Paper 3.3

Energy Flow and Wobbe Metering Based on Velocity of Sound Measurements and Using a Corrective Techique

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1   INTRODUCTION

Gasunie Research gained their years of experience in efficient energy utilization, gas measurement, and gas transport as the in-house laboratory for N.V. Nederlandse Gasunie. This company, which was an integrated gas transport and trading company until the beginning of 2002, has been one of the largest gas suppliers in Europe for several decades. As part of this company, Gasunie Research has always striven to guarantee the continuity of the gas supply, to ensure the safety of gas transport and to enhance the added value of natural gas as a fuel. Gasunie Research developed a wealth of new technology for domestic, commercial and industrial end users, and for the energy sector itself.   The expertise that Gasunie Research has acquired through these activities and the years of practical experience is now made available to third parties.

Energy measurement is one of the main tasks of gas transport companies. New challenges in the gas world, focus the companies with new requirements with respect to energy measurement. (e.g. the variation in gas composition will be larger and will occur more frequently). That's why a number of new developments in energy metering are occurring. Present energy measurement systems for natural gas comprise volume metering, volume conversion from field conditions to reference conditions and calorific value determination at reference conditions. The calorific value, H_{SR}, is mostly determined by compositional assay using a process gas chromatograph. The volume is commonly measured by turbine or ultlrasonic flowmeters or orifice plates. The volume conversion factor can be determined from thermal equations of state, using the gas composition or gas properties, to calculate compression factors or densities.

The cost of ownership of accurate energy flow meters using a process gas chromatograph are high.   For this reason Gastransport Services (the transportation company of N.V. Nederlandse Gasunie) and Ruhrgas AG started a joint project for the development of new energy flow measurement methods, which yield both the calorific value at **field** conditions (for custody transfer stations) and the Wobbe-Index.

These new methods are based on the measurement of three suitable properties (e.g. physical properties or component concentrations) and an accurate correlation between these properties and the gas composition. This calculated gas composition is used to compute the superior calorific value, density and subsequently the compression factor under reference and field conditions and also the Wobbe-Index using traditional methods.

Within the joint project Gasunie Research took on the development of two types of energy meters. The first concept is based on the measurement of the velocity of sound at high pressure (VOS_{high}), the velocity of sound at low pressure (VOS_{low}), and the molar fraction carbon dioxide (X_{CO2}). This combination is particularly suitable at stations with high pressure gas available (P > 40 bar). The second concept is based on VOS_{low} and X_{CO2} too, but uses an instrument yielding the superior calorific value under reference conditions, H_{SR}, as the third input parameter. This combination is particularly suitable for stations with gas pressures below 40 bar. This paper is dedicated to the first combination with two velocity of sound measurements.   However, some field test results obtained with the combination with a calorimeter will be presented also.

1.1   Advantages of the New Correlative Energy Meter

The new energy meter is based on instruments and components, which are in use in the gas industry for a number of years. Therefore, the components used in the new energy meter have already proven to be highly accurate and reliable and if necessary at all, require a low

calibration frequency. This is probably one of the reasons that during the test period of more than one year, no instruments had to be recalibrated and not a single malfunctioning of the applied instruments did occur.

The new energy meter can be easily mounted in a small explosion proof box near the sampling point, making the investment costs relatively low.

Finally, the new meter combines low gas consumption with a fast measuring cycle and is therefore well suited for process control in for example blending stations.

2   PROJECT OBJECTIVES

The objectives of the overall project were to construct an accurate velocity of sound meter and to develop an energy meter based on the measurement of three properties using either one or two velocity of sound measurements. Both laboratory and field tests were conducted to evaluate the performance of the energy meters and to make a comparison with the highly accurate Daniel Danalyzer field gas chromatograph model 500, which is used for billing purposes by Gastransport Services in the Netherlands. Further improvements were made to obtain a high performance Wobbe meter.

3   THEORETICAL BACKGROUND AND CALCULATION PROCEDURE

The correlation method is based on the assumption that natural gas can be characterized as a four-component mixture consisting of nitrogen, carbon dioxide and an equivalent hydrocarbon gas (methane + higher hydrocarbons). The same approach is already used for the SGERG equation [1], [2]. A dedicated iterative method was developed on the basis of this correlative method [3]. Using three input parameters, the composition of the twelve main components in natural gas can be calculated, which can be used to compute the superior calorific value, density, compressibility and Wobbe index.

As stated before, the correlation method requires measured values of three independent gas properties. Preferred are properties, which can be measured with relatively simple but accurate and reliable sensors. The sensors need to be easy to maintain and have costs of ownership considerably lower than the present energy measurement methods. The joint project of Gastransport Services and Ruhrgas revealed a number of combinations of measurable gas properties [4], [5], [6], [7]. Especially the combination of velocity of sound at low pressure, velocity of sound at high pressure and molar fraction carbon dioxide appears to be attractive, because it meets the conditions mentioned before and it is able to give accurate results [8] and is the reason for a dedicated discussion in this paper.

