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CFD Analysis of Flue Gases over Valve Spindle with Rotor Wings in 2 Stroke Marine Diesel Engines

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Abstract : *Earlier in ships, the exhaust valves in 2 stroke diesel engines were actuated by a mechanism, controlled by rocker arms and camshaft. But due to weight and space constraints of the diesel engines of ships, the camshaft and huge rocker arms have been replaced by hydraulic power pack to actuate the valve. As a design modification, rotor wings were also attached to the exhaust valve spindles. When the exhaust valve opens, the exhaust gas rotates the wings and turns the spindle by a certain degree. In this paper, a study about how these rotors extend the lifeline of the spindles has been carried out. The paper outlines the various analyses conducted on the existent spindle design, the boundary conditions input to the software and the various results, namely temperature and pressure variation graphs, and moment reaction acting on the spindle. It also compiles an analysis of how the rotor wings have been modified to attempt to extend the lifeline of the spindles through computational fluid dynamics (CFD) and a comparison of the test results for various designs has been included.*

Keywords: *Computational fluid dynamics(CFD), exhaust gas, finite element analysis(FEA), rotor wings, time between overhauling(TBO), valve spindles*

I. Introduction

During the exhaust stroke of two stroke marine diesel engines, the flue gases are emitted at very high pressure resulting in back pressure acting only on a part of the valve spindle, once it lowers from its seat. A major impact of this behavior is observed on the corrosion patterns of the spindle which is used to open and close the valve at specific intervals. Spindles have a high resistance to temperature and corresponding stresses but due to repeated corrosive action on a single part or section of the spindle, it is needed to be replaced frequently, increasing the cost of maintenance and operation.

A major modification to spindle design came in the form of introduction of rotor wings, on the stem of the spindle, which were aerodynamically constructed to use the kinetic energy of the high velocity flue gases to turn the spindle through an angle before it resumes its seat. The effect of this angular turn is that during the next exhaust stroke, a different section of the spindle will be exposed to the gases and corrosion will take place uniformly over multiple cycles. This in turn led to the increase of the time between overhaul (TBO) of the engines leading to better use of material and resources and lowering of maintenance cost.

Fig1.1 Excessive damage on one section of the spindle

Fig1.2 Actual photo of spindle with rotor wings showing uniform wear rate

This paper is aimed at analyzing the behavior of the exhaust spindle valve of the S60MCC8 engine by Man B&W, its rotation patterns and further trying to increase the TBO by modifying the design parameters, especially angle of inclination of wings to achieve better rotation of spindle leading to a more uniform rate of corrosion over the spindle. The effect of the exhaust gas on the face of the spindle wall giving rise to temperature and pressure variations is the main consideration in the study.

II. Review of literature

The study done by Dr.Ing Holler Fellman [1] gave a detailed description of the different wear mechanisms the spindle valve undergoes. Based on the paper being discussed, adhesion and abrasive wear was found at the valve drive, air cylinder and valve spindle stem. Build-up of deposits in valve spindle guides results in non-symmetric thermal load which leads to “Cobble stone corrosion” and cracks that start under the head radius resulting in a catastrophic failure follows, with parts of the spindle dropping into the combustion chamber. The temperature range shown below will be used as a validation for the results obtained from the CFD analysis conducted further.

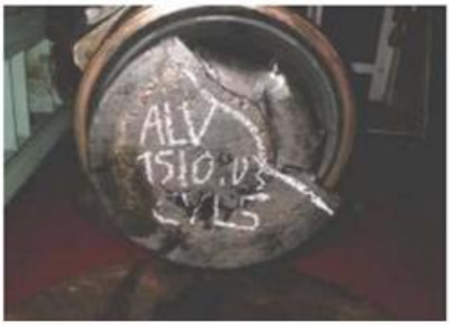


Fig2.1 Catastrophic failure of a repaired valve spindle (RTA 72)

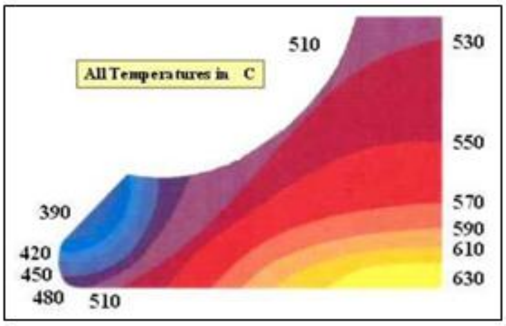


Fig2.2 Typical temperature distribution of a Nimonic exhaust valve head

III. Report on present investigation

3.1 Methodology Adopted

3.1.1 Modelling

The modeling of the specimen spindle with rotor wings was done on SolidWorks. SolidWorks [2] is a 3D mechanical CAD (computer-aided design) program that runs on Microsoft Windows and is being developed by Dassault Systems SolidWorks Corp., a subsidiary of Dassault Systems. SolidWorks is a Para solid-based solid modeler, and utilizes a parametric feature-based approach to create models and assemblies. The spindle and rotor wings were modelled separately and then assembled together. The final assembly was ready after 3 major iterations, taking into consideration the measurements, which were obtained from the industry where the specimen was available and also after adding material to the model.

