HYDROGEN TRANSPORTATION

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Contents

Summary

There are several methods for hydrogen transportation. This topic classifies the methods into (1) continuous transportation and (2) batch transportation. Hydrogen transportation by pipeline is one of the continuous transportation methods, and this continuous method involves transportation of gaseous or liquid hydrogen.

In the case of gaseous hydrogen transportation, in particular, transportation formula is described, where the quantity of gaseous hydrogen is compared with that of natural gas transportation.

Regarding the batch transportation of hydrogen, transportation methods are discussed for gaseous hydrogen, liquid hydrogen and such chemical compounds as metal hydride, methanol, and so on.

For ocean transportation, hydrogen is produced by renewable energy, and the use of

liquid hydrogen, ammonia, and methanol in this transportation method is described particularly in reference to the WE-NET Plan.

1. Introduction

There are many hydrogen transportation methods.

Hydrogen storage methods were mentioned under chapter *Hydrogen Storage*, and can be considered as combinations of hydrogen storage vessels with forms of hydrogen. The forms of hydrogen can be considered separately as the simple substance of hydrogen in gaseous form (at atmospheric pressure, pressurized) or liquid form, or in the form of hydrogen made into compounds or physically adsorbed onto various substances.

Ammonia, methanol, metal hydrides, activated carbon, and glass microspheres can be mentioned as typical examples of the latter form.

Storage vessels include individual storage tanks or cylinders, collective storage cylinders, vessels for the storage of chemical compounds and vessels for the storage of metal hydrides and activated carbon.

Hydrogen storage methods, other than those where hydrogen is kept in stationary storage tanks, can be used as hydrogen transport methods. In other words, hydrogen stored in any of the other types of vessels can be transported by mobile units such as motor vehicles, railway rolling stock, ships, airplanes, etc.

Regarding transportation continuity, transportation methods can be divided into the method of continuously transporting hydrogen using pipelines and the method of doing batch transport of pressurized hydrogen, liquid hydrogen or chemicals such as ammonia or metal hydrides, etc., stored in vessels that are loaded onto mobile units.

However, each method needs its own exclusive pressure-proofed or insulated vessels and equipment, making those methods expensive. Therefore, when a large quantity of hydrogen is to be consumed, it is generally produced, in amounts according to consumption, in the place where it is used; hydrogen transportation is limited to special purposes such as for relatively small-scale hydrogen sales or hydrogen for rocket fuel.

Therefore, the establishment of efficient, economical, and safe hydrogen transportation methods has become an important theme, and research and development are now focused on hydrogen transportation technologies (the majority of which serve for storage as well) using various hydrogen-adsorbing media such as metal hydrides.

Considering the transportation of hydrogen as an energy carrier, among these hydrogen transport methods, those that transport hydrogen in the form of compounds such as ammonia and methanol, etc., are not rational methods for transporting small quantities of hydrogen over short distances.

This is because in this type of method, once hydrogen has been formed, it is then changed to a compound-using energy, and is later extracted from the compound to be used in the place where the hydrogen is needed, again consuming (or losing) energy; this is not economical.

In consideration of these matters, this topic covers hydrogen transportation by pipeline (see *Pipeline Hydrogen Transportation*), batch transportation (see *Batch-system Hydrogen Transportation*) and (mainly) ocean transportation methods (see *Transportation of Hydrogen*, *Ammonia Energy Systems*, and *Alcohol Energy Systems*) which transport large quantities of hydrogen that is produced using renewable energy in consideration of the global environment over long distances.

2. Hydrogen Transportation by Pipeline

Two viable forms are considered for transporting hydrogen by pipeline. One is to pressurize gaseous hydrogen and the other is in the form of liquid hydrogen or slush hydrogen.

2.1 Pipeline Transportation of Gaseous Hydrogen

There are ample records of actual use of this method throughout the world. As previously mentioned, there are many cases in which a company manufactures hydrogen for its own use and sends it to adjacent plants where the hydrogen is consumed; pipelines are generally used in these cases, although the length of each pipeline is usually very short.

But pipelines with long extensions over quite wide areas do exist at a few locations, mainly in Europe and North America. Typical pipelines are introduced below.

