Research Article

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Numerical evaluation of expansion loops for pipe subjected to thermal displacements

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Abstract: The thermal expansion can lead to the high stress on the pipe. The problem can be overcome using expansion loops in a certain length depending on the material's elastic modulus, diameter, the amount of expansion, and the pipe's allowable stresses. Currently, there is no exact definition for the dimension of expansion loops design both for loop width (W) and loop footing height (H) sizes. In this study, expansion loops were investigated with using ratio of width and height (W/H) variations to understand pipe stress occurring on the expansion loops and the expansion loops' safety factor. Relationship between non dimensional stress on the expansion loop pipe was studied numerically by finite element software on several working temperatures of 400°F, 500°F, 600°F, and 700°F. It can be found that stress occurring on the pipes increases as the increases of W/H of the expansion loops and results in a lower safety factor. The safety factor of the expansion loops pipe has a value of 1 when the ratio of loop width and loop footing height (W/H) value was 1.2 for a 16-inch diameter pipe. Stress occurring on the pipe increases with the increase of the working temperature. Expansion loops pipe designed for 400°F can still work well to handle thermal extension pipe occurring on 500°F.

Keywords: Thermal expansion, expansion loop, safety factor

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1 Introduction

Thermal expansion on a pipe is one of the problems in designing a piping system because it can lead to high stress on a pipe. This case can cause fatal damage to the system. Therefore, the study and design are necessary to avoid damaged piping systems due to the thermal expansion [1]. One of the methods used to prevent damage to the piping system is by using expansion loops that can be used to increase designed piping system flexibility [2]. Huang *et al.* [3] have confirmed that flexible branch heat pipe has a larger maximum heat load than the straight pipe. Meanwhile, the other study showed that a flexible pipe with a repeated unit cell had a strong correlation between the repeated unit cell model and the analytical models with some difference in the wire bending stresses [4]. This research also found that the repeated unit cell model is robust and computationally efficient for analyzing flexible pipes [4]. Tang *et al.* [5] have analyzed that an increase in the winding angle of the tensile armor wires and damage to the outer sheath of the flexible pipe decreased the compressive stiffness significantly. Yoo *et al.* [6] have analyzed flexible pipes which aims to improve the convergence of nonlinear analysis by simplifying interactions between layers. The result showed the model was subjected to incremental axial tension, and the overall stiffness decreases due to the progressive failure of tensile armour layers. The inner tensile armour yields first, and the outer tensile armour layer follows. Moreover, Hastie *et al.* [7] have confirmed that increasing the internal temperature causes a drastic rise in the inner liner failure coefficient of pipe under low pressure. Thermal expansion occurring on the pipe depends on the expansion coefficient of the pipe material during working temperature and pipe length. Value of expansion coefficient during work temperature can be found on American Society of Mechanical Engineers (ASME) B3 1.1 about Power Piping ASME Code for Pressure Piping [8]. Jaćimović [9] believes that there might be an issue with the code philosophy concerning the thermal expansion stress range. An overstressed piping element may be deemed acceptable. Total occurring expansion on the pipe over working temperature is based on the design of the piping system [10]. Alhussainy *et al.* [11] have studied small tubes under axial compression and concluded that failure of the small tube due to axial compression was influenced by the ratio of unsupported length to the outside diameter (L/D) value used during the study. When the L/D ratio of the steel tube increased, the ultimate compressive strength will decrease. Moreover, Yudo and Yoshikawa [12] have stated that the buckling moment of a pipe will decrease the more irregular the shaped the pipe is. Buckling moment reduction of the irregular pipe is higher for shorter pipe compared to longer pipes.

Further, Yudo *et al.* [13] have studied using rectangular hollow pipe and concluded that critical moment occurring in the rectangular hollow pipe would increase along with the increase of pipe thickness. Xie *et al.* [14] have investigated the dynamic loading history of the pipe during the S-lay operation based on a test-verified finite element model, and the results have confirmed that the deep-water S-lay operation will lead to obvious plastic deformation of the pipe, which decreases the pipe collapse capacity to some extent. Shehadeh *et al.* [15] have researched the expansion loop in which the result shows that stress occurring in the expansion loop will be lower along with the increase of loop footing height (H) value on the expansion loop with constant loop width (W). Then, Rao *et al.* [16] have proved that using expansion loop and spring supports could be a decrease of stress that occurred in the pipe subjected to operational load and expansion load. Therefore, to make sure that the stresses in the pipe are within the allowable limit. With CAESAR II software version 5.30, Verma *et al.* [17] have analyzed the piping system of high-pressure and high temperature, which produces significant deflections and thermal expansions in the piping network. The flexible loop patterns are used to avoid excessive stresses in the piping network. In the expansion loop pipes, there exists a curve pipe, whether elbow pipe or bend pipe. Yudo and Yoshikawa [18] have explained that the buckling moment will decrease along with reducing the ratio of the curvature radius of curved pipe to diameter of cylinder (R/D) value. Kang *et al.* [19] have mentioned that the relevant equations can be used to estimate the maximum withstand load evaluation of a highly ductile pipe and can also be used to estimate the elastoplastic fracture mechanics parameters using the reference stress method. Sorour *et al.* [20] have studied that the presence of the residual stresses remarkably reduces the pipe bend load-carrying capacity.

