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Evaluation of Hydrogen Blend Stability in Low-Pressure Gas Distribution

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Abstract: Natural gas distribution companies are developing ambitious plans to decarbonize the services that they provide in an affordable manner and are accelerating plans for the strategic integration of renewable natural gas and the blending of green hydrogen produced by electrolysis, powered with renewable electricity being developed from large new commitments by states such as New York and Massachusetts. The demonstration and deployment of hydrogen blending have been proposed broadly at 20% of hydrogen by volume. The safe distribution of hydrogen blends in existing networks requires hydrogen blends to exhibit similar behavior as current supplies, which are also mixtures of several hydrocarbons and inert gases. There has been limited research on the properties of blended hydrogen in low-pressure natural gas distribution systems. Current natural gas mixtures are known to be sufficiently stable in terms of a lack of chemical reaction between constituents and to remain homogeneous through compression and distribution. Homogeneous mixtures are required, both to ensure safe operation of customer-owned equipment and for safety operations, such as leak detection. To evaluate the stability of mixtures of hydrogen and natural gas, National Grid experimentally tested a simulated distribution natural gas pipeline with blends containing hydrogen at up to 50% by volume. The pipeline was outfitted with ports to extract samples from the top and bottom of the pipe at intervals of 20 feet. Samples were analyzed for composition, and the effectiveness of odorant was also evaluated. The new results conclusively demonstrate that hydrogen gas mixtures do not significantly separate or react under typical distribution pipeline conditions and gas velocity profiles. In addition, the odorant retained its integrity in the blended gas during the experiments and demonstrated that it remains an effective method of leak detection.

Keywords: hydrogen blending; gas mixtures; gas distribution

1. Introduction

The underground infrastructure for gathering, transporting, and utilizing natural gas in the US is already in place, but its role in energy-sector decarbonization is uncertain. Currently, natural gas contributes to 32% [1] of energy consumption. To enable natural gas distribution systems to contribute to the goal of deep reductions in greenhouse gas emissions, natural gas distribution companies are accelerating ambitious plans to decarbonize the services that they provide affordably. These companies are planning the strategic integration of renewable natural gas and the blending of green hydrogen produced by electrolysis, powered with renewable electricity developed from large new commitments by US states, such as New York and Massachusetts [2]. There are 2.2 million miles of gas distribution pipelines in the US with asset values in the billions of dollars. These systems are connected to 72 million customers in the US, most in localities that have committed to deep decarbonization [3], some with interim targets as early as 2030 [4]. Most of these systems are regulated by the same governmental agencies that recently adopted these ambitious goals, and many gas utilities support those goals.

In the case of New York City, in April 2021, the New York City Mayor's Office of Sustainability issued the "Pathways to Carbon-Neutral NYC" report [5]. The report discussed several approaches regarding a decarbonized heating system. This report proposed broad electrification of heating and showed the formidable practical and economic challenges of decarbonizing buildings in older urban environments. Many of these buildings are nearly a century old and utilize steam distribution systems. Most electric heat pump systems cannot produce high enough temperatures to produce steam. This report also considered the important role that low-carbon fuels can have in achieving these goals. The report specifically noted that between 40% and 70% of buildings in the city will not likely be fully electrified by 2050. National Grid's own analysis showed that between 30% and 70% of buildings within the urban areas of Boston and New York City and between 5% and 40% of those outside these major cities will be technically difficult or impossible to fully electrify by 2050. Considering that access to reliable heat is required for human health and is required by law in cold climates, the challenges of universal electrification in building heating in places such as Massachusetts and New York illustrate why building heat should be considered a "strategic, high-impact use for clean hydrogen" in at least some cases. While energy efficiency and electrification must be the cornerstones of any effective strategy for decarbonizing buildings, even best-case scenarios for customer adoption of electric heat pumps will leave unabated for decades most emissions from buildings that use heating oil or fossil natural gas to distribute steam inside those buildings.

Hydrogen is the most abundant chemical element on earth and offers enormous potential to transport renewable energy. For decades, hydrogen has been used as a sustainable energy carrier. When hydrogen is converted into useable energy in a fuel cell or combusted to release its energy, the only by-product is water vapor. Green hydrogen, defined as hydrogen produced with clean energy through electrolysis, is entirely carbon free. The US government and several states have committed to decarbonization of all forms of energy and are providing guidance and support for hydrogen through programs such as the US Department of Energy's H2@Scale program [6] and the multi-billion-dollar Hydrogen Hub initiative, begun in 2022. The National Renewable Energy Laboratory in the US has also begun a new research project called HyBlend [7] "to address the technical barriers to blending hydrogen in natural gas pipelines." The HyBlend project is studying the effects on pipeline materials, the environmental aspects of hydrogen blending, and the impacts on end-users. The project presented here is directly synergistic with the goals of the HyBlend project since, as the heating sector begins to decarbonize, blending green hydrogen into the natural gas pipeline would offer near-term optionality for lowering emissions.

Repurposing the natural gas network to deliver low-carbon fuels, including renewable natural gas and green hydrogen, is essential when ensuring an equitable transition to a low-carbon future and abating the most greenhouse gas emissions as soon as possible. A report recently issued by the Center on Global Energy Policy at Columbia University stated that repurposing existing gas infrastructure "can support a pathway toward wider storage and delivery of cleaner and increasingly low-carbon gases while lowering the overall cost of the [clean energy] transition and ensuring reliability across the energy system," and "having some systems, such as industrial and residential heat, remain nonelectrified and instead supplied by gas molecules could lend a very important component of reliability, providing backup should electrical systems go down" [8].

There remains uncertainty about the practicality, cost-effectiveness, and safety of using hydrogen for heating. However, despite a lack of widespread hydrogen distribution, the gas networks in North America have seen hydrogen before. Blends of hydrogen and other gases were first used as residential heating fuel in the 19th century, and today, the Hawaii Gas Company continues to safely deliver residential synthetic natural gas (SNG) containing up to 15% hydrogen to customers across the island of Oahu [9]. Likewise, the gas distribution system in Hong Kong delivers SNG with as much as 51.8% hydrogen [10]. Hydrogen has also long been used in petrochemical, steelmaking, and other industries. To serve these industries, more than 1600 miles of pipelines carrying pure hydrogen exist in

the US today, including three miles of pipeline in upstate New York [11]. These hydrogen pipelines have been operating safely for decades and are very similar to other gas-carrying pipelines.