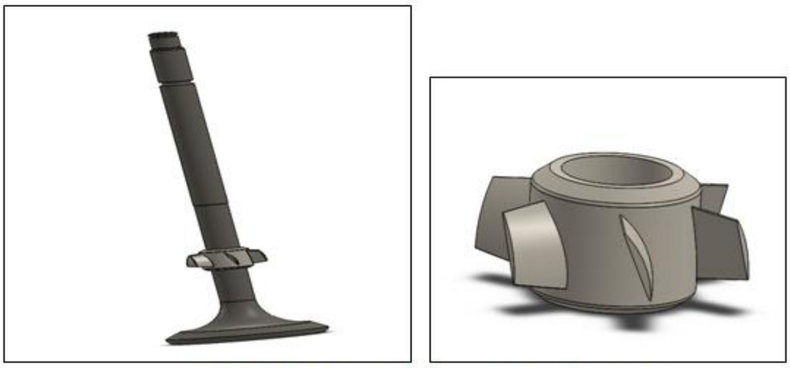


Fig3.1 Final model after various iterations

3.1.2 Analysis

Computational Fluid Dynamics (CFD) uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers are used to perform the calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions. The Navier stokes equation in Cartesian co-ordinates were selected as governing equation of the given problem and for desired results, we used Fluid Structure Interaction System (FSI).FSI is the interaction of some movable or deformable structure with an internal or surrounding fluid flow. FSI can be stable or oscillatory. In this study, for FSI setup we have used ANSYS CFX and ANSYS Static Structural on ANSYS Workbench 2.0, ANSYS 15.0.7 [3]. The first half, where the flow pattern and its temperature and pressure effects on the spindle wall is to be generated has been done using ANSYS CFX and the latter half, where the effect of flow on rotation of spindle is being studied has been done on ANSYS Static Structural.

3.2 CFX Setup

3.2.1 Geometry & Meshing

The geometry was imported and the spindle was suppressed to concentrate only on the fluid domain. The inlet, outlet, cage and spindle wall were defined for ease of location in the further part of the analysis. A grid independence test was carried out with a hex dominant mesh with body sizing of 10mm, 5mm and 3.5 mm. We found that 3.5mm mesh gave us the optimum result with 15.5 lakh elements and the further tests were carried out.

