A Novel Cryogenic Liquid Level Sensing Technique: Harnessing the Optical Properties of a Cryogenic Liquid.

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ABSTRACT: This paper explores the use of a light based measurement technique for the level measurement of cryogenic liquids. Differential pressure transmitters are commonly used to measure the levels of cryogenic liquids such as liquid nitrogen and liquid oxygen in cryogenic tanks. They require the liquid inside the temperature controlled tank to be drawn out into impulse lines. This causes a number of problems, one of the most common one is Chocking of the impulse lines, which ultimately results in a significant loss of material.

KEYWORDS: Cryogenic Liquid Level Measurement, Liquid Nitrogen, Optical Level Measurement.

I.INTRODUCTION:

Whether you are producing steel or nonferrous metals, traditional petrochemicals, or running the most advanced gasification or oxy-fuel process for your clean energy application, your air separation plant plays a significant role in your operations. Air Products has the technology, experience, and resources necessary to design, engineer, construct, and operate a cost-effective gas supply system for your specific application.

Air Products currently owns and operates over 300 air separation plants in over 40 countries worldwide, in all types of applications. In addition to our own plants, we have sold, designed and built over 1000 air separation plants globally. Our cryogenic offering spans from plants with a capability of 50 tons per day to single train facilities with oxygen production capacities beyond 4,000 tons per day, with development for single trains up to 7,000 tons per day. [1]

A company named **Air Products [4]** supplies liquid cryogenic tanks (dewars) in different volumes to meet any requirement.

- For MRI and other applications, we supply liquid helium via 60-, 100-, 250- and 500-liter ruggedly constructed and super-insulated dewars. For the semiconductor, displays, and photovoltaics markets, our specialty chemicals and gases are supplied via our fleet of stainless steel containers, quartz bubblers, ISO containers and Y-cylinders (all developed with individual molecules in mind). We have delivered our specialty chemicals and gases safely and seamlessly to our customers for more than 30 years. By understanding your unique needs, we excel at innovation.
- **Dewar Deliveries and Transfills.** Our North American supply network includes over 13 liquid helium transfill facilities strategically located throughout the U.S. and Canada. Furthermore, dewar deliveries are dispatched from over 70 local transfill stocking locations. That means, no matter where you are, it’s likely we are nearby. If you are in our service areas, we can deliver and pick up dewars in our privately owned trucks, saving you common carrier charges and reducing the risk of dewar damage during transport.
- **Centralized Dewar Tracking to Provide On-Time Delivery.** Air Products tracks its dewars at a computerized central logistics center. Dedicated to servicing helium customers, the center maintains continual control of production and delivery, helping us anticipate your needs and maintain dependable delivery schedules around the clock.
- **Full-Service Cryogenic Supply.** In addition to helium, you can also rely on Air Products for all your liquid nitrogen needs for precooling, as well as a comprehensive line of industrial gases and specialized high-purity regulators and cryogenic liquid transfer hoses.[2]

Nitrogen and Oxygen are two major gases required from the Utility block of any Petroleum based industry in cryogenic form. Nitrogen is the most crucial one because it is used for Inert Blanketing of Inflammable and Explosive substances.

Nitrogen is produced from the atmospheric air by a process called the "Cryogenic Air Separation", in which the air from the atmosphere is cooled to sub-zero temperature, which converts the Nitrogen to Liquid and it then separated on the basis of its molecular weight.

The chemical and physical properties of Liquid Nitrogen are:

Chemical Formula	N2
Molecular Weight	28.01
Boiling Point @ 1 atm	–320.5°F (–195.8°C)
Freezing Point @ 1 atm	–346.0°F (–210.0°C)
Critical Temperature	–232.5°F (–146.9°C)
Critical Pressure	492.3 psia (33.5 atm)
Latent Heat of Vaporization	856 Btu/lb (199.1 kJ/kg)
Expansion Ratio, Liquid to Gas, BP to 68°F (20°C)	1 to 694

Liquid Nitrogen, which is a Cryogenic liquid is also widely used on a large scale in various industries, most commonly for the purpose of cooling, thus making their monitoring highly crucial.

II. LITERATURE STUDY

The storage tanks play a very big role in the system design of the paper. Because, the system designed in this paper is contained in the storage tank.