Numerous efforts around the world are focusing on the delivery and use of hydrogen blended natural gas for many uses [12]. The demonstration and deployment of hydrogen blending have been proposed broadly initially at 20% of hydrogen by volume [13]. The US gas industry views extensive testing and detailed trials as essential to uncover the full potential for hydrogen and to understand what modifications may be needed to safely transport hydrogen on a broad scale. Several studies have tested individual household appliances and found that they are compatible with hydrogen of blends up to 20%. A recent project in Staffordshire, United Kingdom, called HyDeploy [14] confirmed these findings by introducing a 20% hydrogen blend city-wide, observing that appliances performed well, and no increase in appliance malfunction was observed. One underlying assumption throughout the work in this field is that blends of natural gas and hydrogen exhibit the physical properties of a homogenous mixture of the blended gas. A homogeneous mixture is necessary to ensure the predictable integrity of pipelines, the consistent and reliable operation of customer-owned equipment, and the ability to quickly detect leakage for safety and environmental reasons. Reliable and consistent leakage detection is necessary for service personnel and emergency responses, as well as for those who use gas service. Leak detection today is accomplished through both stationary and portable electronic detection devices and through human olfactory detection. There are existing certification standards for detectors [15], including UL 2075, "Standard for Gas and Vapor Detectors and Sensors." Gas detectors listed according to this test standard and related standards must operate reliably with both existing natural gas and hydrogen blends.

Reliability and safety are paramount when evaluating even the smallest changes to gas networks and gas composition. There has been little published research on hydrogen blending specifically in low-pressure gas distribution systems because it has only recently been proposed to meet pressing climate change objectives. To blend hydrogen safely, extensive testing and detailed trials are essential to uncover the full potential for hydrogen and to understand what modifications may be needed to safely produce, transport, store, and blend hydrogen. This study focuses on the blending of hydrogen and methane, the primary component of natural gas. Given the difference in their chemical properties, the primary question studied in this report is whether separation or stratification of the gas naturally occurs in distribution pipelines or whether the gas remains homogenous regardless of blending rate and operating pressure.

The safe distribution of hydrogen blends in existing networks requires the hydrogen blends to exhibit similar behaviors as current supplies, which are also mixtures of several hydrocarbons and inert gases. The natural gas distribution systems in the US receive gas supplies from multiple production sources around North America. These different supplies have varied by location and over time. The US gas industry has developed protocols for ensuring acceptable gas composition [16]. Current mixtures are known to be sufficiently stable in terms of a lack of chemical reaction between constituents and to remain homogeneous through compression, transmission, and distribution. The same is predicted for hydrogen but, since hydrogen is considered non-condensable, not for liquefaction [16], which is not an essential aspect of future hydrogen operations. The introduction of hydrogen blends is only the latest in a series of significant changes to gas supplies over decades. In particular, the density of hydrogen is significantly smaller than that of natural gas. The chemical properties of hydrogen and natural gas relevant to gas distribution operations are shown in Table 1.

Table 1. Chemical Properties of Hydrogen vs. Natural Gas [17].

	Natural Gas	**Hydrogen**
Atomic Weight (g/mol)	19.0	2.016
Density (g/L)	0.717	0.08988
Flammability Limits in Air (by volume)	5.3 to 15	4 to 75
Autoignition Temperature (°F)	813	858
Mass diffusivity in air (mm^2/s)	23.98	78.79
Joule-Thomson Effect	Temperature decreases when pressure is decreased.	Temperature increases when pressure is decreased.

These differences in properties potentially allow for the unintended separation of gases within the pipe depending on the pipeline conditions of pressure, temperature, and flow regime but not orientation.

As noted earlier, recent interest in mixing hydrogen with natural gas to decarbonize the energy sector has renewed research into these gas mixtures in various ratios [18–20]. However, this discussion must first be viewed from the perspective of the flow of these gases in a typical pipeline and the associated physics principles. For long distance transport, natural gas must be compressed to maintain its flow [21], and it follows established physics laws. The gas is compressed in transmission pipelines to pressures typically ranging from 500 to 1400 psig. However, the initial pressure would drop as a function of distance, so a series of compressors are placed every 50 to 100 miles along the length of the transmission pipeline, thus creating pressure differentials and allowing the pressure to increase as needed to keep the gas moving until it reaches the city gate for distribution. A general equation for steady-state flow [22] considers the momentum equation applied to a portion of pipe of length dx, inside which flows a compressible fluid with an average velocity u, for example, natural gas, assuming steady state conditions, where ρ is the gas density, p is the gas absolute static pressure, A is the area of the pipe cross-section (πD 2/4), and dH represents a variation in height, and the resulting correlation results in a differential equation [22]: In this equation, f is the Darcy friction coefficient which is related to the wall shear stress [22].

Although it is known that the energy content of natural gas is three times that of hydrogen, the implications of tripling the gas volumetric flow rate of hydrogen in existing natural gas infrastructure may not be straightforward. Moreover, a wide discrepancy can exist in the flow properties of two fluids under the same flow conditions due to their differences in physical and chemical properties [18]. Therefore, safe transport of hydrogen in natural gas pipelines will require a thorough understanding of the impact of the lower density and higher compressibility characteristics of hydrogen and the modifications that would be required to prevent hydrogen embrittlement and seepage in gas pipelines. Since the molecular motion of gas molecules at room temperature allows thorough mixing, any gas mixture is assumed to be homogeneous, and stratification is not considered. Moreover, though H_2 and CH_4 have different densities, the gaseous form ensures gravity separation while flowing through a pipeline is not a factor. Work is also under way to allow for facile separation of H_2 from CH_4/H_2 mixtures at the city gate. For example, fuel cell-mediated separation to capture pure methane from the CH_4/H_2 mixture was reported [23].

