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Expanders for dispersed power generation: maintenance and diagnostics problems

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Abstract

The article discusses the problems related to the operation of various types of expansion devices used in small cogeneration systems. Both volumetric and dynamic expanders were considered, including scroll, screw, vane, piston and turbine expanders. For each of these solutions, principles of operation were explained as well as major advantages and disadvantages. The results of experimental research on several expanders of various types were also presented. The overview of expanders included in this paper, along with basic operational problems and functional characteristics, is the collection of valuable information facilitating selection of a suitable expander for specific applications. This is particularly important in the context of search for new energy sources and opportunities to improve the energy efficiency of available energy resources.

Keywords: Expansion devices; Expanders; Turbines; ORC systems; Cogeneration

1 Introduction

One of the main directions of changes in modern power engineering is the development of small energy systems powered with local renewable energy resources. Small-scale installations produce thermal and electrical energy, meeting the energy needs of individual customers or small customer groups, while reducing the load of national power systems and the adverse impact of human activity on the environment. Organic Rankine cycle (ORC) cogeneration system is one of the modern technologies enabling production of heat and electricity on a small scale.

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A source of thermal power for such systems may be either a modern boiler (designed for the combustion of biomass, biogas or other locally available fuels) or a renewable source (such as geothermal energy or a solar collector). The power generated in such a system can be sufficient for thermal and electric energy needs of a single-family house or an agriculture holding [1].

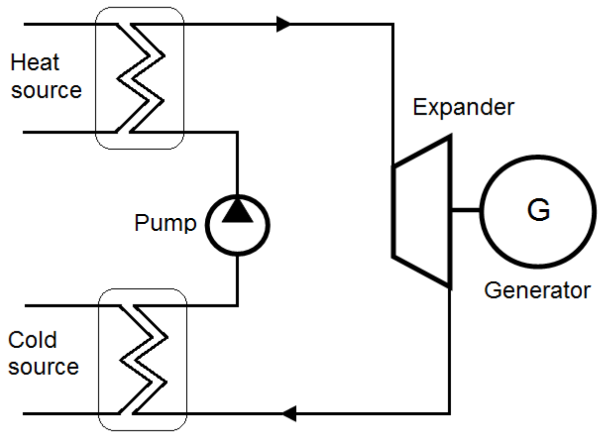

Figure 1: Diagram showing the expansion device operation in an ORC system.

In ORC systems, various types of expansion devices are used for the production of electricity. Through such devices, it is possible to convert thermal energy contained in a low boiling medium's vapour to mechanical energy on a rotating shaft, which is subsequently converted to electrical energy in a generator (Fig. 1). Due to the necessity of acquiring a profound theoretical knowledge and practical experience and to the need to apply the advanced engineering tools at the design stage, expansion devices are considered to be the most technically advanced subassemblies of ORC systems. These devices require precise production and assembly technologies. Consequently, all this contributes to a small amount of expansion devices of this type being available on the market. In the case of most commercially manufactured devices, it is required that the operator follows restrictive operating procedures and the technical oversight may be performed only by qualified personnel.

In ORC systems, different types of expansion devices are employed, depending on power and temperature demands or technical properties of a low boiling medium. Among the most popular currently are screw, scroll, vane, piston and turbine expanders [2–4]. Each of these constructions has both advantages and drawbacks which determine its applications range and estimated service life. Some expanders have severe constraints related to flow parameters and power outputs. Because efficiency and reliability of the entire cogeneration system are strongly dependent on an appropriate selection of the expansion device, the main functional characteristics of the most popular heat engines – intended to be operated as ORC systems' subassemblies – are discussed in detail in the following parts of this article.

2 Classification of expansion devices

Expansion devices can be divided into groups according to various criteria such as technical or operational characteristics [5,6]. Two different groups can be differentiated, namely the positive displacement (also known as volumetric) expanders and dynamic expanders, according to their working principle. Positive displacement expanders make a fluid move by trapping a fixed amount and forcing (displacing) that trapped volume into the discharge port. The working medium's movement in these machines is cyclic, unlike in the case of turbine expanders, where a continuous flow of the medium is maintained. Expansion devices can be classified in several large groups depending on the construction of operating elements:

- scroll expanders,
- screw expanders,
- vane expanders,
- piston expanders,
- gear expanders,
- turbine expanders,
- ejector expanders.

