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Optimizing IC Engine Exhaust Valve Design Using Finite Element Analysis

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ABSTRACT: *In order to develop an exhaust valve with high thermal and structural strength, experimental investigations are often costly and time consuming, affecting manufacturing time as well as time-to-market. An alternative approach is to utilize computational methods such as Finite Element Analysis, which provides greater insights on temperature distribution across the valve geometry as well as possible deformation due to structural and thermal stresses. This method significantly shortens the design cycle by reducing the number of physical tests required. Utilizing the computational capability, this research aims to identify possible design optimization of the exhaust valve for material and weight reduction, without affecting the thermal and structural strength.*

Keywords: *Design Optimization, Exhaust Valve, Finite Element Analysis, Structural Analysis, Thermal Analysis*

I. INTRODUCTION

Exhaust valves are utilized in 4-stroke internal combustion engines to allow the exhaust gases to escape into the exhaust manifold. Due to the exposure to high temperature gases, exhaust valve design is of a crucial interest. Apart from high thermal stresses, these valves are also exposed to cyclic mechanical stresses during opening and closing, causing them to fail prematurely. It is quite evident that a common cause of valve fracture is fatigue. Valves fail due to cyclic loading at high temperatures. High temperature is also responsible for decrease in hardness and yield strength of valve material, and also causes corrosion of exhaust valves [5]. As such, factors such as temperature, fatigue life, material strength and manufacturing processes are to be considered in order to design a valve that operates without premature failure. Exhaust valves with better material strength can provide significant benefits in cost reduction while also reducing its weight [1]. Several material studies show that Magnesium alloy [2] and Nimonic105A [3] are some of the best suitable materials for exhaust valves. Modifying the exhaust valve by varying its position size and shape and with particular thermal and structural considerations, helps in increasing the rate of heat transfer from the seat portion of the exhaust valve, thereby reducing the possibility of knocking [4]. Utilizing finite element analysis, exhaust valve design can be optimized without affecting its thermal and structural strength [6]. A study is carried out on exhaust valve with and without air cavity using finite element approach.

By creating an air cavity inside the valves stem, it acts as an insulating medium and prevents the heat flow; hence the need of providing insulation coating on valves is minimized. The main motive of this is to reduce the weight of engine and cost associated with thermal coating. Results observed in the engine valves revealed that after creating an optimized air cavity in the valve, thermal stresses and temperatures at all nodal points decrease lightly.

II. MODEL SELECTION

In order to carry out thermal and structural analysis, exhaust valve from a single-cylinder engine is selected. The details of the valve model are as shown in the table.

Table 1. Engine specifications for exhaust valve selection

Engine Type	Single Cylinder, 4-Stroke
Cylinder Bore Dia.	50 mm
Displacement	97.2 cc
Max. Power	7.2bhp/8000 rpm

The calculated dimensions of the valve for a single cylinder engine application are tabulated below:

Table 2. Valve dimensions

Valve Head Diameter	20 mm
Valve Stem Diameter	5 mm
Stem Length	65.30 mm
Valve face angle	45^0
Thickness of Valve Head	5 mm

The material of the valve is an Aluminum Alloy EN52 consisting of following mechanical properties.

Table 3. Material Properties

Yield Strength @ 600^0C	250 N/mm^2
Tensile Strength @ 600^0C	240 N/mm^2
Modulus of Elasticity	210 KN/mm^2
Thermal Conductivity	21 W/mK
Specific Heat Capacity	500 J/Kg K
Co-efficient of Thermal Expansion	24.5 x 10^{-6}

ASSUMPTIONS

1. Under normal operation, when the valve is properly seating at the cam ramp, stresses arising from seating are quite moderate. They can become very high when the valve train is improperly engineered so that the valve bounce occurs, or when the engine is over speeded or the valve lash is improperly set. In this analysis the stresses due to valve seating has been not taken into account assuming a normal operation.
2. The distortion stresses in a valve arise due to misalignment of valve with the seat. The valve head must deflect to accommodate to the seat, and this causes bending stresses in the stem. Under most conditions, gas pressures and spring loads will be sufficient to bring the valve head into conformity with a mildly distorted seat.
3. The engine considered for the analysis is a medium range engine (500 kW). It is assumed that it is air cooled.
4. The heat generated inside the chamber is taken away by water chamber around cylinder liner and in the cylinder head.
5. The valve keeps popping up and down. The analysis has been done for a stationary valve assuming that the fatigue life of the valve is very high and the stress arising due to that has been neglected.

