Liquid Hydrogen Properties

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KAERI

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제 출 문

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본 보고서를 "냉중성자 감속기 개발 및 안전해석" 과제의 "Liquid hydrogen Properties" 기술보고서로 제출합니다.

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요 약 문

Ⅰ. 제목

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Ⅱ. 목적 및 필요성

열 수력 계산에서 수소물성에 관한 데이터를 이용하기 위하여, 작동유체인 수소의 정확한 열역학 및 열 전달 물성 치들을 많은 보고된 문헌들로부터 수집하여 체계화 할 필요성이 있었다.

Ⅲ. 내용 및 범위

기본적인 수소의 분자는 두 개의 형태를 가지며, 평행한 핵 스핀들을 갖는 형태를 Ortho-hydrogen이라 하며, 서로 다른 방향의 핵 스핀들을 갖는 형태를 Para-hydrogen이라 한다. 이들 두 형태의 혼합 비율은 그 혼합물의 온도에 의존한다. 그러나, 이 보고서에서는 주로 HANARO-CNS 장치의 작동온도 범위에서 Para-hydrogen과 equilibrium-hydrogen의 물성 치를 중점으로 다루었다. 논의된 수소의 물성 치들은 차례로 포화증기압, 액체수소의 밀도, 포화기체상의 수소 밀도, 증발잠열, 액상 및 기상의 열전도도, 점도, 액체 수소의 열용량, 그리고 포화 수소 기체의 열용량 등이다. 위의 물성 치들 중에서 수식화 되어 있지 않은 물성 데이터들은 열 수력 계산에서 쉽게 이용할 수 있게 하기 위해 수식으로 표현하였다.

Ⅳ. 결과

본 보고서에서는 액체 수소의 열역학 및 열 전달 물성 치들이 거론되었다. 문헌에 보고된 실험으로 얻어진 데이터를 정리하기 위한 여러 수식들은 모든 고려된 온도에서 높은 정확도로 액체 수소의 다양한 물성 치들을 계산 할 수 있게 되었다.

Ⅴ. 활용계획 및 건의 사항

체계화된 수식들과 수행된 계산의 결과는 액체수소를 작동유체로 사용하는 열 수력 계산을 위한 입력 데이터로 이용될 것이며, 추후에 액체수소를 작동유체로 하는 다른 계산에서도 사용 될 것이다.

SUMMARY

Ⅰ. Project Title

   Liquid Hydrogen Properties

Ⅱ. Objective and Importance

   In order to utilize the data for hydrogen properties in thermo-hydraulic calculation, it is necessary to collect and to systematize very precisely the thermodynamic and transport properties of the working substance, hydrogen.

Ⅲ. Scope and Contents

   Elemental molecular hydrogen exists in two basic forms; moreover, the form having parallel nuclear spins is called ortho-hydrogen and that with anti-parallel spins is called para-hydrogen.   The abundance ratio of two forms depends upon the temperature of the mixtures.   The considered data in this report, however, are particularly focused on the properties of para-hydrogen or of equilibrium-hydrogen around the working temperature range of the HANARO-CNS.   The discussed properties of hydrogen are, in turn, the pressure of saturated vapors, the density of liquid- and gas-phase hydrogen on the saturated line, the heat of vaporization, thermal conductivity in the liquid phase and in the gas phase, viscosity, and heat capacity of liquid hydrogen and of gas-phase hydrogen.   Those properties are presented and developed in the form of equation so that it is easy to be used in the thermo-hydraulic calculation.

Ⅳ. Results

   The thermodynamic and transport properties of liquid hydrogen are considered in this report. Several equations to fit the experimental data allow calculating the various properties of liquid hydrogen with high accuracy at all considered temperatures.

Ⅴ. Proposal for Applications

   The results of these calculations and these formulated equations can be used as an input data for the thermo-hydraulic calculation using liquid hydrogen. They will be applied to the future other calculation, in which liquid hydrogen will be a working substance, as well.

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1. Introduction

1) For thermo-hydraulic calculation using hydrogen, it is necessary to know very precisely the thermodynamic and transport properties of the working substance. In our case, it is liquid hydrogen.

2) The properties of hydrogen have been presented in many different publications. Therefore, it was decided to collect and to systematize the required data of hydrogen especially for liquid state in this report. Some data for hydrogen in the form of equation are absent from available publications and will be developed and presented in this report.

3) Elemental molecular hydrogen exists in two basic forms. The form having parallel nuclear spins is called ortho-hydrogen and that with anti-parallel spins is called para-hydrogen [1].   The properties of these two forms in any bulk quantity of hydrogen depend upon the temperature of the mixture as shown in Table 1-1 [2][3].   The high temperature mixture is 75% ortho-hydrogen and 25% para-hydrogen and is termed normal-hydrogen.   The equilibrium mixture at the boiling point temperature (20.4 K) of normal hydrogen is 99.79% para-hydrogen and 0.21% ortho-hydrogen and called simply para-hydrogen [4].

4) Consequently, the properties of liquid hydrogen in this report will be used in the upcoming experiment so that the data from this report are particularly focused on the properties of para-hydrogen or of the equilibrium ortho-para concentration of hydrogen around the working temperature range of the experiment.

Table 1-1. Ortho-Para composition of hydrogen at equilibrium

Temperature [K]	Percentage in para form in hydrogen [%]	Heat of conversion [cal/mol]
10	99.9999	338.648
20	99.8210	338.649
20.39	99.7890	338.648
30	97.0210	338.648
33.10	95.0340	338.648

2. The pressure of saturated vapors

1) The pressure of saturated vapors of hydrogen with various ortho-para concentrations has been almost fully studied through experiments. The studies comprised practically entire temperature range from the critical to the triple point (see table 3-2).

2) The pressure of saturated vapors of hydrogen with a normal ortho-para concentration and/or of hydrogen with equilibrium ortho-para concentration at the temperature of 20.4K was studied within the following temperature ranges: from 10 K to 23.57 K [5]; from 19.560 K to 24.445 K [5]; from 13.793K to the critical point [7]; from 13.947 K to 33.18 K [8].

