply conditions (i.e., varied heat source temperatures) and different system configurations (one or two expanders in operation). The results of the research confirmed that after a proper modification of the design, standard multi-vane pneumatic motors can be applied as expanders in ORC systems.



Figure 7. A view of the expanders applied in the test stand implemented in 2009 at the Wrocław University of Technology. (**a**) A view of the expanders, featuring 1.5 kW of power each; (**b**) A view of the expanders, featuring 300 W of power each.

Then, in order to determine the opportunity of the test stand miniaturization, the expanders were replaced with machines featuring lower power output and smaller dimensions. Multi-vane expanders featuring a maximum power of 300 W and the following geometrical parameters were applied: D = 37.5 mm, d = 34 mm, e = 1.75 mm, z = 4. In these expanders, vanes are pressed to the cylinder surface with the help of the rings. Similarly to previous research, experiments were performed under varied heat supply conditions (i.e., varied heat source temperatures) and different system configurations (one or two expanders in operation). During the experiments, the pressure of the working fluid at the inlet to the expander ranged between 1.5–3.5 bar. Comparative analysis of the experimentally obtained results indicated that compared to larger expanders, smaller expanders are characterized by smaller gas consumption, and the application of vane-guiding rings provides an easier start-up of the expander and greater reliability of its movement by eliminating the risk of jamming the vanes in the slots. The obtained research results proved again the suitability of the multi-vane expanders for application in ORC systems, and what is more, that it is possible to miniaturize their external dimensions and thus the dimension of the ORC systems. The results of these experiments were presented in different publications, see, e.g., [59–62]. Moreover, using the above-described test stand, the applicability of the heat storage devices for ORC system powering was experimentally analyzed [63]. The results of these experiments were presented in [64]. These experiments proved that the characteristic features of the multi-vane expanders (such as low vapor consumption and low pressure at the inlet to the expander) make these machines very promising for application in small ORC systems driven by heat storage devices [64].

The good operation of the applied small expanders in low-boiling working fluid conditions led to choice of the set of the design guidelines for the next stage of research. The aim of this experimental campaign was the implementation of the prototype micro-power ORC system, which was dedicated for domestic usage. This system was implemented in 2016, and its general view is presented in Figure 8a. The system was comprehensively described in [65]. The multi-vane expanders tested in the above-described experiments were used in this test stand. Their low vapor consumption made it possible to apply heat exchangers with a much smaller volume than those in the previous test stand. Thus, it was possible to adopt plate heat exchangers in the test stand. The main subassemblies of the system are: a plate evaporator, a multi-vane pump, a working fluid reservoir, and a multi-vane expander. R123 was used as the working fluid. A number of experimental studies were carried out using this test stand. The main aim of these experiments was the investigation of the influence of the heat source and heat sink thermal parameters on the multi-vane expander operation. The experiments were carried out for varied temperatures of the heat source (ranging from 45 °C to 85 °C).



Figure 8. A general view of a micro-power ORC test stand implemented in 2009 at the Wrocław University of Technology. (**a**) A view of the gas boiler (1) and the test stand (2); (**b**) A view of the test stand and components: evaporator (1), condenser (2), multi-vane pump (3), working fluid reservoir (4), and multi-vane expander (5).

