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Performance of Thermal Barrier Coating on Exhaust System Component

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ABSTRACT

Thermal management in automobiles is important to keep the passenger cabin and heat sensitive components away from thermal effects. Hence various types of insulation methods are used to reduce the thermal effects. Heatshields are the most common method of thermal insulation. They can be classified into various types based on their construction architecture and insulation materials. Some of the heat shielding systems contain fibre materials that are hazardous to health due to their carcinogenic effects and hence not recommended. With increasing space constraints in the compact vehicle architecture designs, packaging space is premium, limiting the size of heatshields. In addition, from durability aspect, heatshields alone are not adequate to withstand high temperatures during the service life of exhaust systems. Hence the role of Thermal Barrier Coating (TBC) as an alternative solution comes effective.

TBC's are ceramic coatings which can take care of extended heat loads and temperature differences. This coating not only provides thermal insulation but also improves the fatigue life of substrate material. Hence in this paper, the application of TBC on exhaust system components with respect to thermal insulation and thermo mechanical fatigue are studied. Virtual analysis and physical test are carried out to validate the results. TBC coating on exhaust component shows promising results.

KEYWORDS: Thermal barrier coating; Atmospheric plasm spray; Thermo mechanical fatigue analysis; Thermal Test; Yttria stabilized zirconia.

Introduction

The exhaust system plays an important role in IC (Internal Combustion) engine. Modern automotive exhaust system deals with both carrying away the exhaust gas and noise dampening. The main durability issue is associated with the thermal loading and vibration loading. With the increase in demand for high performance engine, the downsizing and turbo charging has led to formation of other failure elements such as vibration oscillation. Thermal barrier coatings are generally used on metals which are operating at higher temperatures. This type of coatings can take extended heat loads and temperature differences.

YSZ (Yttria Stabilized Zirconia) is a popular material used in the field of automotive and aero applications. These coatings not only provide thermal insulations but also protection from physical degradation of components due to wear and tear. The structure of TBC (Thermal Barrier Coating) consists of bond coat and topcoat. The bond coat temperature often goes up to 1237 K – 2700 K. It is usually applied to the substrate material by using APS (Atmospheric Plasm Spray) or EB-PVD process depending on the composition. High service temperature makes it popular in automotive application such as exhaust manifolds[3]. In automotive field it is coated on Piston head, engine components etc[2]. In this study Virtual and Physical test for thermal and thermo-mechanical fatigue analysis is carried out for Pipe and Pipe with TBC. 8YSZ material also exhibit good spallation resistance[4].

There are different types of ceramic coating materials available depending on the specific application[4]. According the material data sheet[1] following are the properties of 8YSZ

Chemical Composition: 8YSZ TBC Coat (ZrO_2 $8Y_2O_3$)

Product	Metco-204 NS
ZrO_2	77.6
Y_2O_3	7.0-8.0
SiO_2	0.3
TiO_2	0.2
$Al2O_3$	0.2
Fe_2O_3	0.2
Other oxides	1.0
Monoclinic Phase	10
HfO_2	2.5

Specification	Data
Coating process	Atmospheric Plasma Spray
Porosity range	8-20%
Microstructure	Homogeneously porous and finely micro cracked

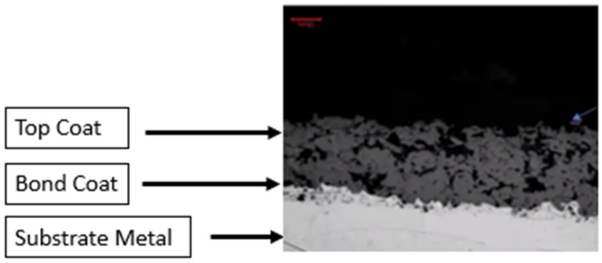

Fig. 1. Metallography of TBC coat.

