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# Investigation of Nozzle Shape, Number of Nozzles and Nozzle Inclination Angle and Its Optimization

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***Abstract***
A pressure vessel is a container that holds gases or liquids at a **pressure** significantly different from the ambient pressure. The nozzles were essential for inlet and outlet of liquid. A pressure vessel analysis is critical for its proper operation. In the present work, aspects have been considered regarding position and orientation of nozzles according to stress and deformation obtained. The whole objective is to use FEA simulation, and determine the best design solution. Two different type of nozzles viz. radial and tangential were incorporated. Different number of nozzles and different inclination angle of nozzle were also incorporated to study the effect of nozzle geometry. However, design of pressure vessels is based on solvent extraction process. It is observed that radial nozzle induced higher stress values as compared to tangential nozzle. However, as inclination angle increases, maximum stress values are increasing for pressure vessel with tangential nozzle as compared to radial nozzle.

***Keywords:*** *Finite Element Analysis, Nozzles, Pressure Vessels, Radial nozzle, Tangential nozzle, Nozzle inclination angle*

## 1. Introduction

A pressure vessel is a canister designed for storage of fluids at an elevated pressure. These are used in a variety of sectors, including steel factories, and have a wide range of uses. In addition to the primary equipment, such as the blast furnace, pressure vessels require nozzles or apertures to meet particular standards, such as inlet or outlet connections. Pressure vessels have applications in various fields such as gasoline storage, receiver, and reactor in nuclear power plant. Pressure vessel designer need to take into consideration various factors for designing pressure vessel such as dimensions, operating conditions, theories of failure, methods of fabrication and construction methods. It is expected that incorporating a nozzle on the vessel wall will remove some material from the vessel, resulting in non-uniform stress distribution. Because nozzles generate a geometric discontinuity in the vessel wall, the distribution of stress in the junction area and the rest will differ. Around the entrance, a stress concentration is formed. As a result of these enormous stresses, the connection may break. As a result, a pressure vessel analysis is critical for its proper operation. For inflow and outflow of fluid in pressure vessels, nozzles are required. If nozzles are present on the dish end's peak, they do not disrupt the vessel's symmetry. However, this process necessitates nozzles be positioned on the pressure vessel's edge; which disrupt the vessel's symmetry. The eccentricity created by the nozzles can sometimes result in the formation of a pair, which can result in a structural imbalance. The nozzle will have a complicated interaction in the case of a tangential nozzle. Though tangential nozzles were originally patented for performing oil quenching of furnaces in ethylene manufacture, they have important advantage. The flow from tangential nozzle is such that it keeps the walls of the pressure vessel wetted.

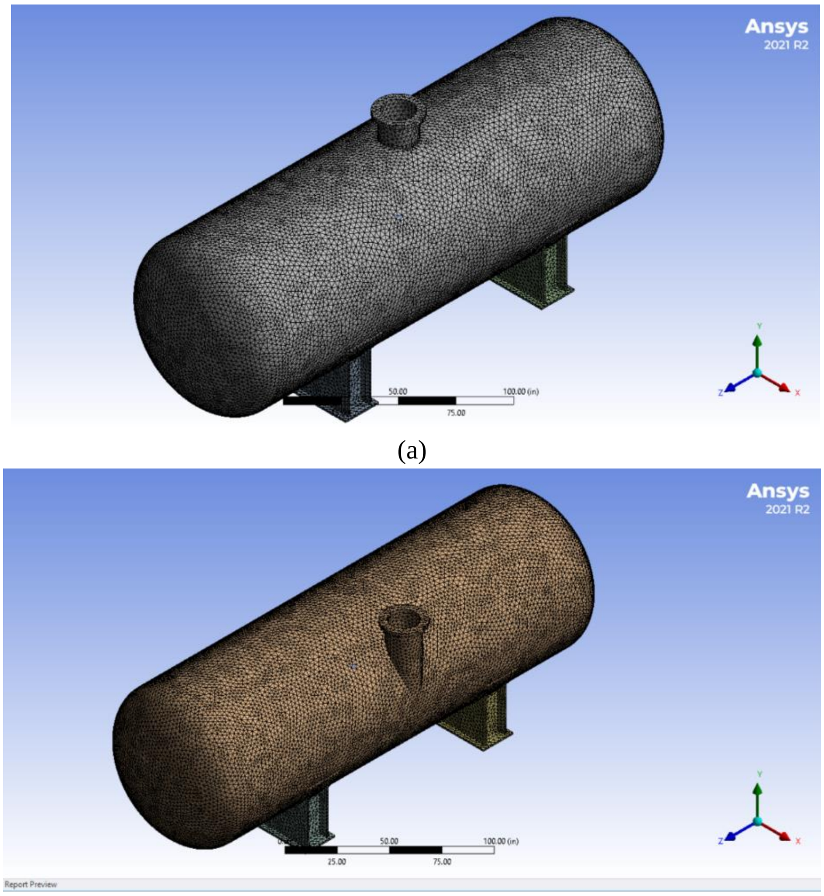
Various researchers have worked on analysis of pressure vessel using number of techniques. Porter et al. [1] presented a practical approach of utilization of a finite element software for the analysis of pressure vessel component. Further, they discussed element type selection criteria, features; and some element formulations. Furthermore, they discussed practical evaluation tolerances. Diamantoudis and Kermanidis [2] used several finite element techniques to compare cylinder-nozzle junction. When using the design- by-formula technique to create a high-strength steel pressure vessel, they discovered a disadvantage in terms of limit load capability. Mackerle [3] given a bibliographic review of FEMs employed for analysis of components and piping of the pressure vessel. They classified papers into different categories of analysis.

