JURNAL IPTEK
MEDIA KOMUNIKASI TEKNOLOGI
homepage URL : ejurnal.itats.ac.id/index.php/iptek

Stress Analysis of High-Pressure Steam Header Manifold from Power Boiler to Distribution System Piping Using The Caesar II Software

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ARTICLE INFORMATION

Journal of Science and Technology – Volume 27 Number 2, December 2023

Page:
113 – 120
Date of issue :
December 30, 2023

DOI:
10.31284/j.iptek.2023.v27i2.4652

ABSTRACT

In the construction of the oleochemical plant project, there is a steam pipe that experiences excessive stress during the stress analysis phase using stress analysis software. The pipe is connected to either a boiler or a steam generator equipment. Recalculation is necessary, including for the allowable pipe span and pipe flexibility, to address the excessive stress. The pipe falls into the category of critical pipe, thus requiring stress analysis after the recalculation is performed. The stress analysis is conducted using sustained load, occasional load, and thermal load based on ASME B31.3. The calculation of the allowable pipe span takes the smallest value between the minimum distance based on stress limit and deflection limit, which is 19,006 ft, and the minimum required number of supports, which is 22. The results of the calculation for the allowable pipe span are acceptable as the number of supports meets the minimum required amount. The flexibility calculation yields a value smaller than K1, specifically 0.000916, indicating that the pipe is declared flexible. The highest stress value at node 688 for sustained load is 18,389.3 psi, and the highest value at node 688 for occasional load, it is 18,399 psi. The highest stress value for thermal load, 1420.6 psi, is found at node 168. The stress values for all three load cases do not exceed the allowable stresses. Therefore, the design is declared safe during operation.

Keywords: *Allowable Span; Flexibility; Occasional Load; Sustain Load; Thermal Load*

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PUBLISHER

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ABSTRACT

Dalam proyek pembangunan pabrik oleokimia, terdapat pipa uap yang mengalami tegangan berlebih selama fase analisis tegangan dengan menggunakan perangkat lunak analisis tegangan. Pipa ini terhubung pada boiler atau *equipment* pembangkit uap. Perhitungan ulang diperlukan, termasuk untuk *allowable pipe span* dan fleksibilitas pipa, guna mengatasi tegangan berlebih. Pipa termasuk dalam kategori *critical line*, sehingga memerlukan analisis tegangan setelah perhitungan ulang dilakukan. Analisis tegangan dilakukan dengan menggunakan beban sustain, beban okasional, dan beban termal berdasarkan ASME B31.3. Perhitungan *allowable pipe span* yang diizinkan mengambil dari nilai terkecil antara jarak minimum berdasarkan batas tegangan dan batas defleksi, yaitu 19.006 ft, dan jumlah *support* yang dibutuhkan minimum, yaitu 22. Hasil perhitungan *allowable pipe span* diterima karena jumlah penopang memenuhi jumlah minimum yang dibutuhkan. Perhitungan fleksibilitas menghasilkan nilai yang lebih kecil dari K1, yaitu 0,000916, yang menunjukkan bahwa pipa dinyatakan fleksibel. Nilai tegangan tertinggi di *node* 688 untuk beban sustain adalah 18.389,3 psi, dan untuk beban okasional adalah 18.399 psi. Nilai tegangan tertinggi untuk beban termal, yaitu 1420,6 psi, ditemukan di node 168. Nilai tegangan untuk ketiga *load case* tidak melebihi tegangan yang diizinkan. Oleh karena itu, desain dinyatakan aman selama beroperasi.

