ISSN 2229-5518

Temperature distribution in two teeth in mesh of spur and helical 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; two test rigs, first test with spur gears and second one with helical gears. The gears used in the experiments and simulations are of the same dimensions. Verification of experiments was done using the finite element method,a high technique 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 to the end of mesh. In experimental we used 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 another 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 of contact between two teeth on mesh without any difficulty of experimental setup especially in the area of contact between two teeth in mesh as well as save wasting time and cost for measurements, besides, simulation presents higher accuracy and precision of finite element mesh. These temperatures 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 compared with numerical results (COMSOL-Program).

Index Terms— Finite, Simulation, Mesh, Temperature, Spur, Helical

1 Introduction

Nowadays, researchers tend to use uncertainty methods for measuring temperature distribution of gears during meshing. This research introduces and investigates the vital problem of gears which 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 the experiment, we measured the temperature at five different points, one at the middle and two in the right and two in the 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 loses friction 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 [3,4]. However, when tooth load is increased, thermal damages occurred and the fracture of tooth and the surface melting was formed due to an immediate increase of temperature[5]. Out of mesh surface temperature is not a constant along the tooth profile at steady state running conditions[6]. 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[7]. An experimental technique to measure the temperature of relevant regions of a gear in mesh and under load was demonstrated [8]. Both into-mesh and out-of-mesh position produced the lowest pinion tooth temperatures [4]. 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 [10]. Use of the finite-element method (FEM) in gear contact has been widely documented, as demonstrated by [11]. 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 [12, 13]. The analysis of numerical results obtained by FEM calculations confirms that developed 3D FEM gear models give excellent results [14]. Analysis of results show that the FEM method is more efficient and effective [15]. Finite element method for simu-

ISSN 2229-5518

lation of thermography used inspection in gears [16].

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2. Theoretical analysis of gears temperature

2.1 The temperature emitted

Gear contacts, is relied on equation: $Pe = aU/(2k)$, 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

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

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

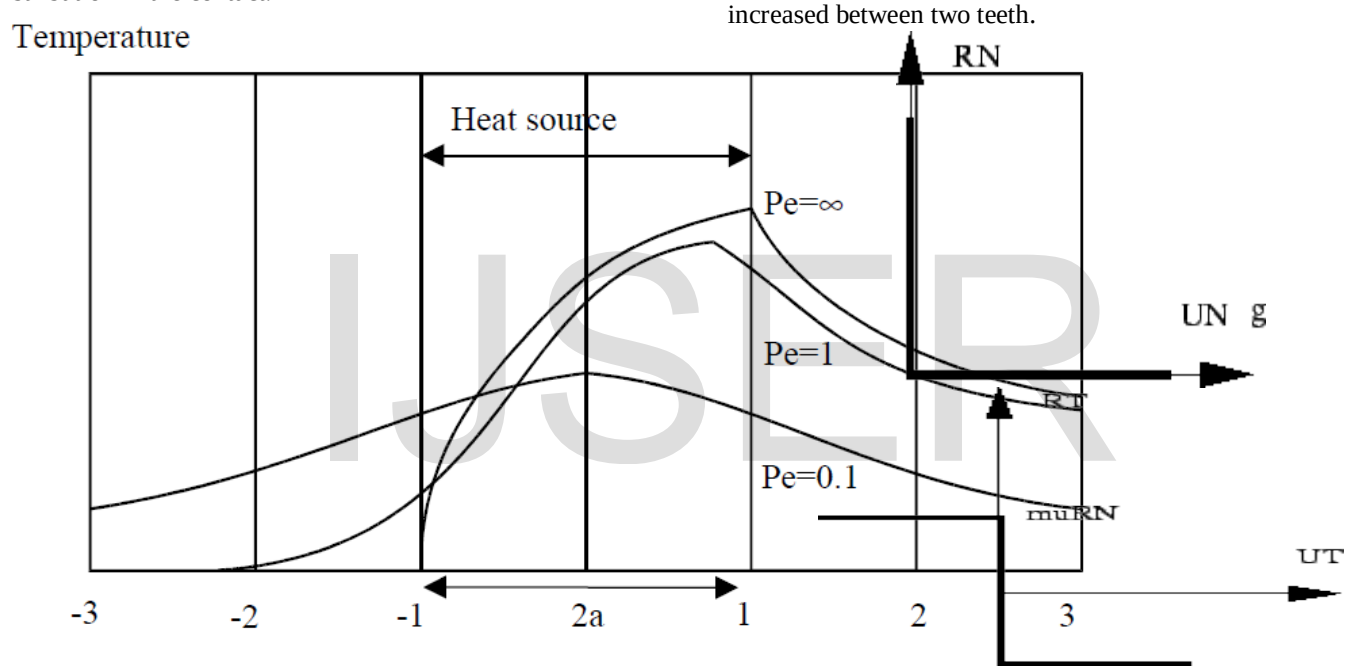

Fig. 1 Steady state surface temperature profiles in a half space moving under a heated band of width 2a for various values of the Peclet number, Pe.

