Establishing the energy content of natural gas residential consumption : example with Belgian field-test applications

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Abstract. In the context of the much-needed energy transition, monitoring of residential energy appliances is more and more common in order to evaluate (and improve) their field-test performance in real applications. Many residential heating appliances use natural gas as energy source : residential gas boilers, gas engine heat pumps, gas absorption heat pumps; fuel cell-based cogeneration units, internal combustion engine cogeneration units, *etc*. Unfortunately, for simplicity and costs reasons, only the volume of the consumed natural is measured at the inlet of the monitored residential heating appliance. This volume, and the equivalent energy level that it contains and that is required for efficiency calculations, is affected by the atmospheric pressure and the temperature at the field-test site, as well as by the always varying natural gas composition. This paper demonstrates the method that has been used in Belgian field-test studies conducted on residential heating appliances to establish the energy content of the consumed natural gas.

1. Introduction

Targets of temperature increase compared to pre-industrial levels have scientifically been linked to remaining carbon budgets of future Greenhouse Gases (GHG) emissions allowed for all humanity [1]. Actually, in its Sixth Assessment Report (AR6) released in early 2022, Intergovernmental Panel on Climate Change's Working Group III (IPCC WGIII) has reported that if humanity does not exceed 890 $GtCO_2$ of emissions from January 1st 2020, it will have 2 out of 3 chances of not exceeding the +2°C maximum limit set in the 'Paris Agreement' back in 2015 [2]. Mitigating GHG emissions is generally associated to the 'low carbon transition' [3], i.e. to the 'energy transition'.

Beside lowering the energy demand, i.e. the 'energy sobriety principle' [4], and increasing territorial carbon absorption [5], it is usually considered that one main pillar of the much-needed energy transition lies in the 'energy efficiency' [4]. Efficiency is always crucial at all levels, both in case of fossil fuel and renewable energy use. For heating appliances at residential scale, energy efficiency establishment and enhancement often require field-test monitoring of energy consumptions. Although the electrical consumption of electrical appliances (such as electrical heat pumps) is quite trivially measured and monitored (an example of electrical energy meter has been shown in figure 1), the energy consumption of gas-fed appliances is not that easily established.

Indeed, as the energy content of natural gas depends on its varying chemical composition (which requires specific and expensive laboratory hardware, such as chromatographs), it is unrealistic to measure (continuously) it at every residential monitoring field-test sites.

Therefore, in most applications, the only sensor placed on residential gas inlet pipe is a simple diaphragm gas volume meter (such as the one shown in figure 2), which can also serve as a base for billing purposes.

Figure 1. Example of residential field-test electrical energy meter ('MT174' by Iskraemeco)

Figure 2. Example of residential gas (volume) consumption meter ('BKG4-T' by Elster)

Gas consumed volume is converted into energy content either thanks to the gas High Heating Value (HHV), usually used when water vapour contained in the gas is able (or should be able) to condense, or thanks to the Low Heating Value (LHV). Nowadays, most applications use the HHV as reference because gas appliances technologies have been improved to recover the latent energy in the gas water vapour.

As it will be seen the following section, HHV are measured (by the gas provider) and provided in 'reference conditions' of pressure and temperature. Those figures are usually available freely on the local gas provider website (or they also can usually be requested over emails). Unfortunately, the 'reference conditions' of temperature and pression are not the ones that occur at the field-test delivery sites. Therefore, the conversion of the field-test measured gas volume into energy content thanks to the HHV (provided by the gas provider) is not trivial and requires to establish some conversion factors. The aim of this paper is to report a documented method for this to be performed.

It is worth mentioning that, with the upcoming of 'power to gas' technologies (such as biomethanation) [6] or biomethanization [7], the method described in this paper is not only relevant with conventional (fossil) natural gas appliances, but also with biogas (renewable) appliances.

