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Design analysis of turbines for co-generating micro-power plant working in accordance with organic Rankine's cycle

Jarosław Mikielewicz,
Marian Piwowarski,
Krzysztof Kosowski.

Abstract

This paper presents results of a design analysis of turbines for co-generating micro-power plant working in accordance with organic Rankine's cycle and using biofuel. The heat power range from 25 kW to 100 kW with corresponding available electric power from 2kW to 12kW, was considered. Designs of axial-flow turbines (single-stage and multi-stage ones, also those partially fed), radial-flow and axial-radial -flow ones, were analyzed. Particular variants of the solutions were compared to each other.

***Keywords**: micro power plant, microturbines, organic Rankine cycle, turbine design*

Introduction

In the subject-matter literature steam micro-turbines are considered to be such devices which produce output power of the order of a few kW or even W. For last years greater and greater interest paid to such machines and their dynamic development has been observed. Hybrid co-generating systems, either three-generating or combined gas-steam ones can be most often met [1-3,10-13,16,18-21,24,25,27]. Steam turbines may find application to micro-power plants which co-generate electric power and heat. A micro-power plant based on water steam turbine, described in [14], can serve as an example. The system delivers electric power amounting from 0,5k W to 4,6 kW as well as heat power - from 2 kW to 25 kW. In the literature can be met examples of steam micro-turbines of much lower values of output power, built with the use of the MEMS technology (Micro-Electro Mechanical System) [6÷8]. Apart from the traditional medium, i.e.water vapour, also low-boiling media, as a rule organic ones, are taken into consideration. In this case the Organic Rankine Cycle (ORC) is dealt with. For many years such installations of electric power output of the order of several hundred kW or MW have been used in power plants based on geothermal sources [4,5,17,26]. On the market are already available the co-generating systems working on organic media, e.g. the power plant of 300÷600 kW electric power and 1500÷2800 kW heat power, or that of 200÷1000 kW electric power and 1000÷6000 kW heat power [9]. However only a few examples can be found of ORC installations of output power smaller than 100 kW, which operate in co-generating systems (e.g. the ORC-CHP system intended for biomass combustion [23], or the systems generating: 72 kW [22] or 30 kW [15] of electric power). Under research are: a turbine set of 5÷12 kW electric power at 70÷115ºC inlet temperature of working medium (R134a, R245fa, R22, R6xx, R7xx) [15], and a power plant working on n-pentane and developing 1.5÷3 kW power (at 90÷100ºC vapour temperature) [21].

Problems faced by designers of such turbines are associated with very small volumetric flow rate of working medium. It leads to small values of height of flow-part blades (hence to increased loss of flow rate) and high values of rotor speed, namely from a few dozen to over a hundred thousand rpm, usually.

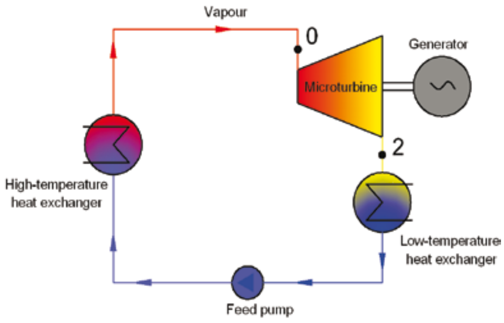

***Fig. 1**. Schematic diagram of micro-power plant cycle*

In all the considered variants the power plants operated on the Solkatherm®SES36 working medium. Calulations were performed in compliance with the power plant schematic diagram shown in Fig. 1, for four values of the cycle's thermal power: 25 kW, 50 kW, 75 kW and 100 kW. Particular variants, depending on a heat power value, differred from each other only by value of working medium flow rate, and its parameters at turbine inlet, as well as pressure behind the turbine were the same for all the considered cases:

-the pressure at turbine inlet, $p_0 = 1464$ kPa,

-the temperature at turbine inlet, $t_0 = 140\ {}^0C$,

-the pressure behind the turbine, $p_2 = 189$ kPa.

Within the frame of performed design analyses the following types of microturbines were taken into account:

- single-stage axial-flow turbine,
- two-stage axial-flow turbine,
- four-stage axial-flow turbine,
- single-stage radial-flow turbine,
- single-stage radial-axial-flow turbine.

