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Safety in design during piping engineering

A process engineer must complete the preliminary preparations of process flow diagrams, material and energy balances, piping and instrumentation diagrams (P&IDs), process control philosophy, and identification of the hazardous nature of raw materials, chemicals, byproducts and final products. Afterward, documents including process equipment layout drawings (plan and elevation) and unit plot plans are issued to engineers from other disciplines.

Involving engineers from different disciplines in the design phase provides unique perspectives that add value to basic documents, such as improved safety design features. Discipline engineers are required to consider design and safety requirements that are applicable for their specific domain as per local, national, international, industry-specific and company standards and regulations, and good engineering practices.

The role of a piping engineer during the design of piping systems is explored here, as well as how that piping engineer can—from the initial design phase—lower the risks that can arise from handling hazardous materials, contribute to reducing potential liability and help create a safer environment for the public.

Role of a piping engineer. Piping engineers play an important role in the selection of proper materials and in preparing design specifications of piping system components. They develop specifications for insulation, painting and piping installation, and provide significant contributions to the overall plant and piping layout by coordinating with other engineering disciplines to optimize layout details.

A piping design engineer should have knowledge of various standards, code requirements and industry-specific practices. This ensures safety from the design stage onward, minimizing risks as much as is reasonably practicable.

What is safety in design? Safety in design concerns the mitigation of identified risks and hazards during conceptual planning, as well as the basic and detailed design engineering stages of a project. This includes a focus on the selection of proper materials, manufacturing, erection and installation processes to enhance process plant safety and efficient operation throughout its life. Safety in design encompasses all components and aspects of a plant, including layouts, materials, equipment, tools, controls, products and the environment.

For hazardous systems, safety aspects like system integrity and fire safety must be incorporated into the design of a piping system. The selection of construction materials, connecting joint designs, valve type and trim, testing and examination requirements, design and installation should be detailed so that the required degree of integrity in the piping system can be determined.

What constitutes a piping system? Piping systems include pipes, valves, flanges, threaded joints, gaskets, hoses, drains, vents, traps, strainers, inline and offline instruments, and other elements. Piping is the largest threat to plant safety due to the large number of joints that are spread over the entire facility.

Selection of suitable construction materials. Proper materials selection provides safety against brittle fracturing of piping. Important considerations in the selection of construction material for a safe piping system include:

- Material compatibility with process fluids under all operating and accidental pressure and temperature parameters
- Changes in concentration and/or content of the fluids carried in piping and the surrounding environment
- Erosion and corrosion mechanisms that may be present
- Past experience from similar operating plants.

Piping material specifications (PMS) are developed in line with ASME B 31.3 fluid service categorization, with an emphasis on standardizing all piping commodities for use on a project. A well-defined PMS in an automated engineering environment eliminates any chance of casual or unintended errors and helps ensure that intended safety procedures at the PMS design stage will be translated to construction deliverables.

For non-metallic piping materials, various limitations such as temperature, pressure, sensitivity to ultraviolet light, surge, impact loads, vibration and higher thermal expansion coefficient must be carefully accounted for when determining material specifications. The weaknesses of these materials usually require closer pipe supports and, in many cases, a continuous structural support is considered a more viable solution.

Underground piping must withstand external loads in addition to internal fluid pressure. Underground piping must be capable of bearing the soil load above it, groundwater buoyancy, traffic loads from the surface and loads caused by potential earthquakes. Leakage detection and repair are inherently difficult in underground piping, so it must be limited to non-hazardous services and requires cathodic protection, coating, wrapping and encasing.

Minimum wall thickness and stress analysis. Calculating minimum pipe wall thickness is performed in accordance with piping design codes, such as ASME B31.3, to ensure pipe safety against failure due to hoop stresses resulting from internal pressure. By performing stress analyses, a piping engineer can ensure piping safety against failure due to excessive plastic deformation, incremental collapse and low cycle fatigue. Design codes achieve this by providing rules on how piping loads and stresses caused by internal pressure, self-weight, thermal expansion and occasional loads due to earthquake, snow and wind are evaluated for stresses. These combined stresses are then compared against the allowable limits to confirm compliance.