The results showed that the internal efficiency of the tested expander ranged from 17.2% to 43.1%, and was dependent on the temperature of the heat source and the expansion ratio, which was kept in the range of 1.54 to 4.33. It was also determined that for the tested expander, the optimal expansion ratio is ca. 2.0 [65]. Then, the experimentally obtained data sets were applied as the input data to the comprehensive numerical analyses on the thermodynamic and flow processes inside the working chambers of the multi-vane expanders. The simulation results were presented in [66–68]. The modeling results showed that in the case of the tested expander, the steering angles were wrongly selected, which results in the recompression of the working fluid in the final stage of the rotor revolution just before the evacuation of the gas from the working chamber to the outlet port. The numerical results showed the character of the gas flow inside the expanders' working chambers, which allowed visualizing the vortices inside the working chambers and near the vane. The numerical results also showed the leakages of the working fluid between the working chambers. What is more, the modeling results identified a leakage between the inlet and the outlet ports, which significantly limited the efficiency of the expander. Then, the authors applied the numerical model developed in [66,67] for an optimization analysis of the expander; the results were presented in [68]. The main aim of these analyses was finding the optimal angle of the expanders' outlet port in order to minimize or eliminate the effect of the recompression of the working fluid and thus increase the expanders' efficiency. The influence of the type of working fluid on the performance of the expander and the optimal expansion ratio was also determined numerically. The analyses were performed for the following working fluids: R1234yf, R1234ze, R134a, R245fa R236fa, R365mfc, acetone, and propane. The results of the simulation showed that the optimal expansion ratio for the expander analyzed varied in the range of 3 to 4 for these working fluids, and the internal efficiency of the expander varied in the range of 12% to 35%. The highest internal efficiency was obtained for R245fa and R365mfc. Then, in order to optimize the expander design, the influence of the position of the machines' outlet port was numerically analyzed. The results proved that the position of the steering edges has a significant impact on the working conditions and the efficiency of the multi-vane machines, and for the expander analyzed, the optimal angle of the outlet port position is about 46°. Currently, two more prototypes of the multi-vane expanders are being prepared for experimental analysis [68].

4.2.2. Czech Technical University in Prague (Czech Republic)

Experimental and modeling studies on the application of the multi-vane expanders in ORC systems took place at the Czech Technical University in Prague (Czech Republic). These research studies were summarized in [69]. Four in-house made laboratory test stands are described in this paper. These test stands utilize different working fluids, such as e.g., hexamethyldisiloxane (MM). The general views of these test stands are presented in Figure 9 (adapted from [69]). Two types of in-house designed and built multi-vane expanders featuring different geometrical dimensions were experimentally investigated. The experimentally determined internal efficiency of these expanders varied in the range of 40% to 50%, while obtained the power output varied in the range of 1 to 8 kW, depending on the applied working fluid and experimental conditions. The issue of the impact of the leakages on the performance characteristics of these multi-vane expanders was treated in [70].



Figure 9. The general views of the ORC test stands implemented at the Czech Technical University in Prague [69]. (a) First experimental ORC unit; (b) Second experimental ORC unit; (c) WHR (Waste Heat Recovery) demonstration unit; (d) combined heat and power (CHP) biomass-fired 3.5-kW ORC unit. Reproduced with permission from Vaclav Novotny, Energy Procedia; published by Elsevier, 2017.

4.2.3. University of L'Aquila (Italy), Brunel University London (England) and City University London (England)

The application of multi-vane expanders in ORCs was also investigated at the University of L'Aquila (Italy) in cooperation with Brunel University London (England) and City University London (England). In [71] the authors presented the results of the experimental analyses regarding the application of a multi-vane expander in an experimental ORC plant. A general view of this test system is presented in Figure 10a (adapted from [71]). The applied multi-vane expander featured the following geometrical dimensions: the diameter of the cylinder D = 76 mm, the length of the cylinder L = 60 mm, the diameter of the rotor d = 65 mm, the eccentricity e = 5.5 mm, a 4.4° angle of the opening edge of the inlet window, a 49.4°, angle of the closing edge of the inlet window, a 200.1° angle of the opening edge

of outlet window, a 317.4° angle of the closing edge of the outlet window, and the number of vanes z = 7. The main aim of the experiment was to determine the expander efficiency, change of the gas pressure in the working chambers in order to assess the expanders' indicated work, and the efficiency of the ORC system. The R236fa was applied as the working fluid. The hot oil from the lubrication system of the industrial compressor was adopted as the heat source for the ORC system. Results of the long-term experiments confirmed the durability of the expander. For a heat source temperature of 110 °C and a heat source power of 19 kW, the mechanical power of the expander was equal to 1.7 kW, and an ORC system efficiency of 7.65% was obtained. The opportunities for the optimization of the design of the applied expander in order to increase its efficiency and reduce the internal leakages were pointed out in [72]. In [73] the authors presented an analysis of the possibility of applying the ORC system for recovering the waste heat from internal combustion engines. An experimental test stand consisting of the ORC system integrated with the IVECO (Industrial Vehicles Corporation) automotive engine that adopted a mixture of R236fa and 5% of POE (Polyolester) oil as a working fluid was designed and implemented. The multi-vane machine was applied as the expander, and was coupled with a generator. A general view on this test system is presented in Figure 10b (adapted from [73]). The experiments proceeded under varied conditions of the heat supply (i.e., at variable engine speeds). The results showed that at an engine speed of 3225 rpm and torque of 182 Nm, a multi-vane expander mechanical power output of 1.9 kW (3% of engine power), ORC efficiency ranging from 3.8% to 4.8%, and expander efficiency ranging from 47.5 to 53.3% could be obtained. Possible ways of optimizing the processes of filling and evacuating the working fluid from the multi-vane expander in order to increase its isentropic and volumetric efficiencies were pointed out in [73].



