Heat transfer analysis of thermal barrier in high temperature fluid vessel

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Abstract
High temperature fluid storage and handling vessels require to maintain large temperature gradient between the fluid surfaces to top of the vessel. This is achieved by the usage of baffle plates. High temperature failure modes such as ratcheting, creep and fatigue damage, mainly under thermal loadings, decide the vessel life. Tests are conducted in high temperature fluid test vessels on models of shells subjecting them to axially varying temperature gradients to simulate thermal ratcheting which affects the free level variations vessels facing high temperature fluid. Baffle plates are used to maintain the temperature on of the surface of the test vessel below 100 degrees centigade. The transfer of heat through radiation is contained through the baffle plates. The heat transfer analysis of the baffle plates gives clues of the number of baffle plates required to maintain the top surface in the required temperature. The objective of the project is to design the thermal barrier using baffle plates. The initial calculation of required baffle plates is done using theoretical method available in literature. A computer program is developed to perform similar calculations for various calculations with different parameters of design. Theoretical analysis only considers radiation mode of heat transfer which is the predominant mode of heat transfer where high temperatures are present. But in reality both conduction and convection plays a role in heat transfer. At the same time multimode heat transfer is very complex for theoretical analysis. Hence, Finite element method is used to analyze to improve the design of the baffle plate arrangement.

Keywords: Vessel, Thermal Barrier, Baffle Plates

1. Introduction
High temperature fluid storage vessel is used in industries around the world for storing and testing high temperature fluids. The high temperature fluid can be molten metals and salts and other thermic fluid. Typically the nuclear industries in fast reactors use sodium at temperature of around 500°C to 600°C [1]. In gas turbine industry Thermal barrier coating
(TBC) systems are used since the 1980s. [2] Molten salts can range typically from 1000°C to 2000°C. The high temperatures heat the surrounding drastically. The high temperatures can fail the sealing equipment in the lid of the high temperature fluid vessel as 70mm. The flange is fixed with 20 M16 bolts. The lid is given a thickness of 70mm. The first prerequisite for fabricating the thermal barrier coatings (TBCs) with excellent performance is to find an optimized coating structure with high thermal insulation effect and low residual stress [4]. There have been a number of studies, analytical, numerical as well as experimental, pertaining to fluid flow and heat transfer involving the geometry of a vertical channel [5].

This can lead to high temperature failure modes such as ratcheting, creep and fatigue damage, mainly under thermal loadings, decide the vessel life. Bolted flange joints at the top provide ease for the insertion of equipment to be tested. Silicone "O" rings are used for leak-proof sealing in the bolted flange joint. The high temperature of the closure flange joint poses problems; these are leakage from the "O" ring seal, minimization of heat loss, and temperature control working environment. Hence, there is a need to keep the top flange temperature below 100°C, and heat transfer minimization is required from hot liquid sodium to closure flange joint. A large variety of numerical methods have been used to analyze the problems of heat transfer [6, 7] this requirement is achieved by providing thermal resistance in the path of heat transfer. The yield strength and modulus of elasticity of steel are reduced by 70% at 350°C and less than 50% at 600°C. [8, 9]. From the literature survey it is found that material selection of baffle plates and thermal barrier coating have a high influence in heat transfer rates. In this present study the optimized number of baffle plates required with high heat transfer rates is designed and analyzed using Finite element Analysis.

2. Materials and methodology

The vessel of design is made according to the requirement temperature, pressure and volume capacity of the vessel. The shell thickness and bottom plate of the vessel is designed using ASME method. The flange design is made according to ASME code. The various thermal barriers are analyzed and baffle plates are selected as the suitable thermal barrier. The baffle design is calculated using the equations available in literature and is optimized using trial and error method. The data is fed into a custom made computer program based on requirements to calculate the number of baffle plates required to limit the temperature at the lid to below 100°C. The calculated data is used to model the design into CAD model and the model is analyzed using finite element method.