THEORETICAL HEAT FLUX AND STRUCTURAL STRESSES

1. Calculation of Mean Effective Pressure:

Cylinder Bore Diameter : 50mm

Stroke Length = 50mm

Power = 7.2 BHP

= 7.2 x 0.746

= 5.37 KW

RPM = 8000 RPM

Area of Cylinder (A) = π / 4 x D2

= π / 4 x 50 x 50

= 1963.50 mm^2

Now brake horse power BHP = Pm x L x A x N x K / 60000

Mean Effective Pressure Pm = BHP x 60000 / L x A x N x K

= 5.37 x 60000 x 1000 / 50 x 1963.50 x 8000 x 1

= 0.41 MPa

1. Heat flux can be expressed by using equation=

$$q = -kA1 \frac{\partial T}{\partial x}$$

Where, k = thermal conductivity = 21W/m K = 0.021 W/mm K

∂T = Temperature of the valve head = 588^0K

∂x = Length in x direction = 70.30 mm

Now, the weight of the stem valve from the CAD model = 0.0159 Kg.

Length of the valve = 65.30 + 5 = 70.30 mm

So the mean area of the stem valve A1= (Weight / (Density x L1)

= 0.0159 / 0.00000785 x 70.30

= 28.811 mm^2

So,

q = - (0.021 x 28.81) (10)/70.30

= - 0.08606 W

Therefore,

Heat flux from engine cylinder to exhaust valve **= -0.08606 W**

2. Stress on the exhaust valve can be calculated by=

$\sigma = P/A$

Where, σ = Stress

P = Load or Pressure acting on the valve head = 0.41 MPa = 0.41 x 314.16 = 128.81 N

3. Total deflection or change in length can be given by

$\Delta l = \alpha \times \Delta t \times L1$

E = Modulus of Elasticity = 210 KN/mm^2

α = Co-efficient of thermal expansion = 11.635 x 10^{-6}

Δt = Temperature Difference between hot and cold region = 588-578 = 10 K

= 11.635 x 10^{-6} x 10 x 70.30

= 0.00817 mm

Therefore, change in length is **0.00787 mm**

Thermal Strain $\varepsilon = \Delta l / L1$

= 0.00817 / 70.30

= 1.16 x 10^{-4}

Thermal Stress $\sigma = \varepsilon \times E$

= 1.12 x 10^{-4} x 210000

= 24.43 MPa

III. FINITE ELEMENT ANALYSIS

The finite element method is a numerical procedure that can be used to obtain solutions to a large class of engineering systems, including stress analysis, heat transfer, fluid flow and electromagnetism. Experimental analysis may help the researcher understand where these stresses arise in a component, hence lead to the prevention of such outcomes. Finite element analysis may support experimental findings and predict results for more complex situations. There are many finite element method software programs available to yield various engineering solutions, however the ANSYS finite element program was used in the current research, as it is widely available within the university. Hence the followings sections are specific to the ANSYS program.

In order to perform the thermal analysis, following assumptions will be used based on the following tabulated data:

Table 4 Thermal boundary conditions

Cylinder temp. during expansion	588 K
Exhaust Gas Temperature	578 K
Room Temperature	298 K
Density of the Material	7865 Kg/m^3