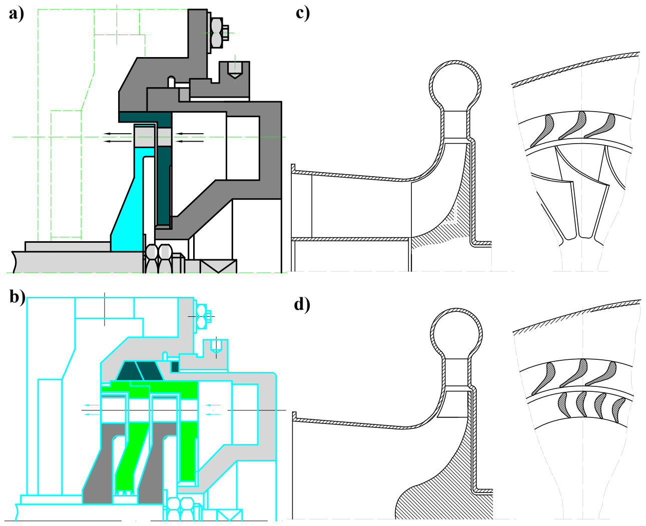

Fig. 2**. Examples of the considered constructional types of micro-turbines:* ***a) *single-stage axial-flow turbine,* ***b)*** *two-stage axial-flow turbine,* ***c)*** *radial-axial-flow turbine,* ***d)*** *radial-flow turbine*

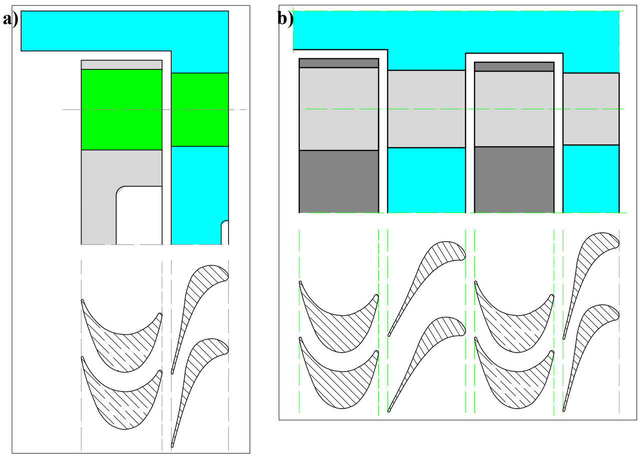

Fig. 3**. Examples of flow part of micro-turbines:* ***a) *single-stage axial-flow turbine,* ***b)*** *two-stage axial-flow turbine*