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

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 thermaldiffusivity 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 $q_o$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 [17].

$$T_{\max} = \frac{2 \cdot a \cdot q_o \cdot \delta_{theory}}{K_s \sqrt{\pi (1 + P_e)}} \quad (4)$$

2.2 Contact law

The hard particle model (two teeth in contact) implies two "contact law", a. unilateral condition if the separation velocity UN g of two teeth is positive then the normal force is zero and there is friction between two teeth the temperature is reduced between them. If, on the other hand, separation velocity UN g is zero, i.e. the two teeth stag in contact, then RN can have a positive indefinitely large value so as to prevent interpenetration this is shown as a graph, Signorini's graph, in Fig. 2(left) and the temperature increased between two teeth.

Fig. 2Shows the Signorini graph (left) and coulomb's friction (right).

2.3 Coulomb's law

If the sliding velocity UT is nonzero, then the frictional force RT resist sliding and its value is given by the coefficient of friction μ times the normal force N and the temperature between two teeth is to decrease. If, on the other hand, UT is zero (nonsliding contact), then RT can take any value in the interval (-μN, +μN) and the temperature between two teeth is increases, this is shown in Fig.2 (right) as a graph.

3. Simulation analysis

3.1 Simulations for spur gear

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

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freedom is 111852 and complete mesh consists of 16522 elements as shown in Fig.3.

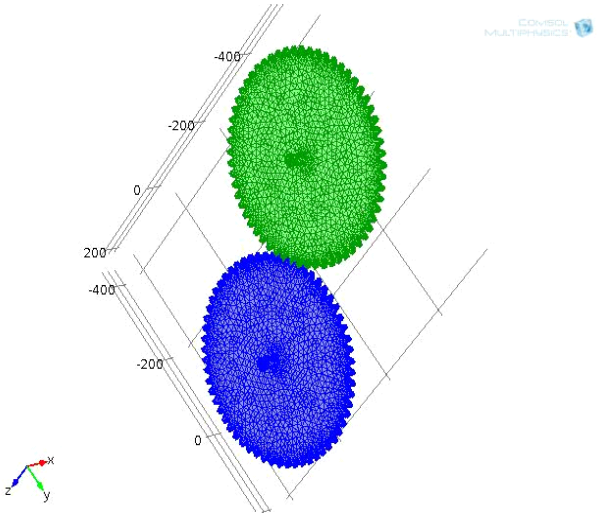


Fig.3 Shows fine mesh of two spur gears.

Figure4 (left) shows finite elements distributed on the face width of two gears and on the surfaces of gears as well (right). Atthe beginning of simulation, we prepared a solidwork files containing two spur gears in mesh after worth, we make a program simulation prepared to receive live link for thesolidworks. 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].

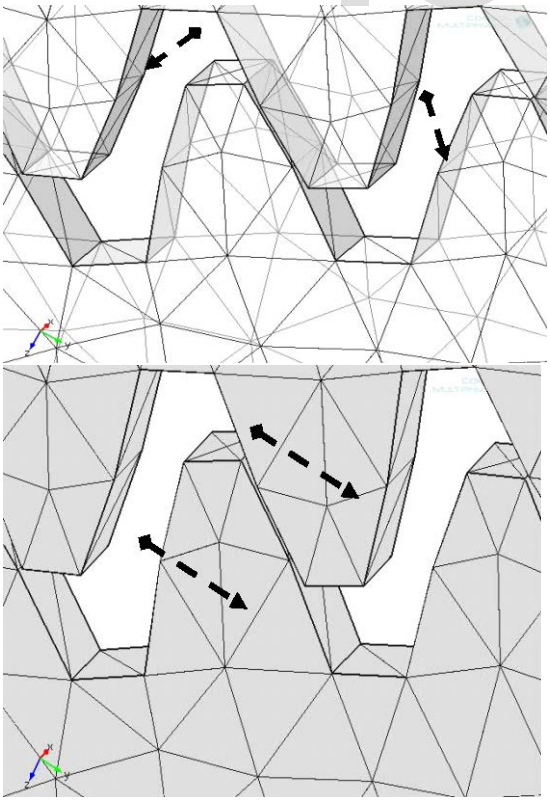


Fig. 4 Shows finite element distribution on face widths (left) and the surfaces (right) of teeth.

Fig. 5 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.

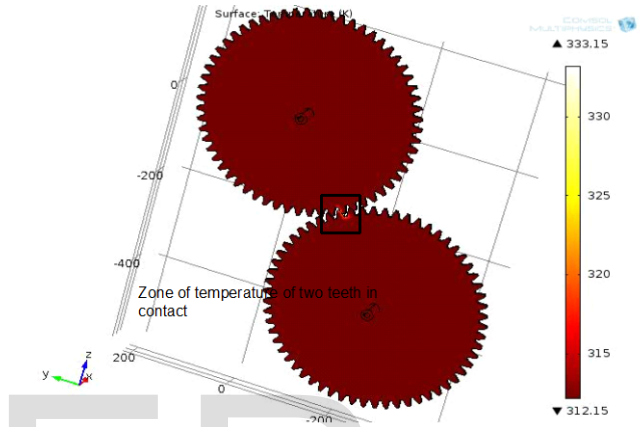
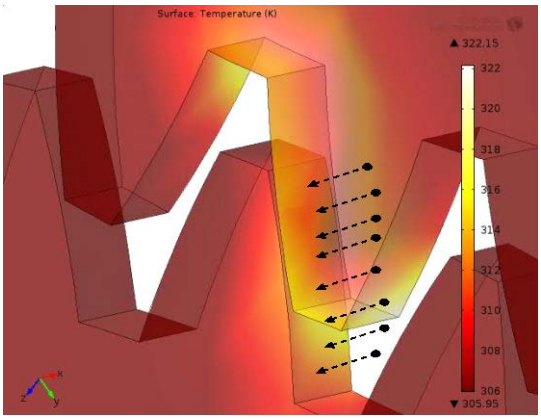


Fig. 5 shows two spur gears in mesh, and dotted circle indicates the higher temperature of two teeth in mesh.