This exact method has been used for several field-test monitoring studies, on several gas-fed residential space heating appliances, such as Solid Oxide Fuel Cells (SOFC) [8], Proton Exchange Membrane Fuel Cells [9, 10, 11] or absorption heat pumps [12].

2. Establishing the HHV of the consumed gas at the field-test delivery conditions

As stated, HHV are established by the gas provider from regular samples on the high or medium-pressure pipes (and not on the low-pressure pipes at the delivery points of the field-test studies). They usually are performing this hourly according to the composition of the gas (usually measured thanks to a chromatograph) and their combustion enthalpy at 25 °C and 1 atm [13]. The volume of the gas mixture sample from high or medium-pressure pipes is measured as well by the gas provider and

converted to a "normalized" volume at 0 °C and 1 atm (reference conditions) according to equation (1), which corresponds to the real gases equation of state [14]:

$$V_N = V_B \frac{P_L}{P_N} \frac{T_N}{T_L} \frac{Z_N}{Z_L} \qquad (1)$$

Where V_N is the normalized volume at 0 °C, i.e. 273.15 K (T_N) and 1 atm, i.e. 101325 Pa (P_N), V_B is the measured volume of the gas sample whose composition is established thanks to a chromatograph at T_L and P_L (also measured on the high or medium-pressure pipes by the gas provider). Z_N and Z_L are the compressibility factors of the natural gas mixture and can also be established according to the composition, the temperature (either T_N or T_L, explained above) and the pressure (either P_N or P_L, explained above) [15]. Similarly, the method of establishing the compressibility factor of natural gas mixtures can be applied according to other inputs (such as the density) and is well documented as the SGERG-88 method [16].

Therefore, the HHV are provided in 'references conditions' for the 'metered volume' (T_N and P_N), but the reference for the combustion is different (25 °C, i.e. 298.15 K, from here onwards called $T_{r,C}$ and P_N). However, those are different from the delivery conditions so a relation similar to equation (1) must be implemented to convert the monitored gas volume V_M adequately according to the HHV references conditions. So, one obtains $V_{M,N}$:

$$V_{M,N} = V_M \frac{P_D}{P_N} \frac{T_N}{T_D} \frac{Z_N}{Z_D} \qquad (2)$$

Where P_D, T_D and Z_D are respectively the pressure, temperature and compressibility factors at the delivery point of the field-test study, which are unfortunately not measured.

Nevertheless, delivery temperature T_D can usually be assumed at 15 °C, i.e. 288.15 K, because gas meter used in field-test studies are often said to ensure temperature compensation via 'a bimetallic element', which is the case for the 'BK-G4T' shown in figure 2 [17]. Indeed, the error curve for similar uncompensated meters (called 'BK-G4') is supposed to be null at 15 °C, which can be therefore considered as their metering reference. Thanks to temperature compensation, the accuracy range of the sensor can be extended from -10 °C to 40 °C and since the only additional feature is the "bimetallic element" for temperature compensation, the 15 °C reference is assumed to remain. This means that the field-test volume given by the gas meter, whatever the temperature changes between -10 °C and 40 °C, is the same as if the temperature had stayed constantly to 15 °C.

Unfortunately, pressure is usually not compensated in any way with conventional gas meters and since it is not measured in the low-pressure pipes at the field-test monitoring sites (as opposed to the high or medium-pressure pipes where the HHV are established), assumptions must be made. The delivery pressure P_D is affected by the barometric pressure at sea level (meteorologic variable), by the altitude of the delivery point and of course by the main gas distribution pressure regulator setting (and its well-known imperfections such as boost and droop [18]). This pressure regulator aims to control the operational pressure and flow of the gas [19]. It is placed upstream of the gas meter (mostly for metering accuracy [20]). In most countries (such as in Belgium), it is used to reduce the pressure from the high or medium-pressure gas distribution pipes to 21 mbar to meet the requirements of residential standard gas appliances [21] (and this pressure requirement is also specified in official industrials standards [22]). However, in Belgium, natural gas comes from different sources, which implies different gas compositions and different HHV, which leads to the appellations 'lean' and 'rich' gas, respectively for the natural gas source providing the lower and the higher HHV [23].

