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Analysis of Fuel Consumption of HCNG Bus for US and European Test Codes

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Abstract

This study examines the US and European test codes for fuel consumption calculation of natural gas fueled vehicles, and analyzes the suitability for the HCNG(Hydrogen added Compressed Natural Gas) fueled vehicles. The fuel consumption calculation formula is derived by the balancing relation of the carbon weight of the fuel with vehicle exhaust gas. US code do not limit the composition of test gas fuel, but European code specifies reference test fuel (G20, G23). Since the natural gas composition differs from country to country, there are various problems in calculating the fuel economy of a natural gas fueled vehicle. In the case of HCNG fuel that is hydrogen added natural gas, the fuel economy calculation results are compared according to the US and EU codes, and significant differences occur when the required conditions are not satisfied.

Keywords: Fuel consumption, CNG(Compressed Natural Gas), HCNG(Hydrogen added CNG), Emission, CWF(carbon weight fraction), P2P, Protocol

INTRODUCTION

Fuel economy is expressed in the unit of driven mileage per vehicle output power or per consumed energy driving test mode and it's an important performance indicator for energy efficiency of the vehicle [1]. There are many testing methods determining the fuel economy like direct measuring of fuel mass consumed or indirect calculating fuel burned with the result of exhaust gas concentration analysis. Many countries choose carbon balance method as the standard fuel economy test and it's the indirect calculating with the exhaust gas concentration. You can determine both the exhaust gas and fuel economy with one test driving by the carbon balance method[2].

The fuel economy test for the vehicles using natural gas as fuel in US is explained in 40 CFR 600.113-12 revised in 2012[3]. The US test code adopts carbon balance method also and fuel density at 20'C, one of the important coefficients in calculating procedure should be specified. In EU, UNECE Regulation No. 101-Revision 3 presents the fuel economy test procedure for the natural gas fueled vehicles and the standard test fuel density is fixed as 0.654kg/m^3 which is the value at 15'C[4]. It uses average fuel density value in the calculation procedure and the test code specifies different calculating coefficients for various gas fuels like HCNG(Hydrogen added Compressed Natural Gas).

The important rules in the fuel economy calculation of the test code for natural gas fueled vehicles has been investigated in this study and we did some case studies for CNG and HCNG fueled vehicles. There could be considerable errors in the fuel economy results otherwise you should use valid properties for the calculation procedure. It shows that you should use proper properties for various natural gas fuels because the gas composition changes for the manufactures or the gathered countries[5]. The study proposed some rules for the proper gas properties in the fuel economy calculation procedure of the test codes.

FUEL ECONOMY TEST CODES OF US AND EU

The US EPA(Environmental Protection Agency) legislates the calculation procedure for the fuel economy in SI unit system as follows[6],

$$Fuel\ economy(km\ /\ m^3) = \frac{CWF_{NG} \times D_{NG}}{A+B+C+D} \qquad (1)$$

Where,

$$A = 0.749 \times CH_4$$

$$B = CWF_{NMHC} \times NMHC$$

$$C = 0.429 \times CO$$

$$D = 0.273 \times (CO_2 - CO_{2NG})$$

$CWF_{NG} = Carbon\ weight\ fraction\ of\ natural\ gas\ fuel$

$CWF_{NMHC} = Carbon\ weight\ fraction\ of\ NMHC\ natural\ gas\ fuel$

$D_{NG} = Density\ of\ natural\ gas\ fuel\ at\ 20℃, 101.3kPa$

$CH_4, CO, NMHC, CO_2$
$= Mass\ of\ exhaust\ gas\ compositions\ per\ distance\ (g/km)$

$CO_{2NG} = FC_{NG} \times D_{NG} \times WF_{CO2}$
$= mass\ of\ CO_2\ included\ in\ the\ natural\ gas\ fuel$

Where,

$$FC_{NG}\ (m^3/km) = \frac{0.749 \times CH_4 + CWF_{NMHC} \times NMHC + 0.429 \times CO + 0.273 \times CO_2}{CWF_{NG}\ \times D_{NG}}$$