Kata kunci: *Allowable Span; Flexibility; Occasional Load; Sustain Load; Thermal Load*

INTRODUCTION

In the construction of the oleochemical plant project, there is a steam pipe that experiences excessive stress during the stress analysis phase using stress analysis software. The pipe is connected to a boiler or steam generator equipment used to transport steam to various equipment or processes within the plant. Stress analysis on the steam pipe allows engineers and designers to identify areas that are vulnerable to structural failure or excessive deformation. By understanding the levels of stress that may occur, preventive measures or necessary repairs can be taken, such as reinforcing the pipe with additional supports, using vibration dampers, or modifying the pipe geometry. Through accurate stress analysis, the risk of structural failure in the steam pipe can be reduced, minimizing potential material losses and equipment damage. Furthermore, stress analysis plays a crucial role in ensuring compliance with applicable industrial safety standards and regulations. Stress analysis is also required because the pipe falls into the category of a critical line. According to [1], this criterion applies to cases where the piping system is connected to static equipment nozzles. Since the pipe falls under the critical line criterion, stress analysis needs to be conducted. This piping system has a flow rate of 13.3 tonnes per hour with a design pressure of 130,534 pounds per square inch (psi) and a design temperature of 417.2ºF. The piping system uses API 5L Gr. B material with a nominal pipe size of 16 inches and a STD schedule.

The weight of the pipe and fluid is considered a sustained load, thus the pipe requires support. Supports come in different types, such as hanger/support, restraint, and vibration absorber [2]. Hanger/support functions to support the weight of the piping system. Restraint functions to limit displacement caused by thermal/dynamic loads. Vibration absorber functions to limit displacement caused by vibration (wind, earthquake, and fluid flow). The determination of allowable pipe span between supports is crucial as it considers safety and cost (pipe erection) [3]. In previous studies, the determination of allowable pipe span includes the calculation of total pipe weight, maximum allowed distance between pipe supports, maximum bending stress, and deflection calculation [4]. To calculate the total pipe weight, first, the weight of the pipe, fluid, and insulation (if any) is calculated. The next step is to calculate the maximum allowed distance based on deflection and stress limits. The pipe span value is taken from the smallest value from those calculations. Several studies on flexibility calculations have been carried out. [5] states that flexibility studies of a piping system are aimed to ensure that the static stress, static force, and static deflection due to pressure and weight loads are safe. [6] defines the static analysis of a piping system influenced by weight, thermal expansion, support displacement, internal pressure, and external pressure. [7] performs stress analysis on the steam power plant piping system design using CAESAR II, especially because of hangers and expansion joints. The main objective is to obtain sufficient piping system flexibility to overcome thermal expansion loads, in addition to meeting stress and displacement criteria. [8] conducts research on flexibility calculations using the simplified flex analysis method that shows the pipe path to determine whether the system is flexible or not. According to [9], stress analysis is an activity to obtain the behavior of the piping system. [10] performs stress analysis on the vertical loop connected to the equipment. Stress analysis includes sustained, occasional, and thermal expansion loads as well as nozzle load analysis using the pump operating method and values taken from design and operating conditions. In this study, the calculation of allowable pipe span, flexibility calculation, and stress analysis will be carried out based on sustained, occasional, and thermal expansion loading conditions as well as nozzle load analysis with reference to [10] and [11]. The analysis is performed using stress analysis software to determine the stress and load received by the system.

METHOD

Maximum Allowable Pipe Span

The Maximum Allowable Pipe Span calculation is performed to determine the maximum distance between supports. The allowable span calculation uses imperial units for all measurements.

$Wpipe = \frac{\pi}{4}\ x\ (OD^2 - ID^2)\ x$ Density Pipe $x\ length$ ….. (1)

Wfluid = $\frac{\pi}{4}\ x\ (ID^2) x\ length\ x\ Density\ of\ Fluid$ ….. (2)

Wvalve = (Gate valve 16" & Flange "$/length$) ….. (3)

Supports for pipes must be spaced based on three considerations: [12]

a. The ability to place supports in the desired location.
b. The allowable distance between supports.