Equipment connected to piping is susceptible to failure due to excessive loading. The loads that are exerted by the piping during all operating or standby conditions should be correctly evaluated. Rotating machines, such as turbines, compressors and pumps, are particularly sensitive to loads transferred by piping, which can cause misalignment, vibration and reduced design life.

A detailed stress analysis of the connected piping will reveal the loads under various conditions, such as the heatup and cooldown of the tower, ground settlement of the tank foundation and the hot, cold and standby conditions of the turbine, compressor and pump. A piping stress engineer will then take further measures to limit these loads within the acceptable range, which ensures the full design life of costly equipment and can prevent accidents.

Piping joints. The weakest points in a piping system are the connecting joints. Leak prevention by design begins with the relative ranking of the piping and valves joints used in a piping system. Only a full penetration butt-weld is considered as strong as the parent pipe; the use of other types of piping joints, including longitudinal seam welds and circumferential welds, can weaken the piping system. The reduction in strength due to a longitudinal seam weld in the pipe must be accounted for when performing minimum wall thickness calculations using the weld quality factor. The reduction in pipe strength due to circumferential welds should be accounted for in the weld joint strength reduction factor. Other joints, like flanges, valve body, bonnet and stem seal types, also add to the weakness of piping, and can cause accidental leakage. Evaluating these joints when subjected to fire may require changes in the joint design to achieve the required safety. For example, metal seated valves will perform better in a fire, so a change of an elastomeric gasket to a metallic gasket that can survive under fire will create a fire-safe flanged joint.

When performing stress analysis calculations to comply with ASME B31.3 or B31.1, a stress intensification factor (SIF) should be included in the calculation as a measure of weakness associated with various connecting joints to fittings. A full penetration butt-weld should have an SIF of 1, as it is considered as strong as the parent pipe. Fillet welds on slip-on and socket-weld flanges should have an SIF of 1.2 and 2.1, respectively. The threaded connection should have an SIF of 2.3. For a typical stub-in branch connection (as an SIF depends upon size of run pipe, its thickness and pad thickness), an in-plane SIF should be 3.9 and an out-of-plane SIF should be 4.9, including a reinforcing pad with a thickness the same as the run pipe, which will strengthen the connection and reduce the SIF to half the value. A welding tee may still be a better choice, considering the extra effort needed to weld the pad.

Selection of gaskets. The integrity of the flange joint seal is dependent on the gasket. Flange bolts work like a spring and provide a uniform force while the gasket remains intact. Flange leaks on gasket failures are due to excessive pressures or temperatures. Bending moments on a flange as a result of load or thermal expansion of pipe can also be a reason for flange leakage. A detailed stress analysis and flange leakage calculation should be performed to ensure the safety of critical piping.

Gasket material selection based only on design, pressure, temperature and material compatibility may prove inadequate. Wherever necessary (e.g., isolation valves), all joints must survive a fire long enough to allow minimum time to emergency responders.

Flanged joints are essential for equipment requiring frequent disconnection for maintenance or repair. A spiral wound gasket with a graphite filler should be considered, as this can withstand higher temperatures.

Vibration. When piping is subjected to vibrations due to connected equipment or flow, it becomes open to alternating stresses and can eventually fail due to fatigue after completing a designed number of fatigue cycles. In such conditions, slip-on and socket welded connections can fail due to weak fillet welding, which can affect the safety.

Restricting small-bore piping to a safe distance from the compressor discharge is a good practice to limit fatigue damage. Depending on the criticality of the service, a detailed assessment of vibrations and piping fatigue safety may be required to ensure the intended service life without failure.

Valves. Isolation valves play a key role in achieving safe design goals during plant operation and accidental conditions. These valves may be manually or remotely operated, depending on the process needs. A fire-rated or fire-safe valve must be considered for a critical isolation requirement, and it should be located at an accessible and safe place in the event of an accident. Check valves are deployed to ensure flow only to the desired direction or a no flow. The valve should be installed correctly as indicated by P&IDs, otherwise it will only block the flow. Also, it should be confirmed that flow direction markings on the check valve are correct to allow and block the flow as intended by the design.

