Design and Development of Piping and Instrumentation (P&ID) for Novel Acetonitrile Process

Research Article

Design and Development of Piping and Instrumentation (P&ID) for Novel Acetonitrile Process

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ABSTRACT

This study presents the design and development of a detailed piping and instrumentation diagram (P&ID) for a novel acetonitrile production process based on bioethanol catalytic ammoxidation. Presently P&IDs are developed based on conceptual process which can lack systematic integration of process control and safety elements. Therefore, a systematic approach to P&ID is essential. The objective of the work is to translate the proposed reaction pathway into a safe, operable, and standardized engineering design suitable for pilot-scale implementation. P&IDs are analyzed to bridge the gap between process development and practical plant reaction pathway into a safe, operable, and standardized engineering design. Detailed P&ID were prepared on basis process flow diagram and material balance calculations were used to define stream flows and equipment identification. Instrumentation, control loops, and safety systems were integrated in accordance with ISA and ISO standards to ensure safe and operable pilot-scale process design. The result suggests that systematic development of P&ID provides a reliable engineering foundation for pilot-scale implementation, hazard analysis, and future process scale-up.

1. Introduction

In the present study, acetonitrile is a major organic chemical that is widely accepted in the chemical industries, extractive processes, distillation in the petrochemical industry, and development of cosmetics, pharmaceuticals, and agricultural products, among other uses and is a volatile colorless liquid with an odor similar to ether [1]. In recent years, increasing interest in sustainability chemical production has motivated researchers to develop alternative acetonitrile synthesis routes on renewables feedstock such as bioethanol [2]. For the proposed acetonitrile process, although bioethanol-based route offers environmental and economic advantages, their practical process flow and well-integrated process design. For pilot scale acetonitrile production, early-stage engineering influence plant operability, stability, reliability, and safety performance. Standard chemical engineering practice emphasizes that detailed process documentation and systematic design procedures to translate conceptual process to workable plant.

Among process design documents, the P&ID serves as central engineering reference for equipment layout, piping systems, measurement devices, control loops, and safety provisions [3,4]. However, for pilot scale and emerging process, instrumentation and safety elements are not systematically integrated in during early design stages. Inadequate representation of control loops and safety systems may lead to unstable operation, equipment, or safety risks. Therefore, detailed development of P&ID that mention clearly all controls, equipment, and interlock functions is necessary for reliable plant performance [5].

P&ID are widely used in engineering, procurement and construction as the primary documents for representing process equipment, piping systems, and instrumentation. The advantage of this acetonitrile P&ID is that all major components, control loops, and safety are systematically documented. However, in many pilot-scale and emerging processes, instrumentation and safety elements are often incorporated at later stages, resulting in incomplete integration of control and safety systems. In such cases, inadequate representation of interlocks, alarms, and control strategies may lead to operability challenges and increased safety risks [5].

As part of this research, I propose a development of P&ID for newly developed process of bioethanol to acetonitrile. In first step, defined the core process inputs as flowrate, temperature, pressure, composition that guide me the entire system design and equipment required.
Established codes like ISA S5.2 and relevant ISO standards that ensure safe, reliable, and compliant design fabrication and operation of process systems. Second step a clear schematic showing major equipment, process lines, flow direction, and key operating parameters. A foundational step to quantify input, output, accumulation of mass and energy essential for process validation. Third step to create a detailed inventory of all process equipment with tag number, specifications, quantities, and design parameters for procurement and layout planning. Determine pressure drops, line sizing, pump head, and flow velocity to ensure efficient and reliable fluid transport through piping systems. Subsequently A detailed schematic showing equipment, pipelines, valves, instruments, and control loops used for design, safety, an operation. It is systematic development of a P&ID for acetonitrile process [6].
This study makes several academic and engineering contributions. First, a systematic methodology of developing a detailed P&ID for acetonitrile it will also provide structured reference for any other pilot-plant process into detailed and operable plant. Process instrumentation and control loops for temperature, pressure, flow and level are integrated into P&ID to ensure stable and reliable operations. The developed P&ID provides a detailed reference that supports detailed engineering, hazard analysis, commissioning, and future scale-up of the bioethanol-based acetonitrile production process.

2. Design Methodology

The Process for P&ID Development focuses on production of acetonitrile has been carried out using AutoCAD, Smart plan P&ID.

