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RELIABILITY ESTIMATION OF CSKD USING PROBABILISTIC TECHNIQUES

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Abstract: The compressor suction knockout drum is a type of pressure vessel which is used to remove the liquid droplets carryover in gases to protect the downstream process equipment. The knockout drum helps in improving the life of the compressor and resists the corrosion. The present work deals with design, modelling and static structural analysis of the compressor knockout drum. The first step involves generating the model using CATIA V5. Later, the model is dumped into ANSYS software to perform static, fatigue and modal analysis. The von Mises stresses are estimated at locations such as the crown, equator, and shell portions of the drum. The von-Mises stresses are obtained by analytical approximation and compared with ANSYS results. Now the internal pressure and thickness of the drum are assumed to be random and Monte Carlo simulations are used to know the statistical nature of von Mises distribution at various locations of the drum. Finally, the reliability of the drum is to be estimated using Random variable approach.

Keywords: Knockout drum, Modelling, Static analysis, Fatigue life, Random variable.

I. INTRODUCTION

This The Compressor Suction Knockout Drum (CSKD) is a critical pressure vessel used in petrochemical, oil & gas, and chemical processing industries to separate liquid droplets from gas streams, thereby protecting downstream equipment such as compressors. It operates primarily on gravity-based separation, where liquid accumulates at the bottom while vapor exits from the top, ensuring improved efficiency and reduced corrosion in process systems.

Designing CSKD involves addressing complex stress distributions arising from internal pressure, external loads, and structural discontinuities such as nozzle connections. Since conventional design standards (e.g., ASME codes) may not fully capture localized stress behavior, advanced numerical methods like Finite Element Analysis (FEA) are required for accurate stress prediction and safe design optimization.

In this study, a CSKD is modeled using CATIA, followed by static, fatigue, and modal analysis using ANSYS to evaluate deformation and von-Mises stress at critical locations. Analytical results are validated against numerical simulations to ensure accuracy. Furthermore, recognizing uncertainties in operating conditions such as internal pressure and material thickness, a probabilistic approach using Monte Carlo simulation in MATLAB is employed. This enables estimation of stress variability, probability of failure, and overall system reliability.

The outcomes provide insights into the structural integrity, reliability, and performance optimization of CSKD, contributing to safer and more efficient pressure vessel design.

II. LITERATURE REVIEW

[1] V.N. Skopinsky,AD. Kozakgn 198, Pp 317-323, 2000
This presented work on modeling and stress analysis of nozzle connection in Ellipsoidal head of pressure vessel under external loading, they used Timoshenko shell theory and the finite element method, , non-radial and offset connection have non-uniform distribution of stress on the interaction curve between the nozzle and the head, This study illustrates the significance of the angular parameter for non-radial nozzle connections. For non-central connections, the maximum effective stress decreases as the angle increases.

[2] V.N. Skopinsky and A.B. Smetankin (Stress in Ellipsoidal Pressure Vessel Heads with Non-Central Nozzle) (June-2000)
Authors presented the structural modeling and stress analysis of nozzle connections in ellipsoidal head subject to

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external loading. Timoshenko shell theory and the finite element method are used. The characteristics of structural modeling for ellipsoid–cylinder shell intersections, the numerical approach, and the SAIS (Stress Analysis in Intersecting Shells) specialized computer program are described. A parametric study of the effects of geometric parameters on the maximum effective stresses in the ellipsoid-cylinder intersections under loading was performed. The results of the stress analysis and parametric study of the nozzle connections are presented.

[3] M.H. Toorani (Dynamics of the Geometrically Non-Linear Analysis of Anisotropic Laminated Cylindrical Shells) (November-2003)
A general approach, based on shear able shell theory, to predict the influence of geometric non-linearities on the natural frequencies of an elastic anisotropic laminated cylindrical shell incorporating large displacement and rotation is presented in this paper. The effect of shear deformations and rotary inertia are considered in the equation of motion. The shearable shell theory is applied to obtain the shape function matrix. The analytical solution is divided into two parts. In one, the displacement functions are obtained by exact solution of the equilibrium equation of a cylindrical shell based on shear able shell theory. The mass and linear stiffness matrices are derived by exact analytical integration. In part two, the modal coefficients are obtained for these displacement functions. The second and third order non-linear stiffness matrices are then calculated by precise analytical integration and superimposed on the linear part of equation to establish nonlinear modal equation.