Under external loads, Skopinsky and Smetankin [4] proposed a structural modeling and stress analysis of nozzle connections. They also ran a parametric study to see how geometric parameters affected the maximum effective stress at ellipsoid-cylinder junctions. Wu et al. [5] calculated the plastic limit moment for the cylindrical vessel with the nozzle under in-plane moment loading experimentally and computationally. They also studied the plastic limit moment for cylindrical vessels in the presence of an in-plane nozzle moment parametrically. Jiang [6] analyzed reliability of pressure vessel with nozzle using ANSYS software. They concluded that results obtained based on reliability formula are more authentic for reflecting real reliability. Yin et al. [7] investigated stress analysis and fracture mechanics works performed to evaluate nozzles located in reactor pressure vessel (RPV). Praneeth and Rao [8] investigated pressure vessel and piping design using finite element analysis (FEA). Further, they compared theoretical and numerical values of stresses for both solid wall and multilayer pressure vessel. Using ANSYS software, Lv and Wang [9] investigated the stress state of the nozzle zone at the pressure vessel's channel, solid modeling for the channel, and straight pipe. They discovered that the symmetrical area of stress concentration is at the channel-pipe junction, and the greatest stress is at the inside of the nozzle zone of the channel, which is less than the material's yield stress. Using PVElite software, Vyas et al. [10] created a vertical pressure vessel. They came to the conclusion that high stresses at junctions are produced by discontinuity shear stresses and moments that exist to keep the junction compatible. Lee et al. [11] performed evaluation of structural integrity of reactor pressure vessel (RPV) bottom head without penetrating nozzles. They found that thermal load was most significant factor in failure of RPV. Further, they found that equivalent plastic strain results are lower than critical stain failure criteria. Al-Gahtani et al. [12] conducted a numerical evaluation of a local pressure in a repaired spherical pressure vessel to check structural integrity of the nozzle-to-shell connection. They also presented the results of a research that looked at the effect of cap size on stresses around the nozzle-shell junction. They came to the conclusion that the minimum needed cap size is related to the nozzle size. Ahmed et al. [13] used a commercial algorithm to construct and analyze a pressure vessel and compare stresses between different shapes. They also improved the pressure vessel's structural design to meet thermal and structural demands. The complete thermos-mechanical stress study for reactor pressure vessel (RPV) was described by Chaudhry et al. [14]. They discovered that the clad-vessel interface is the most stressed point in the RPV wall, and the governing transient is an emergency shutdown state. They also looked at the structural integrity of the re-circulation nozzle to rule out the likelihood of fracture start or spread. Gupta et al. [15] utilized PVElite software to calculate pressure vessel design parameters such as shell thickness and nozzle data. ANSYS software is also used to quantitatively study parametric changes. Lu et al. [16] used a multi-linear kinematic hardening model to simulate the plastic behavior of reactor pressure vessel nozzle belt. Further, they obtained stress distribution, extension of plastic region and plastic limit load. Kozák et al. [17] investigated cavitating flow in the converging-diverging nozzle. Further, they presented an unsteady cavitating flow computation fluid dynamics (CFD) simulation. Wadkar et al. [18] studied current research in evaluation of stress concentration factor in pressure vessels. They also designed and analyzed various features of the pressure vessels using theoretically and numerically (using ANSYS software). They found that high localized and secondary bending stresses are present in the pressure vessels. Many conservatisms connected with guidelines for designing pressure vessels based on elastic calculations were highlighted by Faidy [19]. For diverse failure types, they enhanced existing codified rules with alternatives to elastic assessment. BAlAc et al. [20] performed numerical investigation of equivalent 3D finite element model of pressure vessel with nozzle. They found that in the most critical areas next to one of the nozzles, crack-initiation takes place. Further damage growth was simulated using XFEM. They estimated critical crack length and number of pressure cycles to the final failure. Sun et al. [21] used the extended finite element technique (XFEM) to model ductile crack propagation and identified varied fracture widths for different base wall thicknesses. The crack propagation law and the form influence on the ultimate bearing capacity of the total structure were also investigated for crack tips of various shapes. Kushan et al. [22] used computer simulations to investigate the impact of a secondary nozzle located near a primary nozzle. They also looked at how the geometry of the vessel and nozzle openings, the size of the reinforcement, the center-to-center distance, the axial distance, and other factors impact maximum stress. Jin et al. [23] analyzed Weibull stress in the nozzle of pressure vessel. To prevent stress classification, Li et al. [24] suggested a design by analysis (DBA-L) technique. They discovered that the DBA-L technique accurately predicted appropriate allowed loads and that it may be used as a substitute for stress classification. Noraphaiphipaksa et al. [25] performed a simulation study of pressure vessel through hydrostatic test. They found that reason for failure of pressure vessel component was improper geometrical design and location of openings. Therefore, they designed and evaluated modified pressure vessel with obround openings, thicker sight port, and large reinforcement pads. Using ANSYS software, Karthikeyan et al. [26] investigated a basic unfired vertical cylindrical pressure vessel with torispherical head and Y-forged skirt support. They used a design by rule (DBR) technique to compare the performance of two kinds of steels with estimated outcomes. They also discovered that the DBR technique was quite cautious. Arunkumar et al. [27] designed and optimized a horizontal pressure vessel using an analysis software and suggested appropriate head shape, optimal location of inlet and outlet nozzle and location of supports. Bozkurt et al. [28] developed a finite element model for analyzing the limit load of a single- nozzle cylindrical pressure vessel under various combinations of internal pressure and external loading. Bandaru et al. [29] investigated the heat transfer efficacy of an upward multi-nozzle array of water sprays striking a heated plate surface in an experimental research. They discovered that employing a multi-nozzle array technology to cool the reactor's lower head's enormous surface area might be a viable option.