$WF_{CO2} = CO_2\ weight\ fraction\ of\ natural\ gas\ fuel$

The formula converts to shorter forms in case for the natural gas fuel without CO_2 as follows[7],

$$Fuel\ economy(km\ /\ m^3) = \frac{CWF_{NG} \times D_{NG}}{A+B+C+D} \qquad (2)$$

Where, $D = 0.273 \times CO_2$, *and other coefficients are same as in the Eq. 1.*

The carbon balance method makes use of the fact that the carbon molecules should be maintained before and after fuel burning and the fuel properties fixed by fuel carbon weight fraction and density. The upper formula applies both to the normal hydrocarbon gas fuel and hydrogen added natural gas fuel like HCNG. The fuel density is determined in the condition of 20'C and 101.3kPa ambient temperature and pressure. The fuel heat value of 20'C ambient temperature should be applied to the fuel economy in the unit of mileage per calories, i.e. mile per kcal. The temperature and pressure conditions should be specified because the gas fuel density changes by the temperature and pressure[8].

Fuel economy test code for natural gas fueled vehicles of EU is explained in the UNECE Regulation No. 101-Revision 3 Annex 6 revised in 2013. The calculating formula for fuel economy in the unit of consumed fuel volume per 100km driving [m^3/100km] is as follows,

$$FE = \frac{0.1336}{0.654} \times (0.749 \times HC + 0.429 \times CO + 0.273 \times CO_2) \qquad (3)$$

Where,

FE = Fuel economy (m^3/100km)

HC, CO, CO_2
$= Mass\ of\ exhaust\ gas\ compositions\ per\ distance\ (g/km)$

The fuel density at 15'C, 1atm is used for the calculation and its value is 0.654kg/m^3 for natural gas. Table 1 compares the test codes of US and EU.

Table 1: Comparison of fuel consumption calculation codes for natural gas vehicles

Country	US	EU
Code Title	40 CFR 600.113-12.	UNECE R101-R3
Method	Carbon balance	Carbon balance
Test fuel	Unspecified	Specified (G20[1], G23[2])
Temperature for fuel density	20℃	15℃

[1] G20 : 100% of methane

[2] G23 : 92.5% of methane + 7.5% of Nitrogen

CNG fueled vehicle can be tested with the G20 fuel in the EU test code because natural gas is mainly methane in composition. But the HCNG fueled vehicle is not suitable for any specified fuel in the EU test code and the fuel economy test results may be different from normal performance operated with HCNG fuel. Therefore it's necessary to modify the test code for HCNG fuel vehicles in EU[9].

UNECE R101-R3 Amendment 2 modifies the formula for hydrogen added gas fuel like HCNG as follows,

$$FE = \left(\frac{910.4 \times A + 13.6}{44.655 \times A^2 + 667.08 \times A}\right) \times [(\frac{7.848 \times A}{9.104 \times A + 136}) \times HC + 0.429 \times CO + 0.273 \times CO_2] \qquad (4)$$

Where,

FE = Fuel economy (m^3/100km)

A = Mixed percentage of natural; gas in HCNG (%)

HC, CO, CO_2
$= Mass\ of\ exhaust\ gas\ compositions\ per\ distance\ (g/km)$

Table 2 shows the various coefficients in the calculation formula for US and EU each. The fuel carbon weight fraction of CNG corresponds to the value of pure methane and the fuel density is chosen without nitrogen for G20 and G23 fuel in the EU test code. Therefore the US test code is more flexible for the added natural gas fuel like HCNG because you can modify for changed fuel compositions. The test results for Korean CNG and HCNG fueled vehicles has been studied next chapter for the test codes of US and EU to compare and to suggest more suitable test method of those vehicle types.