Although a majority of previous investigations have been reviewed to explore the development of expansion loop design. There is limited study in the comprehensive assessment of expansion loop design to assess the influence of geometric, thermal and mechanical design parameters on the pipe safety. The issue is crucial since the result could be guidelines for the design of expansion loops in pipeline systems. To address this issue, numerical assessment of expansion loops of pipe subjected to thermal displacements is evaluated. The relationship between non dimensional stress on the designed expansion loop pipe was studied by nonlinear finite element analysis (FEA) on several working temperatures of 400-700°F. The pipe material used for a high-temperature study based on the Piping Materials Guide is American Standard Testing and Material (ASTM) A 106 [21]. In this case, the design parameter used was the ratio between loop width and loop footing height (W/H) with 12 total variations analyzed in three different nominal pipe sizes.

2 Description of numerical method

In this work, simulations are implemented numerically using a finite element software package. The finite element method is a numerical technique ideally suited to digital computers in which a model is discretized into smaller but finite sub-structures (element) that can be represented by equations. For modelling and simulation purposes, the physical parameters of the expansion loop need to be defined in the first step. Then, the simulations are performed using nonlinear finite element analysis to investigate the influence of the mentioned parameters on the structural behaviour.

2.1 Calculation parameters

The expansion loop studied in this study was an asymmetrical expansion loop with three pipe spans and an expansion loop located in the middle span as shown in Figure 1. The loop length used can be seen in Table 6. Required total expansion loop length/bend length (L_2) to absorb thermal expansion of the pipe can be calculated using Eq. (1). Moreover, the bending radius of the expansion loop pipe was designed using a short bend radius. Abdalla [22] has observed that the combined load carrying capabilities increase as the number of milter welds increases. Balakrishnan *et al.* [23] have studied that ratcheting was the principal reason for failure for long bend radius elbows. In contrast, for short bend radius elbows, reserved plasticity was the reason for failure.

$$L_2 = \sqrt{\frac{3ED\Delta}{144\sigma_A}} \quad (1)$$

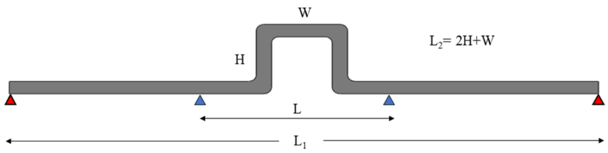

Figure 1: Symmetrical Expansion Loop.

$$L_2 = W + 2H \tag{2}$$

Where:
L_2 is bend length required to absorb expansion (ft), E is modulus of elasticity of pipe (psi), D is outside pipe diameter (inch), Δ is expansion to be absorbed by the loop (inch), σ_A is pipe allowable stress (psi), W is loop width (ft), and H is loop footing height (ft).

In this study, stress analysis of the expansion loops pipe designed for 400°F was conducted using ASTM A106 Grade A used as a material with 16 inches, 20 inches, and 24 inches of nominal pipe size (NPS) with the thickness of 0.2 inches. The parameter used was the ratio between loop width and loop footing height (*W/H*). Variations of W/H used in this study were 0.25, 0.5, 0.75, 1, 1.05, 1.1, 1.15, 1.2, 1.25, 1.5, 1.75, 2. The parameter used for 16, 20 and 24-inch diameter can be seen in Table 1. Yu *et al.* [24] have explained that J-integral resistance curve, critical initial fracture toughness, critical initial fracture toughness stretch zone width method, and stress zone width are higher at lower crack depth ratios and gradually decrease with increasing crack depth. Expansion loop model designed to work at 400°F temperature with W/H 0.25, 0.5. 0.75 and 1 will be studied using displacement changes due to thermal expansion from 400°F up to 700°F, which are shown in Table 2.