Lean gas, also called 'type L' gas, is supposed to be progressively replaced (in Belgium) by 2030 by rich gas, also called 'type H' gas [24]. The existence of lean gas on part of the Belgian market subsequently lead to some changes in the recommended pressure regulator setting (25 mbar instead of the usual 21 mbar for 'type H' gas) [25].

Barometric pressures at sea level P_M constitute data that can easily and freely be gathered. For example, in Belgium, it is measured in Uccle and provided hourly by the Royal Meteorological

Institute of Belgium (RMI). Uccle, near Brussels, is considered as the reference climatology Belgian station [26].

Altitude of the monitoring field-test sites can also be gathered easily. For example, in Belgium, it can be established based on the coordinates of the field-test sites thanks to the CalcMaps website (www.calcmaps.com/fr/map-elevation/).

The relationship between altitude h (m) and its corresponding atmospheric pressure P_h (Pa) can be established thanks to equation (3) [27] :

$$P_h = P_0 \left(1 - 0.0065 \frac{h}{T_0}\right)^{5.2561} \tag{3}$$

Where P_0 and T_0 are defined as the International Standard Atmosphere (ISA) conditions at Mean Sea Level (MSL) [28]. For information, T_0 is equal to T_D, i.e. 288.15 K whereas P_0 is equal to P_N, i.e. 101325 Pa.

Thanks to the actual RMI barometric pressure data at sea level P_M (Pa), thanks to the actual external temperature monitored onsite T_M (K) and knowing that temperature decreases with altitude at constant rate of -6.5 K per km up to the tropopause according to ISA assumptions [29], one can replace P_0 and T_0 in equation (3) to achieve better accuracy for modelling the onsite atmospheric pressure $P_{h,M}$ (Pa). One thus obtains equation (4):

$$P_{h,M} = P_M \left(1 - 0.0065 \frac{h}{T_M + 6.5 \frac{h}{1000}}\right)^{5.2561} \tag{4}$$

Pressure at the delivery point P_D is thus equal to the onsite modelled atmospheric pressure $P_{h,M}$ additioned to the pressure regulator setting P_{reg} :

$$P_D = P_{h,M} + P_{reg} \tag{5}$$

Where, in Belgium, P_{reg} is equal to 21 mbar for 'type H' gas or to 25 mbar for 'type L' gas, as explained. Since the actual pressure regulator devices of the field-test are not known, their potential imprecision (such as the well-known boost and droop [18]) can only be neglected.

The compressibility factors at the delivery conditions Z_D and in reference conditions Z_N cannot be established based upon the available data stated above (the gas provider does not usually disclose the composition of the gas nor its density in order to be able to implement the SGERG88 model [16]). It is worth mentioning that the SGERG88 model is considered as too complex to be solutioned by hand so, even if the relevant data were available, one would still need the proprietary software to run it.

However, even if Z_N has not been provided, one can assume that it has been established by the gas provider in reference conditions T_N and P_N. Similarly, Z_D would have been calculated at the assumed temperature T_D and pressure P_D (that have been previously established). Fortunately, equation (2) only requires the ratio of the compressibility factors and not their absolute values, and this ratio can be estimated thanks to acknowledge relevant conversion factors [30] :

$$\frac{Z_{0°C,1atm}}{Z_{15°C,1atm}} = 0.9996 \tag{6}$$

Equation (6) assumes a reference composition of the natural gas mixture (surely different from the real one). By assuming that the real composition of the natural gas used in the field-test sites during the whole study would only affect the absolute value of the compressibility factor and not its ratio over a given (small) temperature range, by assuming that the slight pressure difference between P_D and 1 atm, i.e. the reference pressure of equation (6), does not affect the ratio of compressibility factors over the given temperature range either, one obtains equation (7):