Interestingly, the segregation of gas mixtures in dynamic systems, i.e., pipelines, was recently reported for flowing H_2-CH_4 gas mixtures [24] under specific conditions. Another recently published paper by Alkhatib et al. [25] also noted that the thermodynamic properties of H_2 and CH_4 mixtures are well studied, though under a small range of temperatures, pressures, and hydrogen compositions. The compressibility factor (Z), single-phase density (ρ), isobaric heat capacity (Cp), speed of sound (ω), JT coefficient (μJT), and viscosity (η) were measured and compared favorably to modeling. Therefore, the research focused

on a theoretical study of the effect of added hydrogen on the thermodynamic properties of natural gas and established that each of these factors determine actual mixture properties.

This report outlines the methodology and results of testing for homogenous blended gases with consistent composition in each test within a conventional distribution pipe at varying blend rates and pressures under expected flow conditions.

To evaluate the stability of mixtures of hydrogen and natural gas, National Grid performed new experiments to simulate distribution pipelines with flowing hydrogen blends at varied rates of up to 50%. A 100-ft. long pipeline was outfitted with ports at intervals of 20 feet, to extract samples from the top and bottom of the pipe. Samples were analyzed for composition, and the effectiveness of the odorant was also evaluated.

The plan for this series of experiments was to compare samples taken from different points along the pipe and at different orientations. If separation of gases occurred, variations in gas composition would be observed, as indicated by variations in the actual higher heating value (HHV) and would be measurable at points down the pipeline or between the points at different orientations to the pipeline. HHV is the attribute of natural gas that is used for determining billed amounts to customers and is used in the design of end-use equipment. HHV is used as the determining factor since variations in hydrogen content in blended gas will have a measurable impact on HHV. For example, a 5% variation in hydrogen content inside a pipeline will result in a 3.7% variation measured HHV, which is far greater than a variation measurable by typical devices.

This experiment also included an evaluation of the potential for chemical reactions of hydrogen inside distribution pipelines with common odorants used for leak detection that might render those odorants ineffective. The use of odorants and their measurement and performance criteria are prescribed in utility regulations [26]. The same blended gas samples used to evaluate the potential for separation were also available to observe any measured changes in odorant concentration. To evaluate the potential for loss of odor or odorant fade, also called odorant masking, blended gas samples were tested for odorant concentrations. These concentrations were then used to determine gas distribution performance indicators for human olfactory response by calculating the threshold detectable level (TDL) and readily detectable level (RDL) [26] in air. Minimum standards for these performance factors have been established by various state regulatory agencies in the US.

2. Materials and Methods

To evaluate the stability of mixtures of hydrogen and natural gas, National Grid designed and performed new experiments to simulate a section of gas distribution pipeline with flowing hydrogen blends and varied blend rates.

The primary goal of the experiment was to replicate modern gas distribution pipeline conditions and determine what, if any, separation would naturally occur when hydrogen and methane, the primary components of natural gas, are blended. To accomplish this task, a 100 linear foot section of 2-inch diameter high density polyethylene (HDPE) pipe was erected horizontally outdoors. This material and size of pipe are the most common being installed today by National Grid, including in those areas where hydrogen blending is expected. HDPE pipelines less than 4″ in diameter represent more than 25% of the miles of pipeline in operation today [11]. The pipeline section was operated under shade to prevent heating from the sun, thus creating temperature variations. Sampling ports were installed at the top and bottom of the pipe, at the 6 and 12 o'clock orientations and every 20 feet, to collect gas samples that could be analyzed utilizing a commonly used portable gas chromatograph, a Micro GC Fusion 3-Module System Micro Gas Chromatograph [27]. A heat exchanger was assembled to heat/cool depressurized gas to keep temperatures controlled. The gas at the outlet was connected to a commercially available outdoor cooking grill to mimic household gas loads, and a standard flow meter was used to monitor the outlet gas flow rate. The entire arrangement is shown in Figure 1.
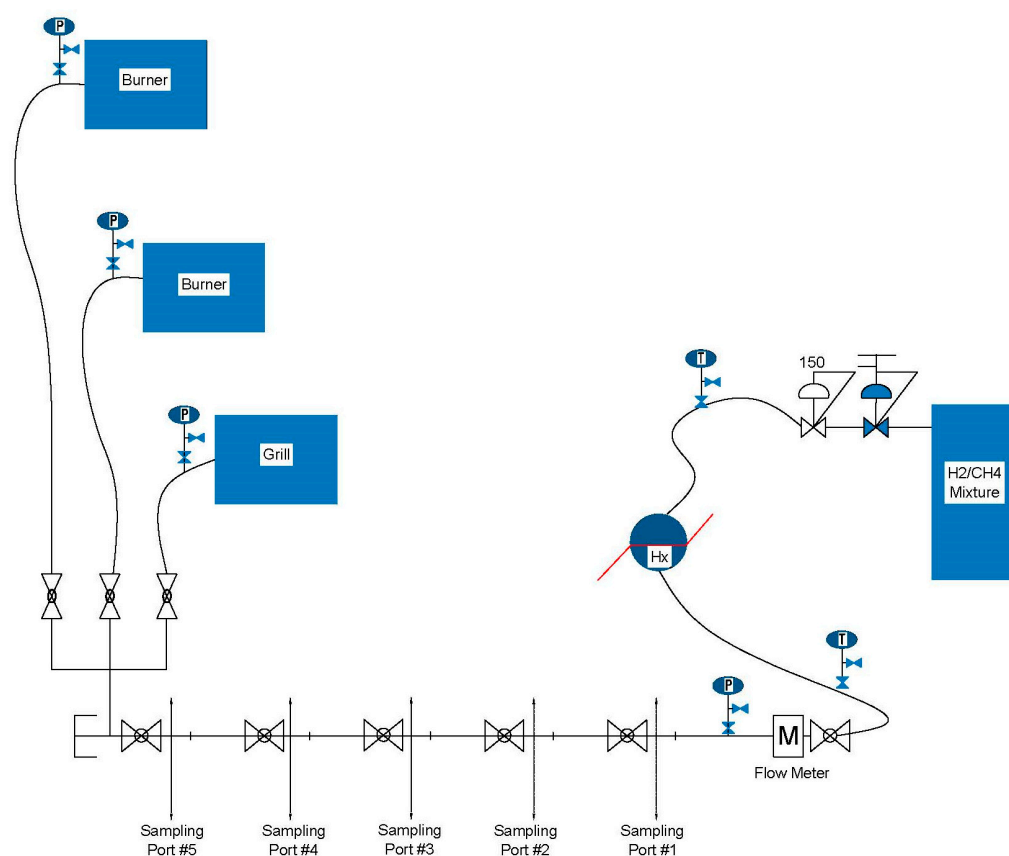
Figure 1. Natural Gas-H$_2$ Blending Experiment Setup.