3) The data for hydrogen with equilibrium ortho-para concentration at the temperature of 20.4K (99.789 % p-H_2) with a broad temperature range, from 13.793 K to 33.898K, is presented in the paper [7]. The table 2-1 and 2-2 represent experimental data from the above-listed works.

4) The data from various authors, on the pressure of saturated vapors of hydrogen isotopes, has been analyzed in the papers [9][10][11]. In addition, the following formula has been obtained for hydrogen with a normal ortho-para concentration at the temperature range from the triple point to critical point:

$$\ln P = 15.52059 - \frac{1.027498 \times 10^2}{T} + 5.338981 \times 10^{-2} T - 1.105632 \times 10^{-4} T^2 \quad (2\text{-}1)$$

where P is in Pa.

5) The parameters of Frost-Kalkwarf's equation for all hydrogen Isotopes were calculated on the basis of Van der Waals' constants in the paper [10]. These parameters describe experimental data with a high accuracy. The function of saturated vapor pressure for e-H_2 is at the temperature range from the triple point to critical point as follow:

$$\log P = 4.74952 - \frac{47.0410}{T} + 0.31609 \log T + 0.02054 \frac{P}{T^2} \qquad (2\text{-}2)$$

where P is in mmHg.

6) For the pure-component hydrogen from the triple point to 30K the parameters

of the Clausius-Clapeyron equation were calculated in the paper [11]. The function of saturated liquid-gas vapor pressures for e-H_2 is at the temperature range from the triple point to critical point as follow:

$$\ln P = 10.57411 - \frac{1.013378 \times 10^2}{T} + 5.432005 \times 10^{-2} T - 1.105632 \times 10^{-4} T^2 \text{ (2-3)}$$

where P is in mmHg.

Table 2-1. Saturated vapor pressure of hydrogen with a normal ortho-para concentration

T [K]	P[mmHg]	T [K]	P[mmHg]	T [K]	P[mmHg]
[5]		**[6]**		**[8]**	
13.957	54.0	21.323	986.6	21	909.0
14	55.4	22.047	1196.8	22	1207.6
15	95.0	22.803	1445.9	23	1533.7
16	153.3	23.412	1675.0	24	1938.8
17	235.2	23.941	1897.4	25	2415.3
18	345.9	24.445	2125.7	26	2968.6
19	490.8	**[8]**		27	3607.0
20	675.7	13.947	54.0	28	4335.8
21	906.4	14	55.5	29	5163.4
22	1189.0	15	95.0	30	6099.8
23	1529.6	16	153.5	31	7144.8
23.573	1753.3	17	235.6	32	8314.4
[6]		18	346.6	33	9614.0
19.560	587.8	19	492.5	33.18	9864.8
20.092	694.7	20	677.2		

Table 2-2. Saturated vapor pressure of hydrogen with the equilibrium ortho-para concentration at the temperature of 20.4K (99.789% of para-hydrogen).

T [K]	P[mmHg]	T [K]	P[mmHg]
[5]		**[7]**	
13.957	57.4	18.018	362.7
14	58.8	19.048	517.5
15	100.4	20	699.2
16	161.2	21.053	949.1
17	209.3	22.222	1295.5
18	246.2	23.256	1669.5
19	360.6	24.096	2025.0
20	700.3	25	2463.8
21	937.0	26.316	3216.5
22	1226.3	27.027	3683.7
23	1574.9	28.169	4530.0
23.573	1803.5	29.412	5598.6
[7]		30.303	6467.4
13.793	52.2	31.250	7490.5
14.184	65.2	32.258	8709.8
15.267	114.5	32.787	9415.0
16	161.1	33.333	10202.1
17.094	255.4		

7) The following equation [12] is introduced to evaluate the accuracy of the functions to calculate the saturated vapor pressure at each temperature in the comparison with experimental data of various authors. The functions of (2-1) for n-hydrogen and of (2-3) for e-hydrogen have the high accuracy as presented in table 2-3.

$$\varepsilon = \frac{\sqrt{\sum \left(\frac{P_{exp} - P_{calc}}{P_{exp}} \times 100 \right)^2}}{n}$$
(2-4)

Table 2-3. Calculation error using function (2-1) from [9], using function (2-2) from [10], and using function (2-3) from [11] in comparison with experimental data of various authors

Material	Temperature range [K]	Data source	Number of experimental points	Used equation	ε [%]
n- H_2	13.957-23.573	[5]	12	(2-1)	0.050
	19.56-24.445	[6]	8		0.116
	13.947-33.18	[8]	22		0.186
e- H_2	13.957-23.573	[5]	12	(2-2)	5.316
				(2-3)	**0.086**
	13.793-33.333	[7]	22	(2-2)	5.361
				(2-3)	**0.046**

3. Density

1) Experimental data of liquid hydrogen density for the temperature range from the triple point to 20 K are shown in the paper [5].   The paper [8] presents the data for the range from the triple point to the critical point.   The table 3-1 represents experimental data from the above papers.
2) The Data from [8] agree with the results from [5] with the high accuracy up to 0.033 % for normal-hydrogen and up to 0.047% for para-hydrogen.

Table 3-1. The experimental data of liquid hydrogen density from [5] and [8]

T [K]	P_s [mmHg]		Density [kg/m^3]			
			[5]		[8]	
	n- H_2	p- H_2	n- H_2	p- H_2	n- H_2	p- H_2
13.803		52.82		76.40		76.42
13.947	54.04		76.60		76.60	
14	55.63	59.13	76.57	76.11	76.56	76.25
15	95.53	101.08	75.74	75.42	75.72	75.39
16	154.05	161.88	74.85	74.53	74.84	74.52
17	236.06	247.00	73.91	73.59	73.90	73.58
18	347.17	361.76	72.92	72.60	72.94	72.62
19	492.48	511.48	71.90	71.57	71.90	71.61
20	677.16	701.48	70.84	70.50	70.80	70.52
20.268		760.00				70.22
20.380	760.00		70.42		70.38	
21	908.86	937.08			69.66	69.40
22	1192.44	1225.88	68.42		68.42	68.17
23	1533.68	1572.44			67.10	66.89
24	1938.76	1984.36	65.68		65.70	65.49
25	2415.28	2466.20			64.18	63.98
26	2968.56	3026.32	62.51		62.54	62.34
27	3606.96	3670.04			60.72	60.53
28	4335.80	4403.44	58.72		58.70	58.50
29	2883.44	5234.12			56.42	56.20