2.2 Model and applied boundary condition

Models will be studied at 400°F working temperature, so the distance between the guide (*L*) and distance between anchor (*L1*) are obtained, which is shown in Table 3. Loop required length to control pipe expansion at 400°F is shown in Table 4. The full model of pipe with expansion loops was investigated with FEA-based software.

The boundary used in this study was the single point constraint (SPC) which restricts the movement of a single node in any of 6 degrees of freedom (dof). The degree of freedom in SPC consisted of translation X, Y, Z (dof1, dof2, dof3) and rotation of X, Y, Z (dof4, dof5, dof6). SPC was added in anchor, guide, and middle section of loop parts according to Figure 2. SPC on anchor part has dof1= dof2=dof3=dof4=dof5=dof6=0, SPC on guide part was dof2=dof3=0, and SPC on middle part of loop is dof1=0. The weight used was displacement change on the anchor parts, which was equal to total expansion on the pipe. Weights were added into both anchor parts, valued half of the total expansion in each anchor towards opposite directions, as shown in Figure 2. The weight used in the analysis of model 400°F with temperature variations was half of the total expansion value, as shown in Table 4 inputted using displacement change in each anchor.

Table 1: Parameters of expansion loop pipe at 16, 20, 24-inches pipe diameters.

		16-inch		20-inch		24-inch	
Nr.	W/H	W (ft)	H (ft)	W (ft)	H (ft)	W (ft)	H (ft)
1	0.25	4.2	16.9	4.2	16.9	5.6	22.2
2	0.5	7.6	15.2	7.6	15.2	10	20
3	0.75	10.4	13.8	12	16	13.6	18.2
4	1	12.7	12.7	14.7	14.7	16.7	16.7
5	1.05	13.1	12.5	15.1	14.4	17.2	16.4
6	1.1	13.5	12.3	15.6	14.2	17.7	16.1
7	1.15	13.9	12.1	16.1	14	18.3	15.9
8	1.2	14.3	11.9	16.5	13.8	18.8	15.6
9	1.25	14.6	11.7	16.9	13.5	19.2	15.4
10	1.5	16.3	10.9	18.9	12.6	21.4	14.3
11	1.75	17.7	10.1	20.5	11.7	23.3	13.3
	2	19	9.5	22	11	25	12.5

Table 2: Analytical parameter of different temperature.

NPS (inch)	400 (°F)	500 (°F)	600 (°F)	700 (°F)
16	2.940	3.885	4.935	5.985
20	3.276	4.329	5.499	6.669
24	3.528	4.662	5.922	7.182

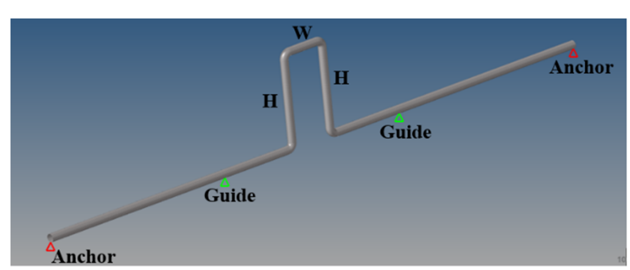

Figure 2: Applied boundary condition.

The method used in this study was nonlinear static analysis with 3D solid element mesh. The solid element in

Table 3: Anchor and guide distance.

NPS (inch)	L (ft)	L_1 (ft)
16	35	105
20	39	117
24	42	126

Table 4: Required loop length.

NPS (inch)	Total Expansion (inch)	L_2 (ft)
16	2.940	38
20	3.276	44
24	3.528	50

finite element analysis has certain advantages compared to the shell and has desirable characteristics in numerical calculations: i.e., the solid element has no geometric limitations, requires no geometric preprocessing, and allows stress and strain to be profiled through the thickness. The selection of a 3D solid element is based on the result of a validation test between numerical test and analytical calculation in Table 5. The recorded stress of a 16-inch diameter pipe with $W/H = 1$ using 3D solid model discretization has good agreement with the analytical result, indicating small error compared with shell-based discretization. Furthermore, the mesh size used was 1 unit, with 0.25 units in width in this case. The total node amount in the pipe diameter parts was increased to get a better mesh shape, which total node was 336 for the 16-inch diameter pipe, 420 nodes for the 20-inch diameter pipe, and 502 nodes for the 24-inch diameter pipe, as shown in Figure 3.

