Thermo Structural Analysis of Cryogenic Fluid Circuit

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***Abstract*—The Cryogenic piping circuit under discussion is designed to handle the Liquid Hydrogen and is one of the important piping networks present between the heat exchanger and the ground delivery terminal of Cryogenic upper Stage in Geo Synchronous Launch Vehicle of Indian Space Research Organization at Sriharikota.It consists of many flow components like vacuum jacketed control valves, check valves, instrumentation withassociated piping elements like expansion joints/loops and various support elements (anchors, Guides, V-stops etc). This Paper mainly discusses about the thermal stresses induced in the piping circuit when liquid Hydrogen flows through it and how these stresses can be reduced by incorporating various expansion loops/joints with optimal placement of supports. Towards this, a Process &Instrumentation diagram drawn in AutoCAD version and associated design features have been taken as an input data. Considering the same, a smart P&ID has been generated using Autodesk P&ID software. By considering the given space constraints, a 3D piping layout is developed using Autodesk Plant 3D software. The total piping circuit has been segmented into 5 parts and corresponding nodal isometric drawings were generated. Subsequently the individual isometric segments have been modelled in piping analysis software - "AutoPIPE" and the corresponding loading & boundary conditions are imposed. The analyzed results were evaluated and necessary modifications in flexible elements, supports, component data and nodal distances are carried out in an iterative manner towards achieving the overall code compliance.**

Keywords*— Cryogenic piping, Liquid Hydrogen Filling System, Valves, Expansion Joints, Expansion loops, Anchors, Guides, V stops, Thermal stresses, Process & Instrumentation Diagram, 3D Piping layout, segmented, isometric diagram, Flexible elements, Code compliance

I. INTRODUCTION

Cryogenics is defined as that branch of physics which deals with the production of very low temperatures [1]. In a more operational way, it is also defined as the science and technology of temperatures below 123 K. As the critical temperature of a cryogenic fluid is less than ambient temperature, it cannot be liquefied by the application of pressure alone at or above ambient temperature. Helium, Hydrogen, Neon, Nitrogen, Fluorine, Argon, Oxygen, Methane and Krypton are some of the cryogenic fluids.

Cryogenic engineering deals with the low temperature techniques, processes, design & development of storage equipment and associated transfer circuits. Since the normal boiling point of cryogenic liquids is far less than ambient temperature, these liquids cannot be stored in un-insulated tanks unlike the other liquids. Because of the heat-in-leak, this demands some special constructional aspects while design of storage & handling equipment. This includes double wall construction (vacuum jacket) of the vessel/piping, insulation & well designed suspension system. In addition to the above, proper selection of metallic & non-metallic materials plays a major role in design of the cryogenic systems.

Flexibility is another important factor that needs to be addressed in design of the cryogenic piping circuits. This is achieved by incorporating flexible metallic bellows or expansion loops, as the case may be. In case of complex fluid circuits involving number of branches, bends and associated flow components, estimation of thermal contractions, support reactions and piping stresses involves a greater analytical computations. By using the hand calculations it may not be possible to predict the above in an accurate & effective manner within the given time frame. In addition to the above, establishing the code compliance for the entire piping system is a complex task.

In view of the above, it is necessary to employ an appropriate Finite Element analysis tool to predict the nodal displacements, forces, moments & associated stresses due to various load combinations towards meeting the requirements of the relevant code (Ex: ASME B31.3).

Liquid hydrogen is a lightest and the coldest fluid, having a specific gravity of 0.07 and with a boiling point of about 20K. It is also an excellent regenerative coolant. With oxygen it burns with a colourless flame; however, the shock waves in the plume may be visible. The very low fuel density requires bulky fuel tanks, which necessitate very large volumes. The extremely low temperature makes the problem of choosing suitable tank and piping materials difficult, because many metals become brittle at low temperatures. Because of its low temperature, liquidhydrogen tanks and lines have to be well insulated to minimize the evaporation of hydrogen or the condensation of moisture or air on the outside with the subsequent formation of liquid or solid air or ice. A vacuum jacket often has been used in addition to insulating materials. All common liquids and gases solidify in liquid hydrogen. Liquid hydrogen has two species, namely, orthohydrogen and parahydrogen, which differ in their nuclear spin state. The relative composition of ortho and parahydrogen changes as the hydrogen is liquefied. The transformation from one species to another is accompanied by a transfer of energy. Liquid hydrogen is manufactured from gaseous hydrogen by successive compression, cooling, and expansion processes. Hydrogen gas, when mixed with air, is highly flammable and explosive over a wide range of mixture ratios. Propellant combination involving Liquid Hydrogen & Liquid Oxygen has been applied successfully to space launch vehicles because of its high specific impulse.