Figure 10. The general views of the ORC test stands implemented at the University of L'Aquila. (a) A view of the test stand introduced in [71]—Reproduced with permission from Giuseppe Bianchi, Proceedings of the 8th International Conference on Compressors and Their Systems; published by Woodhead Publishing, 2013; (b) A view of the test stand introduced in [73]—Reproduced with permission from Giuseppe Bianchi, Proceedings of the 33rd UIT (Italian Union of Thermo-Fluid Dynamics) Heat Transfer Conference; published by IOP Publishing Ltd, 2015.

As a side note, it is worth mentioning that the issues related to the application of the different type of multi-vane machines, i.e., the multi-vane pump of an ORC system, were studied in [74]. The authors tested a prototype of the multi-vane pump in an ORC test stand adopting R236fa as a working fluid. The experimental results showed promising values regarding the pumps' volumetric efficiency. Multi-vane pumps were also applied in other ORC systems see, e.g., [56,59,62,64,66–68]. Ref [75] presented the results of numerical modeling a multi-vane expander applied in the ORC system. A multi-vane expander featuring a cylinder diameter of D = 76 mm, cylinder length of L = 60 mm,

and a rotor diameter of 65 mm was modeled in 3D. Modeling was proceeded for the different gap sizes between the vane tip and the cylinder, i.e., 10, 20, and 50 micrometers. The results obtained by numerical modeling were compared with the experimentally obtained data, and a good agreement between these two data sets was found. It was pointed out that further analyses (for variable heights of the gap between the tip of the vane and the cylinder) should proceed. Numerical results related to this expander are also presented in [76,77].

In [78], the idea and numerical modeling results related to the possibility of supercharging the volumetric expanders are presented. The supercharging is based on the injection of the liquid working fluid (with the same thermal parameters as at the inlet to the expander) during expansion into the gas that is contained in the expanders' working chamber. The authors stated that thanks to this solution, the pressure drop in the working chamber due to the expansion is compensated by an additional mass of high-enthalpy working medium [78]. Simulations were carried out using the model of a multi-vane expander featuring the same geometrical dimensions as the expander presented in [71–75]. Vanes featuring a width of 3.96 mm and a length of 17 mm were incorporated into this model. Based on the obtained results, it was concluded that for the given suction conditions and machine rotational speed, the increase of the expanders' mechanical power as a result of supercharging depends mainly on the steering angle at which the suction starts and on the diameter of the inlet pipeline through which the liquid working fluid is injected. It was proved that for optimized injection parameters, the increase of the expander power due to supercharging ranges from 43.0% to 69.8% (with an average value of 50.6%).

In [79], an interesting design of a multi-vane expander with a double inlet was presented. Experimental research on this expander was carried out using the modified test stand, which was introduced in [73]. A comparison of the experimental and modeling results showed the advantages resulting from the use of a double inlet in a multi-vane machine. This solution is especially interesting in case of the multi-vane expanders featuring low volumetric efficiency, in which the application of a dual inlet may increase the machine efficiency to 30% and increase the machine power output to 140% (compared to the expander with a single inlet port). For other multi-vane machines, the application of a dual inlet may result in an efficiency increase of 27–28% with a nearly 100% increase of the mechanical power. The obtained results also proved that the application of the additional inlet does not significantly change the expanders' internal friction.