Table 2: Comparison of the coefficients included in fuel consumption formulas of European and US test code for CNG and HCNG fuel(see Table 4 for fuels)

Country		CNG		HCNG	
		US	EU	US	EU
Carbon weight fraction for Fuel, CWFNG		0.7556	0.7485[1)]	0.7202	N.A
Carbon weight fraction for exhaust gas, CWF	THC	-	0.749	-	0.710
	CH_4	0.749	-	0.749	-
	NMHC	0.809	-	0.809	-
	CO	0.429	0.429	0.429	0.429
	CO_2	0.273	0.273	0.273	0.273
Fuel density	@ 20℃	0.733	-	0.538	-
	@ 15℃	0.746	0.654	0.547	-
CWF_{NG} × density [2)]		0.554	0.490	0.387	0.240

1) The formula shows 0.1336(= 1/0.7485/10) to convert fuel economy unit of [m^3/100km]

2) The temperature for the density is 20℃ in US and 15℃ in EU

CHARACTERISTICS OF KOREAN NATURAL GAS FUEL

The natural gas is supplied from base stations in each areas of Korea in the form of LNG(Liquified Natural Gas) purchased from various gas plants all over the world. It's been published the supplied calories of the gas fuel for each areas according to gas fuel trading rules since 2012 in South Korea[11]. The necessary data is accumulated in the serve in the KOGAS(Korea gas corporation) and the coefficients are gathered by the P2P network[11] and the massive data are regressed by the PC in Ajou motor college[12]. It's more efficient and quick to compute the coefficients by this network protocol in real-time data aquisition and referencing[13]. It's easy to apply the fuel economy formula because those various coefficients like fuel density or carbon weight fraction can be drawn from the published calories related data of gas fuel in Korea. Table 3 shows the thermal and compositional data of Korean natural gas during the last 10 years. The lower five rows of Table 3 shows gas density and carbon weight fraction necessary to calculate the fuel economy.

Table 3: Relations with composition according to calorific value of LNG based city gas

Heating value(MJ/Nm^3)		41.0	42.0	43.0	44.0
Composition (mol%)	C_1H_4	96.71	94.58	92.44	90.35
	C_2H_6	2.35	3.62	4.85	5.99
	C_3H_8	0.57	1.12	1.72	2.37
	iC_4H_{10}	0.07	0.23	0.38	0.52
	nC_4H_{10}	0.10	0.25	0.40	0.55
	iC_5H_{12}	0.00	0.01	0.02	0.02
	nC_5H_{12}	0.00	0.00	0.00	0.00
	N_2	0.19	0.19	0.20	0.21
H/C		3.923	3.863	3.806	3.754
CW_{NG}		0.750	0.753	0.756	0.758
CWF_{NMHC}		0.806	0.808	0.809	0.809
Density (kg/m^3)	0℃	0.744	0.765	0.786	0.807
	20℃	0.693	0.712	0.732	0.752

Fig. 1 shows the relationship between the carbon weight fraction and heating value of the natural gas fuels. The carbon weight fraction of natural gas methane included(CWF_{NG}) or excluded(CWF_{NMHC}) is proportional to the heating value of the fuel[14]. Therefore the carbon weight fraction can be drawn from the heating value of the gas fuel with the linear regressions and the results shows just 0.2% errors. But for the Korean HCNG, the CWF and density should be calculated from the gas composition directly due to the added hydrogen of 30%.

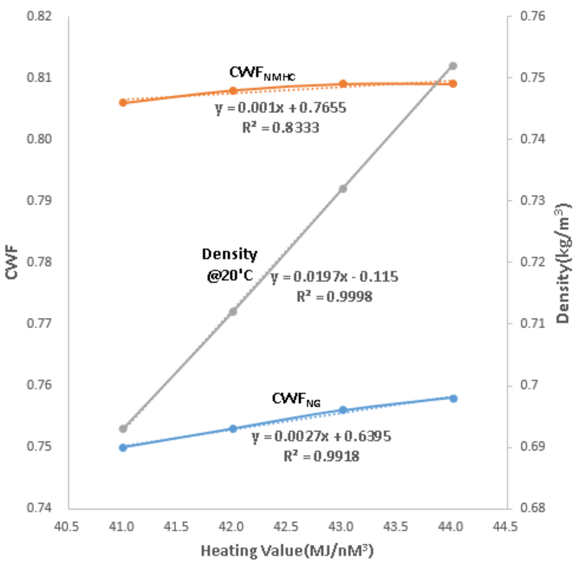

Figure 1: Relationship between heating value and carbon weight fraction(CWF_{NG})

Table 4 shows the low heating values and gas compositions of the Korean HCNG(30% of hydrogen + 70% of natural gas) and natural gas fuel. The fuel economy can be calculated with the carbon related exhaust gas mass per distance, i.e. CO, CO_2, CH_4, HC, as explained in the test codes of US and EU.

