

Design and Development of an Automated Nitrogen Level and Flow Measurement System for Cryogenic Tanks

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Abstract

Cryogenic liquids, particularly liquid nitrogen (LN₂), are extensively used in industrial, medical, scientific, and research applications, where accurate level monitoring and controlled fluid transfer are essential for operational safety, efficiency, and resource optimization. Conventional cryogenic measurement methods often rely on independent level or flow sensing devices, manual observation, or complex instrumentation, resulting in limited automation, reduced accuracy under dynamic conditions, and increased risk of overfilling and cryogenic fluid loss. This study presents the design and development of an automated nitrogen level and flow measurement system for cryogenic tanks. The proposed system integrates a turbine flow meter, a cryogenic solenoid valve, and an Arduino-based control unit to provide real-time monitoring, accurate flow measurement, and automated filling control. Pulse signals generated by the turbine flow sensor are processed by the microcontroller to determine the instantaneous flow rate and cumulative transferred volume. A user-defined target volume is continuously monitored, and the solenoid valve is automatically actuated to terminate the filling process once the preset value is achieved. A digital display provides continuous information on flow rate, cumulative volume, and system status. The proposed system is designed using cryogenic-compatible components to ensure reliable operation under extremely low-temperature conditions. The integrated approach enhances measurement accuracy, minimizes manual intervention, improves operational safety, and reduces liquid nitrogen wastage. The developed system offers a practical and cost-effective solution for laboratory facilities, healthcare institutions, and industrial cryogenic storage and distribution applications.

Keywords: Cryogenic Tanks; Liquid Nitrogen; Level Measurement; Flow Measurement; Cryogenic Instrumentation; Automated Monitoring.

1. Introduction

Cryogenic technology plays a vital role in modern engineering applications where extremely low temperatures are required for storage, preservation, and processing. Among various cryogenic fluids, liquid nitrogen (LN₂) is one of the most widely used because of its inert nature, low boiling point (−196 °C), and cost-effectiveness [9]–[12]. It is extensively utilized in healthcare, food processing, electronics manufacturing, metallurgy, aerospace, and scientific research, where reliable storage and controlled transfer of cryogenic fluids are essential for safe and efficient operation [9], [10].

Accurate measurement and controlled transfer of liquid nitrogen are critical for ensuring operational efficiency, safety, and minimization of cryogenic fluid losses. Traditional methods for monitoring nitrogen levels in cryogenic tanks generally employ manual observation or independent sensing devices such as differential pressure systems, ultrasonic sensors, capacitance-based level sensors, and Coriolis flow meters [1]–[5]. Although these methods are widely adopted, they often suffer from limitations such as reduced measurement accuracy under dynamic operating conditions, delayed response, thermal effects, calibration complexity, and limited automation [13], [17]–[20].

In many practical applications, the absence of an integrated monitoring and control system may result in overfilling, liquid nitrogen wastage, unnecessary operator intervention, and potential safety hazards associated with cryogenic fluid handling. These challenges highlight the need for a reliable, accurate, and automated system capable of simultaneously measuring nitrogen flow and monitoring the filling process while ensuring safe operation of cryogenic storage tanks.

The present work focuses on the design and development of an automated nitrogen level and flow measurement system for cryogenic tanks. The proposed system integrates a turbine flow meter, a cryogenic-compatible solenoid valve, and an Arduino-based control unit to provide real-time monitoring and automatic filling control. The system continuously measures the flow rate of liquid nitrogen, calculates the cumulative transferred volume, and automatically terminates the filling process once the user-defined target volume is reached.

By integrating sensing, control, and automation within a single compact platform, the developed system improves measurement accuracy, reduces manual intervention, minimizes liquid nitrogen wastage, and enhances operational safety. Owing to its simple architecture, cost-effectiveness, and ease of implementation, the proposed system is well suited for laboratory environments, research facilities, and small- to medium-scale industrial applications involving cryogenic fluid handling.