Avoiding excessive permissible stress and load concentration between supports. The conditions of limitation of stress and limitation of deflection based on the weight of the pipe, fluid, and valve can be calculated using the formula from [6], which is:

Based Limitation of Stress

$$Ls = \sqrt{\frac{0.4xZxSh}{W}} \quad ….. (4)$$

Based Limitation of Deflection

$$Ld = \sqrt[4]{\frac{\Delta EI}{22.5xW}} \quad ….. (5)$$

Perhitungan Support

$$\sum s = \frac{Lpipa}{Ls} \quad ….. (6)$$

Pipe Flexibility Analysis

This pipe flexibility analysis will be conducted on the steam line. The value of pipe flexibility can be determined using Equation (7) by finding several variables contained in the equation. The steps to obtain these variables are described below, with reference to [11].

$$\frac{DY1}{(L-U)^2} \leq K1 \quad ….. (7)$$

Stress On The Pipe

The stress that occurs in a piping system can be divided into two categories: normal stress and shear stress. Normal stress includes longitudinal stress, tangential stress, and radial stress. Here are the explanations and formulas to obtain each value of longitudinal stress.

Axial Stress

$$F_{ax} = P\ x\ Ai \quad ….. (8)$$

$$A_i = \frac{\pi(ID^2)}{4} \quad …..(9)$$

$$A_m = \frac{\pi(ID^2 - OD^2)}{4} \quad …..(10)$$

$$S_a = \frac{F_{ax}}{A_m} \quad ….. (11)$$

- Longitudinal Srress

$$S_b = \frac{\sqrt{(i_i M_i)^2 + (i_o M_o)^2}}{Z} \quad ….. (12)$$

- Torsional Stress

$$S_t = \frac{Mt}{2Z} \quad ….. (13)$$

So, longitudinal stress according to [11] is

$$SL = \sqrt{(|S_a| + S_b)^2 + (2S_t)^2} \quad ….. (14)$$

Tangential stress, also known as Hoop stress, is a stress caused by the internal pressure that acts tangentially.

$$SH = \frac{PxIDxL}{2xLxt} = \frac{PxID}{2xI} = \frac{PxOD}{2xt} \quad ..... (15)$$

The stress that has the same direction as the radial axis is called radial stress. This stress is in the form of compressive stress (negative) when it is compressed from the inside of the pipe due to internal pressure, and in the form of tensile stress (positive) if there is a vacuum pressure inside the pipe.

$$Rm = \frac{ro+ri}{2} \quad ..... (16)$$

$$SR = \frac{P(ri^2+\frac{ri^2+ro^2}{rm^2})}{ro^2+ri^2} \quad ..... (17)$$

Allowable Stress

The equation to determine the actual value against the allowable limit for each loading is explained as follows [11].

Allowable Stress due to Sustain Load

The amount of longitudinal stress (SL) caused by pressure, pipe weight, and all components in the piping system is a sustained load that must not exceed the allowable stress (Sh). Sh is obtained from [11]. The allowable stress value for sustained load conditions is determined based on the following equation

$$SL = \sqrt{(|S_a| + S_b)^2 + (2S_t)^2} < Sh \quad ..... (18)$$

Allowable Stress due to Occasional Load

Based on [11], in provision 302.3.6, it is stated that the total longitudinal stress caused by pressure, weight, and other sustained loads, as well as stress resulting from occasional loads such as wind or earthquake, should not exceed 1.33 times the basic allowable stress (Sh).

S due to Occasional load ≤ 1.33Sh ..... (19)

Allowable Stress due to Exspansion Load

The allowable stress due to thermal expansion that occurs in a pipe material and its components due to repeated thermal loading is determined based on [11] in provision 302.3.5.

S due to Thermal load ≤ S_A

$$S_A = f\ (1.25(Sc + 0.25Sh) \quad ..... (20)$$

RESULTS AND DISCUSSION

Pipe Specification

The technical specifications data for the pipe is shown in Table 1, and the fluid specification data is shown in Table 2.

