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Analysis of the dynamics of microturbines bearings lubricated using conventional and unconventional agents

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Abstract

The paper presents the research results of the microturbines dynamics with power of a few to several hundred kW. These are combined heat and power (CHP) units (generating heat and electricity) for houses and for municipalities in the form of Autonomous Energy Regions (ARE). These are key technologies for energy sector with respect to the distributed generation and for small-scale eco-power engineering. The following examples will refer only to the several selected research projects coordinated by the Institute of the Fluid-Flow Machinery of the Polish Academy of Sciences in Gdańsk. The paper will focus on the dynamics of rotors and bearings lubricated by means of low boiling agents, i.e., by means of turbine working medium. Analysis of hydrodynamic instability phenomena, including the development of oil whirl and oil whip has also been carried out.

Keywords: Rotor dynamics; Microturbines; Distributed energy generation

1 Preliminary remarks

The presented in the paper examples will refer to the several selected research projects coordinated by the IMP PAN (Institute of Fluid-Flow Machinery of the Polish Academy of Sciences) in Gdańsk. However, these are the largest research projects in the country regarding the field of RES-based eco-energetics.

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This article will focus on the results of the work related to so-called 'energy-plus' technologies and small and micro-combined heat and power units. These results are the effect of research conducted at the Institute and in cooperation with industrial partners (mainly the Capital Group ENERGA) and more than a dozen research teams from different research centers across the country. These study focuses on the future implementation and is addressed to individual and municipal consumers.

When it comes to the ongoing studies, the construction of the CHP ORC (combined heat and power organic Reynolds cycle) plant is planned (the blocks consisting of a boiler and a microturbine operating with a low-boiling agent using an ORC) with the electric power of several kW and tens of kW of thermal power. In the framework of the another project it is planned to build CHP ORC units of higher power (hundreds of kW of electrical power, thermal power up to several MW). The results of these projects will be thus addressed to individual customers in the form of domestic CHP units, and to the municipal customer as Municipal Energy Centers or Autonomous Energy Regions.

Tracking the discussions in the EU it can be concluded that the domestic CHP units, Autonomous Energy Regions (ARE) and generally distributed energy systems (DES) based on renewable energy sources (RES) play a big role in energy policy and especially in the so-called energy mix not only in Poland but also in EU Coutries [1–8].

Microturbines constitute the most important part of the small devices like DES/RES. Analysis of the work of microturbines and microbearings, their construction and operation is a challenge for many centers around the world.

2 Research objects

The IMP PAN group (that means: IMP PAN, Lodz University of Technology, Gdańsk University of Technology, University of Warmia and Mazury) developed two concepts of microturbines with a capacity of 3 kW (axial flow and radial flow) coupled with multi-fuel boiler with a capacity of 20 kW (biomass or gas fired). As far as microturbines are concerned, the essential idea was to use the low-boiling agent (turbine's working medium) for bearing lubrication, which ensures tight and hermetic construction. Figure 1 shows this idea whereas Fig. 2 shows the photo of test stand in the microturbine laboratory (located at the IMP PAN in Gdańsk) and the photo of multifuel fired boiler.

Currently, laboratory investigations are carried out and as a result the boiler and both versions of microturbines are being tested. After completion of tests, the development of a target version (and perhaps commercial one) of an entire micro-CHP unit is planned. The brief design and initial documentation of such micro-CHP station have already been elaborated – Fig. 3. If this undertakings are successful, it will be the first national construction of this type. Figure 4 shows the developed targeted versions of microturbines.

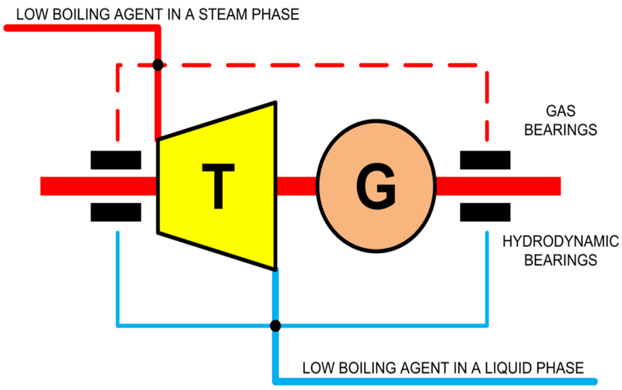

Figure 1: The possibility of utilization of a microturbine's working medium in the liquid and gas phases as a bearing lubricant. The concept of hermetic construction of a turbine and a generator to facilitate the integration with a boiler.