The remainder of this paper is organized as follows. Section 2 presents the literature review, Section 3 describes the system design and methodology, Section 4 discusses the experimental results and system performance, and Section 5 concludes the paper with recommendations for future work.

2. Literature Review

Cryogenic fluid measurement and control systems have been extensively studied because of their critical role in industrial, medical, and scientific applications involving liquid nitrogen (LN₂), liquid oxygen (LOX), and other cryogenic fluids. Accurate measurement of liquid level and flow is essential for ensuring operational safety, minimizing cryogenic fluid losses, and improving process efficiency.

Over the years, several techniques have been developed for cryogenic level and flow

measurement, each offering distinct advantages as well as practical limitations [9]–[15].

One of the most widely adopted methods for cryogenic liquid level measurement is the differential pressure technique. This method determines the liquid level by measuring the pressure difference between two locations within the storage tank [1]. Although the technique is well established and suitable for industrial applications, it requires accurate calibration because the density of cryogenic fluids varies with temperature and operating conditions. In addition, multiple pressure tapping points increase installation complexity and maintenance requirements.

Capacitance-based level measurement is another commonly used technique for cryogenic applications. These sensors determine the liquid level by measuring changes in capacitance caused by variations in the dielectric constant of the surrounding medium [5], [18]. Capacitance sensors provide continuous level monitoring with relatively simple construction; however, their performance may be influenced by temperature fluctuations, frost formation, and vapor accumulation inside the storage vessel, resulting in reduced measurement accuracy under certain operating conditions.

Ultrasonic level measurement systems provide a non-contact approach by transmitting ultrasonic waves toward the liquid surface and measuring the reflected signal [2], [19]. Since the sensing element does not directly contact the cryogenic liquid, these systems reduce sensor degradation and contamination. However, ultrasonic measurements may be affected by vapor turbulence, condensation, and fluctuating gas layers above the liquid surface, particularly during filling operations, thereby reducing measurement reliability in dynamic conditions.

For cryogenic flow measurement, Coriolis flow meters are widely recognized because they provide direct mass flow measurement with high accuracy over a broad operating range [3]. Despite their excellent performance, Coriolis flow meters are relatively expensive, require sophisticated electronics, and may not be economically feasible for laboratory-scale or small industrial installations.

Figure 1 illustrates a representative cryogenic liquid level measurement arrangement used in industrial applications, highlighting a typical cryogenic storage vessel and associated instrumentation employed for liquid nitrogen handling and monitoring.



Figure 1: Conventional Cryogenic Liquid Level Measurement Techniques.

Recent developments in cryogenic instrumentation have focused on integrating sensing, automation, and control to improve measurement accuracy while minimizing manual intervention [17]–[20]. Modern systems increasingly combine real-time monitoring, automated valve control, and digital signal processing to enhance operational safety, reduce cryogenic fluid wastage, and simplify system operation. Nevertheless, many commercially available solutions remain costly and are primarily intended for large-scale industrial applications.

Based on the reviewed literature, it is evident that existing cryogenic measurement systems provide reliable performance individually but often require separate level and flow measurement devices, increasing system complexity and operational cost. Furthermore, limited integration between sensing and automated control may result in overfilling, unnecessary liquid nitrogen losses, and increased operator intervention. To address these limitations, the present work develops an automated nitrogen level and flow measurement system that integrates flow measurement, volume estimation, and automatic filling control within a compact and cost-effective platform suitable for laboratory and small- to medium-scale industrial cryogenic applications.

3. Methodology

3.1. System Design and Planning

The proposed nitrogen level and flow measurement system was designed to provide an automated, reliable, and cost-effective solution for monitoring and controlling the transfer of liquid nitrogen (LN₂) in cryogenic storage tanks. During the design stage, emphasis was placed on

measurement accuracy, operational safety, cryogenic compatibility, ease of installation, and reduction of liquid nitrogen losses. Since cryogenic fluids operate at extremely low temperatures, all major components were selected considering their thermal stability, corrosion resistance, and suitability for cryogenic service.