2.1. Testing Conditions

Pre-mixed blends of hydrogen and methane were purchased from Airgas. The accuracy of gas blends in cannisters provided was within 0.001% by volume. These gas mixtures were also odorized with Scentinel–E [28], a commonly used odorant, excluding anti-freeze, to ensure gas leak detection. Table 2 shows the composition of the gas blends evaluated.

Table 2. Composition of Hydrogen Blends by Volume Used in the Study.

% H$_2$ by Volume	% Methane
1	99
3	97
5	95
12	88
20	80
30	70
46	54
50	50

These blends were tested at a range of pressures commonly used in natural gas distribution piping, listed in Table 3.

Table 3. Effect of Pressure on Blended Gas Composition. The Pressure Range Was Selected to Mimic Existing Natural Gas Distribution Pipes.

1	99	x	x	x	x
3	97	x	x	x	x
5	95	x	x	x	x
12	88	x	x	x	x
20	80	x	x	x	x
30	70	x	x	x	x
46	54	x	x	x	x
50	50	x	x	x	x

2.2. Testing under Static Conditions

Gas consumption in homes and businesses typically varies hour to hour throughout the day. This experiment was also designed to establish whether stratification would occur during sustained periods of little to no movement of the gas; hence, low-flow or no-flow conditions in the pipe were tested. Prior to conducting a flow test, the pipeline system was brought up to the chosen pressure and temperature, and then the gas was held for 2 h under no-flow conditions. A complete batch of samples from all (5) sample ports (top and bottom) were collected and analyzed prior to beginning the flow scenario testing, and in each case, no anomalies or instabilities in readings were observed.

The experiments were conducted over several days with consistent weather. A total of 32 tests were conducted: eight different gas mixtures at four operating pressures, each tested with and without flow. A total of 320 gas samples were obtained and analyzed by the gas chromatograph for HHV and odorant effectiveness, and all results were recorded.

3. Results

The data from all 320 samples were all recorded and reviewed for accuracy and then used to develop the following results to evaluate consistency in HHV measurements for flowing or non-flowing conditions, as well as odorant performance.

3.1. Expected Higher Heating Value (HHV)

The first step was to analytically determine the higher heating value (HHV) of a homogeneous hydrogen blend for comparison with the measured results. The equation below shows the calculation to determine the expected HHV of each blend of gas. With premixed gas from the supplier's laboratory, only hydrogen and methane at varying concentrations needed to be considered. The expected HHV for each blend studied during the experiment is listed in Tables 3 and 4.

$$\text{Expected Higher Heating Value} = (\%CH_4) \times \left(1012 \ \frac{Btu}{scf} \right) + (\%H_2) \times \left(324 \ \frac{Btu}{scf} \right) \quad (1)$$

Source of HHV values [29].

3.2. Measured HHV—Flowing Gas

During flow conditions, the system was brought up to the operating pressure, and the temperature was controlled via a manual shell-and-tube heat exchanger. The system was outdoors, and the experiment was conducted during the warmer months, limiting the ability to cool the blended gas to less than grade temperatures. Instead, the system was operated at a temperature of approximately 80 °F, which is common for exposed piping in the summer when the highest temperature gradients are expected. During flow conditions, a natural gas outdoor cooking grill was used to burn the gas and create a steady flow of approximately 0.5 standard cubic feet per minute (scfm), resulting in a typical velocity of

about 0.36 feet per second (fps) or 0.11 m/s, thus in the laminar flow regime as opposed to turbulent flow, which would in theory favor mixing. The system was operated for 30 min prior to sampling. The gas grill used operated normally with no interruptions or unusual conditions, such as flashback, observed in any test.

The sampling program intentionally opted not to sample each point down the line, instead sampling at points numbered 1, 3, 5, 2, and then 4 to avoid sampling the same slug of gas as it traveled down the pipe. Swagelok fittings were used to create the sampling points at which the sample cannisters were filled. The typical process included repeated filling and purging. The process was conducted 3× before a sample was collected to ensure accuracy.

After collection, the samples were fed into the gas chromatograph, which analytically yielded % by volume gas composition data. The same equation used to predict the HHV of the blended gas was used to provide the measured HHV of the blended gas, using the results from the gas chromatograph for $\%H_2$ and $\%CH_4$.

Table 4 shows the measured results during flow conditions. The results showed a near perfect correlation between measured and expected HHV or Btu content. Every sample pulled from the pipe throughout the experiment was with within 0.45% of the expected value, regardless of its position laterally of vertically on the pipe. Figure 2 presents the data from Table 4 in graphical form and shows the near perfect correlation between the expected and measured results.

Table 4. Expected vs. Measured HHV Under Flow Conditions.

