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# Thermal Rating of Gear Drives Balance Between Power Loss and Heat Dissipation

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## TECHNICAL PAPER

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# Thermal Rating of Gear Drives – Balance Between Power Loss and Heat Dissipation

**Bernd-Robert Höhn, Klaus Michaelis and Thomas Vollmer, FZG**

[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

## Abstract

From the balance between the generated heat in a gear box and the dissipated heat from the gear case surface the mean value for the expected lubricant temperature can be evaluated. The maximum oil temperature in a splash lubricated enclosed gear drive limits the transmittable power. High oil temperatures influence wear, scuffing, micropitting and pitting load capacity of the gears as well as the gear oils' service life.

Experimental investigations of no-load and load dependent gear losses in cylindrical and bevel gears as a function of lubricant type and viscosity, load, speed and temperature are reported. The mean value for the coefficient of friction in a gear mesh is evaluated and compared to measurements in twin disk machines. A rating method for gear mesh power loss is derived.

Investigations, using model and actual gear boxes, show the influence of radiation, free and forced convection as well as conduction to the foundation on the heat dissipation from the gear case surface. The influence of design, size, air velocity, surface finish of the housing, etc., is reported.

The results of such investigations together with accepted rating methods for bearing and seal power loss are introduced into a calculation method for the evaluation of the oil temperature in the sump of a gear box. In sample calculations the possibilities as well as the limits of this thermal rating method is shown.

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# THERMAL RATING OF GEAR DRIVES

## BALANCE BETWEEN POWER LOSS AND HEAT DISSIPATION

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### 1 Introduction

The transmittable power of a splash lubricated gear drive is not only limited by the load carrying abilities but also by the maximum allowable oil temperature in the gear box. From the balance between the generated heat in the gear box and the dissipated heat from the gear case surface the mean value for the expected lubricant temperature can be evaluated. High oil temperatures influence oil ageing as well as wear, scuffing, micro pitting and pitting load capacity of the gears. Therefore besides load carrying capacity rating also thermal rating of a gear drive is necessary.

The paper deals with the evaluation of the different sources of power loss in a gear drive. The main emphasis is laid on the determination of the gear mesh power loss. Also reported are measured data of heat dissipation from model testing and actual gear boxes in practice.

### 2 Thermal Balance

The generated power loss in a gear box consists of the gear losses  $P_{VZ}$ , the bearing losses  $P_{VL}$ , and the seal losses  $P_{VD}$ . In some cases additional losses  $P_{VX}$  of auxiliary devices like e.g. oil pumps have to be taken into consideration. Gear and bearing losses include load dependent (e.g. gear mesh and roller contact) and non-load dependent (e.g. churning and cage friction) losses.

Heat removal from a splash lubricated gear drive is maintained by free and forced convection  $Q_{a,con}$  as well as radiation  $Q_{a,rad}$  from the housing and rotating parts

$Q_{rot}$  (e.g. shafts and couplings) and conduction to the foundation  $Q_{fun}$ .

$$P_{VZ} + P_{VL} + P_{VD} + P_{VX} = Q_{ca} + Q_{rot} + Q_{fun} \quad (1)$$

The thermal balance results in an temperature equilibrium. As most of the parameters depend on oil temperature a solution of the equations is only possible by iteration. For too high temperatures additional cooling through external oil radiators is required with their respective enthalpy stream from the system (Fig. 1).

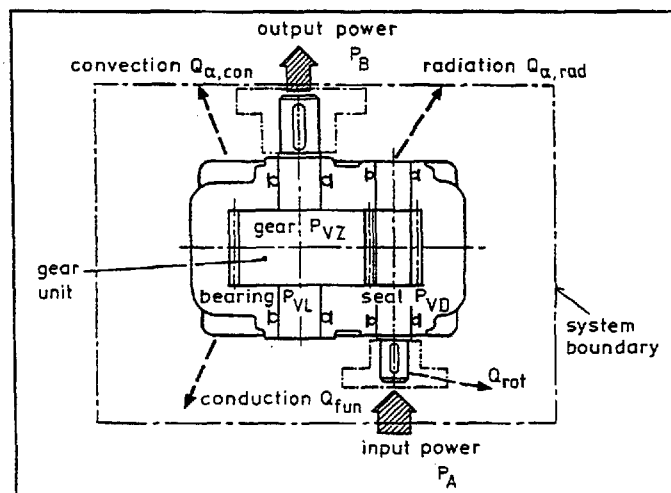


Fig. 1: Thermal balance of a gear unit

### 3 Determination of Power Loss

#### Seal Losses

In most cases the seal losses are less than 0.01% of the nominal transmitted power and are thus negligible compared to other losses in a gear drive. Equations for their evaluation are given by the seal manufacturers, as e.g. by Freudenberg [1]. An approximation is given with:

$$P_{VD} = 7.69 \cdot 10^{-6} \cdot d_{sh}^2 \cdot n \quad (2)$$

The seal power loss is independent of the transmitted power and can therefore be more relevant in the regime of partial power transmission.  $P_{VD}$  increases with tangential speed at the seal lip (Fig. 2). Different pressure at the seal lip, which is designed into the seal, influences the loss quite substantially. Different seal materials also influence the value of  $P_{VD}$ .