Each of these groups includes devices in many varieties that differ essentially with regard to constructional features, such as, for example, number of operating elements, flow direction of the working medium, seals, bearing system, etc. [7]. Turbine expanders cover a large variety of machines including single and multiple stage impulse/reaction turbines (axial-, radial- and diagonal-flow). The division of expansion devices into groups, which includes only the most frequently applied machines, is presented in Fig. 2.

In small ORC systems (up to 100 kWe), positive displacement devices are nowadays mainly used. This is due to their features, such as low flow rate of the working medium, high value of the expansion coefficient, low rotational speeds and resistance to the working medium's wet vapour. In this power range, it is impossible practically to purchase a vapour microturbine that is functionally

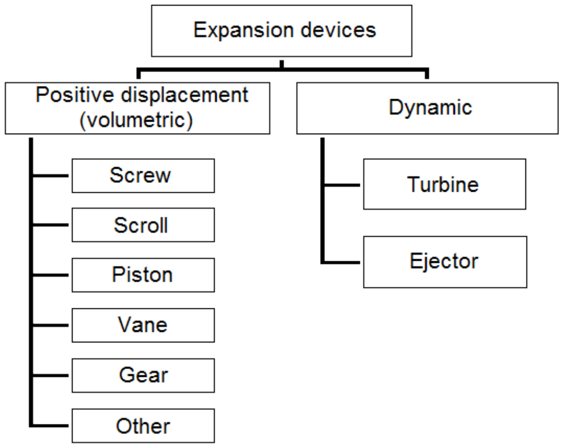

Figure 2: Classification of the most popular expansion devices.

adapted to operation with an ORC system. Overall, it is generally acknowledged that volumetric expanders must be applied for the pressure range up to 1 MPa and temperature range up to 200 °C. For higher temperatures and pressure levels, it is advisable to use turbine expanders.

3 Volumetric expanders

In all volumetric expanders, the working medium vapour expands as a result of changing the volume of confined spaces occurring between a casing and machine's operating elements (e.g., screw-shaped elements, scroll elements or pistons). In order to obtain a very good seal of the aforementioned confined spaces, it is needed to use dynamic seals and elements with a very high accuracy of dimensions and shapes and also lubricate the sealed surfaces. It is also very important to ensure the operating elements make small, precise movements, which is achieved by the application of special accurate bearing systems.

Piston expanders are the oldest type of positive displacement expanders. Expanders of this type have been known for more than 200 years, and were used for driving different mechanisms, e.g. steam machines during the industrial revolution. The working principle of piston expanders is used in many industrial branches, e.g., in automotive and petrochemical industry. In ORC cogeneration systems, the following types of piston expanders are the most frequently encountered:

- reciprocating piston expanders,
- rotary piston expanders (also known as Wankel rotary engines),
- gerotor expanders,
- rolling/swing piston expanders.

The diagram of a reciprocating piston expander presenting its working principle is shown in Fig. 3. The piston is actuated as it is cyclically supplied with a high-pressure vapour sucked in through an inlet port (suction port). After the expansion the vapour is discharged by means of an outlet port (discharge port). Reciprocating motion (which is a repetitive up-and-down linear motion) of the piston sets the crankshaft in motion which successively drives an electric generator. The cyclical nature of operation causes a relatively high noise and vibration levels, which means that piston expanders are not to be operated when people are present in their immediate vicinity. Other disadvantages are: large outer dimensions and a rather quick wear requiring specialized service and periodic replacement of worn parts. Therefore, the use of reciprocating piston expanders is not a common practice in small ORC systems.

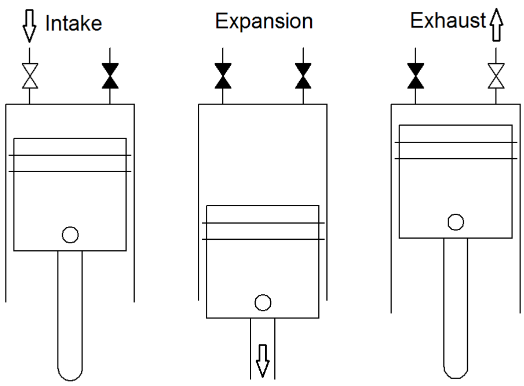

Figure 3: Operation cycle of a reciprocating piston expander.