In Figure 6 we have to take a closer 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).



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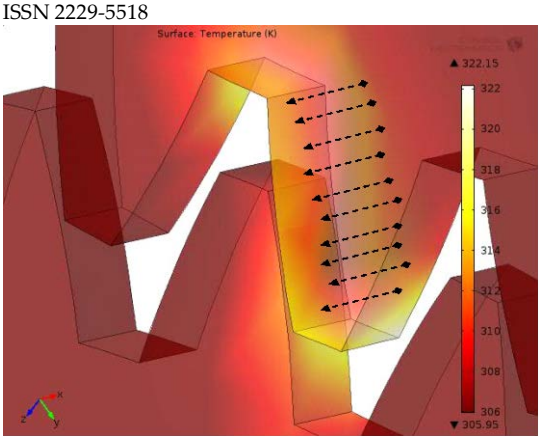

Fig. 6 Arrows illustrate the temperature distribution on face widths of the driver tooth (left), and the driven tooth (right).

Figure 7 shows the higher temperatures are on 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).

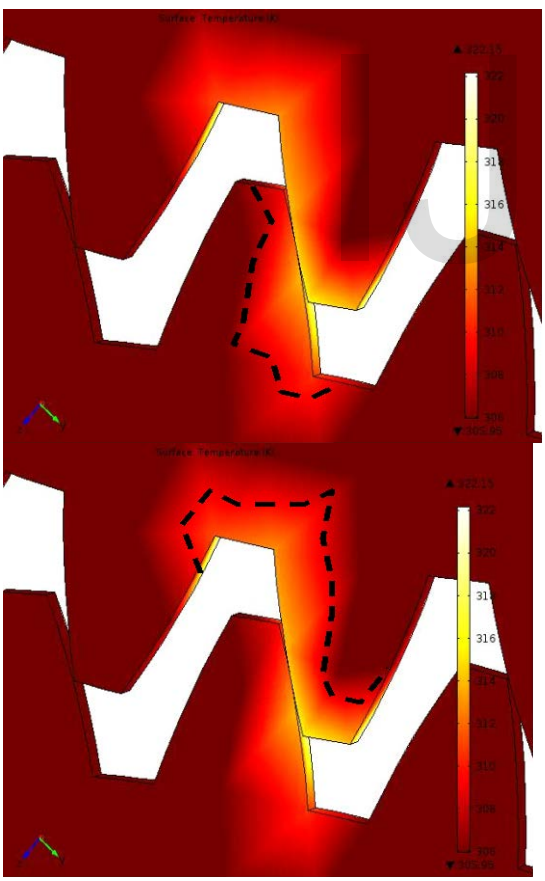

Fig.7 Dotted lines separate higher and lower temperature distribution on surface on two teeth in mesh driver (left) and driven (right).

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 8, which shows the reading of different points in (x, y, z) directions. Table2 shows the reading points, P1, P2, P3 and P4 in three dimensional (x, y, z) and corresponding temperature of each point.

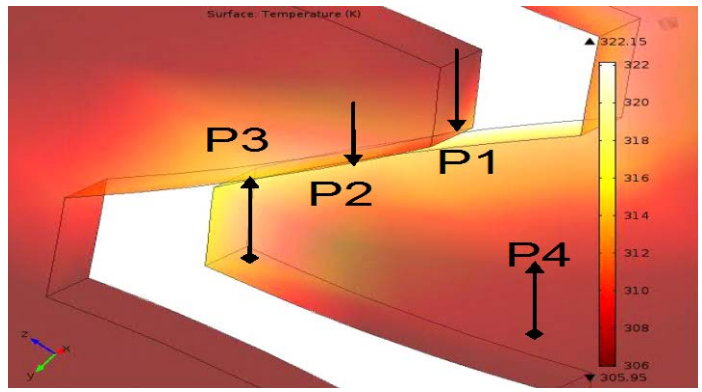

Fig. 8 Shows sample of point measured on surface and face width of teeth.

Table 1 illustrates the temperatures, whichwere 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

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3.2 simulations for helical gears

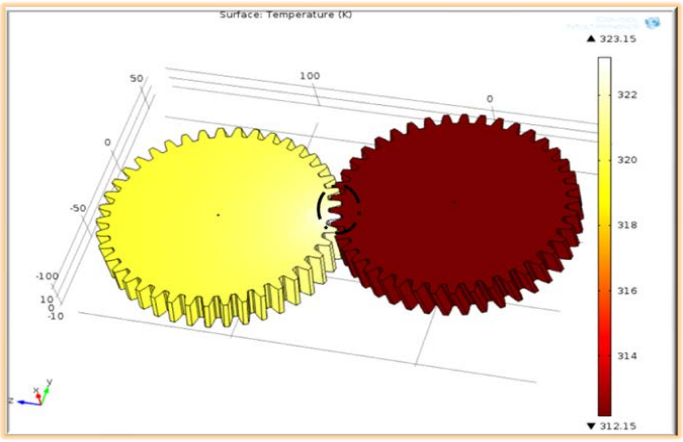

Fig. 9 shows two helical gears in mesh.

