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Structural Integrity Assessment of LPG-Fired Cabinet Dryer Using Finite Element Analysis (FEA)

Nafisah Amalia[1], Yusi Amalia Renaningtyas[1], Nanang Apriandi[2,3*,] Yusuf Dewantoro Herlambang[2], Avicenna An-Nizhami[2], Padang Yanuar[2], Aris Fiatno[4]

[1)]Energy Conversion Engineering Study Program, Department of Mechanical Engineering, Politeknik Negeri Semarang, Semarang 50275, Jawa Tengah, Indonesia
[2)]Department of Mechanical Engineering, Politeknik Negeri Semarang, Semarang 50275, Jawa Tengah, Indonesia
[3)]Center for Applied Energy and Thermofluid Studies, Semarang 50279, Jawa Tengah, Indonesia
[4)]Industrial Engineering Study Program, Universitas Pahlawan Tuanku Tambusai, Kampar 28412, Riau, Indonesia
* nanang.apriandi@polines.ac.id

Abstract

Cabinet-type dryers powered by Liquefied Petroleum Gas (LPG) are widely recognized as an efficient drying solution, particularly for small and medium-sized industries. However, the structural strength and durability aspects of these dryers often receive insufficient attention, although they operate under a combination of static and thermal loads that may potentially trigger structural failure. This study aims to evaluate the structural strength of a cabinet-type LPG dryer using the Finite Element Analysis (FEA) method by considering variations in operating temperature and constant mechanical loading. Simulations were conducted within an operating temperature range of 48.049°C to 75.767°C under a constant load of 40 kg. The key parameters analyzed include total deformation, stress distribution, and structural safety factor. The results revealed a maximum deformation of 1.094 mm and a peak stress of 1030.7 MPa concentrated in the plenum chamber area, identified as a critical zone due to the combined effects of thermal and mechanical loading. The maximum safety factor reached 15, while the minimum value of 0.24255 indicates the need for localized design improvements in certain regions. These findings demonstrate the effectiveness of FEA in predicting the structural response of drying equipment and provide a scientific foundation for enhancing structural safety and reliability. Further studies are recommended to integrate coupled thermal-structural analysis and experimental validation to improve the accuracy of the results.

Keywords: *cabinet dryer; finite element analysis (FEA); safety factor; structural analysis; temperature distribution*

1. Introduction

Drying is one of the essential processes widely applied across various industrial sectors, particularly in the food, agricultural, and plantation industries [1], [2], [3]. The primary purpose of this process is to reduce the moisture content of products, thereby extending shelf life, maintaining product quality, and preventing the growth of microorganisms that can lead to product spoilage [4], [5], [6]. In line with technological advancements, drying equipment has continued to evolve, with cabinet-type dryers [7], [8] being recognized as a more efficient and controlled alternative compared to conventional sun-drying methods.

Cabinet-type dryers powered by Liquefied Petroleum Gas (LPG) have become a popular choice, especially among small and medium-sized enterprises [7], [9]. The use of LPG as an energy source in these dryers offers several advantages, including ease of operation, improved energy efficiency, shorter drying times, and more uniform drying quality [8]. Furthermore, the enclosed design of cabinet dryers provides additional protection for products from environmental contamination during the drying process. Nevertheless, most research and development efforts related to cabinet dryers have focused primarily on thermal performance and drying efficiency [10], [11], [12], with limited attention given to the structural strength and durability of the equipment.

In practical applications, the structural components of drying equipment are subjected to a combination of static loads from the product weight and thermal loads resulting from temperature distribution during operation. If the structural strength is not adequately considered, excessive deformation, material degradation, or even structural failure may occur. Such failures can not only compromise the drying performance and lifespan of the equipment but also pose significant safety risks to users, particularly if failure occurs unexpectedly under high-temperature conditions.

One of the most widely used methods for structural strength evaluation is Finite Element Analysis (FEA). FEA is a computer-based numerical approach [13], [14], [15] that allows for detailed modeling and simulation of structural behavior under various loading conditions, including static, dynamic, thermal, and vibrational loads [16], [17], [18], [19], [20]. Through FEA, it is possible to predict stress distribution, deformation, and the location of potential failure points within the structure with a high degree of accuracy before physical prototyping or experimental testing is conducted.