1. Top Coat 8YSZ
2. Bond Coat NiCrAlY
3. Substrate 409L SS

YSZ is the most preferred material for exhaust applications. YSZ also has the highest level of resistance to spallation at high temperatures (>2000°C) and high corrosion resistance. 8YSZ TBC is sprayed using Atmospheric Plasma Spray Process.This type of process makes use of electrically conductive gas containing charged ions and electrons. Ceramics in the form of wire or powder is sprayed at over 1000 °C on to the substrate material. This coating provides good level of adhesiveness and variety of material choices. Plasma spray is found to be a flexible thermal spray process as it can take into account most of the coating material, different size of particles and shape of substrate material

Methodology

The exhaust component is considered here is a pipe component. The study consists of mainly two parts, the first is the virtual analysis of the models to predict the initial thermal and thermo mechanical fatigue results. Secondly the physical models are tested and those results are used to validate the virtual results and hence to increase the confidence level in FEA model. Virtual analysis is carried out with the help of software's like **Catia, Hyper mesh and Abaqus, TAI-Therm**. Physical test is carried out on thermal test bench and thermo mechanical test bench.

FEA Model

The length of pipe model is about 280 mm. Coating length is selected as 180 mm. Thickness of the TBC coating is 0.250 mm. The diameter of the pipe is taken as 60.5 mm. The modelling of pipe is carried out in Catia. Meshing is carried out in hyper mesh software. The element size selected is 2mm. Mesh dependency study is carried out for different mesh size to check the confidence in FEA model.

Virtual Analysis

1. Thermal Analysis

The initial stage of thermal analysis is to input the material data and boundary condition. Once the initial stage is over next is to create the 3-D geometry of pipe. Geometry clean-up must be performed in Hypermesh to repair the surfaces of geometry. Once the clean-up is done next stage is to mesh the component. If the element number is enough for the analysis, then next stage is to run the thermal analysis in Tai therm. Post processing has to be done to extract the various information from the analysis. The gas inlet temperature is selected as 950°C with a mass flow rate of 80 kg/hr. The flow is selected as 1-D stream. The ambient temperature is selected as 30°C. The model consists of both quad and hexahedron elements. The quality parameters of the mesh are maintained. The emissivity of pipe is taken as that of steel 0.1 and TBC is taken as 0.5.

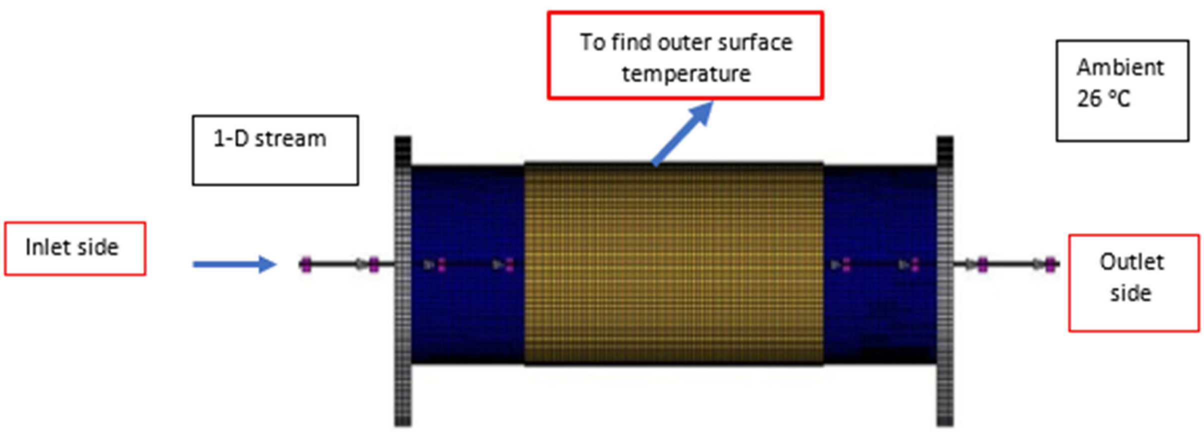

Fig. 2 FEA Model.

Fig. 3. Thermal Analysis Methodology.

