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The dynamics of microturbines lubricated using 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. They 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 IMP PAN (Institute of Fluid-Flow Machinery of the Polish Academy of Sciences) in Gdansk. 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.

Key words: rotor dynamics, microurbines, distributed energy generation.

1. Preliminary remarks

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

This article focuses on the results of the work related to so-called “energy-plus” technologies and small & 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. The 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 plant is planned (the blocks consisting of a boiler and a microturbine operating with a low-boiling agent using an Organic Rankine Cycle (ORC) with the electric power of several kW and tens of kW of thermal power. Within 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 is 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 (ARE).

Tracking the discussions in the EU it can be concluded that the domestic CHP units, Autonomous Energy Regions 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 Countries [1–11].

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 (TUL), Gdansk University of Technology (GUT), University of Warmia and Mazury (UWM)) developed two concepts of microturbines with a capacity of 3 kW (axial-flow and radial-flow) coupled with a multi-fuel boiler with a capacity of 20 kW (biomass or gas fired). As far as microturbines are concerned, the essential idea is 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 a test stand in the microturbine laboratory (located at the IMP PAN in Gdansk) 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 station of this type. Figure 4 shows the developed targeted versions of microturbines.

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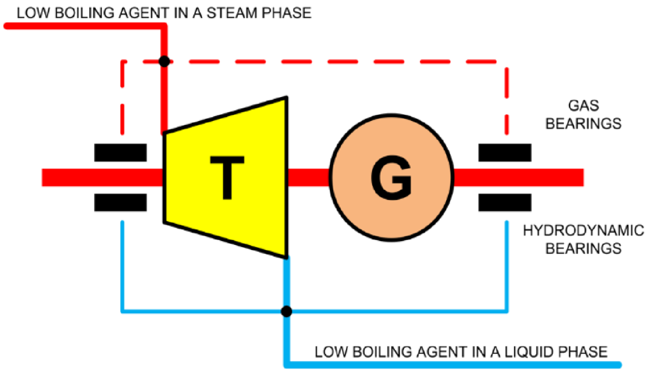

Fig. 1. The possibility of utilization of a microturbine's working medium in the liquid and gas phases as a bearing lubricant. The concept of a hermetic construction of a turbine and a generator to facilitate the integration with a boiler

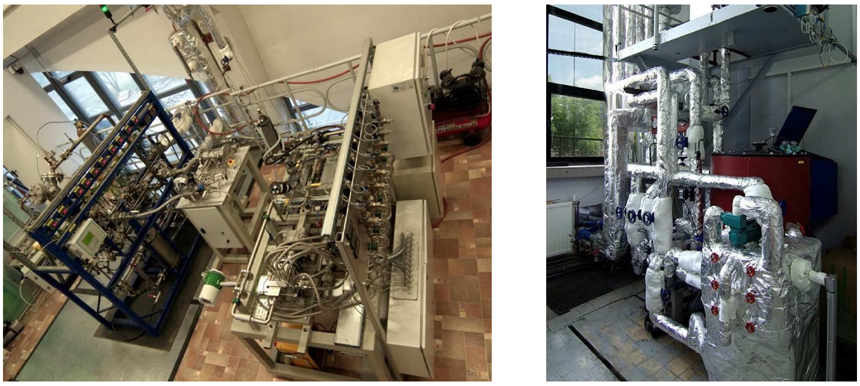

Fig. 2. The laboratory of the IMP PAN in Gdansk, pictures of microturbine test stand (on the left) and multifuel fired boiler (on the right)

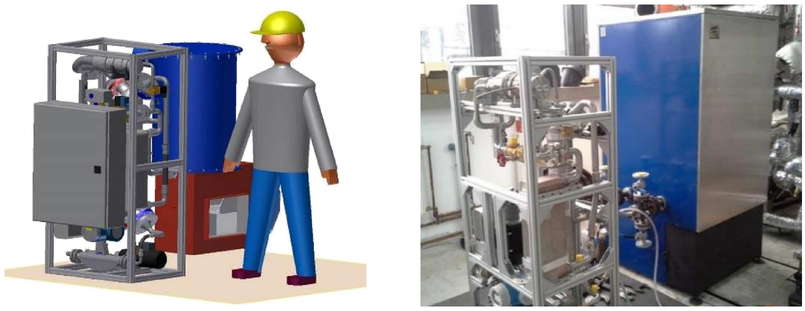

Fig. 3. Target design of Domestic Micro-CHP Unit with ORC after all examinations and tests in the laboratory of the IMP PAN in Gdansk, left – the first concepts, right – commercial version of the installation

