

Journal of Petroleum Science and Technology

Research Paper

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Design and Development of an Optical-Based Analyzer for Real-Time Moisture Detection in High-Pressure Natural Gas

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Abstract

This study presents the design and development of an optical-based moisture dewpoint analyzer employing the chilled mirror technology for real-time dewpoint measurement at high-pressure gas streams. Moreover, the increasing demand for natural gas, along with the negative impact of moisture on energy efficiency and pipeline integrity, highlights the need for accurate moisture detection. Furthermore, the analyzer's innovative design enables direct measurement of dewpoint temperature through the condensation of water vapor as nano-droplets on a cooled mirror surface, overcoming the limitations of traditional methods that operate most of the time at atmospheric pressures. We successfully reproduced our experimental results from the South Pars Gas Complex (SPGC) with HYSYS Process Simulation Software based on the actual gas composition model. This approach confirmed the accuracy of the experimental findings. Ultimately, the results indicate that this analyzer offers a robust, low-maintenance solution for monitoring moisture levels, which is crucial for preventing pipeline corrosion and gas hydrate formation. By addressing the limitations of existing Oxide-Aluminum (Ceramic-based) sensors, this technology enhances measurement accuracy and reliability, contributing significantly to advancements in natural gas quality monitoring.

Keywords: Dewpoint, Moisture Analyzer, Natural Gas, ASTM D1142, HYSYS Simulation.

Introduction

Natural gas has been widely used as an energy source for many years due to its low cost and abundant availability. After extraction, the purification process is carried out in several stages. In addition, the purified gas is then distributed through a network of underground pipelines, where it is transported at pressures in the range of several hundred pounds per square inch. Moreover, natural gas is provided to consumers as an energy commodity, with its energy content quantified in British Thermal Units (BTU) [1,2]. Contaminants like water vapor decrease its BTU value, thereby reducing its overall efficiency as an energy source [3,4]. Moreover, these contaminants lead to corrosion in pipelines over time, posing serious safety risks and necessitating costly replacements [5,6]. As a result, the quality of natural gas is continuously monitored throughout various stages of production and distribution to prevent such issues.

One significant issue of the high level of moisture in natural gas is pipeline corrosion. Natural gas distributors must control the maximum allowable levels of water vapor during production and transportation. Accurate detection of water vapor, often referred to as moisture, is

critical for the safe and efficient transport of natural gas. Inaccurate moisture dewpoint measurements can lead to water vapor condensation within the pipelines. When water condenses and interacts with components such as hydrogen sulfide (H_2S) and carbon dioxide (CO_2), which are commonly present in natural gas, it forms sulfuric acid (H_2SO_4) and carbonic acid (H_2CO_3), further accelerating pipeline corrosion [6-11]. In addition to acid formation, water condensation can interact with hydrocarbons in the gas, leading to the formation of gas hydrate ice-like crystals that can block pipelines or processing units, thus reducing production and hindering gas transmission [12-15].

Moisture in natural gas is measured in two primary ways: moisture concentration and dewpoint temperature. Several techniques have been developed to measure water vapor concentration in natural gas, including sensors based on ceramic capacitance, quartz crystal, electrolytic sensors, and tunable diode laser absorption spectroscopy (TDLAS) [16-19]. However, in all these methods, measurements are typically conducted at atmospheric pressure, which does not reflect the actual high-pressure conditions of gas pipelines. In addition,

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Received 2024-11-25, Received in revised form 2025-05-25, Accepted 2025-07-26, Available online 2025-11-04



measuring at high pressures is inherently more challenging than at atmospheric conditions. Moreover, unlike the aforementioned methods that infer the dewpoint from indirect parameters (such as capacitance or resistance changes), the chilled mirror method directly measures the moisture dewpoint during the condensation process. This method can be applied to gases under high pressure, making it ideal for industries such as natural gas processing, where accurate moisture measurement under pipeline conditions is crucial. The dewpoint of a gas is a thermodynamic property defined as the temperature at which the gas becomes saturated and condensation begins. The moisture concentration correlates with the moisture dewpoint at a given pressure. Since the dewpoint is the result of the thermodynamic equilibrium between the gas and liquid phases, it is influenced not only by the moisture content but also by the pressure and other compositions of the gas sample [20-22]. The dewpoint is a critical parameter, as liquid water in the system leads to the aforementioned problems. In the natural gas industry, tariff contracts for exportation purposes are written in terms of the moisture dewpoint [23,24]. The optical chilled-mirror method is the most accurate approach for measuring water vapor dew point, as it provides a direct measurement based on condensation and verifies the result through optical detection of water droplets on the mirror surface [25-27]. This study focuses on designing and developing a laboratory setup for moisture dewpoint analysis, followed by adapting the analyzer for real-time, online measurement applications. First, the theory behind the chilled-mirror is explained, followed by the design and development of the moisture dewpoint analysis setup. Finally, the results are presented along with data from HYSYS Process Simulation Software and the ASTM-D1142 standard [28].

