Thermo-Fluid-Solid Coupling Analysis in the Steam Generator of a High Temperature Gas Cooled Reactor

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Abstract. This paper is about the high temperature gas cooled reactor (HTGR-10) of China which is an experimental reactor. The thermo-fluid-solid coupling analysis for the steam generator of HTGR is performed in which the steam generator is modelled and then tested for some boundary conditions. The analysis is of key importance as Steam generator is very crucial component of a power plant system that ensures the safety and efficiency of a plant. To predict the thermal distribution in the tubes of a steam generator the coupled heat transfer between the primary and secondary sides must be considered. ANSYS Fluent is used for analysis that employs finite element method to achieve the task. The temperature distribution within the steam generator is analysed. The resulting temperature profile, pressure profile and the velocity profile for the coolant and feedwater is determined. In static structural analysis equivalent stress, equivalent elastic strain and the total deformation produced in the tube under such conditions is calculated. We see that the temperature of feedwater increases continuously as it moves upward in the tube while the coolant (He gas) temperature decreases as it goes down through the shell. The pressure of a coolant decreases as it flows downwards in the shell and consequently its velocity increases in the said direction. The velocity of a feedwater increases gradually as it rises up in the tube due to gradual decrease in its pressure. The equivalent stress, equivalent elastic strain and the total deformation produced in a tube are highly dependent on system temperature, tube material and the geometric configuration of tube.

1. Introduction

High temperature gas-cooled reactors can serve as possible energy generation source as well as the process heat source at different temperatures. Due to simultaneous production of electricity with the recovery and utilization of heat the plant can acts as a combined heat and power plant. Some of the unique features of this type of plant include its inherent safety, passive heat removal system for residual heat, graphite reactor core, free from corrosion problems, eliminates risk of fuel coolant interaction due to coated fuel particles, non-radioactive coolant, higher conversion efficiency and a lower power density [1, 2].

No doubt while talking about nuclear reactors one of the most important concern that quickly comes in mind is the safety of a plant as there have been some of the serious accidents in the past history that have left very tragic after-effects. However, HTGR is considered as an excellent

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candidate in terms of safety features [2, 3]. Therefore, HTGR can be considered as a better future option for energy production.

HTGR-10, a generation IV reactor concept and the first step of China towards modular HTGR development, is an experimental pebble bed reactor of 10 MW located at Tsinghua University in Beijing. For every reactor steam generator is a crucial component. The steam generator design of HTGR-10 consists of a helically coiled tubes and is once through steam generator. Helically coiled tubes are far more efficient than the straight ones because of their higher heat transfer rates as secondary flow is forced by centrifugal force. Additionally this type of heat exchanger has compact size and a large surface area per unit volume [4].

The critical step is to understand the temperature non-uniformity of a steam generator as the thermal non-uniformity will affect the other parameters. Large thermal non-uniformity and the resulting high temperature will damage the structure. Therefore, thermo-fluid-solid coupling analysis is of critical importance for the operation and safety of a plant.

2. Modelling and simulation of steam generator of HTGR-10

The steam generator of HTGR-10 is once through, vertically aligned and counter flow shell and tube type heat exchanger. The primary fluid is helium gas which is used as a coolant and the secondary fluid is water. The material of helical tubes is 2.25Cr1Mo steel owing to withstand at a high temperature of about 750 °C. The different heat capacity of superheated and liquid water regions may generate ruptures and creeps in different layers of tube. That's why the studies for the temperature non uniformity within the steam generator is of significant importance which provides the basis for the design and the construction of this critical component of a plant. Helium gas being coolant will transfer its heat, almost totally by convection, through helical tubes to the feedwater and returns back to the core. The primary system and the flow path of helium is depicted in Figure 1 (a).

