Analysis of Pump Piping Based on Piping Configurations

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Abstract

Pump piping system is most common system in any society, industry and chemical plants. Pump piping is used in almost twenty percent of piping in the world. Hence optimization of this system is critical in terms of capital and annual savings. Many researchers have thrown light on optimization of pump piping considering hydraulics of lines. One of the deciding mechanical design parameter for the selection of pump is force exerted on the pump nozzle by connected piping. By using different piping configurations, effect of force exerted on pump nozzle is being studied in this paper. This force is being calculated and compared for different piping configurations by analytical method and piping analysis software. The strain of piping in these different piping configurations at a particular point is being measured experimentally and compared with piping analysis software results. The most optimum configuration which exerts lesser force on Pump nozzle is being suggested.
Keywords: Pump Piping Design, piping configurations, analytical method, Piping stress analysis software, ASME B31.3, Optimization

I. INTRODUCTION

Piping systems are like arteries and veins of Process Plants. They carry the lifeblood of modern civilization. In a modern city they transport water from the sources of water supply to the points of distribution; convey waste from residential and commercial buildings and other civic facilities to the treatment facility or the point of discharge. Similarly, pipelines carry crude oil from oil wells to tank farms for storage or to refineries for processing. The natural gas transportation and distribution lines convey natural gas from the source and storage tank forms to points of utilization, such as power plants, industrial facilities, and commercial and residential communities. In chemical plants, paper mills, food processing plants, and other similar industrial establishments, the piping systems are utilized to carry liquids, chemicals, mixtures, gases and vapours from one location to another. The fire protection piping networks in residential, commercial, industrial, and other buildings carry fire suppression fluids, such as water, gases, and chemicals to provide protection of life and property. The piping systems in thermal power plants convey high-pressure and high-temperature steam to generate electricity. Other piping systems in a power plant transport high- and low-pressure water, chemicals, low-pressure steam, and condensate. Sophisticated piping systems are used to process and carry hazardous and toxic substances. The storm and wastewater piping systems transport large quantities of water away from towns, cities, and industrial and similar establishments to safeguard life, property, and essential facilities. Pumps are most common equipment in any plant or even domestic and society application. Pumps are used to pump the fluids. In case of brown filed applications, pumps play important role to pump the oil. In the same common type of pumps are centrifugal pump, reciprocating pumps, screw pumps. Most pump installations in process plants have spare units to assure continuous operations by switching to a standby pump if required for maintenance. Pump piping, especially for high temperature service, generally represents one of the more difficult systems to design. Pump piping is being used in 20 percent piping in the world. Piping optimization can be done bases on hydraulic parameters i.e. flow rate, velocity, pressure drop and networking of piping. Design parameters related to mechanical engineering like force and expansions, pipe wall thickness, piping configurations may play role in the optimization of piping. This paper addresses the mechanical engineering approach based on piping configuration in the optimization of piping. Piping design is bases on Kellogg method which is one of the basic and reliable method used.
[9, 10, 14].

II. RESEARCHER'S WORK

There are researchers who worked on many parameters related to pump piping. This includes on hydraulic parameters like flow, velocity, pressure drop for piping optimization etc. Peter T. et.al. Ref. [1]; author have developed the generic software platform Gondwana for the optimization of drinking water distribution networks. It targets a broad spectrum of single and multi-objective problems in the topics of design, network blueprints, water quality, design and location of water quality sensors, among several others. Fulvio B et al. Ref. [2]; in his study, he has focused on hydraulic models to describe water distribution systems(WDS). Hydraulic models represent tools for managing the complexity of WDSs, and a number of optimization methods have been proposed to improve the performance of these infrastructures. The model is also used with a multi-objective genetic algorithm solver to identify different operational scenarios that lead to a reduction of energy consumption and water leakages. A. Bolognesia et al. Ref. [3]; has focused on energy efficiency approach of water distribution system. The evaluation of energy efficiency in water supply systems should account for both actual energy consumed and how efficiently such energy is spent. Author proposes the new concept of Unavoidable Minimum Energy, as the reference for defining an energy efficiency indicator. The optimization process is carried out by coupling the heuristic algorithm GHEST with the EPANET solver and applied to a literature synthetic case study. Ivetic D. et al. Ref. [4]; has proposed ΔQ method is based on hydraulic calculation for finding optimum diameter and optimum path of fluid travel. The suggested approach was tested on New York City distribution network reconstruction example using standard genetic algorithms. Ibrahim et al. Ref. [5]; has proposed particle swarm optimization(PSO) technique to optimize pipe network and size of irrigation piping network with reasonable performance. M. Balaji et al. Ref. [6]; has mentioned that the main work is to optimize the span length, number of supports, and cost of the piping layout by analyzing through modes such as thermal run, weight run, and final run using CAESER-II. The geometrical properties such as diameter, thickness, span length were considered during the design and analysis of the piping layout.