2.1 Design Basis

There are several processes for production of acetonitrile in the literature, including recovery as a byproduct of acrylonitrile through Sohio process, synthesis from acetic acid and ammonia, and direct ethanol catalytic ammoxidation. While studying all the process product recovery remains the dominant industrial source, for Sohio Process. Route based on acetic acid involve higher separation complexity and increased its operating costs. Bio-ethanol catalytic ammoxidation as it has advantage of renewable feedstock utilization, simplified process. This process selected as the development Piping & Instrumentation Diagram (P&ID) [2].
The reaction was carried out at 320 ℃ at reactor in atmospheric pressure were characterized by a relatively low temperature, very low ethylene and polycondensation yields, a small undesired combustion of ammonia. The Continuous operation under flammable and toxic service conditions are assumed, guiding the selection of instrumentation, safeguards, & control loop. The P&ID was developed at a conceptual to pilot-scale design level to translate the novel process concept into practical and operable [2].

2.2 Material Balance

In production of acetonitrile, the main reactions occur in fluidized bed reactor. Material entering and leaving a system is taken into account to enable the mass flow to be identified. Since matter cannot be created or destroyed, material balance is essential to determine the input and output of a system. Input + Generation → Output + Accumulation The equation above shows the mass balance of a reactive system in mathematical form. This system is considered as a reactive system as it involves a reactor which allows the input to mix and form a new product at the output.

Reaction No.	**Reaction**
R1	$C_2H_6O + O_2 + NH_3 \rightarrow C_2H_3N + 3H_2O$
R2	$C_2H_6O \rightarrow C_2H_4 + H_2O$
R3	$C_2H_6O + \frac{5}{4}O_2 \rightarrow CO + CO_2 + 3H_2O$
R4	$C_2H_3N + \frac{5}{4}O_2 \rightarrow \frac{1}{2}CO + \frac{1}{2}CO_2 + H_2O + HCN$
R5	$\frac{3}{4}O_2 + NH_3 \rightarrow \frac{1}{2}N_2 + \frac{3}{2}H_2O$
R6	$CO \rightarrow \frac{1}{2}O + CO_2$

Table No 1- Process Reaction

Stream / Component	Chemical Formula	Molecular Weight (g/mol)	Reaction / Source	Moles (kmol)	Mass (kg)
Ethanol	C_2H_6O	46.07	Feed	100.00	4,607.0
Ammonia	NH_3	17.03	Ammoxidation	28.50	485.4
Oxygen	O_2	32.00	Ammoxidation + Oxidation	40.38	1,292.0
Products / Outlet Streams					
Unreacted Ethanol	C_2H_6O	46.07	Unconverted	5.00	230.4
Acetonitrile	C_2H_3N	41.05	Ammoxidation	28.50	1,169.9
Ethylene	C_2H_4	28.05	Dehydration	9.50	266.5
Carbon Monoxide	CO	28.01	Oxidation	9.50	266.1
Carbon Dioxide	CO_2	44.01	Oxidation	9.50	418.1
Water	H_2O	18.02	All reactions	123.50	2,224.9
Totals	—	—	—	224.88	6,950.9

Table No-2 Material Balance of Bioethanol Process

The provided stream table represents the mass-balance for the bioethanol-based acetonitrile production process, were ethanol, ammonia, and oxygen are the primary feed components entering the reaction system. Ethanol serves as the main carbon source, ammonia acts as the nitrogen donor for acetonitrile formation, and oxygen facilitates the ammoxidation and oxidation reactions occurring within the reactor [2].

2.3 P&ID Development

In this work, the P&ID was developed to translate the conceptual process of bioethanol catalytic ammoxidation into detailed and operable design. The development process starts with process flow diagram, which provided the basis for identifying major process units, streams, and operating intent. This information was systematically expanded to define equipment interconnections, piping arrangements, and control requirements relevant to pilot-scale operation[6].

Figure: 1 Root of P&ID

Developed P&ID has three main element equipment, utility generation and networks, and instrumentation. In acetonitrile process plant pieces of equipment are furnace, storage tanks, distillation column, heat exchanger, vessels, pumps, scrubbers etc. this piece of equipment were tied together to convert raw material to product. Instrumentation was incorporated to monitor and control key process variables such as temperature, pressure, flow rate, and liquid level, which are maintaining stable operation and product selectivity in the acetonitrile process [6].

Safety and operability requirement were addressed during P&ID development appropriate isolation valve, pressure relief valves, vent, drains and bypass lines were installed according to the process requirement. These elements were included to support safe startup, shutdown, and maintenance operations under flammable and service conditions. The arrangement of instrumentation and safety devices was selected to monitor effective process and rapid response to process disturbances.

In this study to ensure the clear identification of process elements, line numbering and instrument labels were assigned using a unform structure throughout P&ID. Equipment tags were assigned systematically to clearly distinguish reactor, separation units, heat exchangers and other systems, while line numbering was used to identify process streams based on service flow, flow direction and operating conditions [7,8].

