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# POWER LOSSES OF WORM GEAR PAIRS

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**Abstract:** In this paper are presented the power losses and sources of their occurrence in worm gear boxes. These are the losses that occur in the coupling of worm teeth and worm gear, losses in bearings, seals and oil churning power losses in the transmission. When the operation of worm gearing is characterized by line contact of coupled elements which is accompanied by significant sliding, the highest value have the power losses in the worm and worm gear coupling compared to other losses in gearing. Among other things, in the paper also presents the expressions that are used for calculation of individual power losses and efficiency of the gearing. The size of the losses primarily depends on the type of coupled material and geometry of worm pair, circumferential velocity (input rotational speed), the type and viscosity of lubricating oil, load, worm shape, and temperature and so on. The paper also deals with the influence of different factors on power losses and efficiency. As the efficiency of the worm pair is significantly lower compared to other types of gear pairs, the appropriate combination of geometric parameters and materials of worm and worm gear, lubrication and working conditions can significantly affect its increase.
**Keywords:** power losses, efficiency, worm gearing

## INTRODUCTION

Gear boxes present the most widespread and the most important group of mechanical transmissions by which the movement, that is torque is transmitted from one shaft to another and transforms by direct touching of teeth. Gear boxes are formed by different connection of gear pairs. [1] These are the most often used power transmissions that can be used for different positions of the input and output shaft, as well as for the very wide range of power, rotational speed and transmission ratios. [1]
Worm gearing as hyperboloid gear pairs whose axes intersect are characterized by the line contact of the worm and worm gear. The line contact is accompanied by the relatively high sliding friction between coupled elements and forming of satisfactory lubricating layer. Apart from sliding friction in worm and worm gear mesh, friction occurs in the bearings, between the gear and oil, in sealing and so on. The consequences of the friction at worm gearing are power losses, lower efficiency, scuffing and damaging of gearing elements, gearing heating and so on. [2]. The highest friction losses occur in worm gear and worm gearing mesh and their size can be significantly affected by selection of parameters that define the gear pairs. The higher friction coefficients mean higher power losses and thus the lower efficiency values of worm gearing.
The worm gearing efficiency has lower value compared to the other types of gear boxes. If they are applied as multipliers the efficiency is less than 50%, while as applied as redactors, with appropriate design it is possible to achieve the efficiency above 90% [1].
A number of authors have researched the influence of different factors on power losses in worm gearings. Magyar and Sauer [3] from Kaiserslautern University have developed a technology for calculation of power losses in worm gearing and have determined that average losses value in worm gear and worm gearing mesh is three times higher compared to losses in gearings (four rolling bearings) which were second in size in total power loss.
Niemann and Winter [4] especially emphasize the influence of worm pair geometry on the efficiency where they showed that by reducing the ratio of mean diameter and centre distance $(d_{m1}/a)$ and at lower transmission ratios the higher efficiency values are obtained. For

example, at transmission ratio $i = 5$ and input rotational speed $n_1 = 1500\,\text{min}^{-1}$ the measured efficiency value was $\eta = 96\,\%$. On the other hand, according to Budynas and Nisbett [5], the increase of worm lead angle ($\gamma_m$) was followed by higher efficiency values.

Stockman et al. [6] using the specially designed equipment have tested the efficiencies of thirteen different gear boxes and found that at lower transmission ratios and higher input torques the higher efficiency values are obtained. They compared the obtained values to catalogue manufacturer's values and found significant discrepancies, because in catalogue usually is cited only one efficiency value for a wide range of transmission ratios, powers and manufacturing technologies.

Mautner et al. [7] have tested the influence of viscosity and type of the oil on efficiency of a large sized worm gearing with center distance $a = 315$ mm using FZG equipment. By using the high viscosity synthetic polyglycol oil (ISO VG 460) the measured efficiency values were higher for approximately 1% compared to lower viscosity synthetic oil (ISO VG 220) and for 3% compared to mineral oil.

Muminovic et al. [8] and Hermann [9] in their papers have also emphasized the advantages of the usage of synthetic oils compared to mineral oils where the higher efficiency values were obtained. Among other things, Hermann [9] also researched the influence of different synthetic oils and found that high-performance synthetic oil produced by "Klüber Lubrication" (Klübersynth GH 6-460) provides significantly less scuffing, less heating of gearing and higher efficiency compared to standard synthetic oils which are used for lubrication of worm gearing defined in DIN 3996 Standard.