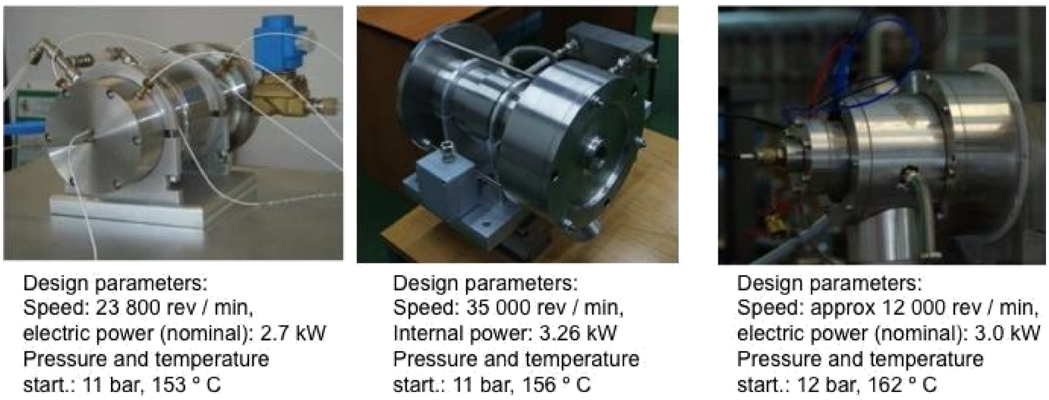

Fig. 4. Domestic Micro-CHP-ORC Unit Microturbines, developed target versions. Elaborated in TUL and GTU in cooperation with IMP PAN. Two pictures on the left: radial and supersonic microturbine, picture on the right: axial microturbine

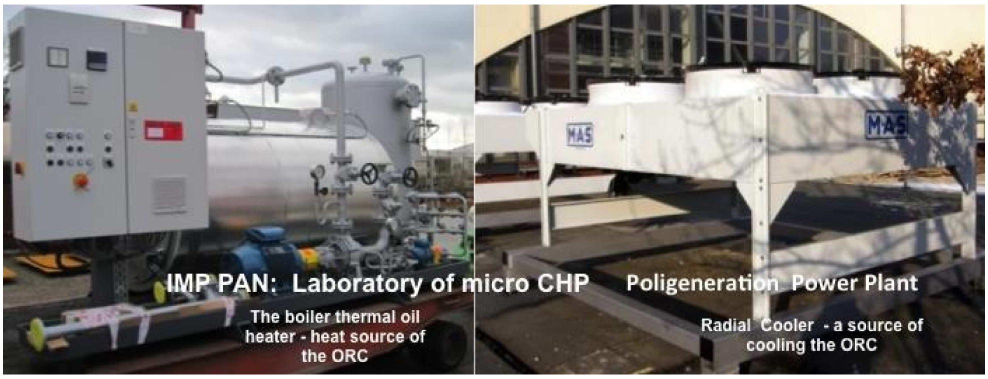

Fig. 5. The largest micro CHP Laboratory in Poland: the polygeneration power plant in IMP PAN in Gdansk

