Temperature distribution in two teeth in mesh of spur gears in 3D FEM simulation and experiment

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Abstract— This work introduces the temperature distribution on the two spur gear in mesh experimentally and simulation using finite element method. In experiment; gear box investigated includes the motor, pump, two spur gears, two shafts and speed change system. The gears are used in experiment and simulations are the same dimensions. Verification of experiment using finite element method that is because highly techniques to investigate the temperature distribution for two teeth of spur gear in mesh. This research deals with the study of the temperature of two teeth from the start of mesh to the end of mesh. In experimental we using laser Gun instrument to measure the temperature of the two teeth of spur gear in mesh. Measure the temperature distribution along the face width of tooth during mesh with other tooth from the start to the end of mesh. The results of simulation are close to the experimental but in fact we can measure the temperature at any point on the gear surface as well as the temperature on the area contact between two teeth on mesh without any difficulty of experiment set up especially in the area contact between two teeth in mesh as well as save wasting time and cost for measurements beside simulation presents higher accuracy and precision of finite element mesh. These temperature are compared between numerical and experimental results. Both results agree very well. This indicates that the experimental model is successful and leads to excellent results comparing with numerical results (COMSOLprogram).

Index Terms— Finite element, Simulation, Mesh, Contact line, Face width, Temperature, Spur, Gear.

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1 INTRODUCTION

Nowadays the researchers tend to using uncertainty methods for measuring temperature distribution of gears during meshing. This research introduces and investigates the vital problem of gears leads to the other defects and wear of gears. This paper presents the technique developed to measure the temperature on various active portions of a gear operating under load, at high speeds, and the results obtained. Comparison of the measured temperatures to computed temperatures utilizing standard methods is also presented. This experimental technique was developed as a part of a larger project to establish temperature distribution on gear boxes at elevated temperatures. The prediction of bulk and surface temperatures of the gear tooth is carried out using finite element method, using COMSOL. The investigations are carried out on the tooth of the spur gear under various operating conditions. In this work, a methodology has been developed to predict the bulk and the surface temperatures in gear teeth using finite element analysis using COMSOL. In experiment we measured the temperature at five different points, ones at the middle and two in the right and two in left of the centre of face width of gear. Ambient temperatures that are too high may result in lube temperatures so high that ineffective oil films are formed, while too low a temperature may thicken oil so much that flow is restricted and certain parts may be starved of lubricant. In either case, abnormal wear may result[1]. The tooth frictional losses and different convective heat transfer coefficients for different portions of the tooth form the input to the model. Failure due to high tooth temperatures can be prevented with the knowledge of temperature distribution in gear teeth under operation [2]. Both into-mesh and out-of-mesh position produced the lowest pinion tooth temperatures [3]. However, when tooth load increased, thermal damages occurred and the fracture of tooth and the surface melting was formed due to an immediate increase of temperature [4]. Out of mesh surface temperature is not a constant along the tooth profile at steady state running conditions[5]. Speed and load affected lubricant fling off temperatures measured across the gear mesh face width and at the axial location due to the helical gear mesh axial pumping [6]. An experimental technique to measure the temperature of relevant regions of a gear in mesh and under load was demonstrated [7]. Both into-mesh and out-of-mesh position produced the lowest pinion tooth temperatures [8]. The generalized integral temperature criterion used by the scoring safety factor[9]. Scuffing is triggered when the temperature in the contact zone exceeds a certain critical temperature [11]. Use of the finite-element method (FEM) in gear contact has been widely documented, as demonstrated by [12]. although it is only recent advances in computational power that has enabled the full non-linear analysis of contact between gear teeth through the mesh cycle; prior research was unable to accurately reproduce the Hertzian stresses and deformations of the tooth profile. In comparison, the use of FSI techniques in the gear contact problem is unexplored. Although scarce, examples of approaching the EHL problem using FSI in other applications have shown promise [13]. The analysis of numerical results obtained by FEM calculations confirms that developed 3D FEM gear models give excellent results [14]. Analysis results show that the FEM method is more efficient and effective [15]. Finite element method for simulation of thermography is inspection in gear inspection [16].

2 THEORETICAL ANALYSIS OF GEARS TEMEPREATURE

In the temperature in gear contacts, $Pe = aU/(2k)$, where a is the semi-contact width, U is the absolute sliding velocity and k is the thermal diffusivity. The temperature distribution according to Williams [17] can be approximated to

$$\vartheta \equiv \frac{q_o \cdot a}{K_s \cdot \sqrt{\pi}} \sqrt{\frac{\kappa \cdot \left(\chi_{pos} + a\right)}{\nu}} \quad (1)$$

Equation (1) corresponds to the curve for an infinite Peclet number and can be used to approximate analytically the temperature distribution in the contact.

