CHAPTER 3

THEORETICAL INVESTIGATIONS

3.1 INTRODUCTION

There exists three fundamental modes of heat transfer, between masses having different thermal levels. They are:

1. Conductive heat transfer within solids,
2. Convective heat transfer from solids to fluids (at rest or in motion) and
3. Radiative heat transfer between masses separated by space.

Although, other modes of heat transfer exist, such as radiation to gases and conduction within fluids. However, according to Harris [3], their effects are too minor to be considered for most bearing applications.

Briefly, three fundamental modes of heat transfer are reviewed below, with reference to heat transfer within and across any bearing assembly. Heat generated due to Radial and axial power lost in the bearing assembly gets dissipated by these modes of heat transfer.

3.1.1 CONDUCTIVE HEAT TRANSFER

Conductive Heat Transfer ($H_c$), the simplest form of heat transfer, is a linear function of difference in the thermal levels $(T_1 - T_2)$ of the two nodes within the bearing assembly. Thus

$$H_c = \frac{Ks}{l} \times (T_1 - T_2) \quad (3.1)$$
The term 'S' is the area normal to the heat flow between the two nodes; 'l' is the shortest distance between the two nodes considered; 'K' is the thermal conductivity of the bearing housing which is generally considered constant. For heat transfer in the radial direction, within an annular structure, such as that through inner and outer ring of the bearing, following form of equation (3.1) is useful:

\[ H_c = 2\pi K W X \left( \frac{\left( T_1 - T_2 \right)}{\ln \left( \frac{R_o}{R_i} \right)} \right) \]  

In equation (3.2), W is the width of the annular structure; \( R_o \) and \( R_i \) are the inner/outer radii of the nodes through which the heat flow occurs. When inner radius is zero, equation (3.2) takes the form of equation (3.1).

### 3.1.2 CONVECTIVE HEAT TRANSFER

Convective Heat Transfer is the most difficult mode of heat transfer to be estimated quantitatively. It occurs within the bearing assembly, as the heat is transferred to the lubricant from the bearing and from the lubricant to other structures within the assembly, e.g., inside walls of the assembly. It also occurs between the outside walls of the assembly and environmental fluid - generally air, but any other medium can be planned.

Convective heat transfer \( (H_v) \) from a surface may be generally described as follows:

\[ H_v = h_v S \left( T_1 - T_2 \right) \]  

\( h_v \) in above equation (3.3),is the heat transfer coefficient which is the function of surface and fluid parameters. \( h_v \), therefore, is a linear function of temperature difference \( (T_1 - T_2) \) : corresponding to surface and fluid, as fluid parameters are considered constant over the range.
The lubricating oil has a higher viscosity and, therefore, oil flow in the bearing assembly can be considered laminar [3]. Eckert [17] states for a plate in a laminar flow field:

\[ h_v = 0.332 \times K \times Pr^{1/3} \times \left(\frac{U}{v_x}\right)^{1/2} \]  

(3.4)

Equation (3.4) estimates \( h_v \) for the heat transfer from bearing to the lubricating oil [3], if \( U \) is taken equal to the mean bearing velocity, \( x \) equal to bearing pitch diameter. \( v \) and \( Pr \) are kinematic viscosity of oil and Prandtl number of oil respectively. Equation (3.4) also estimates \( h_v \) for the heat transfer from the lubricating oil to the inside walls of the assembly, if \( U \) is taken to be one-third of the mean bearing velocity and \( x \) equal to bearing assembly diameter [3]. \( v \) and \( Pr \) have the same meaning as earlier.

3.1.2.1 COOLING THE ASSEMBLY NATURALLY

Consider, the bearing assembly (absorbing the 'powers') is kept in quiescent air. Heat transfer coefficient for such a situation, is given by Jacob and Hawkins as follows:

\[ h_v = 0.3 \times (T - T_a)^{1/4} \]  

(3.5)

In equation (3.5), \( T_a \) refers to the atmospheric temperature of quiescent air (still air).