II. STORAGE AND TRANSFER OF CRYOGENIC PROPELLENTS

After a cryogenic fluid has been liquefied and purified to the desired level, it may be required to store or transport as the case may be. The thermal performance of the storage vessels can range from ordinary to very high depending upon the type of insulation employed and the nature of suspension system. Accordingly the type of insulation will vary between normal foam insulation to Multi-Layer Insulation (MLI) and suspension system can be of non-metallic to metallic construction based on the desired thermal performance. There are six most commonly used insulations. These are listed in order of increasing performance and generally in order of increasing cost. The specific insulation to be used for a particular application is determined through a compromise among cost, ease of application, weight, ruggedness and the required thermal performance of the insulation [2].

The various insulations used are:

a. Expanded foam insulations
b. Gas-filled powders and fibrous insulations
c. Vacuum insulation
d. Evacuated powder & fibrous insulations
e. Opacified powder insulations
f. Multilayer insulations

This project deals with the cryogenic pipelines which are of vacuum jacketed construction and provided with multilayer insulation. Multilayer insulations consist of alternative layers of a highly reflecting material such as aluminium foil, copper foil, or aluminized mylar and a low-conductivity spacer, such as fiberglass mat or paper, glass fabric or nylon net. The reflecting layers may also be separated by crinkling or embossing the sheets so that they touch only at a few discrete points and a spacer is not required.

Multilayer insulations must be evacuated to pressures below 10 mPa to be effective. The amazingly low thermal conductivity of multilayer insulations can be explained by the fact that all modes of heat transfer i.e., radiation, solid conduction and gaseous conduction are reduced to a bare minimum. Radiation is minimized by using many layers of a highly reflecting metal foil. Solid conduction is minimized by the usage of a spacer material or by crinkling the shield material where in the contact points are minimized. Gaseous conduction is minimized by reducing the residual gas pressure to values of the order of 1.3 mPa. This insulation is also known as “Super insulation” due to its high insulation quality and it is generally used for cryogenic vessels as well as long cryogenic pipelines.

III. CRYOGENIC CHILLDOWN

Any cryogenic system which includes pipelines, storage vessels, pumps and associated valve units must undergo a transient chill down period prior to a steady operation. Chill down is the process of introducing the cryogenic liquid into the system and allowing the hardware to cool down to several hundred degrees below the ambient temperature (closest to the fluid temperature). The chill down process requires a procedure to chill down a cryogenic system in a safe and efficient manner. The reason that the highly transient chill down process is extremely complex because when a cryogenic liquid is introduced into a system that has reached equilibrium with the ambient, voracious evaporation occurs and a very high velocity gas mist traverses through the system. As the system cools, slugs of liquid, entrained in the gas, flow through the system in a two-phase film boiling mode. As the system cools further, a liquid quenching front flows through the system and is accompanied by nucleate boiling and two-phase flow. The rate of heat transfer in the nucleate boiling regime is very high and the system begins to cool down very rapidly. As the system rapidly cools down, the two-phase flow passes through several flow regime transitions to single-phase liquid flow. The inherent danger during chill down is that two phase flows are inherently unstable and can experience extreme flow and pressure fluctuations. The hardware may be subjected to extreme stresses due to thermal contraction and may not be able to sustain extreme pressure fluctuations from the cryogen [3].

Therefore, chill down must be accomplished with a minimum consumption of cryogen. As a result, it is important to fully understand the thermo-fluid dynamics associated with the chill down process and develop predictive models that reliably predict the flow patterns, pressure loss, heat transfer rates and temperature history of the system.

IV. PIPING CODE

Each ASME B31 Code section is published as a separate book. Some code sections apply to a specific industry, for example in its current scope ASME B31.1 applies to power plants or steam producing plants fired by fossil fuels (non- nuclear). ASME B31.4 applies to liquid hydrocarbon transportation pipelines, associated tank farms and terminals. ASME B31.8 applies to gas and two phase gathering lines, separators, transmission pipelines and associated compressors, and gas distribution piping [4]. ASME B31.9 applies to building services, typically air and steam. On the other hand, ASME B31.3 is a code of very broad application including chemical, petrochemical, pharmaceutical, utilities in process plants, support systems in pipeline terminals and pumping stations, process of radioactive or toxic materials, food and drug industry, paper mills, etc. The ASME B31 codes provide minimum requirements. They do not replace competence and experience. The owner or the contractor is expected to apply his or her knowledge to supplement the code requirements for a particular application. For example, when systems operate at temperatures that are typically low or high, the owner or the designer may need to impose additional design and fabrication requirements.

