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Thermal Analysis on Exhaust Valve with Thermal Barrier Material

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ABSTRACT

An exhaust valve is the important component in the engine system due to its direct involvement in the combustion and experiencing the high temperature and pressure from the hot gases during the exhaust stroke based on the valve timing for opening and closing. Because of this exposure to exhaust, high thermal loads are induced which leads to the failure of the valve. Therefore, a cooling provision is must to reduce the temperatures due to heat transfer effect or to increase the heat dissipation rate through valve by maintaining it at optimum thermal conditions. The cooling provisions are by filling the valve with sodium making valve hollow inside or by using the thermal barrier coatings on the outer surface of valve. In this an attempt is made to study the importance of cooling provision by doing thermal analysis on the valve geometry with different approaches under full load conditions of engine. The valve geometry is modelled using CAD software and the thermal analysis at steady state is done using Ansys under FEA basis. The expected results are temperature variation, heat flux, rate of heat transfer.

Keywords: Exhaust valve, cooling provision, sodium, thermal barrier coatings (TBC's), thermal analysis, Ansys Fluent, temperature distribution, heat transfer rate.

1. INTRODUCTION

The engine system consists of two valves (inlet and exhaust) plays a key role in the continuous working by letting in fresh air and burnt gases out from combustion chamber as per valve timing for open and close accordingly during the thermodynamic cycle. Both the valves experience the same effects from the combustion but the exhaust valve is critical facing the hot gases, subjecting to the thermal loads due to combustion and flow of gases [1].

With respect to the valve sub divisions, the valve head faces directly to the combusted gases. The valve seat and stem are subjected to the most severe conditions due to the flow of hot gases. To withstand all this thermal effect at various operating conditions, the valve material must possess high temperature properties like hardness, thermal conductivity, fatigue strength etc. Choosing the proper material for the valve having properties to bear high thermal loads can reduce the failure and improve the life. Apart from the material selection, adoption of cooling method can also improve the performance by reducing the thermal effects on the valve [2].

The valve can be cooled either by enhancing the heat transfer rate or by not allowing the high temperatures to pass through it. Both the ways are possible. Rate of Heat dissipation can be made possible by employing the material having high thermal conductivity and also using other material internally to increase the heat transfer rate. The material has to be placed in the valve by making it hollow between the seat and the stem since these parts of valve are more effected regions due to hot gases and the chance of failure is very high. One such material having high thermal conductivity is sodium [3].

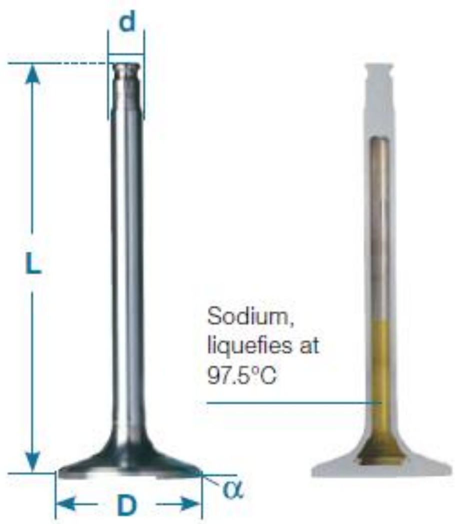


Fig.1 Sodium Filled Hollow Valve

The other method for cooling the valve is using the thermal barrier coatings to resist the high temperatures through valve. Using this, the valve ca be maintained under optimum temperatures. There are different types of coatings with different compositions like MgZrO3, NiCrAl, TiCN etc. These coatings are coated on the outer surface of the valve mostly the portion where the valve is facing the high temperature. The temperatures at these coated regions are very high compared to uncoated regions so as to allow for higher operating temperatures to increase thermal efficiency or reduce the fuel consumption of engines makes to achieve higher compression ratios [4].

2. FINITE ELEMENT ANALYSIS FOR THERMAL ANALYSIS

Thermal Analysis is otherwise called as heat transfer analysis. Heat transfer analysis is used to determine the temperature and heat flux change within different components of a structure caused by any kind of thermal load. Only thermal changes are assumed and the thermal loads applied are in the form of temperature, heat flux or heat loss via convection, radiation. The thermal analysis is done by considering it as steady in this case because Steady state prevails in a heat conducting medium when the temperatures do not change with time, heat transfer remains constant at a point and only the final stage of results are much interested.

Finite element method is a technique to find the unknown variable by solving the respective mathematical governing equations which are in differential form. Here in this, since it is heat transfer problem, the fundamental equations are conduction, convection in differential forms. As the differential equations are difficult to solve for the exact solution, we neglect the high order terms by considering as truncation error. Further if there is any difficulty in solving the differential equation, the equations are simplified by converting into algebraic matrix form to solve for the approximate solution.