A schematic view of the calculation method is shown in Figure 1. The calculation procedure used in the iterative correlation program has the following sequence: an initial gas composition is used to compute the velocity of sound. The computed velocity of sound is compared with the measured velocity of sound. Because the velocity of sound is a function of P and T, these two parameters have to be measured with high accuracy as well.
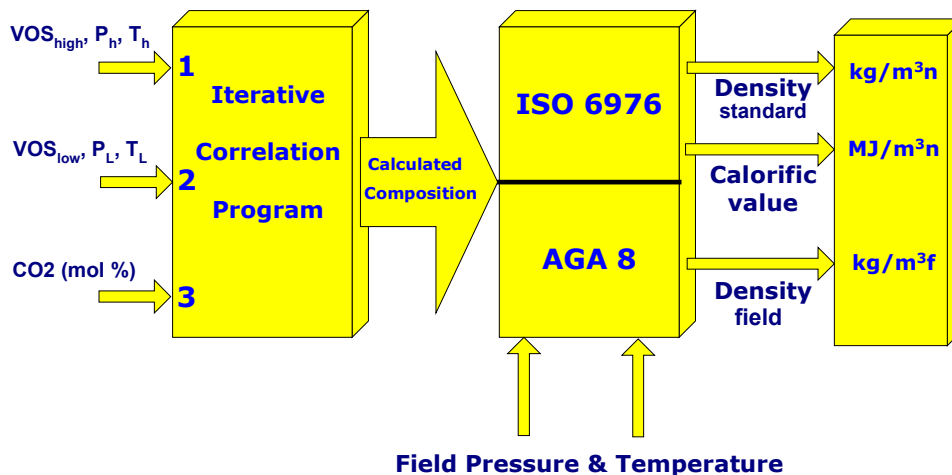
Fig. 1 - Method used to calculate the calorific value, density, Wobbe, etc.
from three independent gas properties

Depending on the differences, the composition is adjusted and the calculation loop is repeated until the absolute value of the differences between computed and measured velocities of sound are less then 0.005%. The final gas composition is used to compute the superior calorific value under reference conditions, H_{SR} in MJ/m^3 (n), the superior calorific value under field conditions, H_S, the densities, ρ_R and ρ and the compressibilities Z_R and Z under reference and field conditions, respectively.

The correlation model itself was validated with several gases of known composition abstracted from the list of GERG-gases [9] and with a number of test gases, which were analysed with a laboratory GC, according to ISO 6974 and ISO 6976. The known composition was used to calculate H_{SR} as well as the velocity of sound at low and high pressure. Both velocities of sound and the molar fraction CO_2, were used as input parameters for the correlation model.

Calculations showed that the correlation model, based on two velocity of sound measurements and the molar fraction carbon dioxide, predicts the superior calorific value within 0.1% for the whole range of natural gases.

Also important is the sensitivity of the correlation model with respect to small deviations (due to random or systematic errors) in the measured data. Calculations showed that 0.01% deviation in VOS_{high} and VOS_{low} result into an error in H_{SR} of -0.11% and +0.12% respectively. The error in H_{SR} increases if the difference in pressure decreases at which VOS_{high} and VOS_{low} are measured. Deviations in the measured temperature of the gas also result in relatively large errors in H_{SR}. A deviation of 0.01% (30 mK) in T_{high} and T_{low}, the temperature of the high pressure and low pressure velocity of sound measurement, induces an error in H_{SR} of +0.07% and –0.06%, respectively. Deviations in pressure and molar fraction CO_2 result in much smaller errors in H_{SR}. If VOS_{high} and VOS_{low} deviate both +0.01%, the errors in H_{SR} are almost compensated (-0.11% + 0.12% = 0.01%). The same situation occurs for T_{high} and T_{low}. Therefore, systematic errors in velocity of sound and temperature measurement (for example due to calibration), result in only relatively small errors in the calorific value.

4   THE INSTRUMENTS

4.1   Velocity of Sound Meters

Preliminary tests were carried out with a Q.Sonic-3 Ultrasonic gas flow meter of Instromet Ultrasonics. Ultrasonic gas flow meters give both gas velocity (the main property) and velocity of sound (secondary property for diagnostics) as output. The results indicated that the method of transit time measurement applied in ultrasonic gas flow meters is very suitable for accurate velocity of sound measurements.

Application of velocity of sound as a measurement in correlative energy metering implicates the following requirements for VOS-meters: (a) high accuracy (better than 0.03%) and very high reproducibility (better than 0.005%); (b) the VOS-meters need to operate with a continuous gas flow, so a small internal volume is important for low gas consumption; (c) the temperature and pressure of the gas in the VOS-meter have to be known accurately and thus only changes in temperature and pressure at a time scale relative large to the measurement time (seconds) are allowed. Besides, the temperature and temperature profile of both VOS-meters should preferably be identical.

Gasunie Research developed in cooperation with Instromet a low volume, highly accurate VOS-meter which fulfils the requirements mentioned above. The new VOS-meter is based on transducers and electronics of the new Q.SONIC-3S compact ultrasonic flow meter of Instromet Ultrasonics. A picture of the new VOS-meter is shown Figure 2. Two identical meters were applied, one for high pressure VOS measurements and one for low pressure VOS measurements. The volume of the VOS-meter was roughly 20×10^{-6} m^3, and the path length was approximately 0.12 m.
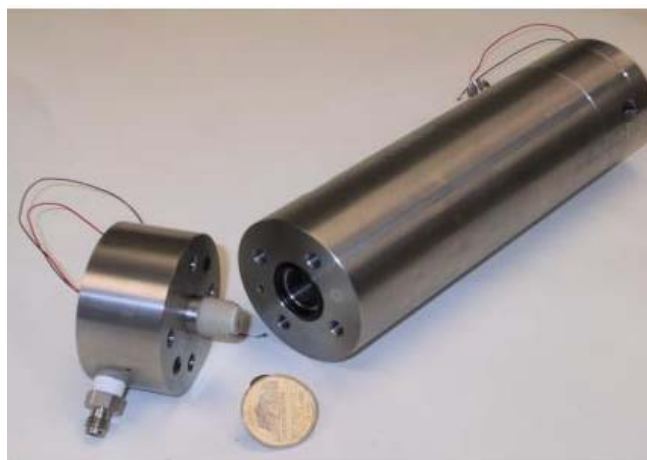