Based on the researcher's studies done, authors have focused only on hydraulic parameters like flow, velocity, pressure drop for piping optimization. Mechanical design parameters like thickness, force & expansion, piping configuration which are also crucial, and needed to be considered in piping system design and optimization.

III. PIPING STRESS ANALYSIS METHODS

Piping systems are complicated systems in terms of different parameters like pressure, temperature, surge, earthquake loads, wind loads etc. acting simultaneously. There two type of analysis are usually done i.e. static analysis and dynamic analysis. The static loads are due to temperature, pressure, equipment movement, weight of fluid etc. The dynamic loads are water hammer, surge, seismic waves etc. which usually create shocks. The piping stress analyses by static analysis consideration are based on following theories or methods, apart from mechanical stress analysis traditional methods:

A. Methods

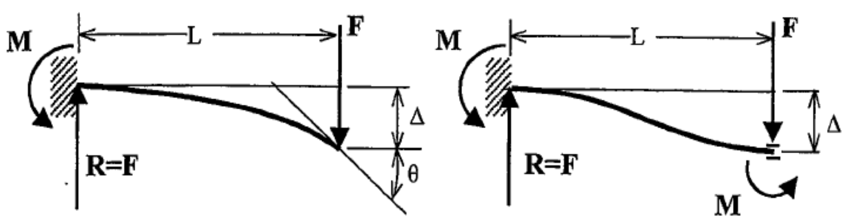
- Guided Cantilever Method (Kellogg's Method)
- Tube turns method
- ITT Grinnell method
- Using Finite Element Technique

B. Model Tests

Piping stress analysis considering dynamic analysis also involve various theories or methods related to vibrations, earthquake design etc. The codes and standards are developed based on these methods only. The analysis of piping system is challenging task and combination of all applicable analysis shall be applied simultaneously. Hence high accuracy and memory computers are required to solve the equations and criteria of combined analyses. [10, 11, 14]

IV. ANALYTICAL CALCULATION METHOD

The guide cantilever method is one of the simplified methods used in piping design, because deflections are assumed to occur in a single plane system under the guided cantilever approximation. The limitation of guided cantilever method are - the system has only two terminal points and it is composed of straight leg of a pipe with uniform size and thickness and square corner intersection, the legs are parallel to the coordinate axes, thermal expansion is absorbed only by legs in a perpendicular direction. As a further refinement of this method, correction factor that allows for reducing the bending moment, due to rotation of the leg adjacent to the one considered can be used. [14]



$$\Delta = \frac{FL^3}{3EI}, \quad F = \frac{3EI}{L^3}\Delta; \qquad \Delta = \frac{FL^3}{12EI}, \quad F = \frac{12EI}{L^3}\Delta$$

$$\theta = \frac{FL^2}{2EI}, \quad M = FL = \frac{3EI}{L^2}\Delta; \qquad \theta = 0, \quad M = \frac{FL}{2} = \frac{6EI}{L^2}\Delta$$

(a) Regular Cantilever Beam (b) Guided Cantilever Beam

A. Pipe Wall Thickness for Internal Pressure:

Stresses developed in the piping due to internal pressure are longitudinal stress and radial stress.