The overall system was developed by integrating a cryogenic solenoid valve, turbine flow meter, stainless-steel lance, nozzle assembly, magnetic pickup sensor, Arduino-based controller, and display unit into a single measurement platform. The system was designed such that the electronic control circuitry remained outside the cryogenic environment, while only the flow-measuring components were exposed to the cryogenic fluid. This arrangement minimizes thermal effects on electronic components and improves long-term operational reliability.

The mechanical configuration of the proposed measurement system is illustrated in **Figure 2**. The assembly consists of a cryogenic solenoid valve mounted at the inlet, followed by a turbine flow meter connected to a stainless-steel probe terminating in a precision nozzle. This configuration enables controlled dispensing of liquid nitrogen while simultaneously measuring the flow rate during the filling operation.

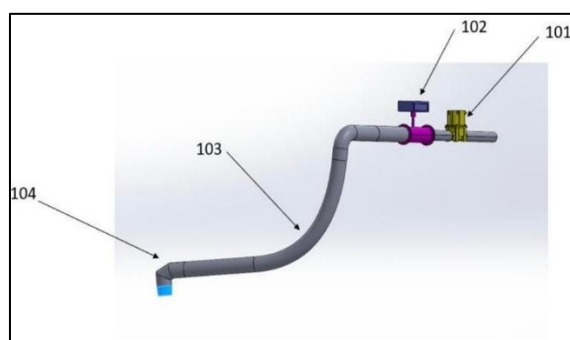


Figure 2: CAD model of the proposed nitrogen level and flow measurement system.

As shown in Figure 2, the liquid nitrogen enters the system through the cryogenic solenoid valve and subsequently passes through the turbine flow meter before flowing along the stainless-steel lance toward the nozzle. The measured flow information is transmitted to the microcontroller, which continuously calculates the cumulative transferred volume. Based on the preset quantity entered by the user, the controller automatically regulates the solenoid valve to terminate the filling operation once the required volume has been achieved.

The detailed construction of the turbine flow measuring assembly is presented in Figure 3. The assembly incorporates a rotating turbine rotor, magnetic flux pickup device, and fixed guide vanes that collectively convert the fluid motion into electrical pulse signals proportional to the flow rate. The compact arrangement enables continuous monitoring of nitrogen flow while maintaining mechanical stability under cryogenic operating conditions.

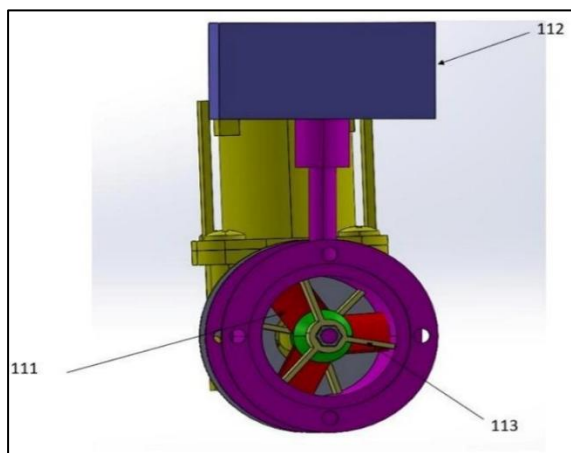


Figure 3: Detailed CAD view of the turbine flow measurement assembly.

The proposed design combines mechanical flow measurement with embedded electronic control to achieve automatic operation without continuous operator supervision. The integration of sensing, control, and flow regulation within a single system provides an efficient approach for liquid nitrogen handling in laboratory, research, and industrial applications. The design also facilitates straightforward maintenance, compact installation, and reliable performance under cryogenic operating conditions, making it suitable for practical deployment in controlled nitrogen dispensing systems.

3.2. System Components and Working Principle

The proposed nitrogen level and flow measurement system consists of a number of mechanical and electronic components that operate together to achieve accurate flow measurement and automated control of liquid nitrogen transfer. The system has been designed to ensure reliable operation under cryogenic conditions while maintaining measurement accuracy and operational safety. The principal components of the proposed system are identified in Figures 2 and 3 and are described below.