Fig. 2 - The low volume, highly accurate velocity of sound meter

Experiments with several gases showed that the difference between measured and calculated velocity of sound was always within 0.04% [10]. The velocity of sound is computed from the known gas composition, pressure and temperature using software based on the AGA8-DC92 equation of state. Deviations can originate from measurement errors, but also result from small GC-analysis errors, which do not show up in the calculated calorific value but do show up in the calculated velocity of sound. The reproducibility of the velocity of sound measurements, 2σ, was better than 0.005%.

4.2   The CO$_2$-meter

The CO$_2$-meter applied in the correlative energy meter, see Figure 3, is a commercially available non-dispersive, dual wavelength near infrared meter, type AGM10, range 0 – 5 mol% CO$_2$, from Sensor Europe. The meter is kept at a constant temperature of 50 °C and is equipped with pressure compensation. The measurement uncertainty is 0.05 mol% and the reproducibility is 0.01 mol%.
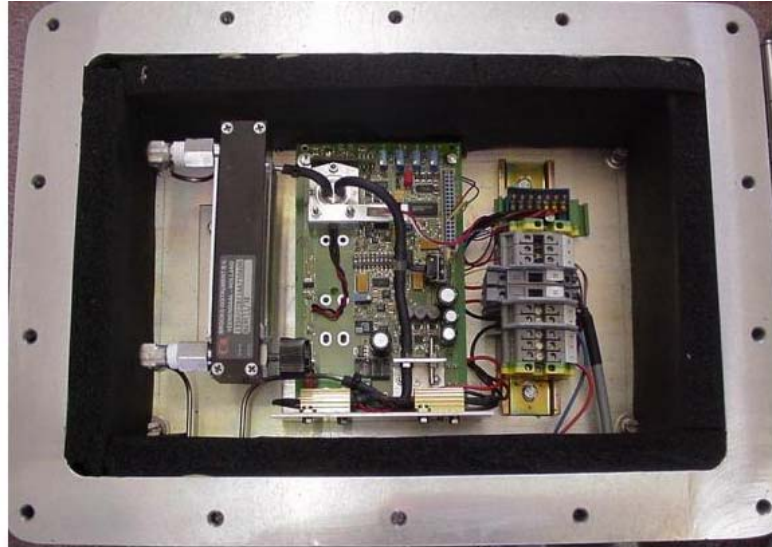
Fig. 3 - The applied CO_2-meter in Eex-housing

4.3 Pressure and Temperature Measurements

The pressure is measured with Yokogawa EJA310A absolute digital pressure transmitters with an intrinsically safe approval. The uncertainty of these transmitters is 0.01 bar and the reproducibility is 0.005 bar. The temperature is measured with 1/10 DIN 4-wire PT100's and Moore Industries TDZ digital and intrinsically safe temperature transmitters. The uncertainty in the temperature measurement is 0.03K, whereas the reproducibility is better than 0.01K.

4.4 The Calorimeter

The calorimeter, which was used to test the low pressure correlative energy meter, was a Tru-Therm of Instromet. This meter determines the heating value of natural gas at reference conditions by means of stoichiometric combustion. The instrument requires a constant oil-free air flow and uses pure methane (quality 4.5) as reference gas. Calibration was carried out every 4 hours.

4.5 The Energy Meter

A schematic view of the correlative energy meter is shown in Figure 4. Natural gas has to be available with a pressure above 40 bar. The pressure is reduced, preferably by low volume reducers, to approximately 40 and 5 bar. Both the high pressure and low pressure gas flow passes a heat exchanger before entering the VOS-meters. The heat exchangers and VOS-meters were placed in an isolated box, which had the possibility to be temperature conditioned. The gas flow was controlled by needle valves downstream of the VOS-meters. Part of the low pressure gas is diverted to the CO_2-meter.

The gas consumption was approximately 2.5×10^{-3} m^3/hr in both VOS-meters, corresponding to a residence time of approximately 30 seconds. A data acquisition system stored the required measurement data: VOS_{high}, T_{high}, P_{high}, VOS_{low}, T_{low}, P_{low} and X_{CO2} and subsequently a computer system calculated the results (gas composition, calorific value, density and compressibility under reference conditions).