Several previous studies have demonstrated the effectiveness of FEA in enhancing the structural safety and reliability of drying equipment. For instance, Sofyan et al. [21] conducted an FEA on the structural frame of an onion drying machine and confirmed that the resulting stress and deformation levels remained within safe limits. Similarly, Rahman et al. [22] utilized FEA to analyze and optimize the structural frame of a fluidized bed dryer, resulting in a design with a high safety margin.

Considering the critical importance of structural strength, especially for LPG-powered cabinet dryers operating at elevated temperatures, further investigation is necessary to comprehensively assess the structural performance of such equipment. Therefore, this study aims to analyze the structural strength of an LPG-powered cabinet dryer using the FEA method. The analysis focuses on evaluating the effects of temperature variations and mechanical loading on stress distribution, deformation, and structural safety factors. The findings of this study are expected to serve as a scientific foundation for providing design recommendations to develop cabinet dryers that are not only thermally efficient but also structurally reliable, safe, and durable.

2. Methodology

This study aims to analyze the structural strength of a cabinet-type dryer powered by LPG using a numerical simulation approach based on FEA. The research stages included the identification of dryer specifications, the development of the numerical model, the determination of testing variations, and the analysis of simulation results.

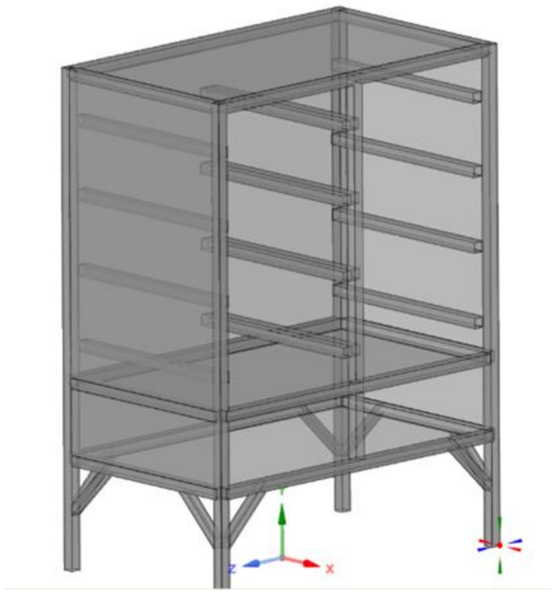

Figure 1. Structural design of the LPG-fired cabinet dryer frame.

The object of this research is an LPG-fired cabinet dryer with a maximum load capacity of 40 kg. The main frame of the dryer is constructed using hollow steel sections with dimensions of 35×35 mm and a wall thickness of 2.3 mm. The outer casing of the dryer is made of steel plates with a thickness of 2.4 mm. The material selection is based on considerations of mechanical strength, thermal resistance, material availability, and cost efficiency. The structural design of the dryer is illustrated in Figure 1.

The numerical model was developed by creating a complete three-dimensional (3D) model of the dryer. A mesh generation process was performed with an element size of 20 mm to ensure an optimal balance between computational efficiency and simulation accuracy, as shown in Figure 2. The target element quality was set at 0.05 to ensure that the generated mesh accurately represents the actual structural conditions.

Figure 2. Generated mesh of the cabinet dryer model with applied element sizing.

Table 1. Material properties of structural steel used in the cabinet dryer frame.

Material	Properties	Value
	Density	7.85e-006 $kg.mm^{-3}$
	Coefficient of Thermal Expansion	1.2e-005 $°C^{-1}$
Structural Steel	*Specific Heat*	4.34e+005 $mJ.kg^{-1}.°C^{-1}$
	Thermal Conductivity	6.05e-002 $W.mm^{-1}.°C^{-1}$
	Resistivity	1.7e-004 ohm-mm

During the simulation process, boundary conditions were applied to reflect the actual operating conditions of the dryer. Fixed supports were assigned to the frame legs, representing the main support points of the structure. Additionally, loads were applied to the drying chamber and plenum area based on the actual positions of the operational loads during the drying process.

