ISSN 2395-1621

Design and Finite Element Analysis of Rope Drum and Drum Shaft for Lifted Material Loading Condition

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ABSTRACT

A crane is a material handling machine equipped with a hoist and wire ropes, used to lift or lower the material loads and move them horizontally. The hoist assembly contains rope drum, driving shaft, wire rope and motor etc. When certain material load is lifted by the hoist, the drum shaft is braked to hold the load till it is transported to other place and unloaded. Thus, the lifted load directly acts on wire rope, rope drum and drum shaft which are key components of hoist. The project work deals with the design of rope drum and drum shaft for a given maximum material load to be lifted. As the rope drum and drum shaft are heavy in actual practice, the work also includes design, manufacturing and testing of reduced size rope drum and drum shaft model to determine the stresses induced in them. A finite element simulation of model is to be used for validation. For safe working conditions, industries over-design rope drum by keeping high factor of safety which turns costly. Thus, a decision is to be made about the size of the drum shaft with minimum material which can assist rope drum properly. This paper explains the design of rope drum-shaft assembly and it's computer aided model based simulation in accordance with the maximum material load to be lifted and the Indian Standards. If required, it is intended to incorporate a certain size of shaft that can assist the rope drum in bearing given loads.

Keywords— **Hoisting mechanism, Rope drum, Indian Standards for wire ropes and rope drum, Finite element analysis, Simulation packages etc.**

ARTICLE INFO

Article History

Received :18th November 2015

Received in revised form :

19th November 2015

Accepted : 21st November , 2015

Published online :

22nd November 2015

I. INTRODUCTION

Material-handling system is an equipment that relate to the movement, storage, control and protection of materials, goods and products during the process of manufacturing, distribution, consumption or disposal. It is a mechanical equipment generally classified into four main categories: storage and handling equipment, engineered systems, industrial trucks and bulk material handling. Most widely used material handling systems are conveyors, cranes, hoists, forklifts, transfer carts, robots etc. Material handling systems are generally used to increase output, control the costs and maximize productivity. Cranes are industrial machines mainly used for materials movements in construction sites, production halls, assembly lines, storage areas, power stations and similar places. Their design features vary widely according to their major operational specifications such as type of motion of the crane structure, weight and type of the load, location of the crane, geometric features, operating & environmental conditions etc.

A. Hoisting Mechanism:

Hoisting is the process of lifting some load from lower position to a higher position with the help of some devices or mechanisms. The hoist mechanism is a unit consisting of a motor drive, coupling, brakes, gearing, rope drum, ropes and load block designed to raise, hold and lower the maximum rated load.

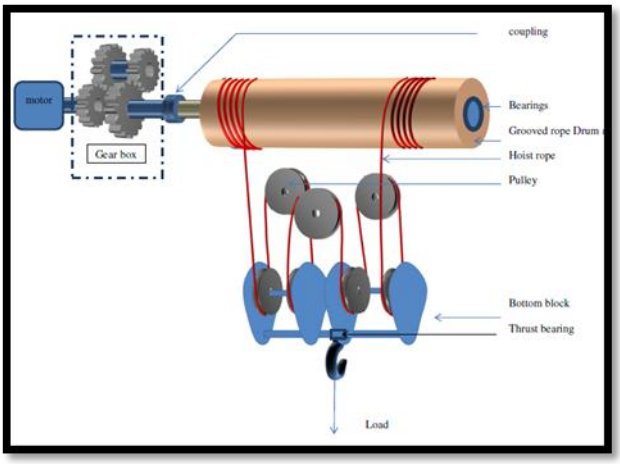

Fig. 1 Example of 8 Fall Hoist System[14]

B. Motivation:

Baggasse briquette is a high quality biomass fuel generally used in dairy firms, tyre manufactures, pharmaceutical companies, sugar industries etc. as a bioler furnace fuel. It is also known as 'white coal'. The briquettes have low density which causes large volume for low mass. Thus, it is tedious to handle briquettes manually while working on a mass scale. The effort is to be made to design a rope drum and shaft assembly which can be assembled into overhead crane to handle the large amount of briquettes in one attempt. Most of the concetration is to be paid to hold the lifted mass and determine it's effects on rope drum and shaft assembly.