2.1 Vessel design

Figure 2 shows the schematic vessel design. A typical vessel was designed based on industrial requirement. It is based on a typical nuclear application design. The vessel is designed to withstand high temperature fluids. The vessel design condition temperature is 700°C centigrade. The vessel design pressure condition is 1 MPa. The material of the vessel is stainless steel grade 304L (SS304L). The allowable stress as per ASME is 120Mpa. The volume of the liquid is approximately designed for 1509 liters. The inner diameter of the vessel is 1000mm or 1 meter and the liquid level is 2000mm or 2 meter high. The thermal barrier required number of appropriate thermal barrier is calculated and added accordingly. Figure: 1 shows the loads acting on the base plate. The vessel thickness is calculated by multiplying the pressure condition of the vessel with diameter of the vessel and dividing the result with the twice the allowable stress off the given material [3]. The value was calculated to be 4mm or 0.004mm. Applying factor of safety of 2 and corrosion allowance of 0.002m the value is taken as 10mm or 0.01m. The base plate thickness is calculated using the formula.
Applying the formula thickness is calculated as 39.5mm. Accounting the corrosion allowance and factor of safety the value is taken as 50mm. The flange thickness is calculated according to method given in ASME code, Section 8, Division 1, and the value is calculated.

3. Finite element analysis

The CAD design is modeled based on the design that was made above using various calculations. This design was then subjected to finite element analysis. The finite element analysis was done using ANSYS software. The finite element analysis was done only for the baffle plate’s portion. The analysis was done based on the axis symmetric analysis. 4 cases were analyses in total.

3.1 Thermal barrier

Thermal barrier in the form of baffle plates is designed and optimized. The dimensions are calculated based on trial and error and CAD modeling and analysis. The number of plates and thickness of the plates is calculated based on optimization and cad modeling and finite element analysis. The value is calculated to be around 10mm. As the requirement of the baffle plates is to limit the temperature at the lid at below 100°C the number of plates is calculated accordingly. The initial calculation was obtained using hand calculation and the obtained result was verified using a custom-made computer program. The verified are modeled in CAD software and the model is analyzed using finite element method.

3.2 Design of thermal barrier

The design of thermal barrier is done in three steps. The dimensions are calculated based on trial and error and CAD modeling and analysis. The number of plates and thickness of the plates is calculated based on optimization and cad modeling and finite element analysis. The value is calculated to be around 10mm. As the requirement of the baffle plates is to limit the temperature at the lid at below 100°C the number of plates is calculated accordingly. There is also a central pipe provided for experiments, testing and instrumentation. The initial calculation was obtained using hand calculation. The material of the baffle plate is stainless steel grade 304L (SS304L). Substituting the values in the formula the number of baffle plates required is calculated as
Table 1 Calculation of number of baffle plates

| Number of Baffle plates, n | Temperature of top flange in °C |
|---------------------------|----------------------------------|
| 0                         | 399.25                           |
| 1                         | 331.49                           |
| 2                         | 289.00                           |
| 3                         | 260.59                           |
| 4                         | 238.54                           |
| 5                         | 221.11                           |
| 6                         | 206.85                           |
| 7                         | 194.91                           |
| 8                         | 184.70                           |
| 9                         | 175.87                           |
| 10                        | 168.12                           |
| 11                        | 161.24                           |
| 12                        | 155.10                           |
| 13                        | 149.57                           |
| 14                        | 144.54                           |
| 15                        | 139.97                           |
| 16                        | 135.78                           |
| 17                        | 131.93                           |
| 18                        | 128.36                           |
| 19                        | 125.06                           |
| 20                        | 121.49                           |
| 21                        | 119.27                           |

As the temperature of the is aimed to be less than 100°C the number of baffle plates required is calculated by using the formula obtained from the literature [10]. Table: 1 shows the number of baffle plates with respect to their temperature at the top of the flange. The required temperature is considered to be below 120°C or 100°C according to different designs the required number of baffle plates required here calculated as 21. The hand calculation is plainly based on radiation mode of heat transfer since the multi-mode heat transfer of the design is very complex to calculate accurately based on hand calculations. These values are only obtained using finite element software. The above result is verified using a customized computer program. The results are further verified using the computer program.
4. Result and Discussions

4.1 Case 1:
For the first case a single baffle plate is considered for analysis. On the whole 3 plates were modeled. In this case the bottom plate was considered as the high temperature fluid at 550°C. The middle plate was the baffle plate. The thickness of the plate was given as 10mm or 0.01m. The top plate represents the lid. The radiation boundary condition was given on the top face of the bottom plate, both the faces of the baffle plate and the bottom face of the lid. Top surface of the lid was given as ambient temperature. The ambient temperature was given as 37°C. The side walls are considered in this case. The Figure No.3 shows the result of the analysis of Single baffle plate. The obtained value was 328°C