One pipeline, with a total extension of about 550 km, is laid in northern France and Belgium, divided into a few lines including the line connecting Isbergues, Waziers, Zeebrugge and Terneuzen, the line connecting Maubeuge and Charleroi, and the line for the Dunkerque region, transporting hydrogen with a high purity of over 99.9% mainly at a pressure of 10 MPa through a pipeline with an inner diameter of 100 mm. Slightly less than 200×10^6 m^3 of hydrogen is said to be transported annually.

A new hydrogen transportation pipeline was recently completed in Belgium, running north-south (Antwerp–Feluy); the inner diameter of this pipeline is 150 mm, its operating pressure is 10 MPa, and its total extension is about 80 km. This new pipeline was constructed making full use of the latest technology; its material quality is API SPEC5L Grade X42, its outer cladding is polyethylene and the pipes are connected by welding.

Other than the previously mentioned pipelines, there is about 40 km of hydrogen-transporting pipeline in the Fos-sur-Mer area in southern France, and about 30 km of hydrogen-transporting pipeline in the area near Carling in eastern France.

Hydrogen with 95% purity at a pressure of about 5 MPa is transported using a pipeline with an extension of about 16 km in the area near Billingham in England.

In Germany, a hydrogen pipeline with an inner diameter of 100–300 mm and total extension of about 220 km, mainly in the Essen region, has connected Dusseldorf and Recklinghausen for over 60 years; this pipeline, with an operating pressure of around 2 MPa, transports industrial-use hydrogen mainly to chemical plants. The quantity of hydrogen it transports is said to reach 1×10^6 m^3 a year.

In the United States, there is a total extension of over 100 km of hydrogen pipelines in the state of Texas. Those pipelines are laid in Corpus Christi, Houston, and Bayport in the suburbs of Houston in the Gulf Coast industrial zone.

In addition, there are a few pipelines with extensions of several kilometers to several dozen kilometers in the state of Louisiana and Iowa in the United States and in the province of Alberta in Canada.

These hydrogen pipelines are laid in industrial zones; therefore many of them are jointly laid with other utility lines for oxygen and nitrogen, etc.

Figure 1 shows the hydrogen pipeline network in northern France/Belgium as an example; Figure 2 shows details of the Utility Distribution System including a hydrogen pipeline, in Bayport, in the United States.