Table 4: The gas compositions and low & high heating values of the Korean HCNG and natural gas fuel

Fuel	HCNG	Natural gas	Unit
C_1	64.63	92.33	mol %
C_2	3.44	4.91	
C_3	1.22	1.75	
i-C_4	0.27	0.38	
n-C_5	0.29	0.41	
i-C_5	0.01	0.02	
n-C_5	0	0.00	
N_2	0.14	0.20	
H_2	30.0	0.0	
Sum	100.0	100.0	
LHV, @ 0℃	30.41	38.87	MJ/Nm^3
LHV, @ 20℃	28.32	36.19	MJ/m^3
HHV, @ 0℃	33.93	43.06	MJ/Nm^3
HHV, @ 20℃	31.60	40.09	MJ/m^3

DISCUSSION

US test code:

Table 5 shows the exhaust gas results of CNG and HCNG fueled buses operated by KOGAS(Korean Gas Corporation) driving WHVC(Worldwide Harmonized Vehicle Chassis) dynamometer test mode of EU[15]. WHVC mode is developed to test large vehicle like bus or truck driving average urban and rural road of EU. The tested CNG fuel is supplied by the local gas station and the CNG is added with 30% hydrogen gas to make HCNG fuel by the KOGAS. The maximum vehicle output power is about 220kW and the engine volume is about 11 liters. It's optimized to perform best fuel economy and satisfied the EURO 6 of exhaust gas regulation. The fuel economy was calculated with the exhaust gas test results of Table 5 according to the US test code in the study.

Table 5: Specifications of tested vehicle types and emission data for CNG and HCNG buses by WHVC mode

Fuel		CNG	HCNG
Engine volume		11 liter	←
Max. Power		220kW	←
Test fuel		Natural gas	CNG 70% + H_2 30%
Exhaust Gas (g/km)	CH_4	0.717	0.320
	NMHC	0.054	0.045
	CO	0.014	1.858
	CO_2	610.34	485.73
	NOx	0.844	0.075

Table 6 shows the fuel economy results calculated with the exhaust gas data of Table 5 and fuel properties of Table 3 according to the US test code. The fuel economy results are $3.31km/m^3$ and $2.90km/m^3$ for CNG and HCNG each. It's better to compare the energy efficiency in the unit of mileage per equivalent heating value due to the difference in the thermal energy release per volume of gas fuel. The fuel economy converted to the diesel equivalent one according to the low heating value at 20'C. The low heating value of CNG and HCNG is 36.19 and $28.32MJ/m^3$ each while 34.9MJ/ℓ for diesel[16]. The fuel economy is converted to the diesel equivalent value as follows.

For CNG : $3.31km/m^3$ X 34.9MJ/ℓ / $36.19MJ/m^3$ = 3.19km/ℓ

For HCNG : $2.90km/m^3$ X 34.9MJ/ℓ / $28.32MJ/m^3$ = 3.57km/ℓ

Therefore HCNG is better than CNG in the view of the fuel economy by 12%. And the diesel equivalent fuel economy value makes it easy to compare gas fuel vehicles with the diesel fueled ones.

Table 6: Fuel consumption results of CNG and HCNG buses based on US codes

Fuel	CNG	HCNG	Unit
Calculated Fuel economy US test code	**3.31**	**2.90**	**km/m^3 1)**
Converted Fuel economy equivalent to diesel 2)	**3.19**	**3.57**	**km/ℓ**

1) Gas volume(m^3) at 20'C, 101.325kPa

2) According to low heating value of diesel(=34.9MJ/ℓ)

EU test code:

The standard natural gas for the EU fuel economy test is specified as G20 and G23. Therefore it's unreasonable to apply the EU test code to the results of the Korean CNG/HCNG fueled vehicle. But it's meaningful to investigate the error made by the direct application of EU code to Korean CNG/HCNG test results. Fuel economy was calculated by the EU test code as in the Eq. 3 and Eq. 4 with the Korean CNG/HCNG test results summarized in Table 5.