T [K]	P_s [mmHg]		Density [kg/m^3]			
			[5]		[8]	
	n- H$_2$	p- H$_2$	n- H$_2$	p- H$_2$	n- H$_2$	p- H$_2$
30	6097.48	6169.68	53.85		53.78	53.50
31	7144.76	7220.76			50.56	50.19
32	8314.40	8398.76	43.28		46.24	45.63
32.976		9696.84				31.43
33.18	9864.8		29.87		29.88	

3.1 Dependence of liquid hydrogen density on temperature

1) For the dependence of liquid hydrogen density on temperature, the reduced form is introduced in this report. The reduced density Ψ was calculated from $\Psi = \rho/\rho_{cr}$. The values of the critical density and other properties are shown in Table 3-2 [2]. In order to simplify the calculation of the dependence of Ψ on the reduced temperature τ, the value of $(1-\tau)$ was used as a parameter of the function.

2) The analysis of the dependence of Ψ, as a function of $(1-\tau)$ showed that it could be approximated with a high accuracy by the following equation:

$$\Psi = a + b(1-\tau)^z \tag{3-1}$$

   where $0 < Z < 1$, $a = 1$.

3) The error resulted from the assumption, "a" is not equal to 1, is shielded due to the accuracy of the critical density selected for the calculations, and the reliability of the considered data [12]. The error of this data automatically moves to the error of the coefficient "b" to compensate the error.

4) The dependence of the reduced density of a liquid on the reduced temperature for para-hydrogen is described by the following equation:

$$\Psi = 1 + 1.7707(1-\tau)^{0.3817} \tag{3-2}$$

5) The average error of deviation, ε, of calculated values of liquid para-hydrogen density from the experimental ones accounts for –0.20%. The graph of these deviations is shown in figure 3-1.

$$\varepsilon = \left(\frac{\Psi_{exp} - \Psi_{calc}}{\Psi_{exp}} \right) \times 100 \qquad (3\text{-}3)$$

Table 3-2. Properties of hydrogen at fixed points

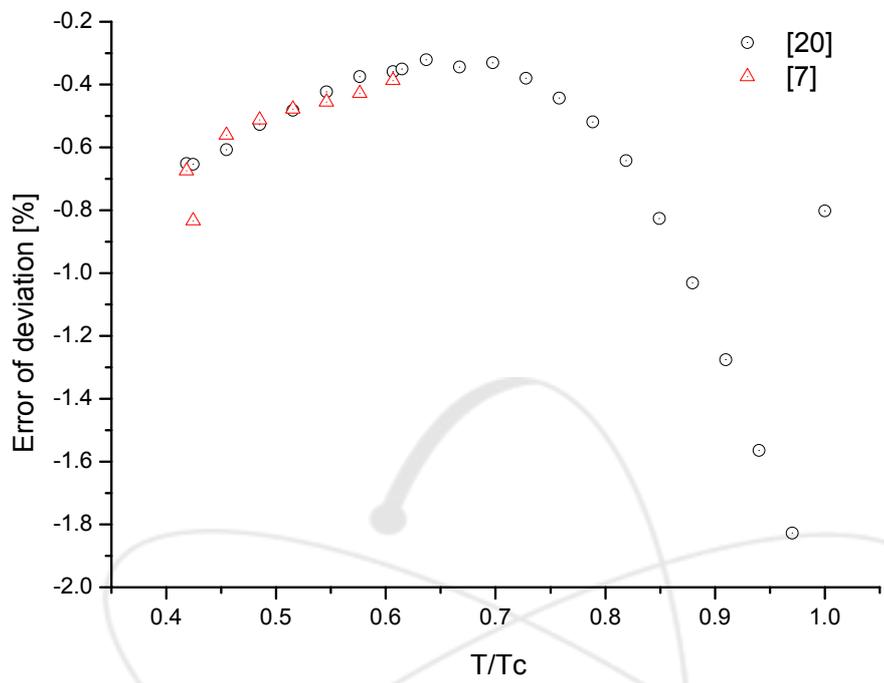|	p- H_2 or e- H_2	n- H_2
Critical Point	T= 32.976 K P= 9696.84 mmHg ρ= 31.43 kg/ m^3	T= 33.19 K P= 9864.8 mmHg ρ= 30.12 kg/ m^3
Normal Boiling Point	T= 20.268 K P= 760 mmHg ρ_{liq} = 70.78 kg/ m^3 ρ_{vap} = 1.338 kg/ m^3	T= 20.39 K P= 760 mmHg ρ_{liq} = 71.0 kg/ m^3 ρ_{vap} = 1.331 kg/ m^3
Triple Point	T= 13.803 K P= 52.82 mmHg ρ_{solid} = 42.91 kg/ m^3 ρ_{liq} = 38.21 kg/ m^3 ρ_{vap} = 0.0623 kg/ m^3	T= 13.957 K P= 54.036 mmHg ρ_{solid} = 86.71 kg/ m^3 ρ_{liq} = 38.3 kg/ m^3 ρ_{vap} = 0.0644 kg/ m^3

Figure 3-1. Deviation of the calculated values of liquid of para-hydrogen density from the experimental data

4. The density of gas-phase hydrogen on the saturated line

1. Table 4-1 shows experimental data of para- and normal-hydrogen density of the saturated gas-phase on the equilibrium gas-liquid line for the temperature range from the triple point to the critical point.

2. For the dependence of hydrogen vapor density on the saturated line on the temperature, the reduced forms of temperature and of density are introduced in this report.

3. Pursuant to the comment of [12], the analysis on data for He, p-H_2, n-H_2, T_2, Ne, and N_2 in the reduced thermodynamic coordinates Ψ and τ showed that the reduced density of gas phase on the saturated line changed with hyperbolic dependence.