From the literature study, it is observed that even if worldwide researchers are involved in design and analyzing of a pressure vessel, still, improvement is required in realistic evaluation of stress and deformation status. Also, minimization of stress concentration is important aspect in the design of pressure vessel. There is limited literature available for comparing performance of radial and tangential (quench) nozzle. Therefore, in the present research work, aspects such as the position and orientation of these nozzles in relation to the stress and deformation obtained must be considered in the current study. Non-linearity in the form of material characteristics and contact non-linearity is taken into account in numerical analysis. The overall goal is to identify the optimum design solution using finite element analysis (FEA) simulation.

## 2. Methodology

Finite element analysis was performed using ANSYS analysis software. The ASME SEC. VIII Div. I code was used in the design of this vessel and its parts. The ASME B 16.5 Standard is the primary source for the pipe flange and flange fittings' dimensions. Using SOLLIDWORKS, pressure vessel models for various conditions are developed. The models were exported as solid STEP files and then imported into the ANSYS Workbench.



(a)

(b)

**Figure 1** Meshed model of pressure vessel with (a) radial nozzle and (b) tangential nozzle

Two types of nozzles viz. radial and tangential were used for the investigation. In addition to that effect of number of nozzles and angular distance between the nozzles also investigated. For both radial and tangential type nozzles, four different number of nozzles selected viz. 1, 2, 3 and 4. Also, with one number of nozzle, four different types of angular distance viz. 0°, 15°, 30° and 45° were used for both the cases radial as well as tangential. The meshed model for both type of nozzles viz. radial and tangential are shown in figure 1.

## 3. Results and Discussion

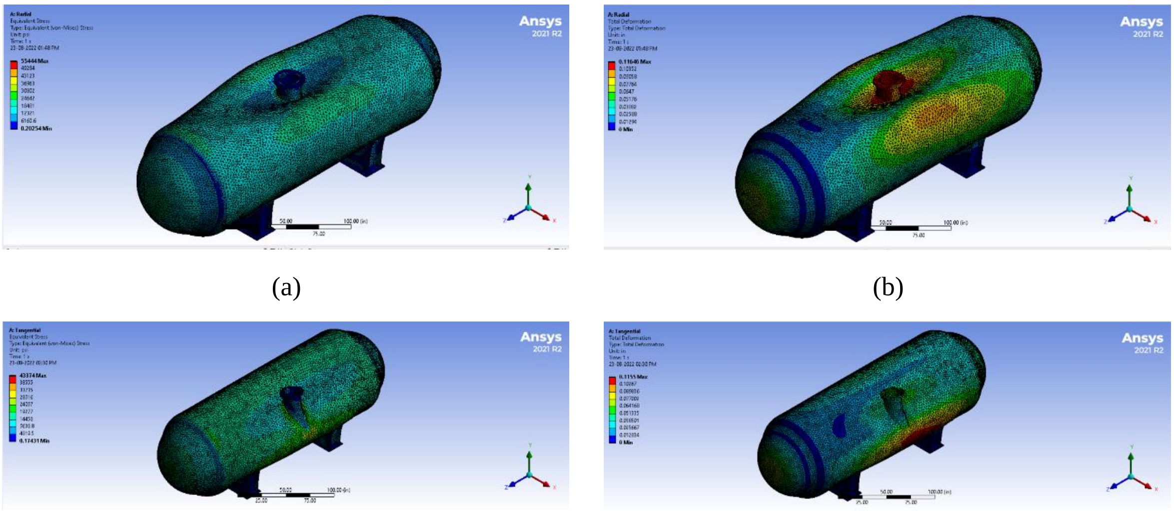
In the pressure vessel, maximum stress is influenced by different parameters such as the type of nozzle, number of nozzle and inclination angle of nozzle. The effect of these parameters on the maximum stress and deformation are elaborated in this section.

### *3.1 Effect of type of nozzle*

The two different nozzle used are radial and tangential. The dimensions of the nozzles are calculated using ASME standards. Table 1 shows the maximum stress and deformation values of pressure vessel with different types nozzle incorporated. Figure 2 shows the stress and deformation contours in both type of nozzles.

**Table 1** Stress and total deformation results with different types of nozzle

| Type of Nozzle | Maximum von-Mises stress (psi) | Maximum total deformation (Inch) |
|---|---|---|
| | Max. | Max. |
| Radial | 55444 | 0.11646 |
| Tangential | 43374 | 0.1155 |



(a) (b)

(c) (d)

**Figure 2** Stress and deformation in different nozzle shapes (a) Stress in radial nozzle (b) Total deformation in radial nozzle (c) Stress in tangential nozzle (d) Total deformation in tangential nozzle