The low pressure correlative energy meter uses the results of VOS_{low}, X_{CO2} and the Trutherm calorimeter, which was connected to the basic gas stream using a reducer and a fast loop.
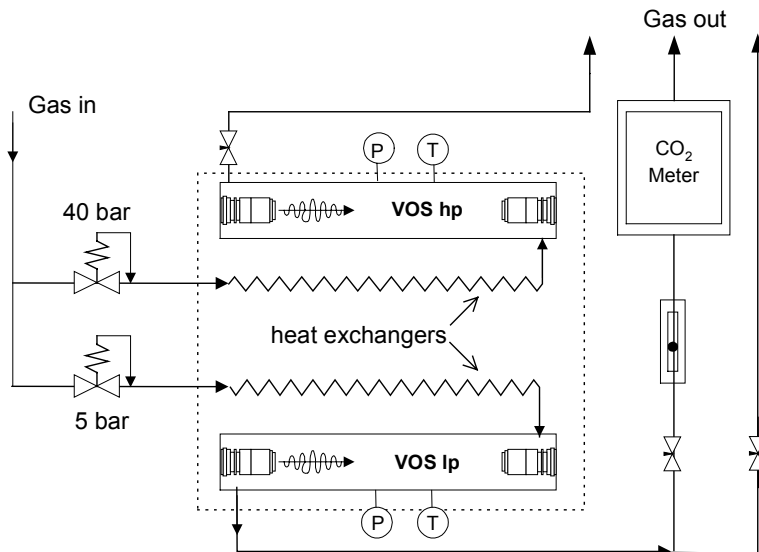
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Fig. 4 - The energy meter based on two velocity of sound and CO_2 measurements.
The components within the dotted lines are placed in an isolated
box, which has the possibility for temperature conditioning

5   RESULTS OF LABORATORY TESTS

In Figure 5 the difference is shown between the calorific value under reference conditions measured with the correlative energy meter and measured with a HP 5890 laboratory GC (with analysis according to ISO 6974 and gas property calculation according the ISO 6976). Gases with large variations in composition were applied, the calorific value varied between 33 and 45 $MJ/m^3(n)$. These tests were performed to show that this correlative technique is applicable for all natural gases.
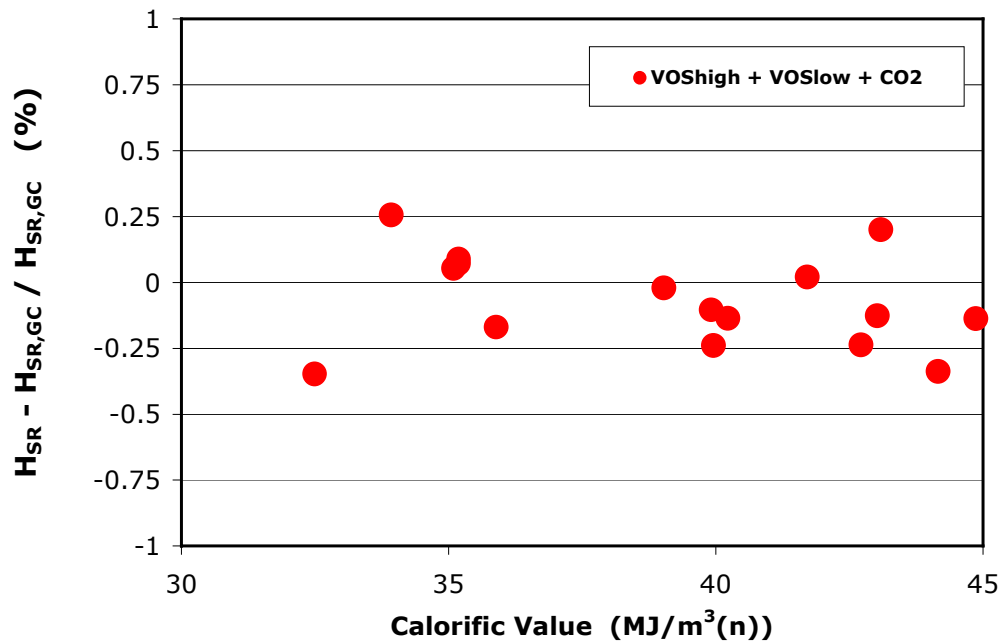

Fig. 5 - The relative deviation in superior calorific value measured by the
correlative energy meter and a laboratory GC

From Figure 5 it can be concluded that these preliminary results indicate that the maximum deviation of H_{SR} calculated from two VOS-values and the molar fraction CO_2 is ±0.3% with respect to the value of H_{SR} obtained from a laboratory GC. The reproducibility, 2σ, of H_{SR} was measured from 100 consecutive measurements, yielding 0.11%, and being independent of the gas composition.

6   RESULTS OF THE ALPHA FIELD TEST

A first field test was carried out to investigate the long term stability, the reliability, the possible effect of fouling on the measuring devices and the possible occurrence of drift in the instruments reading. Also the influence of changes in environmental conditions were studied. The instruments were mounted in a portable cabin, which was placed at a metering station.

A Danalyzer field gas chromatograph was mounted in the cabin as well. The reproducibility of the calorific value calculated from the compositional data generated by the Danalyzer is within ±0.02%. By comparing the results of the new correlative energy meter with the Danalyzer, the topics mentioned above (stability, fouling of meters, drift) could be monitored perfectly. The field GC updates the calorific value every 15 minutes, the correlative energy meter nearly every 10 seconds. Hourly averaged values of the calorific value of both the GC and the energy meter were used to make the comparison between both instruments over a long period of time.

The results of the hourly averaged values of the measured calorific value for a three week period are shown in Figures 6 and 7.