Miltenovic et al. [10] have researched the worm gearing efficiency for the extreme working conditions where they used high-quality synthetic oil (high viscosity oil Klübersynth GH 6-1500) and high-quality material for manufacture of worm pair (hardened bronze/hardened and grounded steel). The measured efficiency values ranged in the interval $\eta = 0.52 \div 0.71$, where the higher values were found at higher loads.

## EFFICIENCY OF WORM GEARING

Efficiency of machines and mechanisms is determined as the ratio of useful and input energy and presents parameter for estimation of technical systems to preserve transported energy. At the same time, it is one of the most important criteria for evaluation of validity of given construction.

At power transmission the efficiency is defined as the ratio of output power toward input power, i.e. resulting toward input work [1]:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{in} - P_G}{P_{in}} = 1 - \frac{P_G}{P_{in}} < 1, \quad (1)$$

where are: $P_{in}$ – input power [*W*]; $P_{out}$ – output power [*W*]; and $P_G$ – total power loss [*W*].

Output power is equal to input power reduced for power which loses in transmission in various resistances ($P_G$) and which is mostly converted into heat. Ratio between power losses and input power $P_G / P_{in}$ presents the level of losses and if this ratio is smaller the gearing efficiency is higher and vice versa.

If $P_1$ denotes power on the worm and $P_2$ denotes the power on worm gear then the efficiency of worm gearing can be determined as follows [1]:

- for the case that the worm is driving element:

$$\eta_p = \frac{P_1 - P_G}{P_1} = \frac{P_2}{P_2 + P_G}, \quad (2)$$

- for the case that worm gear is driving element:

$$\eta_p' = \frac{P_2 - P_G}{P_2} = \frac{P_1}{P_1 + P_G}. \quad (3)$$

The efficiency of worm pair can be determined through the worm lead angle in the central cylinder $\gamma_m$ and friction angle $\varphi_1$ using the following expression [12]:

$$\eta = \frac{\tan\gamma_m}{\tan(\gamma_m + \varphi_1)} = \frac{z_1(q - \mu_1 z_1)}{q(z_1 + \mu_1 q)}, \quad (4)$$

where are: $z_1$ – the number of worm teeth, $\mu_1$ – friction coefficient between meshed gear teeth and $q = z_1 / \tan\gamma_m$ – worm number.

The higher efficiency $\eta$ is obtained for higher values of the angle $\gamma_m$ that is at multipath worms but at the same time lower transmission ratios are obtained. As the efficiency of worm gear pair depends on numerous parameters its values range in the interval $\eta = 0.5 \div 0.95$ % [13]. Efficiency values in relation to the worm lead angle for values of friction coefficient $\mu_1 = 0.05$ and pressure angle $\alpha_n = 20^0$ are presented in Table 1 [5].

Table 1: Efficiency values depending on the lead angle [5]

| Lead angle $\gamma_m$, [°] | Efficiency $\eta$, [%] |
|---|---|
| 1.0 | 25.2 |
| 2.5 | 45.7 |
| 5.0 | 62.0 |
| 7.5 | 71.3 |
| 10.0 | 76.6 |
| 15.0 | 82.7 |
| 20.0 | 85.9 |
| 30.0 | 89.1 |

## POWER LOSSES IN WORM GEARING

During the meshing between flanks of worm gear and worm gearing the certain corresponding normal force is transmitted, leading to significant surface pressures. In addition, between the flanks there is considerable sliding which results in scuffing of the flanks and significant power losses. The power losses in worm toothed gearing basically are composed of losses in worm and worm gearing meshing, bearing and sealing losses and losses due to oil churning power losses (Figure 1).