Fig. 2 Baggasse Briquettes

C. Finite Element Method:

The Finite Element Method[1][2] is a technique used to derive an approximate solution of any complex engineering problem that can be reached by subdividing the problem into smaller, more manageable elements i.e. finite elements. The behaviour of structure can be easily predicted by solving linear equation's sets in the form of matrix algebra for those finite elements.

In FEM, the simulation models may belong to mechanics, acoustics, thermal field, electromagnetic fields or coupled problems. In mechanical problems the elements may be model membranes, beams, plates, solids, fluids etc. This method contains conversion of the available component data into matrices & interpolating differential equations and their processing[3][4]. The pre-processor[4][5][6] is used to develop the finite element model. The pre-processor requires direct user input data which includes Coordinate system, Meshing, Nodes & Elements, Geometrical & Material Constants, Loading conditions etc. After completing this phase, the finite element model is set to solve. The output data is arranged into tabular or graphical form by post-processor[4][5][6]. In case of structural problems, the nodal displacements & stress values at nodal points are given in the tabular form. The knowledge of finite element method is helpful in analysis of the component to be studied, because it is the basic tool used for simulation softwares.

II. LITERATURE REVIEW

Overall design of hoisting mechanism[9]-[11] is generally confirmed to Indian Standard codes[16]-[20]. Study of such codes is carried out first to know basic design procedure. Determination of various dimensions of components is based on standard formulae[7][8] and codes from Indian standards. The present design of rope drum[9] and shaft is to be made to withstand the load due to lifted material. This requires good understanding of loading conditions, rope drum assembly[15] and wire rope selection[14].

For further study it is required to understand all theories of failure so as to calculate the stresses induced in rope drum and shaft analytically and to apply correct failure criterion[13]. The knowledge of techniques used for shaft failure analysis and simulation methods adds to better visualization of experimentation[12][13]. To know the design analysis and simulation procedure, it is important to know the basic Finite Element Method which is embedded in simulation software. A step by step description of method improves the conceptual understanding[1]-[6].

III. METHODOLOGY

The methodology comprises detailed study of rope drum, shaft, articulating components and their assembly. As the material load is determined, it will directly give the value of force acting on wire rope. The load on rope drum and wire rope does not exceed 1 ton, hence a 2 fall system of rope is sufficient to bear the load.

In analytical design of rope drum and shaft, first basic load value is determined. Then, the appropriate wire rope is selected based on Indian standard criteria. The dimensions of rope drum directly depend on the size (diameter) of wire rope. But, the number of wire rope turns on rope drum are calculated with reference to height of lift. Further, the shaft is designed in accordance with the value of torque on rope drum. The design of other essential parts which articulate the shaft and rope drum such as coupling, flanges and key are based on standards and analytical design formulae.

The computer aided model of calculated and derived dimensions of rope drum and shaft assembly is then prepared in CATIA V5. This model is converted in to IGS and STP format so as to input it to finite element analysis software ANSYS.

The experimentation of this work consists, manufacturing of reduced size model with analogous loading conditions. The model would be tested for stresses induced in it when it is subjected to calculated loads. The same experiment model is to be simulated in finite element analysis software in order to cross check the results. The validation is achieved if experimental and finite element analysis results are matched within permissible limits. This will prove the loading conditions being appropriate and same method would be applied for actual CAD model of rope drum and shaft assembly to carry out finite element analysis and predict the results.

IV. ANALYTICAL DESIGN

A. Basic Load Calculations:

Maximum mass of one briquette = m = 2.5 Kg

No. of briquettes on one sack = 12

Mass of one sack = 2.5 × 12 = 30 Kg

Total sacks to be lifted in one attempt = 15 to 30 No's

Maximum total mass to be lifted = M = 30 × 30 = 900 Kg

Total load of mass to be lifted = 900 × 9.81 = 8829 N

Total height of lifting the total mass = H_i = 6 m = 6000 mm

B. Selection of Rope:

As per the specifications, standard wire rope size of nominal diameter 8 mm and type 6 × 37 with steel core is selected. This wire rope has tensile strength and minimum breaking force equal to 1570 MPa and 32 kN respectively[17].

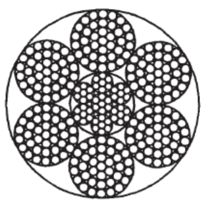

Fig. 3 Wire Rope Cross Section (6 × 37 - Steel Core)[17]

Therefore,

d = 8 mm[17]
S_{ut} = 1570 MPa
F_b = 32 kN = 32000 N

Efficiency of wire rope when it is bent around rope drum,
$\eta = 0.94$

Consider a 2 rope fall system for rope drum design.