2. Thermo Mechanical Fatigue Analysis

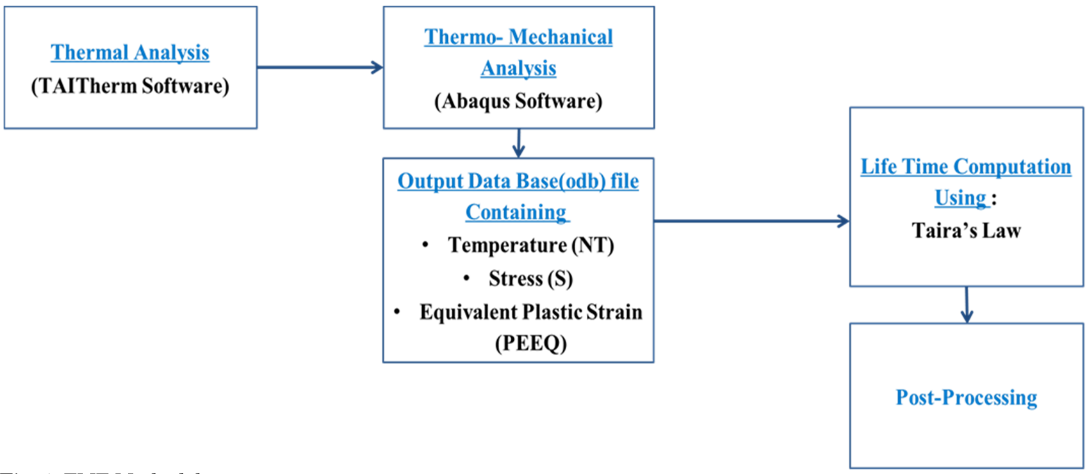

Fig. 4. TMF Methodology.

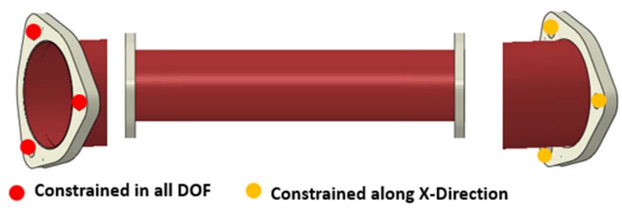

Fig. 5. Pipe FEA Model for TMF.

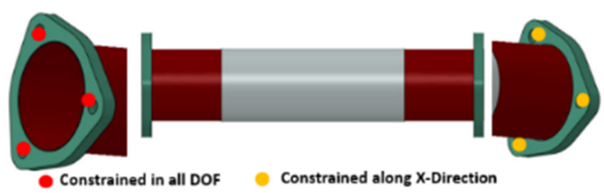

Fig. 6. Pipe with TBC FEA Model for TMF.

Physical Test

1. Thermal Test

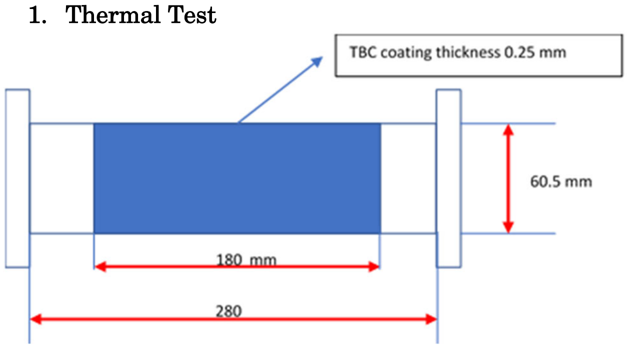

Fig. 7. Dimension of Prototype Model.

Sample Dimension

Pipe models are fabricated similar to the virtual model to carry out the physical test. The length of pipe is about 280 mm. Coating length is selected as 180 mm. Thickness of the TBC coating is 0.250 mm. The diameter of the pipe is taken as 60.5 mm. Pipe material is of the material SS 409L and TBC is 8YSZ. The coating method used here is Atmospheric Plasma Spray Process.This model is to test the exhaust gas flow through exhaust pipe with and without the application of TBC.