4.2.4. Politecnico di Milano (Italy) and Enea Mattei Spa Company

A different research project on the application of the multi-vane expanders in ORCs recovering the waste heat from hot oil was conducted at Politecnico di Milano (Italy) in cooperation with the Enea Mattei Spa company [80]. The experiments were carried out using the ORC test stands adopting R236fa as a working fluid and operating in two configurations: with recuperation and without recuperation. A general view of this test stand is presented in Figure 11 (adapted from [80]). Expanders featuring different geometrical parameters were used in both of the test-stand configurations.

An expander featuring a rotor diameter of d = 80 mm, a rotor length of L = 160 mm, a built-in volume ratio of 3.34, and a displacement of 26.5 cm³ was used in a system without recuperation. In a system with recuperation, the expander featuring a rotor diameter of d = 100 mm, a rotor length of L = 90 mm, a built-in volume ratio of 2.76, and a displacement of 19.95 cm³ was used. The obtained experimental results showed that the system with the recuperation achieves bigger power (3.01 kW) and efficiency (4.96%) than the system without recuperation (2.13 kW and 3.72%, respectively). The obtained mechanical efficiency of the expander was 71.8% (system without recuperation) and 81.5% (system with recuperation). From the results of the exergy analysis, it was found that the expander has a 28.9% effect on the system efficiency. It was also found that the system with regeneration features larger efficiency values than the system without regeneration.



Figure 11. A general view of the ORC test stand implemented at Politecnico di Milano [80]. Reproduced with permission from Stefano Murgia and Gianluca Valenti, Energy Procedia; published by Elsevier, 2017.

4.2.5. University of Rome "Sapienza" (Italy)

The issues related to the selection of the expander to the ORC system used for waste heat recovery from an 8-L bus engine were analyzed at the University of Rome "Sapienza" [81]. By means of modeling, the authors compared the inward-flow radial turbine, screw, scroll, and multi-vane expander. A multi-vane expander featuring a rotor diameter of d = 100 mm, eccentricity of e = 30 mm, cylinder length of L = 260 mm, number of vanes z = 8, and rotational speed of n = 4000 rpm was modeled by the authors. By comparing the obtained modeling results, the authors suggested the choice of screw expanders to the analyzed ORC system. However, they pointed out the positive features of multi-vane expanders, i.e., their low cost, simple design, and easy manufacturing.

4.2.6. Thammasat University (Thailand) and Phranakhon Rajabhat University (Thailand)

Research on the application of the multi-vane expanders in ORC systems harvesting the waste heat proceeded at Thammasat University (Thailand) in cooperation with Phranakhon Rajabhat University (Thailand). In [82], the results of the experimental research, which was conducted using a ORC test stand equipped with the multi-vane expander and using R141b as a working fluid, are presented. A general view on this test stand is presented in Figure 12 (adapted from [82]). The first experiments series were conducted using the specially adapted pneumatic multi-vane motor as the expander. The ORC system was supplied from a heat source whose temperature varied between 70–90 °C. The experimental results showed that the optimization of the expander design is needed in order to increase its efficiency. The authors developed their own design of the multi-vane expander featuring the same dimensions (diameter of the cylinder, diameter of the rotor, and length of the cylinder) as the dimensions of the pneumatic motor that was initially tested, but they modified the geometry of the working medium flow path. The diameter of the expanders' outlet port was enlarged, together with the dimensions of the flow paths milled in the side covers and in the rotor. More detailed descriptions of these modifications is presented in [82]. Then, the expander was experimentally tested. The experimental results are presented in [83]. The temperature of the heat source and heat sink during the experiments were set to 90 °C and 34 °C, respectively. The experimental results showed that the maximum torque of 0.52 Nm at a rotational speed of 3157 rpm can be obtained for the expander tested. The optimum operating conditions of the expander were obtained at the expanders' shaft rotational speed of 4100 rpm. In these conditions, the expander power output was equal to 185 W. At the same rotational speed of the expanders' shaft, the ORC system reached its maximum efficiency of 1.57%.



Figure 12. A general view of the ORC test stand implemented at Thammasat University [82]. Reproduced with permission from Satha Aphornratana, Energy Procedia; published by Elsevier, 2017.