Thus, tension in wire rope[8],

$$P = \frac{\text{Load to be lifted}}{\text{No. of rope falls} \times \eta} = \frac{8829}{2 \times 0.94} = 4696.28 \text{ N}$$

This value must have to be lesser than the safe working load.

Recommended factor of safety for general rope applications[18]
$f_s = 6$

$$\text{Safe working load} = SWL = \frac{F_b}{f_s} = \frac{32000}{6} = 5333.33 \text{ N}$$

Hence, tension in the wire rope < safe working load.
The selected wire rope is safe and acceptable.
Now, each wire diameter in wire rope[7] =
0.45 d = 0.45 × 8 = 3.60 mm

Metallic area of wire rope[7] =
$0.40\,d^2 = 0.40 \times 8^2 = 25.60 \text{ mm}^2$

Pressure on wire rope when it is wound around rope drum & loaded[7],

$$P' = \frac{2 \times P}{d \times D} = \frac{2 \times 4696.28}{8 \times 184} = 6.38 \text{ MPa}$$

This pressure value will also act on rope drum in opposite manner as it offers reaction support to the wire rope.

Recommended minimum value of pressure on rope[7],
$0.0015 \times S_{ut} = 0.0015 \times 1570 = 2.355$ MPa

C. Design of Rope Drum:

Some standard minimum D/d ratios for rope drum are 22[19] and 20[18]. Also, it can be defined as,

D/d[16] = $12 \times C_{df} \times C_{rc} = 12 \times 1.7 \times 1.0 = 20.40$

This value is acceptable up to 27[7].

Select D/d = 23 for further calculations.

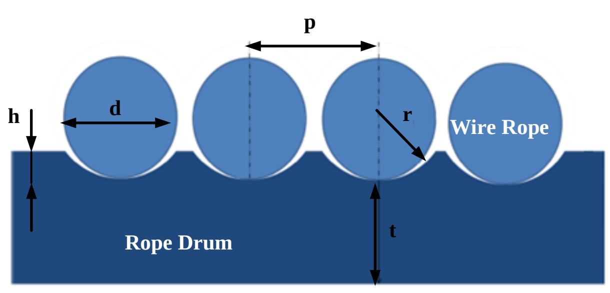

Fig. 4 Rope Drum Cross Section[14]

Thus following dimension parameters of rope drum are required to be calculated.

Inner diameter of rope drum at bottom of groove,
D = (D/d ratio) × d = 23 × 8 = 184 mm

Minimum radius of groove[16],
r = 0.53 × d = 0.53 × 8 = 4.24 mm

Minimum depth of groove[18],
h = 0.35 × d = 0.35 × 8 = 2.80 mm ≡ 3 mm

Outer diameter of rope drum = D + (2 × Groove Depth)
= 184 + (2 × 3) = 190 mm

Pitch of the groove[16],
p = 1.08 × d = 1.08 × 8 = 8.64 mm

Minimum no. of wire rope turns on rope drum[8],

$z = \{\frac{2 \times Hi}{3.142 \times D} + 2\} = 22.76 \equiv 23$ turns

Total length of rope drum[8],

$L = \{\left[\frac{2 \times Hi}{3.142 \times D}\right] + 12\} \times p = \{\left[\frac{2 \times 6000}{3.142 \times 184}\right] + 12\} \times 8.64$

L = 283.02 mm

Here, extra turns of wire rope are considered around rope drum because, the lowest position of load i.e. near the ground must attain minimum three wire rope turns around rope drum.

Assumed length of rope drum = 290 mm

Un-grooved length on both ends = {Welding width + (p/2)}
$= \{10 + \frac{8.64}{2}\} = 14.32$ mm

Thus, effective length of rope drum for wire rope turns,
= 290 - 2 × 14.32 = 261.36 mm

Thickness of rope drum at the bottom of the groove[7][8],
t = 0.02 × D + (6 to 10 mm) = 9.68 mm ≡ 10 mm

Minimum flange diameter[16] = D + (6 × d)
= 184 + (6 × 8) = 232 mm

Therefore, assumed flange diameter for bolting purpose is 280 mm. Let thickness of the flange be 20 mm.