Materials and Methods

Theory of Chilled Mirror Technology

The optical chilled mirror technology relies on the variation in

light intensity detected by the photodetector, which is caused by the presence of water droplets on the mirror's surface [27, 29, 30]. The moisture dewpoint temperature measurement in natural gas is based on the detection of tiny water droplets forming on the surface of a mirror as its temperature decreases (Fig. 1).

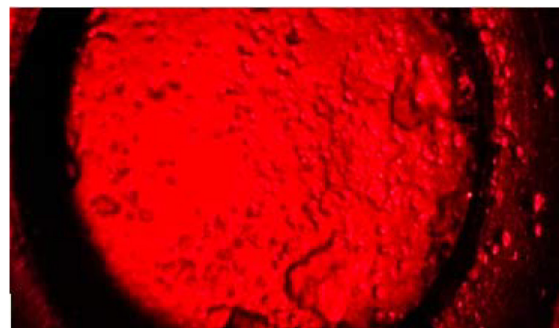


Fig. 1 Condensed water droplets are visible on the mirror surface under red illumination.

Moreover, a chilled mirror gas analyzer operates by continuously passing the gas sample over a polished surface (the mirror), whose temperature is precisely controlled [31,32]. As the mirror cools, the water vapor in the gas sample, which flows across the upper surface of the mirror, will eventually reach its dewpoint. Due to the high surface tension of water, nano-droplets appear on the mirror's surface when the temperature reaches the dewpoint. These water nano-droplets scatter the light directed onto the mirror's surface, and the relevant signals are received and recorded by a photodetector [27,33]. The mirror's temperature is controlled using a **Thermo-Electric Cooling (TEC)** system. In addition, a temperature sensor in direct contact with the mirror monitors the mirror's temperature. Also, the temperature at which a change in the signal received by the photodetector due to the formation of dew is recorded as the moisture dewpoint temperature. Moreover, the theory behind the chilled mirror technology for water vapor detection is illustrated in Fig. 2.

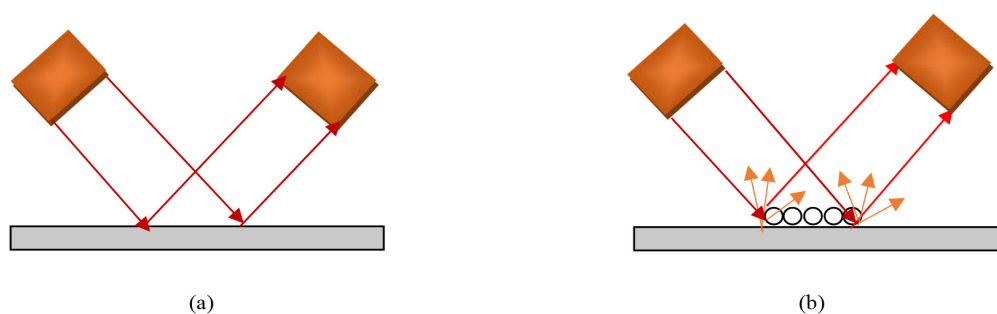


Fig. 2 (a) reflection from the surface of a dry mirror, (b) reflection from the surface of a wet mirror [33].

When a laser beam hits the dry and polished surface of the mirror, most of the light is reflected (Fig. 2a). The angle of incidence in this setup is usually chosen based on practical considerations such as maximizing signal-to-noise ratio, ensuring efficient scattering detection, and accommodating the physical positions of the optical elements that direct, focus, and detect light. Furthermore, during the cooling cycle, as water vapor condenses on the mirror and forms nano-droplets, there is a significant reduction in the amount of light reflected back to the photodetector due to scattering caused by the water dew formation (Fig. 2b). The change in

signal is dependent on the amount of condensation formed on the mirror's surface. Since the dewpoint is a direct indicator of the moisture in the gas, this temperature provides a measure of how much water vapor the gas contains. A reliable conversion between water vapor concentration and moisture dewpoint temperature is based on empirical data from fundamental research conducted by the Gas Technology Institute (GTI) and published in ASTM-D1142.