Table 4-1. Experimental data of hydrogen density on the saturated gas-phase from [8]

T [K]	Density [kg/ m^3]		T [K]	Density [kg/ m^3]	
	n- H_2	p- H_2		n- H_2	p- H_2
13.803		0.12	23	2.514	2.59
13.947	0.126		24	3.178	3.23
14	0.128	0.14	25	4.754	3.99
15	0.208	0.22	26	5.800	4.88
16	0.318	0.36	27	7.054	5.95
17	0.464	0.49	28	8.580	7.24
18	0.654	0.68	29	10.482	8.82
19	0.894	0.93	30	12.964	10.80
20	1.190	1.24	31		13.43
20.268		1.33	32		17.36
20.380	1.320		32.976		31.18
21	1.552	1.60	33.18	29.88	
22	1.990	2.05			

Based on that, the equation of the reduced density for saturated gas-phase para-hydrogen can be formulated as the following form:

$$\Psi = -0.01397 + 0.63032 \exp\left(\frac{-(1-\tau)}{0.16013}\right) + 0.37572 \exp\left(\frac{-(1-\tau)}{0.01365}\right) \qquad (4\text{-}1)$$

4. The values of saturated vapor density calculated from the equation (4-1) within the temperature range from the triple point and the critical point are in a good agreement with the experimental data from [8] within the limits of 1-2%.
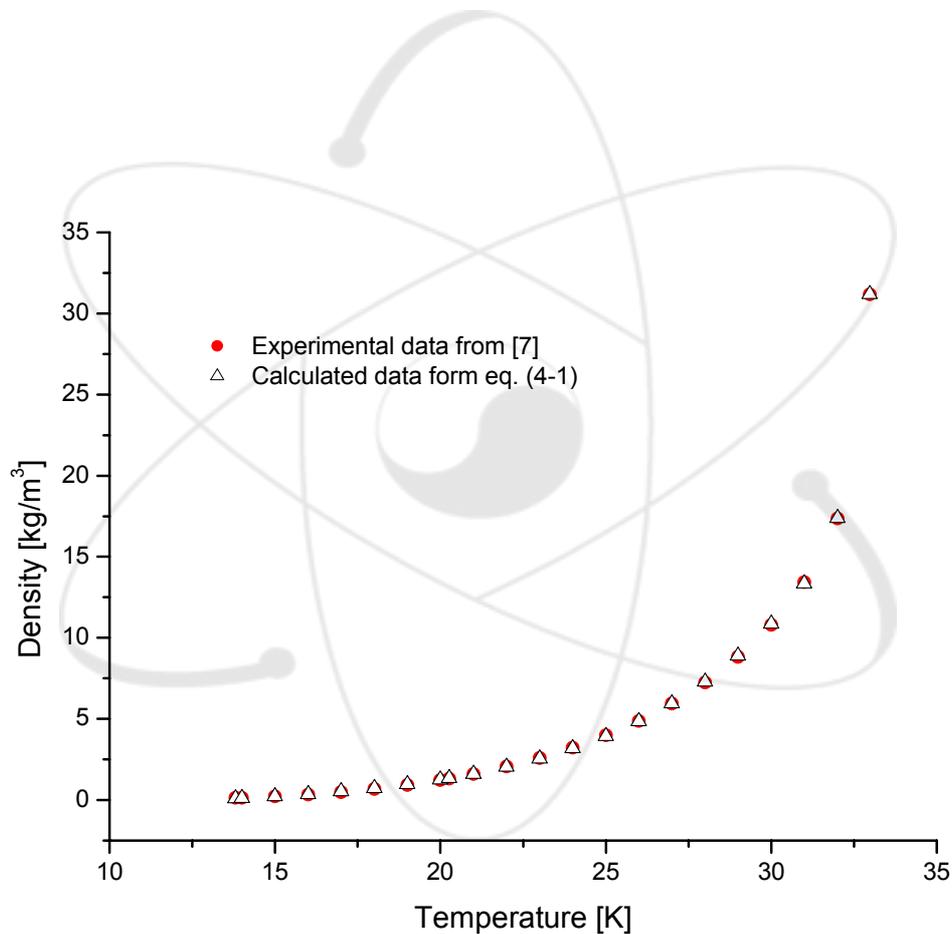

Figure 4-1. The comparison between the experimental data of para-hydrogen vapor density and the calculated ones form the equation (4-1)

5. The heat of vaporization

1) The heat of vaporization is a function of temperature. If sufficiently precise values of the specific volume of the saturated liquid and saturated vapor and the derivative of the vapor pressure are available, the heat of hydrogen vaporization, H, is calculated from the Clausius-Claypeyron equation:

$$H = T(V_g - V_l)\frac{dP_s}{dT} \tag{5-1}$$

where V_g and V_l are specific volumes of vapor and liquid.

2) Using the equation, the heat of hydrogen vaporization is calculated from the parameter value, dP_s/dT, given in the paper [8] and from the above-mentioned data in the chapter 3 and 4. Table 5-1 shows the heat of hydrogen vaporization calculated, which are recommended to be used, with the experimental data [2].

Table 5-1. The heat of hydrogen vaporization

[2]		[8]		
T [K]	H [J/g]	T [K]	H [J/g]	
	n- H_2		n- H_2	p- H_2
14		14	460.03	454.17
15.0	454.38	15	461.70	456.68
16		16	462.54	457.10
17.8	446.43	17	461.50	456.89
18		18	459.40	455.85
19.7	443.50	19	456.06	453.55
20.5	441.41	20	451.24	450.20
21		21	444.97	444.55
22.0	432.21	22	437.02	438.27
23	426.77	23	427.19	430.12
24.75	410.03	24	415.26	420.07
25		25	400.62	407.94
26.2	394.55	26	383.05	392.88