101 - Solenoid Valve

The solenoid valve serves as the primary flow control element of the system. It is an electrically actuated on/off valve that regulates the flow of liquid nitrogen during the filling process. The valve is designed using cryogenic-compatible materials such as stainless steel with suitable PTFE or metallic sealing elements to withstand extremely low operating temperatures. For ease of maintenance and improved thermal isolation, the valve is preferably installed outside the cryogenic region and connected to the storage tank through a flange-mounted arrangement. A manual isolation valve may also be provided upstream to facilitate servicing.

102 - Turbine Flow Meter

The turbine flow meter is the principal sensing device used for measuring the instantaneous volumetric flow rate of liquid nitrogen. It consists of a short stainless-steel flow section containing a freely rotating turbine rotor supported by fixed guide vanes. As the cryogenic fluid passes through the flow meter, the rotor rotates at a speed proportional to the flow rate, thereby enabling accurate measurement of the transferred volume. The meter body is fabricated from 316L stainless steel to ensure compatibility with cryogenic service, while ceramic or cryogenic-grade bearings are employed to minimize friction and ensure stable operation.

103 - Stainless-Steel Lance (Probe)

The stainless-steel lance provides the mechanical passage for liquid nitrogen from the flow meter to the required measurement location inside the cryogenic tank. The probe is manufactured from 304 or 316 stainless steel because of its high mechanical strength, corrosion resistance, and excellent performance at cryogenic temperatures. For long insertion lengths, the probe may be vacuum jacketed to reduce heat leakage and minimize unnecessary boil-off. Sealed electrical feedthroughs are incorporated at the upper flange to transmit signals from the magnetic pickup device to the controller.

104 - Nozzle

The nozzle is located at the terminal end of the probe and regulates the discharge characteristics of liquid nitrogen. It converts the available pressure into a controlled jet, thereby producing stable flow conditions during dispensing. The nozzle is precision machined from stainless steel

and is designed with an appropriately sized orifice to limit pressure loss and reduce cryogenic evaporation. Depending on the application, different nozzle geometries may be employed to optimize the discharge characteristics.

The detailed working mechanism of the turbine flow meter is illustrated in Figure 3, where the internal sensing elements responsible for flow measurement are identified.

111 - Turbine Rotor

The turbine rotor consists of multiple balanced blades mounted on a low-friction shaft. As liquid nitrogen flows through the meter, the rotor rotates at an angular velocity proportional to the volumetric flow rate. The rotor is manufactured from stainless steel or other cryogenic-compatible materials to ensure dimensional stability and reliable operation at low temperatures.

112 - Magnetic Flux Pickup Device

The magnetic pickup device detects the rotational motion of the turbine rotor by sensing changes in magnetic flux generated as each blade passes the sensor. The resulting electrical pulse train is transmitted to the microcontroller, where it is processed to calculate the instantaneous flow rate and cumulative transferred volume. To improve reliability, the pickup assembly is thermally isolated from the cryogenic region and electrically shielded against external interference.

113 - Fixed Guide Vanes

The fixed guide vanes are positioned upstream of the turbine rotor to straighten the incoming fluid stream and reduce flow turbulence before it reaches the rotating blades. They also provide structural support for the rotor assembly and contribute to improved measurement stability by maintaining a uniform flow profile within the meter.

During operation, liquid nitrogen first passes through the cryogenic solenoid valve before entering the turbine flow meter. The flowing liquid rotates the turbine rotor, and the magnetic pickup converts the rotor motion into electrical pulses. These pulses are processed by the Arduino-based controller to determine the instantaneous flow rate and the cumulative transferred volume. Once the user-defined quantity of liquid nitrogen is reached, the

controller automatically de-energizes the solenoid valve, terminating the filling process. This integrated arrangement enables accurate flow measurement, automated filling control, and reliable operation under cryogenic conditions while minimizing manual intervention and liquid nitrogen losses.