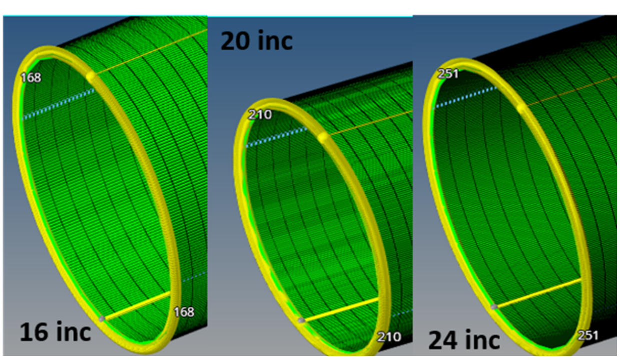

Figure 3: The number of nodes in each pipe diameter variation models.

3 Numerical result and discussion

The purpose of the FEA results discussion is to describe the relationship between the stresses that occurred in the designed expansion loop pipe and thermal displacement. In the first part, a discussion of the calculation results of 12 W/H variations at a 400°F working temperature is presented. In the last part, the influence of increasing working temperature on the designed expansion loop pipe with 4 W/H variations is discussed.

3.1 Calculation result on design temperature

The pipe will undergo thermal expansion which values are based on the pipe length and working temperature following Table 4. Thermal expansions are occurring in the expansion loop pipe cause the pipe to undergo stresses on the pipe bend expansion loop, as shown in Figure 4.

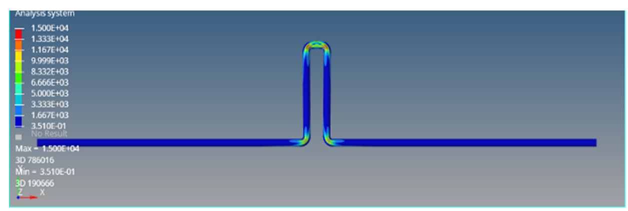

Figure 4: Stress occurring in the expansion loop pipe.

Figure 5 indicates the correlation between stress occurring in the pipe with the W/H value of the expansion loops when thermal expansions occur on the 16-inch, 20-inch, and 24-inch diameter pipes for 400°F working temperature, as shown in Table 2. The vertical axis shows the non-dimensional unit of stress (σ_A/σ) where σ_A is allowable strees given by ASME code B31.3 [1] and σ is stress occurred in the pipe. The lowest recorded stress occurs in the expansion loop with W/H value of 0.25, and the highest recorded stress in the expansion loops with W/H value is ∞ (straight pipe). Pipe stress will increase along with an increase in W/H value. Stress occurring on the pipe caused by the thermal expansion will have a higher value if the W/H value is higher. The non-dimensional unit of stress (σ_A/σ) of the 16-inch diameter pipe has the value of 1 when the W/H value is equal to 1.2. This means that expansion loops which W/H values equal to 0.25 up to 1.2 can work properly in dealing with thermal expansion of the pipe, while expansion loop stress which W/H from 1.4 to ∞ cannot work correctly in dealing with thermal expansion of the pipe.

Table 5: Validation test between numerical test and analytical calculation.

Model discretization	Stress of pipe at W/H=1 (psi)		Error (%)
	Numerical test (present study)	Analytical calculation based on ASME B31.3	
3D Solid element	1.926 x 104	1.884 x 104	2.2
Shell element	2.787 x 104	1.884 x 104	47.9

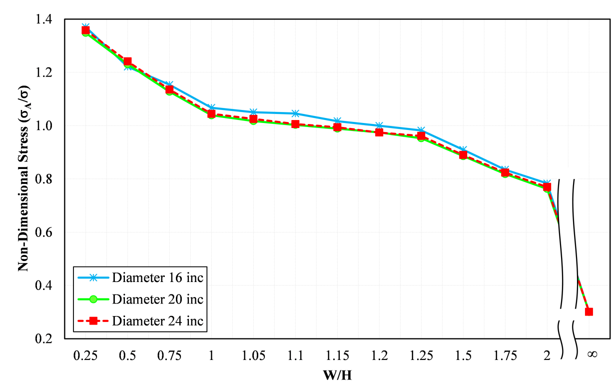

Figure 5: Relationship between σ_A/σ with *W/H* of Expansion Loop at 400°F temperature.