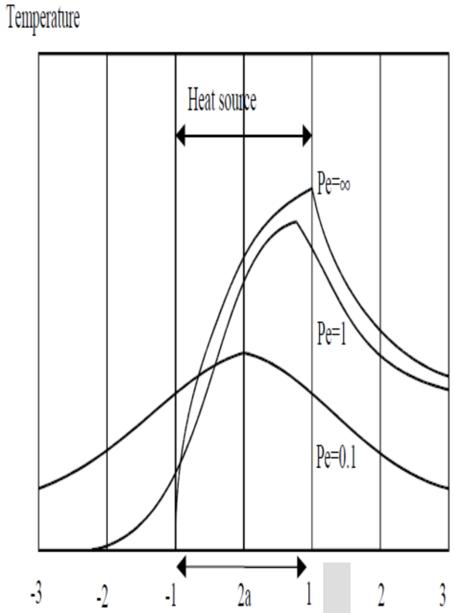

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Fig. 1 Steady state surface temperature profiles in a half space moving under a heated band of width 2a for various values of the Peclet number, Pe.

$$q_o = \mu \cdot p_{mean} . \nu \quad (2)$$

Xpos is the position of the point in the contact *Pmean* is the mean pressure in the contact and *v* is the velocity. *Ks*, and κ are the thermal conductivity and thermal diffusivity respectively.
Equation (3) is the heat transfer equation, which only takes account of perpendicular heat transfer into the material. *T* is temperature, *t* is time and *x* is distance into the material.

$$\frac{\partial T}{\partial t} = \kappa \cdot \left(\frac{\partial^2 T}{\partial x^2} \right) \quad (3)$$

Equation (4) is the maximum contact temperature according to Tian and Kennedy previously discussed. Here *q0* is the energy input, *a* is the semi contact width, *Pe* is the Peclet number and δ*theory* is the division of heat between the bodies in contact and calculated according to [18].

$$T_{\max} = \frac{2 \cdot a \cdot q_o \cdot \delta_{theory}}{\mathrm{K}_s \sqrt{\pi \left(1 + P_e\right)}} \quad (4)$$

3 SIMULATION

Material in computer simulation is Steel AISI 4340, heat capacity at constant pressure 475[J/(kg*K)], thermal conductivity 44.5[W/(m*K)], coefficient of thermal expansion alpha 12.3 [1/K], density 7850[kg/m^3], Young's modulus 205e9[Pa] and Poisson's ratio 0.28. Simulation chosen fine an element size, number of degrees of freedom is 111852 and complete mesh consists of 16522 elements as shown in Fig.2. Figure3 (left) shows finite elements distributed on the face width of two gears and on the surfaces of gears as well (right). In the beginning of simulation we prepared a solidworks files contain two spur gears in mesh after worth we make a program simulation prepared to receive live link for solidworks. Steady state thermal analysis is carried out on gear teeth of different sizes of commercial gearboxes under different operating conditions to predict the temperature distribution [2].

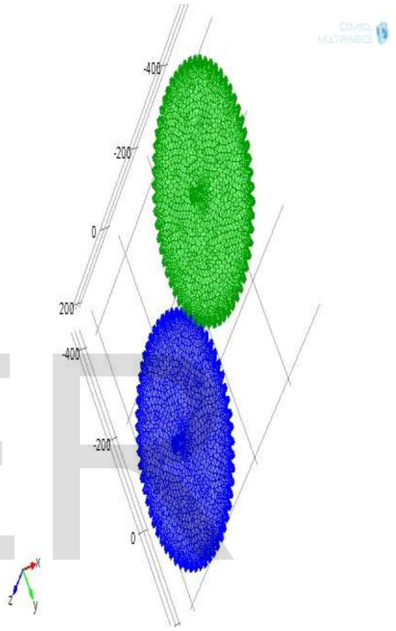

Fig.2 Shows fine mesh of two spur gear.