T [K]	H [J/g]	T [K]	H [J/g]	
	n- H_2		n- H_2	p- H_2
27.3	372.38	27	361.05	374.89
28.3	351.46	28	361.92	352.92
29		29	335.98	325.93
30.0	297.90	30	303.76	293.09
31.3	238.91	31	262.34	250.62
32.6	138.07	32		189.95
33.19	0.00			
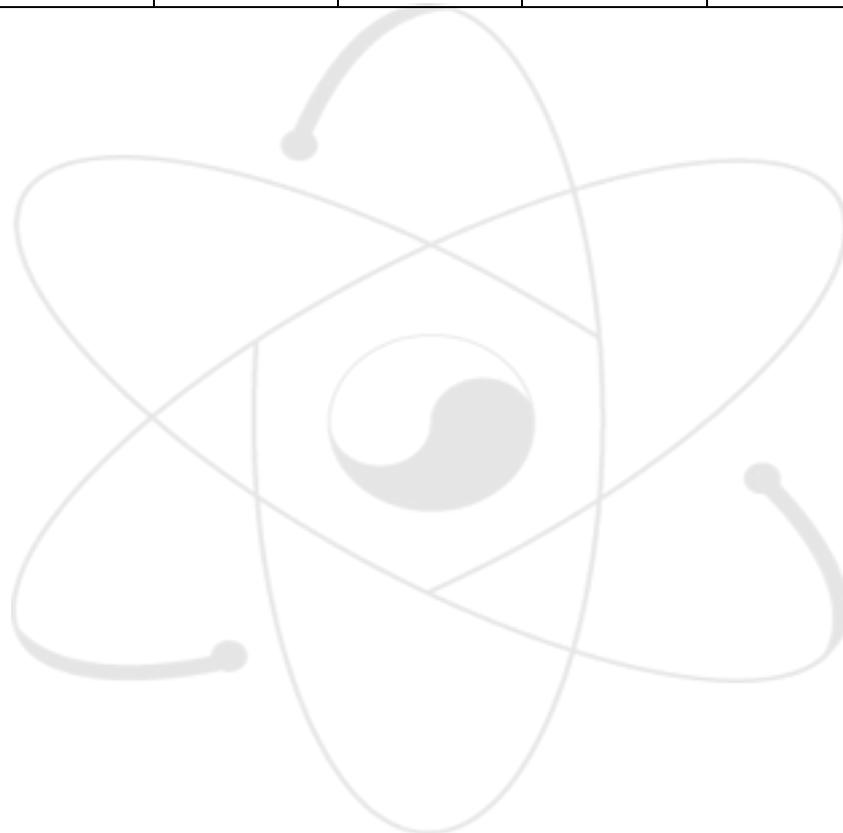
6. Thermal conductivity

1) The experimental data on the thermal conductivity of hydrogen for the temperature range from 13.835 K to 3000 K at 0.101315 isobar and at 0.15 isobar are shown in the handbook based on the thermodynamic data of NASA [13].

2) Persuant to the study of Roder, H. M. [14], the thermal conductivity of compressed liquid hydrogen increases with both density and temperature and is independent on the ortho-para composition of liquid hydrogen. The experimental data of the thermal conductivity for saturated liquid para-hydrogen are shown in Table 6-1. The thermal conductivity of the saturated liquid increases with temperature at temperatures below about 24 K according to Table 6-1. This similar behavior is also reported in [8].

3) The paper [15] shows the experimental results of the thermal conductivity of para- or normal-hydrogen for the temperature range from 16 K to 25 K, which are in Table 6-3, and accounts for the nature of the thermal conductivity that the ortho-para composition of hydrogen does not affect. However, in comparison with [14] and [8], the data from [15] tend to be overestimated by almost 15% due to the experiment conduction technique.

4) On the basis of the experimental data from [14], the polynomial equation of the thermal conductivity for saturated liquid hydrogen is formulated with the high accuracy up to 98.6 % in comparison with the experimental data:

$$K = 4.22843 - 0.6662T + 0.04676T^2 - 0.00135T^3 + 0.000013673T^4 \qquad (6\text{-}1)$$

where K is in mW/cm-K. This equation is recommended to be used when the thermo-hydraulic calculation is conducted at the temperature range from 25 K to 30 K.

5) The following equation of the thermal conductivity for liquid hydrogen is created at the temperature range from 14 K to 27 K using the data from Table 6-2 within the limits of 1.517% in order to avoid larger error:

$$K = -7.27782 + 1.44637T - 0.09698T^2 + 0.00295T^3 - 0.0000342666T^4 \qquad (6\text{-}2)$$

where K is in mW/cm-K.

Table 6-1. The thermal conductivity of saturated liquid para-hydrogen from [14]

T [K]	K [mW/cm-K]	T [K]	K [mW/cm-K]
17.0	0.911	25.0	0.997
19.5	0.962	30.0	0.867
22.0	0.999		

Table 6-2. The thermal conductivity of liquid hydrogen from [8]

T [K]	K [mW/cm-K]	T [K]	K [mW/cm-K]
14.0	0.745	24.0	1.010
15.0	0.826	25.0	0.998
16.0	0.881	26.0	0.983
17.0	0.924	27.0	0.962
18.0	0.952	28.0	0.934
19.0	0.971	29.0	0.901
20.0	0.984	30.0	0.867
21.0	0.998	31.0	0.850
22.0	1.007	32.0	0.928
23.0	1.011		

Table 6-3. The thermal conductivity of saturated liquid hydrogen from [15] (unit of T: K, unit of K: mW/cm-K)