As shown in Figure 9, the dotted line circle indicates to the temperature distribution between two teeth of two helical gears in mesh.

In Complete mesh consists of 11449 elements,custom 11567 and Number of degrees of freedom solved for 63731 and Fine, custom 64190 and time takes for the Solution is time 11 s.

In Figure 10 arrows indicate to the temperature distribution at surface of tooth of driven gear during meshing, which temperature arise in the surface of driven on the tooth of driven gear than the tooth of driver gear during mesh.

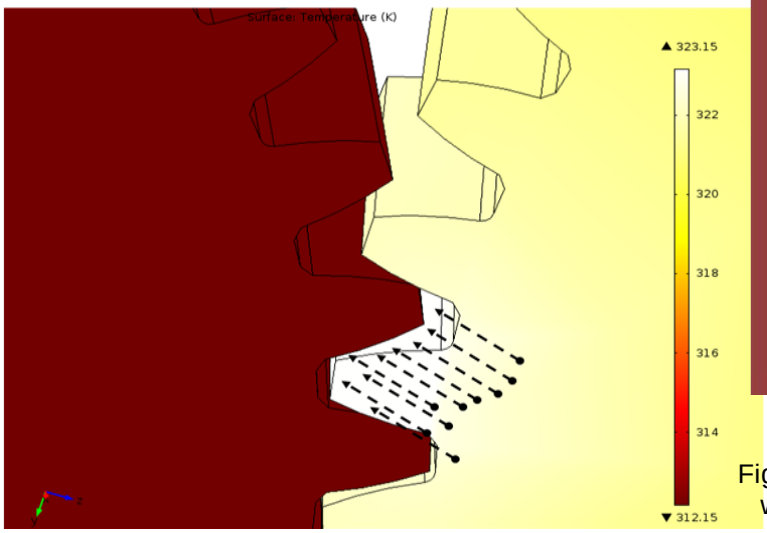

Fig. 10 shows temperature distribution on the surface of the tooth of the driven gears meshed with the tooth of driver gear.

As well the arrows in Fig. 11 illustrates the temperature of face width of the driven gear the change of colors indicates to higher temperature from region to other region as indicated at barcode in the left side of Figure.

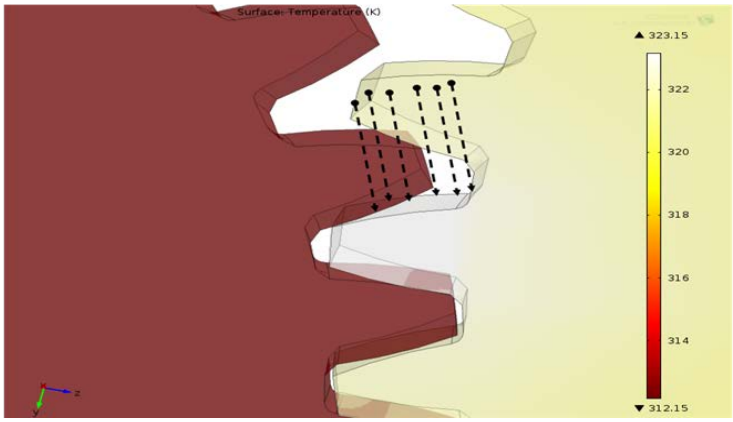

Fig. 11 shows the temperature distribution on the face width of tooth of driven gear.

The temperature distribution on the tooth width of driver gear during meshing as shown in Fig. 12 that the arrows indicates to this region.

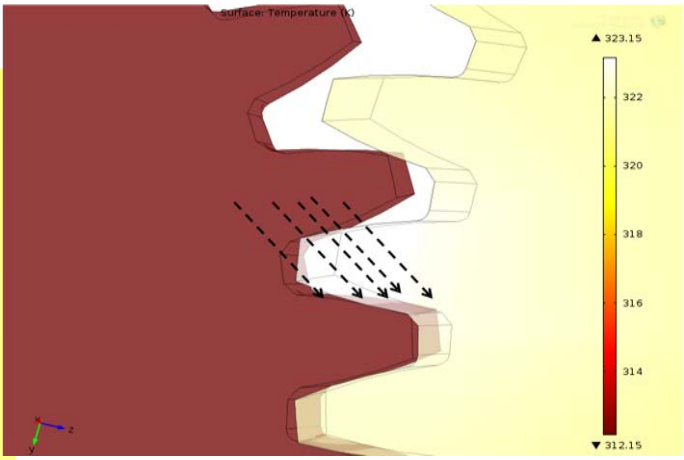

Fig. 12 shows the temperature distribution on the face width of tooth of driver gear.

Figure 13 express on the temperature distribution of tooth

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of driven and driver at the surfaces and face width during mesh of two teeth of helical gears in three dimensions.