In FEA, the equations are solved in stepwise i.e., the physical model is divided into number of elements having nodes at its end. Nodes are the entities where the results of unknown variable are expected and the elements are the entities connecting the nodes through which the loads are distributed. That means the physical model of the geometry is converted into mathematical model by dividing into number of elements or grids. In between, each element has a shape function to define the shape of the element because of which the approximation of results is defined. The mathematical equations are written for each element and assembled in the matrix form. Solving the matrix, we find the unknown variable as result. FEA method is not exact but approximate.

3. STATEMENT OF PROBLEM

This thermal analysis is concerned with the diesel engine exhaust valve. The engine assumed in this is 4 stroke diesel engine and water cooled with certain rated power. The thermal analysis performed in this study is done at steady state for all the conditions such as:

A. On the solid exhaust valve
B. On the hollow exhaust valve
C. On the valve filled with sodium in the seat and stem portion in the hollow portion
D. On the valve coated with TiCN material on the head face with 1mm thickness
E. On the valve filled with sodium in hollow portion and coated with TiCN on the face of head with 1mm thickness.

All the above-mentioned conditions are analysed at the worst thermal loading conditions. The steps involved in performing the analysis using Ansys:

a. Modelling valve geometry using CAD software with available dimensions avoiding the unwanted features
b. Meshing the geometry by maintaining the quality
c. Setting up the physics by assigning the material, applying the thermal loads and constrains
d. Solving for the required results
e. Post- processing the results

The dimension parameters of exhaust valve are mentioned in the table 1. The material and their properties are mentioned in table 2 and the boundary conditions in the form of temperature in ˚C and heat transfer coefficient(h) in W/m^2-K used for this thermal analysis are mentioned in table 3.

3.1. Geometry

A geometrical model of the valve is done using CAD software by considering all the parameters from bottom head to top tip. The geometry used in this analysis is shown in fig.2 to fig.5 according to the conditions mentioned above and the corresponding dimensional parameters are shown in table 1

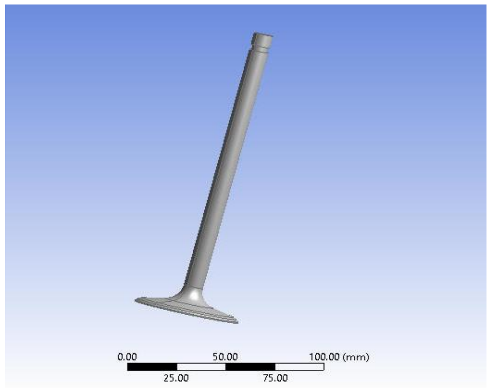
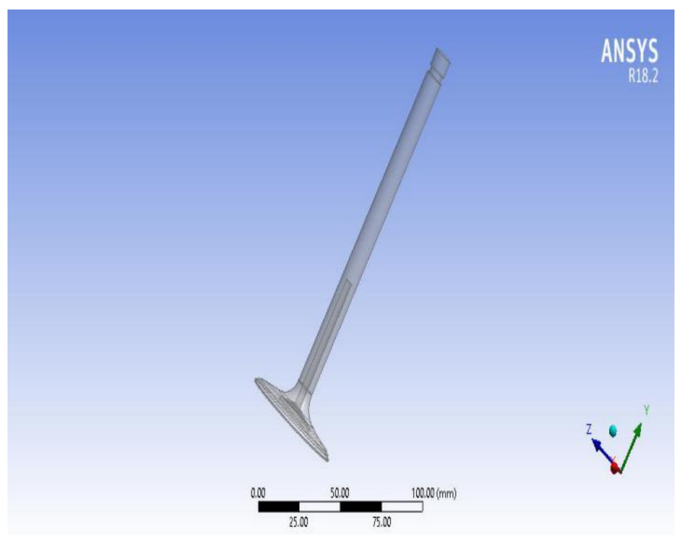


Fig.2 Valve Geometry without sodium and without coating

(2a)



(2b)