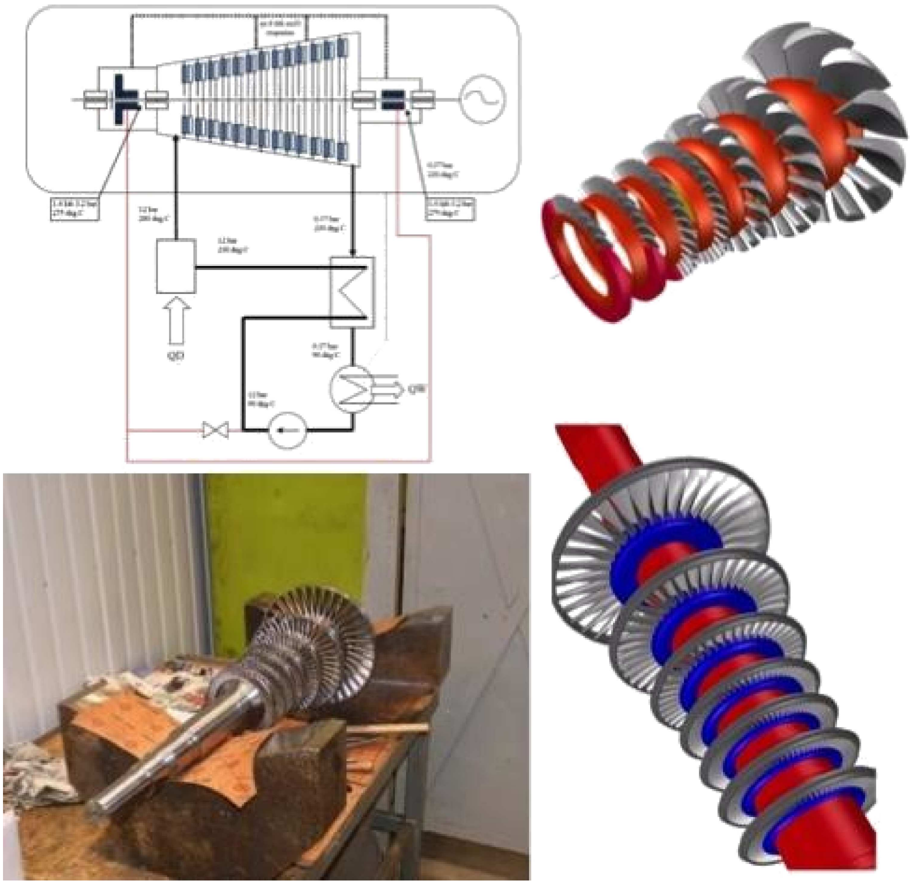

Fig. 6. IMP PAN Laboratory: ORC turbogenerator (own solutions). Axial turbine 9000 rev/min, Power 100 KW. Course of the working medium in the turbine (silicone oil) including the circulation in journal bearings. Utilization of a microturbine's working medium as a bearing lubricant

In the IMP PAN there is currently constructed the 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.

Basing on the ideas, presented in Fig. 1, have developed several versions of microturbines. One of such constructions is shown in Fig. 6.

Figure 7 shows a sketch of the turbine rotor and the finite element method (FEM) discretization scheme.

Dynamic analysis of the rotor and bearings was carried out using own tools developed in the IMP PAN, namely the computer system MESWIR – Fig. 8 [9]. The 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. The program MESWIR was developed for large rotor-bearing systems and, based on these objects has been verified many times [9]. This program can be used to facilities of lower power as in Figs. 6 and 7, provided that the flow of lubricant in the bearing is a single phase (liquid or gas) of known characteristics. In the case of low boiling lubrication the above fact may be a certain limitation as long as we are not able to identify accurately the operating conditions of the bearings.

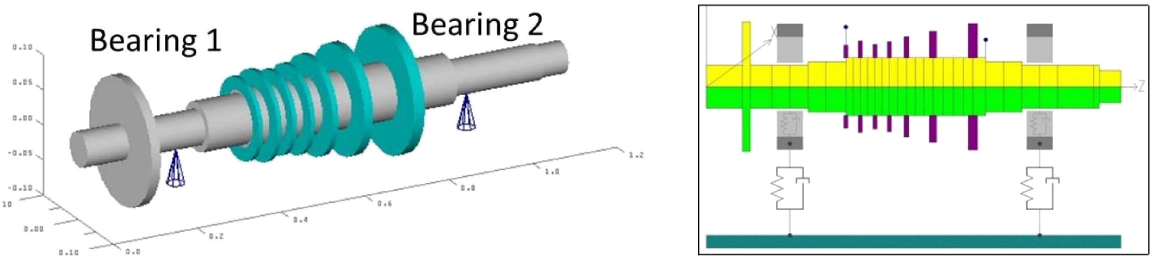

Fig. 7. Geometry and FEM discretization of the rotor microturbines from Fig. 6. The analysis was carried out using a computer system MESWIR (Ref. 9)