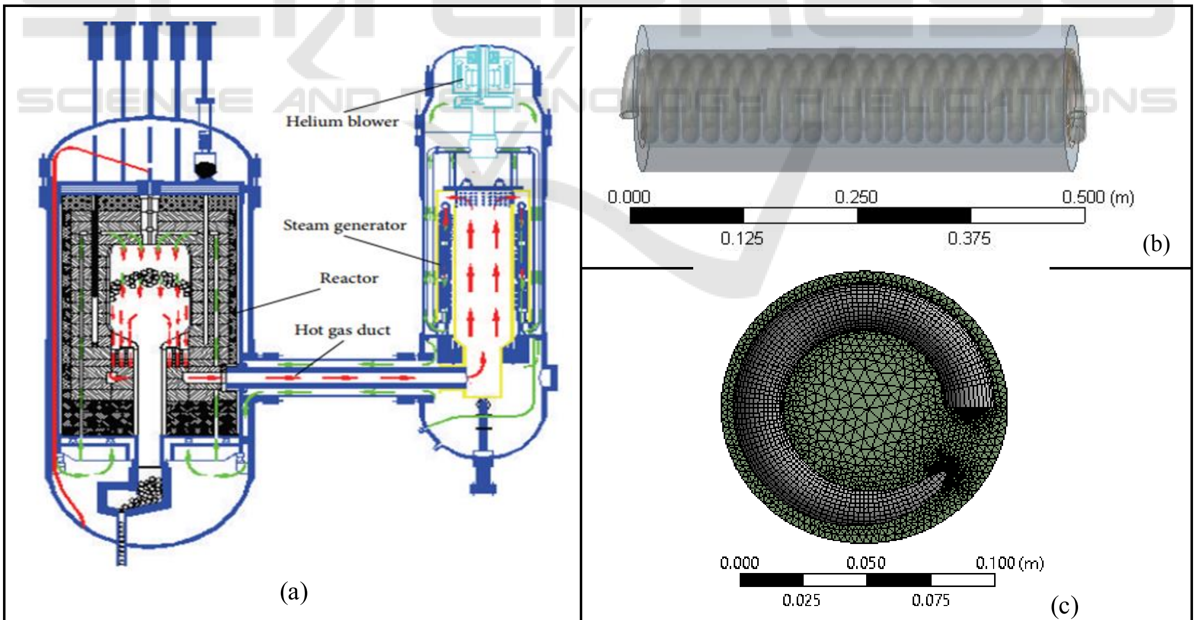


Figure 1. (a) Primary system of HTGR-10, (b) geometric model of the steam generator, and (c) the front view of a steam generator after meshing.

On the basis of steam generation there are three sections of steam generator i-e pre-boiling region, boiling region and the superheated region which constitutes the complicated geometry of the steam generator and to model the entire geometry demands enough memory and hardware capacity. So, just the pre-boiling region is modelled and analyzed. The geometric model of the steam generator is shown horizontally in Figure 1 (b) that consists of tube and shell which is developed using SolidWorks software. The height of the steam generator for the pre-boiling region is about 0.5 meter, the tube diameter is 18 mm and the inner diameter of the casing tube (shell) is 139 mm. The helical ascent angle is 3.66^{o} which results in a total of 22 number of turns for a pre-boiling region. Some of the structural parameters of the steam generator are shown in Table 1.

The model is then imported to Ansys for the required analysis. Here the tube is filled with water and the space between the tube and the shell is filled with helium gas. Figure 1 (c) shows the top view of the steam generator that includes the tube and the gas in meshed form while the shell body is suppressed. The mesh result generates about 2.9 million elements on which simulation is performed. One mesh interface in our model is the tube inner surface and the feedwater interface while the other one is the tube outer surface and the helium gas both of which are thermally coupled. Fluent module of Ansys is used to perform thermo-fluid-solid coupling analysis that employs the pressure velocity coupling method via SIMPLE algorithm for fluid flow and finite element method for both the steady-state thermal and static structural analysis. The finite element method is a numerical technique for finding approximate solutions for both partial differential equations and integral equations.

Some of the process parameters for the steam generator of HTGR-10 are shown in Table 2. Boundary conditions for both the primary and secondary sides are chosen at 50% of rated load as shown in Table 2. As mentioned previously our model just covers the pre-boiling region of the steam generator and hence the inlet temperature of the helium gas is chosen to be 350 ℃ while the primary pressure is 3 MPa. The water inlet temperature is 104 ℃ while its pressure is chosen to be 4.59 MPa. The inlet velocities of both the coolant and feedwater are calculated using mass flow rates as shown in Table 2.

Table 1. Structural parameters of Steam Generator.