Fig.2a. Sectional View of Valve with hollow portion in head-stem and seat

Fig.2b.3D view of valve with hollow portion inside in head-seat and stem

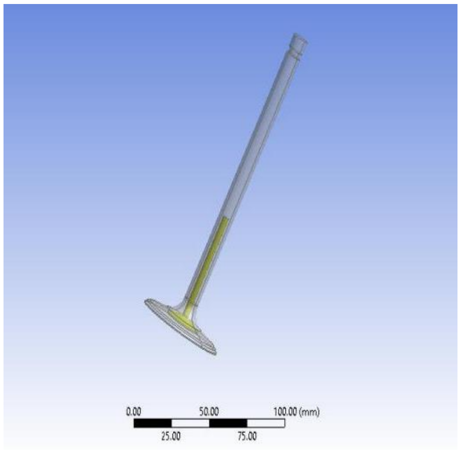


Fig.3 Valve filled with sodium

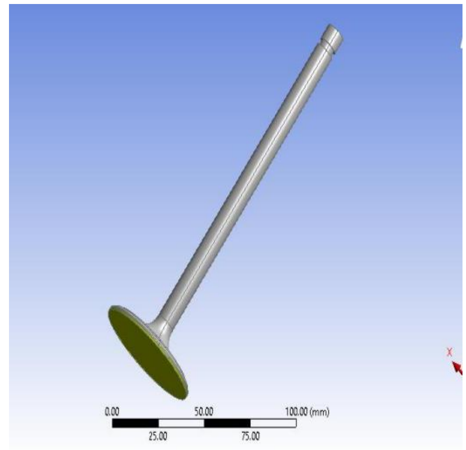


Fig.4 Valve with TiCN coating of 1mm thick

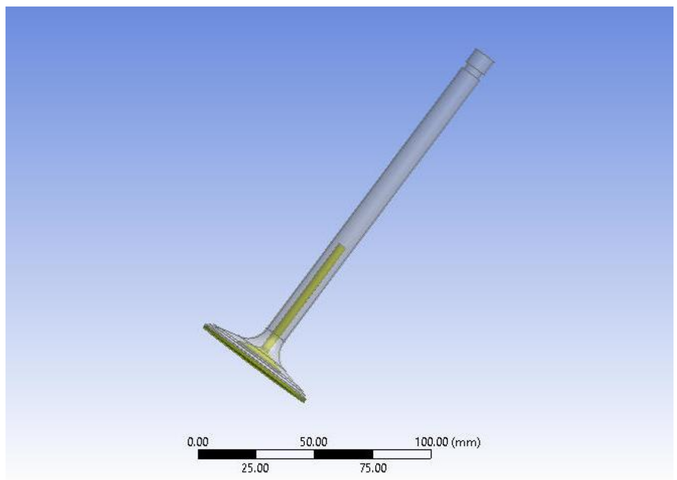


Fig.5 Valve filled with sodium inside and coated with TiCN on head face of 1mm thickness

Table 1 Geometrical dimensions of the valve

S. No	Description	Measurements(mm)
1	Diameter of head(D)	54
2	Thickness of head(t)	0.63
3	Seat Angle	45˚
4	Angular length of seat	1.6
5	Radius of fillet between stem and seat	2
6	Length of Stem(L)	140
7	Diameter of Stem	10
8	Length of Groove between tip and stem	3
9	Diameter of the groove	8
10	Length of tip	7

3.2. Materials and their Thermal Properties

Selection of material is very important step in the product development of valve. Generally, iron-based steel alloys, iron alloys and cobalt alloys are used for the manufacturing of valve. Among steels there are different combinations of alloys with different compositions like EN24, CrSi steel etc. Economically, iron-based steel alloys costs less when compared to other. Therefore, in this analysis an attempt is made by selecting Steel SUH 1 type with required thermal properties. Likewise, the sodium and thermal barrier coatings are selected based on their availability, cost with respect to their thermal properties. The materials and their properties used for this thermal analysis are mentioned in table 2.

Table 2 Materials and their properties

S. No	Material Name	Density in kg/m^3	Thermal Conductivity (W/m-K)	Specific Heat in J/kg -K
1	Steel SUH 1	9010	30	520
2	TiCN	3260	20.	1002
3	Sodium	927	135	4.50

3.3. Meshing the geometry

Meshing the geometry is simply converting the physical model into mathematical model by dividing into number of small entities called elements connected with nodes at each element end. Nodes are the entities where the result of unknown variable is expected. There are various types of elements based on their 1D, 2D, 3D type of the geometry. In this analysis, 3D linear tetrahedral elements are used making the mesh fine at the critical locations like important features, more thermal loads acting regions. The geometries with sodium and coating are also meshed accordingly maintaining the fineness in mesh and quality of skewness.