Table 7 shows the calculation results of the EU code. It compares the EU code results with the US code results processed in the previous analysis. The fuel economy is lower for the EU test code applied. It's lower by 11% for CNG and by 14% for HCNG. It's the difference in the temperature for the gas density and test fuel itself for the EU code that makes the fuel economy lower than for the US code. It shows that you should choose the proper test code and apply right gas properties like gas density and carbon weight fraction to calculate real fuel economy. And it's necessary to establish the proper standards for the fuel economy test of CNG/HCNG fueled vehicles.

Table 7: Difference of fuel consumption between US and European codes for CNG and HCNG buses tested by conventional natural gas fuels

Fuel	CNG	HCNG	Unit (Temperature)
EU	2.93	2.49	km/m^3 @15'C
US	3.31	2.90	km/m^3 @20'C
Difference (%)	∆0.38 (11%)	∆0.41 (14%)	-

Temperature effect:

It's necessary to specify the reference temperature for the gas volume in the fuel economy calculation expressed in the unit of mileage per volume, i.e. km/m^3 because the fuel mass changes with the temperature for CNG/HCNG fuel. The fuel economy changes with the temperature applied to the calculating process. Table 8 shows the calculated fuel economy results of HCNG for several temperature points with Eq. 2 of the US code. The fuel consumption per unit volume decreases as the reference temperature goes up but the fuel consumption per unit calories increases.

The reference temperature is different for the US and EU fuel economy test code. It' better to apply the US test code for CNG/HCNG fueled vehicle because you can consider the change in gas compositions and modify the calculation procedure. The reference temperature is 20'C for the US code and 0'C for Korean natural gas trade list. Therefore it's necessary to be careful in applying the gas properties and heating value in fuel economy calculation.

Table 8: Fuel consumption by US code according to reference temperature change(HCNG case)

Fuel Economy		Low heating value	Density	Fuel economy	
		MJ/m^3	kg/m^3	km/m^3	km/GJ
Applied Temperature	0℃	30.50	0.577	3.11	102.0
	15℃	28.82	0.547	2.95	102.3
	20℃	28.32	0.538	2.90	102.4

CONCLUSION

The fuel economy test codes of US and EU were investigated in the study and applied the calculation process to Korean CNG/HCNG fueled vehicles. Several conclusions made in the study as follows.

① The fuel economy is calculated with the fuel properties and exhaust emission. The fuel compositions can changes in the US code but the test fuel is specified as G20 and G23 in the EU code.

② The fuel economy of EU code is lower by 11% for Korean CNG and 14% for Korean HCNG than the value of US code. It's the difference in the test fuel compositions. And it's better to apply the US code for the flexibility in choosing the test fuels.

③ It's better to make same the reference temperature of US code(20'C) and Korean gas trade list(0'C) but it needs more discussion and study henceforward.

④ The necessary data of gas fuel is gathered by the P2P network between the serve in the KOGAS and PC in Ajou motor college for real-time data acquisition for better efficiency.

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NOMENCLATURE

- Nm^3 : Volumn in standard ambient state(0℃, 101.32kPa)
- HHV: high heating value
- LHV: low heating value
- MJ, GJ: Mega Joule(10^6 joule), Giga Joule(10^9 joule)
- H/C: mole ratio of hydrogen and carbon(hydrogen/carbon)
- CWF_{NG} : Carbon weight fraction of natural gas

$$\mathrm{CWF_{NG}} = \frac{\sum_{i=1}^{n} Mole\ fraction\ of\ carbon\ molecule{,}i \times Number\ of\ carbon\ atoms\ of\ i \times 12.011}{\sum_{i=1}^{m} Mole\ fraction\ of\ each\ molecule{,}i\ in\ fuel \times Weight\ of\ molecule{,}i}$$

- CWF_{NMHC}: Carbon weight fraction without methane

$$\mathrm{CWF_{NMHC}} = \frac{\sum_{i=1}^{n} Mole\ fraction\ of\ carbon\ molecule{,}i{,}without\ methane \times Number\ of\ carbon\ atoms\ of\ i \times 12.011}{\sum_{i=1}^{m} Mole\ fraction\ of\ carbon\ molecule{,}i{,}without\ methane \times Weight\ of\ molecule{,}i}$$