Parameters	Unit	Value
Helical ascent angle	Degree	3.66
Heater outer diameter	mm	18
Heater helical diameter	mm	112
Vertical tube pitch	mm	22.5
Central tube outer diameter	mm	83
Casing tube inner diameter	mm	139
Heater length	m	31.82
Heater total height	m	3.96

Table 2. Process parameters of Steam Generator.

Parameters	Value at 30% of rated load	Value at 50% of rated load
Primary pressure (MPa)	3.0	3.0
Helium inlet temperature (°C)	643	661
Helium outlet temperature (°C)	194	212
Helium flow rate (kg/h)	125	208
Feedwater pressure (MPa)	4.21	4.59
Feedwater temperature (°C)	104	104
Steam exit pressure (MPa)	4.0	4.0
Steam exit temperature (°C)	440	440
Steam flow rate (kg/h)	102	102

3. Results and discussion

In heat exchanger the fluids exchange energy without being mixed by means of solid wall. Thus, this solid wall plays a key role in the performance of a steam generator. Heat is exchanged between the fluids mesh by mesh and a good mesh leads to a better solid fluid interaction. Results include the temperature distribution within the shell and tube of a steam generator, the pressure and the velocity profile of both helium gas and feedwater, all of which are highly dependent on one another. While in static structural analysis, stress, strain, and the resulting total deformation produced in a tube are calculated and analyzed. The temperature profile of feedwater and coolant is shown in Figure 2.

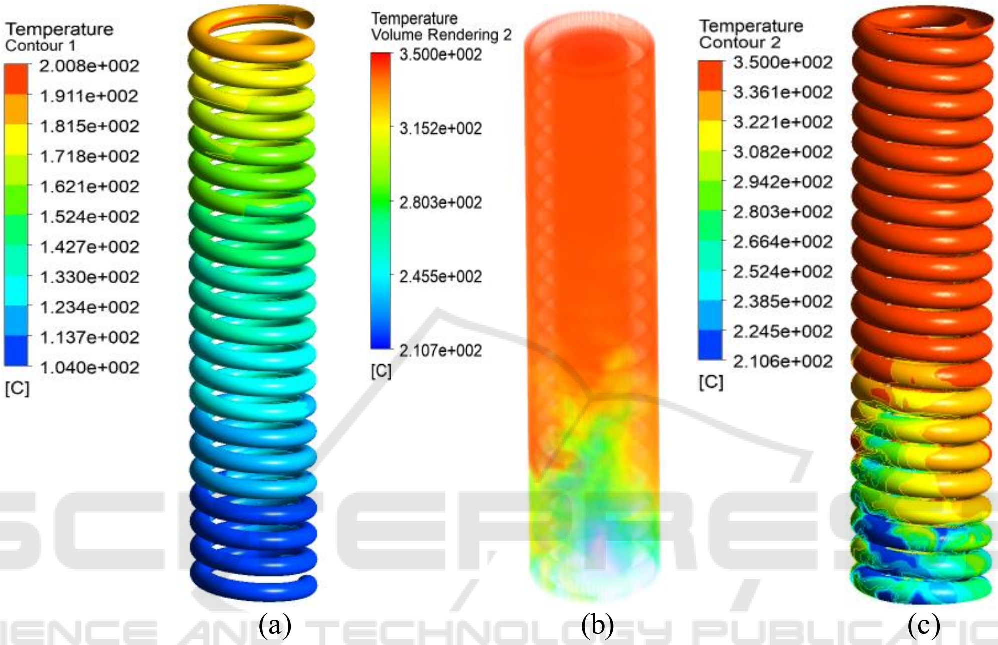


Figure 2. Temperature distribution of feedwater **(a)** within helical tube, **(b)** of helium gas in shell side of steam generator**,** and **(c)** of helium gas that is in contact with the helical tube.

From the results we see that the heat transfer between the downward flowing helium gas and the upward flowing feedwater results in a greater temperature difference at the inlet and outlet of feedwater as its temperature gets elevated from 104°C to about 191°C which is enough for a pre-boiling region as shown in Figure 2(a) and on comparing the above case (a) and case (c) we see that the temperature of external tube wall is higher than that of internal tube wall. The inlet temperature of a helium gas which is 350°C, as our model includes just the pre-boiling region and not the whole steam generator, doesn't change much until it comes down where after transferring its heat to feedwater becomes 280°C and finally 210°C at the outlet as shown in Figure 2(c) which is in accordance to Table 2. In the whole phenomena heat transfer is accomplished by forced convection. The results are in accordance with those of Ref. [5-7].