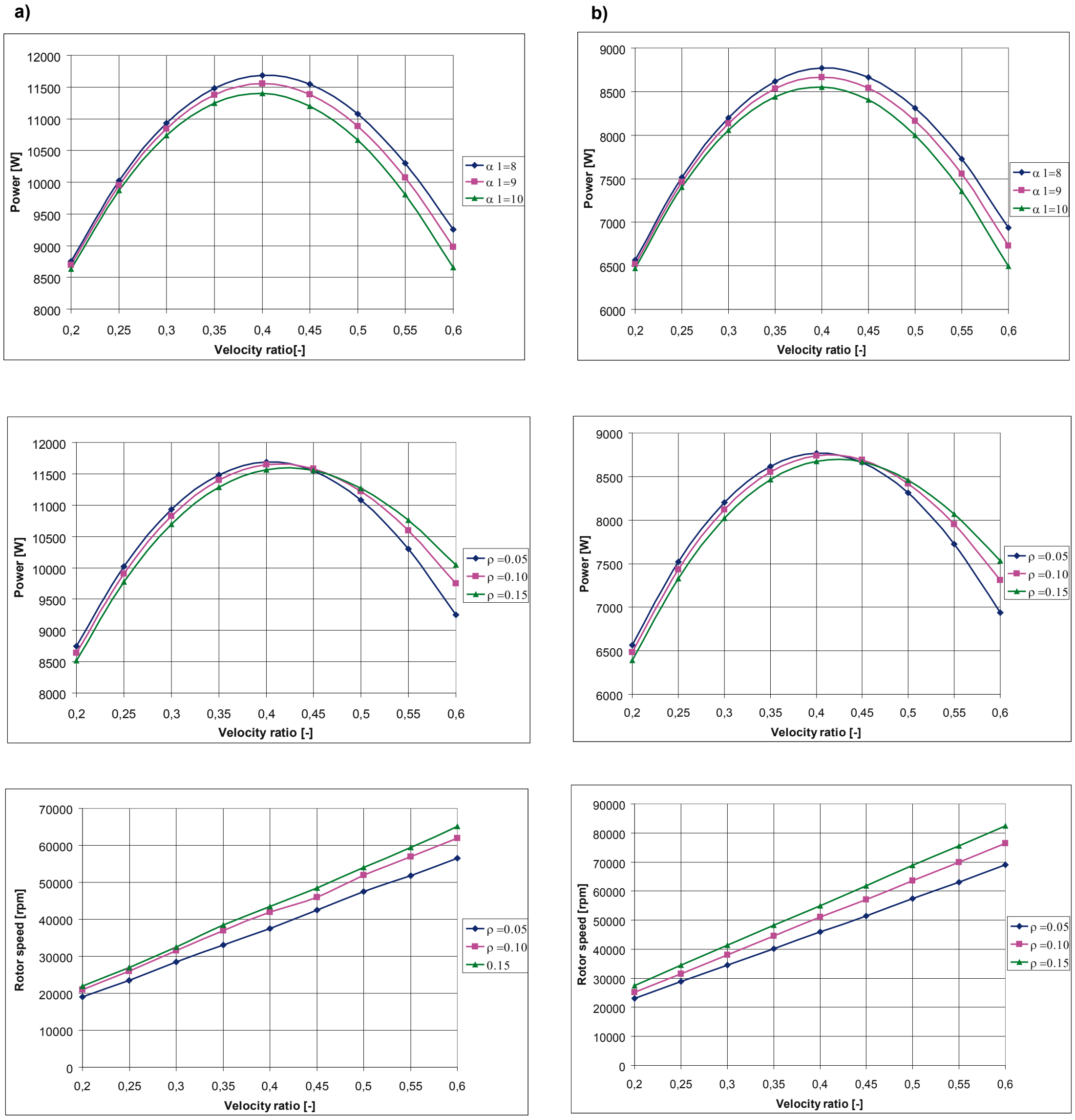

Fig. 4.** Examples of design characteristics of single-stage axial –flow turbine: turbine output power in function of velocity ratio for three assumed values of the angle α_1, turbine output power in function of velocity ratio for three assumed values of the reactivity ρ, rotor speed in function of velocity ratio for three assumed values of the reactivityρ,* ***a) *plant's heat power – 100 kW,* ***b)*** *plant's heat power – 75 kW*