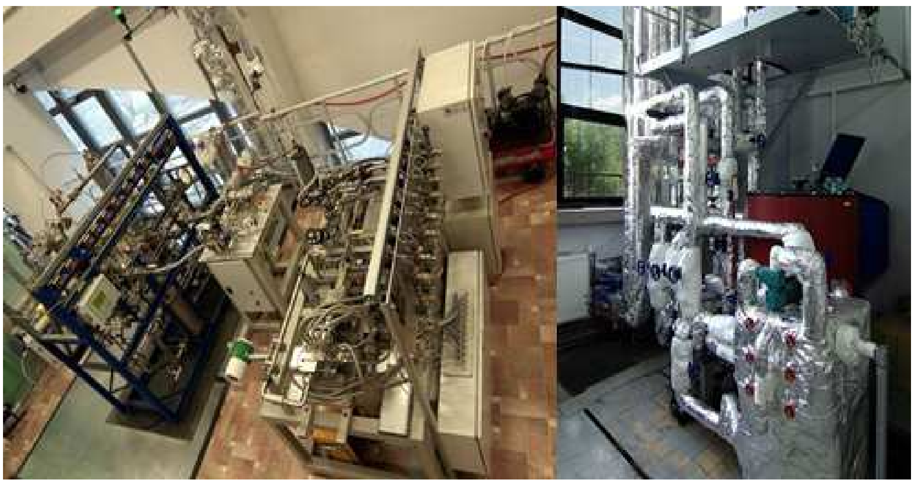

Figure 2: The laboratory of the IMP PAN in Gdańsk: pictures of microturbine test stand (on the left) and multifuel fred boiler (on the right).

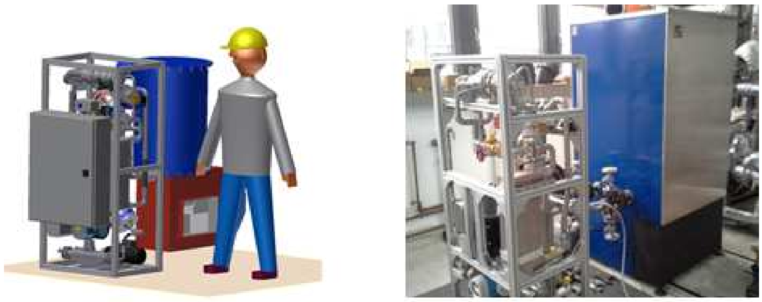

Figure 3: Target design of Domestic Micro-CHP Unit with ORC after all examinations and tests in the laboratory of the IMP PAN in Gdansk: the first concepts (left), commercial version of the installation (right).

Figure 4: Domestic Micro-CHP ORC Unit. Microturbines: developed target versions. Elaborated in TU Łódź and TU Gdańsk in cooperation with IMP PAN. Two pictures on the left: radial and supersonic microturbine; picture on the right:axial microturbine.

Figure 5: The largest in Poland micro-CHP Laboratory: the poligeneration power plant in IMP PAN in Gdańsk.