4.2.7. Bournemouth University (England)

The above-described applications of multi-vane expanders in ORC systems focused on waste heat recovery. However, multi-vane expanders were used also in ORCs driven by other heat sources. At Bournemouth University (England), ORC systems adopting multi-vane expanders and driven by solar heat were tested. The research results were published in [84–86]. In [86], the results of experimental tests on an ORC test stand adopting a modified multi-vane pneumatic motor featuring a maximum power of 800 W and a maximum rotational speed of 4000 rpm were presented. The applied working fluid was HFE-7000. During the experiments, the expander power of 146.74 W and an isentropic efficiency of 58.66% was obtained. The exergy analysis showed that the expander is the second-largest source of exergy losses in the system. Further experimental analysis and modeling results related to this expander were presented in [85]. Modeling results indicated that the pressure of the gas at the inlet to the expander has a significant impact on the efficiency of the ORC system and the efficiency of the solar collector. For the fixed values of the pressure at the inlet to the expander of 1.068 bar and 4.271 bar, the modeled efficiency of the multi-vane expander was equal to 53.48% and 69.67% respectively, and the power output was equal to 56.78 W and 170.08 W, respectively.

The optimization analysis showed that the working fluid pressure of 3.04 bar at the inlet to the expander reaches a maximum power of 170.43 W. In these conditions, an ORC system efficiency of 6.62% was obtained. In [84], the modeling of multi-vane expander operating conditions in an ORC system driven by solar heat was presented. Modeling was proceeded for 24 working fluids. Numerical analysis showed that highest expander efficiency is obtained for the expansion ratio of ca. 2.5 for majority of the applied working fluids (i.e., for R134a and R1234yf, the expander reached its maximum efficiency for the expansion ratio of ca. 2.0). A minimum expender efficiency (35.61%) was obtained for R134a for the expansion ratio of 1.5, and a maximum expander efficiency (70.1%) was achieved for 1-butene for the expansion ratio of 2.5.

4.2.8. Ferdowsi University of Mashhad (Iran) and RMIT University in Bundoora (Australia)

Multi-vane expanders were also applied in the prototypes of the domestic ORC systems fed by heat obtained from fuels combustion. In [87], the authors presented the results of experimental analysis carried on a prototype of a micro-power gas-fired ORC CHP system dedicated for application in residential buildings at Ferdowsi University of Mashhad (Iran) in cooperation with RMIT University in Bundoora (Australia). The in-house made multi-vane expander was applied to the research system. The side covers of the expander were made of carbon steel (1045), and the cylinder was made of cast iron. The outlet port of the machine was made bigger than the inlet port in order to obtain higher expansion rates. The rotor and the shaft were made of carbon steel (1045). Six vanes were applied in the machine. The seals were made of NBR (nitrile rubber). The heat source for the system is hot water, whose temperature varied during the experiments in the range of 65 to 85 °C. Depending on the temperature of the heat source, the experimentally obtained isentropic efficiency of the expander ranged between 37–45% while the electrical efficiency ranged between 0.75–1.66%. The mechanical power output of the multi-vane expander ranged between 65–140 W. The maximum electrical power of the tested system was equal to 77.4 W, which was obtained for a heat source temperature of 84.1 °C. In these experimental conditions, an ORC system electrical efficiency of 1.66% was obtained.

4.2.9. University of Nottingham (England)

In [88], the results of the experiments that were carried out at University of Nottingham on a prototype of the domestic micro CHP ORC system adopting a multi-vane expander and utilizing a heat obtained from biomass combustion were reported. The expander was coupled with a car alternator. The experimental results showed that putting the load on the alternator resulted in decreasing the speed of the expander, increasing of the pressure at the inlet to the expander, and an increase of the expansion ratio. The results proved that in the analyzed configuration of the test stand, it is possible to obtain up to 860.7 W of electrical power and 47.26 kW of thermal power with an electricity-generating efficiency of 1.41% and CHP efficiency of 78.69%. For these experimental values, the obtained expander efficiency was equal to 53.92%, the alternator efficiency was equal to 50.94%, the boiler efficiency was equal to 80.85%, and the ORC system efficiency was equal to 3.78%. The need to improve the efficiency of the expander and biomass boiler (being the main components limiting the efficiency of the ORC system) was pointed out.