Fig.6 Mesh of solid valve

1	Number of Nodes	39571
2	Number of elements	185299

Fig.7 Mesh of hollow valve

1	Number of Nodes	112799
2	Number of elements	572992

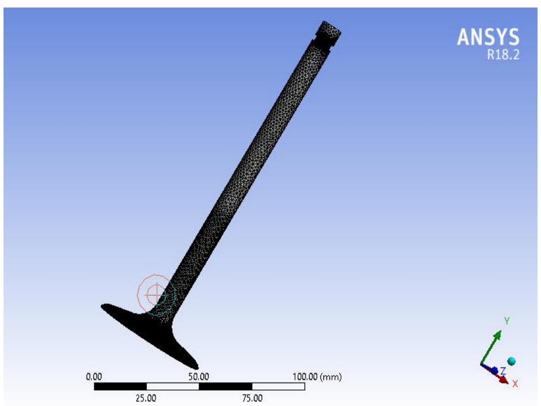


Fig.8 Mesh of sodium filled valve

1	Number of Nodes	149631
2	Number of elements	751577

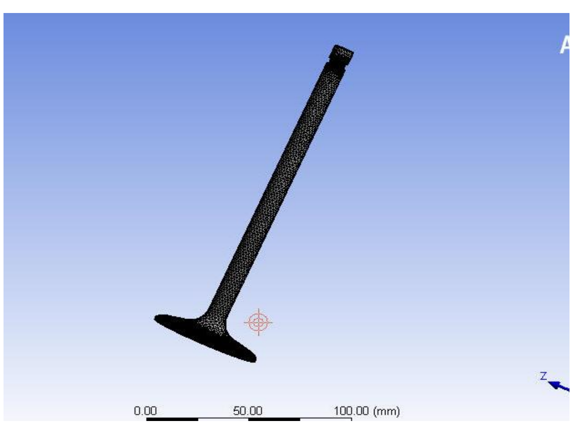


Fig.9 Mesh of valve with TiCN coating

1	Number of Nodes	136366
2	Number of elements	257646

1	Number of Nodes	247980
2	Number of elements	824765

Fig.10 Mesh of valve with sodium and TiCN coating

Meshing is not only just diving the physical model into number of elements; the divided elements must maintain the quality. The best quality of the elements results in more approximate solution. The quality parameters of mesh are warpage, skewness, aspect ratio etc. Skewness is the important quality parameter which defines whether the elements comprises the shape of the entire physical model. Skewness valve ranges between 0 and 1. The elements with skewness valve closer to 1 is considered as worst and close to 0 or between 0-0.5 are considered as the better elements. In all the above meshes, the quality is maintained and the skewness valve is 0.3 on an average which is acceptable.

3.4. Boundary Conditions

Boundary conditions are the values that indirectly create the thermal environment in and around the surroundings of valve. Same boundary conditions are applied to all the conditions in this analysis study to compare the results mentioned in table 3. The thermal loads applied are taken as the worst case [6].

Table 3 Boundary conditions

S. No	Location	Temperature ˚C	Heat Transfer Coefficient(h) in W/m^2-K
1.	Combustion face of head	1000	348
2	At the seat portion	700	450
3	At stem	500	5814
4	At tip	600	42

3.5. Setup in Ansys Fluent

- Solver type is Pressure based under steady state
- Energy equation is used to solve in model
- Material and their properties are taken from Table 1
- Cell Zone conditions are assigned with respective and maintained as solid
- Boundary conditions are taken from table 3
- Hybrid Initialization is done with all necessary adjustments in calculation activities, report monitoring graphs, convergence criteria valves

- Finally, the calculation is done with certain number of iterative steps until the solution is converged.
- The results are extracted by post processing the solution in the form of plots, contours etc.

3.6. POST-PROCESSING

Case 1: Solid Valve geometry without sodium and without coating

Total Heat Transfer Rate	(w)
combustion_faces	158.79234
valve_seat	-100.84862
valve_stem	-59.186772
valve_tip	1.3556474
Net	0.11259957