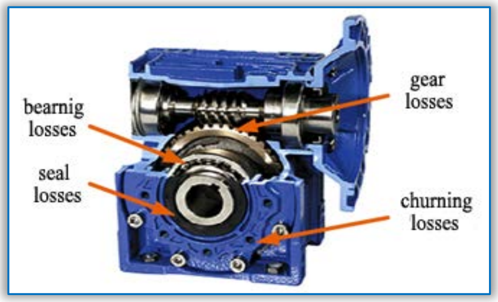


Figure1: Power losses in worm toothed gearing [6]

Gear box while operating dissipates energy so that at the output it receives power which is less than the input power for the loss size. The difference between input ( $P_{in}$ ) output power ( $P_{out}$ ) is called overall power loss $P_V$ which can be calculated using the following equations:

$$P_V = P_{VZ} + P_{VL} + P_{V0} + P_{VD} + P_{VX} \quad (5)$$

Therefore, total efficiency of worm toothed gearing can be calculated using the following expression [14]:

$$\eta = 1 - \frac{P_V}{P_1} = 1 - \frac{(P_{VZ} + P_{VL} + P_{V0} + P_{VD} + P_{VX})}{P_1}, \quad (6)$$

where are: $P_1$ – input power [W]; $P_V$ – overall power loss [W]; $P_{VZ}$ – load-dependent gearing losses [W]; $P_{VL}$ – load-dependent bearing losses [W]; $P_{V0}$ – no-load gearing and bearing losses [W]; $P_{VD}$ – sealing losses [W]; $P_{VX}$ – other losses [W].

The proportion of individual power losses (dependent on load and no-load) in overall gear box power loss is presented on Figure 2.

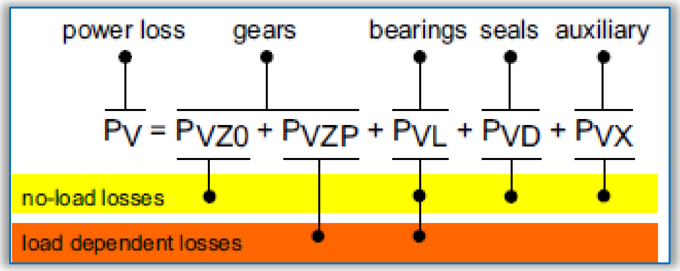


Figure 2: Power losses in gearbox [15]

Power losses in gear mesh $P_{VZ}$ represent the highest loss proportion in overall power losses $P_V$ of worm pair, especially at minimum speed and high torque (figure 3). High power losses are explained by significant sliding between flanks of meshed worm teeth and worm gear.

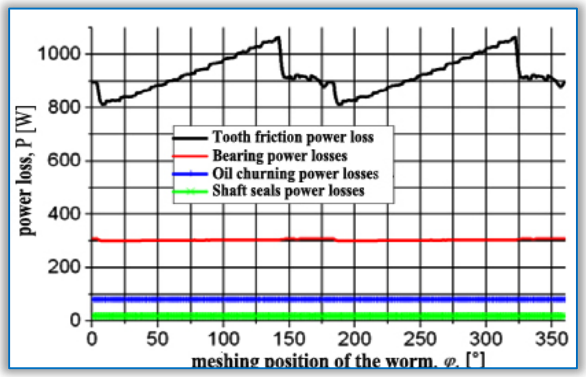


Figure 3: Power loss components in worm toothed gearing ( $T_2 = 500$ Nm, $n_1 = 1500\,\text{min}^{-1}$, mineral oil ISO VG 150) [3]

In the literature, there is a large number of expressions for the calculation of power losses in worm toothed gearing. According to V. Nikolic [11], power that is lost on overcoming the sliding resistance at meshing in worm pair is:

$$P_{VZ} = F_N \cdot \mu_z \cdot v_k, \quad (7)$$

where are: $F_N$ – normal force on the flank of the tooth, $\mu_z = \tan\rho$ – friction coefficient of worm pair and $v_k$ – sliding velocity.

In case that lubrication of gear pair was done by dipping, that worm is placed underside and that rolling bearings are mounted, the power losses at no-load can approximately determine by applying the following equations:

$$P_{V0} = 10^{-7} a \left(\frac{n_1}{60}\right)\left(\frac{v_{40}}{1.83} + 90\right), \quad (8)$$

where are: a – center distance[mm], $n_1$ – rotational speed per minute and, $v_{40}$ – kinematic viscosity of the oil at $40^0$C [$mm^2/s$]

Bearing losses can be approximately determined based on following ratios:

$P_{VL} = P_1(0.005...0.01)$ – for mounted 4 rolling bearings,

$P_{VL} = P_1(0.02...0.03)$ – for mounted 4 sliding bearings.