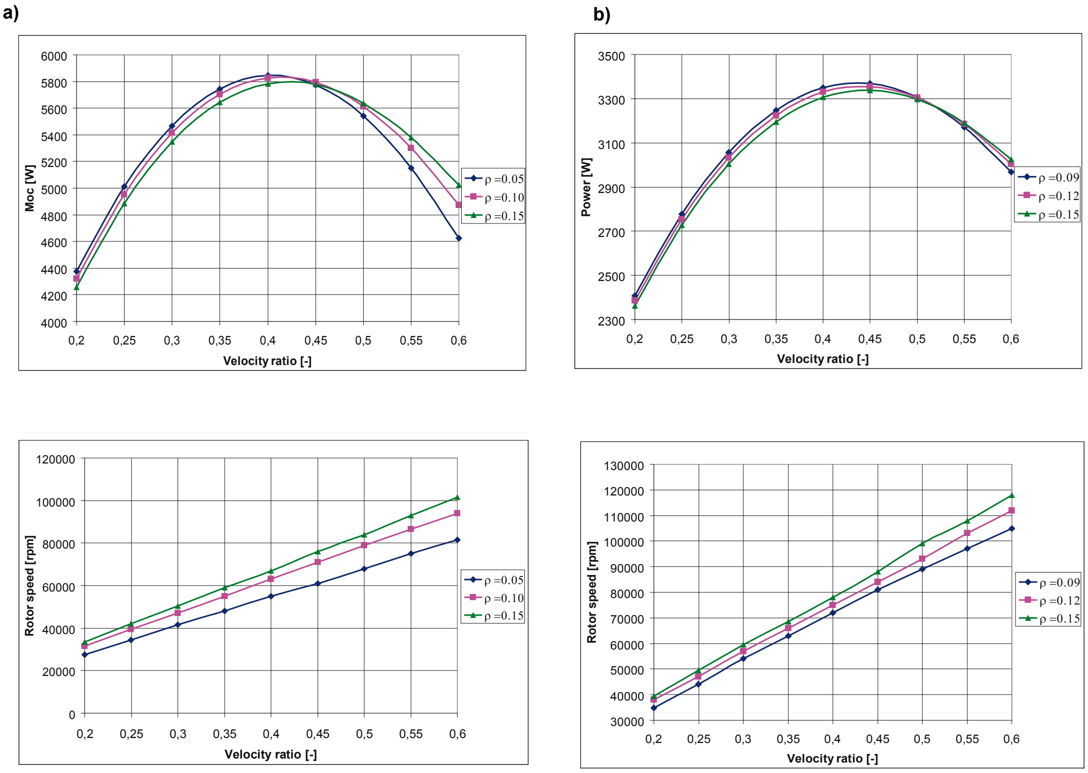

***Fig. 5.** Examples of design characteristics of single-stage axial-flow turbine: turbine output power in function of velocity ratio for three assumed values of the reactivity ρ, rotor speed in function of velocity ratio for three assumed values of the reactivity ρ,*
***a)** plant's heat power – 50 kW,* ***b)** plant's heat power – 25 kW*

Examples of the considered design solutions are presented in Fig. 2. For all the variants preliminary optimization of main design parameters was performed and appropriate blade profiles were selected. Examples of the flow part of single-stage and two-stage axial-flow turbines are given in Fig. 3.

Results of design analyses of micro-turbines

Calculations of flow-part of turbine were performed by assuming different sets of values of main design parameters such as: velocity ratio, reactivity and outlet angle of guide vanes grid. Examples of design characteristics are presented in Fig. 4 for plant's heat power values: 100 kW and 75 kW, and in Fig. 5 for plant's heat power values: 50kW and 25kW. For the greatest heat power value (100 kW) of the considered co-generating systems, the electric power value of ~11,5 kW can be obtained at the rotor speed of about 45000 rpm. For the smallest considered heat power value (25 kW) the above mentioned quantities amount to about 3.35 kW and 80000 rpm, respectively.

Possible elaboration of series of types of turbines which would be suitable for the power range of 25 kW ÷ 100 kW and of the same design and similar gabarites, has been also considered. It was decided that all turbines, regardless of their power, would be built of the same rotor and the only difference would consist in adjusting the feeding arc of vane blades grid, respectively. It was assumed that the 100 kW turbine would operate with full feeding arc, hence turbines of smaller power values would operate with smaller feeding arcs, respectively. Examples of design characteristics of single-stage axial-flow turbines working with partial feeding are presented in Fig. 6. Application of feeding arc makes that power values of turbines working with partial feeding are smaller than those of turbines with full feeding (compare Fig.4 and Fig.5 with Fig.6), however in the variants of smaller power values rotor speed values were significantly lower, e.g. for the plant's heat power of 25 kW, when partial feeding has been applied, the turbine's electric power decreased from 3,35 kW to 2.65 kW, but with accompanying drop of rotor speed from about 80000 rpm to about 40000 rpm. Significantly lower production costs would be reached as a result of standardization, application of rotors of the same design to all variants, and possible selection of a generator intended for lower rotational speeds (definite influence on price of turbine set).

Similar design calculations were carried out for the remaining constructional types of turbines in question; their results are presented in Tab. 1. For the presented solutions suitable electric generators were selected; their main particulars are attached also in Tab. 1.