3.1.2.2 COOLING THE ASSEMBLY BY COIL

If the bearing assembly is cooled by cooling coils, submerged in the oil bath, they should be aligned parallel to the shaft so that, a laminar cross flow is obtained, resulting in better heat transfer coefficient, \( h_v \). Eckert [17] gives the following relation for \( h_v \) in cross flow:
\[ h_v = 0.6 \times \frac{K_0}{D_t} \times (U \times \frac{D_t}{v})^{1/2} \]  \hspace{1cm} (3.6)

Equation (3.6) stated above approximates the heat transfer coefficient of the coil used for cooling the bearing. Notations \( K_0 \), \( D_t \) are oil conductivity and outside diameter of the tube respectively. Harris [3] suggests that 'U' should be taken equal to one-fourth of the mean bearing velocity. \( D_t \) of 10 mm and ratio of tube length to \( D_t \) are considered to be '25' and '50', in this work.

### 3.1.2.3 COOLING THE ASSEMBLY BY FAN

If the bearing assembly is cooled by forced flow of air by fan over the assembly (velocity: 'U'). Eckert [17] suggests, following equation for the calculation of '\( h_v \)'.

\[ h_v = 0.3 \times \frac{K_a}{D_h} \times (U \times D_h/v)^{57} \]  \hspace{1cm} (3.7)

In equation (3.7) above, \( K_a \), \( D_a \) and \( D_h \) are air conductivity, air kinematic viscosity and bearing housing diameter respectively.

### 3.1.2.4 COOLING THE ASSEMBLY BY FIN

We have observed in equation (3.3) that heat flow can be increased by increasing '\( h_v \)' or 'S'. '\( h_v \)' can be increased by providing either coil cooling (3.1.2.2) or fan cooling (3.1.2.3). 'S' can be increased by providing fin as an integral part of the bearing assembly.

Palmgren [1] gives the following formula to approximate the external area of the bearing assembly:

\[ S = \pi \times D_h \times (W_h + D_h/2) \]  \hspace{1cm} (3.8)
In equation (3.8) above, \( W_h \) represents the width of the bearing assembly. By providing fins, above area of the bearing assembly can be increased by the factor required. This factor has been taken as '2' and '4', in this work.

3.1.3 RADIATIVE HEAT TRANSFER

Bearing assembly dissipates heat to the surrounding structures by way of radiation also. Radiative heat transfer \( (H_r) \) from a small structure to a large enclosure, is given by Jacob and Hawkins [18] as follows:

\[
H_r = 4.875 \times 10^{-8} \times \varepsilon \times S \times (T^4 - T_a^4)
\]

(3.9)

In equation (3.9), \( \varepsilon \) and \( T \) are the emissivity (dimensionless) and temperature of bearing assembly (in absolute units).

3.2 HEAT FLOW ANALYSIS

To obtain a theoretical solution to the heat flow problem across the bearing assembly, method of finite difference as demonstrated by Dusinberre [11] is applied to the system, under consideration.

3.2.1 INTRODUCTION

For finite difference method applied to the steady state heat transfer problem, various points or nodes are selected throughout the system being analyzed. At each of these nodes, temperature is determined. In steady state heat transfer, heat influx to any point is equal to heat efflux; therefore, the sum of the heat flowing toward a temperature node is equal to zero. Figure (3.1) shows a heat flow diagramme at node 'O', which shows that its nodal temperature is affected by the temperatures...
of each of the surrounding nodes. It may be noted here that number of nodes in
the system is by choice and number may be smaller or greater. Assuming that (i)
heat flow occurs only by conduction (ii) all areas 'S' for heat flows and flow path
lengths 'I' are different and (iii) the material in non-isotropic so that conductivity is
different for all flow paths, we, therefore, get,

\[ H_{1,0} + H_{2,0} + H_{3,0} + H_{4,0} = 0 \] (3.10)