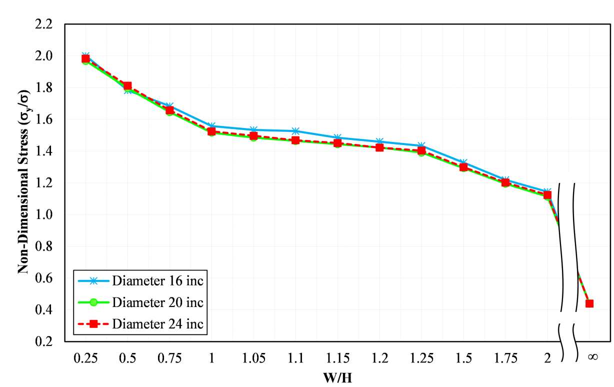

Figure 6: Relations between σ_y/σ with W/H of expansion loop at 400°F temperature.

Stress occurring on the pipe caused by the thermal expansion will have a higher value when the W/H value is higher. The non-dimensional unit of stress (σ_A/σ) of the 20-inch diameter pipe has the value of 1.003 when W/H= 1.1, this means that expansion loops with W/H values of 0.25 up to 1.1 can work properly in handling the thermal expansion of the pipe while the expansion loop stresses of the pipe which W/H= 1.5 up to W/H=∞ is unable to work properly in handling the thermal expansion of the pipe. Stress occurring on the pipe due to thermal expansions will have a higher value if the W/H is of higher value. Non dimensional stress (σ_A/σ) of the 24-inch diameter pipe has the value of 1.006 when W/H= 1.1, which means that expansion loops with W/H values = 0.25 up to 1.1 can work properly in handling the thermal expansion of the pipe while for expansion loop stress of those with W/H= 1.15 up to W/H=∞ is unable to work properly in handling the thermal expansion of the pipes.

Figure 6 shows the relation between stress occurring on the pipe with W/H value of the expansion loops when thermal expansion is occurring on the 16 inches 20 inches, and 24-inch diameter pipes at 400°F working temperature as shown in Table 4. The vertical axis shows the non-dimensional unit of stress (σ_y/σ) where σ_y is yield stress of the material given by ASTM 106 [21] and σ is stress occurred in the pipe. Non dimensional unit of stress (σ_y/σ) on the 16, 20, 24-inch diameter pipe which W/H value 0.25 up to W/H= 2 shows values of more than 1 that means expansion lops pipe with W/H value = 0.25 up to 2 for 16, 20, 24-inch diameter pipe are experiencing lower stress value of the pipe yield stress. Straight pipe (W/H=∞) with 16, 20, 24-inch diameter will undergo stress that exceeds yield stress on the pipe, hence the pipe will be damaged due to thermal expansion of the pipe with 400°F temperature. Hence it can be proven that the use of an expansion loop can prevent damage to the piping system due to thermal expansion of the pipe. In previous study, Shehadeh *et al.* [15] conducted a parametric evaluation to optimize the dimensions of the expansion loop in accordance with ASME B31.3. The effect of reducing length of the loop (L) and width (W) was investigated. It can be found from the result that expansion case cannot be affected significantly while reducing width of the loop. Furthermore, systematic investigation of thermal expansion using another design parameter (W/H) is crucial to be investigated comprehensively.

3.2 Calculation result on increasing temperature

Expansion loop with 0.25, 0.5, 0.75, and 1 W/H value designed for 400 °F temperature is studied by applying temperature increase up to 700°F. The higher the working temperature is, the highest the occurring thermal expansion, as shown in Table 2. Figure 7 shows relations between stress occurring on the pipe with 400°F up to 700°F working temperature as shown in Table 2 on the 16-inch pipe diameter with 0.25, 0.5 0.75, and 1 W/H values. The vertical axis represents the Non dimensional unit of stress (σ_A/σ). The higher working temperature of a pipe leads to higher thermal expansion and increases the stress value of the pipe. Hence the σ_A/σ value is lower. Figure 8 shows the relations between stress occurring on the pipe with 400°F up to 700°F as shown in Table 2 on the expansion loops with the 16-inch diameter with 0.25, 0.5 0.75, and 1 W/H value. The vertical axis shows a non-dimensional unit of stress (σ_y/σ). Higher working temperature causes the pipe to undergo higher thermal expansion and increase of stress value on the pipe, so the (σ_y/σ) is lower. Pipe will be damaged if the working temperature reaches 700°F because stress occurring is exceeding yield strength represented in 0.982 (σ_y/σ) value for W= 0.25H, 0.9 for W= 0.5H, 0.827 for W= 0.75H and 0.765 for W= H.

