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Analysis of Pump Piping for Optimum Routing Within Nozzle Allowables

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ABSTRACT

Pump piping system is one of the most common systems in any society, industry and chemical plants. The design of pump piping system considers various parameters simultaneously like fluid properties, deign conditions, supporting of system etc., hence very complex analysis consideration are required. The loads especially due to expansion or contraction of piping mainly cause deformations, leakages of flange joint, misalignments which will not be acceptable.

The Pump piping system in one of the process plant wherein loads on the pump nozzles due to piping system are exceeded the limit specified by pump manufacturer is considered in this paper. The main aim of the project is to bring these loads within allowable limits by various majors like modifying piping routing, changing the support types and locations, provide additional flexibility etc. So the detailed stress analysis of a pump piping is being performed as per process piping codes B31.3. The causes of generated excess loads and moment are being found out by detailed analysis in FE Analysis software. This is followed by repetition of analysis of modified routing and supporting of the system so that, finally stresses & moments developed are within allowable limits under static conditions. The cost analysis also been done for each modification so that system shall be finally optimum in terms of cost.

Keywords— **Pump Piping Systems, Pump Nozzle Allowables, Stress Analysis, ASME B31.3, Optimization of Piping**.

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I. INTRODUCTION

Pumps are mainly being used to transfer the service fluids or gases from one location to other. In case of upstream oil and gas filed applications, pumps play important role to pump the oil or gas from the wells and transfer to the onshore storages or pipe lines. The common type of pumps are centrifugal pump, reciprocating pumps, screw pumps etc. which are used universally. 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 for thermal flexibility.

The pump piping systems are associated with facilities of high degree of responsibility, stress analysis represent a fundamental stage of the piping design, in order to prevent failures and cause of accidents. The piping systems are subjected to multiple loads, stress analysis is a complex task. Besides the stresses caused by the piping weight, fluids and isolation, piping systems are also subjected to temperature changes, internal and external pressure, and occasional events such as water hammer, wind and earthquakes.

Usually, the greatest challenge in the piping stress analysis is to provide the system, enough flexibility to absorb the thermal expansions. Nowadays, the pipe stress analysis covers much more than flexibility analysis, however it still is one of the main tasks of the engineers to work in this area. The piping shall be routed initially considering flexibility, and then it will be easier for stress engineer to do the stress analysis and avoid back and fro communications within piping department. Many times due to the inexistence of a quick method that allows a verification of the flexibility of subjected systems, they turn out to be too stiff or too flexible.

The objective of this paper is to present stress analysis of pump piping systems to limit the nozzle loads within the allowable limits. [6, 8, 11, 16].

II. RESEARCHERS WORK

There are researchers who worked on many parameters related to pump piping. This includes finalization of nozzle allowables, modification of pump piping etc. Peng et.al. Ref. [19] has stated that the current allowable for piping loads on rotating equipment nozzles specified by manufacturers are too low. These allowables shall be increased to accommodate the design requirement of connecting piping system. Marscher et.al. Ref. [17] has mentioned that the pump reliability problem is responsible for the large amount of maintenance cost in chemical plants, refineries, and many electric utilities. Author also highlights about proper selection of pump for that application. Steiger et.al. Ref. [13] has suggested the modification of Horizontal process Pump to comply with API- 610 specified forces and moments. Simizu et.al. Ref. [10] a senior researchers studied the analysis of nozzle load for process pump. They have found that under extreme conditions, pump may require to withstand nozzle loads which are often exceeds criterial stated in API610. They have gone in details of shaft end displacement of centrelines mounted pump under nozzle loads. Peng et.al. Ref. [9]had raised the concern about the change in reliability of equipment due to connecting piping. So the piping shall be designed such that minimum loads shall be transferred to the connecting equipments so that reliability can be improved. Head et.al. Ref. [11] raised the problem of thermal distortion of pump due to hot fluid handled, They have studied the design and operation of pump for hot standby service. Peng et.al. Ref. [4] The Appendix-P of ASME B31.3 is the guideline provide for doing stress analysis of piping system. Author has presented the stress criteria background and explain why the Appendix P is formulated based on confusing logic that may very well lead to unsafe design of the piping system.

Based on the researchers studies done till date, it is mainly focus on how to overcome the low nozzle allowable provided by manufactures. Various methods and approaches were discussed to comply this low allowable, without increasing the project time, material and cost. Literature work does not adequately specify the design modification so that the pump allowables can be kept within limit by routine modification in pump piping and to satisfy the latest edition requirement of API 610. Therefore, there is requirement of modification in piping routing and supporting to reduce the nozzle loads of pumps.