On substituting equation (3.1), we get,

\[ K_1 X S_1/I_1 (T_1 - T_0) + K_2 X S_2/I_2 (T_2 - T_0) + \]
\[ K_3 X S_3/I_3 (T_3 - T_0) + K_4 X S_4/I_4 (T_4 - T_0) = 0 \] (3.11)

Let

\[ K_1 X S_1 / I_1 = F N (0, 1) \] (3.12)
\[ K_2 X S_2 / I_2 = F N (0, 2) \] (3.13)
\[ K_3 X S_3 / I_3 = F N (0, 3) \] (3.14)
\[ K_4 X S_4 / I_4 = F N (0, 4) \] (3.15)

On substituting equations (3.12) to (3.15), in equation (3.11), we get,

\[ FN (0,1) X (T_1) + FN (0,2) X (T_2) + FN (0,3) X (T_3) + FN (0,4) X (T_4) - \sum_{i=1}^{i=4} K_i X S_i/I_i X T_0 = 0 \] (3.16)

Let

\[ \sum_{i=1}^{i=4} K_i X S_i / I_i = F T (0) \] (3.17)
On substituting equation (3.17) in equation (3.16) and re-arranging, we get:

\[ \begin{align*} 
& F_N(0,1) \times T_1 / F_T(0) \ + \ F_N(0,2) \times T_2 / F_T(0) \ + \\
& F_N(0,3) \times T_3 / F_T(0) \ + \ F_N(0,4) \times T_4 / F_T(0) - T_0 = 0 \tag{3.18} 
\end{align*} \]

Let

\[ \begin{align*} 
& F_N(0,1) / F_T(0) = COEF(0,1) \tag{3.19} \\
& F_N(0,2) / F_T(0) = COEF(0,2) \tag{3.20} \\
& F_N(0,3) / F_T(0) = COEF(0,3) \tag{3.21} \\
& F_N(0,4) / F_T(0) = COEF(0,4) \tag{3.22} 
\end{align*} \]

On substituting equations (3.19) to (3.22) in equation (3.18), we get,

\[ \begin{align*} 
& COEF(0,1) T_1 + COEF(0,2) T_2 + COEF(0,3) T_3 + \\
& COEF(0,4) T_4 - T_0 = 0 \tag{3.23} 
\end{align*} \]

It may be noted that equations (3.19) to (3.23), evaluate influence coefficients of the four indicated temperatures \( T_1, T_2, T_3 \) and \( T_4 \) respectively which affect the nodal temperature \( T_0 \).

If we have a system, differing from the one depicted in fig. (3.1), equation (3.11) requires to be modified to account for convection and/or radiation in lieu of conduction.

Consider figure (3.2) which depicts that nodal temperature \( T_0 \) is affected by heat source \( HTGEN_0 \) and three surrounding nodes 1, 2 and 3 with which, the mode of heat transfer is conduction, convection and radiation respectively. Here, equation (3.11) takes the following form:

\[ \begin{align*} 
& HTGEN_0 + K_1 X S_i / l_i(T_i - T_0) + 0.3 X A_{20}(T_2 - T_0)^{1.25} \\
& + 4.875 \times 10^{-6} X \varepsilon X ((T_3+273)^4 - (T_0+273)^4) = 0 \tag{3.24} 
\end{align*} \]
It may be noted that heat flow terms in equation (3.24) are according to the equations (3.1), (3.3), (3.5) and (3.9). The term HTGEN₀ is the heat generated at node '0'.

Let

\[ K_i \times S_i / l_i = FT (0) \]  \hspace{1cm} (3.25)
\[ \text{COEF} (0,1) = 1 \]  \hspace{1cm} (3.26)
\[ \text{COEF} (0,2) = 0.3 \times A_{30} / FT (0) \]  \hspace{1cm} (3.27)
\[ \text{COEF} (0,3) = 4.875 \times 10^8 \epsilon / FT (0) \]  \hspace{1cm} (3.28)

On substituting equations (3.25) to (3.28) in equation (3.24), we get;

\[ HTGEN₀ + \text{COEF} (0,1) \times T₁ + \text{COEF} (0,2) \times (T₂ - T₁)^{1.25} + \text{COEF} (0,3) \times ((T₃+273)^4-(T₀+273)^4) - T₀ = 0 \]  \hspace{1cm} (3.29)

The term HTGEN₀ / FT (0) may be called COEF (0,0), which corresponds to the heat generated term at node '0'.