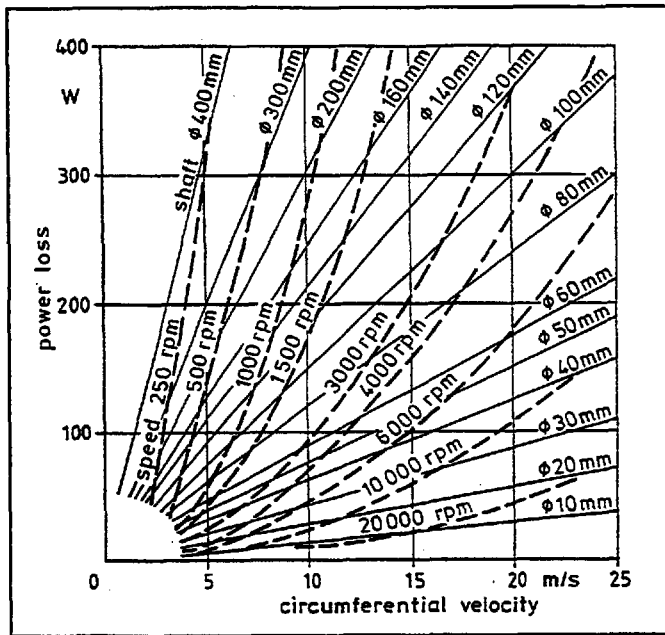


Fig. 2: Lip oil seal power loss

#### Bearing Power Losses

For many anti-friction bearings the power loss is in the range of 0.1% of the transmitted power. For the often used tapered roller bearings the power loss can be much higher, it can also vary substantially with the applied preloading and the grade of run-in of the bearing.

From experimental data the bearing manufacturers provide approximations for the evaluation of bearing power loss. These calculation methods are often derived from the equations of Eschmann [2], with a portion of non-load dependent  $T_{VL0}$  and load dependent loss torque  $T_{VLP1}$  (Fig. 3). For axially loaded roller and needle bearings an additional loss torque  $T_{VLP2}$  has to be taken into account:

$$T_{VL} = T_{VL0} + T_{VLP1} + T_{VLP2} \quad (3)$$

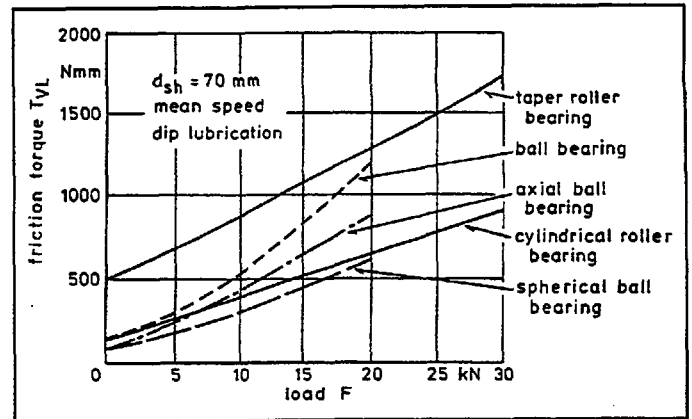


Fig. 3: Friction torque of roller bearings

The total power loss of an anti-friction bearing is then calculated from

$$P_{VL} = T_{VL} \cdot \omega = T_{VL} \cdot \frac{\pi \cdot n}{30} \quad (4)$$

For the evaluation the SKF-method [3] is proposed with a portion of non-load dependent loss for  $v_{oil} \cdot n < 2000 \text{ mm}^2/\text{s min}$ :

$$T_{VL0} = 1.6 \cdot 10^{-8} \cdot f_0 \cdot d_m^3 \quad (5)$$

for  $v_{oil} \cdot n \geq 2000 \text{ mm}^2/\text{s min}$ :

$$T_{VL0} = 10^{-10} \cdot f_0 \cdot (v_{oil} \cdot n)^{2/3} \cdot d_m^3 \quad (6)$$

with  $f_0$  as a function of the bearing type and the lubrication (see Table 1).