In our automated setup, once the dewpoint is established using our optical system, a feedback mechanism adjusts the mirror temperature to maintain the conditions for stable

measurements. The cycle time is approximately 10 minutes. Once the measurement cycle is complete, the mirror is heated up to eliminate condensation and then cooled again for continuous measurements.

Design and Development of Moisture Dewpoint Analysis Setup

The moisture dewpoint analysis setup is composed of the following key components: a pressure regulator, a solenoid valve, a filter for gas particles, a moisture dew point sensor assembly, electronic and control circuits, a flow meter, and a needle valve. Moreover, a pressure regulator is used to control the gas pressure before it enters the analyzer chamber, as gas pressure in transfer lines can fluctuate in gas fields and refineries. In addition, the solenoid valve regulates the flow of gas into the system by automatically opening and closing, as managed by the electronic control board. The gas filter is utilized to separate particles with sizes bigger than 5 microns. The dewpoint analysis setup is shown in Fig. 3. Moreover, the mechanical design of the moisture dewpoint sensor has been performed using SolidWorks 2020.

The main components of the moisture dewpoint sensor assembly are the gas inlet and outlet, optical system, TEC element, chilled mirror, mirror holder, and pressure and temperature sensors. An aluminum heat sink is located beneath the TEC to dissipate the heat effectively. The sensor is made of stainless steel 316L to ensure corrosion resistance. The optical system (shown as the black box in Figure 3) consists of a diode laser along with a lens and detector. Laser light is directed onto the mirror surface and collimated by the lens into the detector on the opposite side. Changes in the reflected light intensity caused by scattering from water droplets and the mirror temperature changes are recorded. The electronic board manages the operation of the entire system, including supplying current and voltage to various components, collecting and processing signals, and converting them into measurable physical parameters.

Results and Discussion

A LabVIEW-based interface was developed to enable real-time, online monitoring of light intensity variations in response to temperature changes during the water vapor condensation process in the gas. In addition, the figure below illustrates the variation in light intensity with temperature during a single dewpoint measurement cycle of cylindered natural gas from the South Pars Gas Complex (SPGC) refinery in our laboratory. As illustrated in Fig. 4, the reflected light intensity from the dry mirror surface remains nearly constant, but exhibits a noticeable reduction once dew condensation begins. Also, this decline is due to light scattering caused by the small water droplets that accumulate on the mirror's surface. Moreover, the light received by the detector fluctuates, decreasing further as more droplets accumulate on the mirror's surface. However, once the surface is fully covered with water droplets, they form frost points on the mirror, which then increases the intensity of the reflected light. This indicates the formation of frost. After the measurement cycle ends, the mirror is heated to remove any condensation and prepared for the next measurement cycle.

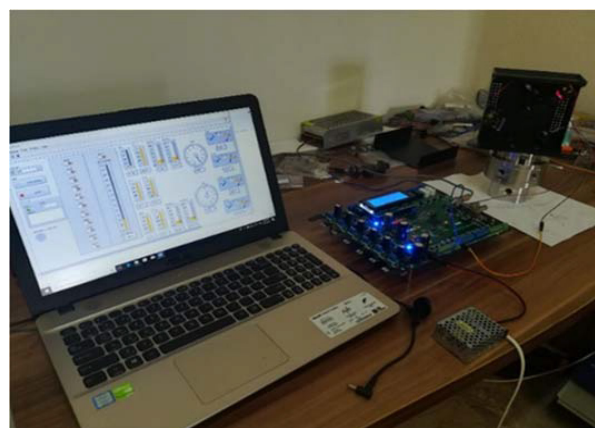


Fig. 3 Moisture dewpoint analysis setup in the laboratory.