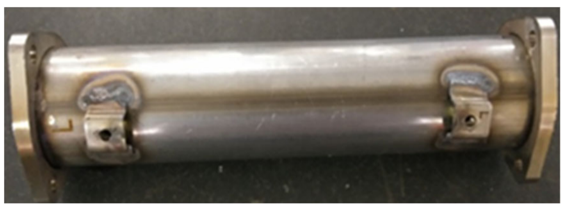

Fig. 8. Physical Model Pipe.

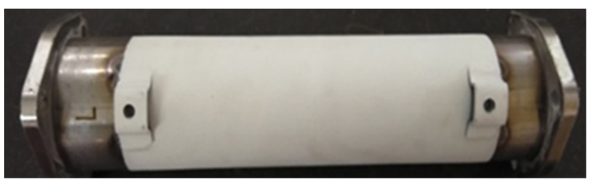

Fig. 9. Physical Model Pipe with TBC.

Thermal Test Procedure

The pipe samples are tested in Thermal test bench. It consists of inlet and outlet section. Inlet section consist of a burner where hot gas is heated to the required condition. Thermocouples are mounted on the pipe by wielding and on TBC surface using a thermocouple rod. The outlet section consists of exhaust where the hot gas leaving through the pipe is taken out. Thermocouples are welded on to the pipe surface at required locations. These thermocouples are connected to the data logger through various adapters. Data logger continuously records the temperature values which are received from the thermocouples. Temperature values for every second is recorded.

The gas inlet temperature is selected as 950°C with a mass flow rate of 80 kg/hr

2. **Thermo Mechanical Fatigue Test**

TMF testing incorporates servo controlled axially loaded equipment. The test component is made to undergo thermal cycle with a desired temperature and time history. There is no load applied on the component at this stage. Later the component is both thermally and mechanically strained. LCF takes in to account the yielding of material due to increase in thermal and mechanical loads. It uses strain-life approach. Temperature fields is determined by thermal finite element analysis

- Cyclic temperature load is applied between 400 °C and 950 °C
- Mass flow of gas is maintained at 80 kg/Hr
- Red plot shows the critical thermal load and blue plot shows the actual thermal plot
- Frequency of thermal load is applied for 1000 cycles

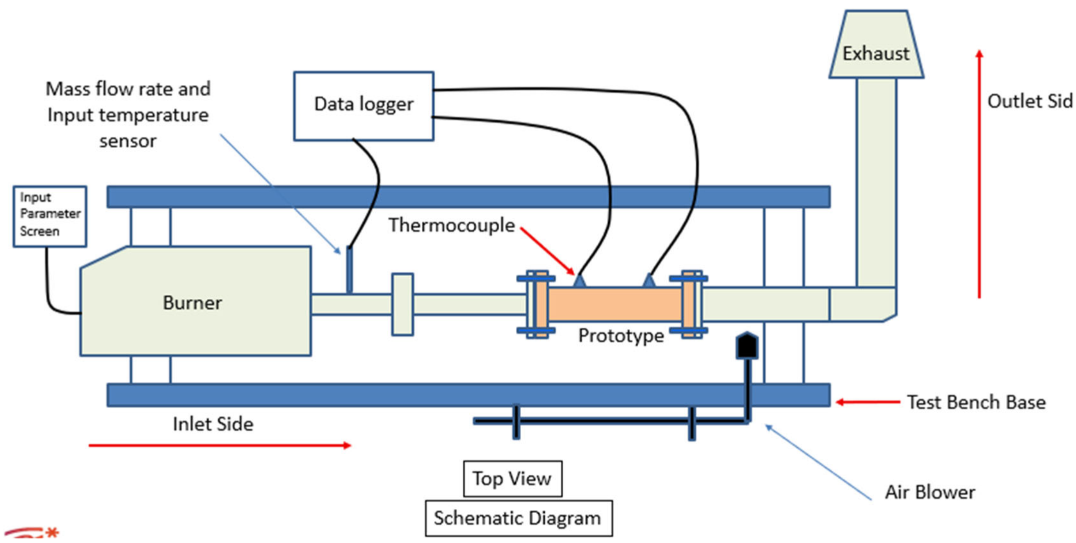

Fig. 10. Schematic figure of Thermal Test Bench.