[4] P. BALICEVIC, ET.AL {Pp 10-13, 2007}
presented work on the "ANALYTICAL and NUMERICAL solution of internal forces by cylindrical pressure vessel with semi-elliptical heads," the "solution for internal forces and displacement in the thin-walled cylindrical pressure vessel with the ellipsoidal head using the general theory of thin-walled shell of the resolution," the "distribution of the forces and displacement in thin-walled shell," and "finite element analysis of the cylindrical pressure vessel.

[5] Shafique M.A. Khan (Stress Distributions in A Horizontal Pressure Vessel and the Saddle Supports) (May-2010)
The author performed an analysis to determine the stress distribution in a horizontal pressure vessel and its saddle support. The results were obtained using a three-dimensional finite element analysis, where one quarter of the vessel was modeled with detailed representation of the saddle support. The physical basis for selecting a specific ratio between the distance of the support from the vessel end and the total vessel length is also explained.

[6] L. Xue (Parametric FEA Study of Burst Pressure of Cylindrical Shell Intersections) (June-2010)
The paper deals with analyzing the burst pressure of cylindrical cells. An elastic–plastic large deflection analysis approach is employed to evaluate the burst pressure and fracture location of cylindrical shell intersections using nonlinear finite element analysis. To verify the accuracy of finite element, result author carried out experimental burst test by pressurizing test vessels with nozzles to burst. The results show that the proposed equation resulting from parametric analysis can be employed to predict the static burst pressure of cylindrical shell for a wide range of geometric ratios.
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III. METHODOLOGY

The methodology adopted in this study involves a combination of design, numerical analysis, and probabilistic techniques to evaluate the reliability of a Compressor Suction Knockout Drum (CSKD).

1. Design and Modelling
The CSKD geometry was developed using standard pressure vessel design data obtained from datasheets and ASME guidelines. Individual components such as shell, dish end, nozzle, manhole, and reinforcement pads were first created

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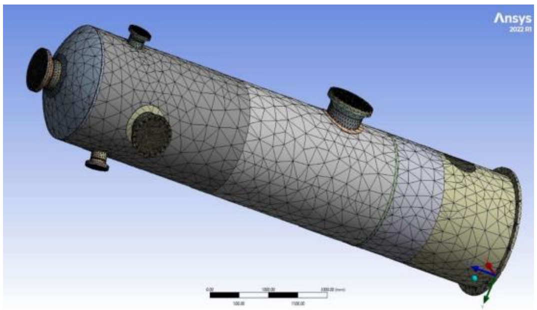
as 2D drawings and converted into 3D models using CATIA V5. These parts were then assembled to form the complete CSKD model based on dimensional and alignment constraints.

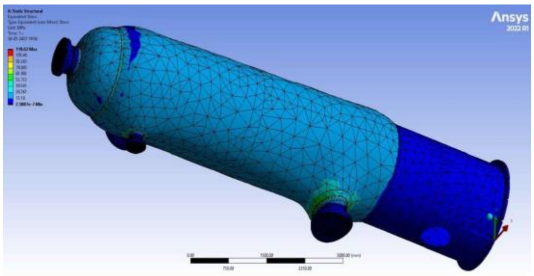
2. Finite Element Analysis (FEA)
The assembled CATIA model was exported in IGES format and imported into ANSYS Workbench for numerical analysis. The following steps were used:

- Material properties (structural steel) were assigned.
- The geometry was discretized using **tetrahedral meshing** (~55,541 elements and ~114,371 nodes).
- Appropriate boundary conditions (fixed support and internal pressure loading) were applied.
- Static structural analysis was performed to determine:
    - Total deformation
    - Equivalent (von Mises) stress
    - Principal stresses

The results were evaluated at critical regions such as the shell, crown, and equator, and compared with analytical solutions to validate the model.



Meshing in Ansys



Equivalent Von-Mises stress

3. Analytical Calculations
Analytical stress calculations for cylindrical shells and dish ends were performed using standard equations for:

- Longitudinal stress
- Hoop stress
- Shear stress
- Von Mises stress

These results were used as a benchmark for validating ANSYS simulation outputs.

