ABSTRACT

Gear units are now being used more at higher speeds and heavier loads and hence, are frequently subjected to high temperature operations. The study of the operation of worm gear transmissions shows that seizure due to scuffing is a dangerous type of damage. This results from a breakdown of the oil film because of high temperature at the contact zone.

Conventionally, the elements of gearbox, including the gear pair, are designed based on mechanical strength aspects. But many machine elements, such as bearings, gears, etc. fail in service, not only due to the mechanical stresses exceeding the limits, but also due to high temperatures produced during operation. Hence, there is a need to ensure in design, that thermal limits are not exceeded within the stipulated operating conditions, so that premature failure due to high temperatures can be avoided. Therefore, it is essential to have knowledge of the thermal behaviour of the units at the design stage itself. This can be achieved by predicting the temperature distribution in gearboxes under various operating conditions using virtual models and arriving at an acceptable design based on both mechanical and thermal aspects.

In this work, thermal numerical models were developed to predict the thermal behaviour of worm gearboxes. These models can be used as tools for evaluating their thermal performance before the physical prototype is built. They can also be used for making accurate predictions of their thermal capacities so that under-rating of the gearbox units due to uncertainties in their thermal behaviour can be avoided. This will help in the

utilisation of the gearboxes to their full capacity. Also, improvements in design can be tried out on the computer models and optimum designs can be arrived at.

Three numerical models have been developed to predict the thermal performance of the gearboxes under various operating conditions. Any numerical model developed requires validation with experiments, so that the same can be used reliably. In order to validate the numerical models developed in this work, a test rig has been designed and fabricated for conducting experiments. Six parameters, namely, the size of the gearbox, the load, the input speed, the viscosity of the lubricating oil, the level of oil in the gearbox and external cooling by means of fan were identified as variables for experimentation and three levels were assigned for each parameter. Since 729 experiments were to be conducted for the above combination of six parameters with three levels for each parameter, Taguchi's Design of experiments concept was adopted to arrive at an L_{27} array, where, 27 represents the number of experiments to be conducted. The experiments were conducted on commercial single reduction worm gearboxes and the observed data recorded.

The first of the three numerical models developed was based on a lumped mass approach using simple heat balance in a worm gearbox. Frictional heat input and convective heat transfer coefficients were estimated for different operating conditions and applied as input to the model. Transient temperatures of the bulk of the gear pair, the oil and the casing were predicted for gearboxes of various sizes under different operating conditions. The parameters that were varied in the experimentation have been considered in the numerical model also. The effects of these parameters on the thermal performance of the gearbox units have been investigated. The influence of the surface area of external fins has also been studied.

A comparison of the temperature results of the lumped mass approach with the corresponding experimental observations shows a good correlation in the general trends of the results, but the temperature values are found to be lesser than the values measured in the experiments. The lumping of masses and the assumption that the entire volume of oil participates in the heat transfer by convection may probably be the reasons for the deviations.

The first model, i.e., the lumped mass model, does not give the temperature distribution in the different elements of the gearbox unit. Hence, in order to obtain knowledge on the temperature variations within each component of the unit, a second model was developed. This is a global finite element model, which consisted of the gear pair, the shafts, the oil and the casing. A quarter model of the unit was built owing to symmetry, with the aim of minimizing the memory and time requirements. The frictional heat and the convective coefficients estimated for the previous model were applied as boundary conditions for this model. Finite element steady state thermal analysis was carried out on gearboxes of different sizes and under the various operating conditions mentioned earlier.

A comparison of the temperature results obtained using the finite element model of the gearbox unit with experimental values has shown good agreement. The general trends of the results are found to be similar to those obtained from the lumped mass method and both the sets of results are found to be in agreement with results published in by others in literature.

The third numerical model developed in this work was aimed at predicting the gear tooth bulk temperature profile using finite element method, so as to study the local thermal pattern on the tooth. This model was used to perform steady state thermal analysis on one tooth of the worm wheel. In this model, the heat input from the meshing zone is averaged out over one revolution, so that there is a steady heat input on each tooth through a revolution of the gear. Different convective heat transfer coefficients were estimated and applied on the hub surfaces of the tooth and the land portions. The model was applied to gear teeth of different sizes for various operating conditions and the bulk temperature profiles were obtained. Since it is difficult to measure the temperatures on the teeth of running gears in experiments, the results obtained from this model were compared with the corresponding results of the global analysis of the gearbox mentioned earlier, which were validated with experimental data. The comparison shows good agreement between the gear tooth temperatures obtained form the two models. The results are found to match with the results published by others also.

With the aim of developing empirical relations for the prediction of the rise in gearbox oil temperature and the rise in gear tooth temperature, regression analysis was performed on the temperature data obtained from the two finite element models developed. Multiple linear regression of the power form was adopted for the two models. The rise of temperature of the oil in the worm gearbox was modeled as a function of the heat generated in the gear box, the rate of heat dissipation by convection from the surface of the worm and the overall convective heat transfer coefficient from the oil to the atmospheric air. The rise in the bulk temperature of the tooth of the worm wheel was modeled as a function of the frictional heat generated at the teeth-meshing zone, the rate of heat dissipation by convection from the hub surface of the gear tooth and that from the land portion of the tooth. Comparisons between the data obtained using two the empirical relations and the numerical results obtained by the finite element models indicate very close correlation between the regression data and the finite element analysis data. The empirical curves are estimated to fall within one standard deviation of the numerical values on nearly 68% of the data points taken for the prediction of temperature rise of oil and on nearly 70% of the data points taken for the prediction of temperature rise of gear tooth. The ANOVA results of the two models show that both the models are valid at a high significance

The empirical equations developed can be used as a quick and easy means of estimating the bulk temperature of the oil and the gear tooth for various operating conditions.

The temperature data obtained by the numerical models proposed can be used for the thermal rating of gearbox units by predicting the onset of scuffing mode of failure of the gears. The oil temperatures predicted using the global thermal analysis of quarter models of gearboxes and the gear tooth bulk temperatures predicted using the single tooth analysis can be used to establish the maximum safe value of power the gearbox unit can transmit without the gears undergoing scuffing. Thus, more accurate thermal ratings can be made and under-utilisation of the gearbox units can be avoided.

It is believed that the industries concerned with the design and manufacture of gearboxes will find the design-oriented methodology proposed in this work useful in the thermal rating of gearboxes without resorting to physical tests and in making improvements in designs so as to achieve better thermal characteristics during operation.