The interesting results of the numerical and analytical modeling of multi-vane expanders operation in ORCs were presented in [89,90].

4.2.10. Magna Powertain Company (Austria) and Politecnico di Milano (Italy)

In [89], the authors presented a modeling of a multi-vane expander featuring an elliptical cross-section of a cylinder designed for application in small-scale ORC systems, which took place at Politecnico di Milano (Italy) in cooperation with the Magna Powertain Company (Austria). Modeling was carried out using OpenFOAM software. Different operating conditions of the expander were considered, i.e., the rotational speed of the expander shaft was varied (the following speeds were used for the modeling: 1250 rpm, 1000 rpm, and 750 rpm). Modeling results were compared to the experimental data obtained using the test stand in which R245fa was used as a working fluid. The maps of the working fluid pressure, velocity, and temperature inside the expanders' working chambers and the variation of the internal leakages and the expander power output were obtained as a result of modeling.

4.2.11. Jilin University (China)

In [90], the design and modeling results on the novel multi-vane expander with a variable expansion ratio were presented. The research was conducted at Jilin University (China). In this expander, the opening of the outlet port can be regulated (depending on the expansion ratio) in order to adjust the expander operating conditions to the variable operating conditions of the ORC system. The expander was modeled in the GT-SUITE 7.4 software; then, a series of simulations on its operation in variable operating conditions (i.e., the values of pressure and temperature at the inlet to the expander) were carried out using the model. The modeled expander featured the following geometrical dimensions: diameter of the rotor of d = 100 mm, eccentricity of e = 16 mm, inner diameter of the cylinder of D = 134 mm, thickness of the vane of g = 5 mm, length of the vane of h = 45.3 m, length of the cylinder of L = 140 mm, expansion ratio of $\sigma = 1.55$ –3.02, and number of vanes z = 4. It was assumed that the expander will be used in an ORC system to harvest the waste heat from a

car engine. Modeling was carried out for the R123 working fluid and for the fixed shaft rotational speed of 1500 rpm. The following parameters were varied: the working fluid pressure at the inlet to the expander varied in range of p = 0.3 to 0.64 MPa, the working fluid temperature at the inlet to the expander varied in range of 353.15 to 476.15 K, and the working fluid pressure and temperature at the outlet of the expander were fixed and set to 0.1 MPa and 300 K, correspondingly.

The modeling results gave the following conclusions: the influence of inlet pressure on the expander efficiency is significant, and when the working fluid pressure at the inlet to the expander is increasing, the expansion ratio should be changed to a higher value. It was also proved that the expansion ratio should be regulated only in the optimal range of values, because its excessive increasing can in effect lead to the overexpansion. The expander efficiency of 40.93% was achieved for a working fluid pressure at the inlet to the expander of 0.3 MPa and the expansion ratio of 1.83. An expander efficiency of 68.37% was achieved for a working fluid pressure at the inlet to the expander of 0.4 MPa and an expansion ratio of 2.84. The modeling results also showed that the optimal expansion ratio does not depend on the temperature of the working fluid at the inlet to the expander. These authors also carried out an exergy analysis of this expander. The results of exergy analysis indicated that the expansion ratio has a significant impact on the expanders' efficiency, and its reduction may (under certain operating conditions) lead to a significant increase of the expander exergy efficiency.

4.2.12. Normandie University in Saint-Lô (France)

In [91], the authors presented a thermodynamic analysis and the results of an experiment on the application of a multi-vane compressor and a multi-vane expander in a small-scale refrigeration system consisting of an ORC system combined with a refrigeration cycle. The research was conducted at Normandie University in Saint-Lô (France). Modeling was carried out for 12 working fluids. The authors selected R1270 as the optimum working fluid. The modeling results show that the system can achieve cooling power of 0.6 kW at a cooling temperature of 5.5 °C using a heat source with a thermal power of 2 kW and a heat carrier temperature of 65 °C. The authors stated that the combination of a multi-vane compressor with a multi-vane expander in one housing can be carried out in a simple way.