Figure 9 shows relations between the stress of the pipe with 400°F working temperature up to 700°F as shown in Table 4 on the 20-inch diameter expansion loops pipe with 0.25, 0.5 0.75, and 1 W/H value. The vertical axis represents the non-dimensional unit of stress (σ_A/σ). Higher working temperature causes the pipe to undergo higher thermal expansion and increase in stress value. Thus the (σ_A/σ) value is lower. Figure 10 shows relations between the stress of the pipe with 400°F working temperature up to 700°F as shown in Table 4 on the 24-inch diameter expansion loops pipe with 0.25, 0.5 0.75, and 1 W/H value. The vertical axis represents the non-dimensional unit of stress (σ_A/σ). The vertical axis represents the non-dimensional unit of stress (σ_y/σ). Higher pipe working temperature causes the pipe to undergo higher thermal expansion and causes an increase of stress value, so the (σ_y/σ) is lower. Pipe will be damaged if the working temperature reaches 700°F because the stress value exceeds yield stress represented by σ_y/σ valued 0.967 for W = 0.25H, 0.882 for W = 0.5H, 0.808 for W = 0.75H and 0.745 for W = H.

Figure 11 indicates the relation between stress that is occurring on a pipe with a working temperature of 400°F up to 700°F shown in Table 4 on the 24-inch diameter expansion loops pipe with W/H 0.25, 0.5 0.75, and 1 value. The vertical axis indicates non-dimensional stress (σ_A/σ). The higher the working temperature of the pipe causes a large thermal expansion of the pipe, and this leads to the stress value of the pipe increase so that the value of σ_A/σ will be lower. Figure 12 indicates the relation between stress that is occurring on the pipe with working temperature 400°F up to 700°F shown in Table 2 on the 24-inch diameter expansion loops pipe with W/H 0.25, 0.5 0.75, and 1 value. The vertical axis indicates non-dimensional stress (σ_y/σ). The higher the working temperature of the pipe causes a large thermal expansion of the pipe and leads to the stress value of the pipe increase so that the value of (σ_y/σ) will be lower. The pipe will be damaged when the working temperature reaches 700°F because the stress that occurs will exceed the yield stress value of the pipe that shown with (σ_y/σ) valued 0.974 for W= 0.25H, 0.890 for W= 0.5H, 0.814 for W= 0.75H, and 0.749 for W=H.

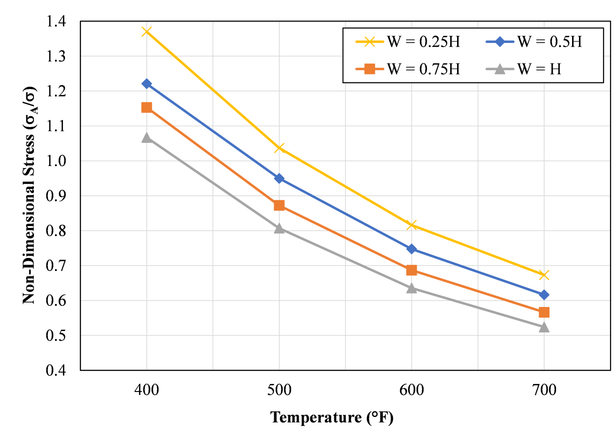

Figure 7: Relationship between σ_A/σ of the 16-inch diameter expansion loops pipe with increasing temperature.

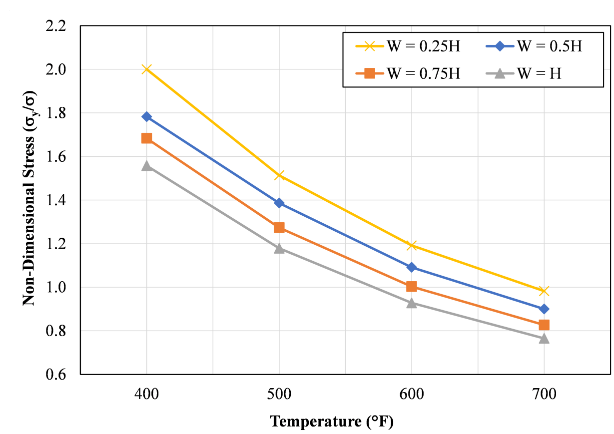

Figure 8: Relationship between σ_A/σ of the 16-inch diameter expansion loops pipe with increasing temperature.