The tanks range in capacity from 3,000 to > 450,000 litres and come with standardised working pressures of 18, 22, or 36 bar respectively. They are standardised to ensure smooth distribution logistics and cost-efficient series production and also comply with the European Pressure Equipment Directive (PED) or ASME VIII, Div. 1. LITS tanks (Leading International Tank Standard).

Each tank is vacuum-insulated and can be delivered as a vertical or horizontal installation. The inner vessels and piping are made of stainless steel to ensure high-grade cleanliness – particularly important for the food and electronics industry. The outside shell is specially coated and a vacuum-perlite system with a molecular sieve adsorbent is applied to ensure outstanding insulation. [6]

Our basic aim is to measure the level of Liquid Nitrogen in the storage unit without using only Optical measurement methods.

We want to steer clear from the idea of Differential pressure based level sensors because they choke and get blocked due to the low operating temperature. Similarly, we want to stay away from the use of Ultrasonic or RADAR level, because they would come with a requirement that the containment of the Liquid Nitrogen be open to the atmosphere, and that is highly unadvisable.

A basic flow diagram of a Nitrogen Plant will look like the following,

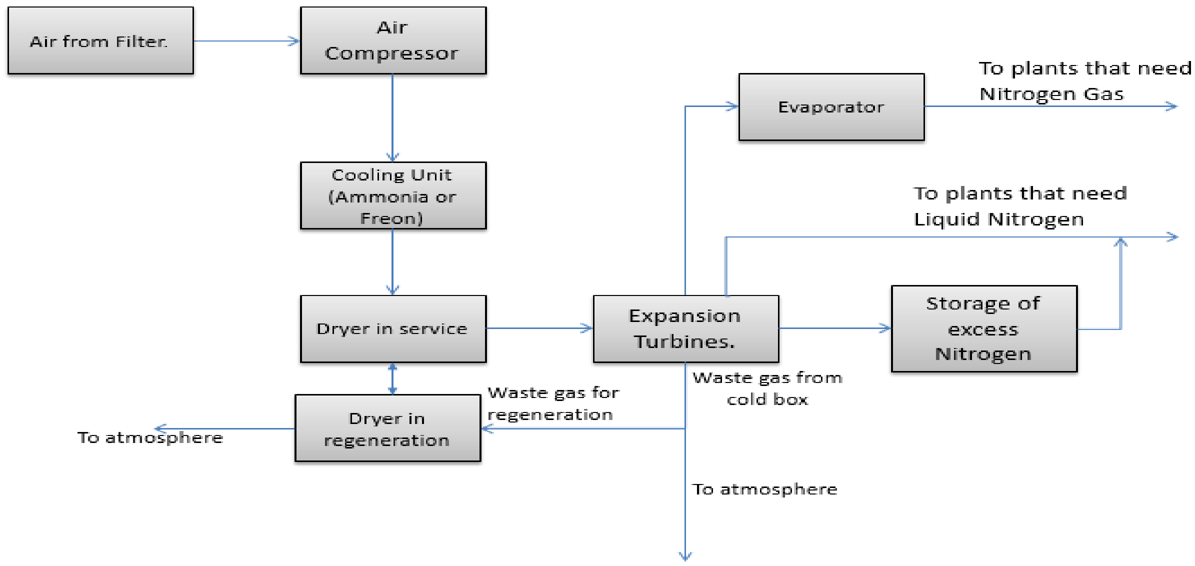

Figure 1: Basic setup of a Nitrogen Plant.

When a differential pressure cell is used for level measurement, the cryogenic tank is usually surrounded by a thermally insulated and evacuated cold box. The low pressure side of the direct acting differential pressure cell is connected to the vapour space above the cryogenic liquid. As the liquid nitrogen approaches the high pressure side of the differential pressure cell (which is at ambient temperature), it comes into contact with the air trapped in the impulse pipes. The carbon dioxide gets extensively cooled, forming solid dry ice, which ends up blocking the pipes. This is referred to as *choking*. Once choking occurs, it can be cleared by a process called *flushing*.
Flushing is a process where the Level Transmitter is first isolated from any other peripheral or dependant equipment, then the flow is allowed to flow at a 100% rate and that flow is allowed to drain for some predefined amount of time. This causes the choking to clear, but causes a substantial loss, because we regularly drain a lot of cryogenic liquid.