5. Summary and Conclusions

This article presents a review on the experimental and modeling research on the application of multi-vane expanders in ORC systems. Table 2 summarizes the results of the experiments, which analyzed ORCs with integrated multi-vane expanders in different scientific units. Analysis of these experimental data and the results of the mathematical and numerical modeling gives the following conclusions:

- Research on the possible application of the multi-vane expanders in ORC systems has been conducted in many scientific and industrial units since the late 1970s.
- Multi-vane expanders were adopted in ORCs driven by the different heat sources, including waste heat, solar heat, or heat obtained from the combustion of gas or biomass.
- In experimental studies, multi-vane expanders featuring different geometrical dimensions were analyzed. In all of the cases, it was possible to put these machines in operation.
- Specially adapted multi-vane pneumatic engines can be applied as the expanders in ORC systems.
- Reviewed experiments were conducted using the following substances: R11, FC88, alcohol, water, R113, R114, R123, isopropylbenzene, hexamethyldisiloxane (MM), R236fa, R141b, R245fa, HFE-7000, R601a, and R1270.
- Power output of the multi-vane expanders applied in ORC systems ranges between 65 W and 8 kW.
- Rotational speed of the multi-vane expanders applied in ORC systems ranges between 1200–4100 rpm.

- Absolute pressure of the working fluid at the inlet to the multi-vane expander ranges between 1.5–6.39 bar.
- The isentropic efficiency of the multi-vane expanders applied in ORC systems ranges between 17.2–55.8%.
- Efficiency of the ORC systems adopting multi-vane expanders ranges between 0.75–7.65%.
- The reported experimental results show that the expansion ratio of the multi-vane expanders applied in ORC systems ranges between 1.3–4.33.
- Multi-vane expanders have many advantages compared to the other types of expanders that can be used in ORC systems. The following advantages were mentioned by different authors: simple design, easy manufacturing, low vapor consumption, and a low range of operating pressures.
- The development of computer-aided design techniques at the latest time resulted in a number of publications related to numerical simulations of the operation of the multi-vane expanders in ORC systems. These publications gave a new look on the flow and thermal processes inside different multi-vane expanders, and showed that the arrangement of the steering edges has a significant influence on the expander operating conditions.
- Possibility of the optimization of the design of multi-vane expanders with the help of modeling and numerical simulations resulted in innovative designs such as, for example, the multi-vane expander with two inlets, a supercharged multi-vane expander, or a multi-vane expander with an adjustable expansion ratio.
- Further experimental and modeling works aimed at the optimization of the multi-vane expanders design and increasing its efficiency should be constantly performed. These works should be specially focused on the application of the innovative working fluids and construction materials.
- Special focus should also be paid to the innovative designs of the multi-vane expanders.
- Multi-vane expanders are a good alternative to the other types of expanders that are applied in small-power and micro-power ORCs.
- It is possible to implement multistage multi-vane expanders (a two-stage expander was applied by the General Electric Company).
- In some of the papers assessed, see e.g., [56,59,62,64,66–68,92–94], research results related to the application of the multi-vane pumps in ORC systems are reported. The works on their application should also be further explored.

In addition to the above-mentioned conclusions, the review reveals common features of multi-vane expanders. The influence of geometrical dimensions of the expander on the obtained power and rotational speed is visible. Large expanders feature greater power than smaller ones, while smaller expanders feature higher rotational speeds than larger ones. It is worth noting that the largest expander that has been used so far in the ORC system featured a power of about 8 kW. Experimental and modeling results proved that the influence of the position of the steering edges on the machine operating conditions and obtained performance is common for the expanders analyzed (i.e., the optimal arrangement of the steering edges position is similar for different multi-vane expanders, regardless of the geometrical dimensions and the design). The reviewed experiments showed that the biggest influence on the obtained power and efficiency of the multi-vane expander is that of the gas pressure, rather than the gas temperature at the inlet to the expander. What is more, the results of the reviewed experiments (which were carried out by different researchers on different test stands) unanimously indicate that multi-vane machines feature an optimal expansion ratio (usually ranging from 2 to 4). For those values of the expansion ratio, the power and efficiency of multi-vane expanders reaches maximum values. Thus, increasing the pressure at the inlet to the machine above the optimum value is disadvantageous, because it can lead to a decrease in the expanders' power and efficiency.