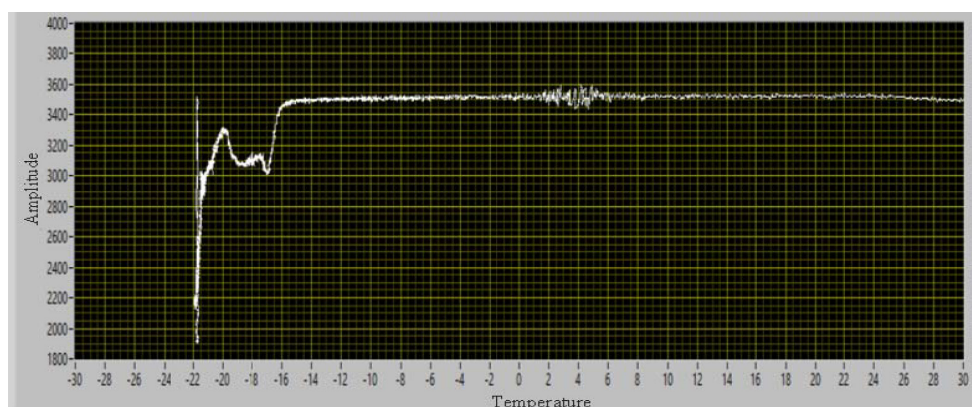


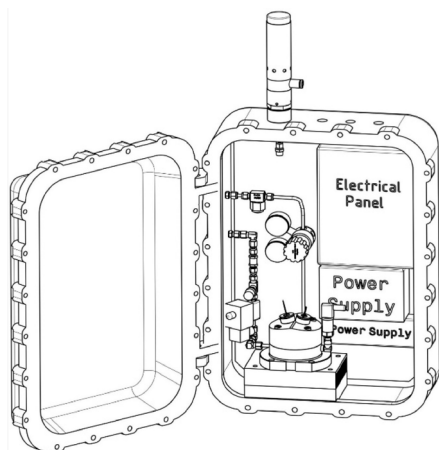
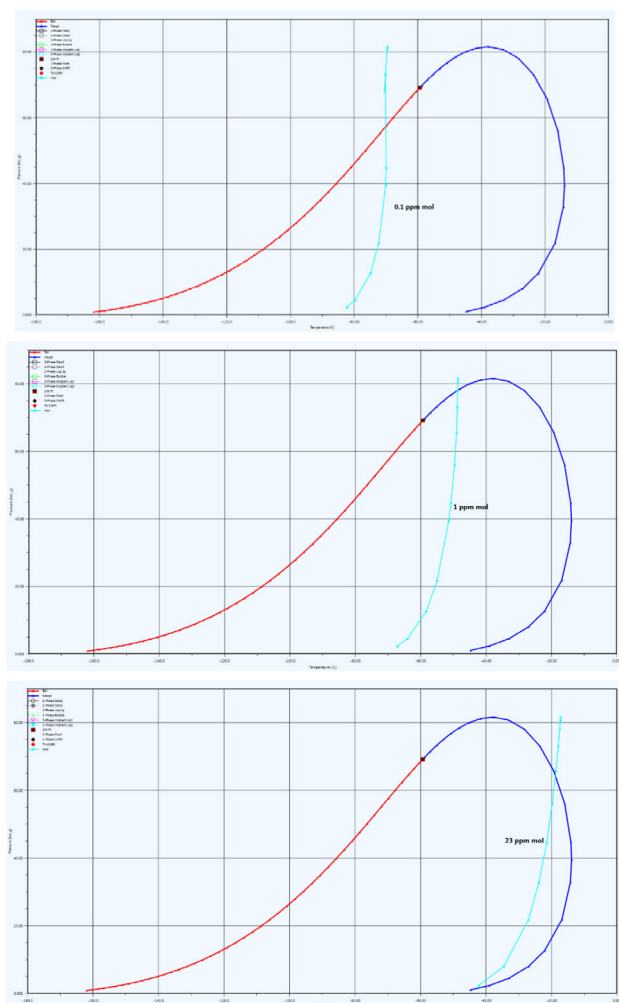
Fig. 4 Reflected light intensity variation with temperature during a single measurement cycle.

To evaluate the performance of our dewpoint analysis setup and ensure the accuracy and precision of its results, we conducted dewpoint measurements on different days at various pressure conditions. Moreover, the findings are summarized in Table 1. Also, it is noted that the dewpoint temperatures listed for each test represent the average values obtained from around 100 measurement cycles conducted over 24 hours.

Table 1 demonstrates a logical relationship between pressure and dewpoint temperature. As pressure rises, the dewpoint temperature similarly increases. Following initial tests in our laboratory, to enable real-time, online measurements at SPGC, we relocated and modified our setup within an explosion-proof enclosure. This adjustment ensured safe measurement operations in a potentially hazardous environment, meeting the required safety standards. The overall view of the moisture gas analyzer is shown in Fig. 5.

Table 1 Dewpoint measurements of water vapor in natural gas at various gas pressures.

Test number	Pressure (Bar)	Dewpoint (°C)
1	26	-30.6±0.5
2	36	-27.1±0.3
3	46	-22.7±0.4
4	56	-20.0±0.5
5	66	-18.1±0.1

**Fig. 5** Schematic view of the moisture gas analyzer, showing key components.**Fig. 6** Natural gas phase-envelope simulated using HYSYS Process Simulation Software for moisture dewpoint at various water vapor concentrations of (a)0.1, (b)1, and (c)23 ppm.