The overall power loss in rolling bearing can be calculated based on SKF recommendations using the following expression [16]:

$$P_{VL} = M \cdot n \cdot \frac{\pi}{30} \times 10^{-3}, \quad (9)$$

where is *M* total bearing friction torque that represents the sum of following losses:

$$M = M_{rr} + M_{sl} + M_{drag} + M_{seal}, \quad (10)$$

where are: $M_{rr}$ – rolling friction torque, $M_{sl}$ – sliding friction torque, $M_{seal}$ – friction torque of seals, $M_{drag}$ – friction torque of drag losses.

Sealing power loss depends on the rotational speed *n* and internal diameter of sealing $d_i$ and is calculated using the following expression [17]:

$$P_{VD} = 7.69 \times 10^{-6} \cdot d_i \cdot n. \quad (11)$$

Power loss on flanks of worm and worm gear on the part $\Delta l$ of the immediate contact lines can be determined by the following expression [18]:

$$dP_V = \mu_h \cdot W_b \cdot \Delta l \cdot V_g, \quad (12)$$

where are: $\mu_h$ – oil friction coefficient; $W_b$ – load along the contact line; $V_g$ – sliding velocity.

Power loss depending on the rotation angle $\varphi_1$ along the whole contact line *l* can be calculated as:

$$P_V(\varphi_1) = \int dP_V. \quad (13)$$

Average value of power losses that occur between the flanks of meshed gears is:

$$P_{ave} = \frac{P_V(\varphi_1)}{n_{\varphi_1}}, \quad (14)$$

where $n_{\varphi_1}$ is a number of different meshing positions.

Overall power loss due to friction in the worm and worm gear meshing can be determined according to AGMA standards [19]:

$$P_{loss} = \frac{V_t W_f}{1000}. \quad (15)$$

Thereby the output power of worm pair is determined according to following expression:

$$P_{output} = \frac{n W_{tg} d_g}{1.91 \times 10^7 m_G}, \quad (16)$$

where are: $V_t$ – sliding velocity on mean diameter of the worm [m/s]; $W_f$ – friction force [N]; n – worm rotational speed [min$^{-1}$]; $W_{tg}$ – tangential force [N]; $m_G$ – transmission ratio; $d_g$ – mean diameter of the gear [mm].

Based on previous expressions given in AGMA Standard, the worm pair efficiency is:

$$\eta = \frac{P_{output}}{P_{input}} \cdot 100 = \frac{n W_t d_m}{1.91 \times 10^7 m_G P_{input}} \cdot 100 \ [\%]. \quad (17)$$

## FACTORS AFFECTING THE POWER LOSSES

In order to affect the reduction of power losses it is necessary to select the ideal combination of geometrical parameters and materials of worm gear pair, lubrication conditions as well as the working conditions. Therefore, it is necessary to know to which extent these parameters affect the efficiency of gear pair.

When it comes to the influence of geometrical parameters, by correlating the ration of mean diameter and axial distance $d_{m1}/a$, lead angle $\gamma_m$, friction coefficient $\mu_z$ and varying of the parameters it can have a significant influence on power losses, and thus on the efficiency $\eta_z$ of worm gearing. Namely, the lower ratio $d_{m1}/a$ leads to the higher efficiency $\eta_z$, while on the other side it leads to the greater sensitivity to pitting and to too great deflection of the worm shaft due to bending [4].

On the other hand, by increasing the lead angle $\gamma_m$ the lower friction coefficient is achieved, and thus the higher efficiency [5,13,20].

Figure 4 represents the influence of lead angle $\gamma_m$ on the efficiency of worm gear pair.

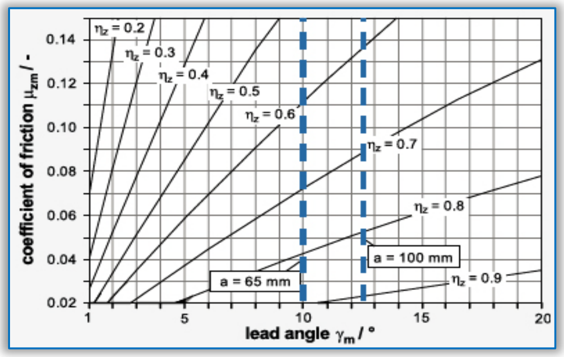


Figure 4: Influence of lead angle $\gamma_m$ on the efficiency of worm gear pair [20]

Among other things, the change of transmission ratio can also affect the efficiency. Namely, the reduction of transmission ratio of worm pair leads to the increase of efficiency, while too big transmission ration can lead to self-locking of worm gearing ($\eta_z < 50\,\%$).

