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Stress Analysis of Steam Piping System

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Abstract

This is about the design of steam piping and its stress analysis of a given process flow diagram. The prime objective of this project is to design the piping system and then to analyze its main components. Wall thicknesses are calculated for all pipes which were found very safe for the operating pressure. For header pipe the calculated wall thickness is 0.114 inch and the standard minimum wall thickness is 0.282 inch which is greater than the calculated one by more than 2.4 times. Different loads such as static loads, thermal loads of all pipes were also calculated. After load calculations, spacing supports carried out. Thermal and static analysis of main system pipe has been done and results were compared with ASME Power Piping Code B31.1. After calculation of all applied loads, standard circular column of 4 inch nominal size were designed and analyzed both manually and on ANSYS software. The results obtained from both methods were compared and found safe under available applied loads.

Keywords: Code B31.1; ANSYS; Steam piping

Introduction

Piping System design and analysis is a very important field in any process and power industry. Piping system is analogous to blood circulating system in human body and is necessary for the life of the plant. The steam piping system, mentioned in the project will be used for supplying steam to different locations at designed temperature and pressure. This piping system is one of the major requirements of the plant to be installed [1]. The goal of quantification and analysis of pipe stresses is to provide safe design. There could be several designs that could be safe. A piping engineer would have a lot of scope to choose from such alternatives, the one which is most economical, or most suitable etc. Good piping system design is always a mixture of sound knowledge base in the basics and a lot of ingenuity. The aim of the project is to design and analyze piping system according to standard piping Codes. The design should prevent failure of piping system against over stresses due to: Sustained loadings which act on the piping system during its operating time. While piping stress analysis is used to ensure:

1) Safety of piping and piping components

2) Safety of the supporting structures

Basically the sizing of this steam piping has already done and contained nearly on $750 \times 300 m^2$ area, including 48 pipes and 52 junctions [2]. The detail of the piping system e.g. length of each pipe, Nominal Pipe Size (NPS) with pipe no. starting from 208 and ending on pipe no. 256 are shown from the following Figure 1. The rest of the data e.g. inlet and out let velocities of each pipe, inlet and out let pressure of each pipe and inlet and out let temperature of each and every pipe are arranged which will be used in further calculations.

This project is about the design of steam piping and its stress analysis of a given process flow diagram. The prime objective of this project is to design the piping system and then to analyze its main components (Figure 2).

This project includes the following tasks:

a) Process design of the complete piping system

b) Structural design of the pipes manually

c) Stress analysis of the pipes using ANSYS or compatible CAE software

d) Structural design of supports manually

Piping Standard and Codes

Before the selection of codes for the steam piping, a little detail about codes, standards and its historical background is given below.

Piping code development

The increase in operating temperatures and pressures led to the development of the ASA (now ANSI) B31 Code for pressure piping. During the 1950s, the code was segmented to meet the individual requirements of the various developing piping industries, with codes being published for the power, petrochemical and gas Transmission industries among others. The 1960s and 1970s encompassed a period of development of standard concepts, requirements and methodologies. The Development and use of the computerized mathematical models of piping system have brought analysis, design and drafting to new levels of sophistication. Codes and standards were established to provide methods of manufacturing, listing and reporting design data [3]. "A standard is a set of specifications for parts, materials or processes intended to achieve uniformity, efficiency and a specified quality". Basic purpose of the Standards is to place a limit on the number of items in the specifications, so as to provide a reasonable inventory of tooling, sizes and shapes and verities [4]. Some of the important document related to piping are:

I. American Society of Mechanical Engineers (ASME)

II. American National Standards Institute (ANSI)

III. American Society of Testing and Materials (ASTM)

IV. Pipe Fabrication Institute (PFI)

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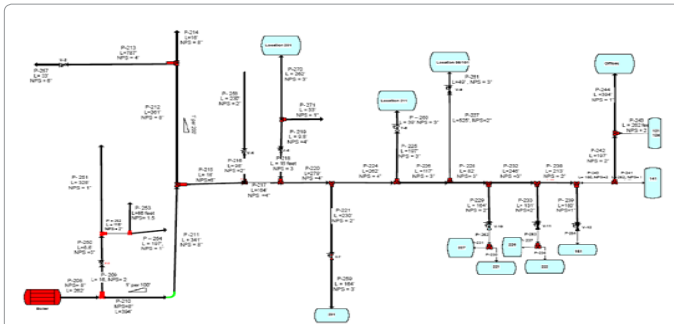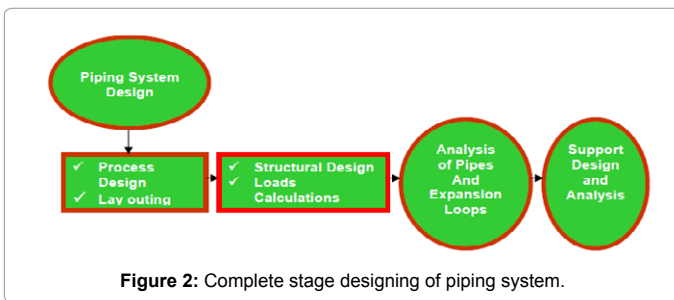
Figure 1: A conceptual model based on health, safety and ergonomic measures for sustainable workplace improvement that increase working capacity and decrease workload.

Figure 2: Complete stage designing of piping system.

V. American Welding Institute (AWS)

VI. Nuclear Regulatory Commission (NRC)

On the other side "A code is a set of specifications for analysis, design, Manufacture and construction of something". The basic purpose of code is to provide design criterion such as permissible material of construction, allowable working stresses and loads sets [4]. ASME Boiler and Pressure vessel codeB31 used for the design of commercial power and industrial piping system. This section has the following sub section [1].

B31.1: For Power Piping.

B31.3: For Chemical plant and Petroleum Refinery Piping.

B31.4: Liquid transportation system for Hydrocarbons, liquid petroleum gas, and Alcohols.

B31.5: Refrigeration Piping.

B31.8: Gas transportation and distribution piping system.

B31.1 Power piping code concerns mononuclear piping such as that found in the turbine building of a nuclear plant or in a fossil-fueled power plant.

B31.3 code governs all piping within limits of facilities engaged in the processing or handling of chemical, petroleum, or related products. Examples are a chemical plant compounding plant, bulk plant, and tank farm. B31.4 governs piping transporting liquids such as crude oil, condensate, natural gasoline, natural gas liquids, liquefied petroleum gas, liquid alcohol, and liquid anhydrous ammonia. These are auxiliary piping with an internal gauge pressure at or below 15 psi regardless of temperature. B31.5 covers refrigerants and secondary coolant piping for temperatures as low as 320ºF. B31.8 governs most of the pipe lines in gas transmission and distribution system up to the outlet of the customer's meter set assembly. Excluded from this code with metal temperature above 450ºF or below - 20ºF. As for as the steam piping is concerned, B31.1 Power piping is used because of its temperature and pressure limitations which is discussed below in detail.

B31.1 power piping

This code covers the minimum requirements for the design, materials, fabrication, erection, testing, and inspection of power and auxiliary service piping systems for electric generation stations, industrial institutional plants, and central and district heating plants. The code also covers external piping for power boilers and high temperature, high-pressure water boilers in which steam or vapor is generated at a pressure of more than 15 psig and high-temperature water is generated at pressures exceeding 160 psig or temperatures exceeding 250ºF. This code is typically used for the transportation of steam or water under elevated temperatures and pressure so this is the reason that why this code is selected for the steam piping system which is external to the boiler [5].

ASME code requirements

Boiler outlet section of the steam system comes under the category of ASME Code B31.1 Power. In order to ensure the safety of the piping system, code requirements should be fully satisfied. For different loads this code incorporates different relationships for stress level as given below [6].

Stresses due to sustained loadings:

The effects of the pressure, weight, and other sustained loads must meet the requirements of the following equation [1].

$$S_L=(PD_O/4t)+(0.75i \times M_A/Z) \tag{1}$$

Where,

P=internal pressure, psi

D_0=outside diameter of pipe, in

T=nominal wall thickness, in

Z=section modulus of pipe, in^3

M_A=resultant moment due to loading on cross section due to weight and other sustained load, in-lb

S_L=basic material allowable stress at design pressure, psi.

Stresses due to thermal loadings

The effect of thermal expansions must meet the following equations [1],

$$iM_c/Z \leq S_A+f(S_h-S_l) \tag{2}$$

Where,

f=stress range reduction factor,

Mc=range of resultant moment due to thermal expansions, lb-in

S_A=allowable stress range for expansions

The rest of term are same as above.