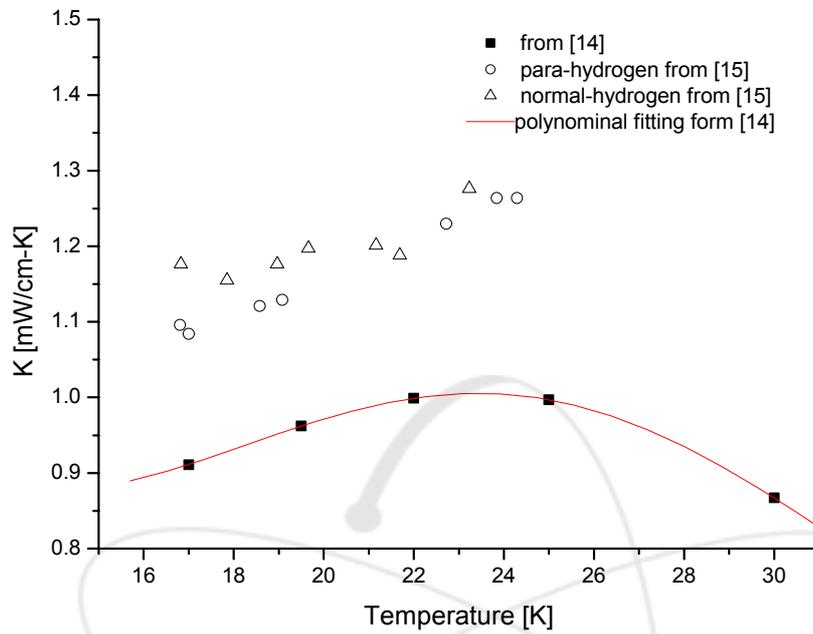| n- H_2				p- H_2			
Experiment 1		Experiment 2		Experiment 3		Experiment 4	
T	K	T	K	T	K	T	K
16.81	1.096	17.00	1.084	16.83	1.176	17.85	1.155
19.08	1.129	18.58	1.121	18.97	1.176	19.66	1.197
23.84	1.264	22.72	1.230	21.16	1.201	21.69	1.188
24.29	1.264					23.23	1.276

Figure 6-1. Thermal conductivity of saturated liquid hydrogen vs. temperature from [14] and from [15]
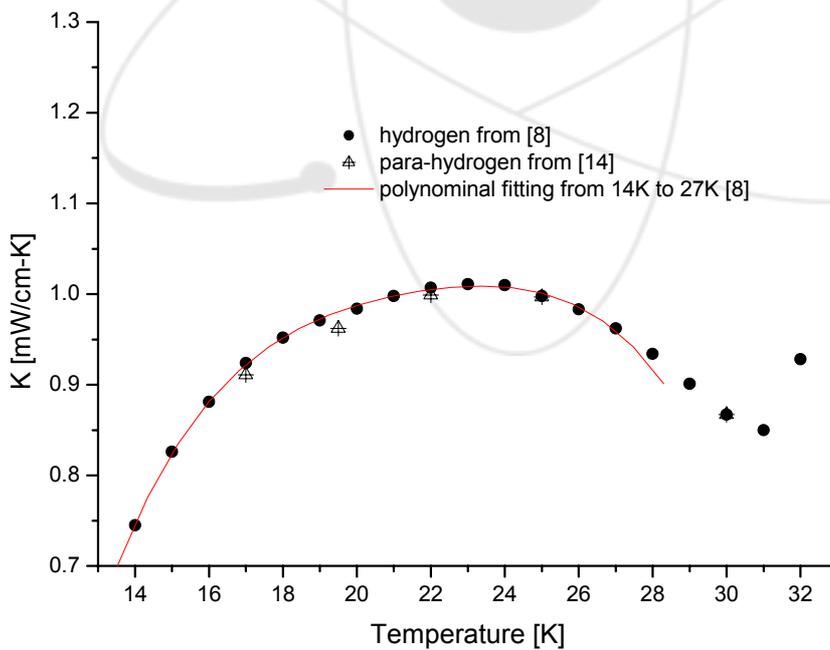

Figure 6-2. Thermal conductivity of liquid hydrogen at temperatures from 14 K to 27 K [8]

7. Thermal Conductivity for gas phase on the saturated line

1) According to the experimental data from the paper [8], the thermal conductivity for gas-phase hydrogen at saturation depends primarily on temperature and on density or pressure.

2) The dependence of thermal conductivity on ortho-para composition is less than 0.5%. In addition, Rodger, H. M. [14] stated that the thermal conductivities of vapor normal- and para-hydrogen are indistinguishable at temperatures below 40 K.

3) Table 7-1 presents the thermal conductivities at the range from 14 K to 30 K [8]. On the basis of these data, the fitting equation of thermal conductivity for the gas-phase hydrogen on the saturation line is followed within the error limit of 0.653%:

$$K = 0.88758 - 0.16616T + 0.01302T^2 - 0.000439767T^3 + 0.00000571565T^4 \quad (7\text{-}1)$$

where K is in mW/cm-K.

Table 7-1. Thermal conductivity of vapor hydrogen at saturation [8]

T [K]	K [mW/cm-K]	T [K]	K [mW/cm-K]
14.0	0.125	23.0	0.202
15.0	0.131	24.0	0.215
16.0	0.134	25.0	0.232
17.0	0.143	26.0	0.250
18.0	0.15	27.0	0.276
19.0	0.158	28.0	0.300
20.0	0.167	29.0	0.332
21.0	0.18	30.0	0.377
22.0	0.188		

8. Viscosity

1. Viscosity defines the force of friction between the layers of gas and liquid. According to the Newton's law:

$$\tau = \eta \frac{dv}{dx}$$

(8-1) where τ is measured in N/m^2,

   dv is the difference in velocities of layers,

dx is the distance between layers,

and η, which is in Pa·S, is the constant of proportionality, also called as dynamical viscosity. Kinetic viscosity, v, is related to η by the formula of $\mu = \eta / \rho$ and measured in m^2/s.

2. The viscosity of gaseous hydrogen and other isotopes of hydrogen mixed with helium were experimented in the paper [16]. The experiments were conducted within a broad temperature range from 14 K to 293 K and a range of low pressure around 0.1 MPa. According to Rietveld, A. O. [16], the viscosity of gas weakly depends on the pressures within the range of the experimental temperatures; therefore, the data can be used for design calculations at the pressure up to 5 MPa.

3. The data on the viscosity of hydrogen in the state of saturated liquid, which are shown in Table 8-1 for normal-hydrogen and Table 8-2 for para-hydrogen, are presented in the paper [8]. Tables of saturated liquid para-hydrogen seems to be up to 5% higher than that of normal-hydrogen at the temperatures; however, there is virtually no difference in viscosity if the comparison is made at the same densities.

4. The following equation of viscosity for saturated liquid para-hydrogen is formulated from the data [8]:

$$\eta = 105.7912 - 9.70893T + 0.33732T^2 - 0.00413T^3 \qquad (8\text{-}2)$$

where η is in Pa·s. It can be used for the temperature range from 14 K to 32 K. The root mean square deviation between the data from Table 8-2 and the equation (8-2) is 1.27 %.