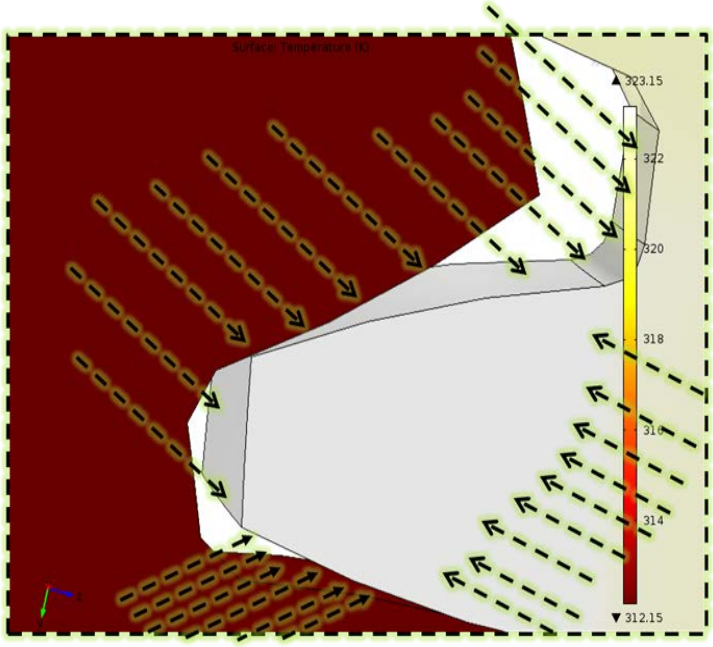

Fig. 13 shows the temperature distribution on surface and the face width of tooth of driven and driver gears.

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 thermocouple as shown in Fig.14[1].

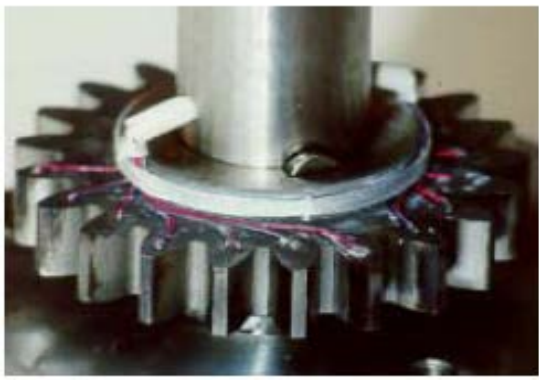

Fig.14 Previous simulations used thermocouple built in gear round the surface (left), concentrate at specific point at the surface (right).

Two test rigs are investigated; each test rig is prepared in two phases.

4.1 Test rig 1

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. 15. 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.

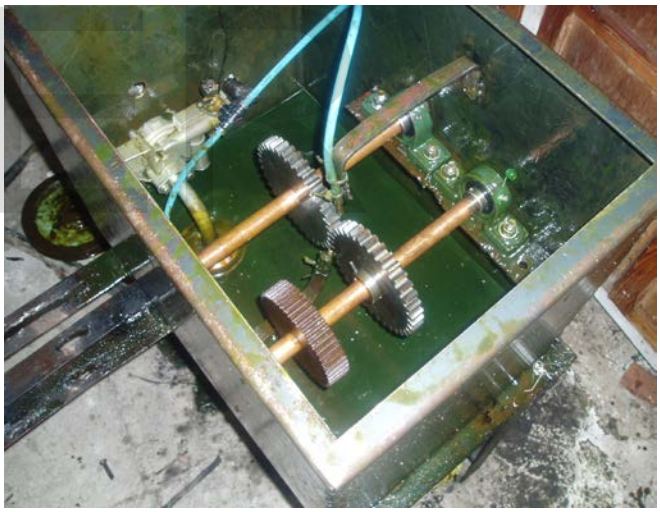

Fig.15 Test rig of spur gears with loading.

4.2 Test rig 2

Second test rig for helical gears without loading as in Figure 16 (left) and with loading which equal to 21.5 N weights of one helical as shown in Figure 16 (right). Material of gears is Alloy Steel 8620, Carbon 0.18 - 0.23 %, Chromium 0.4 - 0.6 %, Molybdenum 0.15 - 0.25 %Nickel 0.4 - 0.7 % , hardness of gears, Yield 393 Mpa., weight of one gear, 2200 gm, No. of teeth=41, module=3, pressure angle =14.5º, helix angle=8º, outside diameter=130 mm, root diameter=114mm, tooth height = 8mm, root fillet radius= 2mm, face width=25mm, Maximum torque effecting on gear=7655 N.m and Laser Gun Temperature to measure

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temperature at contact line of two gears during mesh.