V. MATERIAL SELECTION

For the cryogenic piping design austenitic steels with FCC crystal structure are selected.Theseconstitute the largest stainless family in terms number of alloys and usage. The austenitic steels are non-magnetic and cannot be hardened by heat treatment. They possess excellent ductility, formability and toughness even at cryogenic temperatures. In addition, they can be substantially hardened by cold work. Nickel is the chief element used to stabilize austenite. Carbon and nitrogen are also used because they are readily soluble in the FCC structure. A wide range of corrosion resistance can be achieved by balancing the ferrite forming elements (such as chromium and molybdenum) and austenite-forming elements. The material being used is austenitic stainless steel of 304L grade and its composition is Carbon <0.035%, Chromium 18-20%, Nickel 8-12%, Manganese < 2%, Nitrogen < 0.1%, Iron 66-74% and small quantities of silicon, sulphur and phosphorous.

Factors for selection of material:
Characteristics to be considered in selecting the proper type of stainless steel for a specific application include:

a. Corrosion resistance.
b. Resistance to oxidation and sulfidation.
c. Strength and ductility at ambient and service temperatures.
d. Suitability for intended fabrication techniques.
e. Suitability for intended cleaning procedures.
f. Stability of properties in service.
g. Toughness.
h. Resistance to abrasion, erosion, galling, and sizing.
i. Surface finish.
j. Physical property characteristics.
k. Sharpness or retention of cutting edge.
l. Rigidity.

VI. SELECTION AND SIZING OF PIPELINES

The following guidelines are followed for pipeline sizing:

a. The operating medium and its properties.
b. Material of construction for pipeline.
c. Corrosion allowance.
d. Flow rate.
e. Design Pressure.
f. Allowable pressure drop.
g. Limiting velocity.
h. Design code.

The design of piping is a two-step process

1. Flow design

Minimum cross section of the pipe need to be calculated considering the mass flow rate required, density of the fluid and limiting velocity of the fluid through the pipe.

$Q_L = \rho AV$

where, Q_L = Mass flow rate of the fluid through the pipeline.

ρ = Density of the fluid.
A = Cross sectional area of the pipe.
V = Flow velocity (also known as the limiting velocity).

The limiting velocity (V) is arrived from the allowable pressure drop and general engineering practices.

2. Pressure Design

Selection of pipe schedule need to be carried out as per the sequence given below:

(a) Refer the following table which shows the various sizes/schedules of pipelines available in the market.

Table 1: Standard Nominal Pipe sizes and the thickness corresponding to their Schedule [5]

Nominal Pipe size		Outer Diameter (mm)	Schedule (thickness in mm)		
Mm	inch	mm	5S	10S	40S
6	1/8	10.30	-	1.24	1.73
8	¼	13.70	-	1.65	2.24
10	3/8	17.10	-	1.65	2.31
15	1/2	21.30	1.65	2.11	2.77
20	3/4	26.70	1.65	2.11	2.87
25	1	33.40	1.65	2.77	3.38
32	1 1/4	42.20	1.65	2.77	3.56
40	1 1/2	48.30	1.65	2.77	3.68
50	2	60.30	1.65	2.77	3.91
65	2 1/2	73.00	2.11	3.05	5.16
80	3	88.90	2.11	3.05	5.49
90	3 1/2	101.60	2.11	3.05	5.74
100	4	114.30	2.11	3.05	6.02
125	5	141.30	2.11	3.4	6.55
150	6	168.30	2.11	3.4	7.11
200	8	219.10	2.11	3.76	8.18

(b) Select the pipe with nominal size based on the diameter calculated.

(c) The minimum thickness [6] needed for the pipe to sustain the design pressure is given by

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

where, C = Sum of mechanical, corrosion and erosion allowances
D = Outside diameter of the pipe
P = Internal design gauge pressure
S = Allowable stress of the material
Y = A coefficient which depends on material selected and operating temperature. For Austenitic steels at cryogenic temperatures it is 0.4.

(d) Selection of pipe schedule shall be with a thickness greater than the calculated thickness by considering manufacturing allowance of 12.5% on wall thickness.

Problem considered in our current project:

Design of pipeline considering the following inputs:

a. Medium: Liquid Hydrogen
b. Flow rate : 2.2 Kg/s
c. Density : 70.2 Kg/m^3
d. Design Pressure: 13.75 bar.
e. Limiting velocity: 7 m/s.
f. Material of construction: SS304 L
g. The allowable stress for the pipe material: 115 MPa.
h. Corrosion allowance : 0

Using the above described procedure we can conclude that a pipe of 80 mm 10 Scheduleis needed for the given loading conditions. But as cryogenic piping is a critical piping of complex configuration we select the next pipeline size i.e., 80 mm 10 Schedule.