Table 8-1. Viscosity of saturated liquid normal-hydrogen [8]

T [K]	$\eta \times 10^6$ [Pa·s]	T [K]	$\eta \times 10^6$ [Pa·s]
14.0	25.43	21.0	12.84
15.0	23.02	22.0	11.87
16.0	20.39	23.0	11.05
17.0	18.29	24.0	10.26
18.0	16.56	25.0	9.57
19.0	15.15	26.0	8.90
20.0	13.92		

Table 8-2. Viscosity of saturated liquid para-hydrogen [8]

T [K]	$\eta \times 10^6$ [Pa·s]	T [K]	$\eta \times 10^6$ [Pa·s]	T [K]	$\eta \times 10^6$ [Pa·s]
14.0	25.07	20.0	13.54	28.0	7.52
14.5	23.41	20.5	13.06	28.5	7.24
15.0	22.13	21.0	12.53	29.0	6.96
15.5	20.07	21.5	12.06	29.5	6.70
16.0	19.75	22.0	11.61	30.0	6.49
16.5	18.56	23.0	10.81	30.5	6.12
17.0	17.77	24.0	10.08	31.0	5.81
17.5	16.85	25.0	9.35	31.5	5.57
18.0	16.05	26.0	8.72	32.0	5.19
18.5	15.38	26.5	8.41	32.5	4.75
19.0	14.70	27.0	8.10	32.7	4.39
19.5	14.13	27.5	7.81		

9. Heat capacity of liquid hydrogen

1. The data on the heat capacity, C_s, of liquid hydrogen with a normal ortho-para concentration on the line of saturation are presented in the paper [5]; moreover, the data on the heat capacity, C_p and C_v, of liquid hydrogen at the constant pressure and at the constant volume are shown in the paper [8]. Table 9-1 represents the data from [5] on the heat capacity of liquid n-hydrogen at saturation, C_s, and the data from [8] on the heat capacities of liquid p-hydrogen at the constant pressure, C_p, and at the constant density, C_v.

2. Hydrogen having ortho-para molecular forms possesses a large dependence of specific heat on composition in the state of solid, but not in the state of liquid [8], that is, the difference in the specific heats for different ortho-para compositions in the liquid state are very small, so the effect of the concentration can be negligible.

3. The heat capacity C_s can be described within the error limit of 0.24% by following equation:

$$C_s = 14.43877 - 1.691T + 0.10687T^2 - 0.00174T^3 \qquad (9\text{-}1)$$

   where C_s is in J/g·K.

4. The values of heat capacities C_s and C_p along the saturated line are very close to each other as represented in Figure 9-1.

Table 9-1. The heat capacities of C_s, C_p, and C_v of liquid hydrogen from the experimental data of [5] and [8]

Temperature	Heat Capacity [J/g·K]		
[K]	C_s [5]	C_p [8]	C_v [8]
13.803		6.57	4.75
14	6.92	6.66	4.78
15	7.24	7.04	7.95
16	7.59	7.46	5.13
17	8.01	7.96	5.31
18	8.45	8.49	5.47
19	8.93	9.03	5.62

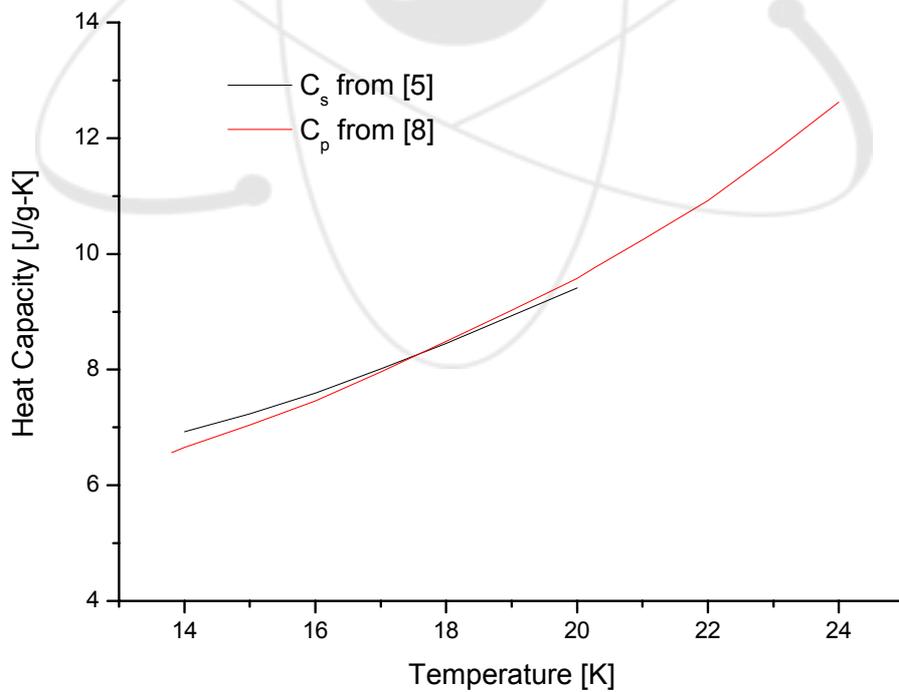| Temperature	Heat Capacity [J/g·K]		
[K]	C_s [5]	C_p [8]	C_v [8]
20	9.41	9.58	5.76
20.268		9.77	5.79
21		10.25	5.87
22		10.92	5.97
23		11.76	6.06
24		12.63	6.13
25		16.68	6.19
26		14.90	6.25
27		16.47	6.31
28		18.70	6.37
29		21.82	6.45
30		27.10	6.54
31		37.41	6.67
32		67.33	6.90
32.976			9.94

Figure 9-1. The heat capacities C_p and C_s at the saturated line

10. Heat capacity of gas-phase hydrogen on the saturated line

1. The experimental values for the heat capacities of hydrogen in the gas state are shown in Table 10-1.   Differences in specific heats between para-hydrogen and other ortho-para compositions exist for the gas states; however, they are not noticeable that is less than 1% at temperatures below 40K.
2. Data from Table 10-1 can be fitted by the next equation:

$$C_p = 10.90773 + 0.00217 \exp\left(\frac{T}{3.27514}\right) \qquad (10\text{-}1)$$

where C_p is in J/g·K. It can be used for the temperature range from 14 K to 30 K within 2.5% deviation between the experimental data and equation (10-1). In common, for the vapor hydrogen the values of heat capacity at saturation, C_s, are taken to be the same as C_p; on the other hand, the values of C_v are lower than C_s at all temperatures above 5K [8].