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 of flexibility analysis, apart from mechanical stress analysis traditional methods:

1) Approximate Methods
   - Guided Cantilever Method
   - Chart Solutions
2) Exact Analytical Methods
   - Simplified Kellogg's Method
   - General Kellogg's Method
   - Using Finite Element Technique
3) 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. [8, 12]

IV. NUMERICAL CALCULATION & FEA VALIDATION

The guide cantilever method is being selected for the validation of FEA software used for the analysis. This 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. Some of the methods to analytically find the stresses are Tube turns method, ITT Grinnell method, M. W. Kellogg Method. [15]

The section of piping system show in Fig. 1 with both ends fixed is being considered with pipe of 12.7 mm thick, material as ASTM A53 Gr.B, design temperature of 83 deg C. Basic allowable stress at 83 deg C is 137.9 N/mm2 (as per ASME B31.3 table –A1). Ambient temperature is 10 deg C.

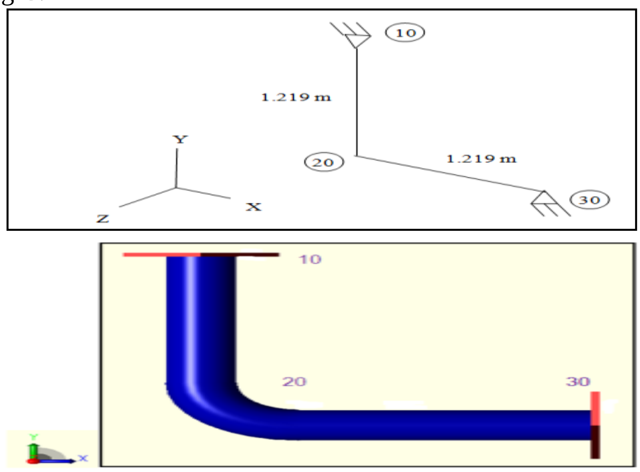

Fig.1 Problem schematic & FEA Model(CAESAR-II)

As per ASME B31.3, allowable displacement stress range SA is given by following equation:

SA =Allowable stress range = f (1.25 Sc + 0.25 Sh)
= 206.85 N/mm2 (as per ASME B31.3 table –A1)

Here Sc is basic allowable stress at minimum metal temperature and Sh is basic allowable stress at maximum metal temperature at life cycle time of plant as per ASME B31.3. f =1.0 for 7000 load cycles.

Deflection of individual let is calculated as below:
Expansion Δ in individual leg is calculated by formula,

$$\Delta = \alpha \cdot \Delta T \cdot L = 1.06 \text{ mm}$$

The individual legs absorb the following portion of the thermal expansion in Y-direction:

$$\delta_Y = (L^3 \cdot \Delta Y) / \sum(L^3 - L_Y{}^3) = ((1.2192)^3 \times 1.064) / 1.812 = 1.266 \text{ mm}$$

Where,
ΔY = lateral deflection in the Y-direction for the leg under consideration, mm.
L = length of the leg in question, m.
ΔY = overall thermal expansion of system in Y-direction, mm

Now finding correction factor ‘f’ from Kellogg’s graphs L/LA and putting in the below equation,

$$\text{Bending stress, } SE = (SA \times \delta m)/(f \times \delta) = 68.7436 \text{ N/mm}^2.$$

So generated bending stresses are within the design limits and design is safe.

The bending moment is calculated as below:
$Mb = SE * Z = 27620$ N-m

Now verifying results of FEA (CAESAR-II) software by modelling same system and inputting same parameters as mentioned in above example.

TABLE I
COMPARISON OF FEA AND MATHEMATICAL CALCULATIONS

Sr. No.	Description	Mathematical calculation	CAESAR II result
1	Bending moment	27,620 N-m	26,985N-m
3	Deflection	1.06 mm	0.9 mm

The above Table-I show that results obtained by guided cantilever method are inline with CAESAR-II software results. So FEA software can be used for stress analysis of piping system.

V. Stress Analysis Of Pump Piping System

The analysis of pump piping consists of discharge piping. The static analysis of discharge lines of pump existing in refinery is being considered in the current paper. This is the actual problem faced in design of pump piping.