We have seen that systems in fig. (3.1) and (3.2) have 5 and 4 nodes respectively. Therefore, we can have, based on finite difference method, as many as 5 equations, for system of fig. (3.1) and 4 equations, for system of fig. (3.2). These equations, pertaining to a given system, can be solved for nodal temperatures by suitable method numerically.

3.2.2 THEORETICAL MODEL

Figure (2.12) depicts a typical two-bearing assembly, which absorbs radial and axial load of the hydraulic machine.
To analyze the system for its thermal levels, following assumptions have been made, to enable the heat flow analysis to be pursued, on the basis of principles outlined in (3.2.1):

1. The system shown in fig.(2.12) may be divided in '12' nodes (NODE) as shown in fig.(3.3).
2. The inside walls of the bearing assembly are coated with oil and, therefore, they may be described by a single temperature (X(8)).
3. The outer/inner ring raceways may be described by a single temperature (X(4)).
4. The housing is symmetrical about shaft centre-line and vertical section AA. Hence heat transfer in circumferential direction may be neglected.
5. Sump oil may be described by a single temperature (X(1)).
6. Shaft-ends outside the bearing assembly are at ambient temperature (AMTEMP).
7. Radial power loss (HPLOS1) occurs only at radial bearing and axial power loss (HPLOS2) occurs only at thrust bearing. The only heat sources, resulting from power losses assumed, are at designated raceways and no-where else, inside or outside the bearing assembly of the hydraulic machine.
8. The entire surrounding of the bearing assembly of the hydraulic machine is assumed to be at ambient temperature.

Considering the temperature nodes indicated by fig. (3.3), heat transfer system is indicated by table 1. Table 1 also furnishes which equations can be used to determine the heat flow, the heat transfer coefficient, etc. Table 1, therefore, gives all necessary
heat flow terms for all modes of the system under consideration. We can, therefore, develop 12 equations, corresponding to 12 nodes from table 1. It may be noted that for each row of the table 1, one equation pertaining to that nodal temperature can be easily developed.

To illustrate, refer the first row of the table 1 which conveys that nodal temperature at node '1' is affected by the nodal temperatures 2, 3, 4, 6, 7 and 8 by convective heat transfer. Hence, equation similar to that of (3.10) can be put up by using heat flow terms, given in table 1. Thus 12 equations corresponding to 12 'nodes' can be put up in the format shown in (3.2.1), e.g., equations (3.23) and (3.29) as the case may be.

Table 2 indicates the heat transfer area 'S_i' where 'i' corresponds to ith row and 'j' corresponds to jth column.

### 3.2.2.1 SYSTEM EQUATIONS

On the basis of the foregoing discussion, following equations, describing the thermal levels of the bearing assembly (fig. 3.3) can be developed:

\[-X(1) + \text{COEF}(1,2) \times X(2) + \text{COEF}(1,3) \times X(3) + \text{COEF}(1,4) \times X(4) + \text{COEF}(1,6) \times X(6) + \text{COEF}(1,7) \times X(7) + \text{COEF}(1,8) \times X(8) = 0\]  
\[-X(2) + \text{COEF}(2,2) + \text{COEF}(2,3) \times X(3) = 0\]  
\[-X(3) + \text{COEF}(3,1) \times X(1) + \text{COEF}(3,2) \times X(2) + \text{COEF}(3,4) \times X(4) = 0\]  
\[-X(4) + \text{COEF}(4,1) \times X(1) + \text{COEF}(4,2) \times X(2) + \text{COEF}(4,3) \times X(3) + \text{COEF}(4,4) = 0\]
\begin{align*}
- X(5) + \text{COEF}(5,4) X X(4) + \text{COEF}(5,10) X X(10) + \\
\text{COEF}(5,6) X X(6) &= 0 \quad (3.34) \\
- X(6) + \text{COEF}(6,1) X X(1) + \text{COEF}(6,5) X X(5) + \\
\text{COEF}(6,10) X X(10) + \text{COEF}(6,11) X X(11) &= 0 \quad (3.35) \\
- X(7) + \text{COEF}(7,1) X X(1) + \text{COEF}(7,9) X X(9) + \\
\text{COEF}(7,10) X X(10) + \text{COEF}(7,12) X X(12) &= 0 \quad (3.36) \\
- X(8) + \text{COEF}(8,1) X X(1) + \text{COEF}(8,3) X X(3) + \\
\text{COEF}(8,8) + \text{COEF}(8,9) X X(9) &= 0 \quad (3.37) \\
- X(9) + \text{COEF}(9,1) X X(1) + \text{COEF}(9,7) X X(7) + \\
\text{COEF}(9,8) X X(8) &= 0 \quad (3.38) \\
- X(10) + \text{COEF}(10,5) X X(5) + \text{COEF}(10,6) X X(6) + \\
\text{COEF}(10,7) X X(7) - \text{COEF}(10,4) X (X(10)-\text{AMTEMP})^{2.5} + \\
\text{COEF}(10,8) X ((X(10)+273)^{4}-(\text{AMTEMP}+273)^{4}) &= 0 \quad (3.39) \\
- X(11) + \text{COEF}(11,6) X X(6) - \text{COEF}(11,8) X (X(11) - \\
\text{AMTEMP})^{2.5} - \text{COEF}(11,9) X (X(11)+273)^{4}-(\text{AMTEMP}+273)^{4}) &= 0 \quad (3.40) \\
- X(12) + \text{COEF}(12,7) X X(7) - \text{COEF}(12,9) X (X(12) - \\
\text{AMTEMP})^{2.5} \cdot \text{COEF}(12,10) X ((X(12)+273)^{4}-(\text{AMTEMP}+273)^{4}) &= 0 \quad (3.41)
\end{align*}

It may be noted that the terms, \text{COEF}(4,4) and \text{COEF}(8,8), appearing in equations (3.33) and (3.37) respectively are heat source terms, corresponding to nodes '4' and '8' respectively. Moreover the term \text{COEF}(2,2) in equation (3.31) is a constant term involving, \text{AMTEMP} due to conductive heat transfer through the shaft.

It may be noted that the term \(X(1)\) corresponding to the sump oil thermal level, is the most frequented term, among all terms, in above equations. As a result, usually, it represents the thermal level of the bearing assembly.
It also may be observed from above equations that equations (3.30) to (3.38) are linear, but equations (3.39) to (3.41) are non-linear, due to convection and radiation terms in them.

3.3 NUMERICAL SOLUTION OF EQUATIONS

A system of non-linear equations represented by equations (3.30) to (3.41) may not be solved by direct numerical methods of iteration or relaxation. Therefore, Newton-Raphson method, given by Korn and Korn [12] was used for solution of above equations. Newton-Raphson is briefly stated below:

Newton-Raphson method states that for a series of non-linear functions $F_i$ of variables $X_j$, the following algorithm is true:

$$F_i + \frac{F_j}{X_j} X_j \times C_j = 0 \quad (3.42)$$

Equation (3.42) represents, a system of simultaneous linear equations, which may be solved for $C_j$, which is error on $X_j$. The new estimate of $X_j$ then becomes:

$$X_j = X_{j(0)} + C_j \quad (3.43)$$

New values of $F_i$ may now be determined. The process is continued, until the functions $F_i$ are virtually '0'.

Equations (3.30) to (3.41) were linearized by equation (3.42), assuming error on $X_j$ as one degree Celsius.