Fig.11 Heat transfer rate through solid valve

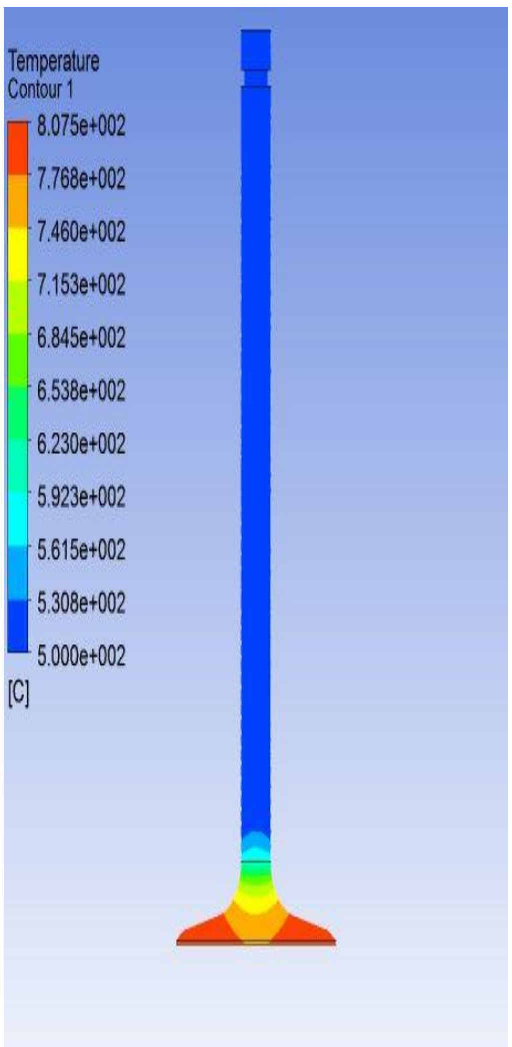


Fig.12 Temperature contour

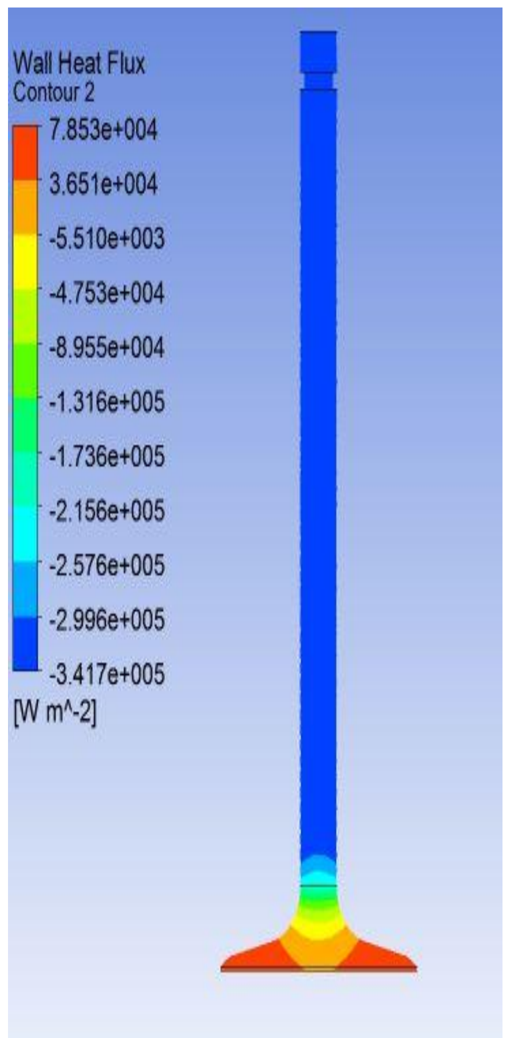


Fig.13 Wall Heat Flux

Case 2: Solid valve with hollow portion in the seat and stem region

Total Heat Transfer Rate	(w)
combustion_face	148.15063
valve_seat	-101.51045
valve_stem	-47.941675
valve_tip	1.5645908
wall-valve_final	-0
Net	0.26309729