Other types of piston expanders are rotary piston and gerotor expanders. Rotary piston expanders are structurally similar to, and often less known than, Wankel combustion engines. In such expanders, the piston with three vertices turns inside an appropriately shaped casing creating confined spaces that increase their volume (Fig. 4a). In machines of this type, there is a continuous wear (adversely affecting seals and efficiency) due to continuous friction between the piston vertices and the casing. The major advantages of these expanders are their small outer dimensions, low weight, low noise level and smooth running. All of these features contribute to enhancing the application possibilities. In gerotor expanders, the rotating piston moves inside its surrounding component (a casing), which has a very similar geometry. The inner component (piston) always has less teeth than the outer component (Fig. 4b). Additionally, the outer component can be stationary or rotary. The centreline of the piston is fixed in a position eccentric to the centreline of the casing. The pressure chambers, inside which expansion of the working medium takes place, are created by the difference in the number of teeth, and the chambers are sealed by close clearance between the teeth of the inner and outer element. The actual friction occurring between the mating elements – unlike in the case of rotary piston expanders – is not very intense. Furthermore, gerotor expanders are characterized by compact structure and silent running. In the last years, there have been also observed efforts to develop other, less popular types of piston expanders (e.g., rolling piston expanders). Rolling piston expanders will not be discussed any further here, since they are not among the most commonly used solutions in ORC cogeneration systems.

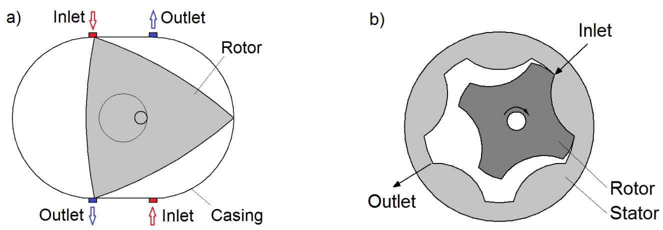

Figure 4: Diagrams of piston expanders: a – rotary piston expander, b – gerotor expander.

There are various types of vane expanders used in ORC installations. Their working principle is based on vane compressors and vane pumps which are used in a wide variety of industrial sectors. The working fluid vapour is expanded in confined spaces which are formed between the rotor, the casing and two adjacent vanes (Fig. 5). In order to maintain seal integrity the vanes are pressed against the casing (by springs inside the vane guides and additionally by the centrifugal force). A vane edge, together with the casing forms a couple with linear friction contact. To minimize friction forces occurring in vane compressors, a small quantity of lubricating oil is usually added to the working medium and operational speed is reduced. It is troublesome in ORC systems, since even a small quantity of oil can significantly alter the operational properties of a low-boiling working medium. Therefore, vane expanders operating with ORC systems are applied mainly in the case of low power installations, in which losses resulting from friction may be negligible.

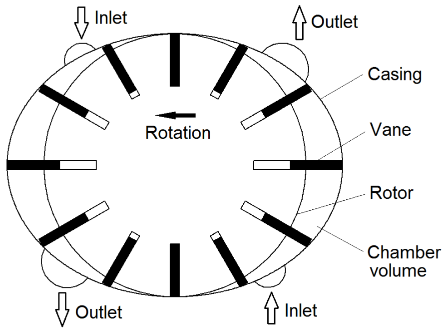

Figure 5: Diagram of a piston expander.

Compared to other expansion devices, vane expanders feature a rather simple structure and low manufacturing costs. Expanders of this type have compact construction, like gerotor and rotary piston expanders, but, unlike those expanders, they do not possess components that must be very precisely manufactured [8–10]. In vane expanders, seal integrity of the structure is achieved in a different manner, i.e., by means of vanes which can be ejected to fit the casing.

Screw and scroll expanders are the most frequently used as expansion devices in ORC cogeneration systems. Currently, units of this type are sold by several companies and they have power levels ranging from several kilowatt to several dozen kilowatt. Their main advantage is high efficiency with good durability and reliability. Screw expanders originate from screw compressors and the expansion effect is achieved by reversing the direction of rotation. They exist in several variations, yet the most popular devices are twin-screw expanders (containing two perfectly matched screw-shaped components). The cross-section of a screw expander is shown in Fig. 6a. The so-called ‘male’ screw is coupled with ‘female’ one. A very precise manufacturing of these two elements is necessary to ensure a good seal between the contacting edges. Expansion of the working fluid takes place in spaces between the screws and the casing. One of the shafts is connected to a generator that produces electricity. Typical rotational speed range for such expanders is from 1500 rpm to 3000 rpm.