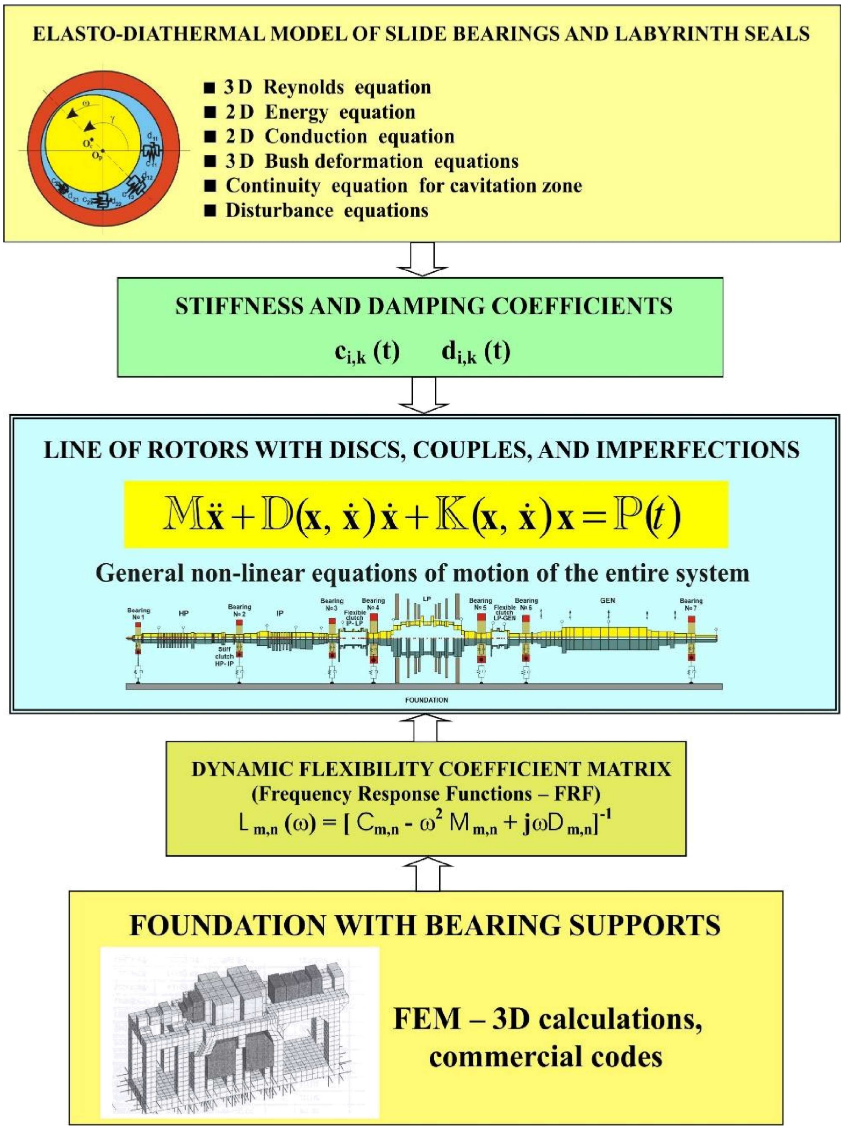

Fig. 8. Block diagram of computer program MESWIR. Nonlinear analysis of rotors dynamics – the set of differential equations (Ref. 9)

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 have conducted research on classical mineral oils. This enables us to do the comparison and facilitate evaluation of possible design solutions. Studies using mineral oils also explain phenomena taking place in the oil film at high rotor speeds (oil whirl and whip).

The object of this study is the bearings similar to 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.

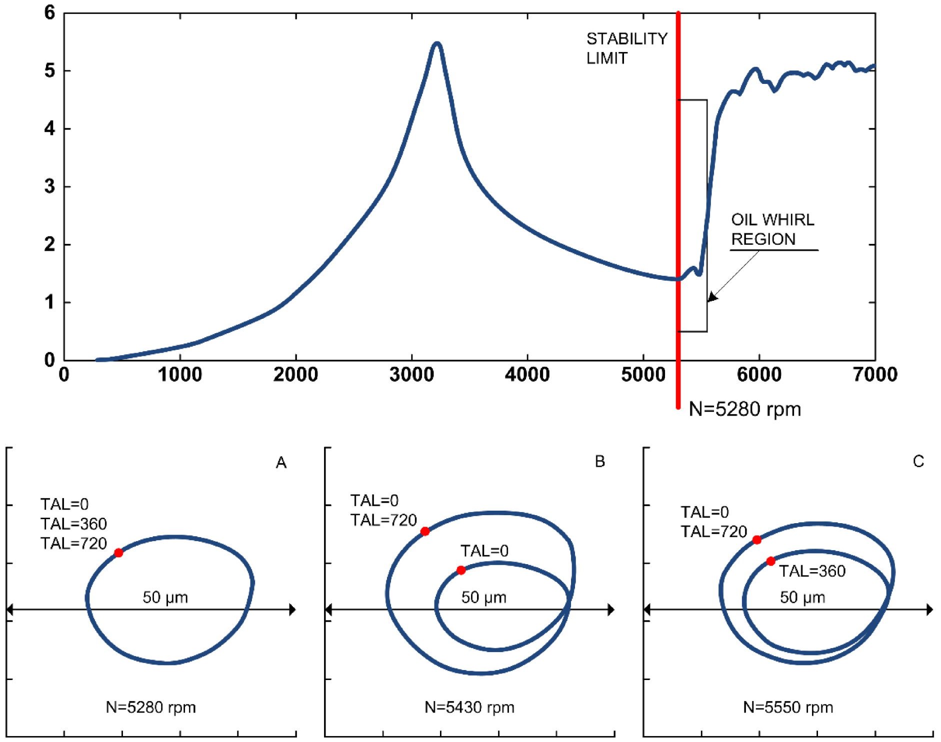

Fig. 9. Computer simulation of development of oil whirls after surpassing the stability threshold of the system – phase of small oil vibrations. Calculations were carried out using MESWIR system [9]