Piping Design Procedure

Process design

This process is based on the requirement of the process variables. It defines the required length and cross sectional area of pipe, the properties of fluid inside the pipe, nature and rate of flow in it. These variables affect the positioning and placements of equipments during

lay outing and routing. The operating and design working conditions are clearly defined. The end of Process Plan Design is the creation of a Process Flow Diagram (PFD) and Process and Instrumental diagram (PID), which are used in the designing and lay outing of the Pipe [7].

Piping structural design

In piping structural design, according to pressure in pipelines, the design and minimum allowable thicknesses are calculated; according to the required codes and standards. ASME codes for various standards are available, for process fluid flow, ASME B31.1 is used [8].

Pipe thickness calculations

Piping codes ASME B31.1 require that the minimum thickness t_m including the allowance for mechanical strength, shall not be less than the thickness [2].

$$t_m=(P \times D_O/2 \times S \times E_q+P \times Y)+A \qquad (3)$$

Where,

t_m=minimum required thickness, inches

t=pressure design thickness, inches

p=internal pressure, psig

Do = outside diameter of pipe, inches

S=Allowable stress at design temperature(know as hot stress), psi

A=allowance additional thickness to provide for material removed in threading corrosion or erosion allowance ,manufacturing tolerance should also be consider

Y = coefficient that takes material properties and design temperature into account

For temperature below 900ºF, 0.4 may be assumed

E_q=quality factor.

Allowable working pressure

The allowable working pressure of a pipe can be determined by Equation [2]

$$P= 2(S \times E_q) \times t/(D_o-2Yt) \qquad (4)$$

Where,

t=specified wall thickness or actual wall thickness in inches.

For bends the minimum wall thickness after bending should not be less than the minimum required for straight pipe [9].

Sustained load calculations

Sustained loads are those loads which are caused by mechanical forces and these loads are present through out the normal operation of the piping system. These loads include both weight and pressure loadings. The support must be capable of holding the entire weight of the system, including that of that of the pipe, insulation, fluid components, and the support themselves [2].

Pipe weight $=(\pi/4) \times \rho_{steel} \times (D_O^2-Di^2) \times (g/g_c)$

Fluidweight$=(\pi/4) \times \rho_{fluid} \times (Di^2) \times (g/g_c) \qquad (5)$

Insulation weight=Insulation factor $\times \rho_{insulation} \times (g/g_c)$

D_0=outside diameter of pipe, in

Di=inside diameter ofpipe, in

t=insulation thickness depends upon NPS, in

g=acceleration due to gravity, ft/sec²

g_c=gravitionalconstant, lbm-ft/ft sec²

ρ_{steel}=density of steel, lb/in³

ρ_{fluid}=density of water, lb/in³

$\rho_{insulation}$=density of insulation, lb/in³

Insulation factor depends on the thickness of the insulation of the pipe.

Static Loads Calculations

For Static loads calculation, considering a pipe no. 208 and taking its section up to first vertical leg of the expansion loop. This pipe is to be considering as a straight beam with uniformly distributed load [10].

Design specifications

NPS (Nominal Pipe Size)=8 in=200 mm

Pipe outer Diameter=8.625 in

Pipe thickness=0.322 in

Total (metal +Insulation +Fluid) distributed weight of pipe=50 lb/ft=4.167 lb/in Section Modulus, Z=16.8 in3

Moment of Inertia, I=72.5 in4

Modulus of Elasticity, E=27.5 Mpsi

For segment A-B as shown in Figures 3-5 below, taking the weight, shear force (Refer Figure 6) and

Moment equation and then using length L_1=22.22 ft

$W(x)=-M_o(x)^{-2} + R_0(x)^{-1}-w(x)^1 -R_1(x-a)^{-1}-M_1(x-L)^{-2}$

$V(x)=-M_o(x)^{-1}+ R_0(x)^0 -w(x)^1 -R_1(x-a)^{-1}-M_1(x-L)^{-2} \qquad (6)$

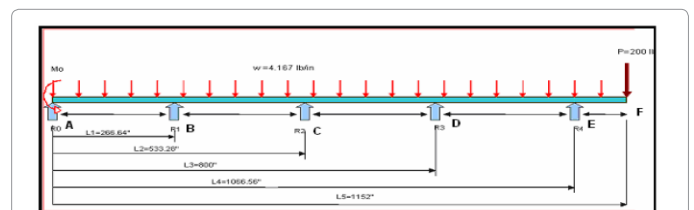$M(x)= -M_o(x)^0 + R_0(x)^1 -w(x)^2 -R_1(x-a)^1-M_1(x-L)^0$