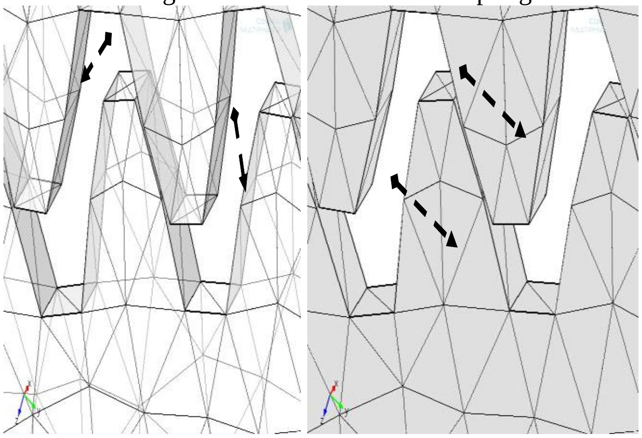

Fig. 3 Shows finite element distribution on face widths (left) and the surfaces (right) of teeth.

Fig. 4 shows two spur gears in mesh, after the compilation of the computer simulation we got the temperature distribution on the two gears in mesh, because the time computation and memory of computer we concentrated the study of two teeth in mesh have dotted circle around the two teeth which indicates the higher temperature of two teeth in mesh.

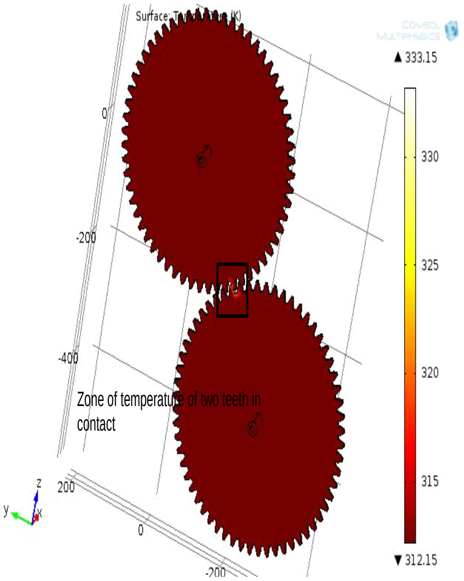

Fig. 4 shows two spur gears in mesh, and dotted circle indicates the higher temperature of two teeth in mesh.

In Figure 5 we have to take a close for two teeth in mesh which illustrates the temperature distribution on the face widths of two teeth at contact line for the driver tooth (left), and the driven tooth (right).

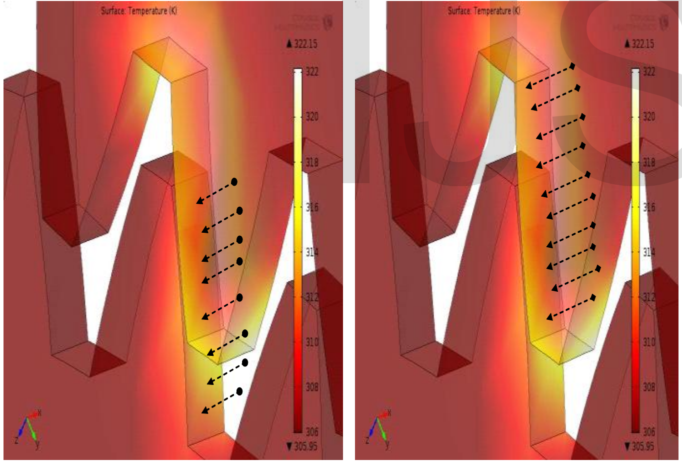

Fig. 5 Arrows illustrate the temperature distribution on face widths of the driver tooth (left), and the driven tooth (right).

Figure 6 shows the higher temperatures are at the contact line between two teeth in mesh and the surface temperatures close to the contact area regardless to the whole teeth. Dotted lines separate higher temperatures close to the contact line of two teeth in mesh and lower temperatures distributed on surface on two teeth in mesh driver (left) and driven (right).