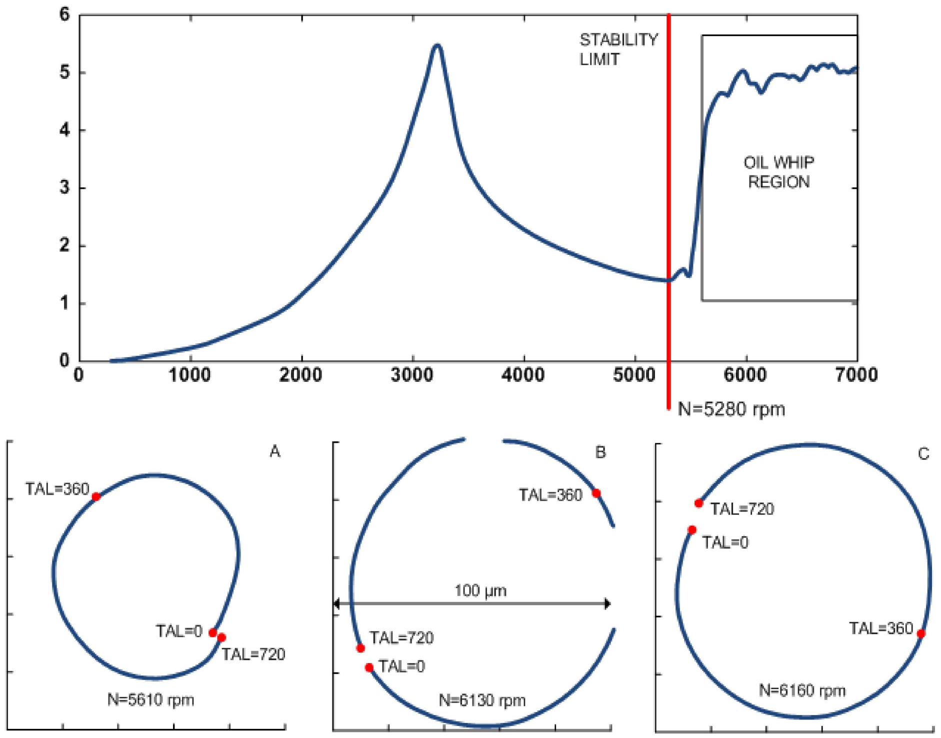

Fig. 10. Computer simulation of development of oil whipping phase – highly developed hydrodynamic instability. Calculations were carried out using MESWIR system after Ref. 9

The results of the computer simulation carried out using the MESWIR system are given in Figs. 9–12. We can observe the development of oil whirls and whips in bearing No. 1 as a function of the increment of rotor rotational speed after the stability threshold has been surpassed.

An interesting conclusion resulting from Fig. 9 is that oil whirls develop by slow splitting of the elliptical trajectory into two loops: external and internal. In the first phase the internal loop decreases, then starts increasing again, during which it moves to the place previously occupied by the external loop.