3.4 COMPUTER PROGRAMMING

For solution of equations (3.30) to (3.41), a computer programme was prepared in FORTRAN 77. The entire programme was split up in the main programme 'NK010' and three sub-routines, 'NONLNR', 'FUNVAL' AND 'SOL'. The sub-routines were taken
from the library. Appendix A encloses the listing of the programmes 'NK010', 'NONLNR', 'FUNVAL' and 'SOL'. Appendix B encloses the flow chart of the logic of the main programme, 'NK010' and the sub-routine 'NONLNR'.

'NK010' was designed to be general and broad-based. Values of AMTEMP, HPLOS1, HPLOS2, and RPM (bearing speed) were varied and values of X(NODE) were computed for every combination of AMTEMP, HPLOS1, HPLOS2 and RPM. Such value of X(NODE) was designated as XX(N,A,HPLOS1,HPLOS2) or simply XX(N,A,H1,H2). This was computed for values of A varying from 0 to 50°C in steps of 10°C, for values of H1 from 0 to 0.15 hp, in steps of 0.05hp and for values of H2 from 0 to 1.6 hp, in steps of 0.4hp. These values of XX (N,A,H1,H2) were found at bearing speed (RPM) of 100 to 400 rpm (mean bearing velocity CGVLTB, of 3 to 12 M/s), in steps of 100 RPM.

The above programme was also run for different values of oil viscosity (ANU), oil density (RHO), oil conductivity (CONDOL), oil specific heat (SPHTOL), housing conductivity (CONDST), and housing emissivity (EMSVTY). Nominal values of ANU, RHO, CONDOL, SPHTOL, CONDST, EMSVTY were: 13 CS(MM/s), 800 Kg/M3, 0.12 Kcal/hrM°C, 0.425 Kcal/Kg °C, 0.14 respectively. Effected variations in values of above property parameters, over the nominal values were about ± 15 to 20 %.

The above programmes were run on IBM compatible PC/XT and/or AT. Operating system used was D.O.S.- version 3.3.

3.5 CONCLUDING REMARKS ON THEORETICAL INVESTIGATIONS

A detailed discussion on the theoretical investigations is given in chapter 5. It may be noted here, that theoretical investigations are valid for a standard two-bearing assembly comprising of '6328' (radial bearing) and '29432. E' (axial bearing)
and a range of operating parameters listed earlier. Therefore, if bearings under consideration, are different than those considered here, then the programme with the data of the selected bearings have to be run again, to obtain the actual thermal levels. As such, heat flow analysis and basic principles of theory are valid for any combination of bearing - whether ball and ball or roller and roller type.

Theoretical model developed, is valid only if assumptions are satisfied. Most assumptions are reasonable. However, if heat sources or sinks are present close to the equipment, such that they can influence the thermal levels of the bearing assembly; the theoretical model can not give acceptable results. The two-bearing assembly is assumed to have only two heat sources, the one at radial bearing (node 4) and the other at axial bearing (node 8).

Moreover, the investigations are for bearings, which are bath lubricated and the maximum peripheral velocity of bearings are not be over 12 M/s, a value which is not exceeded when any thrust bearing is used for absorption of thrust in any hydraulic application.
FIG. 3.1 HEAT FLOW DIAGRAMME AT NODE 'O'-CONDUCTION ONLY

FIG. 3.2 HEAT FLOW DIAGRAMME AT NODE 'O'-CONDUCTION, CONVECTION, RADIATION AND HEAT-SOURCE
NOTES:
1. NUMBERS WITHIN CIRCLE REPRESENT NODE ON THE BEARING ASSEMBLY.
2. DIMENSIONS ARE APPROXIMATE.
### TABLE 1  HEAT TRANSFER SYSTEM

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**NOTES:** Numbers in parenthesis refer to equations used to calculate Heat Flow and Heat Transfer Coefficients. COND., CONV., HSRC. are CONDUCTION, CONVECTION and HEAT SOURCE respectively.
### TABLE 2 AREAS OF HEAT FLOW

AREA - $S_\frac{i}{j}$ M²

$i =$ row, $j =$ column

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