Test Blend	Nominal Pressure	Expected Btu	Average Btu Content	Δ% Btu Content (Ave/Exp)	Btu Content Top Average	Btu Content Bot Average	Δ% Btu Content (Top/Bot)
1%/99%	60 psi	1005.12	1005.19535	0.00750%	1005.192094	1005.198606	−0.001%
	30 psi		1005.2066	0.00862%	1005.203021	1005.210173	−0.001%
	15 psi		1005.20915	0.00887%	1005.209656	1005.208642	0.000%
	7 in w.c.		1005.22165	0.01011%	1005.224149	1005.219156	0.000%
3%/97%	60 psi	991.36	991.268122	−0.00927%	991.2356654	991.3005779	−0.007%
	30 psi		991.195402	−0.01660%	991.1576299	991.2331749	−0.008%
	15 psi		991.215118	−0.01461%	991.1933077	991.2369288	−0.004%
	7 in w.c.		991.21195	−0.01493%	991.154181	991.26972	−0.012%
5%/95%	60 psi	977.6	977.869476	0.02757%	977.7601578	978.0061227	−0.025%
	30 psi		977.467179	−0.01359%	977.4753297	977.4590274	0.002%
	15 psi		977.300404	−0.03065%	977.3025322	977.2982751	0.000%
	7 in w.c.		977.517717	−0.00842%	977.4475519	977.5878829	−0.014%
12%/88%	60 psi	924.44	929.784225	0.57810%	929.7134863	929.8549629	−0.015%
	30 psi		929.161289	0.51072%	929.1773447	929.1452333	0.003%
	15 psi		928.224976	0.40943%	928.2049044	928.2450473	−0.004%
	7 in w.c.		929.179203	0.51266%	929.7134863	928.64492	0.115%
20%/80%	60 psi	874.4	873.071327	−0.15195%	872.9897522	873.1529009	−0.019%
	30 psi		873.839169	−0.06414%	873.8376382	873.8407	0.000%
	15 psi		874.174518	−0.02579%	874.1147958	874.2342401	−0.014%
	7 in w.c.		874.140792	−0.02964%	873.9236349	874.357949	−0.050%

Table 4. *Cont.*

| Test Blend	Nominal Pressure	Expected Btu	Average Btu Content	Δ% Btu Content (Ave/Exp)	Btu Content Top Average	Btu Content Bot Average	Δ% Btu Content (Top/Bot)
30%/70%	60 psi	805.6	803.9794	−0.20117%	804.0146816	803.9441192	0.009%
	30 psi		803.955343	−0.20415%	804.1279821	803.7827037	0.043%
	15 psi		805.534732	−0.00810%	805.5477617	805.521703	0.003%
	7 in w.c.		805.41906	−0.02246%	805.2713123	805.566808	−0.037%
46%/54%	60 psi	695.52	696.528223	0.14496%	696.7049385	696.351508	0.051%
	30 psi		697.269818	0.25158%	697.3876545	697.1519809	0.034%
	15 psi		697.933584	0.34702%	697.574454	698.2927142	−0.103%
	7 in w.c.		696.739028	0.17527%	696.5187997	696.9592559	−0.063%
50%/50%	60 psi	668	670.94224	0.44046%	671.0419379	670.8425419	0.030%
	30 psi		669.306335	0.19556%	669.2148027	669.3978666	−0.027%
	15 psi		668.753714	0.11283%	668.6412561	668.8661716	−0.034%
	7 in w.c.		668.791505	0.11849%	668.5742101	669.0088	−0.065%
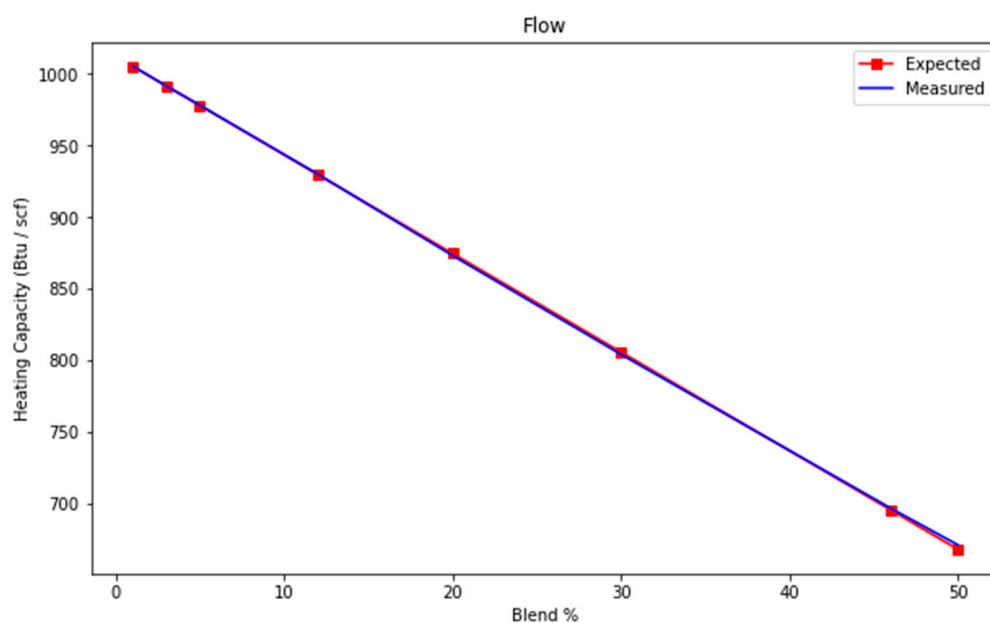
Figure 2. A Plot of Expected vs. Measured HHV during Flow Conditions.

3.3. Measured HHV—No Flow Conditions

Table 5 shows the measured results during no-flow conditions. The results show a near perfect correlation between measured and expected HHV or Btu content. Figure 3 presents the data from Table 4 in graphical form and shows the near perfect correlation between the expected and measured results. There was also virtually no difference in the results under no-flow conditions despite the gas having more time to separate. The blended gas had a nearly identical composition, further establishing that the gas was homogenous. The results displayed in Figure 3 are nearly identical to those in Figure 2.