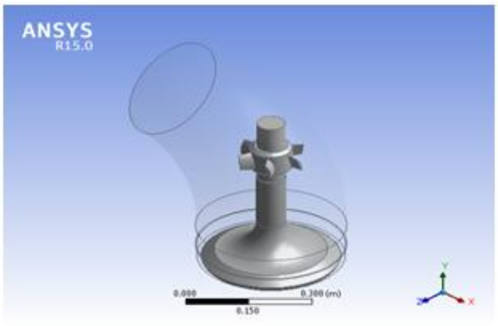


Fig3.2 CFX Geometry

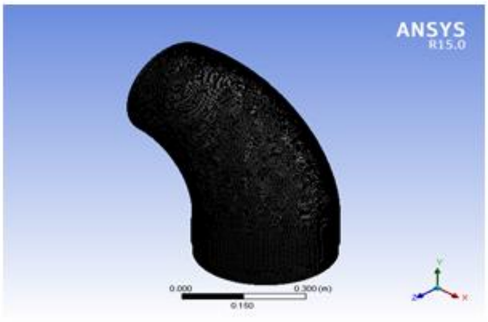
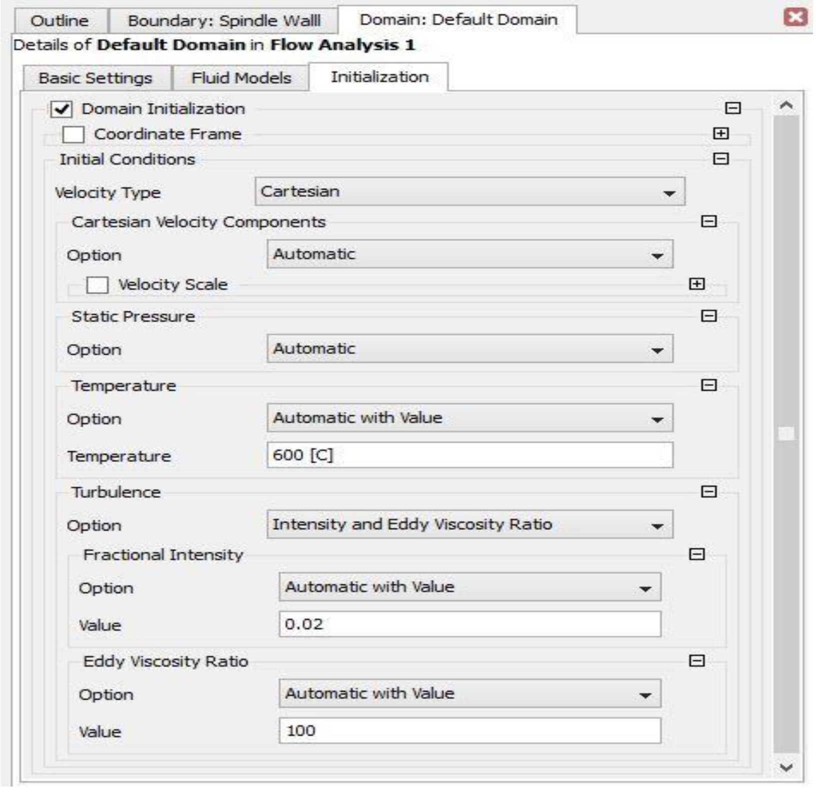


Fig3.3 CFX Meshing

3.2.2 Setup

3.2.2.1. Domain Initialization

A user defined material named ‘Exhaust’ was created with the properties of the exhaust gas. The total energy heat transfer model was selected as energy gets converted into kinetic energy as well as transmitted to the solid spindle. The turbulence model was selected as k-epsilon scalable as within CFX, the turbulence model uses the scalable wall-function approach to improve robustness and accuracy when the near-wall mesh is very fine. The scalable wall functions allow solution on arbitrarily fine near wall grids, which is a significant improvement over standard wall functions. The temperature of exhaust gas at inlet was set at 600°C. Intensity and eddy viscosity ratio – automatic with value of 0.02 (Ranges from .01 to .1) & 100 (Represents Laminar flow) respectively.



Details of **Default Domain** in **Flow Analysis 1**

☑ Domain Initialization
☐ Coordinate Frame
Initial Conditions
Velocity Type: Cartesian
Cartesian Velocity Components
Option: Automatic
☐ Velocity Scale
Static Pressure
Option: Automatic
Temperature
Option: Automatic with Value
Temperature: 600 [C]
Turbulence
Option: Intensity and Eddy Viscosity Ratio
Fractional Intensity
Option: Automatic with Value
Value: 0.02
Eddy Viscosity Ratio
Option: Automatic with Value
Value: 100

Fig3.4 Domain Initialization

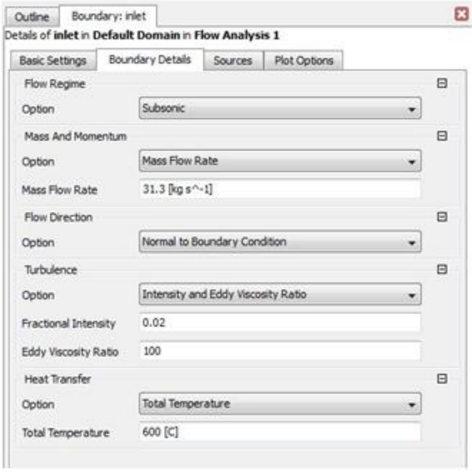
3.2.2.2 Boundary Conditions

Inlet - A mass flow rate of 31.3kg/s [4] was applied with a direction normal to the boundary condition. In turbulence model, intensity and eddy viscosity ratio was chosen with a value of 0.02 and 100 respectively. Under the heat transfer model the total temperature was given as 600°C.

Outlet - An opening type boundary condition was defined to the outlet with an opening pressure of 2.393 bar with direction normal to boundary condition. The turbulence model as defined earlier was used. The opening temperature was set at 350°C [4].

Cage - A no slip smooth wall type boundary was defined to the cage with an adiabatic heat transfer model assuming that no heat transfer occurs across exhaust wall.

Spindle Wall - A no slip smooth wall type boundary was defined to the spindle wall with an adiabatic heat transfer coefficient of 39.8W/m2°C at 600°C [5].