Figure 13 indicates the relation between stress that occurring on the expansion loop pipe with pipe diameter for expansion loop pipe designed for working temperature 400°F. The vertical Axis indicates non-dimensional stress (σ_A/σ). The stress change that occurs on the expansion loop pipe along with the increasing diameter pipe indicates that the value is too significant because the loop length design

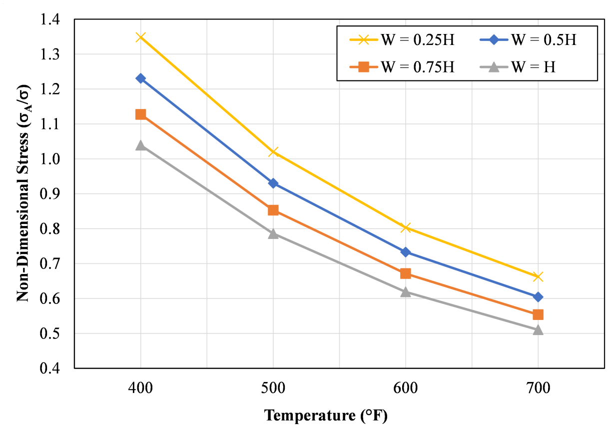

Figure 9: Relationship between σ_A/σ on the expansion loop pipe 20-inch diameter with increasing temperature.

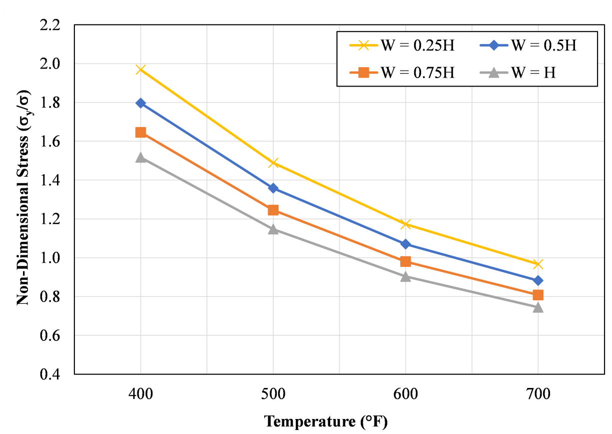

Figure 10: Relationship between σ_y/σ on the expansion loop pipe 20-inch diameter with increasing temperature.

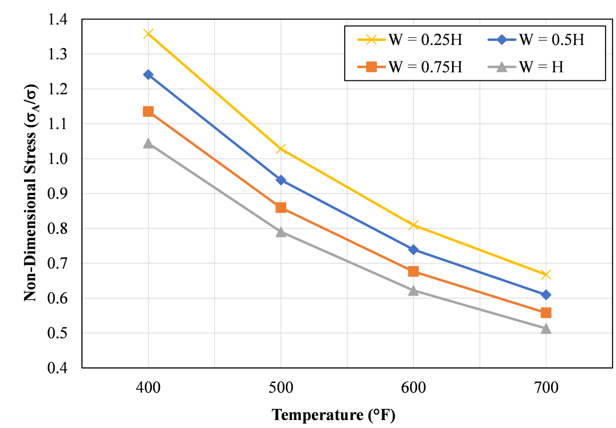

Figure 11: Relationship between σ_A/σ on the expansion loop pipe 24-inch diameter with increasing temperature.

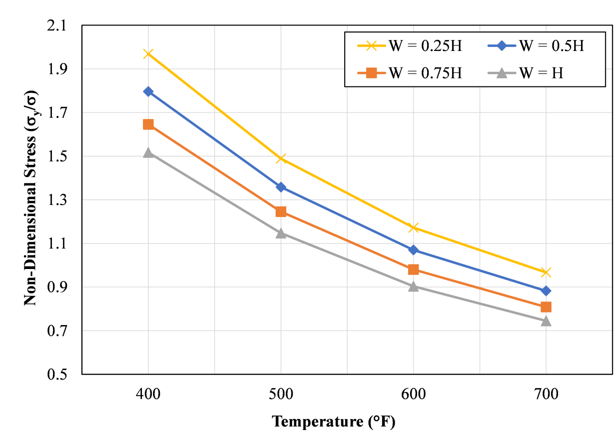

Figure 12: Relationship between σ_y/σ on the expansion loop pipe 24-inch diameter with increasing temperature.