Table 10-1. Heat capacities of C_p and C_v of para-hydrogen in the gas state [8]

Temperature	Heat Capacity [J/g·K]	
[K]	C_p [7]	C_v [7]
13.803	10.60	6.26
14	10.62	6.26
15	10.76	6.29
16	10.94	6.33
17	11.16	6.37
18	11.43	6.42
19	11.76	6.48
20	12.14	6.54
20.268	12.25	6.56
21	12.59	6.60
22	13.14	6.67
23	13.80	6.73
24	14.61	6.80

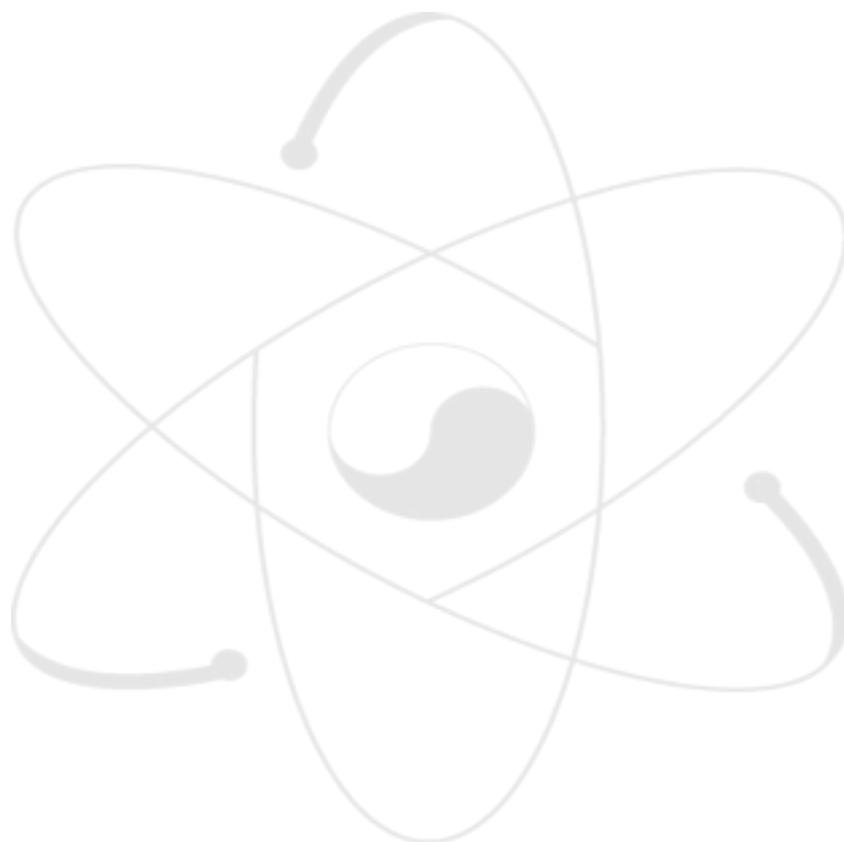| Temperature	Heat Capacity [J/g·K]	
[K]	C_p [7]	C_v [7]
25	15.64	6.87
26	16.99	6.95
27	18.81	7.05
28	21.41	6.67
29	25.34	7.34
30	32.25	7.56
31	46.94	7.89
32	88.42	8.24
32.976		9.83

11. Conclusion

The thermodynamic and transport properties of liquid hydrogen are considered in this report. Several equations to fit the experimental data have been obtained in this report. These equations allow calculating the various properties of liquid hydrogen with high accuracy at temperatures. The results of these calculations and these formulated equations can be used as an input data for the thermo-hydraulic calculation using liquid hydrogen.

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서 지 정 보 양 식

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초록 (15-20 줄 내외)

본보고서는 열 수력 계산에서 수소 물성에 대한 데이터를 이용하기 위하여, 작동유체인 수소의 정확한 열역학 및 열 전달 물성 치들을 많은 보고된 문헌으로부터 수집한 후, 열 수력 계산에 용이하게 이용되기 위해 수식화 되어 있지 않은 데이터는 수식으로 표현하였다.HANARO-CNS 장치의 작동온도 범위에서 Para-hydrogen 과 Equilibrium-hydrogen 에 관한 물성 치를 중점으로 다루었으며, 논의된 수소의 물성치들은 포화증기압, 액체수소의 밀도, 포화기체상의 수소밀도, 증발 잠열, 액상 및 기상의 열전도도, 점도, 액체수소의 열용량, 그리고 포화수소 기체의 열용량등이다. 문헌에서 보고된 실험으로 얻어진 데이터를 정리하기 위해 적용된 여러 수식들은 모든 고려된 온도 범위에서 높은 정확도를 가지며 액체 수소의 다양한 물성 치들을 계산 할 수 있게 되었다.

주제명키워드 (10 단어내외)	수소, 열수력, 열사이펀, 파라수소 전달 물성, 열역학 물성

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Abstract				

The Purpose of this report is to provide the input data, whose characteristic is thermodynamic and transport, in the form of equation for the thermo-hydraulic calculations using hydrogen as a working substance. The considered data in the report are particularly focused on the properties of para-hydrogen and of equilibrium-hydrogen around the working temperature range of the HANARO-CNS. The discussed properties of hydrogen are, in turn, the pressure of saturated vapors, the density, the heat of vaporization, thermal conductivity, viscosity, and heat capccity. Several equations to fit the above-mentioned experimental data allow calculating the various properties of liquid hydrogen with high accuracy at all considered temperatures.

Subject Keywords (About 10 words)	Hydrogen, thermo-hydraulic, thermosiphon, para-hydrogen transport property, thermodynamic property