Plant layout. While deciding plant layout, careful consideration of hazard segregation will facilitate built-in safety. Arranging equipment to minimize piping runs—particularly for costly, large-sized piping and special material piping—will not only save cost, but will also reduce probable leakage points. Placing units closer to their raw material receiving point or finished product dispatch point minimizes material movement. Using site gradient when locating effluent treatment facilities, or other facilities, minimizes energy consumption by utilizing gravity flow feeds. Locate fired heaters so that under any eventuality of leakage, combustible-laden air within a process unit is naturally blown away from the fired heaters by the prevailing wind direction.

In addition to the plot plan review by construction and safety personnel, a review of a 3D model design at 30% completion can further help project safety and constructability causes to finalize the unit plot plan and overall piping layout for further detailed engineering.

Examples of important considerations. Important considerations in process plant piping systems include:

- A fire-rated isolation valve should be in the supply line of flammable fluid before entry to an area, building or unit. An interlock with a fire alarm system and remote operation from a fire-safe location is also equally essential, as such isolation valves can be designed to attain a fail-safe close position in case of power supply failure.
- A fire-rated valve should be used at locations where flow isolation is essential for fire safety, such as at equipment drains and vents.
- For hazardous services, all valves should have welded ends or flanged ends with a fire-safe gasket. All inline valves are designed to remain in the open position during a fire to facilitate draining of fluid to a vessel.
- For acid and caustic services, all probable leakage points, such as flange joints of a valve, equipment or an instrument, must be installed below operator eye level to remain hazard free. Chemical spray guards must be installed at flanges or threaded instrument connections to protect the operator. As a personnel protection measure, a standard and uniform safety shower and eyewash combination unit should be provided for quick drenching and flushing in case of any emergency.

Based on these factors, a piping engineer should provide required inputs to the process engineer when revising P&IDs and process equipment layout drawings for further engineering.

Installation of valves and other components. Valves should be installed with the stems between the vertical and horizontal positions to remain accessible for operation and maintenance without obstructing personnel or traffic movement.

Valve hand-wheels, levers, instruments or other equipment requiring manual operation should be installed in safely accessible elevation/locations and should not obstruct access clearances in all operated positions. Valves should be installed so that the operator will not stand on adjacent pipes, cable trays, handrails or other equipment not meant to be used as a standing surface for the operation, maintenance, repair or replacement of the valve. Proper clearance for wrenches should be provided adjacent to flanged connections for valves and equipment.

Valve hand-wheel extensions and chain operators should only be used when a better alternative is unavailable. These mechanisms require maintenance and are subject to corrosion. Chain operators are a nuisance, may not operate in an emergency and can be a hazard if the chain is left off of its tie-back and hanging in an access way.

Piping systems should be constructed with flanged joints or unions, per applicable piping specifications, wherever frequent maintenance is required. Piping that requires servicing—more than once every 6 mos—should be arranged to preclude the undesired removal of equipment, piping or installation of temporary supports.

Piping connections to heat exchangers, compressors, pumps and locations where pigging and/or steam air decoking will be required should be designed to facilitate equipment removal by means of removable spools, preferably with a change in direction to ease extraction.

Piping supports should be designed to facilitate the removal of connected equipment, vessels, instrumentation and valves without compromising the support of adjacent piping, valves and appurtenances.

The identification and marking of field and shop welds on piping drawings assists the construction team, improves the quality of construction and maximizes shop welding, improving and simplifying inspection and quality assurance.

Strainers and filters are installed to facilitate smooth functioning of process equipment and must be cleaned as per process specified frequency. In many instances, opting for a duplex arrangement will allow for uninterrupted service while one is taken for cleaning. Installing self-cleaning strainers and filters with a duplex arrangement will allow for the optimum uninterrupted service if planned and considered from the design stage.

Steam and condensate piping. Steam supply headers, drip legs and steam traps should be installed at no more than 30 m–50 m apart, and at the bottom of risers or drops. This is essential to preventing water hammer in the system. Drip legs and steam traps are also suggested immediately before isolation valves, pressure-reducing valves and control valves to prevent condensate from accumulating when the valve is closed. The trap will help reduce erosion of the valve seat from condensate and prolong seat life, as well. Attention should be paid to the proper sizing of drip legs, as inadequately sized drip legs are often found, which defeats the purpose and can prove to be unsafe.