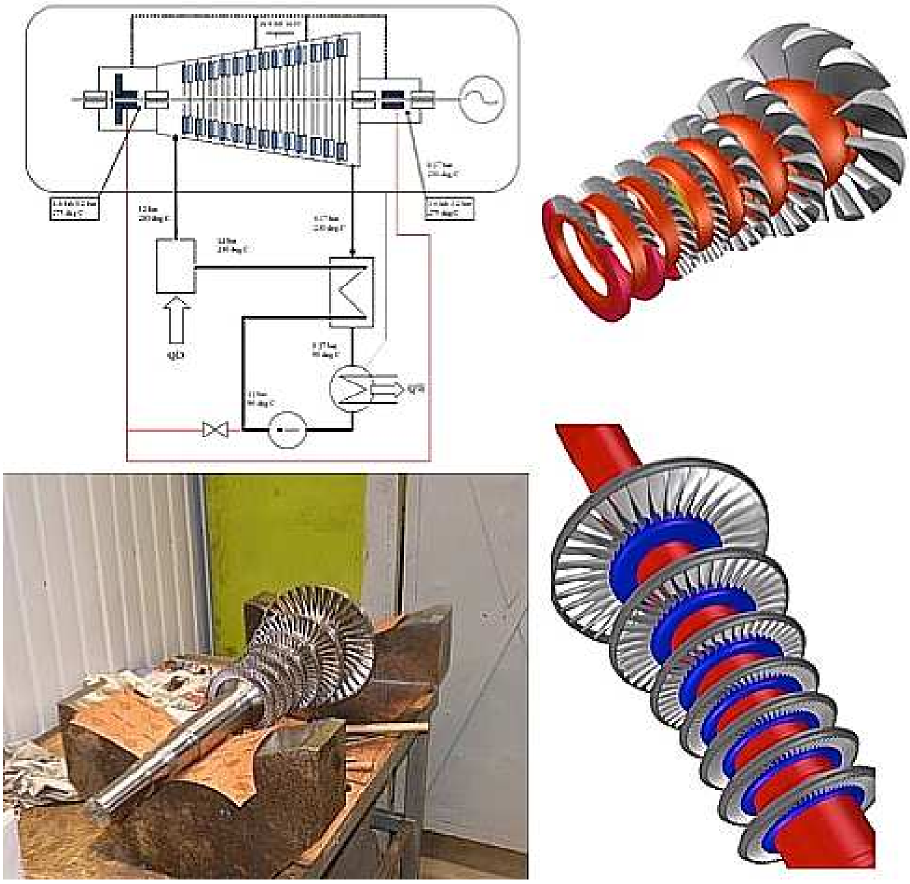

Figure 6: IMP PAN Laboratory: ORC turbogenerator (own solutions).
Axial turbine 9000 rpm and power of 100 kW.

In the IMP PAN is currently constructed second laboratory designed for microturbines of higher power, namely 100 kW – Fig. 5. Such units are provided for construction among others autonomous energy regions ARE. Based on the ideas presented in Fig. 1 have been developed several versions of microturbines. One of such constructions is shown in Fig. 6.

Dynamic analysis of the rotor and bearings was carried out using own tools developed in the IMP PAN, namely computer system MESWIR – Fig. 7 [9]. System MESWIR allows analysis in the nonlinear range, which means that the construction of vibration spectra is possible. From the rotor diagnosis point of view vibration spectra have a crucial meaning.