PROBLEM STATEMENT:

One of the systems used in the refinery, in piping unit consists of 3 pumps with 3 suction and discharge nozzles. The loads exerted by pump piping on the pump discharge nozzles are exceeded limit specified by pump manufacturer. It is required to bring the nozzle loads within the limit by stress analysis (static) of pump piping system. The analysis (static) of complete system is performed in FE Analysis Software (CAESAR-II). This includes finalizing the piping system routing and supports such that the pump nozzle loads are within allowable limits, in turn suggest the changes or modifications in piping system such that the system is optimal in terms of cost.

Below Fig. 2 is the process flow diagram and pump piping details for the design of pump piping system.

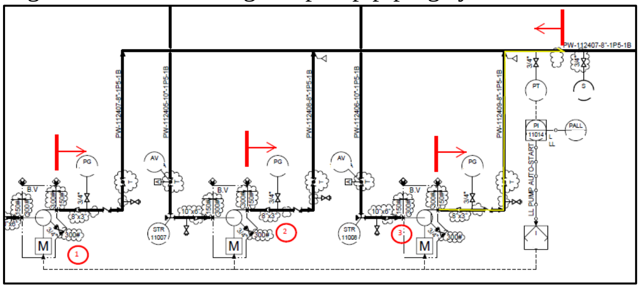

Fig.2 Process Flow Diagram

Pump Data:

Rated Pump Capacity:	110.13 m^3 /hr
Operating Temperature:	83 ^{0}C
Design Pressure:	14.14 barg
Design Temperature:	116 ^{0}C
Allowable nozzle loads (discharge nozzle):	Fz – 2140 N ; Fx –1780N; Fy – 2660N
Specific Gravity of Fluid:	0.97
Discharge Nozzle Size & Rating:	3”, Cl. 300 as per ASME B 16.5

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 mm.

The software used for the analysis is CAESAR II. As described in the problem definition, Fig. 3 shows the three pumps having three discharge nozzles connected to the piping. Due to the layout of the system, force is acting in the X- direction are exceeding the allowable limit of loads on the nozzles specified in above paragraphs.

Case -1] Initial Routing and supporting:

This routing is kind of symmetric routing along discharge line of pump. Then these lines are being connected to common header. Later on this header is tapped around the center of this header and the line is then connected to main header which is on elevated location. The supporting is initially made as first location near pump nozzle as three dimensional stop. Then there is two dimensional stop and subsequently resting supports are used. Following Fig. 3 shows the FEA model and output results of initial routing of the problem statement where nozzle loads are exceeding allowable limits of loads.

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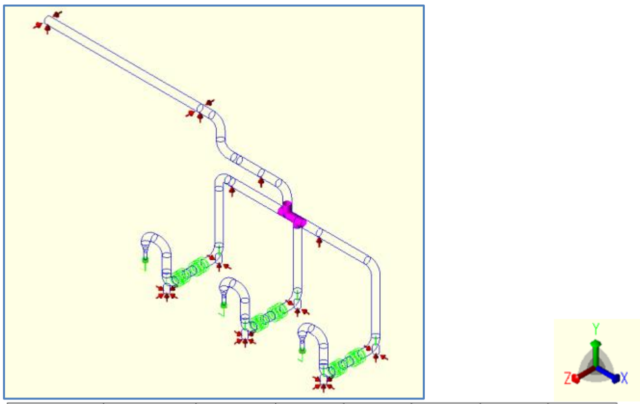


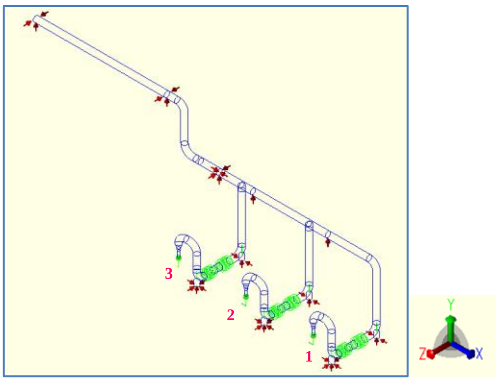
Allowable Loads	Nozzle Node Number	Fx (N)	Fy (N)	Fz (N)	Mx (N-M)	My (N-M)	Mz (N-M)
	1	-524.91	1943.93	-774.01	-157.7	-179.8	358.2
	2	-1637.00	1063.16	-22.24	51.0	-79.2	739.4
	3	-2851.4	97.9	947.5	269.8	115.0	-2851.4
Allowable limit		(+/-) 1779.34	(+/-) 2669.02	(+/-) 2135.21	(+/-) 949.03	(+/-) 1437.11	(+/-) 1898.06

Fig. 3 FEA Model & Results for Case - 1

Due to this routing, nozzle load in X-direction on the pump 3 exceeds the allowable limits mentioned by pump vendor. This is due to uneven distribution of forces along each pump. The supporting made is also need to be verified. The other forces and moments are within limit. However, not a single deviation to pump vendor's data is acceptable. Hence the routing needs to be revised and re-analysed.