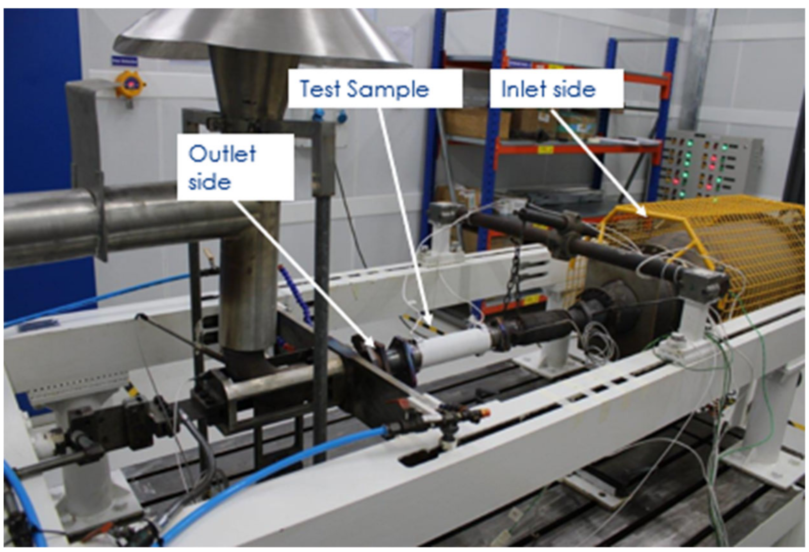

Fig. 11. Thermal Test Bench.