This review shows that multi-vane expanders are applied in low-pressure ORC systems, i.e., the pressure of the working fluid at the inlet to the expander usually ranges from 2 to 10 bar (while the highest working fluid pressure at the inlet to the expander reached 21.9 bar).

Working Fluid	Energy Source	Expander Specifications							tin	tout	Din.	Pout	n;	
		Power kW	Speed rpm	D mm	d mm	L mm	e mm	z -	°C	°C	bar	bar	-	Ref.
1. General Electric Company (USA)														
R11	Electric (b)	2.3	1200-1800	N/A	N/A	N/A	N/A	N/A	105	N/A	N/A	N/A	N/A	
FC88	Solar, Electric (b)	2.37.9	16251625	N/A	N/A	N/A	N/A	N/A	175 175	N/A	14.5	N/A	N/A	[43,44]
Alcohol/water	Gasoline	7.5	1800	N/A	N/A	N/A	N/A	N/A	340	N/A	N/A	N/A	N/A	
2. Cranfield Institute of Technology (England)														
R113	N/A	1.0-2.0	1750-3750	N/A	N/A	N/A	N/A	8	110-120	N/A	4.45-6.39	1.27-1.75	35–55	[45-55]
3. Wrocław University of Science and Technology (Poland)														
R11	Electric	0.6	3000	45	38	60	3.5	4	130-170	106-158	6.2	0.2	28–31	[56–58]
R123	Hot water (Gas boiler)	0.3	3000	37.5	34	22	1.75	4	39–71	37–62	2.0-5.2	1.2–1.5	17.2–43.1	[59-64]
4. Czech Technical University in Prague (Czech Republic)														
isopropyl-benzene	MOC 32 Thermal oil	0.4–0.8	N/A	N/A	N/A	N/A	N/A	N/A	210	130	3.5	0.5	- - 40–50 -	[69]
MM	Flue gas	0.4-0.6	N/A	N/A	N/A	N/A	N/A	N/A	135-150	50-100	1.7–2.7	0.2–1.0		
MM	Flue gas	N/A	N/A	N/A	N/A	N/A	N/A	N/A	150-190	40-90	3.0–5.5	0.4–1.0		
MM	Flue gas	2.0	N/A	N/A	N/A	N/A	N/A	N/A	155–166	62–73	2.8–3.5	0.4-0.65		
		5. Univ	versity of L'A	Aquila (I	taly), Brun	el Univers	sity Londo	on (Engla	nd), City Univ	ersity Londor	ı (England)			
R236fa	Hot oil	1.7–1.9	N/A	76	65	60	5.5	7	72.7–119.5	N/A	9.8–21.9	3.92-6.44	47.5–53.3	[71,73]
				6.	Politecnic	o di Milar	o (Italy),	Enea Mat	ttei Spa (Italy)					
R236fa	Hot oil	3.23	N/A	N/A	80	160	N/A	N/A	85.2	N/A	10.6	3.4	N/A	[80]
R236fa	Hot oil	3.66	N/A	N/A	100	90	N/A	N/A	81.4	N/A	13.0	3.76	N/A	
			7. Than	nmasat	University	(Thailand), Phrana	khon Raja	abhat Universit	y (Thailand)				
R141b	Boiler	0.025-0.18	5 3157-4100	N/A	N/A	N/A	N/A	N/A	70.0–90.0	N/A	N/A	N/A	N/A	[82,83]
8. Bournemouth University (England)														
HFE-7000	Solar heat	0.147	4000	N/A	N/A	N/A	N/A	N/A	45.41	36.36	1.32	0.66	58.66	[84-86]
9. Ferdowsi University of Mashhad (Iran), RMIT University (Australia)														
R601a	Hot water	0.065–140	1350-2680	N/A	N/A	N/A	N/A	6	53.6-72.1	45.4-61.8	2.25-3.2	1–1.4	37–45	[87]
10. University of Nottingham (England)														
HFE7000	Biomass Hot water	0.86	841-860	N/A	N/A	N/A	N/A	4	117.5–118.6	107.3–108.7	6.649–6.724	3.206-3.236	52.38-55.45	[88]

Table 2. Comparison of the results of the experiments that were performed on ORCs with integrated multi-vane expanders in different scientific units.

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