Table 5. Expected vs. Measured HHV Under No-Flow Conditions.

| Test Blend	Nominal Pressure	Expected Btu	Average Btu Content	Δ% Btu Content (Ave/Exp)	Btu Content Top Average	Btu Content Bot Average	Δ% Btu Content (Top/Bot)
1%/99%	60 psi	1005.12	1005.202872	0.00824%	1005.200326	1005.205418	−0.001%
	30 psi		1005.221983	0.01015%	1005.210947	1005.233018	−0.002%
	15 psi		1005.225478	0.01049%	1005.304593	1005.146363	0.016%
	7 in w.c.		1005.212114	0.00916%	1005.223141	1005.201087	0.002%
3%/97%	60 psi	991.36	991.1932953	−0.01682%	991.2254621	991.1611285	0.006%
	30 psi		991.1336416	−0.02283%	991.1043352	991.1629481	−0.006%
	15 psi		991.2389718	−0.01221%	991.2527263	991.2252173	0.003%
	7 in w.c.		991.8773036	0.05218%	991.8903398	991.8642674	0.003%
5%/95%	60 psi	977.6	977.8195396	0.02246%	977.7825704	978.0061227	−0.023%
	30 psi		977.6069001	0.00071%	977.5607124	977.6530877	−0.009%
	15 psi		977.6394134	0.00403%	977.672286	977.6065408	0.007%
	7 in w.c.		977.5552962	−0.00457%	977.6779296	977.4326628	0.025%
12%/88%	60 psi	924.44	929.7331587	0.57258%	929.6615645	929.8047529	−0.015%
	30 psi		929.8903519	0.58958%	929.9769154	929.8037884	0.019%
	15 psi		928.3172582	0.41942%	928.3156259	928.3188905	0.000%
	7 in w.c.		929.0235059	0.49581%	929.6615645	928.3854473	0.137%
20%/80%	60 psi	874.4	873.1238521	−0.14595%	873.1951774	873.0525268	0.016%
	30 psi		874.0380987	−0.04139%	874.0736758	874.0025216	0.008%
	15 psi		874.3069428	−0.01064%	874.4204768	874.1934088	0.026%
	7 in w.c.		874.2145421	−0.02121%	874.433881	873.9952033	0.050%
30%/70%	60 psi	805.6	804.262761	−0.16599%	804.4403469	804.085175	0.044%
	30 psi		804.2156637	−0.17184%	804.4459661	803.9853613	0.057%
	15 psi		803.9415347	−0.20587%	804.3515304	803.531539	0.102%
	7 in w.c.		805.6070473	0.00087%	805.6069961	805.6070985	0.000%
46%/54%	60 psi	695.52	696.6521458	0.16278%	696.4728637	696.831428	−0.051%
	30 psi		697.2818304	0.25331%	697.4075021	697.1561587	0.036%
	15 psi		696.9337841	0.20327%	696.6784167	697.1891516	−0.073%
	7 in w.c.		696.1511517	0.09075%	696.1156773	696.1866262	−0.010%
50%/50%	60 psi	668	670.4622213	0.36860%	670.3412592	670.5831835	−0.036%
	30 psi		669.015767	0.15206%	669.0414735	668.9900605	0.008%
	15 psi		669.2615084	0.18885%	669.613746	668.9092708	0.105%
	7 in w.c.		668.7575991	0.11341%	668.7789813	668.7362169	0.006%
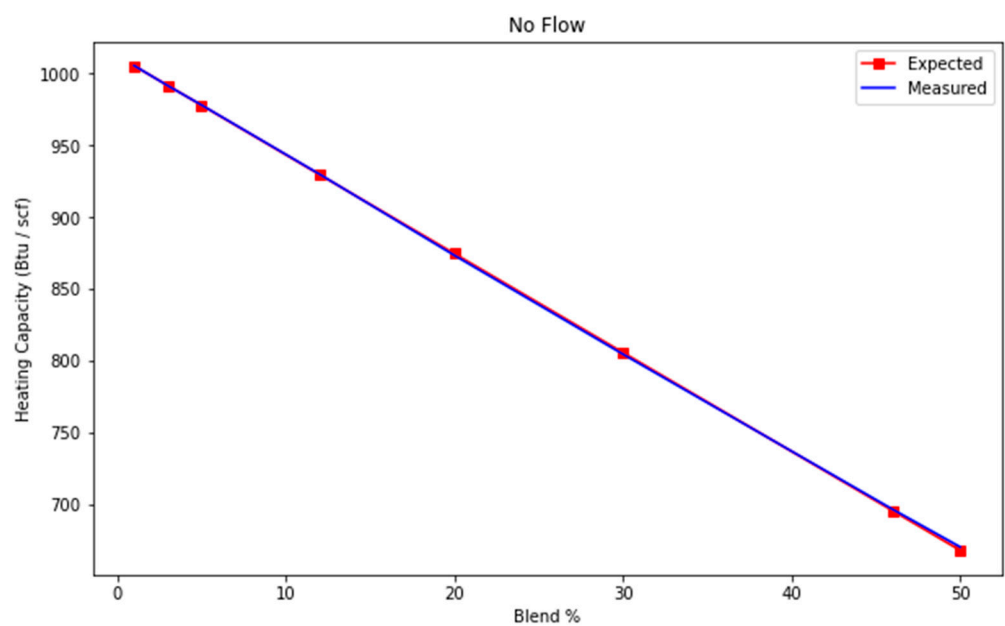
Figure 3. Expected vs. Measured HHV during No-Flow Condit.

3.4. Gas Sampling Data Analysis

While the data show a clearly homogenous mixture at all blends and pressures, one of the key goals of this experiment was to determine whether any stratification vertically would occur. In essence, would the less dense hydrogen molecules begin to separate vertically in the pipe from the methane in the blend? Considering data collected under flow and no-flow conditions, the results continued to show complete homogeneity. The largest difference between the top and the bottom measured gas composition was 0.278, which is equivalent to a difference of 0.0003%. Figure 4 is a graphical representation of the data in Tables 4 and 5 and shows the expected HHV for each blend rate, along with the measured values for all pressures, including all top and all bottom sampling data.