4. Probabilistic Analysis
To account for uncertainties in design parameters, a probabilistic approach was implemented using MATLAB:

- Key input variables such as internal pressure and thickness were treated as random variables following normal distributions.
- Monte Carlo simulation (10^5 samples) was conducted to evaluate variability in stress responses.
- Statistical measures such as mean, standard deviation, probability density function (PDF), and cumulative distribution function (CDF) were obtained.

This approach enabled the assessment of variability in von Mises stress across different locations of the CSKD.

5. Reliability Estimation
Reliability was evaluated using the **stress–strength interference theory**:

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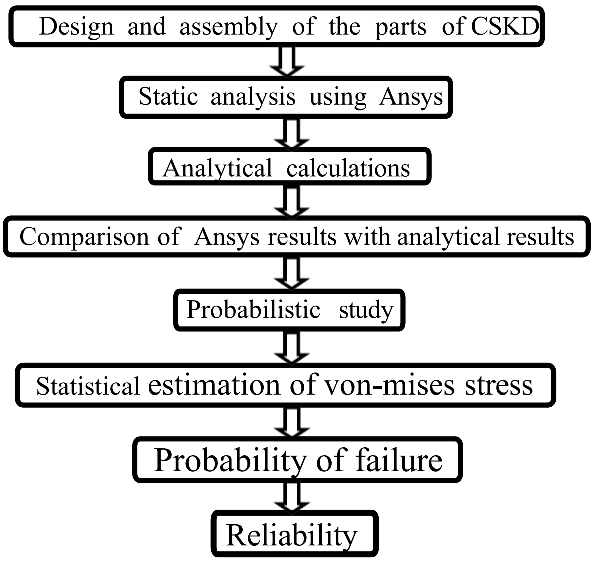
- Failure occurs when applied stress exceeds material strength.
- Probability of failure (Pf) was obtained from overlapping stress and strength distributions.
- Reliability (R) was calculated as:

R=1−PfR = 1 - P_fR=1−Pf

The variation of reliability with respect to different pressure conditions was analyzed to identify safe operating limits.

6. Overall Workflow

The complete methodology follows this sequence:



IV. RESULTS & DISCUSSIONS

The structural performance of the Compressor Suction Knockout Drum (CSKD) was evaluated using analytical methods, finite element analysis (ANSYS), and probabilistic techniques. The results provide insights into deformation, stress distribution, and system reliability under varying operating conditions.

4.1 Static Structural Analysis

The CSKD model, subjected to internal pressure, exhibited non-uniform deformation, with maximum deformation occurring at the junction of the crown and shell region (~0.435 mm), while minimal deformation was observed near the base. Von-Mises stress distribution revealed that maximum stress concentrations occur at the nozzle-shell junction, indicating critical regions prone to failure. The computed stress values remained below allowable material limits, ensuring safe operation under given conditions.

A comparison between analytical and ANSYS results showed close agreement, validating the finite element model for reliable stress estimation.

4.2 Probabilistic Analysis of Stress

To account for uncertainties in design parameters, internal pressure and thickness were treated as random variables and analyzed using Monte Carlo simulation.

The probabilistic results indicate:

- Stress values follow a normal distribution
- Increase in pressure significantly raises means stress and variance
- Thickness variation influences stress dispersion and reliability

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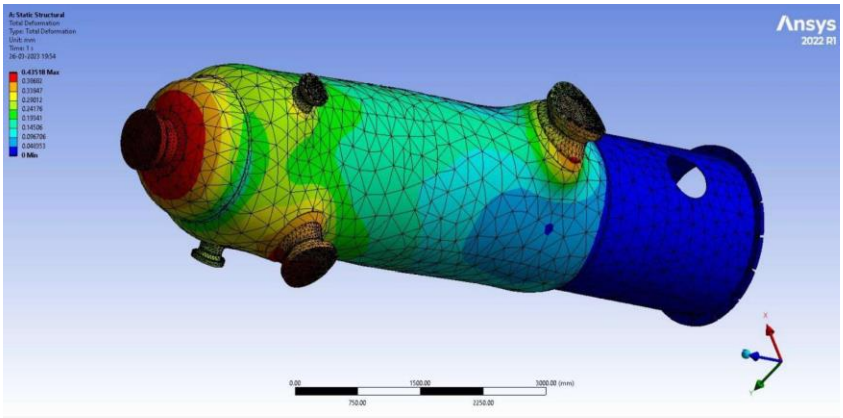


Total Deformation of Pressure vessel

The cumulative distribution function (CDF) confirms that stress values stabilize within a predictable probabilistic range.