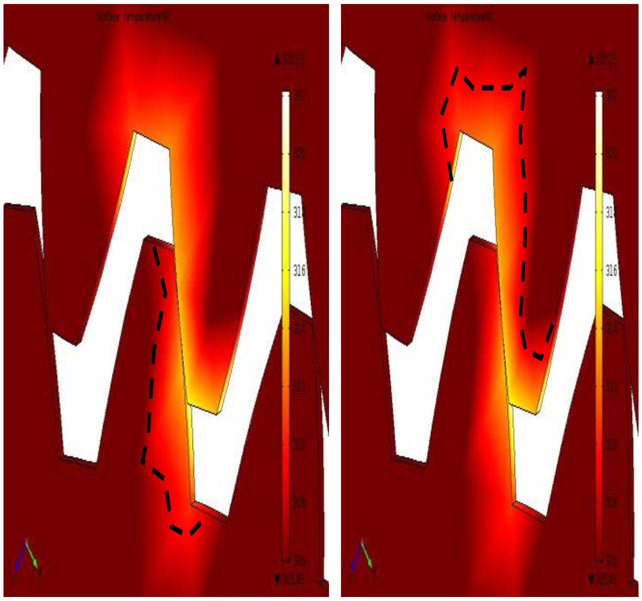

Fig.6 Dotted lines separate higher and lower temperature distribute on surface on two teeth in mesh driver (left) and driven (right).

The program prepared to measure the temperatures on the three dimensions at any point at gear surface and contact line between two teeth in mesh as shown in Figure 7, which shows the reading of differnet points in (x, y, z) directions. Tabel 2 shows the reading points, P1, P2, P3 and P4 in three dimensional (x, y, z) and cooresponding temperature of each point.

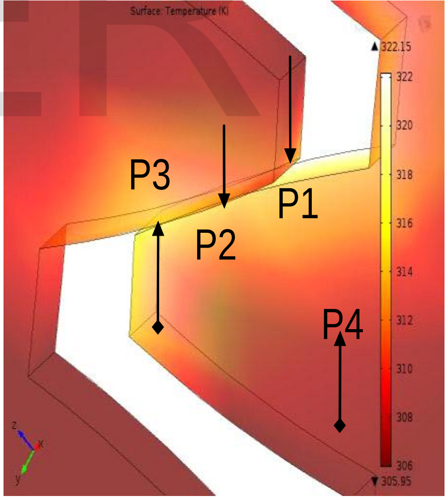

Fig. 7 Shows sample of point measured on surface and face width of teeth.

Table 1 illustrate the temperatures which measured in three dimensions of points P1, P2, P3, P4 and P5.

Table 1. Shows program measured any point on the gear.

Measured points	x	Y	Z	Temperature Value
P1	4.09418	-117.12990	-184.32826	318.345164
P2	6.26226	-117.00164	-184.22107	321.505568
P3	0	-110.18230	-178.53582	313.480666
P4	0.35431	-112.69915	-188.45062	307.424881

4 GEAR DATA AND TEST RIG

This paper investigates the effect of different speed of gear box on the temperature of two teeth of spur gears in mesh. Laser Gun temperature (Infrared Thermometers Cason -32ºc – 380 ºc) was used to measure the temperature as and previous work used thermo couple as shown in Fig.8 [1].

Fig.8 Previous simulations used thermo couple built in gear round the surface (left), concentrate at specific point at the surface (right).

4.1 Test Rig

Phase of test is with loading [18], [19] which equal to 13.5 N and torques, 7.07, 3.53, 2.36 N.m and 1380 g weight of each gear as in Fig. 9. Two gears geometry pitch diameter is 12.4 cm and the face width is 13 mm, gear material is steel 0.3 % normalized carbon, shaft material is_AISI 4130 Steel, normalized at 870C.

Fig.9 Test rig of spur gears with loading.

4.2 Measurement

Test rig prepared in such away to measure the temperature at the contact line of spur gear. Measuring is held at five points along the face width of gears at contact line during meshing, point in the middle of contact line and two points at the left of the middle in equal distances and two points at right side of the middle in equal distances as shown in Figure 10 (right).

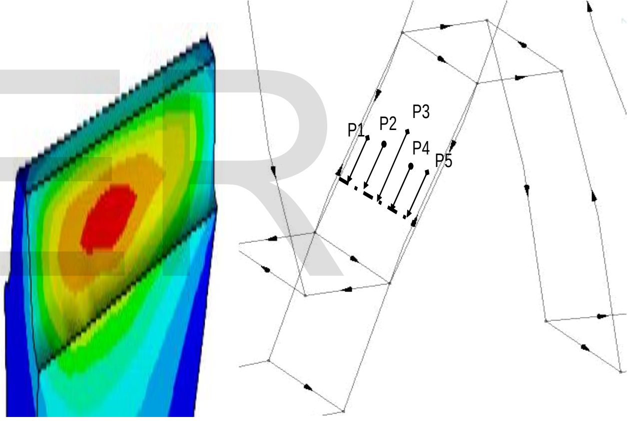

Fig.10 Shows temperature distribution [2], (left), arrows indicate to the five points measured at the face width of spur gear (right).