	1%/99%	3%/97%	5%/95%	12%/88%	20%/80%	30%/70%	46%/54%	50%/50%
Top	1,005.221	991.305	977.585	929.303	873.843	804.726	696.858	669.406
Expected	1,005.120	991.360	977.600	929.440	874.400	805.600	695.520	668.000
Bot	1,005.203	991.279	977.604	929.025	873.893	804.503	697.015	669.417
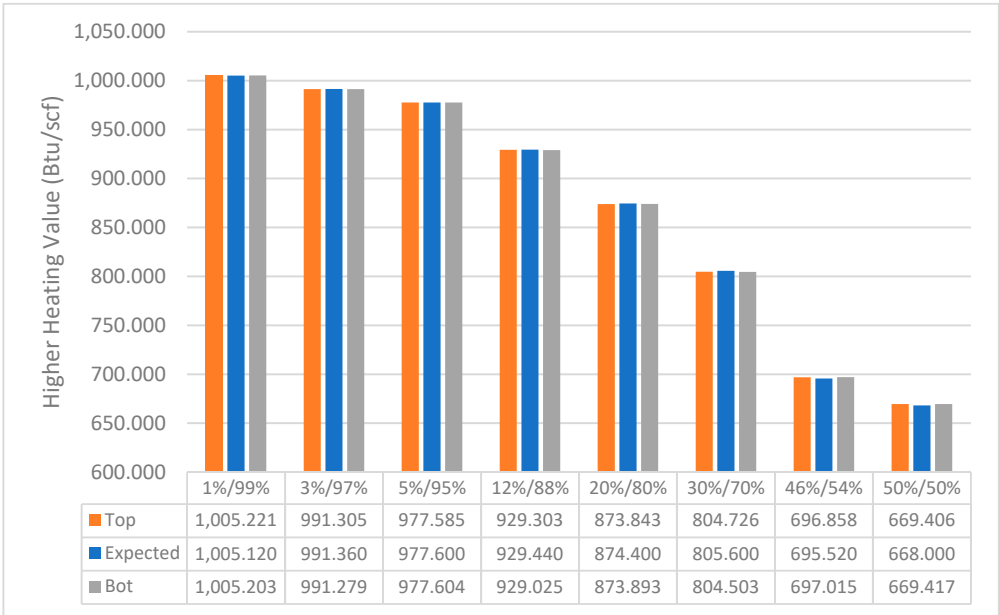
Figure 4. A Plot of HHV as a Function of Gas Blend Ratio for All Completed Runs at All Pressures.

To evaluate the potential for stratification across all typical gas distribution pressures, the data from Tables 4 and 5 include the average of all measured HHVs for the top and bottom ports for each pressure.

3.5. Odorant Evaluation

The terms odorant fade and odor making both refer to the loss of odor [30]. In theory this outcome could be caused by adverse reactions between the odorant and hydrogen due to the special properties of hydrogen, such as its strong reducing agent property. To evaluate the potential for odorant fade, all premixed canisters of blended gases contained an odorant that included sulfur compounds, Scentinel–E, a mercaptan mixture commonly used in commercial gas distribution operations. The odorant concentration was 10 ppm in the gas used for these experiments. Each series of tests was also reviewed for changes in the concentration of odorant, which the gas analyzers used to determine the following two attributes of odorant effectiveness for detection by humans:

(1) RDL—Readily Detectable Level—The concentration in air at which one recognizes an odor as a natural gas odor;
(2) TDL—Threshold Detectable Level—The concentration in air that is the first indication of a slight but recognizable change in odor.

In New York State, the RDL of gas delivered should at no time exceed 0.50% gas in air [26]. The odorant measurements in this experiment varied within a range apparently consistent for pressure and flow throughout the experiments. The samples with higher hydrogen blend rates tended to exhibit and maintain higher mass concentrations of odorant and lower RDL values, as shown in Figure 5. In all, a total of 84 samples were tested for odorant detectability from samples at all test conditions.
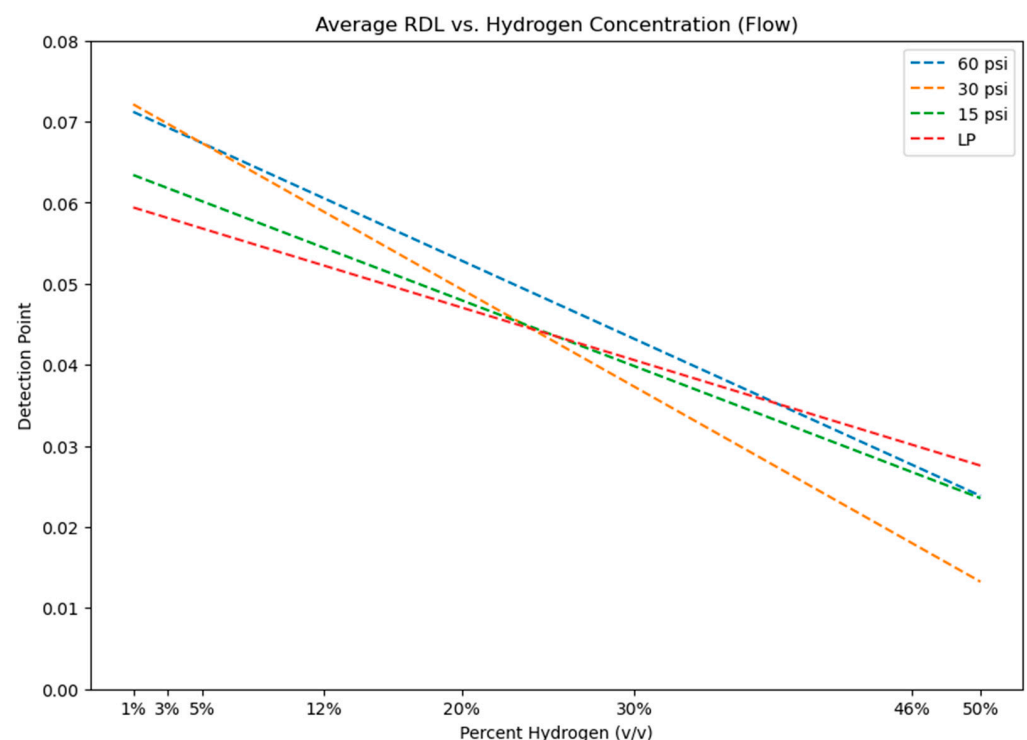

Figure 5. Effectiveness of Odorant as Measured from a Plot of Detection Points versus Hydrogen Percentage in Tested Blends.