$$\frac{Z_N}{Z_D} = \frac{Z_{0°C,1atm}}{Z_{15°C,1atm}} = 0.9996 \qquad (7)$$

Provided that the gas provider has measured the HHV in 'reference conditions' hourly as it is generally the case, equation (2) can thus be fully implemented and the equivalent HHV energy contained in the consumed gas Q_{HHV} for a given duration of n hours is defined by equation (8):

$$Q_{HHV} = \sum_{i=0}^{i=n} \left(V_{M,N_i} \times HHV_i \right) \qquad (8)$$

Where i is the index associated one single hour included in the studied given duration of n hours, HHV_i is the HHV established by the gas provider in references conditions (T_N and P_N) for the hour i, and V_{M,N_i} is the monitored gas volume consumed over the hour i, adjusted to the references conditions (T_N and P_N) thanks to equation (2) and its subsequent assumptions.

It is worth mentioning that the reference temperature of combustion $T_{r,C}$ used in the definition of the HHV, i.e. 25 °C, has not been altered or converted in any way. This means consumed gas HHV energy $\Delta_{E,g}$ and the resulting efficiencies that can be subsequently calculated shall normally highlight the reference temperature of combustion for HHV establishment, and that is not often the case. Indeed, for example, considering that the combustion of a reference natural gas mixture occurs at 0 °C instead of 25 °C (at 1 atm in both cases) would increase the HHV value by a factor 1.0026 [30], which is small but not that unsignificant.

3. Discussions and conclusions

For space heating combustion appliances, keeping the reference temperature at 25 °C, slightly above air comfort temperature and therefore the return temperature to the space heating appliance, seems relevant. However, in practice, the combustion reactants are not heated up to the reference temperature of combustion of 25 °C by thermal exchange with ambiance upstream of the appliance. For example, the natural gas mixture had flowed a significant amount of time in the ground gas network and its resulting temperature before entering the heating system often cannot reasonably be assumed over 15 °C. Same kind of assumptions can be made on the incoming air also required as reactant for any combustion to take place (or combustion-like reactions, such as in residential fuel cells).

Therefore, even with a perfect heating system and combustion, the HHV efficiency could never reach 100% as some energy from the combustion is drawn to heat up the reactants from their actual delivery temperature (not measured) to the fictive reference combustion temperature (25 °C). Thus, the resulting HHV efficiency (specifying the reference temperature of combustion) is not more that the best reproduceable indicator that could be thought of and remains a partially biased image of the real achievable efficiency of the system.

Alternatively, considering a reference temperature of combustion closer to the one of the reactants (for example, 15 °C) is not preferable because this time, some energy from the combustion would similarly be required to heat up the products of the combustion. Indeed, it is not reasonable to consider that the combustion products can exhaust the system at a temperature below a realistic comfort air temperature or even below usual space heating return temperatures (which can be assumed, at no less than 25 °C for low temperature terminal units).

Despite this clarification on the HHV definition, the impact of reducing the calorific value by considering the heating up of the reactant on a temperature range such as 10 K remains very low (compared to monitoring measurement uncertainties that, for instance, can reach about 5% with usual Class 2 heat meters [31], required to monitor the heat rate produced by the space heat appliance). This can be demonstrated thanks to the CoolProp open-source library (www.coolprop.org) in the following example :

- By considering natural gas as pure methane at 1 atm, the energy required to elevate its temperature from 15 °C to 25 °C is 22.2 kJ/kg;
- On the other hand, considering an arbitrary based HHV of 11 kWh/Nm³ used only for the sake of this example (in reference conditions, 1 atm and 0 °C) accounts for about 55.2 MJ/kg (in the same reference conditions, for the same assumed reactant);
- Therefore, it could be considered that the energy required to elevate the temperature of the fuel reduces its reference HHV of about 0.04 %.
- Considering that air, assimilated as a mixture of 21% of oxygen and 79% of nitrogen, also has to be heated from 15 °C to 25 °C (at 1 atm); considering a complete stochiometric reaction for the combustion of methane with that air, would require an additional energy taken out of the reference HHV of 48.3 kJ per kg of methane.
- Therefore, it could be considered that the energy required to elevate the temperature of the air reduce the reference HHV of about 0.087 %.