VII. LOADING CONDITIONS AND SEGMENTATION OF THE CIRCUIT

Classification of loads:

Primary Load:
These are typically steady or sustained types of loads such as internal fluid pressure, external pressure, gravitational forces acting on the pipe such as weight of pipe and fluid, forces due to relief or blow down, pressure waves generated due to water/steam hammer effects.

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Secondary Load:
Just as the primary loads have their origin in some force; secondary loads are caused by displacement of some kind. The displacement loads can be of two types: loads due to the thermal movement of equipment and load due to thermal expansion of the pipe lines. For example, the pipe connected to the nozzle of the storage tank will be loaded in case of tank movement due to its settlement. Similarly, pipe connected to a vessel is pulled upwards because the vessel nozzle moves up due to vessel expansion. Also, a pipe may vibrate due to vibrations in the rotating equipment it is attached to.

A pipe may experience expansion or contraction once it is subjected to temperatures higher or lower respectively as compared to temperature at which it was assembled. The secondary loads are often cyclic but not always. For example load due to tank settlement is not cyclic. The load due to vessel nozzle movement during operation is cyclic because the displacement is withdrawn during shut-down and resurfaces again after fresh start-up. A pipe subjected to a cycle of hot and cold fluid similarly undergoes cyclic loads and deformation.

SEGMENTATION:
Considering the following advantages, complexity of the fluid circuit has been reduced by segmentation
(a) Ease of fabrication: The segmentation is done considering the ease of fabrication by the manufacturer.
(b) Ease of erection: Segmentation also helps in easy erection so that the individual segments can be integrated at site by maintaining the same boundary conditions so that analysis has no impact.
(c) Ease of Transportation: Segmentation also helps in easy transportation as the individual parts can be easily mobilized/positioned in the constrained locations. Usually for the transportation, it is preferred that these parts are made into One/ Two dimensional objects as they consume less space.
(d) Ease of Analysis: Analysis of each individual segment can be carried out with less complexity due to reduced number of nodes as against the whole piping circuit. In view of this, the circuit is usually divided into individual parts from anchor to anchor, as the anchors do not transmit any displacements.

VIII. PIPING FLEXIBILITY

[7] Piping systems shall have sufficient flexibility to accommodate thermal expansion/ contraction or movements of piping supports and terminals with a view to avoid the following:
(a) Failure of piping or supports from over stress or fatigue.
(b) Leakage at joints
(c) Detrimental stresses or distortion in piping and valves or in connected equipment (pumps and turbines, for example) resulting from excessive thrusts and moments in the piping.
The different Displacement Strains are due to:

(a) Thermal Displacements:
A piping system will undergo dimensional changes with the change in temperature. If it is constrained from free expansion or contraction by connected equipment and restraints such as guides and anchors, it will be displaced from its unrestrained position.

(b) Restraint Flexibility:
If restraints are not considered rigid, their flexibility may be considered in determining displacement stress range and reactions.

(c) Externally Imposed Displacements:
Externally caused movement of restraints will impose displacements on the piping in addition to those related to thermal effects. Movements may result from tidal changes (dock piping), wind sway (e.g., piping supported from at all slender tower), or temperature changes in connected equipment.

A displacement stress range greater than that permitted may be allowable if due consideration is given to avoidance of excessive localized strain and end reactions.

(d) Total Displacement Strains:
Thermal displacements, reaction displacements, and externally imposed displacements all have equivalent effects on the piping system, and shall be considered together in determining the total displacement strains (proportional deformation) in various parts of the piping system.

Stresses cannot be considered proportional to displacement strains throughout a piping system, in which an excessive amount of strain may occur in localized portions of the system. Operation of an unbalanced system in the creep range may aggravate the deleterious effects due to creep strain accumulation in the most susceptible regions of the system. Unbalance should be avoided or minimized by design and layout of piping systems, particularly those using materials of low ductility. Many of the effects of unbalance can be mitigated by selective use of cold spring. If unbalance cannot be avoided, the designer shall use appropriate analytical methods/Finite Element analysis tools to ensure adequate flexibility.

[8]Properties used for Flexibility Analysis:

(a) Thermal Stress Range:
Values of thermal displacements to be used in determining total displacement strains for computing the stress range shall be determined as the algebraic difference between the value at 35 maximum metal temperature and that at the minimum metal temperature for the thermal cycle under analysis.

(b) Modulus of Elasticity:
The reference modulus of elasticity at 21°C (70°F), *Ea*, and the modulus of elasticity at maximum or minimum temperatures, *Em.*

(c) Poisson’s Ratio:
Poisson’s ratio may be taken as 0.3 at all temperatures for all metals. More accurate and authoritative data may be used if available.