Figure 5 represents the influence of different transmission ration on the efficiency of worm gearing [21].

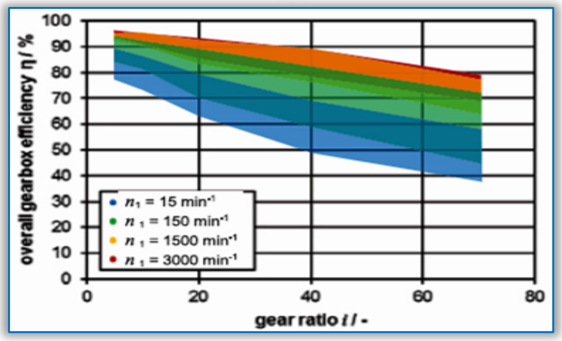


Figure5: Influence of transmission ratio on overall efficiency of worm gearing (worm type ZI, mineral oil) [21]

When it comes to influence of the materials, the higher efficiency is obtained by combining the worm materials made of hardened (case) steel with ground teeth and worm gear made of centrifugal casted tin bronze with the addition of nickel compared to combination with worm gear material of grey iron, aluminium bronze or special brass. By such combination of worm and worm gear materials very favourable tribological characteristics are obtained [1, 22, 23]

Figure 6 represents the influence of materials on the degree of losses for worm gear made of bronze CuSn12Ni and grey iron GJS 400 according to DIN3996.

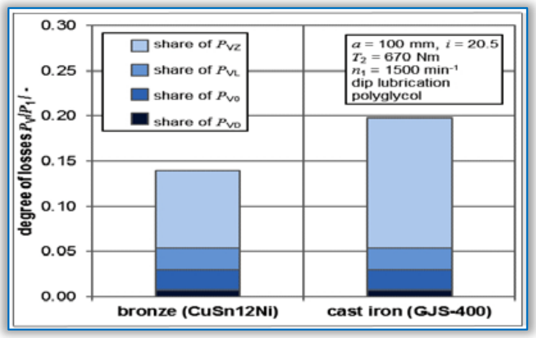


Figure 6: Influence of the worm gear material on the degree of loss $P_V/P_1$ of worm pair [14]

The lower values of friction coefficient in the toothed gearing lead to the lower power losses. The diagram (figure 7) represents the values of friction coefficient for different types of materials out of which the worm and worm gear are manufactured for the conditions of hydrodynamic lubrications. Curve B represents the values of friction coefficient for worm gear made of phosphor bronze and for the worm made of case hardening steel, while curve A represents the values of friction coefficients for worm pair made of cast iron [5].

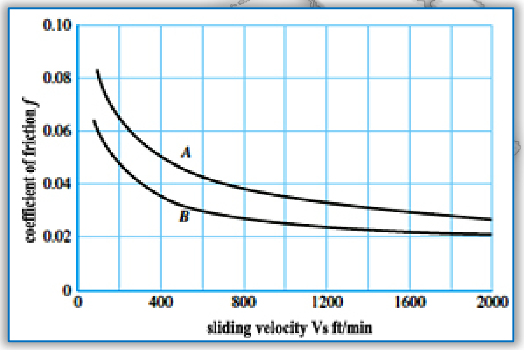


Figure 7: Coefficient of friction for different types of worm and worm gear materials [5]

The value of coefficients of friction differs for almost 20% which mainly depends on the type of worm gear pair material, quality of fine machining and lubrication.

The surfaces of the worm and worm gear, in general, should have less roughness to reduce coefficient of friction and thus the power loss in gearing. The results of experimental research [14] show that the degree of power losses is less for lower values of arithmetic mean profile deviation from the mean line of the profile $R_a$.

Dependence of power losses from the roughness of machined surface, expressed by parameter of arithmetic mean deviation of the profile $R_a$, is presented in Figure8.

Conditions of lubrications, type and viscosity of oil have a significant influence on power losses. Studies have shown that the use of higher viscosity oils (polyglycol ISO VG 460) increases the efficiency by 1 to 2% compared to lower viscosity oil (polyglycol ISO VG 220) and by 3% compared to mineral oil [7]. Higher viscosity oils lead to higher losses in no-load, and generally lead to lower power losses of gearings due to better forming of oil film between the contact surfaces of gear teeth. In general, synthetic oils (polyglycol, polyalphaolefin, ester oils) lead to a reduction of coefficient of friction between the gear teeth compared to mineral oils, which leads to the lower power losses in gearing thus increasing the efficiency [8,9].