The other popular variation of the expansion device used in ORC systems is a scroll expander [11]. Figure 6b shows a diagram of such an expander. Expanders of this type, which are currently available on the market, have power capacities from several hundred watts to 30 kW [2,12]. Their growing popularity among customers results mainly from their operational simplicity and long service life. The working principle of this machine is based on the eccentric movement of

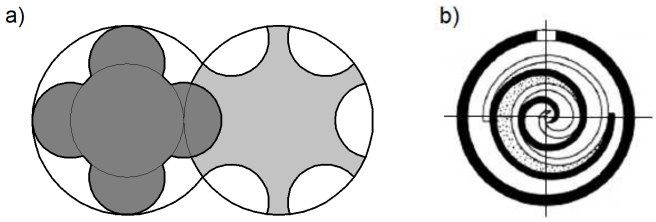

Figure 6: Diagrams of a screw expander (a) and scroll expander [2] (b).

two scrolls, which are eccentrically positioned and one of them is fixed. In this way, the confined spaces are formed in which working fluid vapour is expanded. A very precise manufacturing of the scrolls is an absolutely essential prerequisite for a proper operation of such an expander, as this is the only way of ensuring good seal. Nominal speed of a scroll expander is typically within the range from 1000 rpm to 4500 rpm [13].

A crucial aspect of the expander selection for an ORC system is careful matching of its flow characteristics to remaining elements of the installation. The two key parameters of an expander are expansion ratio and maximum flow rate of the fluid. Moreover, maximum temperature and pressure of the working medium vapour at the evaporator outlet must not be exceeded. It is also necessary to ensure that the materials constituting the expander, which are in contact with the working fluid during operation (e.g., seals), shall be compatible with that fluid. Undoubted advantage of volumetric expanders is the ability to operate with two-phase (liquid or vapour) working medium. Condensation (outdropping of humidity) of working medium's vapour may occur mainly in small installations powered with small and unstable heat sources. This is also the case if the so-called 'wet working medium' is used, and its vapour condenses during expansion.

Positive displacement expanders are characterized by a relatively high efficiency (even in low capacity units), which is difficult to achieve when using a turbine expanders. Highest efficiencies are obtained for screw expanders, reaching up to 90% [14]. In the case of scroll expanders, typical efficiency level is around 80%, which was already experimentally confirmed by independent research teams [15,16]. Different sources give varying information on vane expanders' efficiencies. According to some literature data, vane expanders can attain efficiencies up to 80% [17], although another source states that the actual efficiency can only slightly exceed 50% [2] due to losses resulting from friction. Gerotor expanders achieve highest efficiencies of all types of vane expanders, reaching – under the most optimal operating conditions – up to 85% [15]. Other types of piston expanders can achieve efficiencies in the range from 40% to 60%, depending on construction details and power level.

4 Turbine expanders

High power energy systems (several megawatts or more in capacity) are dominated by turbine expanders. In such machines, there are no confined spaces in which working medium's vapour is expanded, since the expansion occurs on a continuous basis during the flow between the vanes. Expanders of this type can be classified according to many criteria such as operational parameters, structural details, flow direction of the working medium or even intended destination. The general division – according to their working principle – differentiates impulse turbines and reaction turbines (Fig. 7). When turbine characteristics are presented, the number of the so-called turbine stages is usually mentioned. Those stages comprise the sets of guide vanes and rotor vanes (movable vanes). The increasing possibilities for designing of forward-looking, eco-friendly and economically viable turbines lead to the situation in which nonconventional turbine solutions are being developed, constituting a combination of existing constructions and entirely new concepts. Turbine expanders with electric power capacities of up to 1 MW are commonly referred to as 'microturbines' [18]. The machines which fall in this power range are almost exclusively used in ORC installations. Devices of a power higher than 1 MW are rarely used, e.g., in the case of electricity generation from large resources of geothermal energy.

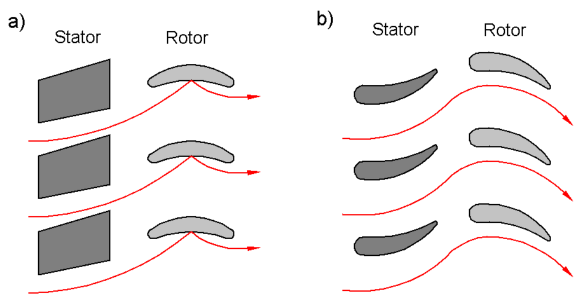

Figure 7: Typical geometries of turbine vanes: impulse turbine (a), reaction turbine (b).