(c) Allowable Stresses:
(i) The allowable displacement stress range $S_A$and permissible additive stresses shall be specified in standards which are primarily stressed in bending and/or torsion.

(ii) The stress intensification factor has been developed from fatigue tests of representative piping components and assemblies manufactured from ductile ferrous materials. The allowable displacement stress range is based on tests of carbon and austenitic stainless steels

(e) Dimensions:
Nominal thickness and outside diameters of pipe and fittings shall be used in flexibility calculations.

Cold spring is the intentional deformation of piping during assembly to produce a desired initial displacement and stress. Cold spring is beneficial in that it serves to balance the magnitude of stress under initial and extreme displacement conditions.

When cold spring is properly applied there is less likelihood of overstrain during initial operation. Hence, it is recommended especially for piping materials of limited ductility. There is also less deviation from as installed dimensions during initial operation, so that hangers will not be displaced as far from their original settings

IX. FLEXIBILITY MANAGEMENT

There are three methods of compensation for thermal movement in a piping system:

1. Designing a flexible piping which utilizes changes of direction to absorb movement.
2. Usage of pipe loops and bends to absorb movements
3. Usage of expansion devices such as metal bellows expansion joints and flexible metal hoses.

EXPANSION LOOPS:

Having positioned the anchors in the system should be examined for flexibility. If an offset occurs in a straight pipeline between two anchors this could provide enough flexibility. Here comes the use of expansion loops.

A good piping designer will always use an expansion loop whenever possible. They are more rugged and require less special treatment when being installed and operated. They can usually be fabricated from common piping components and do not require a special order. Bellows type expansion joints are required to be used in case of space constrained installations and also for certain equipment to minimize thermal loads from the piping system. Because of their construction, they require special care and attention during their installation.

Loops provide the necessary leg of piping in a perpendicular direction to absorb the thermal expansion. They are safer when compared to expansion joints but take more space. Expansion loops may be symmetrical or non-symmetrical. In a symmetrical loop, the expansion joint is placed at the middle of the piping with equal lengths of pipe segments on either side. Hence it is useful to absorb an equal amount of expansion from both directions.

Bellows/Expansion Joints:

Bellows are expansion joints used to absorb the axial and lateral movement (caused by thermal expansion or contraction) of the pipe section in which it is installed. It is not capable of absorbing pressure thrust, which must be restrained by the piping system itself. Bellows joints absorb expansion and contraction by means of a flexible bellows that is compressed or extended. They can also accommodate direction changes by various combinations of compression on one side and extension on an opposing side. Thus, they can adjust to lateral offset and angular rotation of the connected piping. However, they are not capable of absorbing torsional movement. Typically, the bellows is corrugated metal and is welded to the end pieces. To provide the requisite flexibility, the metal bellows is considerably thinner than the associated piping. Thus these expansion joints are especially susceptible to rupture by over pressure. A bellows can also fail because of metal fatigue if the accumulated flexing cycles exceed the designed fatigue life.

A Bellow is a flexible seal. This convoluted part of the joint is designed to flex when the thermal movement in the piping system occurs. Thus by determining the thermal movement that will occur in the piping system, expansion joints may be specified, manufactured and installed in the system to accommodate these movements.

Figure.1. Bellow

Advantages of an Expansion Joint over a Pipe Loop

An expansion joint and a pipe loop are two methods employed to safely absorb thermal expansion or contraction in piping systems due to thermal temperature changes. During a design consideration, where an expansion joint or a pipe loop can be utilized, the major advantages of using an bellow/expansion joint are as follows:

1. Space is inadequate for a pipe loop with sufficient flexibility.
2. A minimum pressure drop throughout the pipe line is required and the absence of flow turbulence from the elbows and piping is required by process flow conditions.
3. The fluid is abrasive and flows at a very high velocity.
4. There is no adequate support structure to support the size, shape and weight of a pipe loop.
5. The pipe loop is impractical and in an application of low pressure or large diameter.
6. Construction schedule does not allow for the man-hours required to install the pipe loop and the piping loop support structure.
7. In most cases it is more economical to use an expansion joint instead of pipe loops.

The various inputs for the Flexibility analysis are
(i) Piping Design inputs
(ii) P & I Diagram

The P & I Diagram gives a representation of sequence and connection of equipment and systems used in the piping network, the various inputs needed, the boundary and operating conditions. A conventional P & I diagram was taken as an input. The same has been converted into a smart P & I diagram using the software "AutoCAD Plant 3D" as shown in the following figure 2, towards generation of a 3D piping layout.