Figure 3: Symmetry of header pipe considering as a beam Solving Segment A-B.
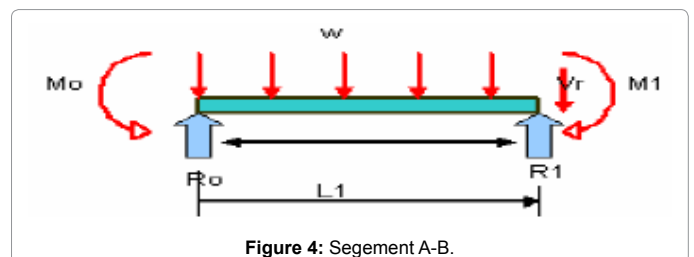

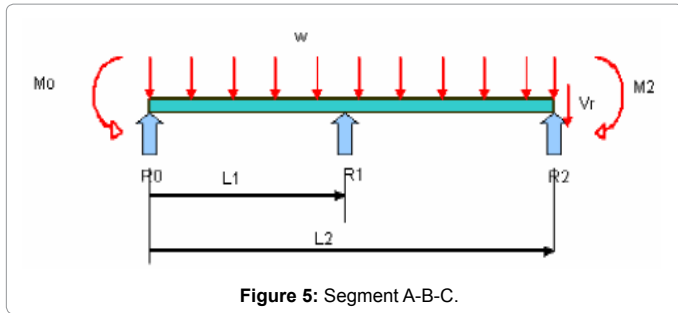**Figure 4:** Segement A-B.

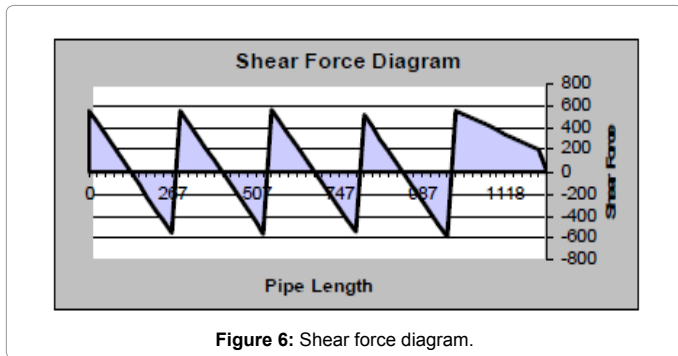**Figure 5:** Segment A-B-C.

Figure 6: Shear force diagram.

Integrating the moment equation twice and putting boundary conditions we get,

$$EIy(x) = -M_0 (x)^2/2 + R_0(x)^3/6 - w(x)^4/24 = 0 \qquad (7)$$

As the segment AB, $x = L_1 = 266.64$ in

$$-M_0(l_1)^2/2 + R_O(l_1)^3/6 - w(l_1)^4/24 = 0$$

$$-35548.44M_0 + 315945.77R_0 - 877634043.8 = 0$$

$$EIy(l_2) = -M_O(l_2)^2 + R_0(l_2)^3/6 + R_1(l_2-l_1)^3/6 - w(l_2)^4/24 = 0 \qquad (8)$$

$$-142193.78M_0 + 252766366.2R_0 + 3159545.78R_1 - 1.404_e^{10} = 0$$

Similarly for segment C-D:

$$EIy(l_3) = -M_O(l_3)^2 + R_0(l_3)^3/6 + R_1(l_3-l_1)^3/6 - R2(l_3-l_2)^3/6 - w(l_3)^4/24 = 0 \qquad (9)$$

$$-320000M_0 + 85333333.33R_0 + 25287743.4R_1 + 3159545.78R_2 - 7.11e^{11} = 0$$

For segment D-E:

$$EIy(l_4) = -M_O(l_4)^2 + R_0(l_4)^3/6 + R_1(l_4-l_1)^3/6 - R_2(l_4-l_2)^3/6 + R_3(l_4-l_3)^3/6 - w(l_3)^4/24 = 0 \qquad (10)$$