Modern steam-powered turbines, which are used in commercial power generation, achieve isentropic efficiencies of 90% or even a bit higher [19]. The irregular flow and the so-called leakage (e.g. interstage leakage around the inner shrouds of the stationary vanes) are the main reasons for power losses in steam turbines.

Some clearance between the vanes and the casing is indispensable for proper operation of the turbine because it allows free movement of the rotor. The decrease in the size and capacity of turbines leads to a relatively large increase in the clearance size above the blades. Therefore, in the case of microturbines, it is practically impossible to achieve the above mentioned efficiency. Isentropic efficiency of ORC microturbines with capacities of up to several dozen kilowatts rarely exceeds 80%. If other favourable features of small steam turbines are taken into account, that efficiency level can be considered satisfactory. In microturbines, the highest efficiency levels are obtained at high rotational speeds, i.e., with the speed of a rotor shaft at tens of thousands of revolutions per minute. In contrast to volumetric expanders, there are no significant losses caused by friction between operating elements of turbines. Some losses occur in bearings, which can be lubricated with oil, but the smallest turbines are the most frequently equipped with gas bearings [20,21]. The great advantages of vapour microturbines are their wear-resistant parts and long service life. Microturbines are compact in size and weight compared to other expansion devices with a similar power level [22]. These machines are also characterized by low noise and vibration levels.

A low resistance to condensation of a working medium is the main drawback of vapour microturbines. Outdropping of working medium can bring about erosion of the blades, thus leading to their damage. Therefore, in the case of ORC systems equipped with microturbines, the so-called 'dry' low boiling mediums must be applied, the vapour of which becomes more dry (more superheated) during the expansion process. Construction of a highly efficient microturbine requires specialized knowledge from different areas of technology and the application of advanced computational tools. Well-designed microturbines' blades usually have complex shapes requiring a very precise and time-consuming mechanical machining.

5 Technical diagnostics of expansion devices

Both positive displacement expanders and turbines are advanced fluid-flow machines requiring periodic inspections and performance tests carried out by qualified personnel to ensure safe and efficient operation. The majority of machines of this type currently available in the market are new solutions, the operational life of which rarely exceeds several years. Even in well-designed structure, when the unit is operating under peak and/or oscillatory load conditions, with an aggressive working medium and/or with periodic technically unavoidable stoppages, technical problems can arise which are difficult to predict. Therefore, periodic examination of the technical state of all key components of a machine and its careful diagnostics (which should be sufficiently sensitive to be able to detect very early stages of defects) are very important.

The following part of the paper presents the exemplary results of diagnostic tests carried out on two interchangeable expansion devices intended for operation with small ORC cogeneration systems. The experimental investigation was conducted in the Micro-CHP Power Plant Laboratory at the Institute of Fluid-Flow Machinery in Gdańsk. The main objective of this research was to determine the actual thermal flow and electrical characteristics of the expanders incorporated into the ORC system operating with a low boiling medium under a trade name HFE-7100 (manufactured by 3M Novec) [16]. Other measurements were performed in parallel so as to be able to assess dynamical state of the machines on an ongoing basis. This allowed, among others, for early detection of various types of defects and undesirable dynamical effects, which could have caused damage of the machines.

A portable device Emerson CSI2140 was used to make assessments of the technical state of the operating machines. It permits simultaneous measurement of many physical quantities using up to 4 measuring channels. The dynamical state of the expanders was evaluated by means of the measurement of the rms value of vibration velocity, the most frequently used parameter in vibrodiagnostics of machinery. Owing to the measurement of this parameter, it is possible to assess the vibration level of the machine on the basis of the relevant international standards (e.g., ISO 10816). The vibration velocity measurements were carried out in the frequency range up to 1600 Hz, with a resolution of 1 Hz. Uniaxial accelerometers were applied as measurement sensors.