Thus, the total reduction impact of heating up the reactants on the reference HHV approaches 0.13%. This is without considering a combustion in excess of air, which is usually the case for gas condensing boilers (in the 1.05 – 1.4 excess of air range) as an optimum choice between thermal efficiency and Nitrogen Oxides (NOx) emissions has to be made [32]. Indeed, increasing excess of air is known to lessen the flame temperature, and therefore the NOx emissions [33], but also the efficiency, by reducing the sensible heat transfer [32]. It is worth mentioning that excess of air also lessens thermal efficiency by reducing the latent heat recovery [32], as it dilutes water vapor contained in the flue gases (lower specific humidity and therefore lower dewpoint to achieve with the latent heat recovery heat exchanger of the gas condensing boiler).

Considering excess of air would even increase the HHV reduction impact (up to about 0.16 % for the worst 1.4 excess of air assumption).

References

[1] J. Rogelj, P. M. Forster, E. Kriegler, C. J. Smith and R. Séférian, "Estimating and tracking the remaining carbon budget for stringent climate targets," *Nature,* vol. 571, no. 7765, 2019

[2] N. Paulus, "Will Greenhouse Gas emission commitments in France and Wallonia respect IPCC's carbon budget ?," *Journal of Cleaner Production,* vol. Under review, 2022.

[3] R. W. Wimbadi and R. Djalante, "From decarbonization to low carbon development and transition: A systematic literature review of the conceptualization of moving toward net-zero carbon dioxide emission (1995–2019)," *Journal of Cleaner Production,* vol. 256, 2020.

[4] I. Campos and E. Marín-González, "People in transitions: Energy citizenship, prosumerism and social movements in Europe," *Energy Research & Social Science,* vol. 69, 2020.

[5] N. Paulus, "From 'equity' carbon budget to individual carbon footprint mitigation pathways : examples for Wallonia and France," *Environmental Development,* vol. Under Review, 2022.

[6] P. Collet, E. Flottes, A. Favre, L. Raynal, H. Pierre, S. Capela and C. Peregrina, "Techno-economic and Life Cycle Assessment of methane production via biogas upgrading and power to gas technology,," *Applied Energy,* vol. 192, 2017.

[7] B. Kumara Behera and A. Varma, "Biomethanization," in *Microbial Resources for Sustainable Energy*, Cham, Springer International Publishing, 2016.

[8] N. Paulus and V. Lemort, "Field-test performance of Solid Oxide Fuel Cells (SOFC) for residential cogeneration applications," *Proceedings of the 7th International High Performance Buildings Conference at Purdue (Herrick 2022),* 2022.

https://docs.lib.purdue.edu/ihpbc/405/

[9] N. Paulus, C. Davila and V. Lemort, "Field-test economic and ecological performance of Proton Exchange Membrane Fuel Cells (PEMFC) used in micro-combined heat and power residential applications (micro-CHP)," *Proceedings of the 35th International Conference On Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems (ECOS 2022),* 2022.

[10] N. Paulus and V. Lemort, "Field-test performance models of a residential mi-cro-cogeneration system based on a proton exchange membrane fuel cell and a gas condensing boiler," *To be submitted,* 2022.