Table 1. Pipe Specification (Material Data)

Description	N	Value	Unit
Outside Diamater 16”	OD	16	inch
Inside Diamater 16”	ID	15.25	inch
Density Pipe	$\rho Pipe$	*0.2836*	lb/in ^{3}
Section Modulus	Z	70.261	inch^3
Moment Inertia	I	562.08	inch^4
Modulus Elasticity	E	27300000	psi
Allowable Stress	S	19745	psi
Max Allowable Stress	Sa	20000	psi
Allowable Deflection	Δ	0.625	inch

Note: Pipe Material API 5L Gr.B SCH STD

Table 1 Fluid Specification (Fluid Steam)

Description	Notation	Value	Unit
Density Fluid	ρFluid	0.05166	lb/in^3
Design Pressure	P (ds)	130.534	psi
Design Themperature	T (ds)	417.2	(F)

Maximum Allowable Pipe Span

In this work, Equations (4) and (5) were used. The calculated value based on the stress limit is 19.006 ft, while the calculated value based on the deflection limit is 27.616 ft. The minimum distance between supports was determined based on the smallest value between the minimum distance calculated from the stress limit and the deflection limit. Therefore, the value used is based on the stress limit of 19.006 ft with a total of 22 supports.

Pipe Flexibility Analysis

The calculation refers to Equation (7). The result of the pipe flexibility calculation is 0.000916. This value is still below the K1 requirement, indicating that the calculation result can be considered flexible. The flexibility analysis calculation can be seen in Table 3.

Table 2 Data and Calculation Results of Pipe Flexibility Analysis

DESCRIPTION	*VALUE*	*UNIT*
L pipe X	185.7382	*ft*
L pipe Y	98.6581	*ft*
L pipe Z	147.9364	*ft*
Coefficient B	3.7	*in./100ft*
ΔX	-30807	*in*
ΔY	-443	*in*
ΔZ	10333	*in*
Resultant Displacement (Y)	-0.0538	*in*
L total	432.3327	*ft*
Distance between two anchors (U)	169.7946	*ft*
Factor (f)	0.95	-
S hot	19745	*psi*
Sa	28439.4375	*psi*
Ea	27300000	*psi*
K1	0.0313	-
$\frac{DY1}{(L-U)^2}$	0.000916	-

Table 3 Output Stress on Stress Analysis Software

No	*Load* Case	*Code Stress* (lb/in²)	*Allowable Stress* (lb/in²)	*Ratio* (%)
1	L3 (*SUSTAINED*) L3 = W + P1	18389.3	19745	93.1
2	L4 (*OCCASIONAL*) L4 = W + P1 + U1	18399	26261.5	70.1
3	L5 (*EXPANSION*) L5 = L1 – L3	18641.4	43384.5	43

Stress due to Sustain Load

The stress value calculations refer to equation (18). Table 4 shows the stress output results in several segments of the steam pipe route. The highest stress value is found at node 688 with a value of 18389.3 psi. These results indicate that the highest stress value due to sustained loading is still below the allowable limit for the design condition.

Stress due to Occasional Load

The calculation of stress values refers to equation (19). Table 4 shows the stress output results in several segments of the steam pipe line. The highest stress value is at node 688 with a value of 18399 psi. This result shows that the stress value due to occasional loads in the design condition is still below the allowable limit.

Stress due to Exspansion Load

The calculation of stress due to thermal expansion loading refers to equation (20). Table 4 shows the output stress results for several segments in the steam pipe route. The highest stress value is at node 168 with a value of 18641.4 psi. This result indicates the stress value due to thermal expansion loading in the design condition is still below the allowable limit.

CONCLUSION

Based on the calculation and analysis results, the calculated allowable pipe span is acceptable because the number of supports has met the minimum required. The flexibility calculation is still below the requirement, so the pipe can be considered flexible. The stress values from all three load cases are still below the allowable stress based on [11], indicating no issue for the design directly attached to the equipment.

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