The material properties used in the simulation were based on the characteristics of structural steel, following international standards (detailed in Table 1). The main material parameters include an elastic modulus according to standard values, a thermal expansion coefficient of 1.2×10^{-5} $^{\circ}C^{-1}$, and a density of 7.85×10^{-6} kg/mm^3. These properties were selected to realistically represent the mechanical and thermal behavior of the material during the simulation process.

Subsequently, testing variations were performed by applying different operating temperatures based on the actual temperature characterization results previously obtained. The temperature range used in the simulation was from 48.049 ˚C to 75.767 ˚C, representing the actual operating conditions of the dryer during both heating and cooling phases. A constant load of 40 kg was applied to the drying chamber to represent the weight of the product being dried. This approach enabled the simulation to accurately represent the operational conditions of the dryer.

The analysis focused on three main structural performance parameters: total deformation (measured in millimeters), equivalent stress (measured in megapascals), and safety factor. These parameters were analyzed to evaluate the structural integrity of the dryer under the combined influence of static and thermal loads resulting from temperature distribution during operation. Through this FEA-based simulation approach, it is expected that a comprehensive understanding of the structural performance and safety of the cabinet dryer can be obtained before experimental testing or actual application.

3. Results and Discussion

3.1. Temperature characterization of the drying chamber

Temperature characterization of the drying chamber was carried out to understand the temperature distribution and fluctuations that occur during the drying process. The results indicate a gradual increase in the chamber temperature during the heating phase, reaching an average peak temperature of 75.767 ˚C. After the heating process was stopped, the temperature inside the chamber gradually decreased following a natural cooling pattern (Figure 3). These findings are consistent with the results reported by Apriandi et al. [8], which demonstrated that LPG-fired cabinet dryers generally exhibit stable and controlled temperature fluctuations within a defined period.

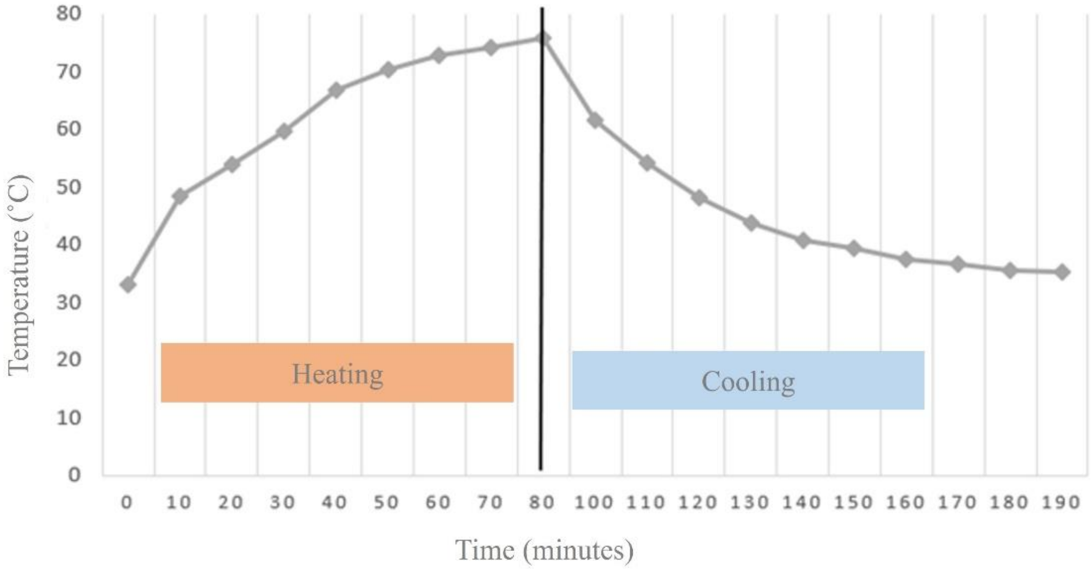

Figure 3. Temperature variation in the drying chamber during heating and cooling phases.

The observed trends in temperature rise and fall are critical for the FEA simulations, as temperature directly affects the mechanical properties of structural materials, particularly steel, which is used for the dryer frame. By incorporating actual temperature variations into the simulations, the FEA results more accurately reflect real operating conditions, enhancing the reliability of the structural analysis.