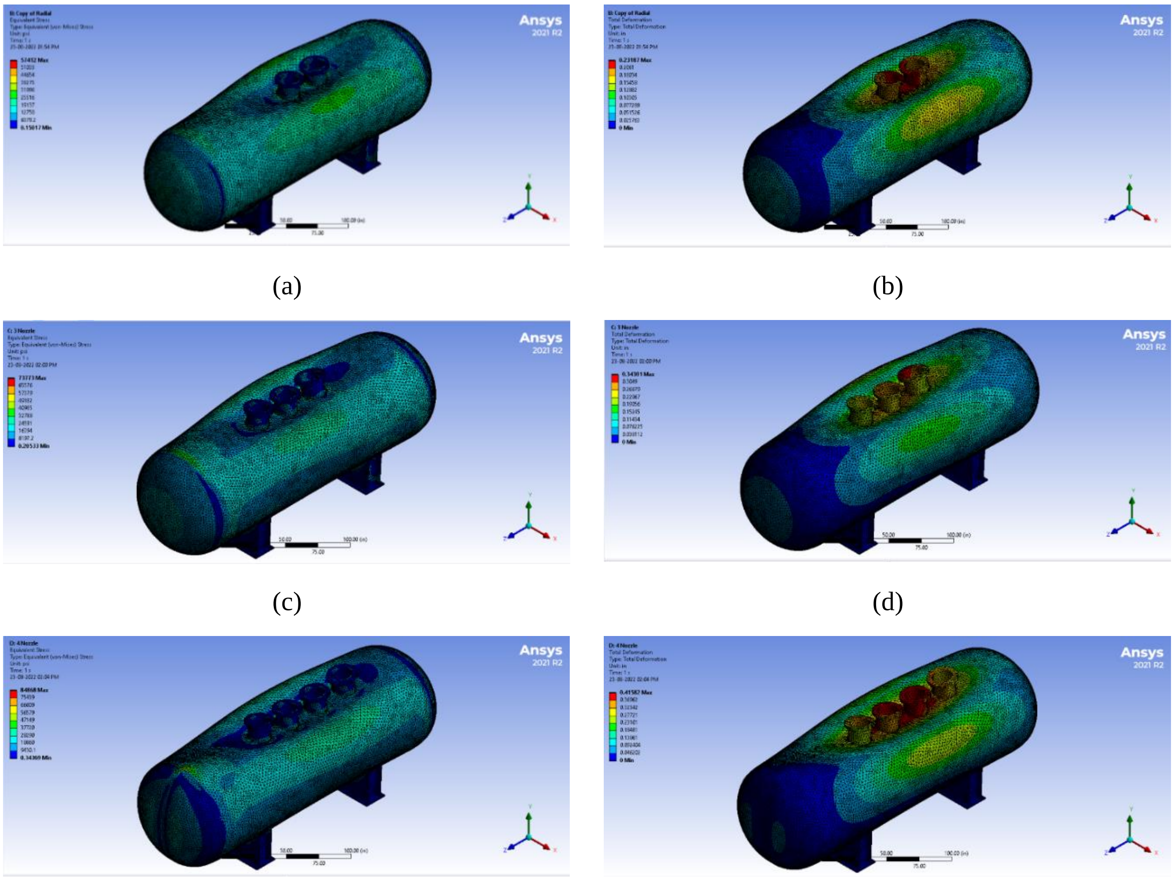
It is observed from table 1 that maximum stress induced as well as the total deformation is less for the vessel with tangential nozzle as compared to the radial nozzle. There is 21.77 % reduction in stress and 0.82 % reduction in deformation observed from the analysis. However, in this case as shown from the figure 1, only one nozzle with 0° inclination angle has been used. Therefore, detailed analysis has been carried out to compare the effect of both type of nozzle with more number of nozzles and different inclination angle.

### *3.2 Effect of number of nozzles*

In the present study, total four different arrangement of nozzles were incorporated viz. 1, 2, 3 and 4 nozzles. To study the detailed effect of different types of nozzles such as radial and tangential, all four types of nozzles were used in both types of nozzle combination. Therefore, total eight experiment run were possible. Table 2 show the maximum stress and maximum deformation results for all eight combinations. Figure 3 shows the stress and deformation for radial type of nozzle while figure 4 shows the same for tangential type of nozzle.

**Table 2** Maximum stress and total deformation results with different number of nozzles

| | Radial | | Tangential | |
|---|---|---|---|---|
| Number of Nozzles | Maximum von-Mises stress (psi) | Maximum total deformation (Inch) | Maximum von-Mises stress (psi) | Maximum total deformation (Inch) |
| 1 | 55444 | 0.11646 | 43374 | 0.1155 |
| 2 | 57412 | 0.23187 | 48309 | 0.17895 |
| 3 | 73773 | 0.34301 | 53772 | 0.21849 |
| 4 | 84868 | 0.41582 | 59951 | 0.27261 |

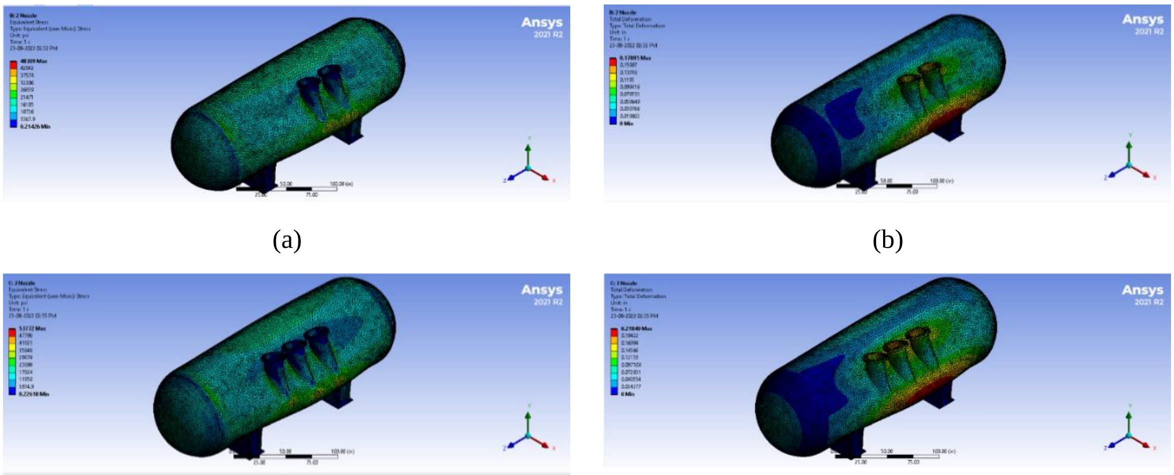


(a) (b)