Torque on rope drum[8] $= T = P + \frac{D+d}{2}$

$T = 4696.28 + \frac{184 + 8}{2} = 450842.55$ Nmm = 450.84 Nm

Crushing stress on rope drum[8] $= \sigma_c = \frac{P}{t \times p}$

$\sigma_c = \frac{4696.28}{10 \times 8.64} = 54.36$ MPa

D. Design of Shaft:

Required torque value = T = 450842.55 Nmm
Diameter of shaft from Indian standard codes[20] = d_s = 40 mm

Transmissible torque value[20]
$= \frac{9.80665 \times \pi \times d_s^3}{4000} = \frac{9.80665 \times \pi \times 40^3}{4000}$

= 492999.91 Nmm ≡ 493 Nm

Here, transmissible torque value > torque on rope drum. Thus, the shaft is acceptable.

E. Design of Key:

Shaft diameter = d_s = 40 mm
Minimum breadth of key[20] = b = 10-12 mm
Minimum height of key[20] = h = 8-10 mm
Minimum height of key slot[20] = t = 5 mm

The key is provided with a head so that, it would avoid and restrict the axial movement of the shaft.

F. Design of Coupling:

The rope drum is supported on a pedestal on right side and shaft on left side. The design of coupling should ease the assembly and disassembly of rope drum and also it should be easy to manufacture. Thus, on right side, the hub of coupling is used as a guide as well as support and rope drum flange is provided with threads in order to articulate the coupling. On left side, the rope drum is connected to shaft through a flange coupling fastened with bolts and key. This ensures easy dismantling of assembly.

Thickness of flange = t_f = 20 mm

Shaft diameter[7] = 2 × t_f = 40 mm

Outside diameter[7] of Hub = d_h = 2 × d_s = 2 × 40 = 80 mm

Length of hub[7] = l_h = 1.5 × d_s = 1.5 × 40 = 60 mm

Minimum pitch circle diameter of bolts[7],
D_{PC} = 3 × d_s = 3 × 40 = 120 mm

Minimum outside diameter of flange[7],
D_f = 4.5 × ds = 4.5 × 40 = 180 mm

No. of bolts required[7] = N = 6

Let the selected bolts are made up of 45C8 material having tensile yield strength equal to 380 MPa[7].
S_{yt} = 380 MPa

Let the factor of safety = 5

Therefore, $S_{sy} = 0.577 \times S_{yt} = 0.577 \times 380 = 219.26$ MPa

Permissible shear stress in bolts,
$\tau = \frac{S_{sy}}{f_s} = \frac{219.26}{5} = 43.85$ MPa
Resisting torque by bolts = M_t = T = 450842.55 Nmm

Total force acting on all bolts $= \frac{T}{D_{PC}/2} = \frac{450842.55}{120/2}$
= 7514.04 N

Force on each bolt $= \frac{\text{Force on all bolts}}{N} = \frac{7514.04}{6} = 1252.34$ N
Minimum diameter of each bolt[7],
$d_1 = \sqrt{\frac{8 \times M_t}{\pi \times D_{PC} \times N \times \tau}} = \sqrt{\frac{8 \times 450842.55}{\pi \times 120 \times 6 \times 43.85}}$

d_1 = 6.03 mm ≡ 7 mm

For ease of assembly, a larger pitch circle diameter is used for articulation of rope drum with shaft through flanges. Hence, preferred bolts are of diameter 10 mm.

V. COMPUTER AIDED MODEL

With reference to above calculations, all dimensions of assembly are determined. Hence, a computer aided model is prepared in CATIA V5 software in assembly mode. The components of assembly are shown by different colours.

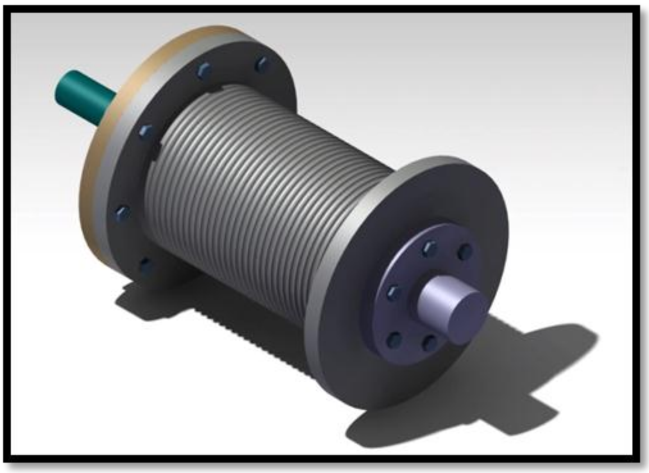

Fig. 5 Rope drum and shaft assembly CAD model (CATIA)

VI. FINITE ELEMENT ANALYSIS PLOTS

The finite element analysis is carried out by applying load in wire rope along middle turns grooves as the material load is assumed to be lifted by 3 meters and held in to position. The value is 4696.28 N.