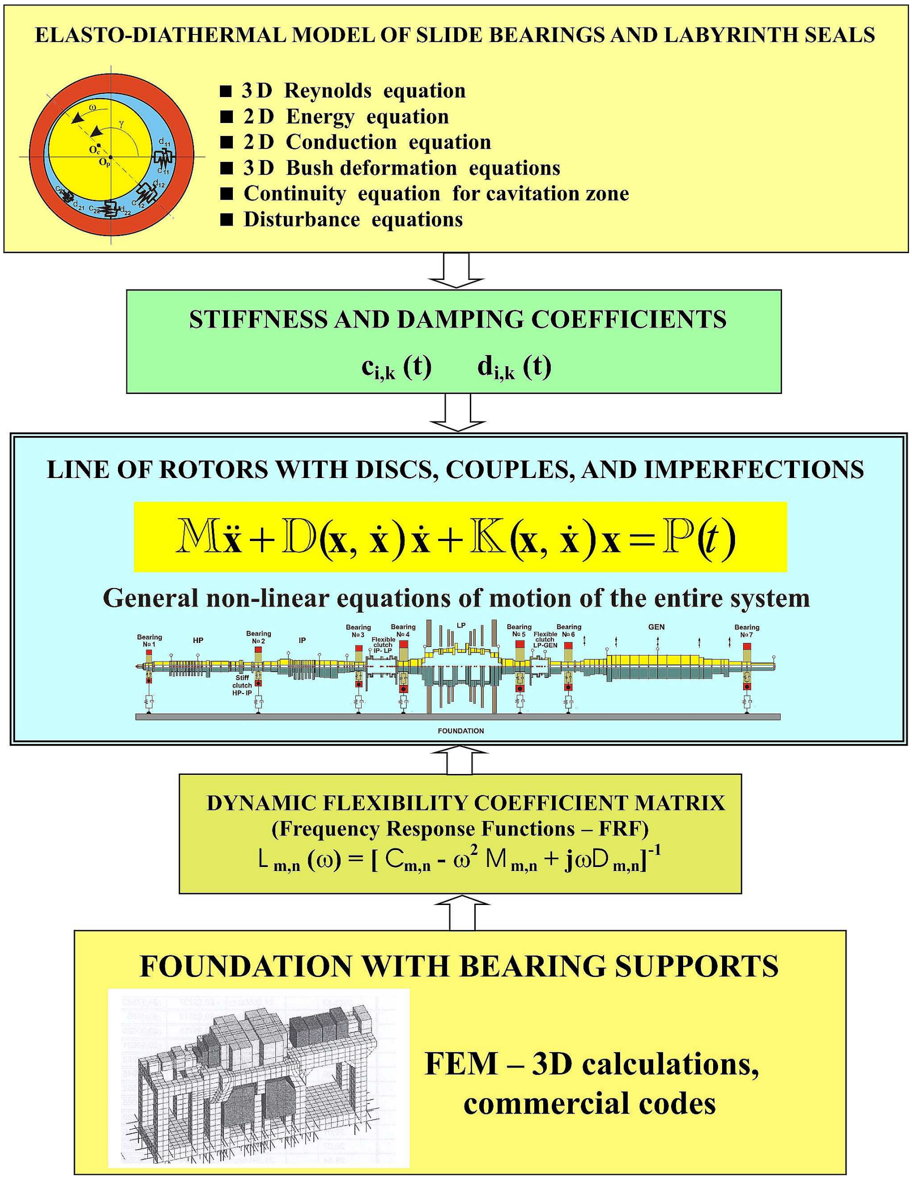

Figure 7: Block diagram of computer program MESWIR. Nonlinear analysis of rotors dynamics – the set of differential equations [9].

Figure 8 shows a sketch of the turbine rotor and finite element method (FEM) discretization scheme.

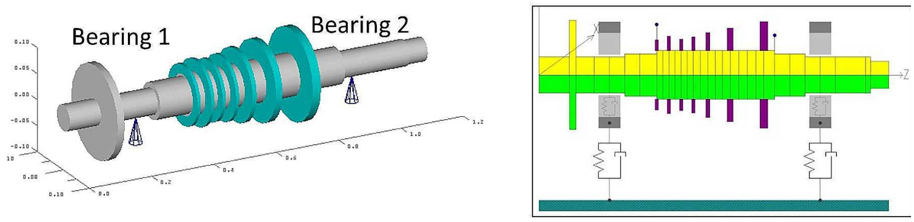

Figure 8: Geometry and FEM discretization of the rotor microturbines from Fig. 6. The analysis was carried out using a computer system MESWIR [9].

3 Research using conventional lubricating agents. Study of highly developed hydrodynamic instability

Before we get into research related to the use of low boiling agents as lubricating medium, we will conduct research on classical mineral oils. This will enable us the comparison and facilitate evaluation of possible design solutions. Studies using mineral oils will also explain phenomena taking place in the oil film at high rotor speeds (oil whirl and whip). The object of this study will be the bearings of microturbine from Figs. 6 and 8. Constant aerodynamic forces acting on the system are computed using the commercial program FLUENT while the dynamic load were the residual unbalance forces taken from ISO standards for this class of machines.