Case -2] Changing Routing and supporting(Trial-1)

Due to exceeded force on nozzle of pump 3, now new routing is being introduced. In this case, the pump discharge piping is made symmetrical till the header and now, the header is not being tapped. This header is continued further and connected to main header with elevation. There is supporting variation as the three dimensional stop is now being introduced at header to distribute loads. The flexibility of system is being improved slightly. The system is again checked for the force and moments generated at pump nozzles. Following Fig. 4 shows the FEA model and output results of revised routing of the problem statement where nozzle loads are exceeding allowable limits of loads.



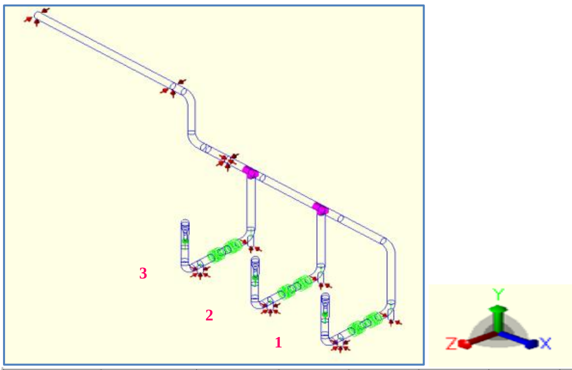
Allowable Loads	Nozzle Node Number	Fx (N)	Fy (N)	Fz (N)	Mx (N-M)	My (N-M)	Mz (N-M)
	1	618.3	2855.8	-1641.4	-376.9	-326.1	-35.4
	2	-600.5	1881.7	-1565.8	-419.9	-230.2	382.6
	3	-1450.2	1210.0	-35.6	95.7	-149.0	674.4
Allowable limit		(+/-) 1779.34	(+/-) 2669.02	(+/-) 2135.21	(+/-) 949.03	(+/-) 1437.11	(+/-) 1898.06

Fig.4 FEA Model & Results for Case – 2

This time, the nozzle load on pump 3 is within the limit; however the load in the Y-direction on pump 1 exceeded the limit. This might be due to the reverse reaction due to insufficient flexibility provided in the piping between new added support and pump nozzle. The reaction of two side pumps act on the centre pump 2. So the nozzle load increased and crosses the limit.

Case -3] Changing Routing and supporting(Trial-2):

Even the routing change is made by conventional way, there is exceed of load on the pump nozzle. Now the connection of pipe to the pump nozzle shall made more flexible. This additional flexibility can be made by turning piping to 45°angle at the pump nozzle connection. This is shown in clear way in the below figure no. 6. The other routing and supporting shall be kept on the similar lines. This is due to the receive the conclusive result. If we vary many parameters at the single time, it will make confusion and endless tries. The revised routing is now analyzed. Following Fig. 5 shows the FEA model and output results of revised routing of the problem statement where nozzle loads & moments are within the allowable limits of loads.



Allowable Loads	Nozzle Node Number	Fx (N)	Fy (N)	Fz (N)	Mx (N-M)	My (N-M)	Mz (N-M)
	1	578.3	885.2	-1063.2	-709.9	-146.8	-336.6
	2	-489.3	520.5	-1227.7	-705.1	-229.7	114.3
	3	-965.3	195.7	-658.4	-466.5	-163.9	308.6
Allowable limit		(+/-) 1779.34	(+/-) 2669.02	(+/-) 2135.21	(+/-) 949.03	(+/-) 1437.11	(+/-) 1898.06

Fig.5 FEA Model & Results for Case – 3

By this routing and supporting, the nozzle loads and moments are within the allowable limits. So this routing can be applied in the actual practice and the problem is solved.