Figure 8 shows the examined scroll expander and the exemplary results of vibration measurements. The expander was manufactured by Air Squared (model E15H22N4.25). Its maximum rotational speed is 3600 rpm and the nominal output power of the electric generator is 1 kW. The expander was connected to the electric generator by means of a magnetic coupling (Fig. 8a). The measurement results, in the form of vibration velocity spectrum, are presented in Fig. 8b. The main vibration component corresponds to the rotational speed value of the expander shaft and occurs at the frequency of 51 Hz (3060 rpm). Moreover, there are more components on this spectrum indicating the presence of high amplitude harmonic vibrations which occurred at higher frequencies. The vibration with amplitudes exceeding 1 mm/s occurred at the following frequencies: 206, 257, 308, 668, 719 and 771 Hz. In view of the fact that the tested scroll expander was recently purchased and is still in very good technical condition, it can be concluded that the vibration velocity spectrum obtained (containing so many components) stems from the nature of the machine operation itself, and not from any defects or dynamical problems. The overall level of the root mean square (RMS) vibration velocity (*Vrms*) was also high as it reached the value of 15.62 mm/s. From the point of view of vibroacoustic diagnostics of machinery, the obtained vibration characteristics are of little use. The overall vibration velocity level has exceeded several times the permissible values specified in the standards for low power machines. The spectrum obtained is also of limited use for the detection of symptoms relating to particular defects, as such a large number of components resulting from the nature of the machine operation itself does not permit unambiguous and consistent interpretation of the additional information. Checking the overall vibration level of the machine and comparing it with the characteristic value (as a basic reference indicator measured, for example, immediately after the expander has been put into service) would prove the most useful in this situation. The machine diagnostics carried out in this way has a limited ability to defects identification.

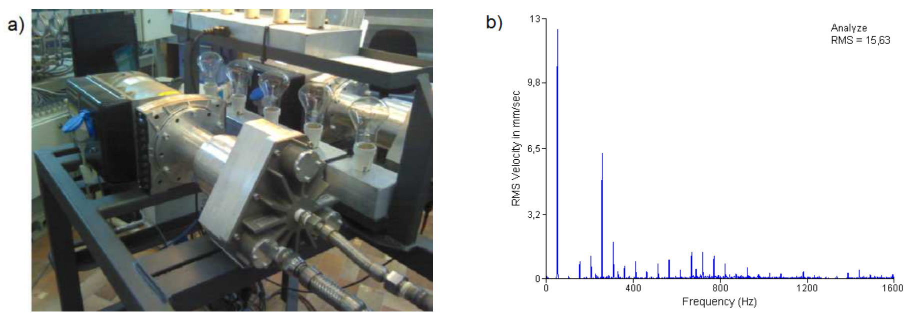

Figure 8: Vibrodiagnostic tests carried out on a scroll expander operating in an ORC system: a) examined expander on the test bench, b) spectrum of the root mean square vibration velocity (*Vrms*) measured on the expander casing.

The exemplary results of vibrodiagnostic tests carried out on the turbine expander are presented in Fig. 9. The examined machine consisted of a four-stage radial-flow microturbine which was fixed with the electric generator on the common shaft. The shaft was supported by two double-purpose (radial-axial) aerostatic bearings which were lubricated by working medium's vapour. The power rating of the microturbine was 3 kW at the nominal speed of 24000 rpm. This microturbine was developed at the IFFM PAS in Gdańsk in cooperation with the Lodz University of Technology (Institute of Turbomachinery), in the framework of the project no. POIG.01.01.02-00-016/08 [23,24]. The supporting frame on

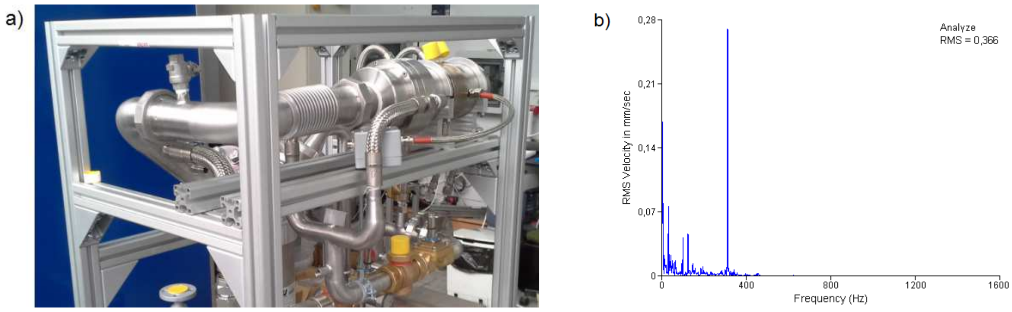

Figure 9: Vibrodiagnostic tests carried out on a vapour microturbine operating in an ORC system: a) examined microturbine, b) spectrum of the root mean square vibration velocity ($Vrms$) measured on the turbine casing.