From Figures 6 and 7 it can be concluded that the energy meter based on two velocity of sound measurements and a CO_2-measurement has a small but almost constant off set compared to the Danalyzer GC. This small off set is caused by the fact that the (2*VOS+CO2) energy meter was calibrated using data from a laboratory GC. The calibration parameters of the VOS-meters were adjusted so that the deviation in measured and calculated VOS for nine different gases was minimal.
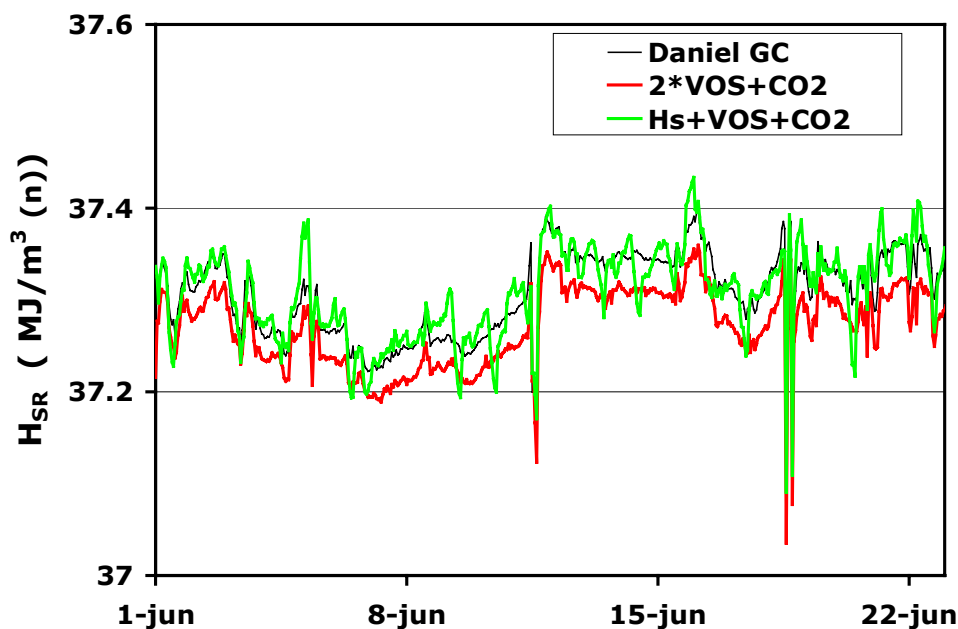

Fig. 6 - The calorific value obtained from the Danalyzer GC, and the two new energy meters.

The mean calorific value obtained from the (H_S+VOS+CO_2) energy meter and from the Danalyzer GC are the same. However the variation in the hourly averaged values of H_{SR} from the (H_S+VOS+CO_2) energy meter is significantly larger compared to the hourly averaged values from the Danalyzer GC, and also compared to the hourly averaged values obtained from the (2*VOS+CO_2) energy meter. This large variation is almost entirely caused by the measurement uncertainty of the calorimeter.
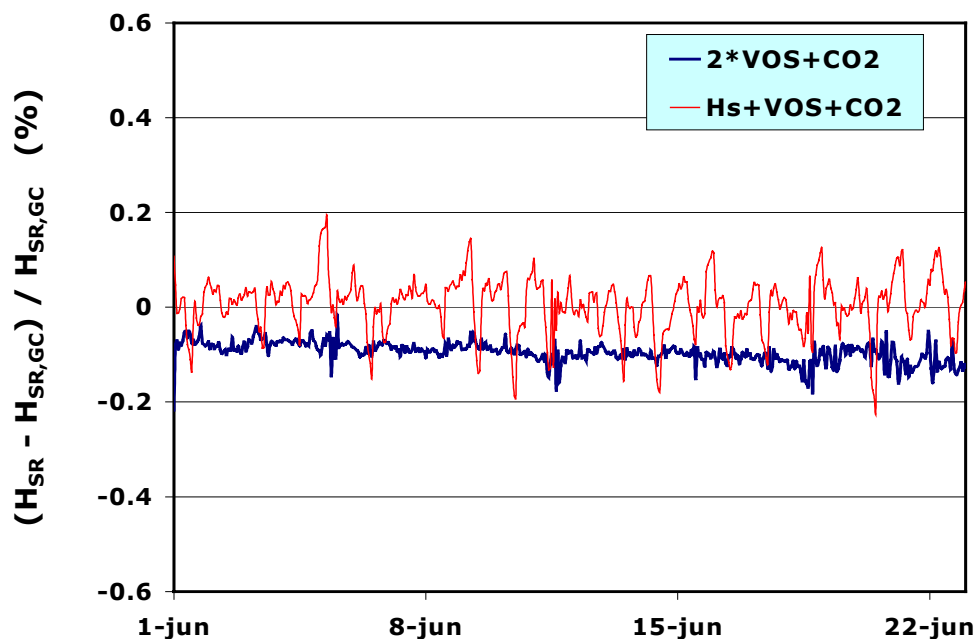

Fig. 7 - The relative deviation between the calorific value measured by the new energy meters and the Danalyzer PGC over a three week period.

The random errors in the measured parameters of the (2*VOS+CO_2) energy meter and the corresponding uncertainty in H_{SR} were determined using 100 measurements during a short period of almost constant gas composition. The results are shown in the second and third column of table 1. The random error of H_{SR} determined from the individual contributions (0.12%) and the measured random error in H_{SR} (0.1%) are in good agreement with each other and with the value given in table 2. It is clear that the random errors in VOS_H and VOS_L give the largest contribution to ΔH_{SR}, followed by the random error in the measured temperatures. The random error in the hourly averaged values of $H_{SR,correlation}$ and $H_{SR,GC}$ are both approximately 0.02%.