ANALYSIS RESULTS

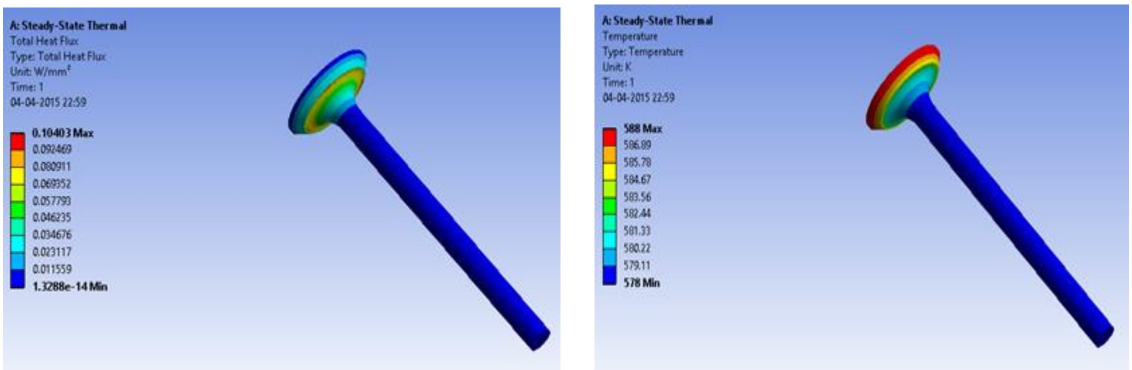

Fig. 1. Heat Flux and Temperature Distribution

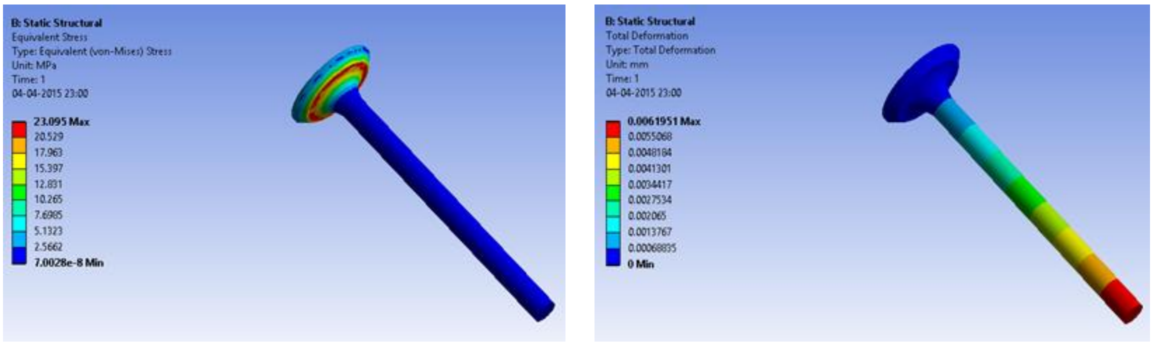

Fig. 2. Stress and Deformation

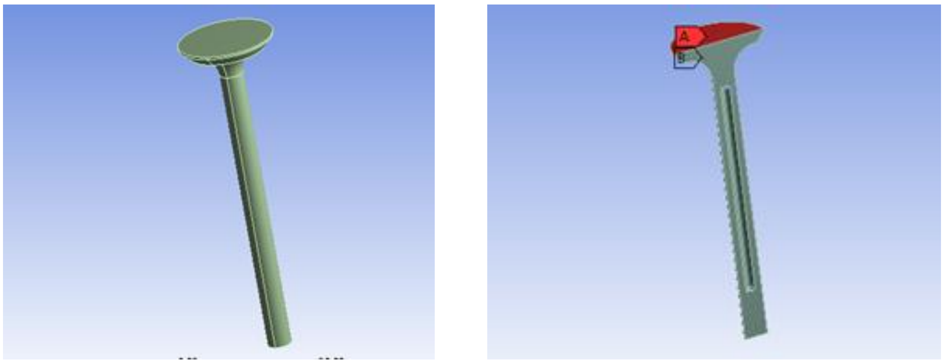

Fig. 3. CAD Model of valve with and without air cavity

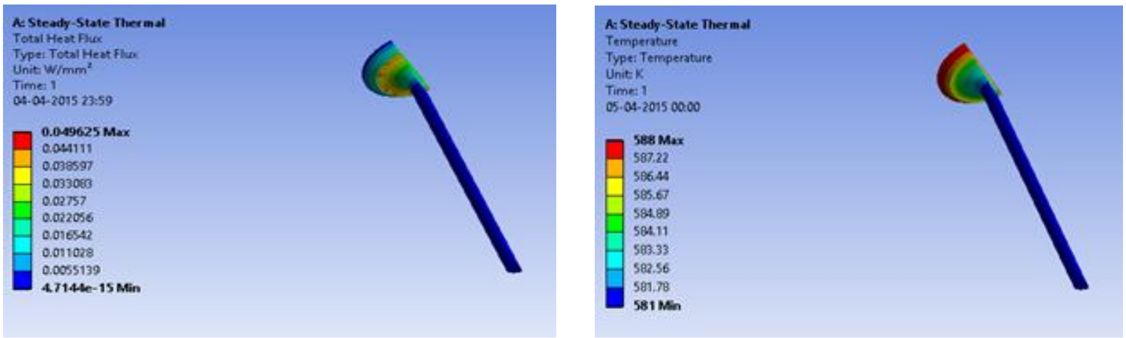

Fig. 4. Heat flux and temperature distribution for optimized valve

IV. RESULTS

Table 5 Theoretical Vs Numerical Result Comparison

Particulars	Theoretical	Numerical
Heat Flux	0.0867 W	0.1043 W
Stress	23.52 N/mm^2	23.095 N/mm^2
Deformation	0.00787 mm	0.0062 mm

Table 6 Analysis results after optimization

Particulars	Weight (Kg)	Heat Flux (W)	Stress (MPa)	Temperature (^{0}K)	Deformation (mm)
Without air cavity	0.0159	0.10403	23.095	588	0.0062
With air cavity	0.0148	0.04962	22.746	588	0.0090

V. CONCLUSION

The results obtained through numerical analysis suggest that the valve design can be optimized to reduce its weight, without affecting permissible stress and deformation values. Due to air cavity, reduction in stress is observed, which further improves valve strength. The weight of the valve is reduced by 17%, which can be further reduced using the same procedure. Considering mass production, significant amount of material can be saved, helping in reduction of the manufacturing costs.

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