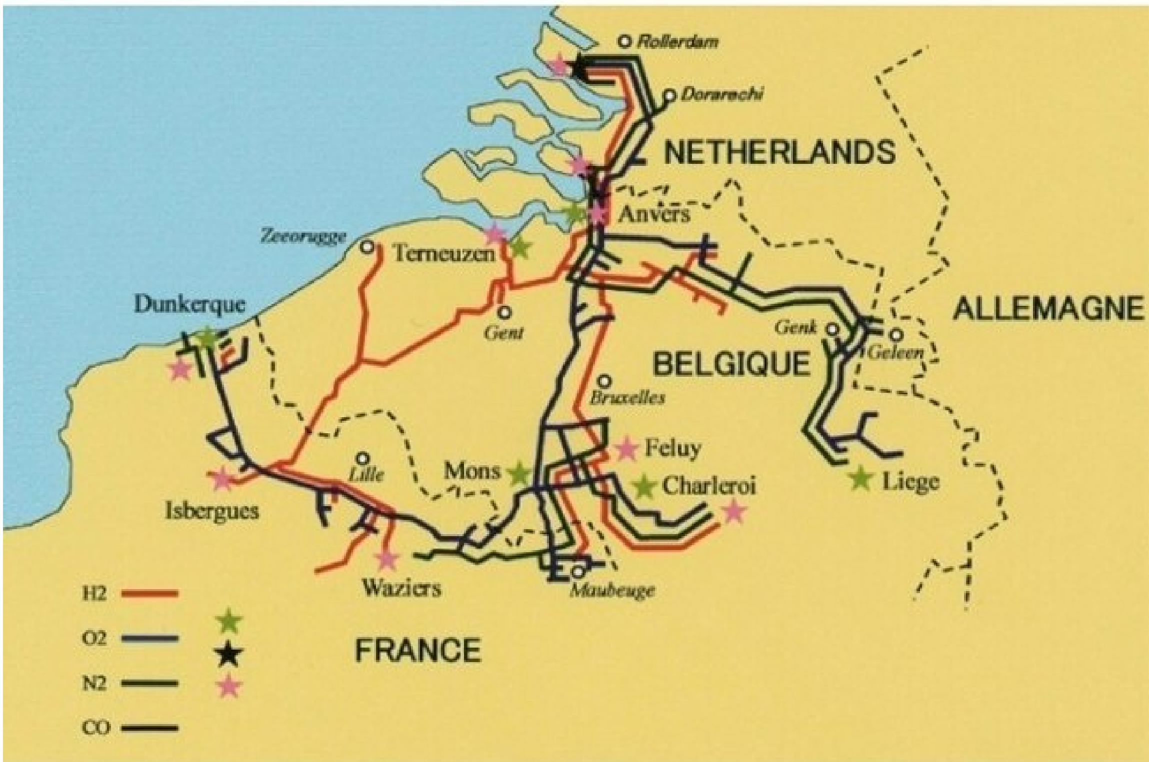

Figure 1. Hydrogen Pipeline Net Work in Northern France - Belgium

When handling hydrogen under pressure using iron and steel materials, the problem of hydrogen embrittlement occurs in some cases, but when pipelines are operated under the conditions of ordinary temperature and a pressure of several MPa, or when hydrogen purity is 99.5% or less, it is said that no serious problems occur even if low-carbon steel pipes are used.

Of course, it is desirable to control the sulfur content of steel material to a low level, to apply normalizing heat treat to the steel pipes, and use high-energy welding process of pipes to avoid hardening of welded sections and of the sections affected by heat during welding.

The previously mentioned hydrogen pipeline network centered around Essen has actually been operating since 1940 with no accidents.

2.2 Transportation Efficiency in Pipeline Transportation of Gaseous Hydrogen

Transportation efficiency of hydrogen pipelines is often compared with that of natural gas. Transportation efficiency is shown by the correlation between the pressure drop caused by transportation distance and the energy quantity (a quantity of heat) of the substance.

Many gas transportation formulas (flow rate formulas) have been proposed. The following formula, Eq. (1), is the one most generally used as the calculation formula for pipelines under stable conditions, where the gas temperature is fixed and is not accompanied by any differences in elevation; it is also used for natural gas transportation calculations:

$$\mathrm{Q} = \mathrm{K} \cdot (\mathrm{P}_1{}^2 - P_2{}^2)^{\frac{1}{2}} \cdot D^{\frac{5}{2}} \cdot S^{-\frac{1}{2}} \cdot L^{-\frac{1}{2}} \tag{1}$$

Transformation of the above formula gives the following formula, Eq. (2):

$$(\mathrm{P}_1{}^2 - P_2{}^2) = S \cdot L \cdot Q^2 \cdot K^{-2} \cdot D^{-5} \tag{2}$$

where:

Q: Gas flow rate (m^3h^{-1})
K: Flow rate coefficient (according to Eq. (3), below)
P_1: Initial pressure ($kg{\cdot}cm^{-2}$) (absolute)
P_2: Arrival pressure ($kg{\cdot}cm^{-2}$) (absolute)
D: Inner diameter of pipe (cm)
S: Specific gravity of gas (air under standard conditions is considered to be 1)
L: Pipeline length (m)