We measured the water vapor dewpoint at various pressures up to 80 bar. Our experimental results were then compared with water vapor dewpoint temperatures calculated by HYSYS Process Simulation under the same temperature, pressure, and gas composition conditions. Based on the gas composition, as shown in Table 2, HYSYS generated a phase envelope for various water vapor concentrations, demonstrating how the moisture dewpoint temperature varies as gas pressure rises (Fig. 6). Our dewpoint measurement results closely aligned with the phase envelope data at a water vapor concentration of 23 ppm, indicating a good agreement. This confirms the accuracy and reliable performance of our moisture dewpoint analyzer. Furthermore, the concentration of water vapor can be determined from the dewpoint temperature by utilizing the ASTM D1142 tables. Moreover, the ASTM D1142 tables cover a range of dew-points and pressures, allowing us to find the corresponding concentration values for the measured dew-points at specific pressure and temperature conditions. The concentration corresponding to the measured moisture dewpoint temperature of -30.6°C (Table 1) is found to be 25.2 ppm. This value is also consistent with the HYSYS simulation data in a mutual way, which shows a concentration of 23 ppm.

Table 2 Input specification of natural gas composition used in HYSYS Process simulation software.

Component	Mole Fraction
H ₂ O	0.000023282
CO ₂	0.013257405
H ₂ S	0.000009097
Nitrogen	0.035259441
Methane	0.854642977
Ethane	0.055541373
Propane	0.023592393
i-Butane	0.004069662
n-Butane	0.006759009
i-Pentane	0.001891254
n-Pentane	0.001680042
Methylcyclopentane	0.000282848
n-Hexane	0.001077783
Cyclohexane	0.000092141
n-Heptane	0.000596949
Methylcyclohexane	0.000144230
Benzene	0.000043072
Toluene	0.000028281
COS	0.000029830
M-Mercaptan	0.000021564
E-Mercaptan	0.000017114
2-Propanolthiol	0.000049622
nBMercaptan	0.000084484
1-Hexanethiol	0.000012790
MDEAamine	0.000000066
n-Octane	0.000298502
Cyclooctane	0.000004206
n-Nonane	0.000113192
Cyclononane	0.000004006
n-Decane	0.000043073
n-C11	0.000010017

Conclusions

This study successfully presents the design, development, and performance validation of an optical-based moisture dewpoint analyzer for real-time measurement of water vapor dewpoint in high-pressure natural gas streams. The analyzer employs a chilled mirror technology to measure moisture dewpoint temperature. Experimental results obtained in the South Pars Gas Complex (SPGC) were validated using HYSYS Process Simulation Software, confirming the system's capability to reliably monitor moisture in natural gas. Utilizing the ASTM D1142 standard, the analyzer accurately determines water vapor concentration, closely matching the value obtained from the HYSYS simulation. The consistency of the results demonstrates the robustness of our analyzer in accurately monitoring moisture levels in high-pressure natural gas streams, highlighting its potential as a reliable tool for natural gas quality monitoring. Currently, gas refineries in the country use Aluminum Oxide (ceramic-based) sensors to measure moisture levels. However, these sensors operate under atmospheric pressure and need frequent calibrations within a short period due to direct exposure to corrosive substances and contaminants in natural gas, which leads to inaccuracies in moisture measurements. In addition, this optical moisture dewpoint analyzer offers significant improvements over conventional Oxide-Aluminum sensors, providing more accurate and reliable moisture content data while also reducing maintenance and repair expenses, thereby contributing to enhanced natural gas quality monitoring. Also, the developed moisture dewpoint analyzer not only enhances the accuracy of dewpoint measurements and moisture concentration determinations but also represents a robust, low-maintenance solution adaptable to oil, gas, and petrochemical industries. Ultimately, this research contributes a significant advancement in gas quality monitoring technologies, with potential for widespread application in natural gas distribution networks and other industries requiring precise moisture control. Furthermore, this design is particularly beneficial for field applications, where real-time and online monitoring of moisture content is essential for maintaining pipeline safety and optimizing gas processing and transportation operation costs.

Acknowledgement

This study was carried out at Pars Smart Sensors Engineering Company, a knowledge-based company in Tehran affiliated with the University of Tehran Science and Technology Park. Special thanks go to the company for their support in commercializing the analyzer, as well as for providing essential infrastructure that was instrumental in conducting this study.

Funding

The author expresses gratitude to the Vice President of Science and Technology for the financial support that enabled this research.

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