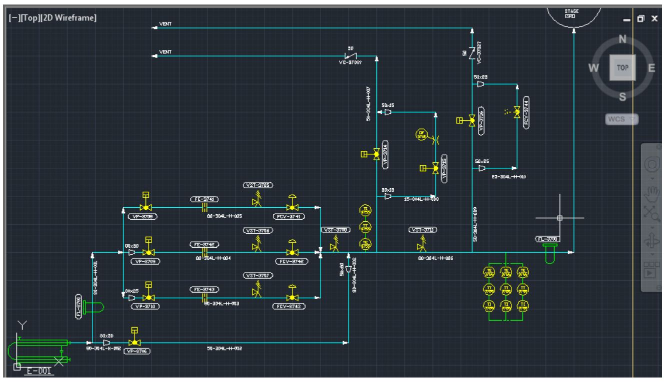

Figure.2. P & I diagram

(iii) 3D Model

The 3D model was constructed using the auto route generator in the software AutoCAD plant 3D as shown in the following figure 3 using the inputs from the smart P & I diagram. The appropriate route has been selected such that less material will be used and more flexibility is incorporated

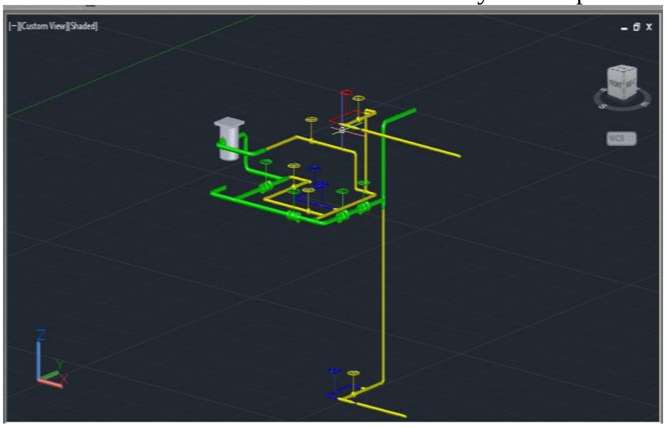

Figure.3. 3D Model

(iv) Isometric Diagram

After necessary segmentation of the whole circuit, it has been broken into 5 segments. In this paper we have presented the isometric diagram of one of the 5 segments we analyzed and the further discussion will be only on this segment.

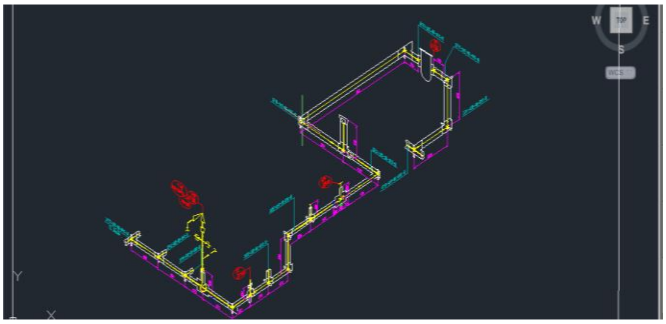

Figure.4. Isometric Diagram

Flexibility Analysis of the segment

Using the inputs from the isometric diagram, a model is constructed in the Bentley AutoPIPE. The operating pressure and temperature of the circuit are 10 bar and 20 K respectively. But by incorporating the safety conditions and the extremes of operating Pressures and Temperatures, 3 load cases are defined and the model is analyzed for the stress ratio under these 3 loading conditions. The 3 cases are:

a. P_1 : 13.75 bar T_1 = 20 K
b. P_2 : 2 bar T_2 = 423 K
c. P_3 : 15 bar T_3 = 303 K

The Valves used in this circuit are all assumed as globe valves which can either be on-off valves or the control valves. [9]By definition, valves are mechanical devices specifically designed to direct, stop, mix, and regulate the flow, pressure or temperature of a process fluid. These are designed to handle either liquid or gas applications. There are many reducers and bends which were also used and these were modelled accordingly in the software. All the bends were assumed to be long bends.

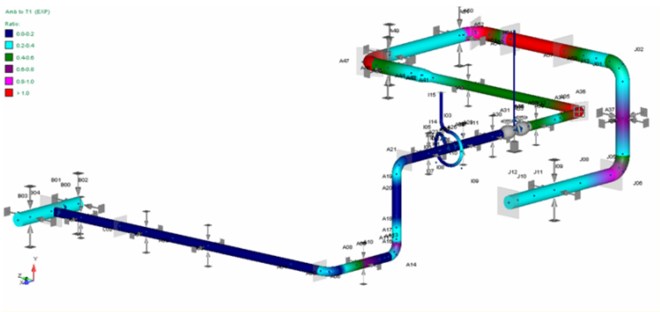

Figure.5. Flexibility Analysis on the model

Incorporation of Flexibility:

We can see in the above Figure 5 that there are a lot of places in the circuit which are having a stress ratio of more than 1. But our aim is to make the stress ratio of the model to less than 0.25 at almost all the points thus maintain a factor of safety of 4. For this we have added a lot of flexible joints like the Bellows in the circuit thus reducing both the Stress ratios and also the displacement strains in the circuit.