Details of **inlet** in **Default Domain** in **Flow Analysis 1**

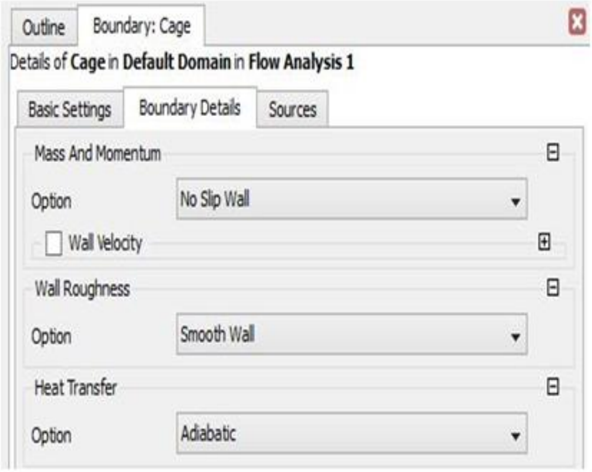
Flow Regime	
Option	Subsonic
Mass And Momentum	
Option	Mass Flow Rate
Mass Flow Rate	31.3 [kg s^-1]
Flow Direction	
Option	Normal to Boundary Condition
Turbulence	
Option	Intensity and Eddy Viscosity Ratio
Fractional Intensity	0.02
Eddy Viscosity Ratio	100
Heat Transfer	
Option	Total Temperature
Total Temperature	600 [C]

Fig3.5 Inlet details

Details of **outlet** in **Default Domain** in **Flow Analysis 1**

Flow Regime	
Option	Subsonic
Mass And Momentum	
Option	Opening Pres. and Dirn
Relative Pressure	2.393 [bar]
Flow Direction	
Option	Normal to Boundary Condition
☐ Loss Coefficient	
Turbulence	
Option	Intensity and Eddy Viscosity Ratio
Fractional Intensity	0.02
Eddy Viscosity Ratio	10.
Heat Transfer	
Option	Opening Temperature
Opening Temperature	350 [C]

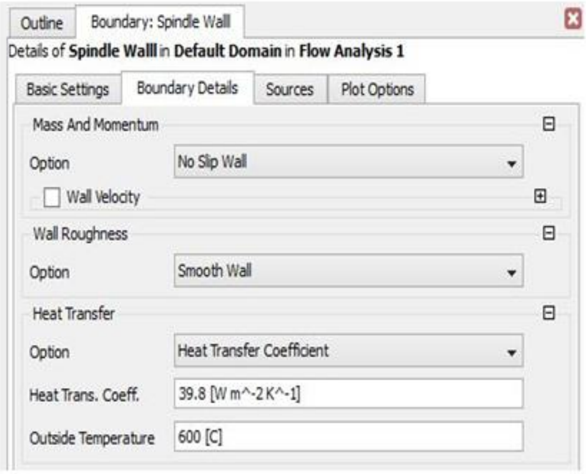
Fig3.6 Outlet details



Details of **Cage** in **Default Domain** in **Flow Analysis 1**

Mass And Momentum	
Option	No Slip Wall
☐ Wall Velocity	
Wall Roughness	
Option	Smooth Wall
Heat Transfer	
Option	Adiabatic

Fig3.7 Cage details



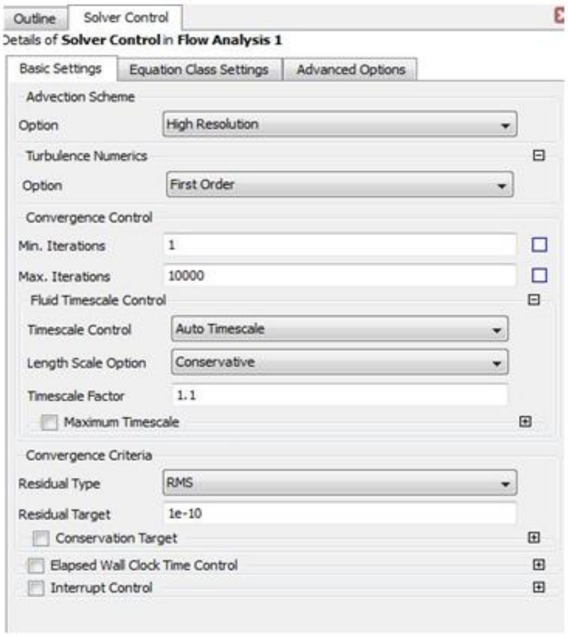
Details of **Spindle Walll** in **Default Domain** in **Flow Analysis 1**

Mass And Momentum	
Option	No Slip Wall
☐ Wall Velocity	
Wall Roughness	
Option	Smooth Wall
Heat Transfer	
Option	Heat Transfer Coefficient
Heat Trans. Coeff.	39.8 [W m^-2 K^-1]
Outside Temperature	600 [C]