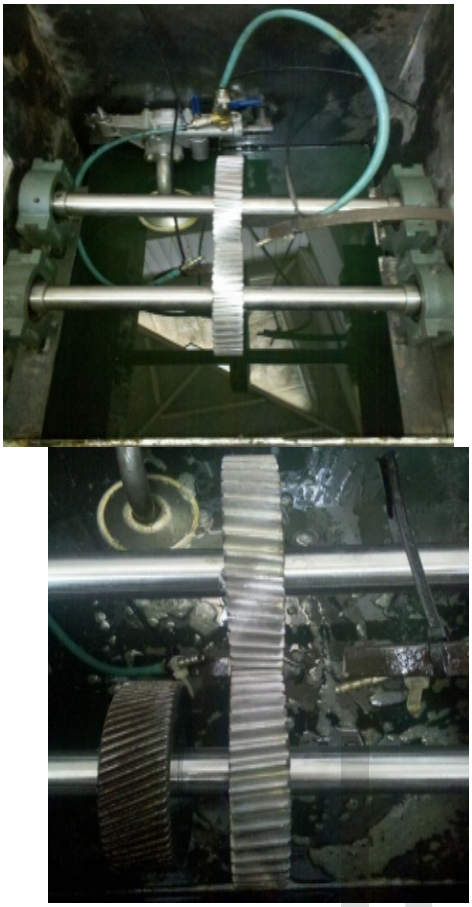
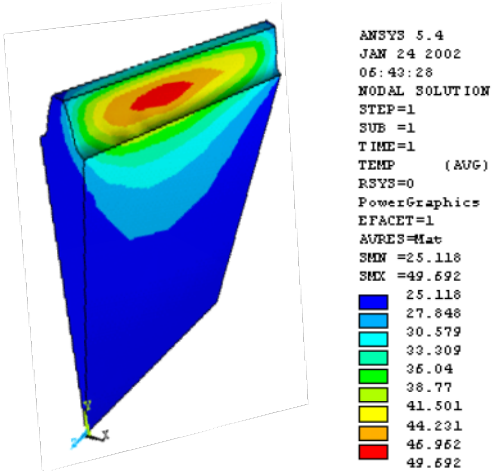


Fig. 16 Helical gears test rig without load (left) and with loading (right).

4.4 Measurements

Test rig is 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 atthe right side of the middle in equal distances as shown in Figure 17 (right).



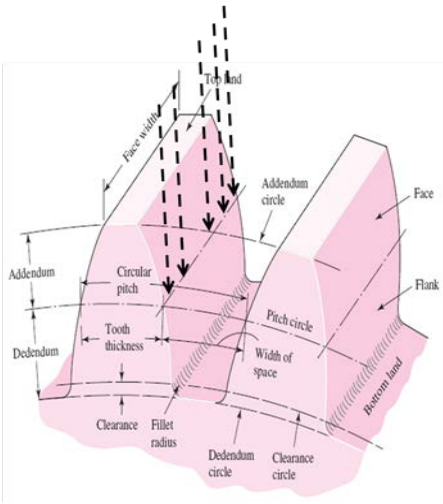


Fig.17 Shows temperature distribution[2], (left), arrows indicate to the five points measured at the face width of spur gear (right).

In helical gears, the measurement is performed at five points at the line contact between to the contact of two teeth of helical gears in meshing at the line of contact of two teeth as the arrows indicate in Fig. 18.

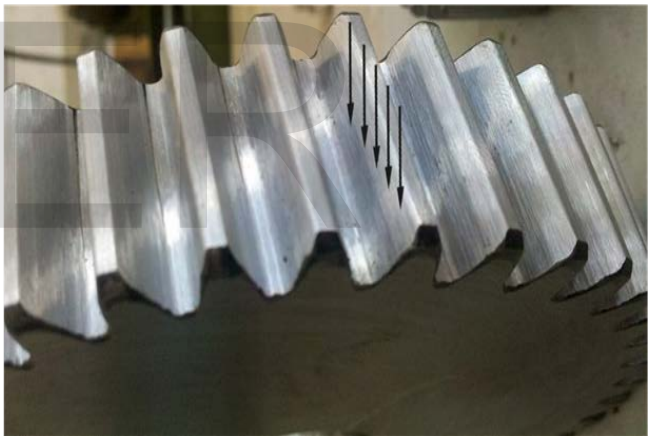


Fig. 18Arrows indicate to the five points measured at the face width of helical gear.

4.3 Experiment analysis

Figures 19, 20, 21 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.

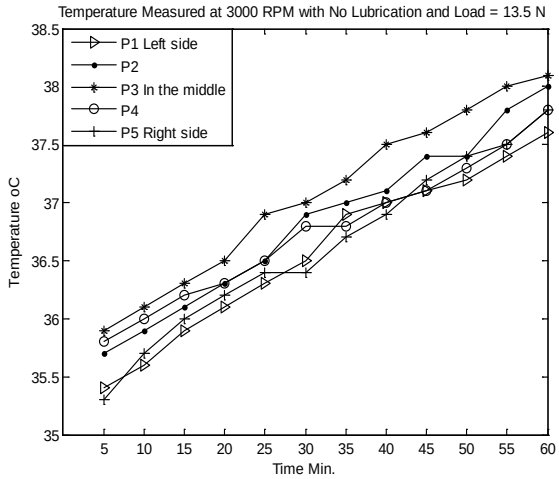


Fig. 19 Illustrates relation between temperature and time at 3000 rpm.

For 6000 rpm in the Figure 20, 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.