The results of the computer simulation carried out using the MESWIR system are given in Figs. 9–13. In Fig. 9, we see the course of the vibration amplitude as a function of rotor speed. Here we see three specific zones: the area of stable work at a speed of 8000 rpm, transition phase (8500 rpm) and the phase of developed instability at 9000 rpm. It is worth noting that the nominal rotation speed is exactly at 9000 rpm. Figure 10 explains the position of the external excitation forces (imbalance) relative to the assumed coordinate system. In Figs. 11 and 12 we see the pressure distribution in the bearing bushing calculated by means of the computer system MESWIR (Fig. 7). At the same forces Q (the gravity load) and R (excitation force) acting on the bearing, pressure distributions in Figs. 11 and 12 are completely different. In Fig. 12 we have already developed hydrodynamic instability (oil whip) and it explains this fact. Figure 13 fully confirms this result.

The presented studies show that oil as the lubricant is not a good option. This means that we can still apply the low boiling medium or ball bearings.

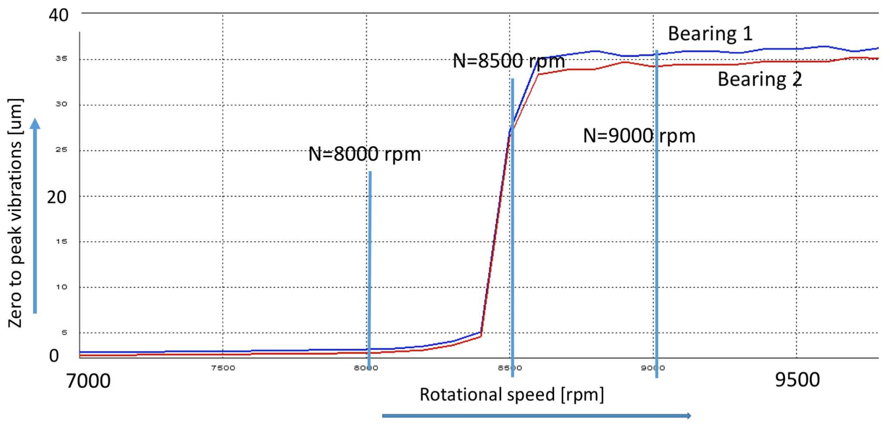

Figure 9: Course of the vibration amplitude as a function of rotor speed. Research object: bearing No. 1 of microturbine from Figs. 6 and 8.

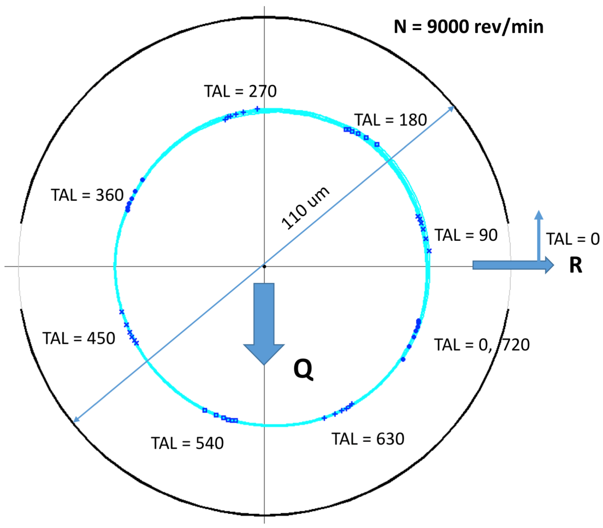

Figure 10: Adopted coordinate system. Location of excitation force R (unbalance) in relation to the gravity load Q. Points TAL represent marker positions on the trajectory when the exciting force vector directs horizontally right.