(c) (d)

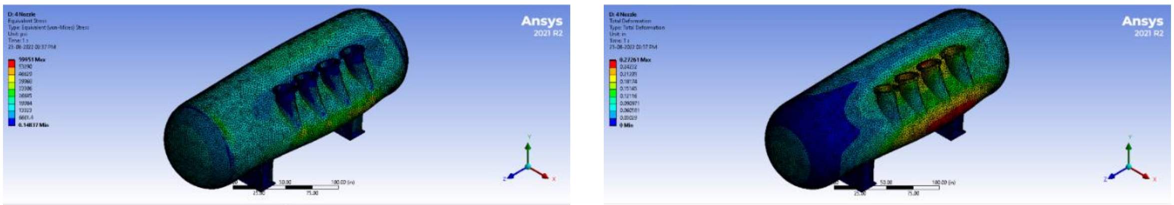
(e) (f)

**Figure 3** Stress and deformation in vessels with radial nozzles (a) Stress with two nozzle (b) Total deformation with two nozzle (c) Stress with three nozzle (d) Total deformation with three nozzle (e) Stress with four nozzle (f) Total deformation with four nozzle



(a) (b)

(c) (d)



(e) (f)

**Figure 4** Stress and deformation in vessels with tangential nozzles (a) Stress with two nozzle (b) Total deformation with two nozzle (c) Stress with three nozzle (d) Total deformation with three nozzle (e) Stress with four nozzle (f) Total deformation with four nozzle

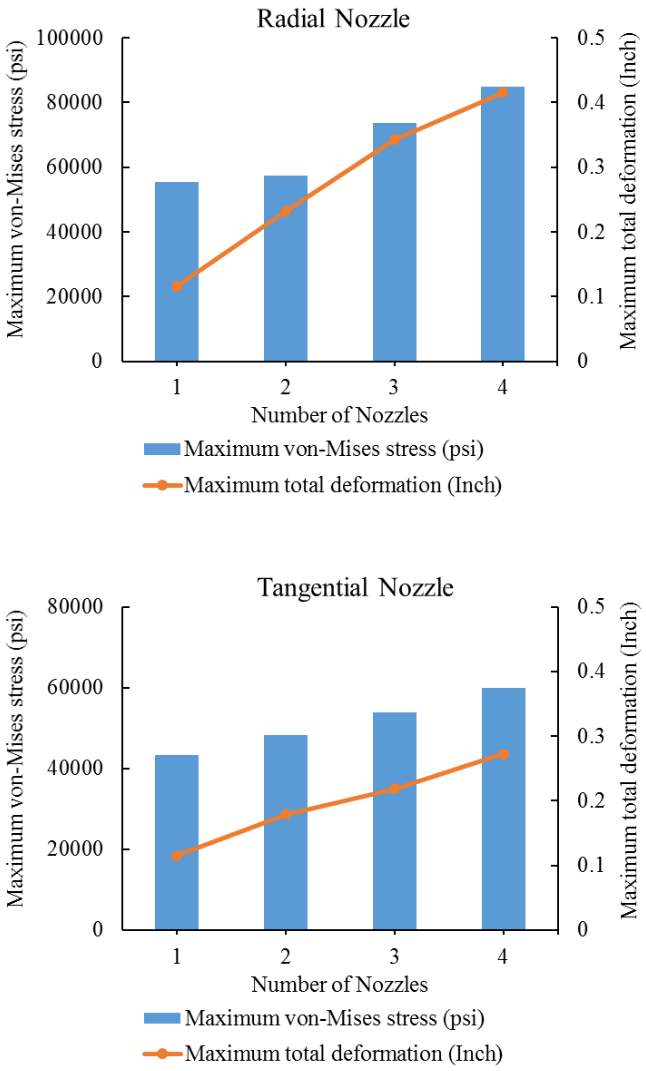


**Figure 5** Effect of number of nozzles on maximum stress and deformation values

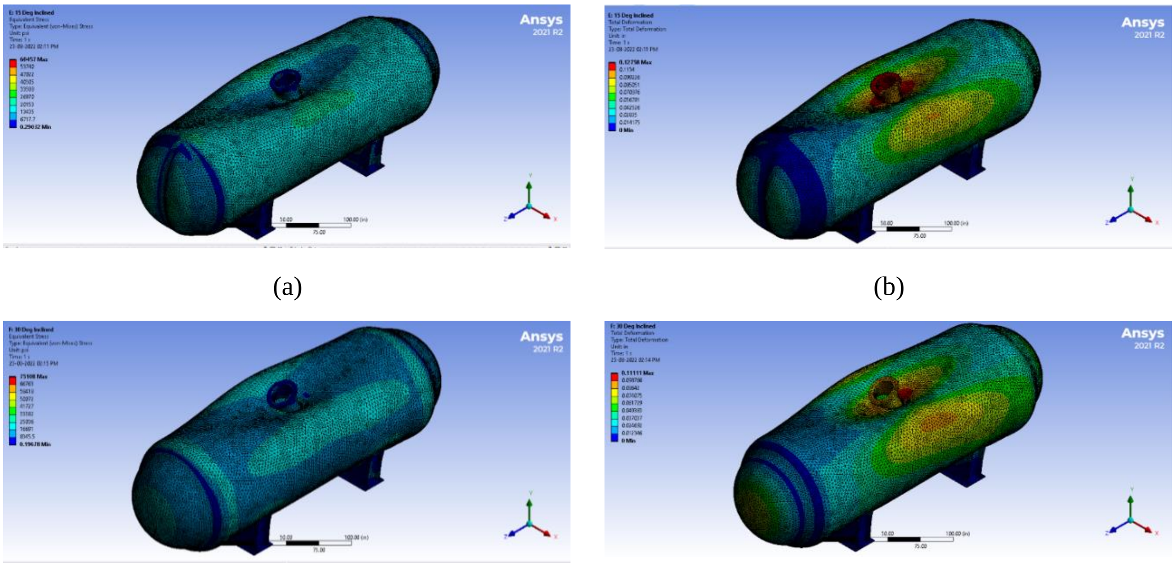
Figure 5 shows the graphical representation of effect number of nozzles on stress and deformation value for radial and tangential type of nozzle. From the both the graphs it is observed that with the increment of number of nozzles, the induced stress is increase in both the cases, radial as well as tangential type of nozzle. There is 53% increment observed in the case of radial nozzle when total four nozzles were incorporated as compared to only one nozzle. However, for the tangential nozzle, the total increment is 38.22%. This results shows that the effect of number of nozzles is greatly affects the vessel with tangential nozzles as compared to the vessel with radial nozzles. However, the overall results of stress and deformation both are higher for radial nozzle as compared to tangential nozzle for each case.