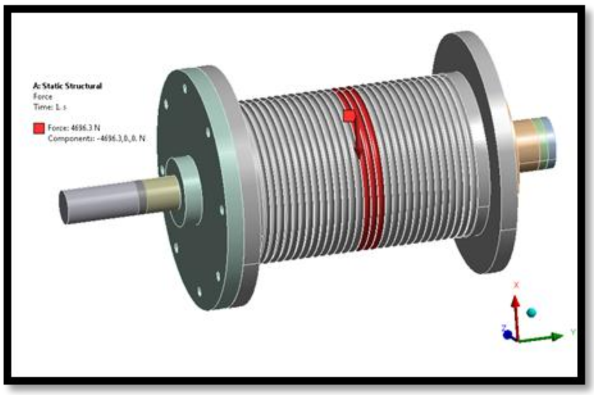

Fig. 6 Load on rope drum due to tension in wire rope

Also, the wire rope is wound around rope drum. Hence, a pressure is exerted on remaining grooves on left side in order to simulate actual loading condition.

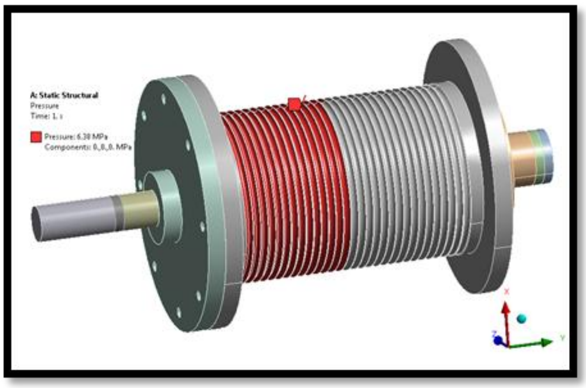

Fig. 7 Pressure on grooves due to winding of wire rope around rope drum

The model is fixed on shaft side so as to simulate braked condition and on pedestal side, it is free only to revolve about axis. All other degrees of freedom at pedestal are restricted. Further, the meshing is done and the stress results are interpreted.

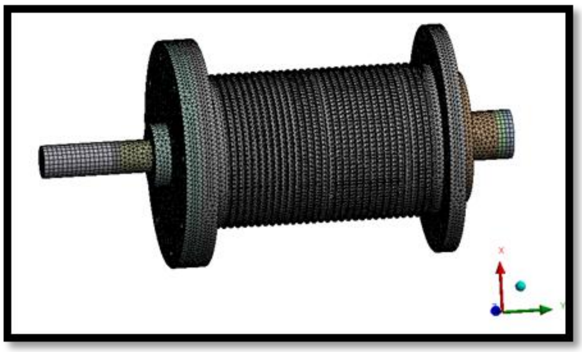

Fig. 8 Meshing of rope drum and shaft assembly

Finite element analysis of assembly shows that, maximum stress condition is observed to be on shaft as shown in Fig. 9. It means, the assembly is likely to fail at this position.