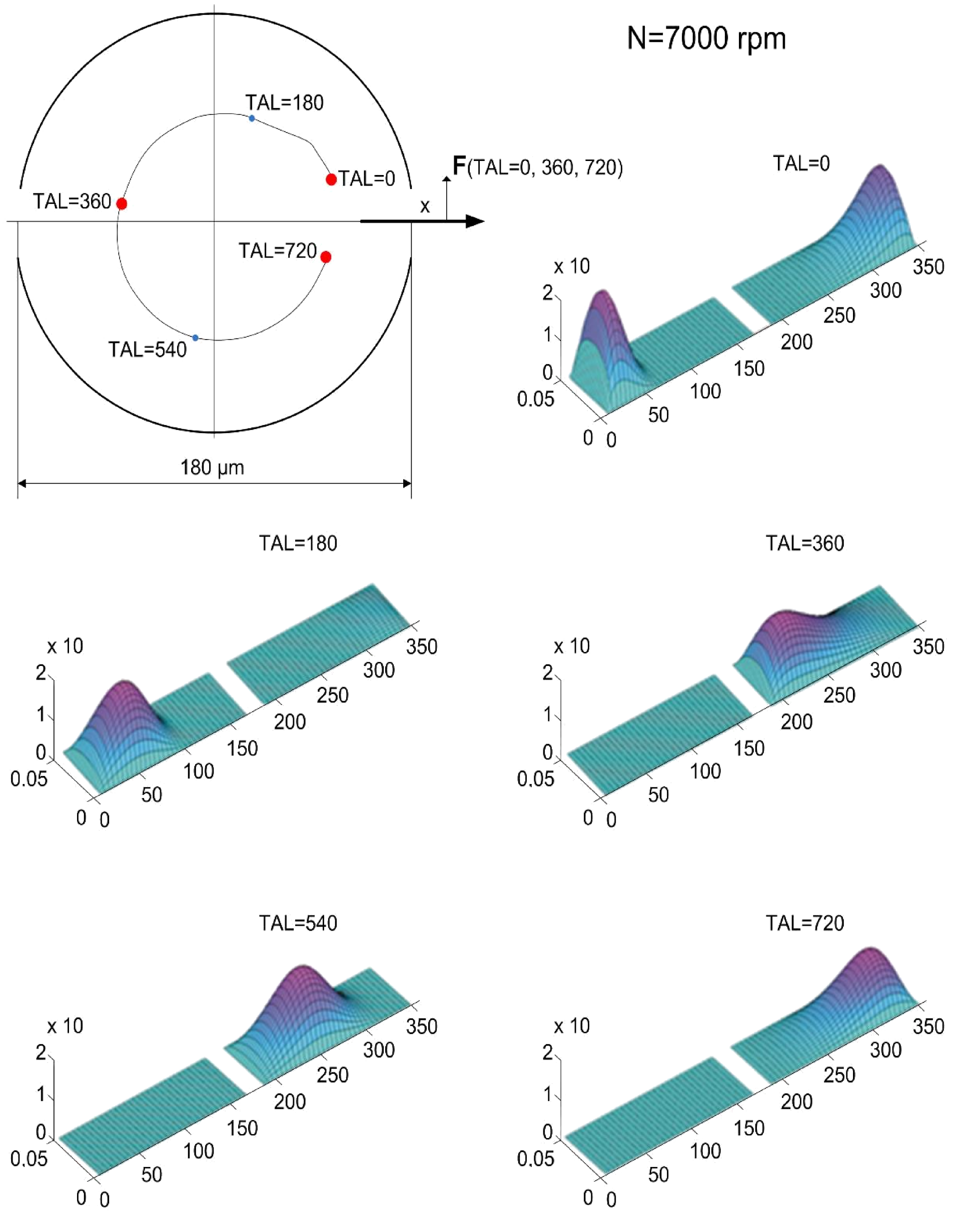

Fig. 11. Instantaneous hydrodynamic pressure distributions in the bearing for selected journal positions on the trajectory within the oil whipping range. The trajectory is presented on the background of the bearing clearance circle

The initial external loop decays with time, and in the final whirl development phase we have only one trajectory of a shape close to a circle. The whirls start the next, much more dangerous development phase, which is oil whipping. This situation is illustrated in Fig. 10. The observation of phase markers, i.e., the locations on the trajectories corresponding to external excitation force vectors directed horizontally to the right in the assumed reference system (TAL= 0, 360, or 720 degrees) provides practical data on the diagnostic factor referring to the hydrodynamic instability, as illustrated in Figs. 11 and 12.

Figure 11 shows that in advanced phases of oil whipping the same position of the external excitation force vector (unbalance vector) corresponds to three different pressure distributions and, as a consequence, three different dynamic states of the bearing. It means that this state is represented by as many as three phase markers in the recorded trajectory range between 0 and 720 degrees. In this convention the oil whirls have two phase markers, while the range of stable operation of the machine have one marker. This is illustrated in Fig. 12. The conclusions resulting from the analysis of Fig. 12 can be of high importance for monitoring the hydrodynamic instability, as they deliver practical measure of this type of states in the form of a number of phase markers. Obviously, other diagnostic determinants can be named which are specific for oil whirls and whips (vibration spectra, for instance), but they are neglected here due to limited volume of the paper and its aim.

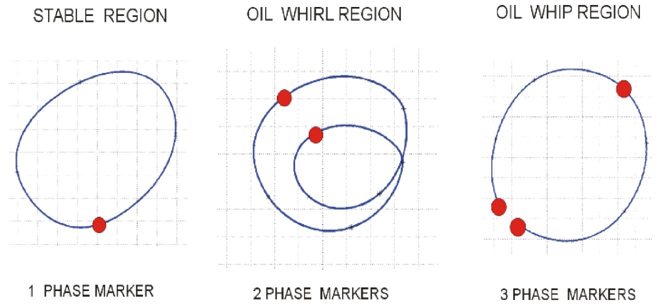

Fig. 12. Proposed classification of hydrodynamic instabilities in the system and introduction of diagnostic determinants

From the point of view of the microturbines operation is also interesting to examine the behavior of the bearings in the case of hybrid lubrication (pressurizing the siphon pockets) and of increased supply pressures. The results show Figs. 13–15.

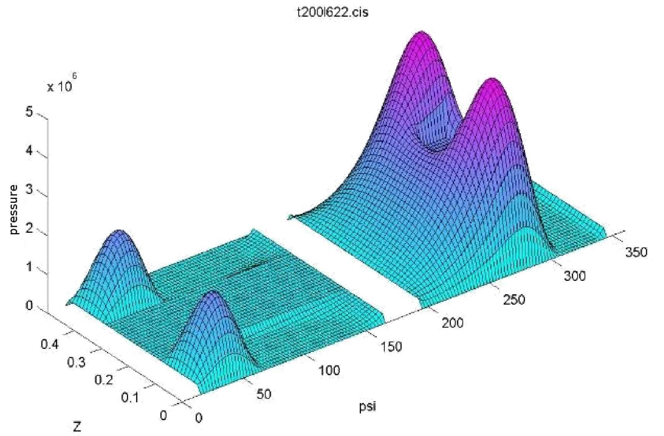

Fig. 13. Hybrid lubrication. Pressure distribution in the bearing with the siphon pressure $p_{lew} = 2$ MPa and the supply pressure in oil pockets $p_0 = 0.2$ MPa