### *3.3 Effect of number of nozzles*

In the present study, total four different arrangement of inclination angle of nozzle were incorporated viz. 0°, 15°, 30°, 45°. To study the detailed effect of different types of nozzles such as radial and tangential, all four types of nozzles were used in both types of nozzle combination. Therefore, total eight experiment run were possible. Table 3 show the maximum stress and maximum deformation results for all eight combinations. Figure 6 shows the stress and deformation contours for radial type of nozzle while figure 7 shows the stress and deformation for tangential type of nozzle.

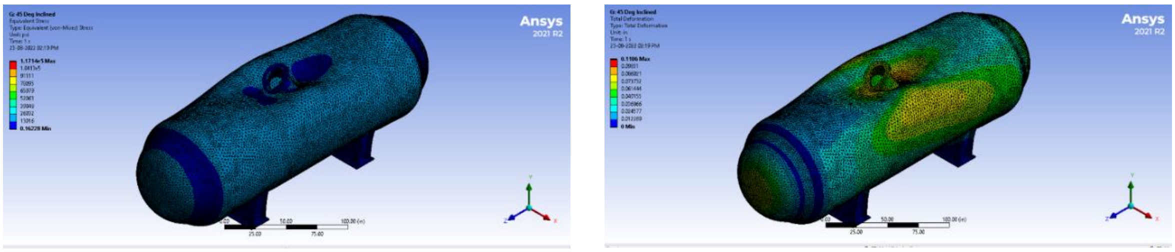
**Table 3** Maximum stress and total deformation results with different inclination angle of nozzle

| | Radial | | Tangential | |
|---|---|---|---|---|
| Inclination angle of Nozzles | Maximum von-Mises stress (psi) | Maximum total deformation (Inch) | Maximum von-Mises stress (psi) | Maximum total deformation (Inch) |
| 0° | 55444 | 0.11646 | 43374 | 0.1155 |
| 15° | 60457 | 0.12758 | 60220 | 0.12442 |
| 30° | 75108 | 0.11111 | 104570 | 0.15505 |
| 45° | 117140 | 0.1106 | 192010 | 0.21842 |



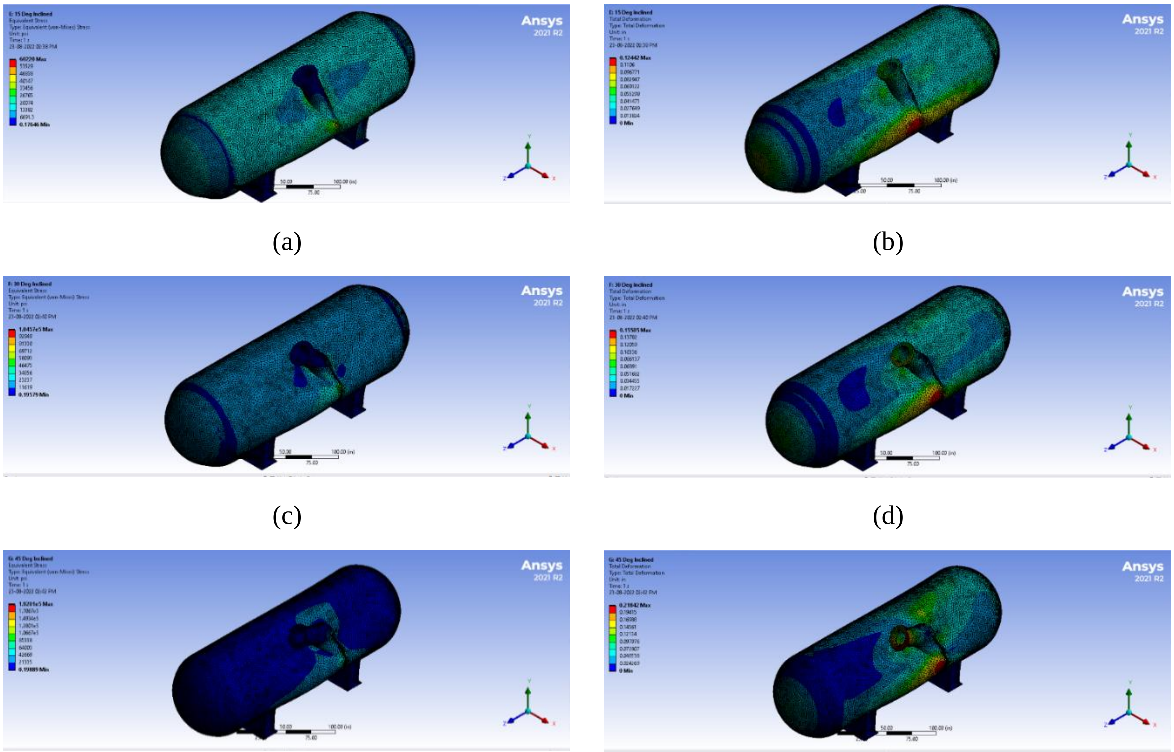
(a) (b)