3.2. Structural deformation

The FEA simulation results indicate that the maximum structural deformation occurred in the plenum chamber area, with a value of 1.094 mm when the dryer operated at the maximum temperature of 75.767 ˚C. The location of this maximum deformation near the plenum chamber is logical, considering that this area is closest to the heat source and bears the direct load from the drying product. In other words, this area is subjected to the combined effect of mechanical and thermal loads, making it reasonable for deformation to be concentrated at this critical point.

The magnitude of the deformation is relatively small compared to the overall dimensions of the dryer and the thickness of the structural frame, indicating that, in general, the structure remains within safe limits and does not experience plastic deformation that could compromise its performance. The observed increase in deformation with rising temperature aligns with the known behavior of steel materials, where elevated temperatures tend to reduce the elastic modulus, making the structure more susceptible to deformation [20].

These findings provide valuable academic insight for the design of cabinet dryers, highlighting the need for particular attention to be given to the plenum chamber area regarding material selection, frame thickness, and geometric configuration to minimize the risk of excessive deformation. Furthermore, the results reinforce the validity of FEA as a predictive tool for analyzing structural deformation responses under combined thermal and mechanical loads.

3.3. Stress distribution

The stress distribution analysis of the dryer structure shows that the maximum stress occurred in the plenum chamber area, with a value of 1030.7 MPa when the dryer operated at the peak temperature of 75.767 ˚C (Figure 4). The coincidence of the maximum stress location with the maximum deformation area indicates the presence of a stress concentration in that region. This phenomenon is consistent with structural mechanics theory, which states that stress concentrations commonly occur at geometric discontinuities, joints, or areas subjected to combined high loads [18].

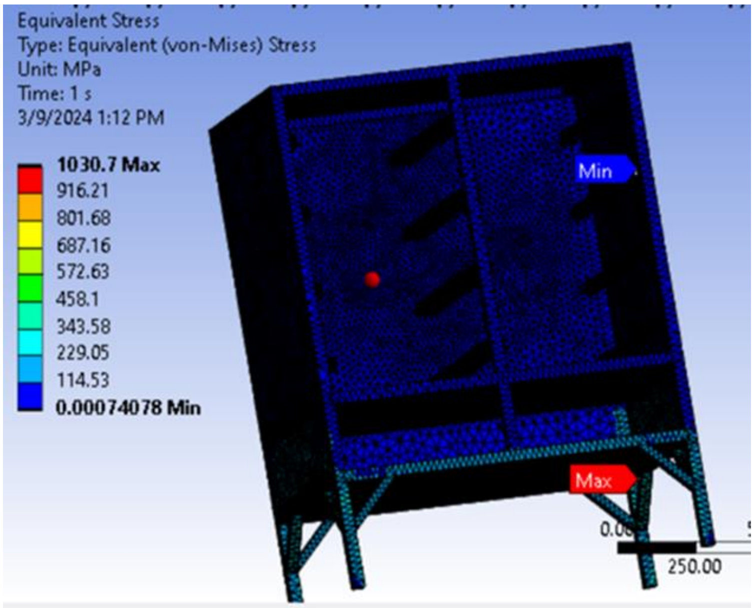

Figure 4. Equivalent stress distribution of the dryer structure at maximum operating temperature.

The magnitude of the stress remains within the allowable limits for the steel material used, indicating that the structure does not experience material failure. The observed decrease in stress during the cooling phase also demonstrates consistency between the simulation results and physical phenomena, where lower temperatures contribute to the reduction of thermal stresses within the material.

From an academic perspective, these results emphasize the importance of considering stress distribution in the design and optimization process of drying equipment, particularly in critical areas such as the plenum chamber. The findings also provide opportunities for further design improvements, such as the addition of stiffeners, modifications to the frame geometry, or the use of alternative materials with superior thermal resistance in regions prone to high stress concentrations.

3.4. Safety factor analysis

The safety factor is a critical parameter for evaluating structural strength and reliability. The simulation results indicate that the maximum safety factor achieved was 15, while the minimum value was 0.24255 (Figure 5). A safety factor greater than 1 generally indicates that the structure is safe under the combined mechanical and thermal loads applied. The highest safety factor was observed when the dryer operated at its peak temperature, suggesting that even with increased deformation and stress, the structure maintains a sufficient margin of safety [22], [23].