Table 1 - Variation in the calculated calorific value with respect to measured random
errors (2σ) in the input parameters, during the alpha field tests.
P_{VOSH} and P_{VOSL} were respectively 39 and 5 bar.

Parameter	Alpha field test	
	Δ(Parameter) 2σ (%)	ΔH_{SR} (%)
CO_2	0.2	0.001
VOS_H	0.006	0.075
T_{VOSH}	0.003	0.021
P_{VOSH}	0.01	0.002
VOS_L	0.006	0.092
T_{VOSL}	0.003	0.019
P_{VOSL}	0.1	0.011
ΔH_{SR}(calculated):		*0.12%*
2σ of ΔH_{SR}(measured):		*0.10%*

During the alpha field test the variations in the calorific value measured by the ($2*VOS+CO_2$) energy meter were often larger than the value calculated above. These variations were mainly caused by the large temperature fluctuations in the cabin due to weather influences. This leads to a continuous sinusoidal variation in the temperature of the velocity of sound meters, resulting in internal temperature gradients in the VOS-meter bodies. These gradients are responsible for small deviations between the real gas temperature in the velocity of sound meters and the temperature measured by the Pt100.

Control measurements with a test gas made in regular intervals, showed clearly that both VOS-meters did not show any significant drift during the alpha field test. In Figure 7 the difference between the calorific value measured by the ($2*VOS+CO_2$) energy meter and the Danalyzer is not constant, which might be an indication for drift of an instrument. After examining all measured data, it appeared that the temperature of the VOS-meters increased continuously in this period, resulting in a somewhat lower calorific value measured by the correlative energy meter. This temperature effect was already discovered in an earlier phase during calibration tests at different temperatures [10].

Tests with different gases showed that the systematic error in the VOS-measurements is slightly depending on the type of gas measured. Until now it is not possible to address the exact source of this (small) deviation. It is possible that the VOS measurement itself is slightly gas dependent, on the other hand the AGA8 calculation model or the uncertainty in the concentration of the components obtained by a GC analysis could be responsible for this error too. For example it appeared that gas analysed on two identical lab GC's, resulting in the same superior calorific value, still show some very small differences in the composition. These small differences in composition are responsible for a difference of 0.04% in the calculated VOS.

The other instruments (CO_2-meter and pressure and temperature transmitters) did not show any drift during the alpha field test.

In Table 2 the results obtained during this duration test are summarised. Using monthly averaged calorific values, the difference between the ($H_S+VOS+CO_2$) energy meter and the Danalyzer GC is less than $\pm$ 0.02%. The difference between the ($2*VOS+CO_2$) energy meter and the Danalyzer GC is between –0.11% and –0.14%. The offset is mainly due to the calibration method of the new meter. The measured reproducibility (2σ) of the difference in

calorific value between the new energy meters and the Danalyzer GC was approximately 0.1%. Because the reproducibility of the Danalyzer GC is better than 0.02%, it can be concluded that the reproducibility of the new energy meters is approximately 0.1%, which corresponds with the value measured during the laboratory tests.

Table 2 - The results of the duration tests for the energy meters (**A**: Hs+VOS$_{low}$+ CO2, **B**: VOS$_{high}$+VOS$_{low}$+CO2) compared with the Danalyzer.

	April and May		June		July	
Meter-type	A	B	A	B	A	B
H$_{SR}$ (averaged)	37.230	37.184	37.429	37.278	37.429	37.486
H$_{SR}$ - H$_{SR}$(Danalyzer)	-0.016%	-0.141%	0.010%	-0.109%	-0.003%	-0.138%
Reproducibility (2σ)	0.09%	0.102%	0.132%	0.093%	0.096%	0.092%

7 IMPROVEMENTS REQUIRED FOR A COMMERCIAL PRODUCT.

Experiences obtained during the field test and an assessment of the experimental uncertainties of the measured properties indicated the possibilities for a number of improvements. It was recognized that the successful implementation of this technique into a commercial product would benefit from the implementation of a number of improvements.

These improvements are:

a. *An identical and constant temperature for both VOS meters*
   With both VOS-meters in one housing, kept at a constant temperature above ambient, the random error in the computed calorific value is reduced, while temperature control is still simple, accurate and thus low cost. By making a cylindrical housing of aluminium and covering the surface with a heat tracing, the axial and radial temperature gradients are minimized, see figure 8. The temperature can be kept constant at 323K $\pm$0.005K by using an Omron temperature controller and a PT100 with Moore Industries transmitter.