The data indicated that that RDL values did not exceed 0.15% gas in air. As the hydrogen blended portion increased, on average, the measured RDL decreased, meaning the odorant was more effective at higher hydrogen concentrations. This trend was consistent for all test pressures. Furthermore, 40% of measured RDL values of blends were less than

0.05%, and the majority of those values detected at less than 0.05% were at hydrogen blend rates of 30% of higher.

4. Discussion

The results outlined in this study directly demonstrate that hydrogen blended natural gas mixtures remain homogenous in distribution piping regardless of the blend ratio or operating pressure in the range tested, (0–50% by volume). Samples collected from the top or bottom of the test pipe both showed near perfect correlation with the expected HHV of the mixture. Furthermore, when the experiment was repeated under no flow conditions, the measured HHV was nearly identical. The gas remained homogenous with no stratification of hydrogen and methane noted in the results. While there are no documented studies of hydrogen-natural gas blend stability in gas distributions systems found in the literature, the results of this experiment were also compared with similar studies of potential blended gas separation in general that included computational fluid dynamic (CFD) modeling of hydrogen blends:

The first project reviewed was the use of CFD modeling by the Institute of Gas Innovation and Technology at Stony Brook University using ANSYS software [31]. Their analysis was based on blended gas flowing at 30 °C (86 °F) and at a pressure of 60 bar (882 psia), far greater than the typical temperatures and pressures in operating gas distribution lines, thus resulting in significantly higher than anticipated pipeline velocities and pressure drops. The purpose of this study was to evaluate an upper bound for estimating compression costs [24]. The ANSYS study results describe hydrogen separation, regardless of the blend ratio and velocities, to a greater degree with higher pipe roughness, such as cast iron, and to a slightly lesser degree with smoother polyethylene pipe due to the cross-sectional velocity profiles predicted. This paper found that the hydrogen concentrations in the pipelines do have a direct relationship with the gas mixture velocity due to the presence of hydrogen in the mixture, which increases the compressibility factor, thus leading to a decrease in the gas density, resulting in an increase in the gas velocity The results reported in the present study utilized operating pressures and gas velocities that are typical of commercial pipes and far slower than in the analysis. The results of the studies are not inconsistent; rather, it is concluded that it may be advisable to limit gas velocities with hydrogen blends to limit velocity gradients and potential separation.

The second study results were reported from the Center for Hydrogen Safety (CHS) in 2022 [32]. This study also used CFD modeling software of gas transmission piping using ANSYS software in three cases: straight pipe, elbow, and tee with orifice at a pressure of 1000 psig. The CHS results indicated the absence of H_2 segregation if the wall temperature was equal to the gas temperature. Small variations were predicted where temperature differences exist between the blended gas and the pipeline wall. It was demonstrated that it was primarily thermal diffusion that caused segregation, and the gravity had negligible effects. Additionally, under the conditions studied, H_2 segregation has been identified for several key piping components, and thermal diffusion is the major driving factor: for up to 6% H_2 concentrations, spiking has been predicted, while 1–2% was typical. Larger H_2 concentration spiking is predicted in low-speed, high temperature recirculation zones near the wall if the pipe wall temperature is higher than that of the contained gas.

The results shown here for odorant detection are also consistent with the recent literature review conducted by the Gas Technology Institute [30]. Their study concluded, "No evidence was found for any masking tendencies in commonly used odorants like THT or TBM with hydrogen." While catalytic reactions of ethyl mercaptan with hydrogen on disulfides of molybdenum and tungsten yield hydrogen sulfide, neither catalyst has shown any activity at temperatures less than 572 °F [33], and these reactions are thus not evident in gas distribution piping. The present study supports the GTI findings. These results are also consistent with findings of the H4Heat project and Scottish Gas Networks [34], which used a sulfur-based odorant called "odorant NB," the most common in gas distribution today in the UK today, and which stated that "the conclusion is that for a 100% hydrogen

gas grid used for heating (similar to the current natural gas grid), the current Odorant NB would remain the suitable odorant."

5. Conclusions

The conclusions from these experiments are in two parts: (1) the homogeneity of hydrogen and methane mixtures; and (2) the lack of chemical reactions between hydrogen and the sulfur compounds used as odorants and the effectiveness of these odorants.

The results conclusively demonstrate that natural gas-hydrogen mixtures in gas distribution systems will show homogeneous behavior, i.e., the gases do not naturally separate under typical distribution pipeline conditions or temperatures, pressures, and gas flow rates or at times of no flow. This conclusion is consistent with the referenced analytical studies of mixtures of natural gas and hydrogen. This finding and this conclusion support the concept that hydrogen can be blended with low-pressure natural gas for delivery by natural gas distribution systems without concern regarding the potentially negative consequences of mixture separation.

The use of odorants is the first line of defense in identifying pipeline leakage in low-pressure gas systems, and the results shown here conclusively demonstrate that the commonly available sulfur compounds used as odorants today do not react with hydrogen blended gas, under either flowing or non-flowing operation. Specifically, the odorant provided in the blended gas, Scentinel–E, retained its chemical integrity, indicating the absence of any chemical reaction in the pipeline; thus, the odorant did not fade or experience odorant masking for hydrogen blends of up to 50% by volume. Furthermore, when odorant performance was measured using established performance indicators, such as RDL, the performance met the current standards for human detection, and no trend toward not meeting this standard was observed. Thus, it is concluded that, under the conditions tested, the odorant remains an effective method of leak detection for the hydrogen blends expected to be used both for service personnel and for the customer.

The overall conclusion from these evaluations is that the blending of hydrogen and natural gas in low-pressure gas distribution systems is feasible from the perspective of chemical stability with performance like that of the natural gas distributed today.

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