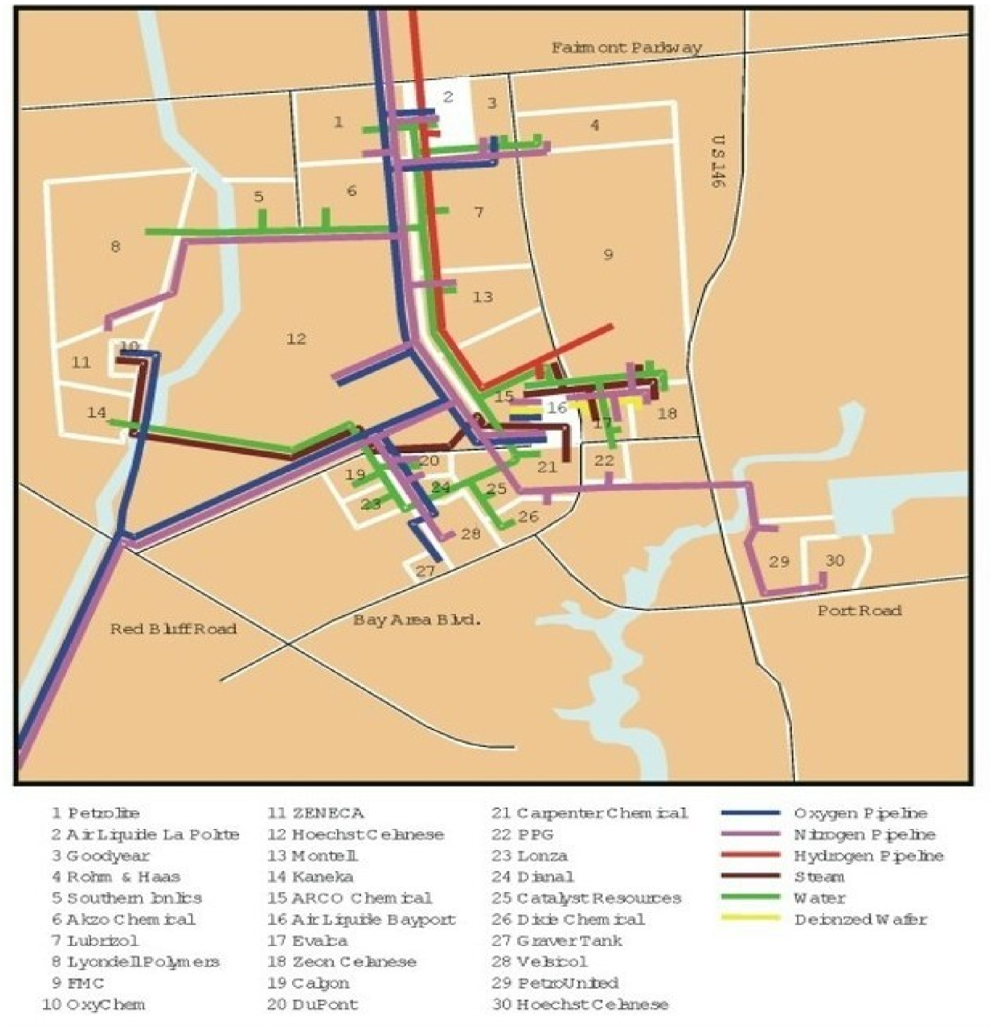

Figure 2. Hydrogen Pipeline with Utility Distribution System in the U.S. (an example)

The flow rate coefficient, K, is the constant determined by the compressibility factor (Z), gas temperature (T (K)), and friction coefficient (f) as shown in the following formula, (3):

$$K = 3.83 T_0^{\frac{1}{2}} \cdot (ZT)^{-\frac{1}{2}} \cdot f^{-\frac{1}{2}} \qquad (3)$$

where,

Z: Compressibility factor

T: Gas temperature (K)

T_0: Temperature under standard conditions (273.15 K)

f: Friction coefficient

$f^{-\frac{1}{2}}$: Transportation coefficient

The compressibility factor and transportation coefficient are obtained from empirical formulas, details of which are given in the Appendix I.

Comparing the transportation capacity for hydrogen with that for natural gas shows that, for instance, when transportation of large quantities of these is done at high pressure as shown in Table 1, calculated using the conditions of initial pressure of 70.0 kg cm^{-2} abs, arrival pressure of 20.0 kg cm^{-2} abs, pipeline inner diameter of 60 cm and pipeline length of 50 km, the energy transportation quantity of hydrogen is about 72% (about 2.60 times by volume) compared to that of natural gas (the 46.05 MJ m^{-3} type used for city gas).