Circumferential stresses (Hoop stress)

$$\sigma_H = PD/2t \text{ -------\{ Mechanical Handbook\}}$$

Longitudinal stresses

$$\sigma_L = PD/4t \text{ -------\{ Mechanical Handbook\}}$$

Considering stringent of above two equations:

$$\sigma = PD/2t$$

As per ASME B31.3, thickness of pipe due to internal pressure(t) is given by,

$$t = \frac{PD}{2(SEW + PY)}$$

Where P is the design internal pressure, D is outside diameter, S is the allowable stress value, Y is factor related to temperature, W is weld joint strength reduction factor.

B. Straight Pipe Configuration:

Let F is load exerted on pump nozzle by pipe, E is modulus of elasticity, α is coefficient of thermal expansion of pipe and A is cross sectional area of pipe. T_1 is initial temperature and T_2 maximum temperatures of pipe, S is the stress developed in the pipe. The original length of pipe is L_o and change in length is ΔL.

So force exerted by pipe on pump flange is given by:

$$F = A \times \alpha \times E \times (T_2-T_1)$$

The stress along the longitudinal axis of the pipe is then:

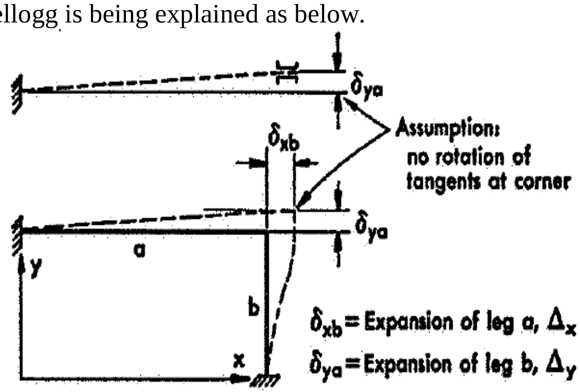
$$S = E \times \alpha \ (T_2-T_1)$$

Deflection in the pipe is given by:

$$\Delta L = \alpha \times L_o \times (T_2-T_1)$$

C. L- Shape and Z- Shape Configuration:

The Guided Cantilever Method by Kellogg is being explained as below.



The individual legs absorb the following portion of the thermal expansion. (Y-direction):

$$\delta_Y = (L^3 . \Delta Y) / \sum(L^3\text{-}L_Y{}^3)$$

Where,

ΔY = lateral deflection in the Y-direction for the leg under consideration, mm.

L = length of the leg in question, m.

L_Y = overall thermal expansion of system in Y-direction, m

L_Y = (L - ΔY) , m.

δm is largest of component deflections δ x, δy or δz.

Deflection capacity (δ) of cantilever beam can be found by graph given by Kellogg.

This deflection capacity should be greater than deflection absorbed by individual leg. ($\delta > \delta_Y$ or δ_x). Then the design is safe.

Then find correction factor “f” from Kellogg’s graphs.

Bending stress,

$$S_E = (S_A \times \delta\, m)/(f \times \delta) \text{ ------------\{}S_A = \text{allowable stress \}}$$

Bending Moment,

$$M_b = S_E \times Z \text{ -----------------\{Z=Section modulus of pipe\}}$$

Force acting,

$F = M_b /L$

L= Length of the pipe on which moment is acting

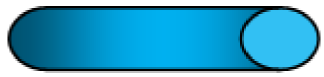
V. ANALYSIS OF PUMP PIPING BASED ON CONFIGURATIONS

In this paper, the discharge piping of pump is being analyzed for different piping configurations. The force exerted by piping on pump nozzle and deflection of pump discharge piping is being analyzed.

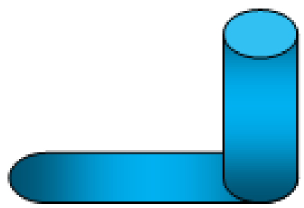
A. Problem Statement:

To find force exerted on Pump discharge nozzle in different piping configurations (straight, L-shape, Z-shape) by analytical method & FEA software (CAESAR II). Do the experimentation on same configurations to find strain in the piping at particular location? Compare the results and find optimum configuration of pump piping which exerts lesser force on the pump nozzle.