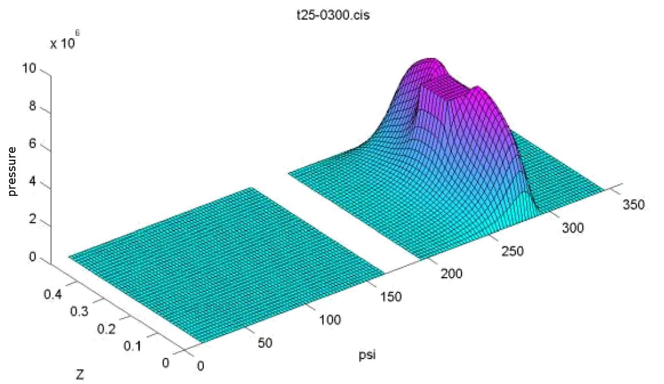

Fig. 14. Hybrid lubrication. Pressure distribution in the bearing with the siphon pressure $p_{lew} = 5$ MPa and the supply pressure in oil pockets $p_0 = 0.2$ MPa

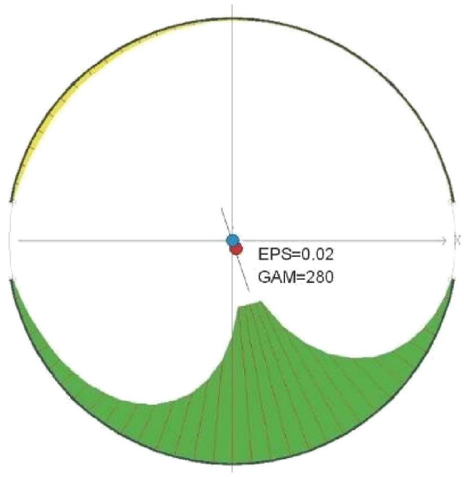

Fig. 15. Pressure distribution in the midline against the clearance circles and bearing eccentricity

These studies show that the increase in supply pressure and the siphon pressure negatively affect the bearing dynamics. This is because the eccentricity of the bearing (EPS) decreases which causes rapid loss of stability. In Fig. 15, as we see, the value of the relative eccentricity is extremely small and is only EPS = 0.02. Such a situation may already be dangerous considering the operation of the entire system.

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. 16. In this case we are dealing with gas phase lubrication, which significantly changes the dynamics of bearings and rotor.

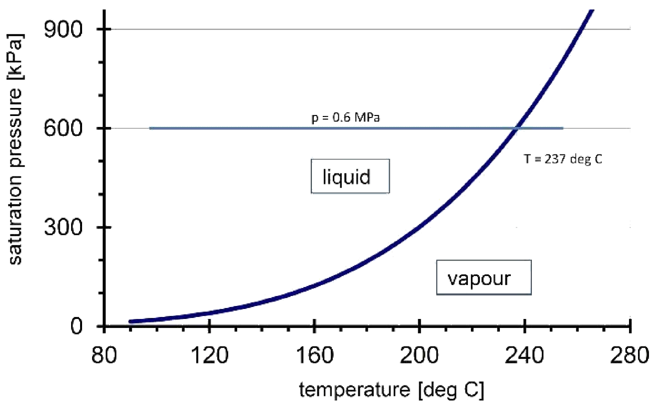

Fig. 16. Characteristics of silicone oil: saturation pressure versus temperature

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. 16, the liquid phase lubrication is possible at a temperature up to 240 degrees C.

The results of the analysis carried out by means of a computer system MESWIR are presented in Figs. 17 to 19.

Figure 17 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. 18 exactly. For the value of $p = 0.6$ MPa in the vibration spectrum appears a strong subharmonic component.

Figure 19 explains why this happens. A large ambient pressure p in the lubricating chamber on the one hand, prevents the lubrication with a liquid phase, but on the other hand, it 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) cannot always be applied in practice, at least in the case of microturbines shown in Fig. 6.