Steam piping should be routed and inclined at 1:100 toward the flow, and supported such that sag between any two supports is insignificant compared to the pipe slope. This will prevent holdup of condensate and maintain piping draining. The branch piping from a steam supply header must be taken from the top of the horizontal portion of the header. This will facilitate separation of condensate from steam.

When connecting a condensate return header, branch lines that discharge condensate to the return header must be connected from the top of the horizontal part of the header. This will prevent any chance of reverse flow of condensate and water hammer in the system.

Selection of hoses. Serious accidents occur due to the failure of various types of flexible hoses that are used to transfer fluids between storage tanks, vessels and transport vehicles. In an unplanned or emergency operation, it is possible that the nearest hose could be deployed to empty a process vessel, without considering its suitability.

Many accidents happen due to improper specifications, clamping arrangements, faulty operations and the use of damaged hoses. It is important to:

- Clearly understand the process requirements and fluids to be handled
- Have a proper system for identifying hoses of different materials
- Provide secure storage for hoses that are not in immediate use
- Check all hoses periodically.

Process engineers, piping engineers and all those involved in the operation, maintenance and housekeeping of a process plant or tank farm area play an important role in reducing the risks that arise due to the improper use of flexible hoses.

3D modeling. Most modern plants are designed using 3D modeling software. Geometry, data and rule settings make the software an indispensable tool for plant engineering. Productivity benefits aside, 3D models are helpful in building safer plants. A model review at 30% completion of detailed engineering serves the goal of finalizing the units, area layouts and plot plan. Constructability, accessibility and approach during operation, unit maintenance, emergency contingencies, spatial segregation, intervening gap and certain features (such as dyke requirements to contain spills) are reviewed at this stage. A model review at 60% completion of detailed engineering is aimed at completing the structural detailing and the piping layout—ensuring that they include low-point drains and high-point vents, ducting and cable trays—to further facilitate the review of safety in the operation and maintenance (O&M) of the plant. The final model review is performed at 90% completion of engineering to close out all remaining minor detailing to complete the 3D model. Maximum value additions usually happen before the 30% model completion, and O&M safety is engineered by the 60% model review.

Insulation specifications. Insulation for piping, whether hot or cold, is needed to conserve energy, as well as protect personnel operating the plant. Therefore, the insulation material must be operator-friendly, harmless, easy to apply and remove, non-degrading, non-combustible and economical. Other considerations include:

- Insulation can absorb water and cause corrosion of piping materials, which can eventually fail and cause an accident
- Insulation can absorb leaking combustible fluid through some piping joints and accumulate and spread through the insulation to become a major fire hazard.

Painting specifications. At a plant site, piping should be painted as per the color coding of process fluids for ease of identification. It should also be labeled to indicate content, flow direction, design temperature and pressure. Painting and marking piping ensures clear identification and prompts the operator to take appropriate measures to eliminate, minimize or contain a risk.

Piping erection and installation specifications. Piping fabrication, erection and installation must strictly follow design drawings and documents issued for the purpose. Any difficulty in implementing the drawings must be reported back to the engineering team and should be performed only after their authorization for the engineering change. Usually, differences will not arise due to the use of a 3D model at the design stage. There could be some late changes in equipment design or deviations from specifications that are not implemented in the 3D model, or there may be an incorrect interpretation of the engineering drawings by fabricators, which is why such differences from design drawings are approved through the engineering team to ensure design safety.

Takeaways. Several safety facets are specific to industry or equipment specifications that must be considered during the design of a piping system for process plants, tank farm areas, cross-country pipelines, pressurized storages and low-temperature or cryogenic storages. For an experienced engineer, most of these design considerations are obvious, not analytical in nature and can be easily adapted into routine design checklists to ensure adherence as a quality check.

Building these safety aspects into the design and specifications of a piping system is important for the safety of any process, and avoidance of these aspects may lead to major catastrophes in a plant. HP

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