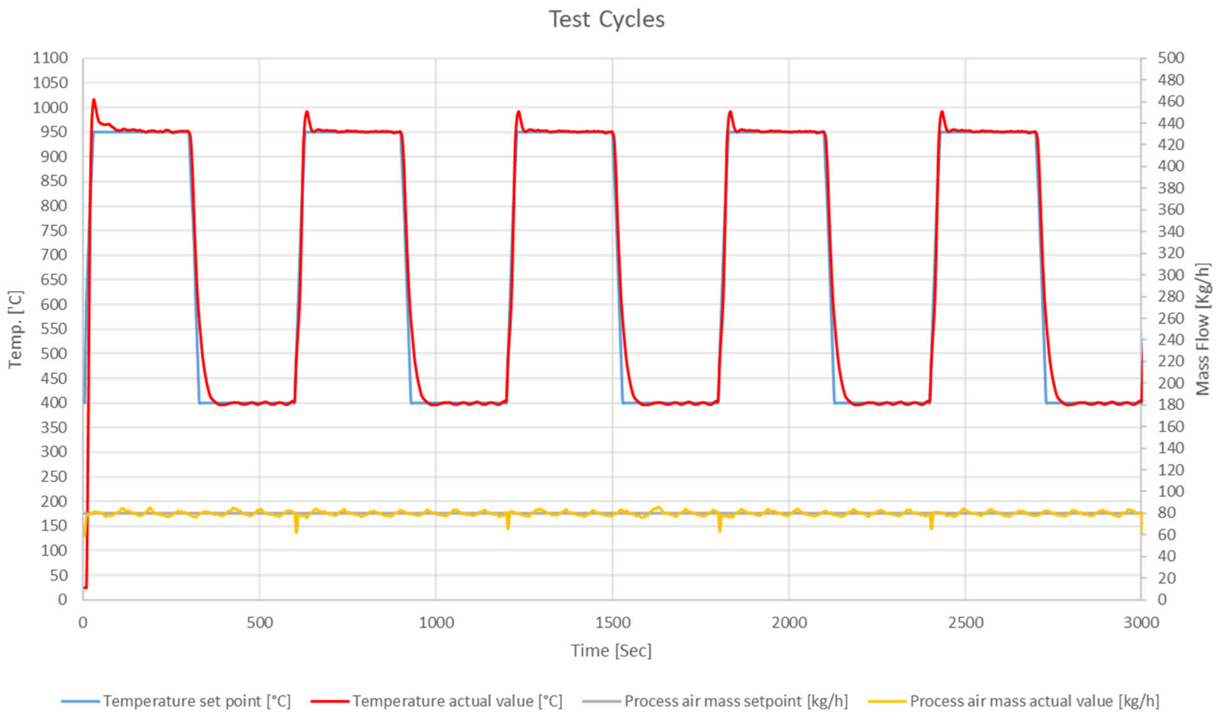

Fig. 12. TMF Input Condition.

Fig. 13. TMF Test Bench.

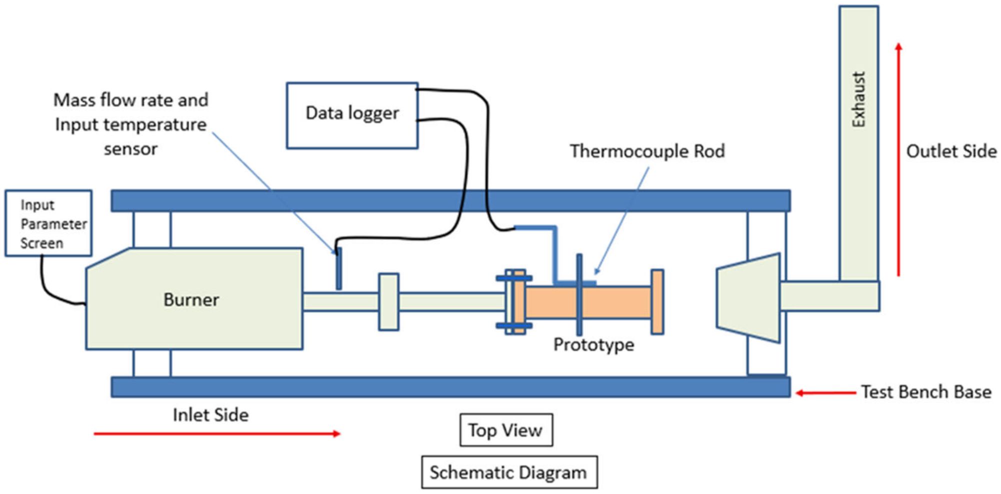

Fig. 14. Schematic Figure of TMF Test Bench.

Result and Discussion

Thermal Result

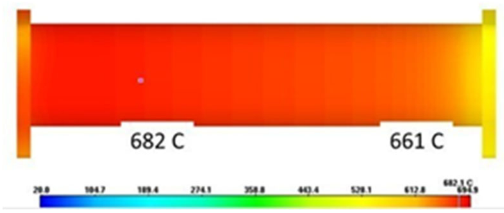

Fig. 15. Temperature Contour of Pipe.

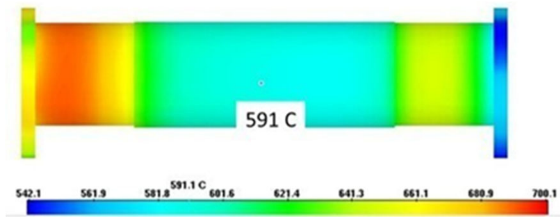

Fig. 16. Temperature Contour of Pipe with TBC.