1) Straight Configuration:



2) L-Shape Configuration:



3) Z-Shape Configuration:

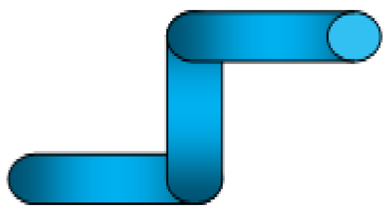


Fig. 1: Typical Pump Piping Configurations

4) Pump Data:

O.D. of pipe =219.1 mm (8”)
Corrosion allowance = 6.35 mm
Operating Temperature = 70 ºC
Pipe Material – ASTM A 53 Gr. B
Operating pressure=10 bar
Design pressure=14.14 bar
Flange rating #150

The piping system consists of piping components basically of carbon steel material. The material of pipe is ASTM A53 Gr.B and other components are of equivalent materials to that of pipes. The thickness has been calculated based on internal pressure (design), and the design temperature with specified corrosion allowance of 6.35 mm. The analysis is done with FEA analysis software. The pipe is located on pipe rack where nozzle is being considered as fixed point. The pump is located on the ground on foundation. The discharge piping nozzle is required to be connected to header pipe by different configurations. The arrangement is as shown in the figure below:

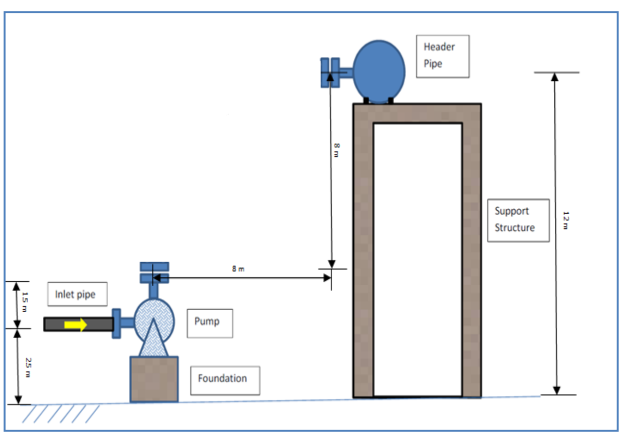


Fig. 2: Pump and Piping connection required

The pipe thickness is first calculating as per above parameters of pump piping. By using Hoop stress formula minimum thickness based on ASME standard is being calculated. This standard has specific consideration of weld strength reduction, creep etc. We will apply corrosion allowance, mill tolerance as adder to the thickness calculated.

5) Straight Configuration:

The pipe is connected directly from pump nozzle to the header pipe in Fig-1. This arrangement is very simple and easy. Now we can calculate the stresses developed in the pipe due to operating conditions. This is being calculated based on mechanical engineering formulas for calculating stresses and strain in both end fixed beam.

6) L-shape Configuration:

The L-shape piping configuration is used to connect pump nozzle to the header pipe in Fig-1. This arrangement is simple however number of piping components increased. Now we can calculate the force exerted by piping due to operating conditions on pump nozzle. This is being calculated based on Guided Cantilever beam method.

7) Z-shape Configuration:

The Z-shape piping configuration is used to connect pump nozzle to the header pipe in Fig-1. This arrangement slightly complicated and number of piping components increased. Now we can calculate the force exerted by piping due to operating conditions. This is being calculated based on Guided Cantilever beam method.

The pump piping system is being analyzed by analytical method and FEA software. The FEA software's can analyses any complex systems within less time. It can give very accurate results with consideration of multiple effects. These software's involves matrix solver methodology among which different software's follow different methodology of solving matrix. Some of the examples of software's used for piping stress analysis are CAESAR II, Auto Pipe, FE Pipe etc. The software used for this project work is CAESAR II, which is commonly used in industry. The software is user-friendly and more accurate. The piping configuration is being modelled in the software and input parameters are being inputted as per problem statement. The static stress analysis is being performed based on design pressure and temperature. The results are being obtained.