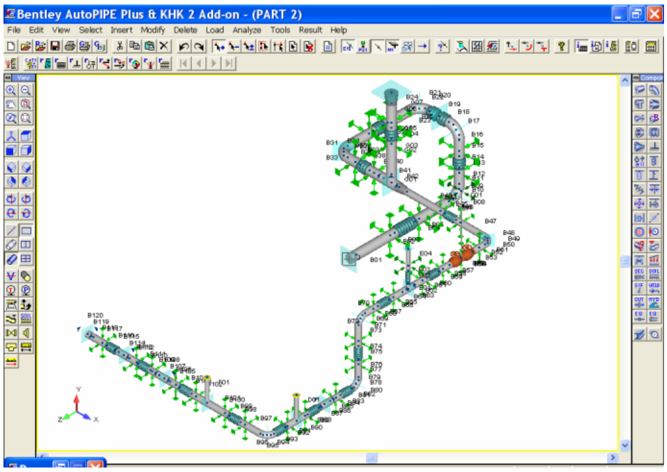

Figure.6. Model after the incorporation of Bellows

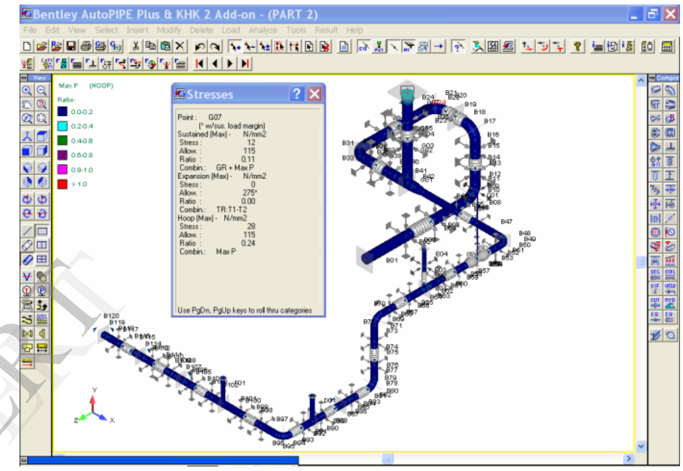

Figure.7. Stress ratio of the Model after the Flexibility incorporation

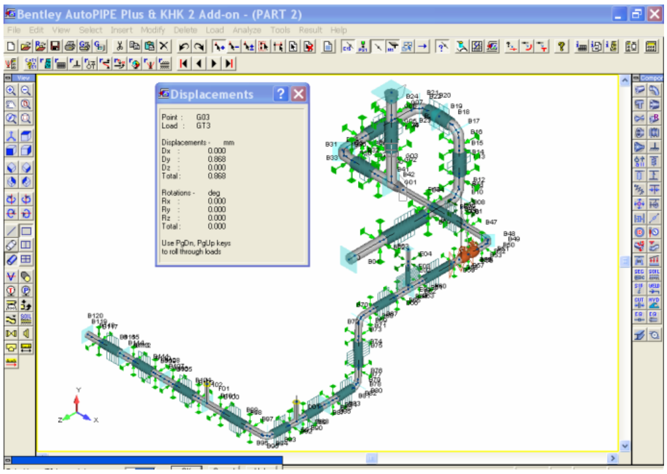

Figure.8. Displacements at each point in the circuit

The above mentioned figures 6, 7, 8 shows the model after the bellows are inserted, code stress ratio and the displacements respectively. [10]The table showed in the figures 7 gives the representation of the maximum stress ratio point and the corresponding load combination whereas the table in figure 8 shows the point with maximum displacement and the corresponding load condition. These results are further summarized in the system summary tabulated below from Tables 1 to 9 which are auto generated by the software used i.e. Bentley AutoPIPE. The displacements, Forces Moments and the stress ratio of each node in the diagram is also given by the software but we are presenting only the points with the maximum of these. These results and the model we made are in compliance with the code ASME B31.3 process piping.