Fig.14 Heat transfer rate through hollow valve

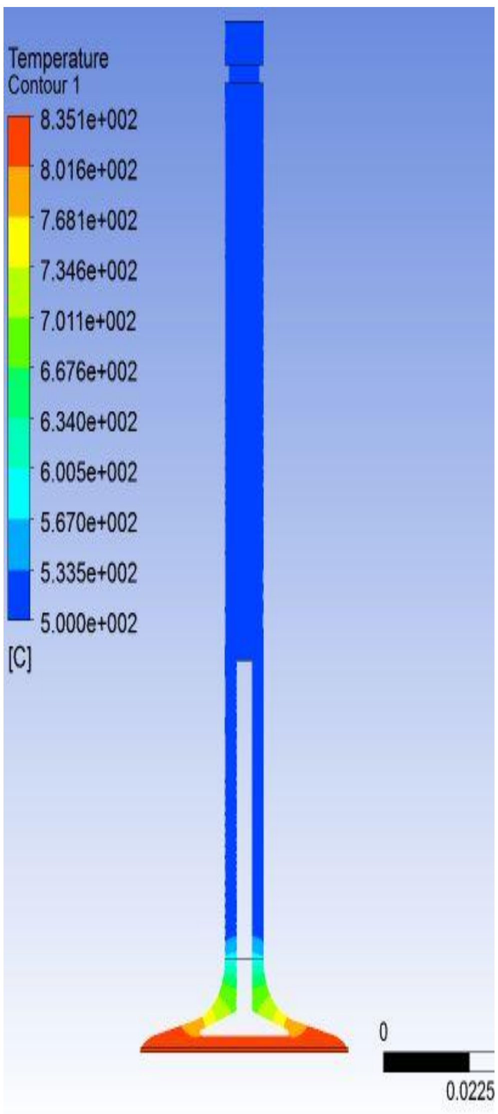


Fig. 15 Temperature contour

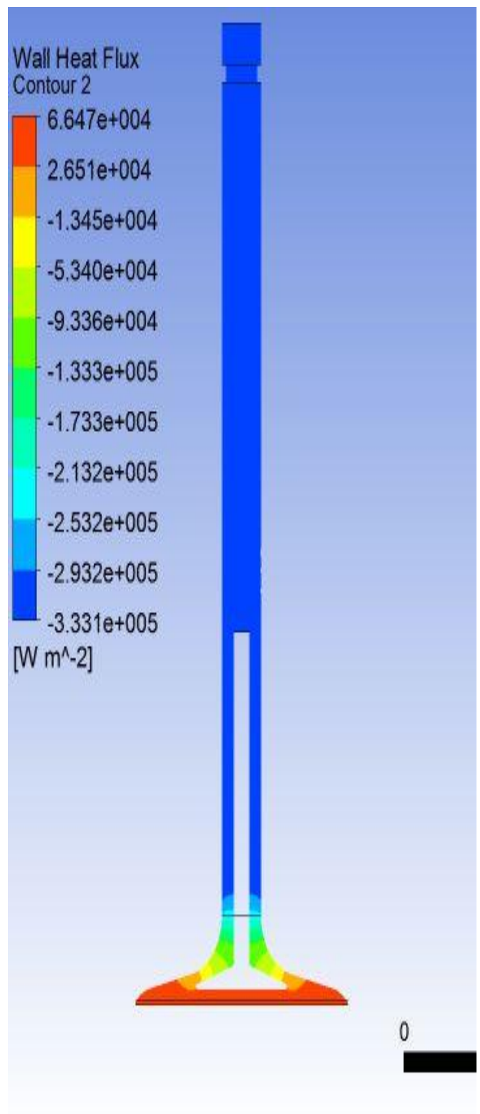


Fig.16 Wall Heat Flux contour

Case 3: Valve with sodium in hollow portion

Total Heat Transfer Rate	(w)
combustion_face	167.22445
contact_region-src	-0
contact_region-trg	-0
valve_seat	-90.053141
valve_stem	-76.550066
valve_tip	1.5641305
wall-13	-0
wall-14	-0
wall-6	-3.2869227
wall-6-shadow	3.3621548
Net	2.2606081