4.3 Experiment Analysis

Figures 11, 12, 13 show raw data of the relation between temperature and time during one an hour, the reading taken each five minutes at five points on the line of contact of two teeth in mesh at different speed of gears under load. For 3000 rpm, the temperature is around 35.2 ºc to 38 ºc.

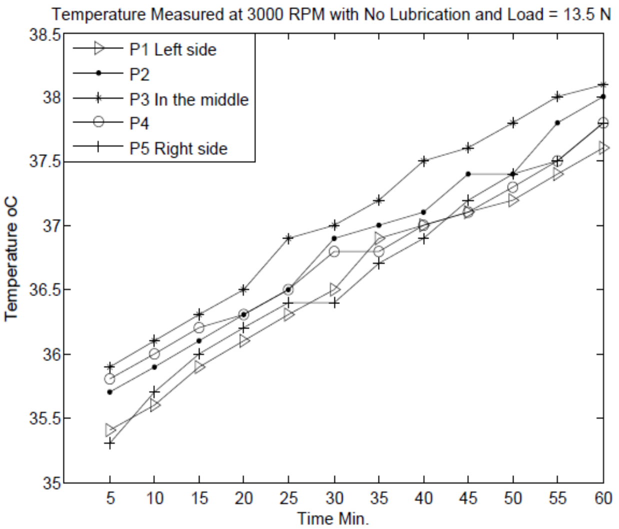

Fig. 11 Illustrates relation between temperature and time at 3000 rpm.

For 6000 rpm in the Figure 12, shows the range of temperature 37.7 ºc to 41ºc. The temperature of the middle point is higher than the other points and the other points are related to the front and rear bearings regardless to the power input.

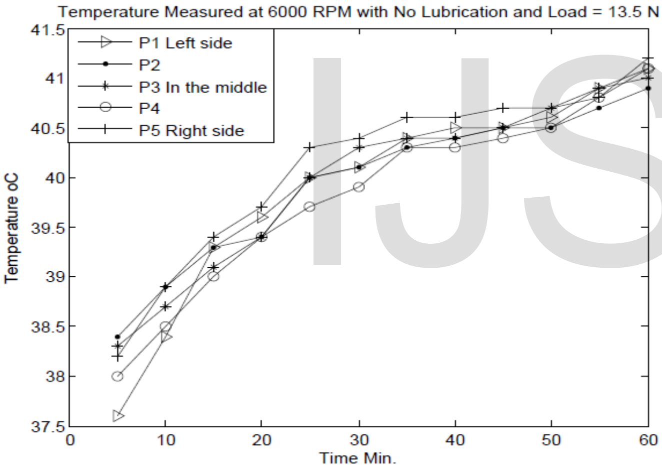

Fig. 12 Illustrates relation between temperature and time at 6000 rpm.

Figure 13 shown the relation between temperature and time at 9000 rpm. The graph indicates the temperatures of the middle point at the line of contact are higher than four points. Regardless to the Figures 10, 11 for 3000 rpm , 6000 rpm, the temperature of speed of 6000 rpm is higher than the 6000 rpm and 3000 rpm. As well as the temperatures of the of the middle point is higher than the four points. The temperatures of the two points beside the middle points are higher than the two points at the edges on left side and right side. The temperature of the right side always higher than the left side which is closed to the input power of the system.

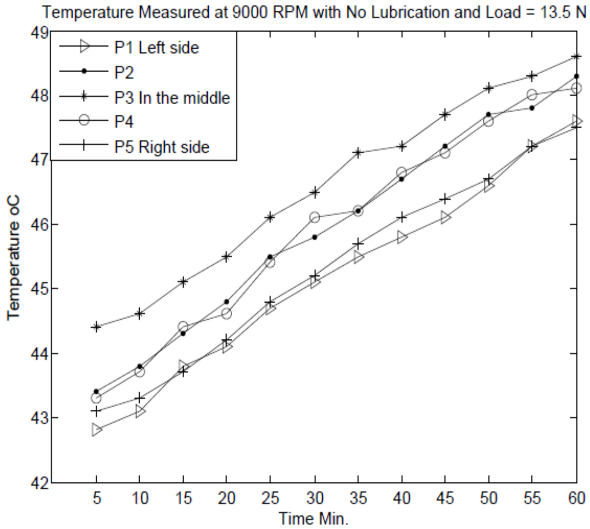

Fig. 13 Illustrates relation between temperature and time at 9000 rpm.