Table 1Maximum displacement (mm) of the Segment

Maximum X :	-2.031	Point : A44	Load Comb.: GR+T1P1
Maximum Y :	-2.184	Point : B01	Load Comb.: T1
Maximum Z :	-1.945	Point : A59	Load Comb.: GR+T1P1
Max. total:	2.184	Point : B01	Load Comb.: T1

Table 2 Maximum rotations (deg) of the Segment

Maximum X :	0.143	Point : B01	Load Comb.: GR+T1P1
Maximum Y :	-0.041	Point : A35	Load Comb.: T1
Maximum Z :	0.034	Point : A14	Load Comb.: T1
Max. total:	0.143	Point : B01	Load Comb.: GR+T1P1

Table 3Maximum restraint forces (Kg) of the Segment

Maximum X :	1105	Point : A17	Load Comb.: GR+T1P1
Maximum Y :	-1026	Point : A08	Load Comb.: GR+T2P2
Maximum Z :	1177	Point : A32	Load Comb.: GR+T1P1
Max. total:	1520	Point : A32	Load Comb.: GR+T1P1

Table 4Maximum restraint moments (Kg-cm) of the Segment

Maximum X :	-75	Point : A17	Load Comb.: T1
Maximum Y :	587	Point : A20	Load Comb.: T1
Maximum Z :	-740	Point : A20	Load Comb.: T1
Max. total:	944	Point : A20	Load Comb.: T1

Table 5Maximum pipe forces (Kg) of the Segment

Maximum X :	1111	Point : A33 N	Load Comb.: GR+T2P2
Maximum Y :	1111	Point : A08	Load Comb.: GR+T2P2
Maximum Z :	1097	Point : A29	Load Comb.: GR+T2P2
Max. total:	1159	Point : A32	Load Comb.: GR+T2P2

Table 6Maximum pipe moments (Kg-cm) of the Segment

Maximum X :	6340	Point : A08	Load Comb.: GR+T1P1
Maximum Y :	7737	Point : A32	Load Comb.: GR+T1P1
Maximum Z :	4801	Point : A17	Load Comb.: GR+T1P1
Max. total:	7737	Point : A32	Load Comb.: GR+T1P1

Table 7Max sustained stress of the Segment

Point	:	G07
Stress Kg/cm2	:	127
Allowable Kg/cm2	:	1173
Ratio	:	0.11
Load combination	:	GR + Max P

Table 8Maximum displacement stress of the Segment

Point	:	A52
Stress Kg/cm2	:	594
Allowable Kg/cm2	:	1761
Ratio	:	0.34
Load combination	:	T1 to T2

Table 9Maximum hoop stress of the Segment

Point	:	G07
Stress Kg/cm2	:	285
Allowable Kg/cm2	:	1173
Ratio	:	0.24
Load combination	:	Max P

X OPTIMIZATION

(a) Optimization of Anchors:

Usually anchors are placed to prevent transmission of displacements from one segment to another segment. If an anchor is removed, the displacements are transferred which may result in excessive deformation of the inner pipe beyond the permissible results. This may cause excessive bending stresses. If adequate clearances between inner & outer pipes, absence of thermal shorting and permissible relative movements of the valve bodies are ensured, we can justify these displacements and declare the piping circuit as safer.

So we need to take into consideration all these things when we optimize the above.

(b) Optimization of Supports:

When the supports are optimized the forces increase in the system as the number of load bearing members are reduced. However the thermal stresses in the system are reduced as there is an increased freedom for displacement. As a contrary, on account of supports optimization, sustained stresses in the system will be increased.

(c) Optimization of Bellows:

As the bellows are the weakest parts in the system they are most susceptible for the damage. Accordingly reliability of the system will increase with the optimization of bellows. When the bellows are optimized, the stress ratio will increase based on the loop length and geometry. Sometimes bellows cannot be avoided where the displacements in a certain loop and some flow components (like valves) cannot be accommodated.

In this design, we took into account all these optimizations and made the best possible design with optimum number of anchors, supports and bellows to meet the code compliance.

XI. CONCLUSION

Design of a Cryogenic fluid circuit involving vacuum jacketed piping with imposed space constraints is a complex task. For practical implementation of such design, a thorough analysis and validation is required. Optimization of design is also an important task towards minimization of overall project cost. Carrying out the above tasks with manual calculations is a time consuming process as the prediction of results impose greater computational requirements.Towards this,an FE model is generated from the 3D drawingsusing the Bentley "AutoPIPE". This model has been segmented and thermo structural analysis was done to know the values of displacements, forces, moments and stresses. These segments were analyzed for the given operating conditions and boundary conditions. The flexibility of these segments is optimally managed by incorporation of expansion loops/joints wherever necessary. The stress ratios, displacements and forces were found to be within the limits. The designed system is found to be in compliance with international piping code ASME 31.3. A factor of safety of 4 had been maintainedin the design as the operational behaviour of the complex cryogenic fluid circuit is critical. The design is carried out in an iterative manner so as to optimize the number of flexible elements and supports while establishing the code compliance.

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