Fig3.8 Spindle wall details

3.2.2.3 Solver & Output Control

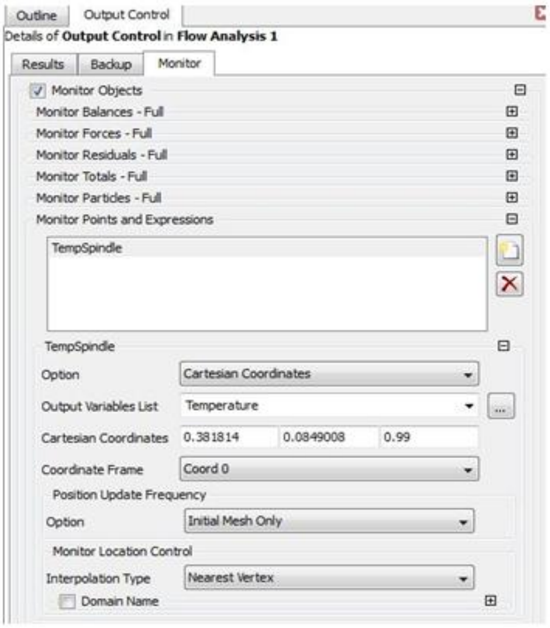
The High Resolution advection scheme was used as all boundary conditions obtained were from manuals provided by the official engine manufacturer and accuracy was a major factor to consider. A first order turbulence numeric model was used as using the High Resolution scheme would increase the test run time. A timescale factor of 1.1 and a convergence criteria of 1e^-10 was selected to ensure that the solution run could complete over 1000 iterations as CFX terminates the run as soon as convergence criteria is met. The temperature on the surface of the spindle wall was defined as the physical parameter in monitor objects. Appropriate co-ordinates were provided.



Details of **Solver Control** in **Flow Analysis 1**

Advection Scheme
Option: High Resolution
Turbulence Numerics
Option: First Order
Convergence Control
Min. Iterations: 1
Max. Iterations: 10000
Fluid Timescale Control
Timescale Control: Auto Timescale
Length Scale Option: Conservative
Timescale Factor: 1.1
☐ Maximum Timescale
Convergence Criteria
Residual Type: RMS
Residual Target: 1e-10
☐ Conservation Target
☐ Elapsed Wall Clock Time Control
☐ Interrupt Control

Fig3.9 Solver control details



Details of **Output Control** in **Flow Analysis 1**

☑ Monitor Objects
Monitor Balances - Full
Monitor Forces - Full
Monitor Residuals - Full
Monitor Totals - Full
Monitor Particles - Full
Monitor Points and Expressions
TempSpindle
TempSpindle
Option: Cartesian Coordinates
Output Variables List: Temperature
Cartesian Coordinates: 0.381814 0.0849008 0.99
Coordinate Frame: Coord 0
Position Update Frequency
Option: Initial Mesh Only
Monitor Location Control
Interpolation Type: Nearest Vertex
☐ Domain Name