When the quantity of hydrogen is relatively small at intermediate pressure, for instance, when the transportation quantity is calculated under the conditions of initial pressure of 9.0 kg cm^{-2} abs, arrival pressure of 5.0 kg cm^{-2} abs, pipeline inner diameter of 30 cm and pipeline length of 3 km, the transportation quantity of hydrogen in terms of energy is about 78% (about 2.81 times by volume) compared to that of natural gas, so at present the quantity of hydrogen energy transported is in a range of slightly below 80% of that of natural gas, a slight disadvantage for hydrogen.

Recently, the method of mixing hydrogen with a certain quantity of natural gas for transport has been studied by some researchers and companies.

Conversion of natural gas transportation and supply networks to the purpose of transportation and supply of hydrogen is expected to be a theme for future studies. In this case, however, caution is needed regarding the following two points.

First is that there is no problem with re-utilization of the pipeline, but the sealability of auxiliary equipment such as fittings, valves, pressure reducing equipment, and compressors, etc., needs to be improved.

The second point is that two items, the decline of economy resulted from the drop in energy transportation efficiency, and the degree of impact of accidents in urban areas, cannot be accurately determined yet.

Development of hydrogen-utilizing appliances with high combustion efficiency is needed as a measure to increase economy.

Case 1												
Transport quantity calculation table (inner diameter: 60 cm, length: 50 km)								Comparison of energies transported				
Item	Arrival pressure P_2	Initial pressure P_1	Average pressure	Inner diameter (cm)	Specific gravity S	Length L (m)			Flow rate	Heating value	Transported energy	Comparison
	$kg\cdot cm^{-2}$(abs)	$kg\cdot cm^{-2}$(abs)	$kg\cdot cm^{-2}$(abs)						$m^3 N\cdot h^{-1}$	MJm^{-3}	TJ	
Natural gas	20.0	70.0	49.6	60.0	0.661	50 000		Natural gas	939 200	46.05	43.25	1
Hydrogen	20.0	70.0	49.6	60.0	0.070	50 000		Hydrogen	2 446 600	12.78	31.27	0.72
Case 2												
Transport quantity calculation table (inner diameter: 30 cm, length: 3 km)								Comparison of energies transported				
Item	Arrival pressure P_2	Initial pressure P_1	Average pressure	Inner diameter (cm)	Specific gravity S	Length L (m)			Flow rate	Heating value	Transported energy	Comparison
	$kg\cdot cm^{-2}$(abs)	$kg\cdot cm^{-2}$(abs)	$kg\cdot cm^{-2}$(abs)						$m^3 N\cdot h^{-1}$	MJm^{-3}	TJ	
Natural gas	5.0	9.0	7.2	30	0.661	3000		Natural gas	71 000	46.05	3.27	1
Hydrogen	5.0	9.0	7.2	30	0.070	3000		Hydrogen	199 800	12.78	2.55	0.78

Common					
Natural gas specifications					
Components	Composition	Heating value	Critical pressure	Critical temperature	Specific gravity
	(%)	MJm^{-3}	$kg\cdot cm^{-2}$ (abs)	K	
CH_4	87.55	39.89	47.3	190.7	0.554
C_2H_6	5.27	69.53	49.8	305.5	1.038
C_3H_8	4.64	93.98	43.5	370.0	1.522
$n\text{-}C_4H_{10}$	2.54	121.74	38.7	425.2	2.006
Total	100.00	46.05	47.0	211.0	0.661

Table 1. Pipeline transport capacity.

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Biographical Sketch

Kunihiro Takahashi was born 28 January 1942 in Japan; graduated from Chemical System Engineering Department, Faculty of Engineering, the University of Tokyo; completed master course with major in engineering, the University of Tokyo; joined Tokyo Gas Co., Ltd.; presently general manager of the Center for Supply Control and Disaster Management, Tokyo Gas Co., Ltd. Previous positions: appointed as a member of General Research Laboratory of Tokyo Gas Co., Ltd. (1967–1977); appointed as general manager of Technical Development Department, general manager of Engineering Department, and general manager of System Energy Department of The Japan Gas Association (1994–1997); appointed as a member of Sub-task-1-committee of WE-NET committee of New Energy and Industrial Technology Development Organization (1994–1997); has held present position since June 1997; studied research themes: research on production processes and catalysts for hydrogen-rich gas and methane-rich gas.