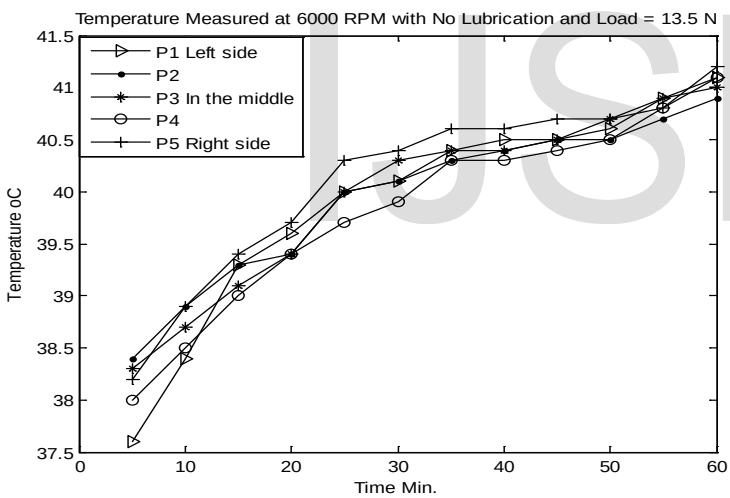


Fig. 20 Illustrates relation between temperature and time at 6000 rpm.

Figure 21 shows 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 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 is always higher than the left side which is closed to the input power of the system.

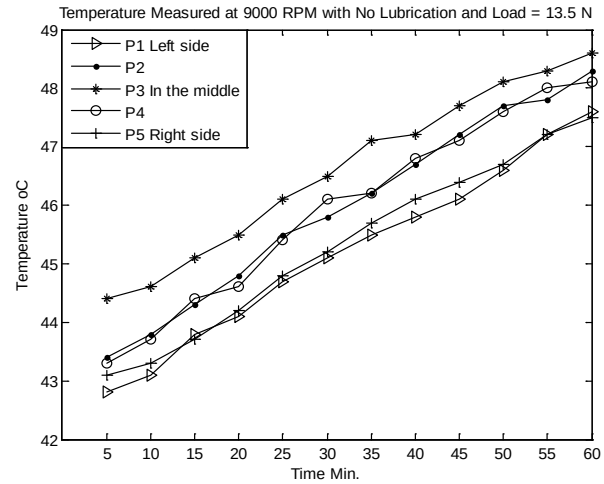


Fig. 21 Illustrates relation between temperature and time at 9000 rpm.

Figure 22, 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.

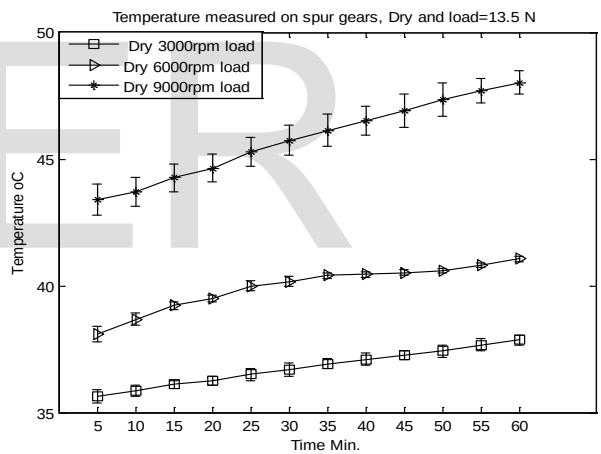


Fig. 22 Illustrates the temperature distribution with different RPM's.

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

ISSN 2229-5518

	Before test	After test
Motor temperature	31.9°c	49.3°c
Room temperature	32.8°c	

In helical gears without lubrication and without load in Figure 23, errorbar 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 and the temperature distribution in the middle point at the contact line between two teeth in mesh.

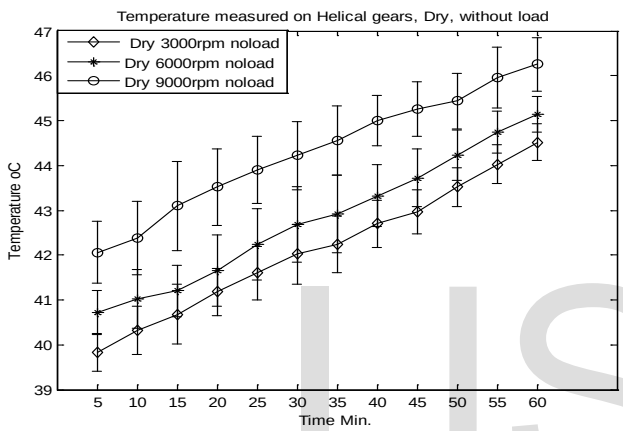


Fig. 23 shows the temperature measured at the five points between two helical gears without load and lubrication.

In Figure 24 indicated that the temperature distribution increased by putting load on the system regardless of the results in the Figure 22 as well as increasing the speed of gears the temperature increased.

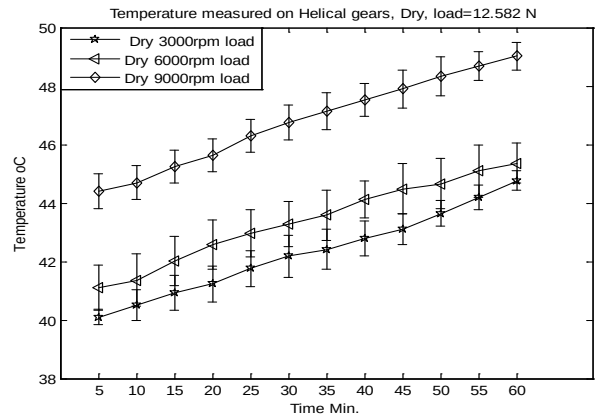


Fig. 24 shows the temperature measured at the five points between two helical gears without lubrication and with load.