Fig3.10 Output control details

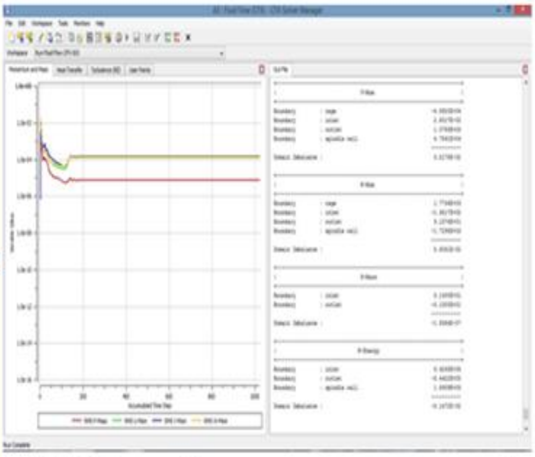


Fig3.11 Mass and momentum convergence graph

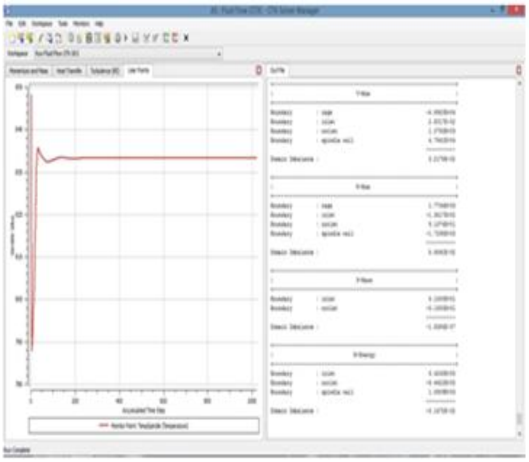


Fig3.12 User point convergence graph-Temperature on spindle

3.2.3 Solution

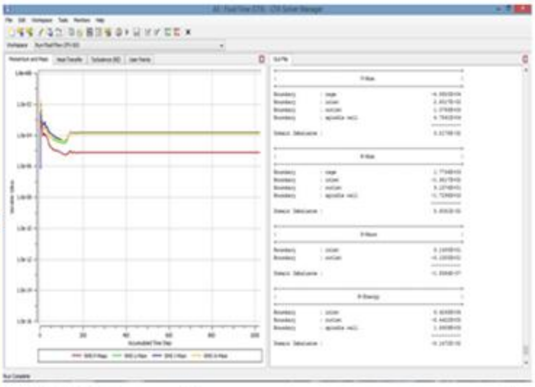


Fig3.11 Mass and momentum convergence graph

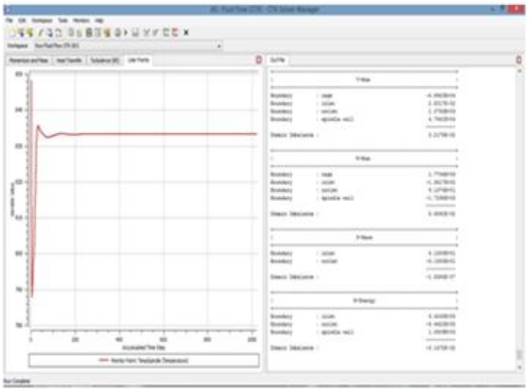


Fig3.12 User point convergence graph-Temperature on spindle

3.2.4 Results

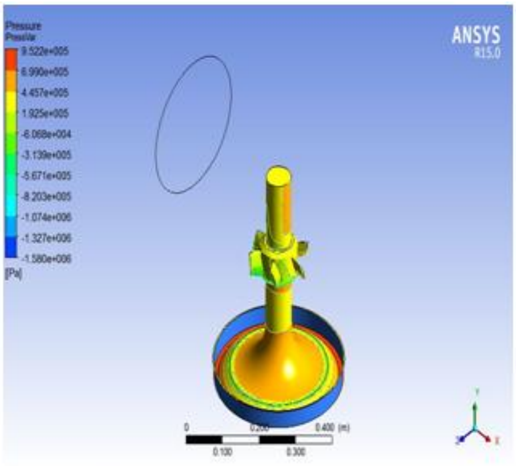


Fig3.13 Pressure contour

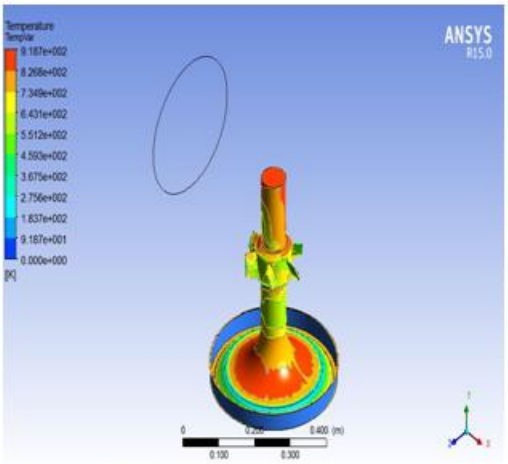


Fig3.14 Temperature contour

3.3 Static Structural Setup

The original spindle geometry with the properties of DuraNickel [5] was imported and a 10mm Hex Dominant mesh was used to mesh the spindle. A remote displacement was applied to the entire spindle with all degrees of freedom constrained. Pressure was imported from the CFX results and applied on the rotor wings as load input to the static structural problem.

The momentary action was set as the required solution.