which the microturbine was mounted is an integral part of the micro-ORC cogeneration power plant powered by the heat energy from a biomass boiler [25]. The vibration velocity spectrum measured on the microturbine casing at the bearing located between the turbine rotor disk and the generator is shown in Fig. 9b. In contrast to the vibration velocity spectrum of the positive displacement expander presented above, the identification of the origin of particular vibration components is much simpler in this case. The highest vibration component had the value of 0.278 mm/s and occurred at 311 Hz which corresponds to the rotational speed of the microturbine shaft that had the value of 18660 rpm during the measurement. In the range of lower frequencies, several vibration components with amplitudes not exceeding 0.1 mm/s occurred, including the ones at 31, 100 and 124 Hz. These were eigenfrequencies of the entire construction corresponding to the rotational speeds of the pumps operating with a low boiling working medium and a thermal oil, which were mounted on the same frame as the microturbine. Because these vibrations were transmitted through a rigid aluminium construction, they were also recorded on the microturbine casing. At higher frequencies, no significant vibration components have been observed. The overall vibration level of the examined turbine was very low ($Vrms = 0.366$ mm/s) and was far below the values given in the standard ISO 10816-1 for the newly commissioned machinery.

As the above examples show, it is very difficult to assess the technical condition of volumetric expanders, especially scroll expanders, solely on the basis of vibration measurement. The vibration spectrum measured on such a machine possesses a number of components which are the result of the nature of the machine operation itself and are not a consequence of any dynamical problems or occurring defects. Therefore, it is virtually impossible to make the selection of reliable diagnostic symptoms. The situation for turbine expanders differs significantly from the above. The technical condition of this type of machines can be successfully assessed on the basis of the measurement of vibration signals. The vibration spectrum obtained from a properly operating microturbine usually contains one main vibration component (corresponding to rotor's rotational speed) and several components with lower amplitudes, the origins of which can be easily identified. Commissioning turbine expanders and evaluation of their dynamical state based on the relevant standards is therefore much simpler. A vibration level of a turbine expander is usually several times lower compared to a volumetric expander with a similar power level. The measurements of sound pressure during the diagnostic tests have shown that the equivalent sound pressure level Leq A did not exceed 65 dB (A) for the radial-flow microturbine and 80 dB (A) for the scroll expander. During the measurements the noise emitted by the other components of the ORC installation, into which were incorporated the tested expansion devices, was also taken into account.

6 Conclusions

The paper deals with those aspects of the various types of expansion devices which are linked to the process of generating electric power in ORC systems. Both volumetric expanders and dynamic expanders were taken into account during the above considerations. The working principles of the most popular constructions were described, along with their main advantages and disadvantages. Special attention was given to issues regarding operation, maintenance and technical diagnostics of expansion devices.

Based on experience gained by the authors and a literature review, the conclusion can be made that positive displacement expanders can achieve high efficiencies at low power capacities, reaching up to 90% in the case of screw and scroll expanders. However, they are only applicable to systems with low power capacities in which working mediums are operating at low parameters. Expanders generally have large sizes because in most of the cases these are slow-running machines. Due the contact phenomena occurring between operating elements, they require periodical technical inspection and replacement of wearing parts. The experimental investigation carried out at the IFFM PAS also showed that, because of the cyclical nature of expanders' operation, the use of standard diagnostic methods based on vibration measurements is not enough to identify without ambiguity the most common defects.

Although turbine expanders can fulfill the same role as volumetric expanders in ORC systems, they possess completely different properties. These machines are usually high-speed within the range of micropower capacities, and can be powered by high-temperature and high-pressure working medium's vapour. High efficiencies of turbine expanders (above 80%) can be achieved only with power capacities of around several hundred kilowatt. Machines based on well-proven designs can operate for many years without any repairs. Using high-speed rotors guarantees high power outputs in combination with compact dimensions and low noise/vibration levels. Well-known and reliable vibrodiagnostic methods can be successfully used for such machines and vibration characteristics obtained by these methods allow for the assessment of their dynamical state and identification of occuring defects.

The examples provided in this paper have indicated that the expansion devices of completely different types can be used interchangeably for the production of electricity in an ORC cogeneration system. In deciding on any particular expander, among other things, its main technical parameters, advantages, drawbacks and limitations should be considered. Before making the final choice it is also necessary to take into account not only efficiency of a device but also operating characteristics, which is very important but often overlooked.

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