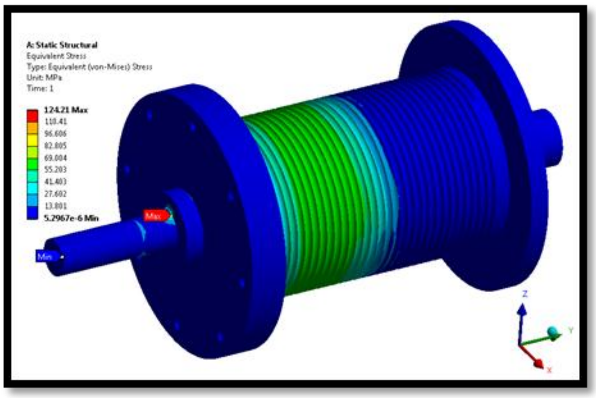

Fig. 9 Maximum Von-Mises stress on shaft

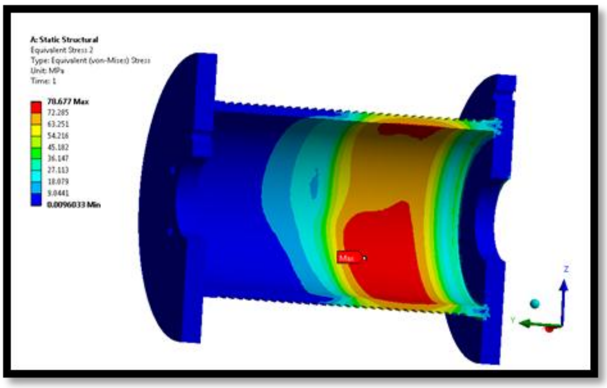

Fig. 10 Maximum Von-Mises stress on rope drum

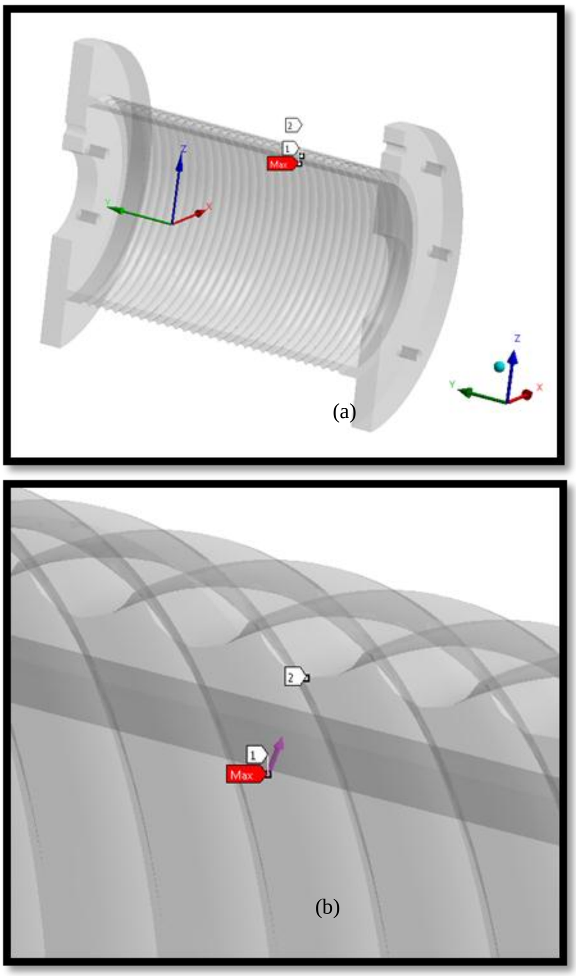

Fig. 11 Maximum Von-Mises stress on rope drum cross section

VII. CONCLUSION

Manual analytical design of rope drum, shaft, flanges, key and coupling is done on the basis of Indian Standards and basic design formulae. The selection of wire rope is the basic criterion on which the whole system is dependent for design. Some components such as key and coupling are designed with reference to standard machine design formulae. The 3D modelling of this assembly is carried out in CATIA V5 and is simulated in ANSYS. The loadings acting on rope drum induce the stresses in the shaft. This effect is studied in order to make a safe structural design of this assembly. The maximum value of Von-Mises stress on rope drum by simulation is 78 MPa, whereas crushing stress value in accordance with calculations is 54 MPa. For a cast steel rope drum material with yield strength 206 MPa and factor of safety 2, the permissible stress value would be 103 MPa. Thus, the design of rope drum is safe. The effect of loading on rope drum induces stress in shaft equal to 124 MPa. The further work will be consisting determination of stresses induced in reduced size model of rope drum and shaft through simulation as well as experimentation to cross check each other and validate actual size model results.

ACKNOWLEDGEMENT

Authors are highly grateful to thank Mr. S.C. Patil, Director of operations, Enersols Industries, Palus, Sangli for constant encouragement, motivation and permission to present this paper. We also express sincere thanks to Mr. P.P. Jagtap (Director of manufacturing & production) and Mr. R.L. Pol (Director of marketing) for valuable guidance and motivation during the course of this work.

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