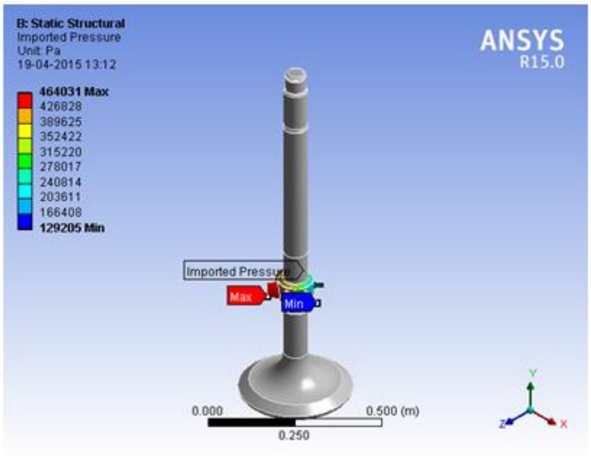


Fig3.15 Imported pressure load

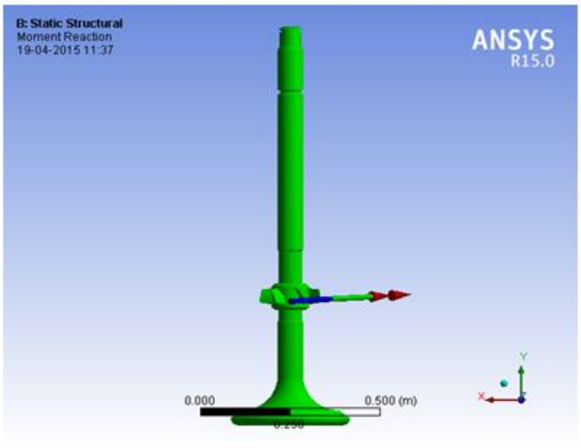


Fig3.16 Moment Reaction

3.4 Design Modifications

To understand the effect of inclination of rotor wings with the horizontal plane, two separate models were designed in SolidWorks. The angle of inclination of the existent rotor wings is 66.4°. This was given a rotation of negative 6° and positive 6° in the two models respectively i.e. a total inclination of 60° and 72° respectively.

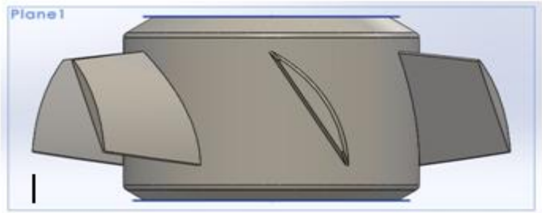


Fig3.17 Rotor model (60° inclination)

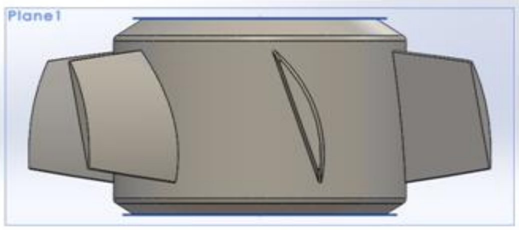


Fig3.18 Rotor model (72° inclination)

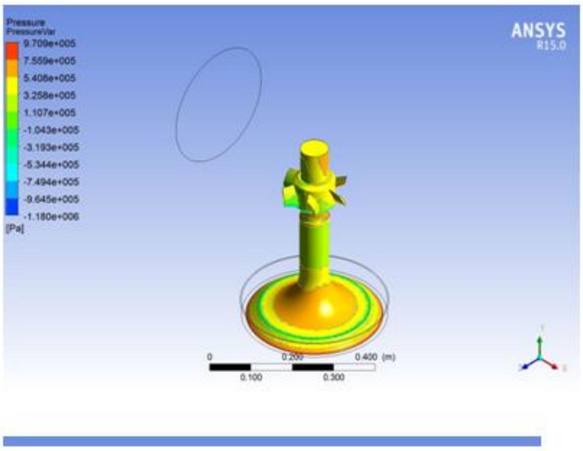


Fig3.19 Pressure Contour (60° inclination)

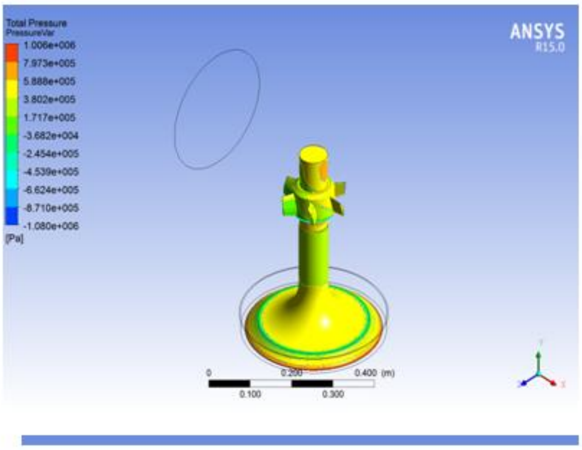


Fig3.20 Pressure Contour (72° inclination)

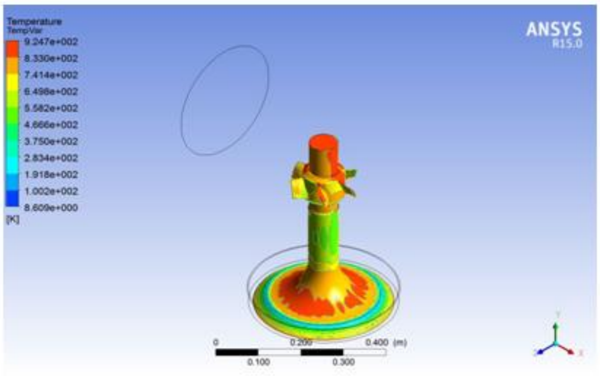


Fig3.21 Temperature Contour (60° inclination)