Fig.17 Heat Transfer rate through sodium filled valve

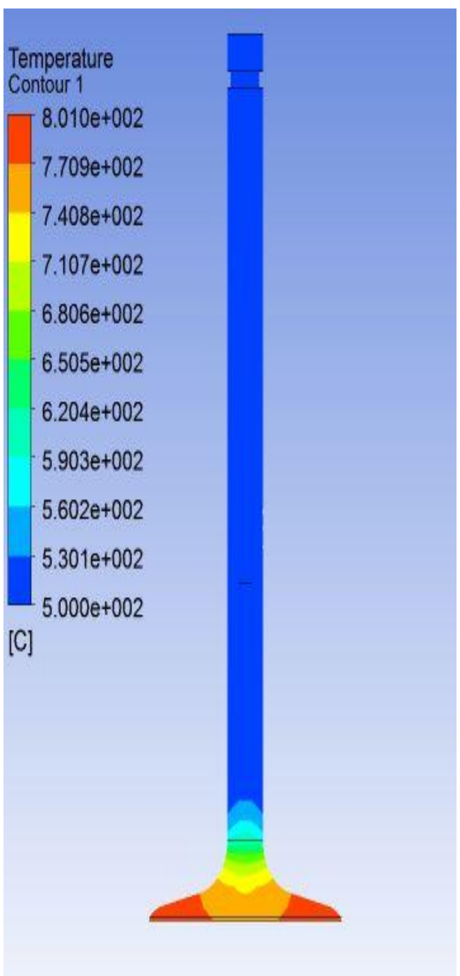


Fig.18 Temperature contour

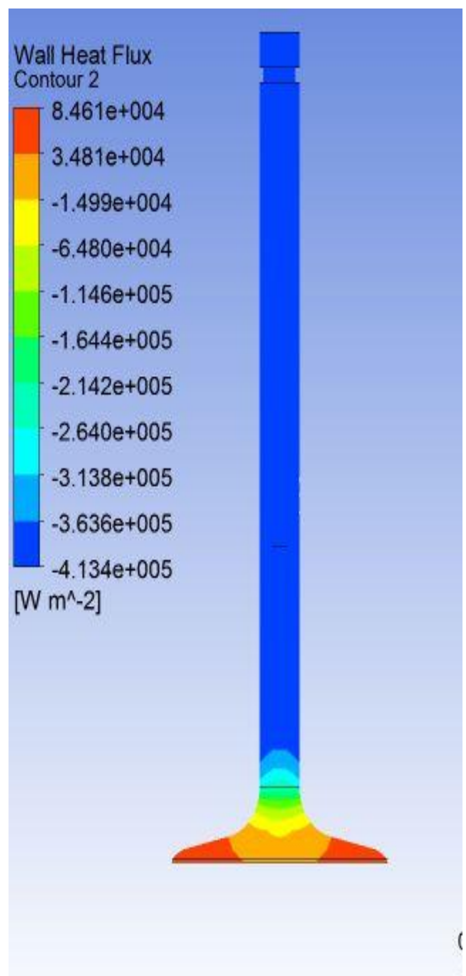


Fig.19 Wall Heat Flux contour

Case 4: Valve with TiCN coating on the face of head with 1mm thickness

Total Heat Transfer Rate	(w)
combustion_face	153.5457
contact_region-src	-0
contact_region-trg	-0
valve_seat	-104.40458
valve_stem	-59.9223
valve_tip	1.5649113
wall-14	-0
wall-15	-0
wall-7	163.09464
wall-7-shadow	-163.05558
wall-coating	9.4047754
Net	0.22757139

Fig.20 Heat Transfer rate through TiCN coated valve

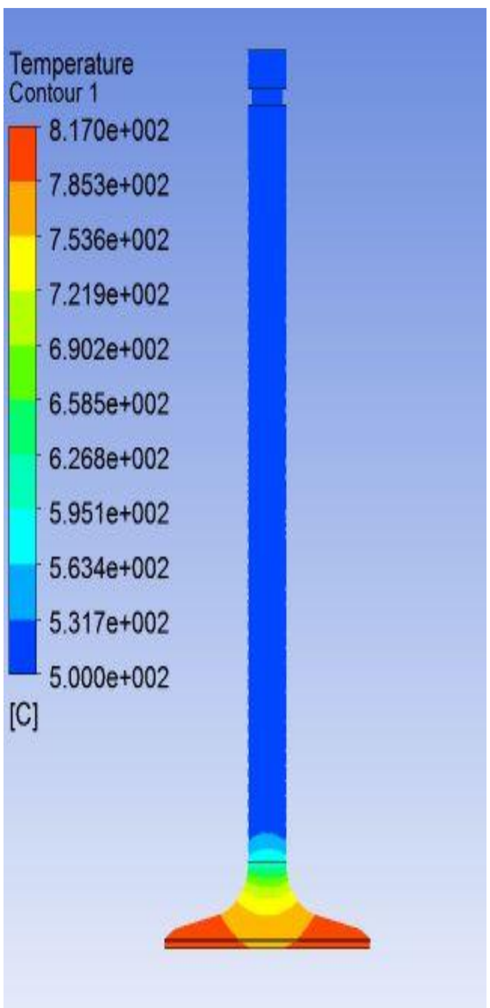


Fig.21 Temperature contour

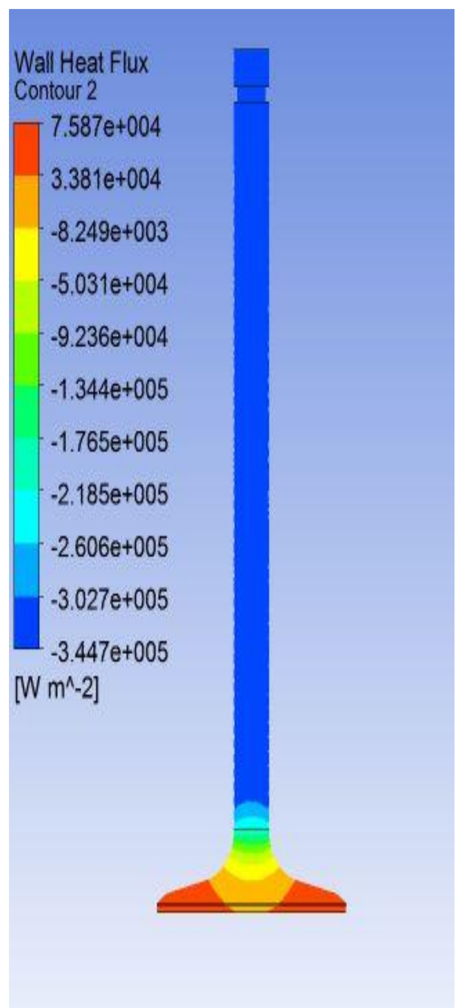


Fig.22 Wall Heat Flux contour

Case 5: Valve filled with sodium in hollow portion and Coated on head face with TiCN of 1mm thickness