Fig. 8 - The high and low pressure VOS-meter in one housing made of aluminium and surrounded by a heat tracing.

b. *Minimising the random error in the VOS measurements*
This was realized by increasing the number of VOS measurements in one cycle and by optimising the parameters of the VOS meters. The improved temperature control also effected the random error in a positive way. The velocity of sound is measured with a reproducibility better than 0.0015% (2σ- value of 20 consecutive measurements at constant gas composition).

c. *A decrease in internal volume of the VOS meters*
The current system requires the availability of natural gas at a pressure of at least 40 bar for the determination of the velocity of sound at high pressure. For the measurement of the velocity of sound at low pressure, the pressure is reduced to approximately 5 bar. A continuous gas stream passes through both VOS-meters. Given a response time of one second, the gas in the VOS-meters has to be completely refreshed at least every second too. A VOS-meter with a volume of 20 x 10^{-6} m^3 requires thus 3 m^3 (n)/hr natural gas at 40 bar, and 0.35 m^3 (n)/hr at 5 bar. A reduction of the internal volume of the VOS meter by a factor of 9 was achieved, reducing the vented natural gas with the same factor.

d. *A decrease in response time*
The response time of the prototype was approximately 20 seconds. By using an alternative data acquisition system and by reducing the volume of the sampling system and the VOS-meters, it was possible to realise a response time of a few seconds. The flow scheme of the new system is shown in figure 9. The pressure in both VOS-meters is determined by back-pressure valves downstream of the VOS- meters and the flow is adjusted by needle-valves upstream of the VOS-meters. The heat exchangers for the high and low pressure gas were integrated in the aluminium cylinder body as well.

e. *Construction of the energy meter in Eex enclosure*
The improved energy meter is mounted in an explosion-proof enclosure before starting the beta- field test.
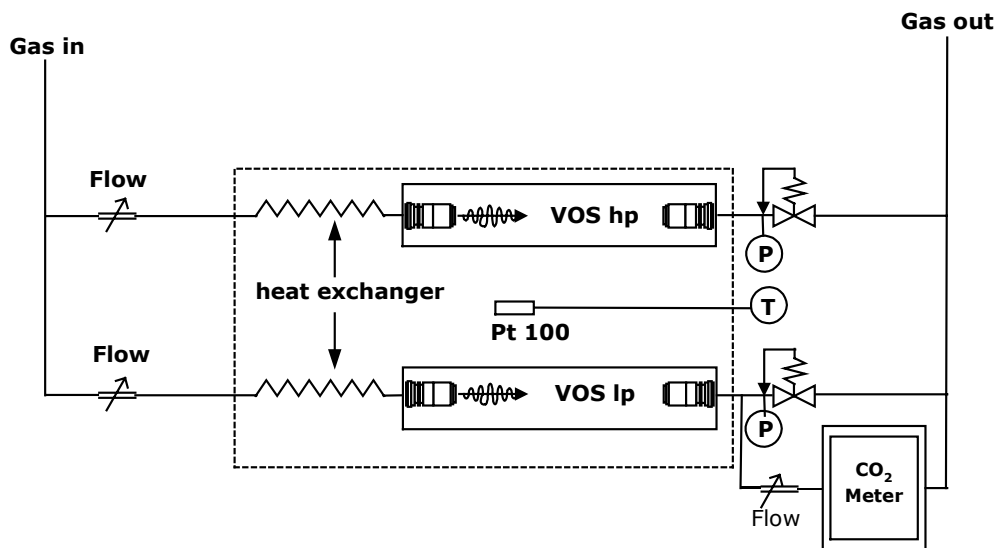

Fig. 9 - A schematic view of the improved energy meter. The aluminium cylinder, which is kept at 323 K, contains the components within the dotted lines.

8 RESULTS OF THE BETA FIELD TEST

First, the improved energy meter was tested at the research facility of Gastransport Services. During these tests both the superior calorific value, H_{SR}, and the Wobbe index, W_i, were calculated and compared to the results of a Danalyzer field GC. The Wobbe index is defined as the ratio of the superior calorific value to the square root of the relative density, d, of a gas:

$$W_i = H_{SR}/\sqrt{d} \tag{1}$$

$$d = \rho_{R,gas} / \rho_{R,air} \tag{2}$$

The Wobbe index is a measure of the amount of energy delivered to a burner via an injector. Two gases of differing composition and calorific value but having the same Wobbe index will deliver the same amount of energy for any given injector under the injector pressure.
Compared to the results of the alpha field test, the random error (2σ) in H_{SR} is reduced from 0.1% down to approximately 0.023%. The random error in W_i is approximately 0.025%, which indicates that the error in the calculated density is also very small.
The uncertainty (approximately ±0.3%) of the improved meter did not change in comparison with the first prototype.

In an additional field test, the long term stability and reliability, the calibration frequency, fouling of the measuring devices and drift due to changes in the measurement conditions were studied. The outcome of the correlative energy meter was again compared to a Danalyzer field gas chromatograph.
In figure 10 the difference in superior calorific value obtained from the correlative energy meter and the GC are shown. It can be concluded that there is no systematic deviation anymore compared to the GC. Also, during this period no drift was detected. The reproducibility of the new energy meter and the Danalyzer are both approximately ±0.02%.