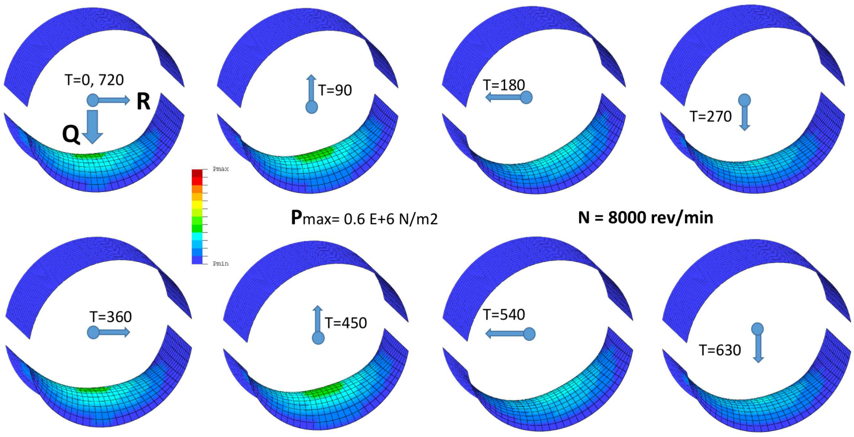

Figure 11: Pressure distribution for the stable operating range of microturbines (8000 rpm) and different position of the force R.

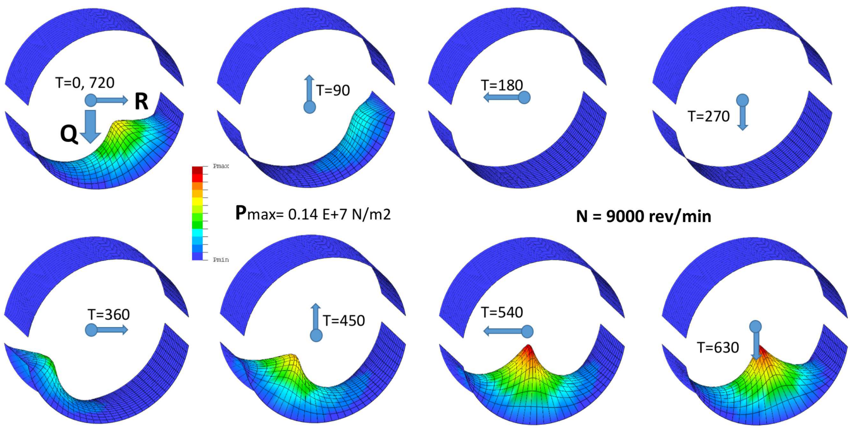

Figure 12: Pressure distribution for the unstable operating range of microturbines (oil whip – 9000 rpm) and different position of the force R.

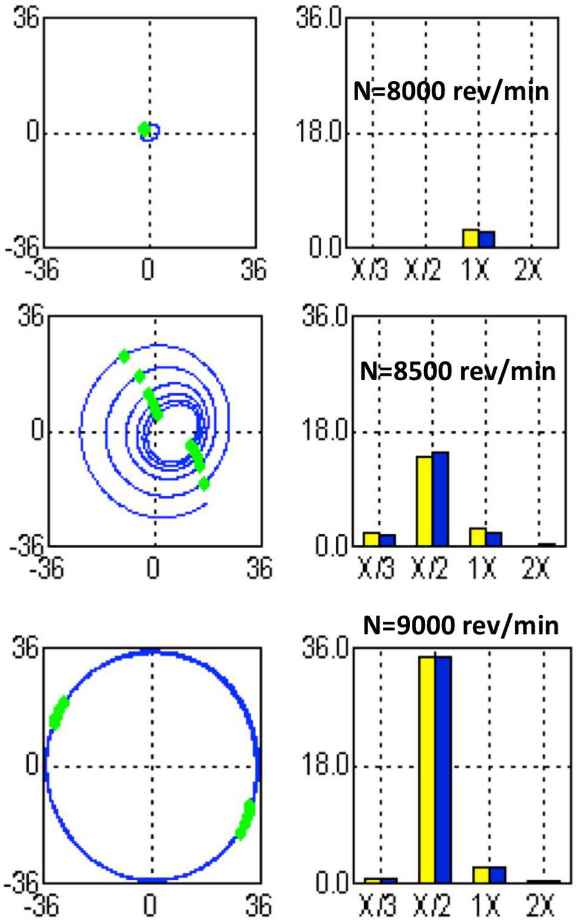

Figure 13: Trajectories and vibration spectra for the three speeds of the rotor.