Total Heat Transfer Rate	(w)
bonded_-_valve_final_to_coating_-src	-0
bonded_-_valve_final_to_coating_-trg	-0
bonded_-_valve_final_to_sodium-src	-0
bonded_-_valve_final_to_sodium-trg	-0
combustion_face	161.29097
valve_seat	-94.350254
valve_stem	-77.310295
valve_tip	1.3537925
wall-18	-0
wall-19	-0
wall-20	172.88509
wall-20-shadow	-172.86942
wall-21	-0
wall-22	-0
wall-9	-3.5154906
wall-9-shadow	3.59436
wall-coating_	11.179522
Net	2.2582763

Fig.23 Heat transfer rate through sodium filled and TiCN coated valve

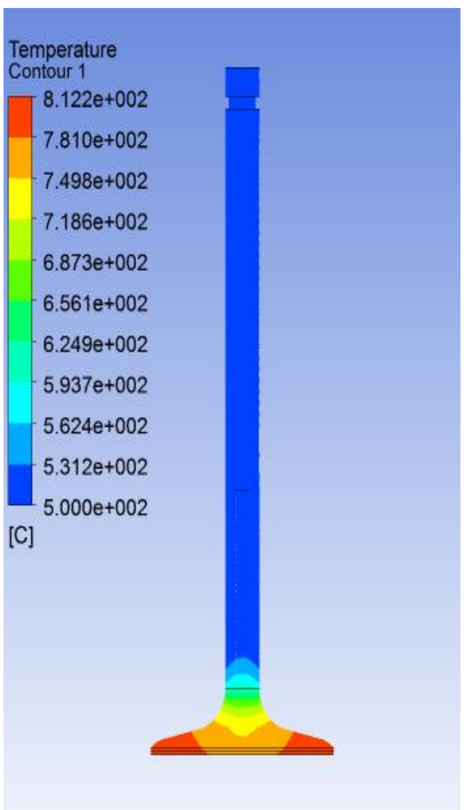


Fig.24 Temperature contour

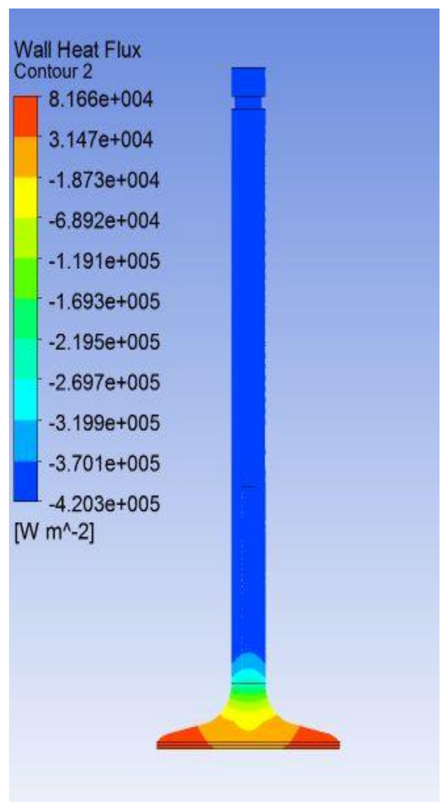


Fig.25 Wall Heat Flux contour

3.7. RESULTS

S. No	Description	Temperature in ˚C		Total Heat Transfer rate in Watts	Wall Heat Flux in W/m^2
		Max	**Min**		**Max**
1	**Solid valve**	807	500	0.11259	78530
2	**Hollow valve**	835	500	0.26309	66470
3	**Valve filled with sodium**	801	500	2.26060	84610
4	**Valve coated with TiCN**	817	500	0.22757	75870
5	**Valve with sodium and TiCN coating**	812.2	500	2.25827	81660

3.8. DISCUSSION

1. From the results, it is very clear that the values obtained for the thermal analysis being done on valve are varying with small amount of difference between them according to the conditions adopted in the problem statement.

2. Our criteria is heat transfer rate through valve should be high bearing the high temperatures. Keeping this as our limit, heat transfer rate is high in 2 conditions i.e., a) Valve filled with sodium with 2.26 Watts having 801˚C as maximum temperature and b) valve with sodium and TiCN coating with 2.25 Watts having 812.2˚C as maximum temperature.

4. CONCLUSION

Taking all the above discussions under considerations obtained from the thermal analysis under steady state done with various conditions mentioned in the problem statement, it is very clear to understand that the valve filled with sodium inside and coated with TiCN (Thermal barrier material) of certain thickness on the head face is best suitable model to improve the performance by sustaining thermal loads due to high temperatures from the hot gases which further can increase the life.

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