[11] N. Paulus and V. Lemort, "Correlation between field-test and laboratory results for a Proton Exchange Membrane Fuel Cell (PEMFC) used as a residential cogeneration system," *Proceedings of the 30e Congrès de la Société Française de Thermique (SFT 2022),* 2022. https://doi.org/10.25855/SFT2022-119

[12] C. Davila, N. Paulus and V. Lemort, "Experimental Investigation of a Gas Driven Absorption Heat Pump and In-Situ Monitoring," *Proceedings of the 9th Heat Powered Cycles International Conference (HPC 2021),* 2022. https://heatpoweredcycles.eng.ed.ac.uk/sites/heatpoweredcycles.eng.ed.ac.uk/files/attachments/HPC2021-proceedings.pdf

[13] ISO 6976, *Natural gas - Calculation of calorific values, density, relative density and Wobbe index from composition,* International Organization for Standardization, 1995.

[14] D. A. Simpson, "Chapter Zero - Introduction," in *Practical Onshore Gas Field Engineering*, United States, Elsevier, 2017, pp. 1-43.

[15] ISO 12213-3, *Natural gas - Calculation of compression factor - Part 3: Calculation using physical properties,* International Organization for Standardization, 2006.

[16] S. Jaeschke and A. Humprheys, "GERG Technical Monograph 5 (TM5) - Standard GERG Virial Equation for Field Use," Groupe Européen de Recherches Gazières, 1991.

[17] BK-G4 and BK-G4T, *High quality residential diaphragm gas meters,* Elster, 2012.

[18] K. Shaw, "Fundamental Principles of Pressure Regulators," in *ASGMT Proceedings*, Houston, 2003.

[19] M. Patil and R. Barjibhe, "Flow Analysis of Gas Pressure Regulator by Numerical & Experimental Method," *International Research Journal of Engineering and Technology,* vol. 5, no. 7, 2018.

[20] Squire Energy, "Gas Pressures - FAQ's," United Kingdom, 2017.

[21] M. Ozturk and I. Dincer, "Development of renewable energy system integrated with hydrogen and natural gas subsystems for cleaner combustion," *Journal of Natural Gas Science and Engineering,* vol. 83, 2020.

[22] IGEM/GM/PRS/41, *Low pressure meter installation kits,* Institution of Gas Engineers and Managers, 2019.

[23] D. Haeseldonckx and W. D'haeseleer, "The use of the natural-gas pipeline infrastructure for hydrogen transport in a changing market structure," *International Journal of Hydrogen Energy,* vol. 32, no. 10-11, 2007.

[24] (F)1736, "Study on the cost-effectiveness of natural gas (CNG or compressed natural gas) used as fuel in cars," CREG, 2018.

[25] Fonds de formation professionnelle de la construction, "Manuel modulaire chauffage central : Module 7 - Installations au gaz - Volume 3 - Annexes (D/2012/1698/15)," fvb·ffc constructiv, Bruxelles, 2012.

[26] M. Dury, S. Ginion and M. Erpicum, "Estimation de la transparence de l'atmosphère par ciel clair

à la Station Scientifique des Hautes-fagnes (SSHF), Mont Rigi, Belgique. Comparaison avec la Station d'Uccle-Bruxelles (IRM)," *Bulletin de la Société Géographique de Liège,* vol. 51, 2008.

[27] M. Cavcar, "The International Standard Atmosphere (ISA)," Eskisehir, Turkey, 2000.

[28] ICAO 7488, *Manual of the ICAO Standard Atmosphere,* International Civil Aviation Organization, 1993.

[29] N. E. Daidzic, "On Atmospheric Lapse Rates," *International Journal of Aviation, Aeronautics, and Aerospace,* vol. 6, no. 4, 2019.

[30] ISO 13443, *Natural gas - Standard reference conditions,* International Organization for Standardization, 1996.

[31] OIML R 75-, *Heat meters. Part 1: General requirements,* International Organization of Legal Metrology, 2002.

[32] F. Liu, L. Zheng and R. Zhang, "Emissions and thermal efficiency for premixed burners in a condensing gas boiler," *Energy,* vol. 202, 2020.