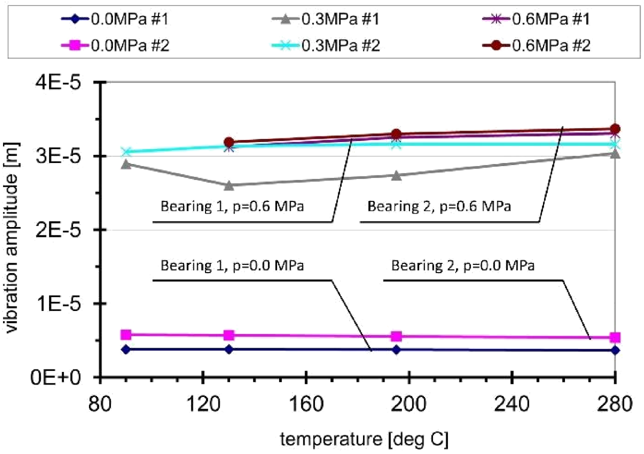

Fig. 17. Course of vibration amplitude of bearings 1 and 2 depending on the ambient pressure of the lubrication chamber p and temperature. External forces acting on the system: fixed aerodynamic forces (calculated from 3D flow analysis) and residual unbalance in accordance with the ISO norm for this 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 (Ref. 9)

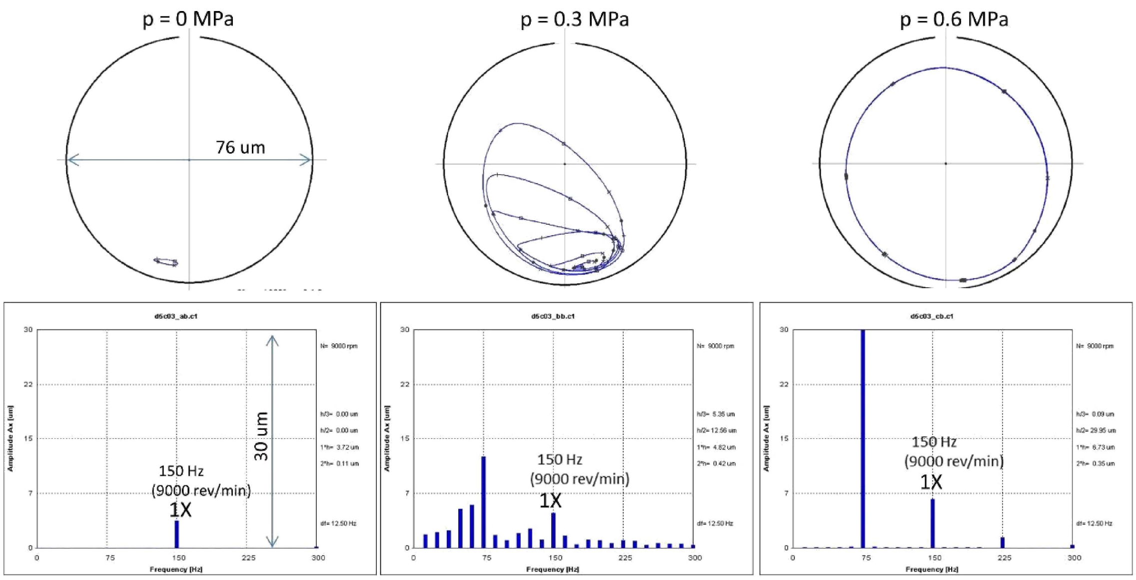

Fig. 18. Trajectories and vibrations spectra calculated for bearing 1 and different ambient pressure of the lubrication chamber p. Object of analysis: the turbine from Figs. 6 and 8. The analysis was carried out using a computer system MESWIR (Ref. 9)

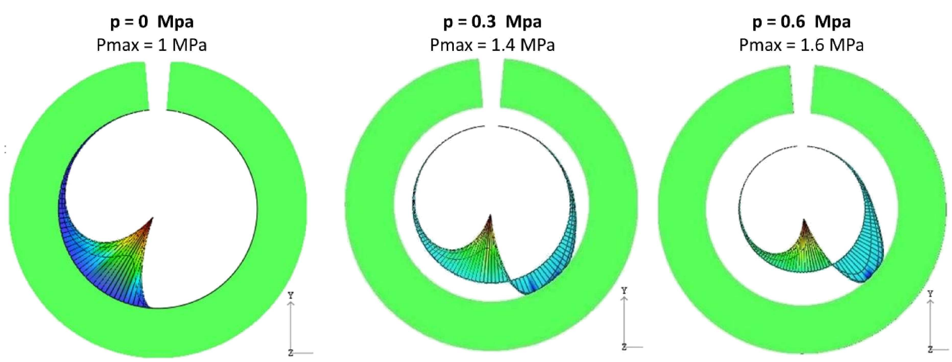

Fig. 19. Pressure distribution calculated for bearing 1 and different ambient pressure of the lubrication chamber p. Object of analysis: the turbine from Figs. 6 and 8. The analysis was carried out using a computer system MESWIR (Ref. 9)

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 Gdansk. 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 microturbines dedicated to the ARE indicates possible difficulties in obtaining stable operation conditions 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 conventional oil. This work is currently being carried out.

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