A number of response time measurements showed that the response time of the new meter approximately 6 seconds and consists of two major contributions. The response time to refresh the gas in the VOS-meters is 2 - 2.5 seconds, whereas the response time of the electronics is 3 - 4 seconds. The latter can still be improved.
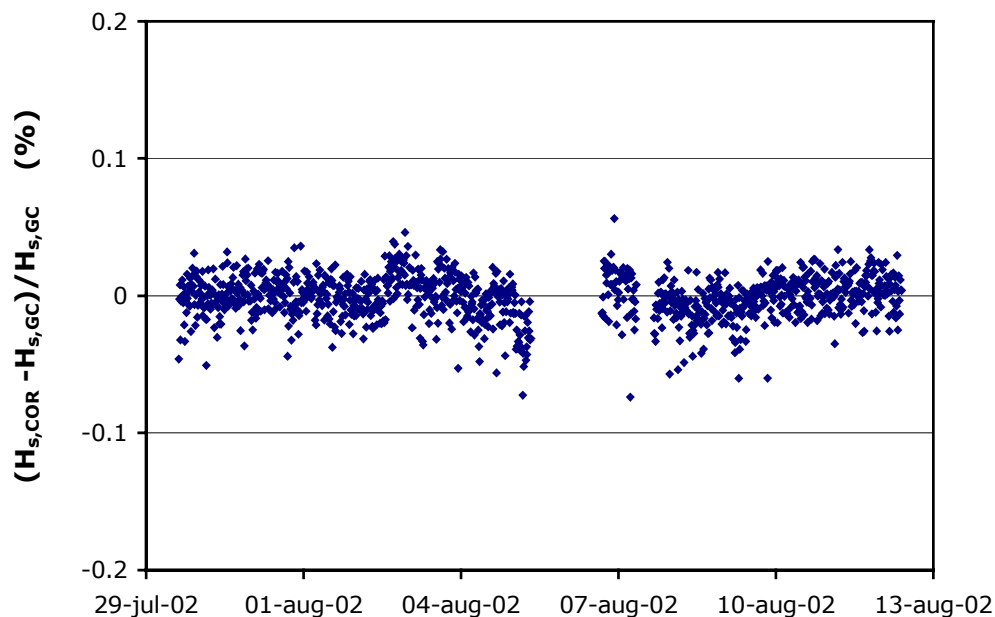

Fig. 10 - The difference between the superior calorific value obtained by the correlative energy meter ($H_{S,COR}$) and the Danalyzer ($H_{S,GC}$) during a period of 14 days.

Again, the random errors in the measured parameters of the improved energy meter and the corresponding uncertainty in H_{SR} were determined using 100 measurements during a short period of almost constant gas composition. The results are shown in table 3. The random error of H_{SR} determined from the individual contributions (0.026%) and the measured random error in H_{SR} (0.023%) are in good agreement with each other. The results of the improvements are evident when looking to the random errors in the measured properties during the alpha and beta field test, see Table 3. The small random error in H_{SR} and W_i is mainly due to the improved VOS-measurements and better temperature control.

Table 3 - Variation in the calculated calorific value with respect to measured random errors (2σ) in the input parameters, during the alpha and beta field tests. P_{VOSH} and P_{VOSL} were respectively 39 and 5 bar.

Parameter	Alpha field test		Beta Field test	
	Δ(Parameter) 2σ (%)	ΔH_{SR} (%)	Δ(Parameter) 2σ (%)	ΔH_{SR} (%)
CO_2	0.2	0.001	0.2	0.001
VOS_H	0.006	0.075	0.0015	0.02
T_{VOSH}	0.003	0.021	0.003	0.003
P_{VOSH}	0.01	0.002	0.02	0.004
VOS_L	0.006	0.092	0.001	0.015
T_{VOSL}	0.003	0.019	= T_{VOSH}	0
P_{VOSL}	0.1	0.011	0.1	0.003
ΔH_{SR}(calculated):		0.12%		0.026%
2σ of ΔH_{SR}(measured):		0.10%		0.023%

9   CONCLUSIONS AND OUTLOOK

Newly developed, low-volume and highly accurate velocity of sound meters provide velocity of sound data, which deviate less than 0.04% from the calculated velocity of sound with a reproducibility within 0.002%.

A sensitivity study revealed that systematic errors in the velocity of sound measurements at high and low pressure result in errors with the same order of magnitude in the calculated calorific value. The same holds for the temperature measurement in both VOS-meters. Random errors in the velocity of sound result in a 10 times higher error in the calorific value.

The calorific value, H_{SR}, can be determined with a maximum uncertainty of $\pm$0.3% with respect to a laboratory GC, by measuring the molar fraction carbon dioxide and the velocity of sound at two different pressures ($P_H – P_L > 35$ bar). Under laboratory conditions the reproducibility was $\pm$0.12%. During the alpha field test the reproducibility of the new energy meter was $\pm$0.1%.

A number of improvements were carried out and at the moment the improved meter is tested in a beta field test. The results of the tests undertaken so far, indicate that the uncertainty (< $\pm$0.3%) and measured reproducibility ($\pm$0.02%) of the improved correlative energy meter are fully comparable with highly accurate field GC's used in custody transfer applications, nowadays.

The new correlative energy meter, based on velocity of sound measurements at 40 and 5 bar and a CO_2 measurement, seems a promising instrument to determine the energy value of gas streams at production sites and custody transfer stations. Due to its short response time of only a few seconds, it is also an ideal instrument to determine the energy value (Wobbe index) of natural gas streams for process control applications such as for example at blending stations.

Furthermore, the costs of ownership for the new system are considerably lower compared to current energy meters and Wobbe meters.

10   NOTATION

d	relative density of natural gas to air at reference conditions
H_{SR}	superior calorific value under reference conditions, $MJ/m^3(n)$
P	Pressure, bar
T	Temperature, K
VOS	Velocity of sound of natural gas, m/s
W_i	Wobbe index
Z	Compressibility of natural gas
$\rho_{R,gas}$	density of natural gas at reference conditions
$\rho_{R,air}$	density of air at reference conditions

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