2.4 Instrumentation and Control

Instrumentation and Control systems were incorporated to ensure safe and stable and safe operation of the bioethanol-based acetonitrile production process under pilot scale conditions. For maintaining process variables such as temperature, pressure, and flow within desired set points in acetonitrile process.[9] As acetonitrile plant operates in the gas phase and involves handling of hazardous and harmful gases, instrumentation and control system play a critical role in P&ID development.

Temperature monitoring and regulation are incorporated in reactor section due to the exothermic nature of ammoxidation reaction and its directly dependent of selectivity of acetonitrile. During reaction under different temperature conditions, nickel-chromium-nickel silicon thermocouple were used due to high-temperature stability and resistance to oxidation at reactor its measuring rang is between -270 °C to 1200 °C and very stable at reactor and heater temperature. [9] Temperature control loop was implemented to regulate heat removal and maintain reactor within the operating range. This approach minimizes risk and enhances process stability, as shown in Figure 2.

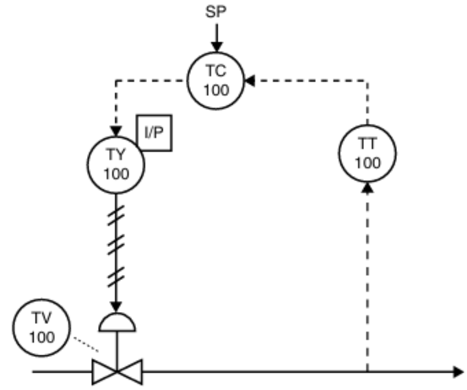

Figure: 2 Temperature control loop

Pressure monitoring and control were incorporated across major process units to ensure safety and protect equipment from overpressure. In acetonitrile production reaction are carried out under specific pressure and if the gas generated during the process cannot be discharged in time, it will inevitably affect the internal pressure of equipment, which may affect the reaction rate of the equipment.[9] Pressure indicators and control valves were positioned to allow appropriate action during process distribution, as presented in Figure 3. while pressure relief devices are added to overall safety system to prevent against abnormal operating process. [8]

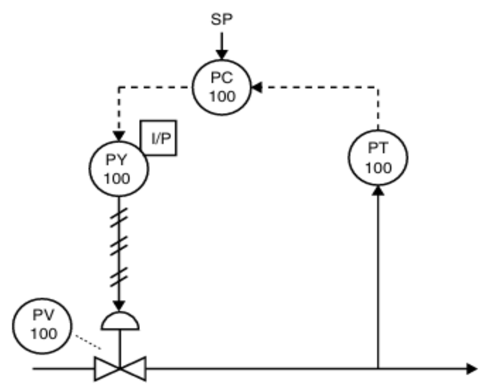

Figure: 3 Pressure control loop

Flow control strategies were applied to regulate feed rates of bioethanol, ammonia and air. Flow directly reflects the specific production of the product to be used in equipment and at same time, it preliminarily estimates the pressure condition generated by the product. Accurate flow measurement and control were necessary to maintain stable reaction conditions, achieve consistent material balance, and prevent fluctuations that could adversely affect product yield and process performance, as shown in Figure 4 [6,9].

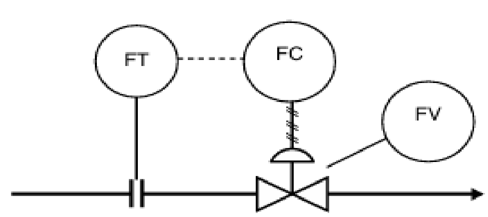

Figure: 4 Flow control loop

Level instrumentation was implemented in separation and storage units to maintain appropriate storage of material to prevent operational problems such as flooding or dry running. Level control loops were designed to ensure smooth operation of downstream units, as illustrated in Figure 5 [6,9].

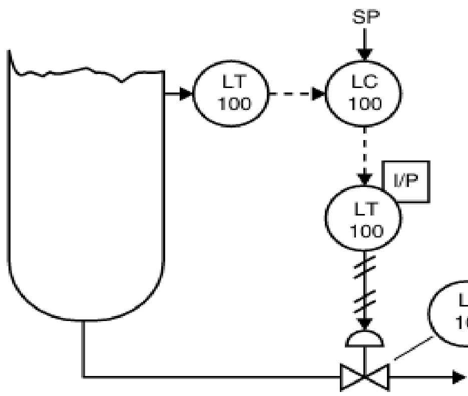

Figure: 5 Level control loop

Although interlock systems are designed to initiate automatic Protective action during abnormal conditions, alarms system play a critical complementary role in process operation. Alarms provide early warning to operators, enabling timely assessment and corrective intervention before interlock activation, control philosophy was designed to support safe, reliable, and flexible operation of the novel process.