Our next results (pressure and velocity) are highly dependent on the previous temperature results. The pressure and the velocity of both the coolant and feedwater plays an important role in the process of heat transfer especially the velocity of coolant which determines the rate of heat transfer. The velocity of feedwater is lower compared to the helium gas as the feedwater takes some time to absorb heat from coolant. The pressure profile of a coolant which is in contact with the tube and the velocity profile for both the coolant and feedwater is shown in Figure 3.

The pressure of a coolant decreases as it flows downwards in the shell as shown in Figure 3(a) and consequently its velocity increases in the same direction which is in accordance with the

Bernoulli's principle. From Figure 3 (b) we see that the velocity of a helium gas flowing vertically downward in a steam generator shows that near the wall of a shell the velocity is almost same and lower compared to the inner region where its velocity is higher. This is expected because pressure of a helium gas decreases as it goes down. On the other hand the velocity of a feedwater shows a slight variation owing to have its slow inlet speed which is 0.18 m/s and also, this is just the pre-boiling region where the water remains in its liquid state. Here the water close to the wall of a tube has lower velocity compared to the inner fluid in tube as shown in Figure 3 (c). This satisfies the no-slip boundary condition somehow as the solid and the fluid have also a minor mutual attraction. However, the trend for the velocity of a feedwater is that, it increases slightly as the feedwater starts flowing up in the tube following by a slight decrease in its pressure in the same direction which is not shown here.

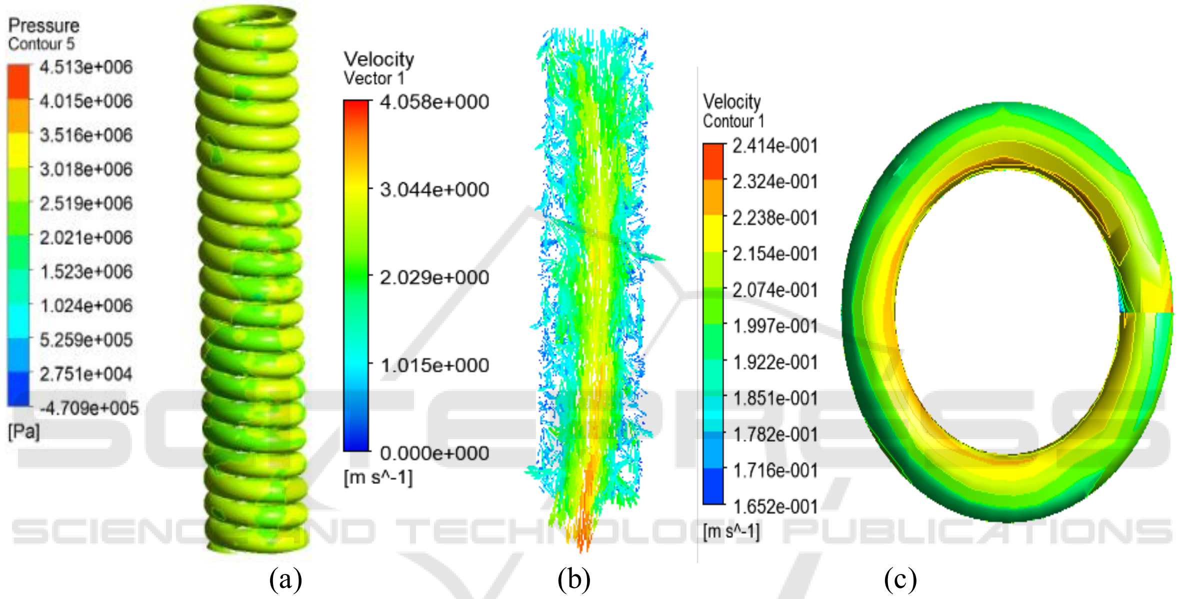
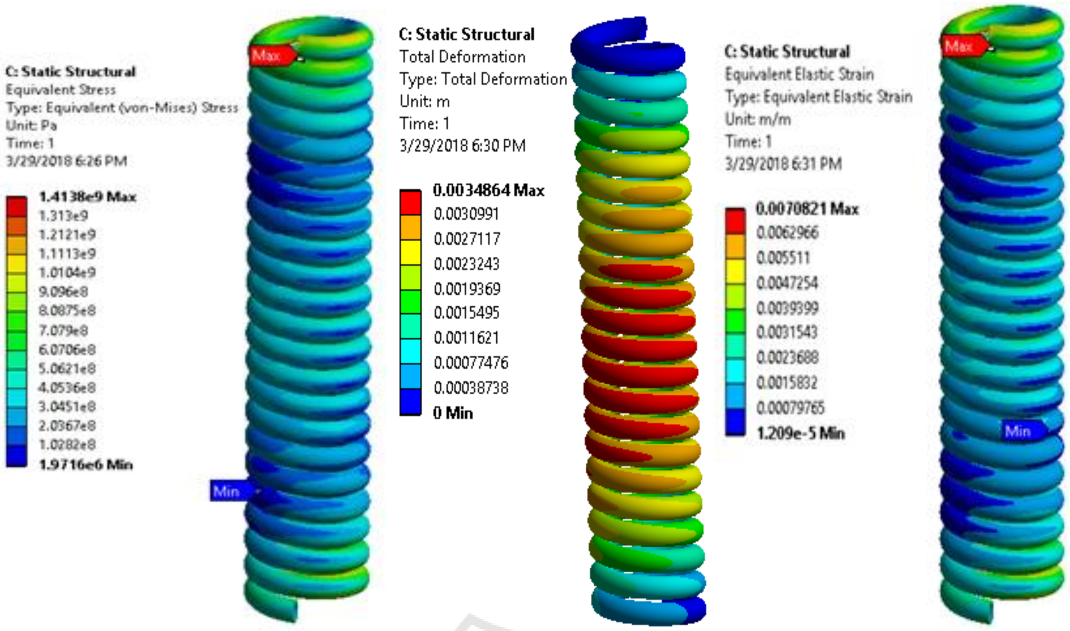