We hope to overcome these shortcomings by exploiting the optical properties of the material to measure the liquid level.

A brief study in the process and data collection gave us this visual representation. This shows how the process of choking happens over a time and how important it becomes to flush the transmitter every now and then.

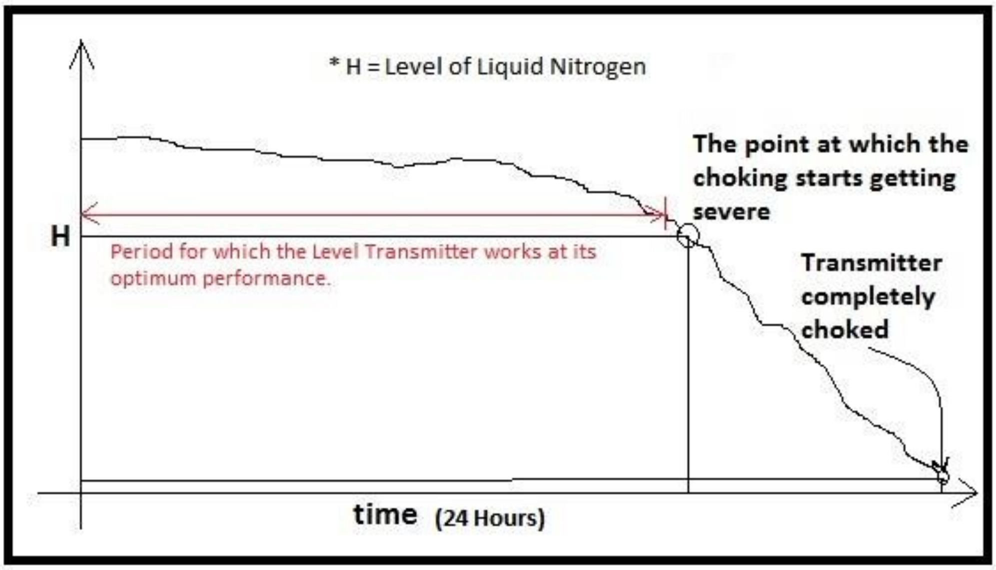

Figure 2: Visualisation of the process of choking.

III. MATHEMATICS:

Now, we try to formulate a relation between the Pressure and Liquid of the Cryogenic Liquid as a function of Refractive index of the liquid. For air it is easy, because air is a dilute gas with a very small refractive index, which is given by: [7]

$$n = 1 - \sum n_i \, \delta_i(k) \qquad (1)$$

In the above equation (1),

$k = Wave\ Number\ (note\ that\ we\ take\ care\ that\ it\ is\ a\ small\ value).$

$n_i = \ The\ number\ density\ for\ each\ species\ of\ molecule.$

$\delta_i(k) = \ Contribution\ to\ the\ index\ from\ this\ molecular\ species.$

Since In the ideal gas limit, which is nearly perfect for air. Thus,

$$n = \frac{P}{kT} \qquad (2)$$

If you double the pressure, you double the deviation from 1. If you double the temperature, you halve the deviation from one, because all the components go with the same ideal gas law:
So the formula for the long-wavelength index of air is

As the process conditions change, the maximum deviation of light will also change. It can be accounted for by using the relationship,

$$\mu\ (P,T) = 1 + \left(0.000293 * \frac{P}{P_0} * \frac{T_0}{T}\right) \qquad (3)$$

Where P_0 and T_0 are the atmospheric pressure and atmospheric temperature (300K) respectively.

A study on the Temperature versus Refractive Index of water(without uncertainity) shows that as the Temperature increases, the Refractive index decreases, which is accurately what the Equation (3) says, a plot is as follows:

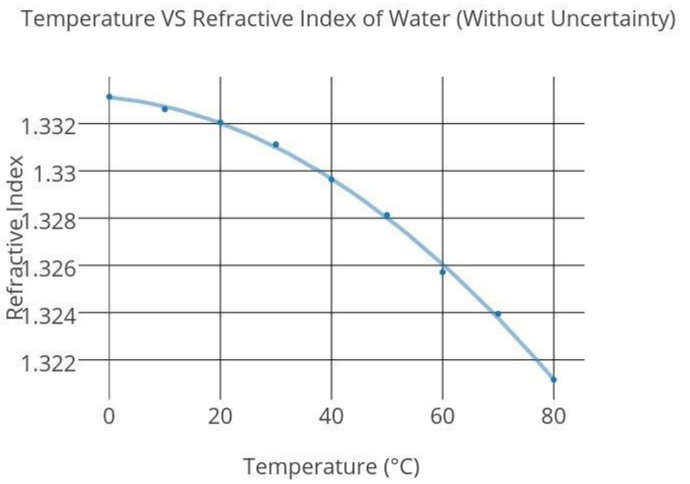

Figure 4: Relationship between Temperature and Refractive index. [9]

Another similar study shows that Pressure and Refractive index are directly related, which again affirms the validity of equation (3). The plot is as follows:

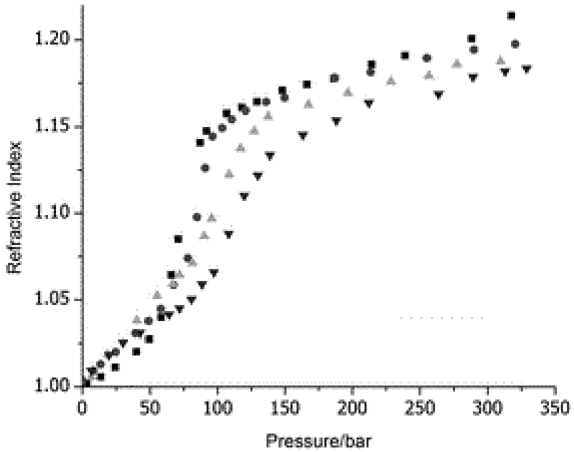

Figure 5: Relationship between Pressure and refractive index. [10]

IV. SYSTEM DESIGN:

The system takes advantage of the bending of light incident on a refractive surface when it hits the interface between the rarer and denser mediums. Which is essentially the Snell's law.

Snell's law of refraction:

$$\boxed{n_1 \sin \theta_1 = n_2 \sin \theta_2}$$

where $\theta_1$and θ_2 are the angles of incidence and refraction, respectively, of a ray crossing the interface between two media with *refractive indices* n_1 and n_2.

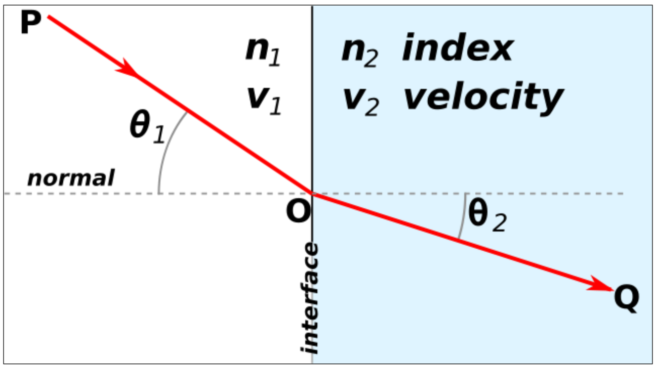

Figure 6: Snell's law

By Snell's law, we have,

$$\frac{n_{nitrogen}}{n_{air}} = \frac{\sin \theta_2}{\sin \theta_1}$$

Refractive index of air is known to be 1, and the refractive index of liquid nitrogen is known to be ~1.2 [3]. Therefore,