4.2 Case 2:
The second case considered 3 baffle plates for analysis. In this analysis 5 plates are modeled. The 3 plates in the middle were the baffle plates. The radiation boundary condition was given on the top face of the bottom plate, both the faces of the baffle plates and the bottom face of
the lid. Top surface of the lid was given as ambient temperature. The ambient temperature was given as 37°C. The side walls are not considered in this case. The Figure No.4 shows the Design and analysis of three baffle plates. The obtained temperature value was 261°C.

Figure 4 Finite Element analyses with three baffle plates

4.3 Case 3:
The third case considered 21 baffle plates for analysis. In this analysis 23 plates are modelled. The 21 plates in the middle were the baffle plates. The radiation boundary condition was given on the top face of the bottom plate, both the faces of the baffle plates and the bottom face of the lid. The side walls are not considered in this case. The Figure No. 5 shows the result of the analysis of 21 baffle plates without side walls. The obtained temperature value was 84.854°C

4.4 Case 4:
The fourth case considers 21 baffle plates for analysis. In this analysis 21 plates are modeled. The 3 plates in the middle were the baffle plates. The radiation boundary condition was given on the top face of the bottom plate, both the faces of the baffle plates and the bottom face of the lid. The side walls are considered in this case. This case also considered multi-mode heat transfer. Convection mode of heat transfer was given on the outer surface of the lid and the outer walls. Conduction mode of heat transfer is considered through axially in the outer wall and the experiment wall and across the baffle plates. The Figure No.6 shows the result of the analysis of 21 baffle plates with side walls. The obtained temperature value at the lid was 73.3°C

Figure 5 Finite Element analyses with 21 baffle plates without side walls
In the first case the theoretical estimation value was observed to be 331°C. The finite element analysis value obtained is 328°C, which is very close to the theoretically obtained value. The difference in the two values arises due to conduction in the baffle plate and the lid. The heat reaching the bottom surface of the baffle plates conducts to the top and then radiate to the lid bottom. This heat conducted to the top of the lid and the heat radiates to the surrounding. This loss of heat is not accounted in the theoretical calculation which gives the value of radiating heat only. The obtained value can be subjected to numerical error. In the second case the theoretical estimation value was observed to be 260.59°C. The finite element analysis value obtained is 261°C, which is very close to the theoretically obtained value. The obtained value is very similar to the estimated value. In the third case the theoretical estimation value was observed to be 119.27°C. The finite element analysis value obtained is 84.85°C. The difference in the two values arises due to conduction in the baffle plate and the lid. The heat reaching the bottom surface of the baffle plates conducts to the top and then radiate to the lid bottom. This heat conducted to the top of the lid and the heat radiates to the surrounding. This loss of heat is not accounted in the theoretical calculation which gives the value of radiating heat only. The obtained value can be subjected to numerical error. In the fourth case the theoretical estimation value was observed to be 119.27°C. The finite element analysis value obtained is 73.3°C. The obtained value is more realistic and accurate because of the induction of the multi-mode heat transfer and the addition of the surface walls which internally radiate the heat and side conduction of the heat through the wall reduces the temperature of the lid. This heat loss is not accounted for in the theoretical calculation which only provides for the radioactive heat transfer. This case also accounts for the convective mode heat transfer which accounts for additional loss of heat transfer. The convective loss of heat happens through the outer surface of the walls and the lid of the vessel.

5. Conclusion

The vessel for high temperature fluid storage and testing is successfully designed. The designed vessel is modeled. Baffle plates were used as thermal barriers in the vessel. The number of baffle plates was calculated theoretically. A computer program was custom made obtaining the number of plates for any given condition of fluid temperature and lid temperature. Since theoretical calculation only considers radiation heat transfer and other modes of heat transfer was not considered, the results are conservative. Finite element analysis was performed to verify the results of hand calculation and include other modes of heat transfer. The first 3 cases match very closely with hand calculation. In the 4th case the
temperatures obtained were more realistic than the conservative answer and the lid temperature is less than the value obtained using manual calculation.

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