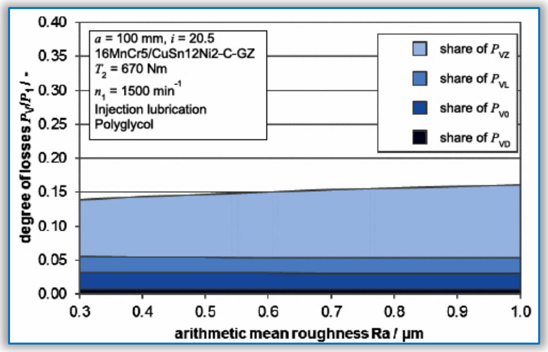


Figure 8: Influence of the arithmetic mean deviation of the profile $R_a$ on the degree of power losses $P_V/P_1$ for gear box [14]

By using synthetic high viscosity oil (ISO VG 460) for lubrication of large size warm gearing, for good lubrication conditions), the measured total efficiency was $\eta = 96\,\%$, especially at higher rotational speed and output torques [7].

The influence of working conditions on worm gearings efficiency is shown in Figure 9. The results were collected during the testing of steel/bronze worm gear pairs with center distance $a$ = 65, 100, 160 and 315 mm on FZG device. For all tests the synthetic oils polyglycol with gradations ISO VG 220 and ISO VG 460 were used.

Experiments have shown that the change in working conditions can significantly influence the efficiency. During the testing the values of efficiency were measured depending on the values of input rotation speed $n_1$ and output torque $T_2$, where was established that they move in the interval $\eta = 84 \div 95\,\%$ [7,23,24].

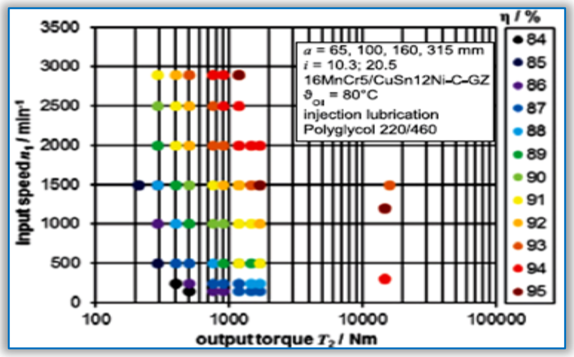


Figure 9: Results of tests of overall efficiency [7, 24, 25]

Based on the experimental research it can be concluded that by increasing the value of input rotational speed and at higher values of output torques the level of power losses $P_V/P_1$ decreases by which the higher efficiency values are obtained.

## CONCLUSIONS

Power losses in gear box vary from 0.5% to over 80% , so that more attention is paid to ways for their reductions in order to influence the increase of the gearing efficiency.

The losses are under great influence of the number of parameters, and one of the most important is the type of material out of which the worm and worm gear are made of. The best tribological properties has a combination of materials of worm gearing made of tin bronze and worm made of hardened and grounded steel. The influence of gear geometry is also a very important parameter. Namely, by reducing the ratio of mean diameter and center distance to a certain extent, lower transmission ratios as well as the increase of lead angle of the warm can have a significant influence to the increase of worm pair efficiency.

The type and viscosity of the lubricating oils have a significant influence on efficiency. Numerous experimental research have shown that, basically, higher viscosity synthetic oils lead to lower power losses (in some cases up to 35%), and thus to higher efficiencies compared to mineral oils. On the other hand, synthetic oils are more expensive than mineral, but during the short time period become cost effective because of numerous advantages comparing to mineral oils.

Different working conditions of worm gearing lead to different efficiency values. Higher efficiency values were measured at hither input rotational speeds and output torques. With the increase of circumferential velocity the oil film between the meshed flanks of the warm and warm gear crates more easily thus increasing the efficiency level.

As the absolute efficiency (100%) cannot exist even in the theoretical considerations and regarding the increasing value and importance of the energy, the task of the constructors/designers is to minimize power losses in the transmission to the extent possible by applying different design solutions and by varying of the parameters that define the work gear pairs.

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