$$568775.12M_0 + 202210929R_0 + 85307735.9R_1 + 252776366.2R_2 + 3156702R_3 - 2.24e^{11} = 0$$

Now taking summation of moment at left end of right end support

$$M_0 + R_0l_4 + R_1(l_4-l_1) + R_2(l_4-l_2) + R_3(l_4-l_3) - wl_1(l_4-a) - w(l_2-l_1)(l_4-b) - w(l_3-l_2)(l_4-c) - w(l_3-l_2)(l_4-c) - w(l_4-l_3)(l_4-d) - wx^2/2 - P \times x = 0 \qquad (11)$$

$$M_0 + 1066.56R_0 + 800R_1 + 533.28R_2 + 266.64R_3 - 2369952.574 = 0$$

Solving the above (7),(8),(9),(10),(11) equation we get

$M_o = -24401$ lb.in, $R_o = 552$ lb, R1=1123 lb R_2=1067 lb,

$R_3 = 1266$ lb

For R_4, taking

$$R_0 + R_1 + R_2 + R_3 + R_4 = wL + 800$$

$R_4 = 159$ l lb. Maximum Bending Moment (Figure 7) $M_{max} = -32741.44533$ lb-in at x =799.92 in

Verification from code

The effects of the pressure, weight, and other sustained loads must meet the requirements of the following equation [1].

$$SL = \frac{PD_0}{4t} + \frac{0.75ixM_A}{Z} \leq 1.0S_h$$

Where,

P = Internal Pressure, psi

D o = Out Side diameter of Pipe, in

t = nominal wall thickness, in

Z=Section modulus of pipe, in³

M_A =Resultant moment due to weight and other sustained loads, lb-in

S_L =Allowable stress at design hot pressure, psi

i =stress intensification factor

$193.7 \times 8.625 / (4 \times 0.322) + 0.75 \text{ x } 1 \times 32700/ (16.8) \leq 1.0 \times 14400$

$2756.92 \leq 14400$

$2.75 \text{ } 10^3 \leq 14.4 \times 10^3$

Piping Analysis on ANSYS

Analysis was performed for the pipe in ANSYS for using the following data.

Element type=Beam 3

Material properties

Modulus of Elasticity=27.5 Mpsi

Poison's Ratio=0.283

Density=0.283 lb/in³

Type of Loads

Four Vertical constraints in the middle and one all degree of Freedom constrained at the start.

Gravity=9.81(386.22 in/sec²)

Final Meshing=96 elements for total length of the beam (Figures 8-10) (22 elements for first four each sections and 8 elements for the last section. Refining the mesh from 24 elements up to 96 elements but there is no change found in deformation values and bending moment values).
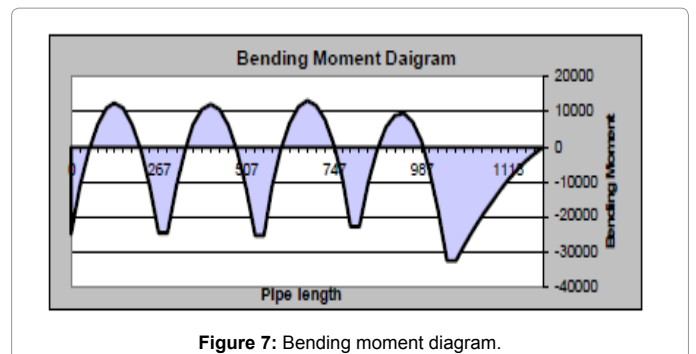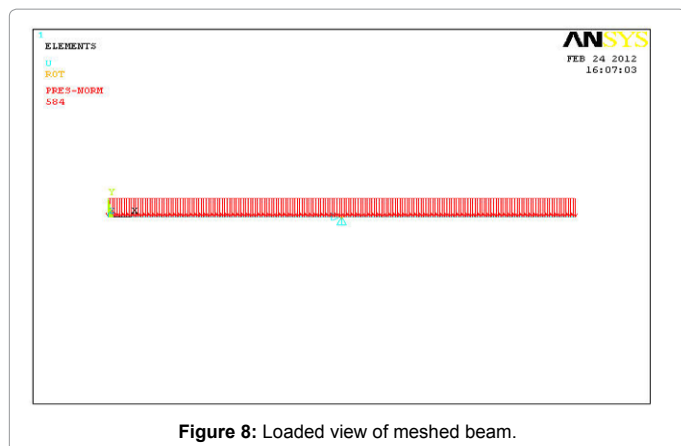