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{1.2}{1}$$

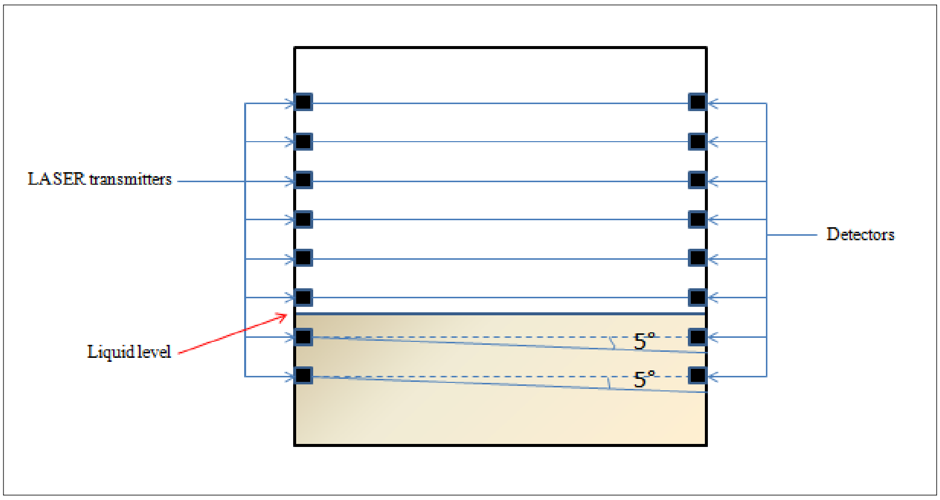

Figure 7: Experimental Setup.

Assuming $\theta_1 = 29.99°$, we can obtain $\theta_2 = 24.62°$. Therefore, the maximum deviation when light passes through liquid nitrogen is 5°.

As seen in figure 2, we have a series of LASER transmitters and detectors fixed at equal heights to be facing each other on the inner walls of the tank.

When the liquid is at a particular level, the space above it in the tank is filled with air. Emitted LASER travels straight and hits the detectors, which in turn give a high signal. Where the liquid fills the tank, the light deviates and the corresponding detectors do not receive light, giving a low signal.

V. RESULTS:

The results from the system designed above can be summarized in the following salient points:

1. This system design incorporates Optical Sensing methods to level sensing applications by taking advantage of the relation between the temperature and pressure with the refractive index of a Cryogenic Liquid.
2. The results of the study made on the system design showed that the problem was completely solved, the figure below shows that:

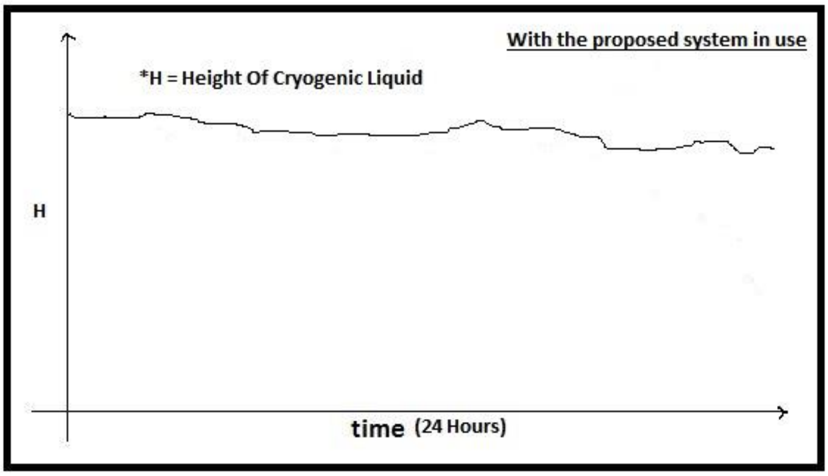

Figure 8 : Results.

3. The system is however, impractical In cases where the applications are to carried out in a closed container. Because, in that case the servicing of the sensors would be a very tedious job.
4. Further signal processing of the output of the system will be an added advantage.

VI. CONCLUSION:

Measurement of cryogenic liquid levels using light based method as described in this paper has overcomes the shortcomings of using a differential pressure cell. The fact that the accuracy of measurement is not important for measurements of non-critical levels can be exploited to achieve higher efficiency. The number of transmitter-detector pairs can be in accordance with geometric progression, and the common ratio can be chosen based on the critical level.

We should always be aware of the health and safety hazards of Liquid Nitrogen while working with it. Being odourless, colourless, tasteless, and non-irritating, nitrogen has no warning properties. Humans possess no senses that can detect the presence of nitrogen. Although nitrogen is nontoxic and inert, it can act as a simple asphyxiate by displacing the oxygen in air to levels below that required to support life. Inhalation of nitrogen in excessive amounts can cause dizziness, nausea, vomiting, loss of consciousness, and death. Death may result from errors in judgment, confusion, or loss of consciousness that prevents self-rescue. At low oxygen concentrations, unconsciousness and death may occur in seconds and without warning. Personnel, including rescue workers, should not enter areas where the oxygen concentration is below 19.5%, unless provided with a self-contained breathing apparatus or air-line respirator. [8]

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