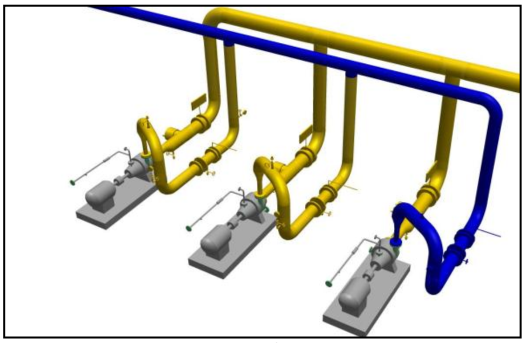


Fig.6 3D Model for Case – 3

VI. Optimization Of Piping

a The optimization of piping can be done by many means. In the simple way, the design and cost comparison among the cases mentioned above shall be the ideal approach to present optimization of design. Scientists have used many methods of optimization like ant colony, genetic algorithm to present piping optimization. However, these are not being used in consultancies due to many drawbacks like time, cost etc.

For this project, the optimization is being achieved mainly by material optimization which in turn results cost optimization. Even if we save in few of the fittings, it will save large amount of commodity, welding, handling, test & inspection cost. If we consider reduction in number of supports or use of simple supports rather than specially designed supports, it will be a cost saver. The standard support usually fabricated and welded at site. However, in case of special supports, these are required special design, manufacturing and installations. Thus the first choice should be simple supports and in extreme cases where simple supports are not practical or not acceptable considering design analysis, special supports shall be used. The problem cases are being analysed in terms of cost of material used in the piping. The best and optimum is design is one which is safe in terms of allowable limits as well as cost effective. This case, we have judiciously used supporting and piping components so that total cost will be minimum. This requires not only design proficiency but also common sense and knowledge of flexibility aspects of piping system. The piping is more flexible, the generated stresses will be lesser in case of pump piping. Thus it is basic criteria which has to be applied so that piping system will be more safe and optimized. The cost optimization in the design is achieved and is tabulated in the following table no. II based on the cases mentioned above. [8, 15, 16, 2]

TABLE II
OPTIMIZATION SUMMARY

Design Options	Design Completeness	Chang in the cost	Final Result
Case-1	Load exceeds the limit	-	Not Optimum
Case-2	Load exceeds the limit	+ 0.8 %	Not Optimum
Case-3	Safe	- 13.9 %	OPTIMUM

The allowable loads compared with generated loads and the respective material cost is being represented in the graphical form in fig. 5 below. Cost of case-1 is considered as basis for cost comparison. Here Y-axis represent the generated force and cost of material and X-axis represents different cases. This shows graphical way that piping routing in case-3 is optimum routing.

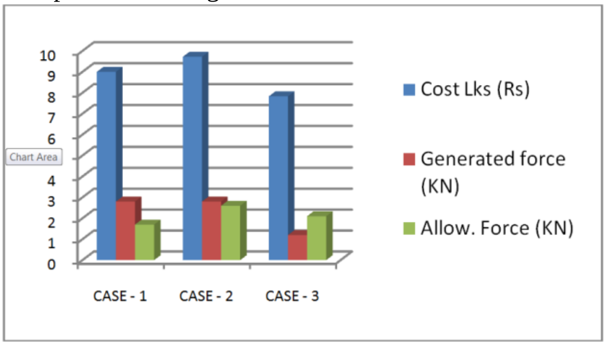


Fig.6 Graphical representation of Optimization

VII. CONCLUSION

Pump piping system can exert lesser loads on the pump nozzle if enough flexibility is being provided. The main cause of nozzle load exceeding the limit as per Case -1 was lack of flexibility in the piping connected to the nozzle loads. The load in X-axis (FX) on nozzle 3 was exceeded. Piping routing and supporting is modified by continuing nozzle piping further as per Case – 2 with which loads in X-axis were reduced, however load in Y-axis (FY) of nozzle 1 is being increased. This is due to still improvement required in terms of flexibility. Finally, the Case-3 is formed by modifying pump nozzle piping by turning it in 45 deg angle, the supports are also slightly modified. The piping routing along with support is being re-analyzed and now the forces and moments are within allowable nozzle loads. By this margin in terms of force are kept around 25% minimum and cost improvement of 13%. This is concluded that pump piping shall be provided with enough flexibility and this shall be considered in the initial stage of piping routing. Some of the means to increase flexibility are 45 deg connections, spring supports, supping used other than anchor supports, think of overall flexibility upto the header piping.

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