For the variant of 100 kW heat power of the power plant the largest electric power values (~ 12,3 kW) were obtained in the case of application of the radial turbine or two-stage axial-flow turbine. In most considered cases the radial-flow turbine as well as two-stage axial-flow turbine turned out to be the most profitable as regards the obtained electric power value. From this point of view the radial–axial–flow turbine appeared the worst.

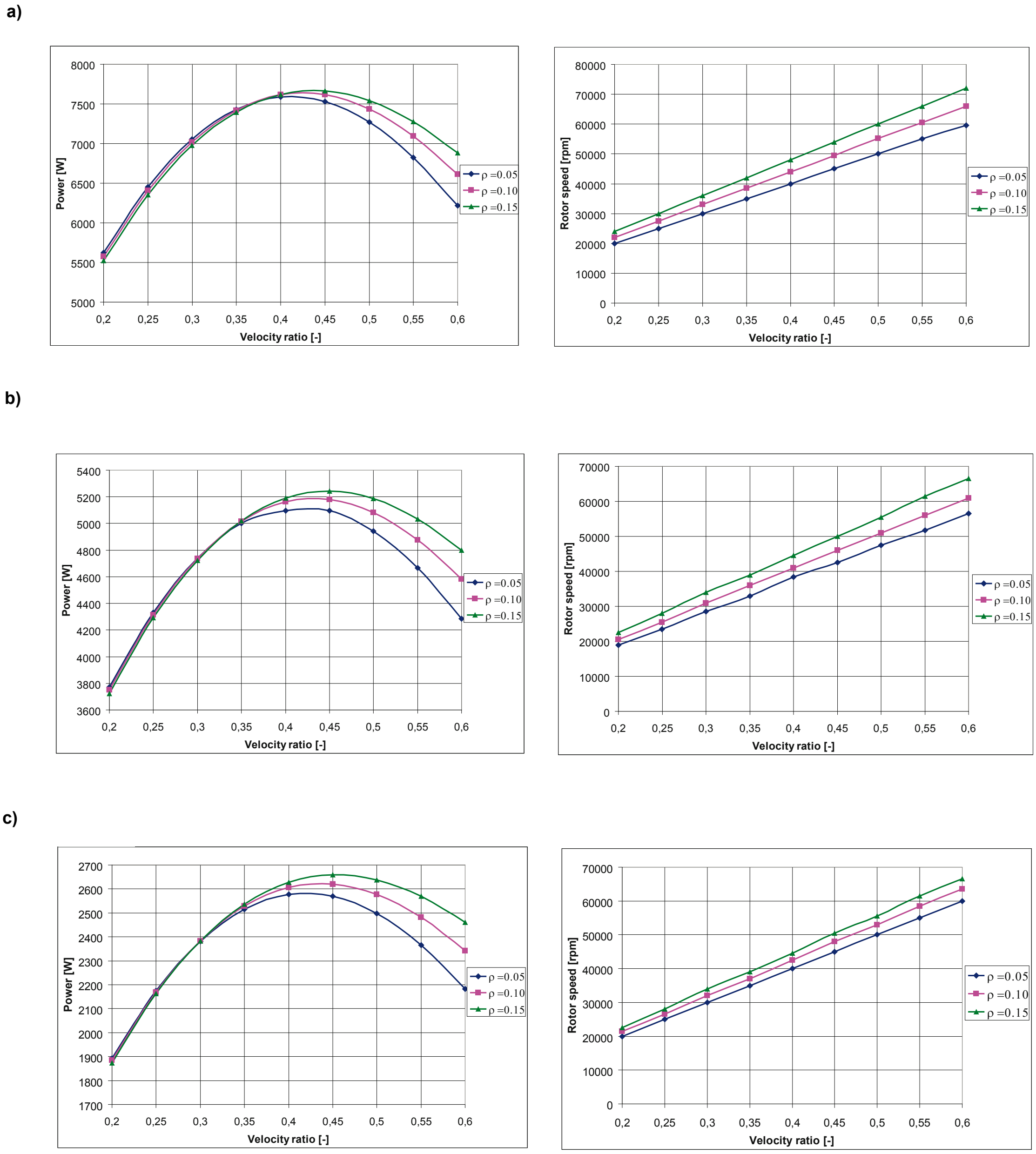

Fig. 6. Examples of design characteristics of single-stage axial-flow turbine with partial feeding: turbine output power in function of velocity ratio for three assumed values of the reactivity ρ, rotor speed in function of velocity ratio for three assumed values of the reactivity ρ
plant's heat power – 75 kW, feeding arc of ~ 0,75
plant's heat power – 50 kW, feeding arc of ~ 0,50
plant's heat power – 25 kW, feeding arc of ~ 0,25