2.5 Safety Integration

Safety considerations were integrated into P&ID development to address associated with flammable and toxic nature of acetonitrile and the non-conventional process configuration.
A system with probability of overpressure is enclosed by pressure device system. In acetonitrile process plant Regulatory frameworks governing pressurized equipment generally mandate adequate protection against overpressure, which is commonly achieved through pressure relief devices. Initially, process hazards were identified using systematic review of the P&ID and operating conditions. Critical deviations as high temperature, overpressure, and loss of cooling may lead consequences on the acetonitrile production [10].
PSDs are installed in different arrangements. The simplest arrangement is a single PSD in series. It play major a role in minimizing the risks A P&ID based HAZOP study consists of several key components that are essential for identifying potential hazards and operability issues in a process plant. The first key component is the formation of a multidisciplinary team consisting of process engineers, safety professionals, and operations personnel who are familiar with the process under review. This team will be responsible for conducting the study and identifying potential hazards and operability issues [10].
The next key component of a P&ID based HAZOP study is the detailed review of the P&ID of the process plant. This involves systematically examining each section of the P&ID to identify potential deviations from the intended design conditions that could lead to hazardous situations or operational issues. The team will then brainstorm potential scenarios that could lead to these deviations and assess their consequences.
Once potential hazards and operability issues are identified, the team will develop effective control measures to mitigate the risks. This may involve implementing engineering controls, administrative controls, or procedural controls to prevent or mitigate the consequences of potential hazards. The final key component of a P&ID based HAZOP study is documenting the findings of the study and developing a comprehensive report that outlines the identified hazards, their consequences, and the recommended control measures

3. Result and Discussion

This study has developed a piping and instrumentation diagram (P&ID) for the proposed novel acetonitrile process. The results are discussed in correlation to the research objective of translating a novel reaction pathway into a safe, operable, and standardized engineering design suitable for pilot scale plant. Developed P&ID serve a visual representation of a process, functional relationships between mechanical equipment, its related piping, instrumentation and system components, Providing a high-level overview of the process flows, control systems and equipment interconnections.
3.1 Development of P&ID for the novel acetonitrile process:
The developed piping P&ID for the proposed novel acetonitrile process based on bioethanol catalytic ammoxidation. The developed P&ID provides a detailed and systematic representation of process equipment, piping networks, instrumentation, control loops, and safety systems.

3.2 Best Practice for Effective P&ID:
To ensure an effective P&ID based on HAZOP study, it has followed a best practice that helped in identifying potential hazards and operability issues in a process plant. Developed P&ID follows, process data, safety, and operability of acetonitrile process and by ensuring that all potential hazards are identified from diverse perspective. This study is essential for preventing accidents, protecting the environment, and ensuring the safety of personnel working in a process plant. By systematically reviewing the P&ID of a process plant, engineers and safety professionals can identify potential hazards, assess their consequences, and develop effective control measures to mitigate the risks.

3.3 Instrumentation and Controls
Regulatory control loops for temperature, pressure, flow, and level were incorporated across major process units such as the reactor, heat exchangers, distillation column, and storage vessels. Temperature control placed in the reactor and separation sections to reaction selectivity and stable operating conditions. Pressure control loops were attached to ensure safe operation under gas phase and flammable service environments. Flow control of feed and recycle streams allows accurate regulation of feed based on reactant ratios and residence time. In addition to regulatory control, alarm systems were integrated to continuously monitor critical variables and promptly notify operators of abnormal deviations. These alarms enhance operator awareness, facilitate timely corrective action, and contribute to improved operational safety and reliability.

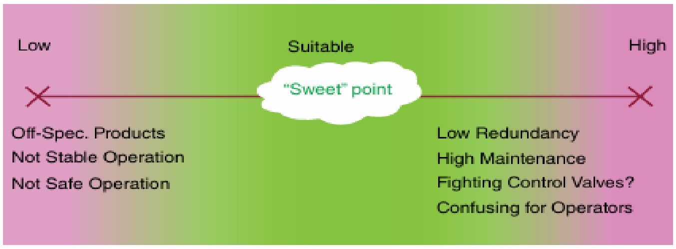

Figure 6: Level of Control

Figure: 6 level of control illustrates the concept of an operational "sweet spot" for regulatory control within the acetonitrile production process. Operating at control range results in off-specification products, unstable process and not safe operation. And on other hand excessive control complexity at the high cause's low redundancy, increased maintenance, inappropriate control valve activity. P&ID targets the central operating region to balance it and to achieve stable operation, product quality compliance and safe plant performance.