3.3. Selection of Components

The selection of system components was carried out by considering the operating requirements of cryogenic liquid nitrogen, including measurement accuracy, thermal compatibility, reliability, ease of integration, and overall system cost. Each component was chosen to ensure stable operation under cryogenic conditions while supporting automated monitoring and control of the nitrogen filling process.

The **turbine flow meter** was selected as the primary sensing element because of its simple construction, reliable operation, and ability to generate pulse signals directly proportional to the volumetric flow rate. The pulse output enables accurate calculation of both instantaneous flow rate and cumulative transferred volume through digital signal processing.

An **Arduino-based microcontroller** was employed as the central processing unit owing to its ease of programming, sufficient processing capability, and compatibility with pulse-based sensors and digital control devices. The controller continuously acquires flow data, performs volume calculations, compares the measured value with the user-defined set point, and controls the operation of the cryogenic solenoid valve.

A **cryogenic solenoid valve** was incorporated to provide automatic regulation of liquid nitrogen flow. The valve remains open during the filling process and is automatically closed when the preset volume is achieved, thereby eliminating manual intervention and reducing the possibility of overfilling and cryogenic fluid wastage.

A **digital display unit (LCD/OLED)** was integrated into the system to provide real-time visualization of important operating parameters, including flow rate, cumulative transferred volume, and valve status. This enables continuous monitoring of system performance and improves user interaction during operation.

In addition to these electronic components, cryogenic-compatible stainless-steel piping, probe assembly, nozzle, and associated fittings were selected to ensure mechanical strength, corrosion resistance, and reliable operation under extremely low-temperature conditions. The combination of these components provides a compact, reliable, and cost-effective measurement system suitable for laboratory, research, and industrial cryogenic applications.

3.4. Hardware Integration

Following component selection, the proposed system was assembled by integrating the sensing, control, and display units into a single measurement platform. The turbine flow meter was installed along the liquid nitrogen flow line to continuously measure the volumetric flow rate, while the cryogenic solenoid valve was positioned upstream to regulate the flow during the filling process. The pulse output generated by the turbine flow meter was connected to the Arduino microcontroller through a suitable signal-conditioning circuit to ensure reliable pulse detection and processing.

The digital display unit was interfaced with the microcontroller to provide real-time information on flow rate, cumulative transferred volume, and valve status. To ensure reliable operation under cryogenic conditions, all electronic components, including the controller, display, and associated circuitry, were housed inside a thermally insulated enclosure located outside the cryogenic region. The complete experimental prototype developed for the present study is shown in Figure 4.



Figure 4: Experimental prototype of the proposed nitrogen level and flow measurement system.

3.5. Software Development and Programming

The control software was developed using the Arduino programming environment to perform data acquisition, flow calculation, display management, and automatic valve control. During operation, the controller continuously acquires pulse signals from the turbine flow meter and converts them into the instantaneous flow rate using the experimentally determined calibration factor (K-factor). The cumulative transferred volume is calculated by integrating the measured flow over time.

The calculated volume is continuously compared with the user-defined target value. When the measured volume reaches the preset quantity, the controller automatically de-energizes the cryogenic solenoid valve, thereby terminating the filling process. Simultaneously, the display unit provides continuous updates of the flow rate, transferred volume, and operational status, enabling the user to monitor the complete filling operation in real time.

3.6. Control Algorithm

The proposed system operates according to a simple closed-loop control sequence. Initially, the operator enters the required quantity of liquid nitrogen through the control interface. Upon receiving the command, the microcontroller energizes the cryogenic solenoid valve, allowing liquid nitrogen to flow through the turbine flow meter. The rotating turbine generates pulse signals proportional to the volumetric flow rate, which are continuously processed by the controller to determine the cumulative transferred volume.

The measured volume is repeatedly compared with the preset value throughout the filling process. Once the target volume is reached, the controller immediately closes the solenoid valve, thereby stopping the flow of liquid nitrogen automatically. This control strategy minimizes manual intervention, prevents overfilling, and improves the overall safety and efficiency of cryogenic filling operations.