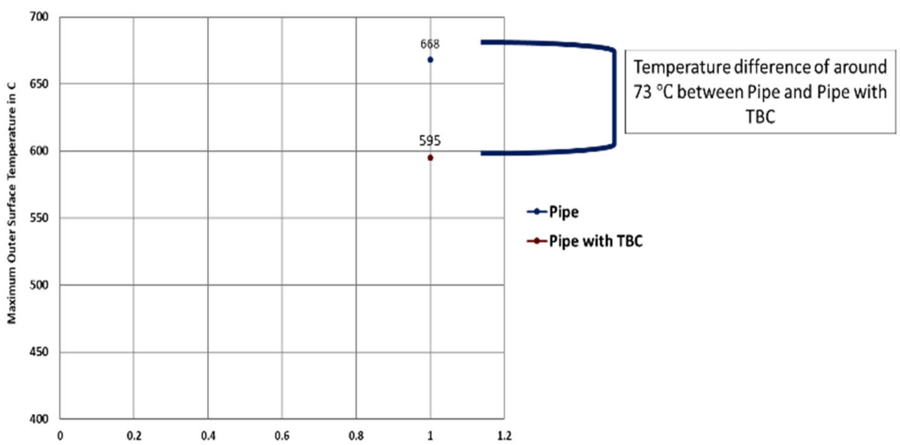

Fig. 17. Temperature plot of Pipe and Pipe with TBC (Physical Test).

From the virtual analysis we can observe around ~**50** °C- **60** °Ctemperature difference with application of TBC coating. From the physical the temperature difference is~**60** °C-**70** °C. Test results are in well correlation with the FEA model

TABLE 1

Thermal Analysis Result (Physical vs Virtual)

	Physical Test	Virtual Analysis
Pipe	668°C	661°C
Pipe with TBC	595°C	591°C

Thermo Mechanical Fatigue Result

TABLE 2

TMF Results (Physical Vs Virtual)

	Physical Test	Virtual Analysis
Pipe	1000 cycles	1000 cycles
Pipe with TBC	1000 cycles	1000 cycles

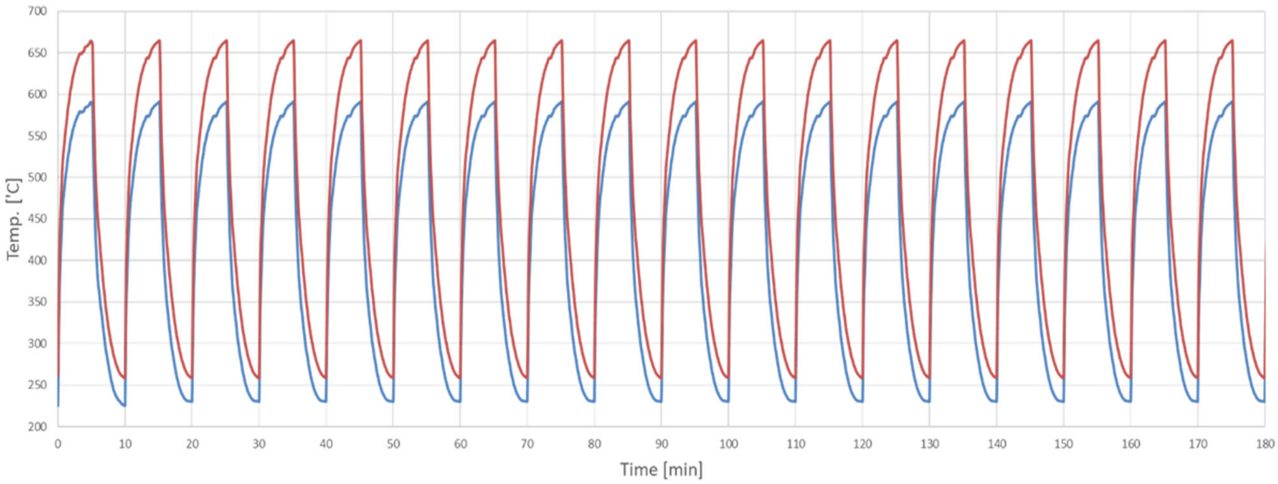

Fig. 18. TMF Output Result Physical Test.

Thermocouple records a outer surface temperature of 670 °C and 590 °C (upper limit) with respect to Pipe and Pipe with TBC respectively. Both the test models sustains 1000 cycle of operation. Both the prototypes sustains 1000 cycles of operation

From the virtual analysis Pipe model sustains around 2100 cycle and wherease Pipe with TBC sustains 2077 cycle of operation. Both are in safe operating limit.