Figure 3. Pressure distribution of a helium gas which is in contact with the tube (a), Velocity distribution of helium gas within shell side of steam generator (b), and velocity of a feedwater in a ring of a helical tube (c).

The above results have considerable impact on static structural analysis parameters. For static structural analysis the equivalent stress, equivalent elastic strain, and the total deformation produced in tube is calculated. This analysis will lead to the improved geometry and material selection for steam generator and consequently increasing the life time of a heat exchanger. The results of this analysis are shown in Figure 4.

The contour plot for the equivalent stress shows that the upper and lower portion of the tube, nearby the inlet and outlet, the tube experiences the higher stresses. This is shown in Figure 4 (a) along with the maximum and minimum points. The reason for higher stress at these portions of the tube is that they are fixed under such condition. For total deformation we see that it is highest at the central section of tube as cleared from the colored contours while there is less deformation at the inlet and the outlet as shown in Figure 4 (b). The results for the equivalent elastic strain depicts that the tube is experiencing more strain at its top and lower section compared to middle one as shown in Figure 4 (c) along with maximum and minimum points.



(a) (b) (c)

Figure 4. For helical tube: The equivalent stress (a), total deformation (b), and the equivalent elastic strain (c).

4. Conclusions

In the energy sector high temperature gas cooled reactors can serve as one of the best option for energy production owing to have some unique features. In this work the performance of a steam generator of HTGR-10 is tested by thermo-fluid-solid coupling analysis using Ansys Fluent. It is concluded that solid fluid interaction studies plays a vital role in predicting the behaviour and performance of any type of steam generator. The analysis provides a better way to analyze the structural and flow properties within the steam generator. Structural analysis is important to determine displacements, stresses and strains. This helps to locate the regions which are under higher or lower stresses and obviously will be helpful in determining the suitable geometry and material selection for a steam generator. This analysis can be proved to be very helpful for all steam generators irrespective of the model and the type of reactor. It can also be very helpful to test a variety of materials for the tube of a steam generator under different conditions. Furthermore, more exact and complete results can be obtained by modelling the whole steam generator.

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