3.7. Calibration

Calibration was performed to establish the relationship between the pulse output of the turbine flow meter and the actual volume of liquid nitrogen transferred. Known quantities of fluid were allowed to pass through the system, and the corresponding pulse counts were

recorded to determine the calibration constant (K-factor), expressed in pulses per litre. The measured values were compared with the actual transferred volume, and minor adjustments were incorporated into the control software to improve measurement accuracy and system reliability.

3.8. Testing and Validation

The developed system was evaluated under different operating conditions to verify its measurement performance and operational reliability. The testing procedure included verification of flow rate measurement, automatic operation of the cryogenic solenoid valve, controller response during filling, and continuous monitoring of system parameters. Particular attention was given to ensuring stable operation under cryogenic conditions and confirming that the controller consistently terminated the filling process when the preset volume was achieved.

3.9. Performance Evaluation

The performance of the proposed system was evaluated based on measurement accuracy, response time of the automatic control valve, operational reliability, and ease of use. The integrated design demonstrated stable operation, accurate monitoring of transferred liquid nitrogen, and effective automatic control of the filling process. The proposed methodology therefore provides a practical and reliable solution for automated nitrogen level and flow measurement in laboratory and industrial cryogenic applications.

4. Discussion

The developed nitrogen level and flow measurement system demonstrated reliable performance during laboratory evaluation, indicating its suitability for controlled cryogenic applications. The integration of the turbine flow meter, Arduino-based controller, and cryogenic solenoid valve enabled continuous flow monitoring and automatic control of the filling process, reducing manual intervention during liquid nitrogen transfer.

The system provides real-time measurement of flow rate and cumulative transferred volume, automatically stopping the filling operation once the preset quantity is reached. This minimizes the possibility of overfilling, reduces liquid nitrogen wastage, and improves operational safety. Its compact design also facilitates

integration with existing cryogenic storage and dispensing systems for laboratory, educational, and small-scale industrial applications.

Compared with conventional techniques such as differential pressure, ultrasonic, and Coriolis-based systems, the developed system provides a simpler and more cost-effective solution for automated nitrogen dispensing. Although high-end systems generally offer higher measurement capability, they require more complex instrumentation and greater installation costs, making them less suitable for small-scale applications.

The study also identified certain limitations. Measurement accuracy depends on proper calibration of the turbine flow meter, and long-term performance under varying operating conditions requires further investigation. Additional field validation across diverse industrial environments would provide a more comprehensive assessment of system reliability and repeatability.

The findings demonstrate that integrating flow measurement with automated control offers a practical approach for cryogenic fluid handling. With further validation and refinement, the system has the potential to support safe, reliable, and cost-effective liquid nitrogen management in laboratory and industrial applications.

5. Conclusion

This study presented the design and development of an automated nitrogen level and flow measurement system for cryogenic tanks. The developed system integrates a turbine flow meter, an Arduino-based control unit, a cryogenic solenoid valve, and a digital display to provide real-time flow monitoring and automatic control of the filling process.

The system continuously measures the flow of liquid nitrogen and automatically stops the filling operation once the preset volume is reached, thereby reducing manual intervention, minimizing nitrogen wastage, and improving operational safety. Its compact design and integrated measurement and control approach make it suitable for laboratory, research, educational, and small- to medium-scale industrial applications.

The experimental evaluation demonstrated the feasibility of the proposed system under controlled cryogenic conditions. Although satisfactory performance was achieved, periodic

calibration and long-term field validation are recommended to further improve measurement reliability under varying operating conditions.

Overall, the proposed system provides a practical and cost-effective solution for automated cryogenic fluid handling. Future work may focus on improving long-term stability, incorporating IoT-based remote monitoring, and evaluating the system across a wider range of industrial cryogenic applications.

Conflict of Interest

The author(s) declare that there are no conflicts of interest regarding the publication of this manuscript.

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