Figure 7: Bending moment diagram.
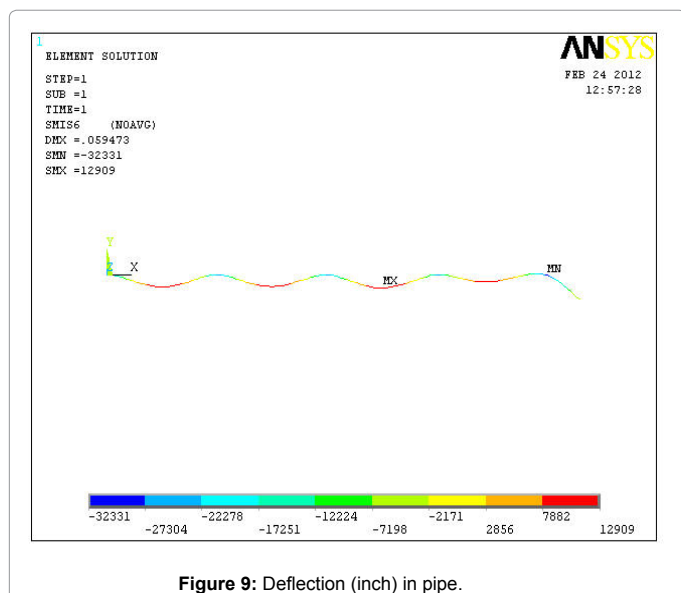
Figure 8: Loaded view of meshed beam.

Figure 9: Deflection (inch) in pipe.

Figure 10: Bending stress (psi) in pipe.

Method	Max. Deflection (in)	Max. Bending (lb-in)
Manual	0.064	32741.445
ANSYS Results	0.0596	32921.00

Table 1: Comparision of analysis of beam.
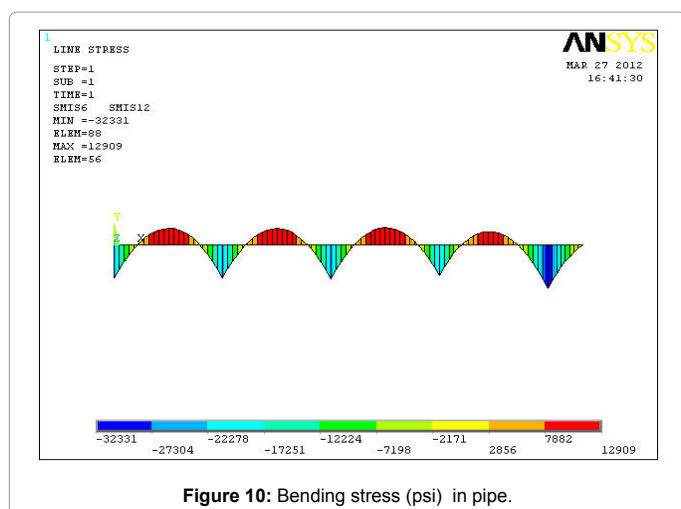
Comparison of analysis

The maximum deflections and bending moment values obtained from both methods are arranged in Table 1.

Results and Discussion

From the results obtained both manually and on ANSYS, the difference in maximum deflection is 6.4% where on the other hand the difference in the max. Bending moment is 1.35%. Deformation is less than 0.1 inch and also the maximum bending stress is 1947.55 psi which is quite less than the allowable stress of the pipe.

Conclusion

Following conclusions are made from the analysis of the designed system.

1. The designed pipe verified all the conditions defined by the ASME Boiler and Pressure Vessel code B31.1. Thickness and working pressure calculated are in the safe limit. Thermal and Sustained analysis results obtained are in the safe limits defined by the Code.

2. Supporting Assembly confirms to the safety requirements of AISC standards.

3. The analysis shows that the complete system is safe and the results are verified by manual calculations and ANSYS software.

4. On the positive side of the manual calculations lays the fact that it gives fully basic concept of the piping system. While the assumptions made during manual calculations make the results slightly differ from the software results.

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