4.3 Reliability Assessment

Reliability was evaluated using the **stress-strength interference method**, where failure occurs when applied stress exceeds material strength.

Key observations:

- Reliability decreases with increasing pressure
- At lower pressure (0.25 MPa), reliability is very high (~99%)
- At higher pressure (0.65 MPa), reliability drastically reduces (~15%)

This indicates that operating pressure is the dominant factor influencing failure probability.

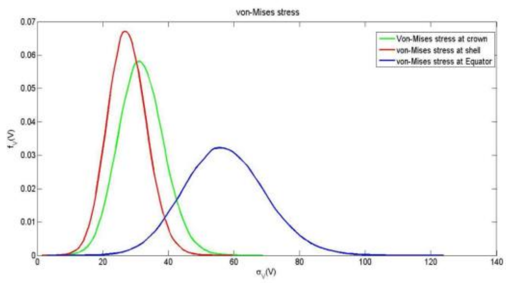
	Max Principal Stress (MPa)		Von Mises Stress (MPa)	
	Analytical	ANSYS	Analytical	ANSYS
Shell Portion	18	21.617	17.07	15
Equator	18	19.71	36.14	40
Crown	25	15.974	19.07	17

Comparison of ANSYS and analytical values

4.4 Stress–Strength Interaction

The overlap between stress and strength distributions defines the failure zone. As pressure increases:

- Stress distribution shifts toward higher values
- Overlap region increases → higher failure probability



Output von Mises stress for different locations

This highlights the importance of design margins and safety factors in pressure vessel design.

4.5 Overall Discussion

The combined analytical, numerical, and probabilistic approach demonstrates that:

- Critical stress regions exist at geometric discontinuities (nozzles, junctions)

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- Deterministic analysis alone is insufficient for reliability estimation
- Probabilistic modeling provides better safety insight under uncertainty

Thus, integrating FEA with probabilistic techniques enhances design accuracy and ensures safer operation of CSKD systems. Comparison of reliability for different pressures:

Parameters	Pressure, MPa									
	0.25		0.345		0.45		0.55		0.65	
	σv(x)	**σs(y)**	**σv(x)**	**σs(y)**	**σv(x)**	**σs(y)**	**σv(x)**	**σs(y)**	**σv(x)**	**σs(y)**
Mean(μ)	41.505	84.87	57.272	85.168	74.700	84.670	91.252	85.013	107.671	85.498
Standard deviation(S)	12.911	25.73	17.852	25.524	23.321	25.635	28.437	25.780	33.737	25.413
Z	2.267		1.307		0.4357		-0.2481		-0.7871	
R=1-P(Z)	0.9880		0.90490		0.67003		0.40517		0.21770	
R%	99.9		98.3		72.4		36.4		15.2	

V. CONCLUSION

The present study successfully investigates the structural performance and reliability of a Compressor Suction Knockout Drum (CSKD) using a combination of analytical, numerical, and probabilistic approaches. A detailed 3D model was developed in CATIA and analyzed using ANSYS to evaluate deformation, stress distribution, fatigue life, and modal characteristics.

The results indicate that the maximum deformation and von-Mises stresses occur at critical regions such as the nozzle-shell junction and crown area yet remain within permissible limits defined by material properties and design codes. Analytical results show good agreement with finite element results, validating the modeling approach.

A probabilistic analysis using Monte Carlo simulation highlights the influence of uncertainties in pressure and thickness on system behavior. It is observed that reliability significantly decreases with increasing internal pressure, emphasizing the importance of incorporating variability in design considerations. The stress–strength interference theory confirms that failure probability increases under higher loading conditions.

Fatigue analysis demonstrates that the CSKD possesses a high fatigue life (≈10^9 cycles) under given operating conditions, indicating durability for long-term use. Modal analysis reveals stable dynamic behavior with low deformation at higher frequencies, confirming structural stiffness.

Overall, the study concludes that the designed CSKD is structurally safe, reliable, and efficient, while the probabilistic framework enhances design robustness by accounting for uncertainties. Future work may include dynamic loading analysis and advanced reliability models for further optimization.

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