The load dependent losses are calculated from:

$$T_{VLP1} = 10^{-3} \cdot f_1 \cdot P_1 \cdot d_m \quad (7)$$

where  $f_1$  is again a function of the bearing type and  $P_1$  is the equivalent bearing load (see Table 2) and:

$$T_{VLP2} = f_2 \cdot F_a \cdot d_m \cdot 10^{-3} \quad (8)$$

where  $f_2$  can be approximated by  $f_2 = 0.006$ .

#### Gear Power Loss

**Non-Load Dependent Gear Loss** - The main influence parameters on the churning losses of the gear blanks are diameter, speed, immersion depth and gear oil viscosity. Additionally the internal gear box design can influence the no-load power loss of gears in a wide range. Fig. 4 shows the influence of circumferential speed and immersion depth on no-load gear power loss. Fig. 5 shows the influence of different operating viscosity of the oil on the no-load gear loss. It has to be mentioned that the oil type has no influence on the no-load losses.

Table 1: Coefficient  $f_0$ 

| Bearing design                                                                                                                           | Type of lubrication                     |                                               |                                         |                                                         |
|------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------|-----------------------------------------------|-----------------------------------------|---------------------------------------------------------|
|                                                                                                                                          | Grease                                  | Oil mist                                      | Oil bath                                | Oil injecti<br>oil bath w<br>vertical sh                |
| Deep-groove ball bearing<br>single-row<br>double-row                                                                                     | 0,75 ... 2 <sup>2)</sup><br>3           | 1<br>2                                        | 2<br>4                                  | 4<br>8                                                  |
| Self-aligning ball bearing                                                                                                               | 1,5 ... 2 <sup>2)</sup>                 | 0,7 ... 1 <sup>2)</sup>                       | 1,5 ... 2 <sup>2)</sup>                 | 3 ... 4 <sup>2)</sup>                                   |
| Angular contact ball bearing<br>single-row<br>double-row                                                                                 | 2<br>4                                  | 1,7<br>3,4                                    | 3,3<br>6,5                              | 6,6<br>13                                               |
| Four-point contact bearing                                                                                                               | 6                                       | 2                                             | 6                                       | 9                                                       |
| Cylind. roller bearing (cage)<br>Series 10, 2, 3, 4<br>Series 22<br>Series 23                                                            | 0,6<br>0,8<br>1                         | 1,5<br>2,1<br>2,8                             | 2,2<br>3<br>4                           | 2,2 <sup>3)</sup><br>3 <sup>3)</sup><br>4 <sup>3)</sup> |
| Cylind. roller bearing (full roller)<br>single-row<br>double-row                                                                         | 5 <sup>4)</sup><br>10 <sup>4)</sup>     | --<br>--                                      | 5<br>10                                 | --<br>--                                                |
| Needle roller bearing                                                                                                                    | 12                                      | 6                                             | 12                                      | 24                                                      |
| Self-aligning roller bearing<br>Series 213<br>Series 222<br>Series 223, 230, 239<br>Series 231<br>Series 232<br>Series 240<br>Series 241 | 3,5<br>4<br>4,5<br>5,5<br>6<br>6,5<br>7 | 1,75<br>2<br>2,25<br>2,75<br>3<br>3,25<br>3,5 | 3,5<br>4<br>4,5<br>5,5<br>6<br>6,5<br>7 | 7<br>8<br>9<br>11<br>12<br>13<br>14                     |
| Taper roller bearing<br>single-row                                                                                                       | 6                                       | 3                                             | 6                                       | 8 ... 10 <sup>2)</sup>                                  |
| Deep-groove ball thrust bearing                                                                                                          | 5,5                                     | 0,8                                           | 1,5                                     | 3                                                       |
| Cylindrical roller thrust bearing                                                                                                        | 9                                       | --                                            | 3,5                                     | 7                                                       |
| Needle roller thrust bearing                                                                                                             | 14                                      | --                                            | 5                                       | 11                                                      |
| Self-alig. roller thrust bearing<br>Series 292 E<br>Series 292<br>Series 293 E<br>Series 293<br>Series 294 E<br>Series 294               | --<br>--<br>--<br>--<br>--<br>--        | --<br>--<br>--<br>--<br>--<br>--              | 2,5<br>3,7<br>3<br>4,5<br>3,3<br>5      | 5<br>7,4<br>6<br>9<br>6,6<br>10                         |

- 1) The shown values are valid for steady conditions. For lately greased bearings (2...4)  $f_0$  is to be used in the calculation.
- 2) The low values apply to the lightweight bearing, and the high values to the heavyweight bearings of a bore series.
- 3) Valid for oil injection lubrication. For oil bath lubrication and vertical shaft the shown value is to be doubled.
- 4) Valid for low rotation speed up to 20% of the reference rotation speed (see bearing tables). At higher rotation speed the  $f_0$  value is to be doubled for the calculation.