is adjusted with the required minimum loop length to overcome the expansion thermal in 400°F temperature based on Eq. (3). The larger the pipe diameter, the higher the expansion and the longer the loop length. Expansion loop With W= 0.25H designed for working temperature 400°F can still working well in overcoming the expansion that occurs when the working temperature increases to 500°F in diameter 16, 20, and 24 inches because it shows a value (σ_A/σ) more than 1. When the temperature reaches 600°F or even higher, so the expansion loop no longer works properly in overcoming the thermal expansion that occurs in the pipe. Figure 14 show the relationship between stress that occurring on the expansion loop pipe with pipe diameter for expansion loop pipe designed for working temperature 400°F. The vertical Axis indicates non-dimensional stress (σ_y/σ). It shows that the non-dimensional stress (σ_y/σ) will be decreased with increasing the value of W/H or increasing the working temperature on the pipe. The expansion loop can work properly when the value of σ_A/σ is lower than 1, and the expansion loop will be damaged when the value of σ_y/σ is lower than 1. The pipe will be damaged when the working temperature increases to 700°F. When the working temperature increases to 600°F, it will inflict damage to the pipes for pipes with expansion loop W= H in diameters 16, 20, and 24 inches and W= 0.75H for diameters 20 inches and 24 inches shown by the value σ_y/σ less than one which mean the stress that occurs in the expansion loop pipe exceed the yield stress value of the pipe that can be seen in Figure 14. The value of σ_A/σ for W/H=∞ (straight pipe) when the working temperature is 400°F will be lower than others W/H when the working temperature increase until 700°F that can be seen in Figure 13, and the value of σ_y/σ for W/H=∞ (straight pipe) when the working temperature is 400°F will be lower than others W/H when the working temperature increase until 700°F that can be seen in Figure 14.

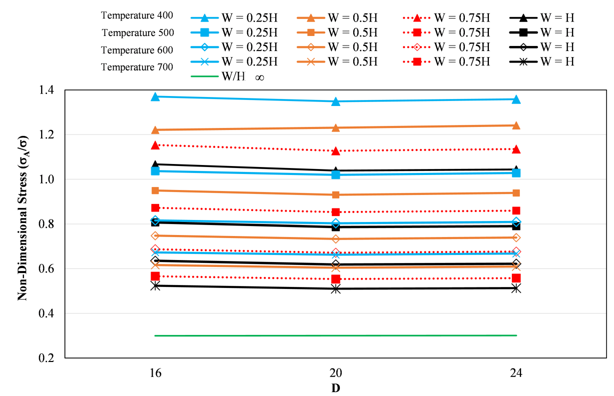

Figure 13: Relationship between σ_A/σ with the pipe diameter (inch).

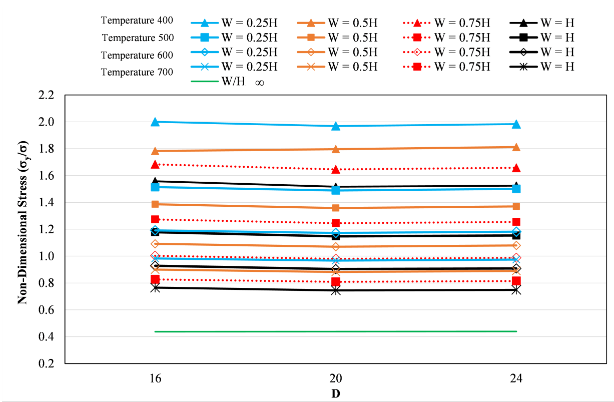

Figure 14: Relationship between σ_y/σ with the pipe diameter (inch).

4 Conclusion

In this study, an analysis of the stress that occurs in the expansion loop pipe was carried out due to the thermal expansion that occurred in the pipe by the working temperature using FEA Software. The following are the result obtained based on the results of the analysis. Stress in the expansion loop occurred at the pipe bend of the pipe. Stress in the expansion loop pipe will be larger as the W/H value increase in the expansion loop pipe. The pipe safety factor will be decreased as the W/H value increases in the expansion loop. The expansion loop can be used to prevent damage to the pipe due to thermal expansion in the pipe. The stress that occurred in the expansion loop pipe will increase with increasing the working temperature pipe. Moreover, the difference in pipe diameters had a slight effect on the stress that occurred on the pipe if the expansion loop used was adjusted to the minimum $L2$ required to overcome the thermal expansion of the pipe. The expansion loop pipe with a W/H 0.25 value can still overcome thermal expansion for an increase in temperature to 500°F. All expansion loop will be damaged when the working temperature increased to 700°F.

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