Summary

Calculations of a few dozen of variants of turbines of various constructional types and different values of main design parameters, were performed. The following turbines were taken into consideration: single-stage axial-flow turbines, two-stage axial-flow turbines, radial-flow turbines and radial-axial-flow turbines. It was demonstrated that in the case of co-generating micro-power plant working with low-boiling medium (in accordance with the ORC principle) the following electric power values are possible to be obtained depending on a heat power value of the system:

-10,4 kW ÷ 12,8 kW (for 100 kW heat power),
-7,6 kW ÷ 9,4 kW (for 75 kW heat power),
-5,0 kW ÷ 6,1 kW (for 50 kW heat power),
-2,4 kW ÷ 3,3 kW (for 25 kW heat power).

Rotor speed values of the considered micro-turbines were relatively high as they amounted to from 21000 rpm to 134 000 rpm depending on working medium mass flow rate, constructional type of turbine and choice of its main design parameters. For many variants one managed to select suitable electric generators. However, because of high rotational speeds, novel innovative design, material and technological solutions should be applied in developing power plants of the kind.

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***Tab. 1.** Specification of main particulars of turbo-generators*

No.	Type of turbine	Particular	Unit	Power plant of 100 kW heat power	Power plant of 75 kW heat power		Power plant of 50 kW heat power		Power plant of 25 kW heat power	
					Full feeding	Partial feeding	Full feeding	Partial feeding	Full feeding	Partial feeding
1	single-stage axial-flow	Average diameter	[m]	0,055	0,048	0,055	0,035	0,055	0,025	0,055
		Length of rotor blade	[m]	0,0058	0,005	0,0058	0,0037	0,0058	0,0027	0,0058
		Power of turbine	[W]	11688	8768	7586	5826	5098	3248	2577
		Rotational speed	[rpm]	40000	46000	40000	63000	40000	76000	40000
		Length of generator	[m]	0,12	0,1	0,1	0,085	0,10	0,085	0,085
		Outer diameter of generator's stator	[m]	0,06	0,055	0,060	0,055	0,055	0,055	0,055
2	two-stage axial-flow	Average diameter	[m]	0,04	0,035	0,04	0,029	0,04	0,02	0,04
		Length of rotor blade (1st stage)	[m]	0,0042	0,0036	0,0042	0,0029	0,0042	0,0021	0,0042
		Length of rotor blade (2nd stage)	[m]	0,0046	0,0038	0,0046	0,0031	0,0046	0,0023	0,0046
		Power of turbine	[W]	12273	9241	8756	6167	5794	3102	2927
		Rotational speed	[rpm]	33600	38500	33600	47000	33600	67000	33600
		Length of generator	[m]	0,126	0,12	0,12	0,100	0,0120	0,085	0,085
		Outer diameter of generator's stator	[m]	0,07	0,060	0,060	0,055	0,055	0,055	0,055
3	radial-axial-flow	Outer diameter of rotor blades grid	[m]	0,0517	0,0402	-	0,0324	-	0,0224	-
		Power of turbine	[W]	10426	7643	-	4974	-	2367	-
		Rotational speed	[rpm]	62081	78846	-	96566	Max. catalogue value: 80 000	136565	
		Length of generator	[m]	0,12	0,1	-		-		-
		Outer diameter of generator's stator	[m]	0,055	0,055	-		-		-
4	radial-flow	Outer diameter of rotor blades grid, d1	[m]	0,061	0,053	-	0,043	-	0,03	-
		Power of turbine	[W]	12306	9231	-	6154	-	3077	-
		Rotational speed	[rpm]	49076	56663	-	69397	-	98143	
		Length of generator	[m]	0,12	0,1	-	0,085	-		-
		Outer diameter of generator's stator	[m]	0,06	0,055	-	0,055	-		-