The result are being tabulated as below:

Table – 1
Analysis result summary

Parameter	*Configuration*	*Value*		*Unit*
		Analytical	*CAESAR II*	
Force at Pump Nozzle	*straight*	*1227*	*1302*	*KN*
	L-shape	*325*	*388*	*N*
	Z-shape	*128*	*124*	*N*
Deflection in the pipe from pump nozzle	*straight*	*8.06*	*10.04*	*mm*
	L-shape	*4.76*	*3.99*	*mm*
	Z-shape	*2.392*	*1.68*	*mm*

From this it is observed that the optimum configuration is Z-shape configuration in terms of force exerted and piping deflection in pump piping.

VI. EXPERIMENTATION

Three typical configurations of piping are straight, L-shape, Z-shape are considered for experimentation (Fig – 4). These configurations are being manufactured with copper material as copper has measurable expansions with small temperature rise from room temperature. These three configurations are exposed to elevated temperature of around same temperature range as that of Pump system. The high temperature effect is being obtained with the help of steam generated by pressure cooker. Both ends of these configurations are made fixed as per the arrangement of pump piping system in problem statement. The expansions in respective direction are being restricted and piping shall have expansions in between these two fixed points. The strains are measured with the help of strain gauges installed on the piping system and temperatures with the help of thermocouple fixed to copper pipe.

The heating facility is a Electric Hot plate with which heat is inputted to the pressure cooker. The cooker half filled with water insider, is placed on the heating plate. The cooker outlet is connected to the small section of copper piping of L shape. Further it was installed with pressure gauge and isolation valve. These are installed to measure pressure in the piping for safety purpose and the isolation valve to control the steam if required. The supporting structure is then connected to cooker which stops the expansion of copper pipe configurations. The three piping configurations are then equipped with stain gauge attached and thermocouple is tied on the same. (Fig – 3)

The experimentation is being performed at indoor location. Due to vary short length of copper pipe, the temperature gradient is minimum.

The schematic of the arrangement is as below:

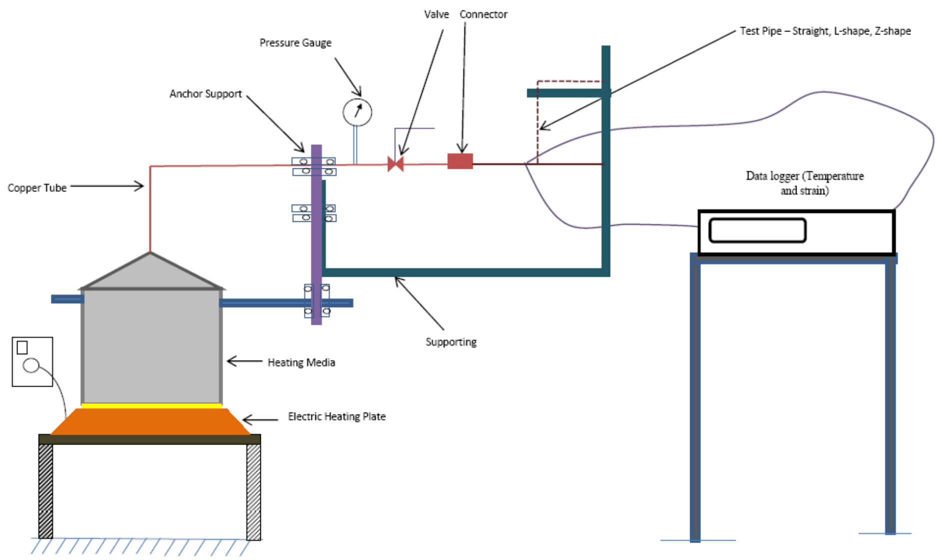


Fig. 3: Experimentation set-up

Fig. 4: Piping Configurations

The experimentation results are being obtained by connecting the data card of data logger with computer. The results are being obtained in MS-excel. Following table summarizes the results obtained. The stain in the pipe is measured with the help of stain gauge with respect to temperature. The strain gauge is being installed at equidistant from the fix point.