4 Research using unconventional lubricating agents – low boiling medium

Returning to the microturbine shown in Figs. 6 and 8 and the idea shown in Fig. 1, we can conclude that the main problem here was the rotor stability in the case where the bearings are lubricated by means of a low boiling medium. This is due to the property of a low boiling medium (silicone oil), namely, the boiling and cavitation at low temperatures – Fig. 14. In this case we are dealing with gas phase lubrication, which significantly changes the dynamics of bearings and rotor. To avoid the two-phase flows, the ambient pressure in a lubrication chamber have been raised up to a value of 0.6 MPa. In this case, as can be seen from Fig. 14, the liquid phase lubrication is possible at a temperature up to 240 °C.

The results of the analysis carried out by means of a computer system MESWIR are presented in Figs. 15 to 17. Figure 15 shows that an increase of ambient pressure in the lubricating chamber to the value $p = 0.6$ MPa results in a sudden increase of the vibration amplitude for both bearings. Bearings are lubricated by the liquid phase of low boiling medium but unfortunately work in the condition of strongly developed hydrodynamic instability. This reveals the Fig. 16 exactly. For the value of $p = 0.6$ MPa in the vibration spectrum appears a strong subharmonic component.

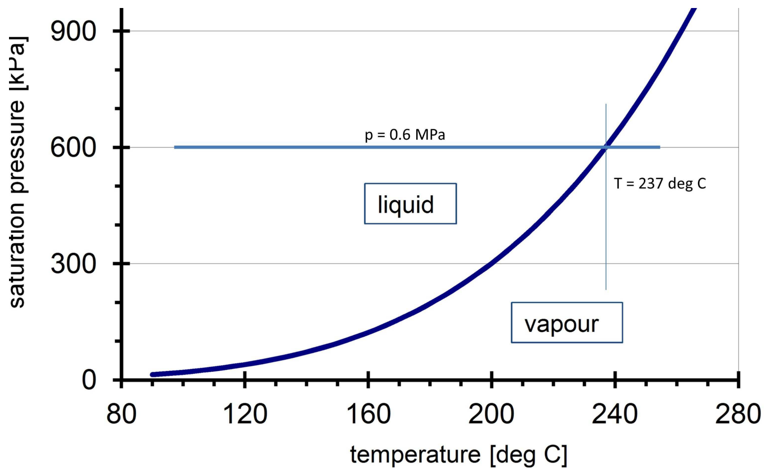

Figure 14: Characteristics of silicone oil: saturation pressure versus temperature.

Figure 17 explains why this is happening. A large ambient pressure, p, in the lubricating chamber on the one hand prevents the lubrication with liquid phase, but on the other hand, totally changes the pressure distribution in the lubricating gap. This pressure is similar now to the distribution with Sommerfeld boundary conditions, which obviously negatively affects the stability of the entire system.

Studies have shown that a very attractive idea of lubrication by means of low-boiling medium (Fig. 1) can not always be applied in practice, at least in the case of microturbines shown in Fig. 6. Bearings are lubricated by the liquid phase of low boiling medium but unfortunately work in the condition of strongly developed hydrodynamic instability.

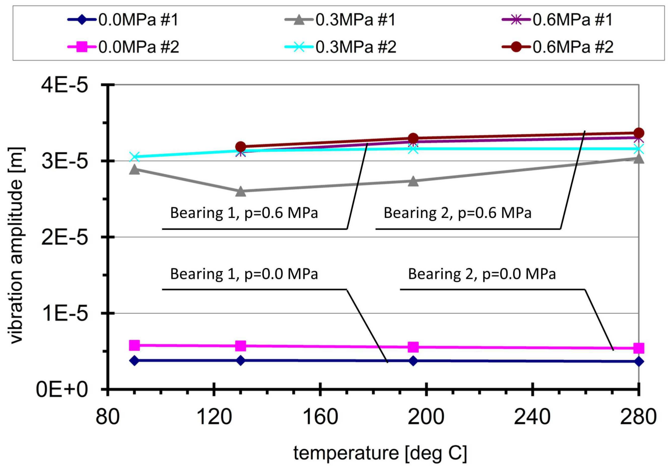

Figure 15: Course of vibration amplitude of bearings 1 and 2 depending on the ambient pressure of the lubrication chamber, p, and temperature. External forces acting on the system: fixed aerodynamic forces (calculated from 3D flow analysis) and residual unbalance in accordance with the ISO norm for this class of machines. Object of analysis: the turbine from Figs. 6 and 8. The analysis was carried out using a computer system MESWIR – Fig. 7 [9].