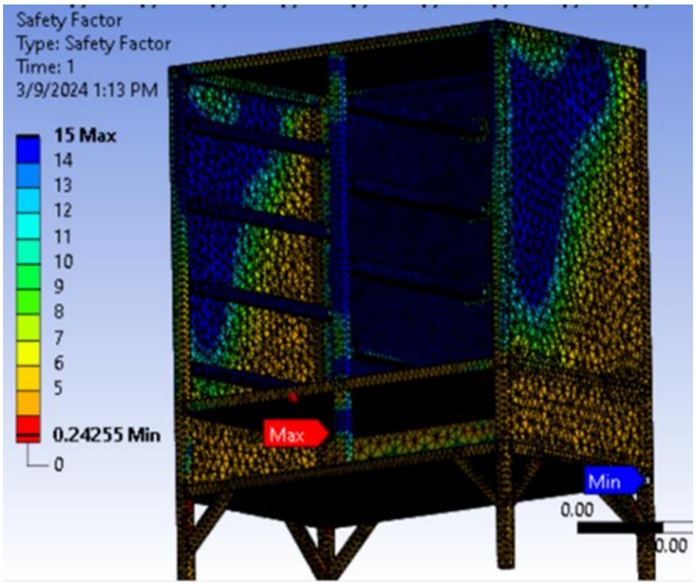

Figure 5. Safety factor distribution of the dryer structure under maximum operating temperature.

However, attention must be given to areas with relatively low safety factor values, approaching 0.24, as these regions are vulnerable to structural failure if exposed to additional loads beyond the design specifications or to material degradation resulting from thermal fatigue. These findings provide both practical and academic input, highlighting that structural evaluation should not solely rely on average or maximum safety factor values but must also account for localized weaknesses within the structure.

From a practical standpoint, the results recommend targeted structural reinforcement in areas with low safety factors through increasing material thickness, using alternative materials with higher thermal resistance, or modifying geometric design features. From an academic perspective, these findings strengthen the argument that FEA is not only useful for predicting general structural behavior but also highly effective in identifying critical areas that have the potential to become structural weak points.

4. Limitations and Future Research

Although this study provides a comprehensive overview of the structural strength of an LPG-fired cabinet dryer, several limitations must be acknowledged. First, the FEA simulations conducted in this research were limited to linear static analysis and did not account for the effects of repeated thermal cycles (thermal fatigue), which may significantly influence the long-term structural durability of the equipment. Second, the simulations did not consider non-uniform temperature distribution or potential manufacturing imperfections that may occur in actual fabricated products.

Future research is recommended to address these limitations by integrating coupled thermal-structural analysis to more accurately capture the interaction between mechanical and thermal loads under realistic operating conditions. Furthermore, experimental validation is essential to verify the accuracy and reliability of the simulation results. In addition, future studies should investigate the effects of repeated thermal cycling and conduct direct material durability testing to provide a more comprehensive assessment of the structural performance and service life of cabinet dryers under real-world operating conditions.

5. Conclusion

This study successfully analyzed the structural strength of a cabinet-type dryer powered by LPG using the FEA method. The analysis focused on evaluating the combined effects of static loads and temperature distribution during operation on the structural performance of the dryer. The simulation results indicate that the dryer structure is capable of withstanding the applied mechanical and thermal loads without experiencing structural failure, with a maximum deformation of 1.094 mm and a maximum stress of 1030.7 MPa concentrated in the plenum chamber area. The maximum safety factor of 15 demonstrates an excellent overall safety margin for the structure. However, the presence of localized areas with a minimum safety factor of 0.24255 highlights the need for further design improvements in specific regions to enhance structural reliability.

These findings confirm that FEA is an effective predictive approach for evaluating the structural strength and reliability of drying equipment before the manufacturing process or physical testing. Moreover, the identification of critical areas with high deformation and stress values provides essential insights for structural optimization, including increasing material thickness, using alternative materials with higher thermal resistance, or modifying the geometric design in vulnerable areas. Overall, this research contributes to providing a scientific foundation for the development of cabinet-type dryers that are not only thermally efficient but also structurally safe and reliable.

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