(c) (d)



(e) (f)

**Figure 6** Stress and deformation in vessels with radial nozzles (a) Stress with 15° inclination angle (b) Total deformation with 15° inclination angle (c) Stress with 30° inclination angle (d) Total deformation with 30° inclination angle (e) Stress with 45° inclination angle (f) Total deformation with 45° inclination angle



(a) (b)

(c) (d)

(e) (f)

**Figure 7** Stress and deformation in vessels with tangential nozzles (a) Stress with 15° inclination angle (b) Total deformation with 15° inclination angle (c) Stress with 30° inclination angle (d) Total contour with 30° inclination angle (e) Stress with 45° inclination angle (f) Total deformation with 45° inclination angle

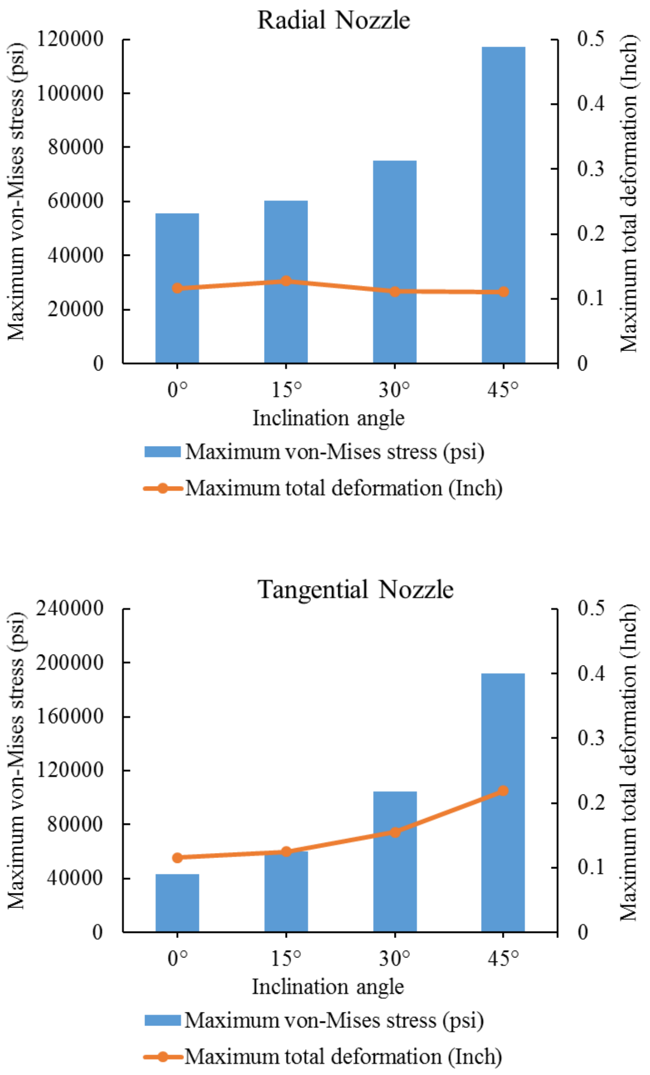


**Figure 8** Effect of inclination angle of nozzle on maximum stress and deformation values

Figure 8 shows the graphical representation of effect of inclination angle on stress and deformation value for radial and tangential type of nozzle. From the both the graphs it is observed that with the increment of inclination angle of nozzle, the induced stress is increase in both the cases, radial as well as tangential type of nozzle. There is 111.28% increment observed in the case of radial nozzle when 45° inclination angle was incorporated as compared to 0° inclination angle. However, for the tangential nozzle, the total increment is 342.68%. This results shows that the effect of number of nozzles is greatly affects the vessel with tangential nozzles as compared to the vessel with radial nozzles. However, in this case increment of induced stress values are more in the case of tangential nozzle as compared to radial nozzle. As in the earlier cases, the maximum stress values are higher in the case of radial nozzles as compared to tangential nozzles. However, in this case of inclination angle, the higher maximum stress has been observed for high inclination angle value for the tangential nozzle as compared to radial nozzle. As shown in the graph, for the 0° inclination angle, higher maximum stress is observed in the vessel having radial nozzle as compared to tangential nozzle. However, for the 15° inclination angle the stress values are almost similar for both type of nozzle. For the 30° inclination angle, the maximum stress value is 39.23% higher for tangential nozzle as compared to radial nozzle. Also in similar way, there is 63.91% increment in stress values of tangential nozzle as compared to radial nozzle for 45° inclination angle of nozzle.

## 4. Optimization

Computational Intelligence Optimization integrates artificial intelligence into algorithms for solving optimization problems. Computational intelligence has been actively developed over the years. Although classic algorithms, such as machine learning and data collection techniques, are all established, they are continually improved. Today, computer intelligence is used directly or indirectly in many applications. In the present work, optimization of maximum stress has been done using Differential Evolution (DE).

DE algorithms are part of evolutionary programming established by Rainer Storn and Kenneth Price for continuous domain optimization problems. In DE, the value of each variable is characterised by a real number. The benefits of the DE algorithm are its simple structure, easy operation and speed. DE is an excellent design tool that can be put to practical use immediately. If the system can be rationally evaluated, this algorithm can provide the means to make the most of it.