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. Fromfinite element simulation, it obviously appeared the temperature distribution of two teeth in contact as well the computed temperature degrees at any point at the spur gear at point is 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.

The experimental results are close to finite element simulation, but 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 ease and accurate results depends on the skills of the programmer. Absolutely, temperature increases in the area of contact along the face width of two teeth. Additionally, at the 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 contacted 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 advanced into real experiment in cost [16]. In this, a computer simulation can overcome the stumbled of impossibility of experiment for measuring 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 [4]. The maximum gear tooth "bulk" temperature measured very close to the involute surfaceof the tooth is considered relevant to surface durability, and the maximum contact temperature at the tooth surface is considered relevant to scoring resistance [8].

REFERENCES

[1]FAILURE ANALYSIS GEARS-SHAFTS-BEARINGS-SEALS, Rexnord Industries, LLC, Gear Group, 1987, www.rexnord.com.

[2] Thyla, P. R. and Rudramoorthy, R., Investigations On Gear Tooth Surface And Bulk Temperatures Using ANSYS,PSG College of Technology, Coimbatore, (2004), INDIA, Conf.

[3] Elshourbagy, S. A. M., Effect of Lubrication on the Quantity of Heat Emission Of Two Spur Gears In Meshing, Proc. of the Int. Conf. On ICAMAME:Tokyo, (2012), pp. 893-896..

[4] Robert, F. H., Effect of Lubricant Jet Location on Spiral Bevel Gear Operating Temperatures, Sixth International Power Transmission and Gearing Conference sponsored by the American Society of Mechanical Engineers Phoenix, Arizona,(1992-8), 13-16.

[5] Yakut, R., Düzcükoðlu, H., and Demirci, M. T. The load capacity of PC/ABS spur gears and investigation of gear damage, Int. Scientific J., V 40, issue1, 2009, pages 41-46.

[6] Koshigoe, S., Murdock, J. W., Akin, L.S. and Townsend, D.P., A Computer Program for the Computation of Running Gear Temperatures Using Green's Function, Seventh Int. Power Transmission and Gearing Conf. sponsored by the ASME: San Diego, California, Oct, (1996).

[7] Robert, F. H., Testing of Face-Milled Spiral Bevel Gears at High-Speed and Load: (2003), *NASA*.

[8] Suren B. Rao and Douglas R. McPherson, Gear Tooth Temperature, www.gearsolutions, (2009), pp. 36-41.

[9] Miroslav, V., Miroslava, N., and Aleksandar, M., Tooth Flanks Scoring Resistance of Noninvolute Teeth Profiles In Plane Toothed Cylindrical Gears, FME Transactions, VOL. 37, No 2, 2009, pp. 103-106.

[10] Blok, H., The postulate about the constancy of scoring temperature. Interdisciplinary Approach to the Lubrication of Concentrated Contacts, NASA SP-237, 1970.

[11] Prášil, L. and Mackerle, J., "Finite element analyses and simulations of gears and gear drives: A bibliography 1997-2006," Engineering Computations, vol. 25, 2008, pp. 196-219.

[12]Moghani, T,Butler, J, Lin, J., and Loring, S., "Finite Element Simulation of Elastohydrodynamic Lubrication of Soft Biological Tissues.," Computers & structures, vol. 85, 2007, pp. 1114-1120.

[13] Yiping, H., Darong, C., Xianmei, K., and Jiadao, W., "Model of fluid-structure interaction and its application to elastohydrodynamic lubrication," Computer Methods in Applied Mechanics and Engineering, vol. 191, 2002, pp. 4231-4240.

[14] Ivana A., and Vera, N., "3D Spur Gear FEM Model for The Numerical Calculation of Face Load Factor", Mechanics, Automatic Control and Robotics Vol. 6, No 1, 2007, pp. 131 - 143.

[15] Xueyi, L., Chaocho, L., Daqian, G., Shoubo, J., and Binbing, H., " Accurate Numerical Analysis of Gear Research Strength Based on the Finite Element Method", Journal of Theoretical and Applied Information Technology, Vol. 46 No.2, 2012, pp. 855-860.

[16] Xin W., Kar W. N., Ying P. L., Jong B. O., Jee-Hou H., Ching S. T., and Anthony G."Finite Element Simulation of Thermography Non-destructive Testing for Gear Inspection", NDT, 2010, conf., pp. 1-17.

[17] Archard, J. F. and Rowntree, R. A., the temperature of rubbing bodies; Part 2, the distribution of temperatures, Wear, vol. 128, (1988), pp. 1-17.

[18] Elshourbagy, S. A. M., Study the Temperature is Generated During Meshing Two Spur Gears, Proc. of the Int. Conf. On ICPSE: China, (2011), pp. 773–777.

[19] Elshourbagy, S. A. M., Investigated the Effect of Higher Speeds on Bearings And Spur Gears, Pro.of the Int. Conf. On ICAMAME:(2012), Zurich.