The temperature difference at full load is 60°C -70°C and at idle load is 30°C-40°C. The Virtual and Physical Test results are in well correlation.

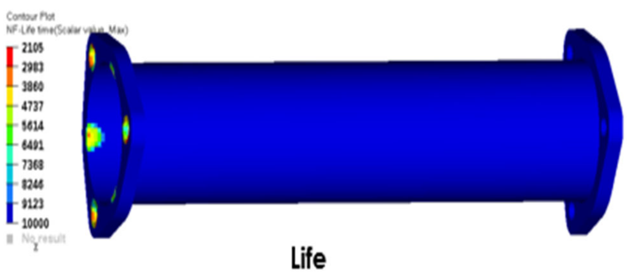

Fig. 19. Life estimation of Pipe.

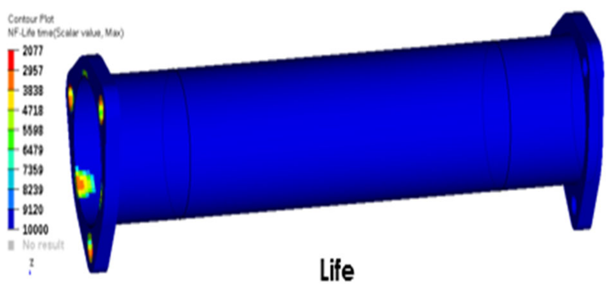

Fig. 20. Life estimation of Pipe with TBC.

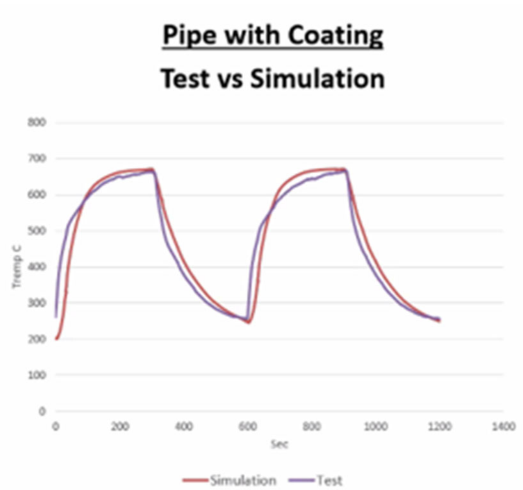

Fig. 21. Test vs Simulation for 670 °C.

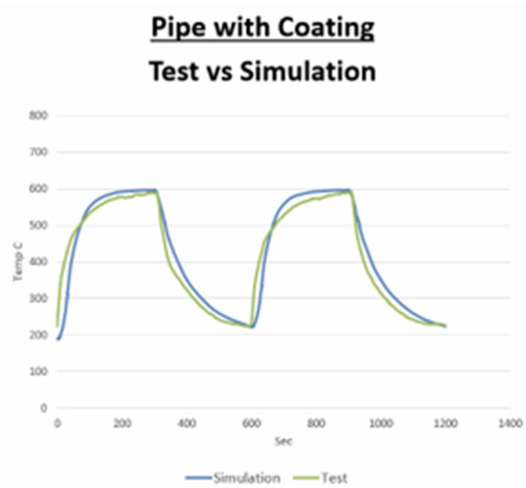

Fig. 19. Test vs Simulation for 590 °C.

Conclusion

- For an inlet gas temperature of 950°C and mass flow rate of 80 kg/Hr we can observe a ~50 °C - 60 °C reduction in temperature on the outer surface in comparison with Pipe and Pipe with TBC
- With respect to the thermo mechanical fatigue life, the test is conducted for 1000 cycle and both the prototypes passed the test
- Oxidation is observed more on pipe surface than on pipe coated with TBC. This shows that pipe coated with TBC has better oxidation resistance

Further Scope of Study

- Further study planned is to carry out the modal analysis and also study the performance of TBC on a catalytic converter

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