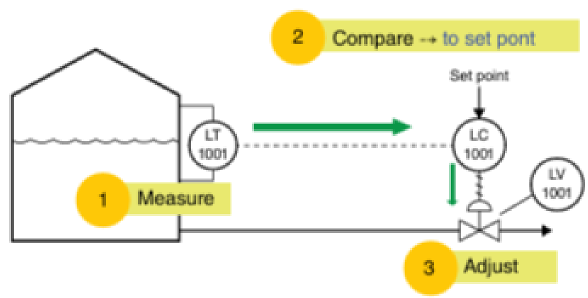

Figure 7: Tank Control Loop

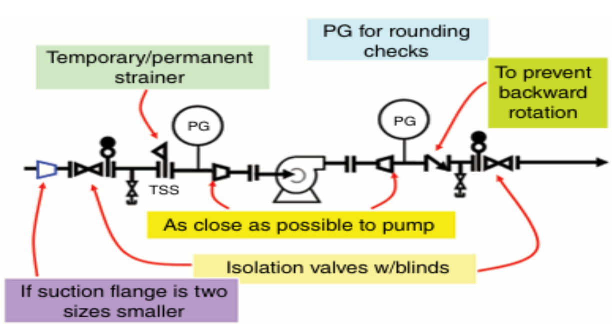

Figure 8: P&ID representation of a centrifugal pump.

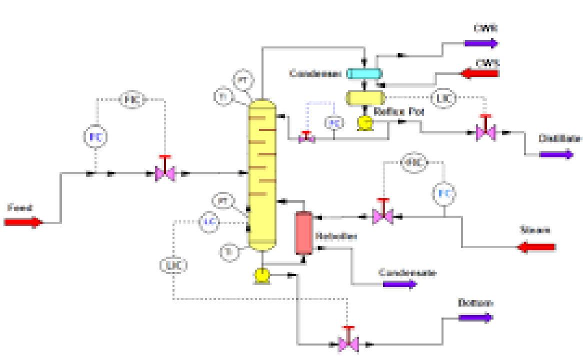

Figure 8: P&ID representation of a distillation column

4. Conclusion

Acetonitrile production is increasingly through all the processes of production for e.g. Sohio Process, synthesis of acetic acid, etc. Newly developed process of acetonitrile from Bioethanol catalytic ammoxidation that needs to be better understood. This study presents the systematic design and development of P&ID for novel acetonitrile production process based on bioethanol catalytic ammoxidation and describing the relevant features for developing P&ID contents all conceptual process and operatable design integrated by process data, material balance, instrumentation, control, and safety considerations within P&ID. More importantly new designed P&ID has been introduced, with the hope of providing safety, standardized diagram showing all equipment, piping, instrumentation, controls system inputs/outputs, and safety features, adhering to industry standards for clarity in design, construction and operation with all components uniquely tagged and referenced.

There are some limitations to this study though. Developed P&ID represents pilot-scale design. Equipment sizing, hydraulic calculations, and mechanical design detail were not performed therefore indeed to guide design intent rather than serve as construction ready document. The instrumentation and control philosophy was developed at a functional level. Detailed control tuning, dynamic simulation, control system architecture (DCS/PLC configuration), and safety integrity level (SIL) determination were not addressed.

The present work establishes a structured foundation for the developed P&ID for a novel acetonitrile process. A number of future studies will be carried out. These includes: Detailed engineering and design development may extend by incorporating piping layouts, equipment sixing, hydraulic calculations, mechanical design, and stress analysis, Dynamic simulation may be conducted to evaluate transient, Advanced safety studies such as quantitative risk assessment, layer of protection and validate the effectiveness of safety systems into the P&ID. Methodology presented in the study can be applied to other emerging chemical processes, enabling systematic P&ID development for non-conventional production routes.

A critical gap between process development and practical plant realization by focusing on the systematic design of P&ID for a novel acetonitrile process. While many studies highlight reaction pathways, process performance few works translate novel chemical processes into operable, safe, and controllable engineering designs. This research demonstrates that P&ID development itself is a significant engineering activity that validates process feasibility, operability, and safety at an early design stage. The study confirms that structured P&ID development is a critical step in validating the feasibility, safety, and design readiness of novel chemical processes.

Overall, the developed P&ID provides detailed engineering, hazard and operability studies, and future scale-up of the novel acetonitrile process, thereby contributing to both academic research and industrial practice in process design and safety engineering.

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