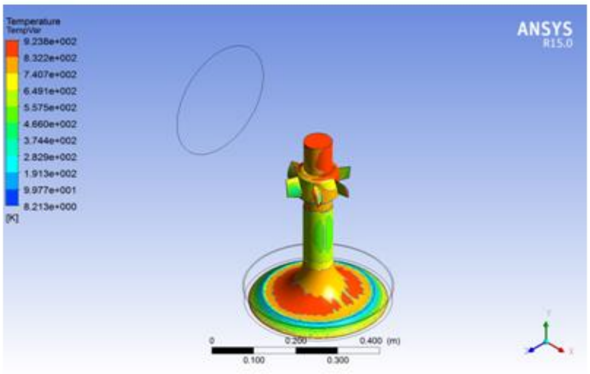


Fig3.22 Temperature Contour (72° inclination)

IV. Results & Validation

Table 4.1 Temperature, pressure and velocity for various configurations of valve spindle

		Temp Range on Spindle Head (K)	Pressure range On Rotor wings (x 10^5 Pa)	Velocity range of Exhaust gas at outlet (m/s)
1.	Without Rotor Wings	843.4 – 984.2	-	544.4 – 975.9
2.	With Rotor Wings	734.9 - 903.4	3.139 – 4.457	389.7 – 776.9
3.	Modified at 60°	741.4 – 924.7	3.258 – 7.559	349.5 – 698.9
4.	Modified at 72°	740.7 – 923.8	3.802 – 5.888	351 – 701.2

From the above table and the temperature contours of the model, we can observe how the various properties of flow, temperature and pressure change with the addition of rotor wings. Comparing the temperature range on the spindle without rotor wings and the existing model with rotor wings for a specific number of cycles, we find that the temperature range acting on the specific face of the spindle without rotor wings due to the back pressure is the same as that on the entire face of the spindle with rotor wings. This results in uniform wear on the spindle and increasing its TBO. In the modified models the temperature range is approximately the same.

Table 4.2 Moment reactions for various configurations of valve spindle

		Total Moment Reaction (N-m)
1.	With Rotor Wings	209.14
2.	Modified at 60°	333.9
3.	Modified at 72°	195.34

Comparing the existing model's results to those of the model with 60° angle of inclination, it was observed that the moment reaction has greater value for the latter. This indicates that the spindle will have a larger degree of rotation with rotor wings inclined at 60°.

Validation for velocity of exhaust gas & temperature on spindle head

The manual of the engine under consideration, S60MCC8 by Man B&W helped in providing the necessary formulae to calculate the velocity of the exhaust gas at the desired cross-section in the exhaust cage. The value of velocity was calculated at the outlet of the exhaust cage [4].

Mass density of gas (ρ) was expressed as;

$\rho = 1.293 \times 273/ (273+T) \times 1.015$ kg/m^3

where $T = 245^{o}$C , exhaust gas temperature at specified MCR[4]

$\boldsymbol{\rho = 0.685}$ **kg/m^3**

Further the exhaust gas velocity (v) was calculated using the following expression;

$v = (M/\rho) \times 4/ (3.1415 \times D^2)$ m/s

where D = 330 mm @ Outlet (measured at the industry where the specimen was available)

$v = 31.3/0.685 \times 4/ (3.1415 \times 0.33^2)$

v = 534.239 m/s

Table 4.3 Comparison of values of exhaust gas velocity

Velocity of exhaust gas at outlet of cage (with rotor wings) in m/s	
Value obtained from CFD Simulation(average)	583.3
Calculated value	534.24

From the above table, it can be seen that the simulation results are a close match with the calculated value of the velocity of exhaust gas. This validates the boundary conditions and values given as input in the software during CFD analysis.

Table 4.4 Comparison of values of temperature range on spindle head

Temperature range on spindle head In K	
Range obtained from CFD simulation	734.9 - 903.4
Range given in study by Dr. Ing. Holler Fellman	663-903

The temperature variations obtained during the CFD simulation was in the same range as that obtained by Dr. Ing. Holler Fellman [1] in his study, under the same conditions.

V. Conclusion

Thus, the study has been concluded, covering all points and objectives as desired. A comparative analysis of various designs has been given for better understanding of the designing parameters. The results achieved at the end of the project could enable further research in the same topic. The procedures used and methodologies adopted would help future researchers determine how TBO of the ships could be increased. There is also scope of using advanced CFD Analysis to modify various other parameters that have been used throughout the project to help improve the efficiency of working of the spindles and further reduce the uniform rate of corrosion over the spindle

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