### *Initialization*

In this optimization technique, the first step is to generate the population of applicant solutions by allocating random values to individual parameter. Here, an initial population $X$ must be created using Eq. (1).

$$X_i^0 = X_{min} + \rho_i(X_{max} - X_{min}) \tag{1}$$

Where, $i$=1,2,3,……,$N_p$ and $\rho_i$ is a random number.

### *Mutation*

Progeny is generated by mutation and crossover operators. Mutation operatives are responsible for presenting new particles into the population. To accomplish this, the mutation operative generates mutant vectors by perturbing a randomly selected vector ($X_{r1}$) and using the difference between two randomly selected vectors ($X_{r2}$ and $X_{r3}$) according to Eq. (2). Here, $F_s$ is the mutation constant.

$$X_i^{G+1} = X_{r1}^G + F_s(X_{r2}^G - X_{r3}^G) \tag{2}$$

Where, $F_s$ € [0, 2] and $r_1$, $r_2$ and $r_3$ are randomly selected.

### *Crossover*

The crossover operative generates an experiment vector. In DE, two types of crossovers are used: binomial and exponential. In the case of a binomial crossover, a random number in the range [0, 1] is generated and compared to the crossover constant $C_r$. If the random value is less than or equal to the crossover constant, the parameter is taken from the mutation vector. Otherwise, the parameters are taken from the target vector as given in Eq. (3). Crossings maintain population diversity and prevent regional convergence. The range of the crossover constant must be in [0, 1].

$$X_i^{G+1} = \begin{cases} X_i^G, & if \ \ rand \le C_r \\ X_i^{G+1}, & otherwise \end{cases} \tag{3}$$

Where, $i$ = 1, 2, …, $N_p$.

### *Selection*

The selection operative selects the vectors that make up the population of the next generation. This operative compares the fitness of the experimental vector to the fitness of the corresponding target vector and selects it as shown in Eq. (5).

$$X_i^{G+1} = arg \ \ min \left\{ f(X_i^G), f(X_i^{G+1}) \right\} \tag{4}$$

$$X_b^{G+1} = arg \ \ min \left\{ f(X_i^{G+1}) \right\} \tag{5}$$

Where, *arg min* is the best individual.

For the optimization of the maximum stress, the fitness function model is determined by regression analysis. In the present work, the objective function was to maximize the stress value. The regression equation and determination co-efficient $R^2$ were determined using Minitab software. Eq. (6) is the objective function for maximizing the stress value for radial nozzle and Eq. (7) shows the objective function for tangential nozzle.

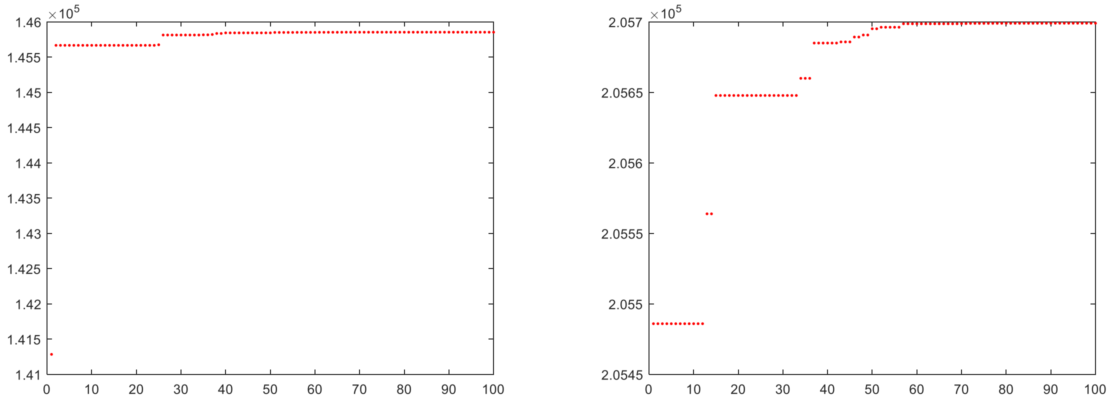
*Maximizing stress = 33597 + 1348 (Inclination Angle) +12899 (Number of Nozzles)* (6)

*Maximizing stress = 19115 + 3164 (Inclination Angle) + 11051 (Number of Nozzles)* (7)

Number of unknown variable = 2

Lower bound = [0 1]

Upper bound = [45 4]



(a) Radial nozzle (b) Tangential nozzle

**Figure 9** Convergence curve

The convergence characteristics chart of DE is shown in Figure 9. Convergence curve shows that maximum stress of 1.4585e5 MPa is obtained after 40 iterations for radial nozzle and maximum stress of 2.0571e5 MPa is obtained after 50 iterations for tangential nozzle. In both the cases, it is observed that maximum stress values obtained for 45° inclination angle and 4 number of nozzles. The FEA analysis has been done separately for both the cases, and in first case, the vessel with 4 nozzles gave better performance while in the second case, nozzle with 45° inclination angle gave better results. However, the optimization results gave the combined effect of both the parameters and thus maximum value of stress is higher than the individual results observed from the FEA analysis.

## 5. Conclusion

In the present work, investigation of nozzle shape, number of nozzles and nozzle inclination angle has been carried out using FEA analysis. Following conclusion have been drawn from the analysis:

- When only one nozzle is incorporated at 0° inclination angle, pressure vessel with radial nozzle resulted into more stress value as compared to tangential nozzle.
- As the number of nozzles are increasing, the maximum stress value is also increasing for both type of nozzle in the vessel.
- At the higher inclination angle of nozzle, the pressure vessel with tangential nozzle resulted into more stress value as compared to radial nozzle.
- Optimization results showed that by using higher number of nozzles and higher number of inclination angle, the combined effect of both improve the performance.

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