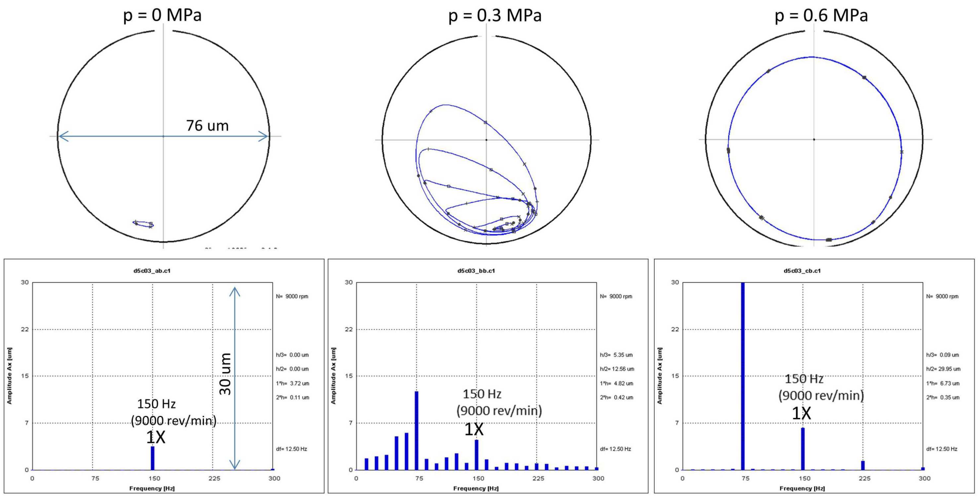

Figure 16: Trajectories and vibrations spectra calculated for bearing 1 and different ambient pressure of the lubrication chamber, p. Object of analysis: the turbine from Figs. 6 and 8. The analysis was carried out using a computer system MESWIR [9].

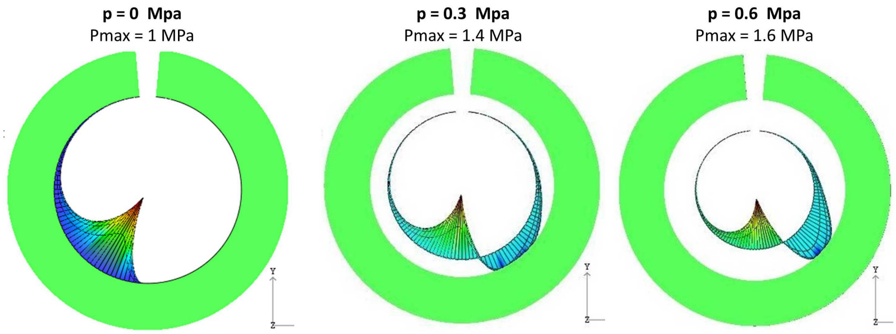

Figure 17: Pressure distribution calculated for bearing 1 and different ambient pressure of the lubrication chamber, p. Object of analysis: the turbine from Figs. 6 and 8. The analysis was carried out using a computer system MESWIR [9].

5 Concluding remarks

This paper presents only a few selected examples of specific devices (DES/RES) developed within research projects conducted by IMP PAN in Gdańsk. These are:

- domestic CHP Units,
- CHP plant in selected municipalities as an example of a ARE (Autonomous Energy Regions)

All of the above installations and laboratories might play an important role in the development of small-scale distributed power generation in Poland and EU countries.

The analysis of the dynamics of the microturbines dedicated for the ARE indicates possible difficulties in obtaining stable operation condition of the system. The bearing lubrication by means of low boiling medium is not always possible.

The results indicate a further two microturbines development paths, namely gas lubrication (gas phase of low boiling medium) or ball bearings. This work is currently being carried out.

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