A. Straight Configuration:

Table -2
Strain gauge reading – Straight configuration

r. No.	Temperature ° C	µ strain (µ m /m)
1	40	-401
2	50	-923
3	60	-1955
4	70	-8716

B. L-shape Configuration:

Table - 3
Strain gauge reading – L-shape configuration

Sr. No.	Temperature ° C	µ strain (µ m /m)
1	40	91
2	50	150
3	60	191
4	70	265

C. Z-shape Configuration:

Table - 4
Strain gauge reading – Z-shape configuration

Sr. No.	Temperature ° C	μ strain (μ m /m)
1	40	49
2	50	87
3	60	154
4	70	188

The above data shows the following:

1) Strain in the pipe increases with increase in temperature.
2) Strain in case of Z-configuration is lesser than other configurations.

VII. CONCLUSION

Analysis of pump discharge piping has different approaches with the use of process design parameters like velocity, flow, pressure drop. Pump piping system also can be analyzed considering different piping configurations. The optimum configuration can be the one which exerts lesser force on the pump nozzle and lesser deflection in the piping. Referring to the problem stated in this paper, the pump discharge piping is being analyzed with straight, L-shape and Z-shape configurations. The Z-shape configuration is exerting lesser force on pump nozzle and results in lesser deflection of piping. This was also being checked by experimentation wherein strain in the piping configuration is being measured. In this case of experimentation also, the Z-shape configuration experienced lesser strain. Hence the Z-shape configuration can be considered as most optimum configuration. Moreover, similar to the system hydraulic checking approach, piping system can also be analyzed mechanically with different configurations. More complicated configurations can be tested with the same approach with advance software tool and most optimum configuration which exerts lesser nozzle loads and forces on piping supports can be find out.

REFERENCES

[1] P. Thienen et al., “Gondwana: a generic optimization tool for drinking water distribution systems design and operation”, Science Direct, Elsevier, 2015.
[2] F. Boano et al., “Water distribution system modelling and optimization: a case study”, Science Direct, Elsevier, 2015.
[3] A. Bolognesi et al., “Energy efficiency optimization in water distribution systems”, Science Direct, Elsevier, 2014.
[4] Ivetic D. et al., “Implementing ΔQ method to accelerate the optimization of pressurized pipe network”, Science Direct, Elsevier, 2014.
[5] I. Mtolera et al., "Optimization of Pipe Networks Layout and Size, Using Particle Swarm optimization", International journal, 2014.
[6] M. Balaji., “Optimization Of Piping Layout With Respect To Pressure And Temperature Using Caeser-Ii”, Mechanica Confab, 2013.
[7] Blinco L. et al., “Genetic Algorithm Optimization of Operational Costs and Greenhouse Gas Emissions for Water Distribution Systems”, 16th Conference on Water Distribution System Analysis, WDSA 2014, Science Direct, Elsevier, 2014.
[8] Sharma P. et al., “Design and analysis of Process Plant Piping System”, International Journal of Current Engineering and Technology, 2014.
[9] M. Nayyar, Piping Handbook, 7th ed., McGraw-Hill, 2000.
[10] S. Kannappan, Introduction to Pipe Stress Analysis, Knoxville, Tennesse, John Wiley & Sons, 1985.
[11] L. Peng S. Peng; Pipe Stress Engineering; Peng Engineering, Texas, ASME Press, 2001.
[12] S. Spielvogel, Piping Stress Calculations Simplified, 5th ed., New York, Byrne Associates, Inc., 1961.
[13] E. Wilson, Plant Instrumentation, 4th ed., Industry Publication, 2001.
[14] M. Kellogg, The M.W. Company, Design of Piping Systems, 2nd ed., New York, John Wiley & Sons, 1956.
[15] ASME B31.3, Process Piping. ASME, American Society of Mechanical Engineers, 2008.