Figure 14, error bar shows the analysis of different speed of rotation of gears 3000 rpm, 6000 rpm and 9000 rpm. The temperatures have increased with an increasing the speed of gears as well as the temperature is increased with the time increased.

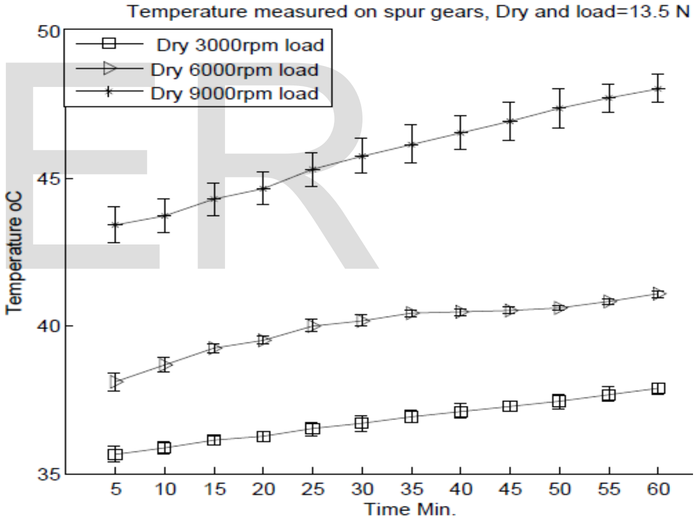

Fig. 14 Illustrates the temperature distribution with different RPM's.

Testing temperature of two spur gears along the contact line without lubrication (Dry work) at 9000 r.p.m , torque 2.36 N.m, with loading equals to13.5 N as shown at Table 2. Table 2 shows the measurements of temperatures of the different components of test rig, bearings (front-rear), motor (before and after test), and room temperature before test.

Table 2 Temperatures measured in room and motor bearings.

	Temperature measured before test		Temperature measured after test	
Bearing on	Front bearing	Rear bearing	Front bearing	Rear bearing
Shaft 1	32.8 ºc	32.6 ºc	59.3 ºc	55.6 ºc
Shaft 2	32.2 ºc	32.6 ºc	54.8 ºc	57.9 ºc

	Before test	After test
Motor temperature	31.9ºc	49.3ºc
Room temperature	32.8ºc	

5 CONCLUSION

In this research, we investigated the distribution of temperature on the surface of spur gears in meshing as well as contact area of two teeth in mesh. Definitely finite element simulation obviously appeared the temperature distribution of two teeth in contact as well the compute the temperatures degrees at any point at the spur gear at point in three dimensions. Finite element simulation introduces the actual temperature in X-direction, Y-direction and Z-direction coordinate. Besides to computation of temperature in three dimensions it was making different types of element size to make clear and accurate finite elements size.

In experimental results is the close to finite element simulation but in finite simulation gave us the wide flexibility to compute the temperature distribution at any point at spur gear surface or contact area between two teeth in three dimensional in ease and accurate results depends on the skills of the programmer. Absolutely, temperature increased in the area of contact along the face width of two teeth. Additionally at surface and two teeth around the face width are increased. Temperature is higher at teeth of gear (driven gear) than the pinion (driver gear). Which a key point that circumstances of two teeth of spur gears in mesh.

Recommendation putting material coated at the teeth of contact to avoid the increase of temperature and the change of mechanical properties of gears. Another recommendation it is to make a hole of teeth to prevent the transition of temperature to another tooth that is released of contact or still to be contact next. Difficulty for estimate the temperature experimentally and setting up the test rig and instruments. By this way, simulation could reduce cost and time wastage when it is advance into real experiment in cost [20]. In this a computer simulation can overcome the stumbled of impossibility of experiment for measure each point over the two gears in meshing. This computer simulation presents the temperature distribution over the two gears in meshing but the challenges are the possibility of computer time, speed, and area storage in computer. Results introduce the ability to control the temperature of the gear tooth material at the mesh be demonstrated. The computer simulation can be used for evaluating the thermal characteristics of gearboxes at the design stage itself, eliminating the need for physical experimentation. These virtual simulations and experiments aid in the rating of gearboxes for their thermal capacity and to design cooling requirements [2]. The maximum gear tooth “bulk” temperature measured very close to the involute surface of the tooth is considered relevant to surface durability, and the maximum contact temperature at the tooth surface is considered relevant to scoring resistance [8].

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