Analysis of the metrological performance of diaphragm gas meters in a city distribution network

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1 Background

Nowadays, in the italian distribution networks almost totally diaphragm gas meters are installed and it is quite usual to find very old meters still operating, because of the lack of a strict law regarding their legal duration until 2009, when finally a maximum legal duration of 15 years have been fixed [1].

The italian Authority for natural gas (AEEG) recently issued the mandatory resolution 155/08 [2] regarding the gradual substitution of all the old domestic gas meters installed in the italian distribution networks, in order to guarantee strict metrological performance for the consumers (also by correcting in the new models of gas meters the measured volumes with the operative gas temperature).

In such a wide market (only in Italy about 20 millions domestic gas meter are installed) the reduction of costs and the development of new components and materials in the gas meters are continously pursued both by meters manufacturers and gas city companies. Furthermore, the very old gas meters installed (before 1990) were manufactured with animal diaphragms, and it is common opinion that this can induce significant errors because of the decay of the performance of the diaphragm itself. In recent years (after 1990) the animal diaphragms have been replaced by synthetic ones, expected to be more resistant and reliable.

In this background, in order to better plan the substitution operations (involving about 350,000 gas meters only in Genoa up to 2016) in function of drift, age and installation of the meters and to properly define right customer policies, Genova Reti Gas commissioned to LAMI, the industrial measurement laboratory of the University of Cassino, and to Palmer, the Scientific Park of Southern Lazio, a detailed analysis of the gas meters installed in the gas city network of Genoa, by performing several performance tests [3, 4, 5, 6, 7].

Futhermore, the attention to unaccounted for gas (UAG) is nowadays continuously increasing both at transport and at distribution level and to this aim the knowledge of the metrological performance of the meters play a very critical role [8, 9].

2 Aims

On a representative sample of domestic diaphragm gas meters installed in the distribution network of Genoa and in compliance to the main applicable parts of the actual international standard EN 1359:2006 [3] the following metrological performance test have been conducted: i) error of indication, ii) pressure absorption, iii) external leak tightness, iv) resistance to internal pressure. After the metrological performance tests, all the meters have been disassembled and visually checked and then a planarity analysis of the moving couplings (grids and distributing valves) have been performed.

In particular, the errors of indication have been compared both to the limits of the actual EU MID Directive [4] and to the limits of the Italian legal metrology law in force at the meter's manufacturing times.

As well known, the EU MID Directive [4] doesn't fix any rule on subsequent verifications, leaving to each member state the faculty to define its own approach guaranteeing the continuity with the existing national rules. Obviously, it is clear that the subsequent verifications of gas meters (even in service) have to be fully regulated and, to this aim, the italian Authority for legal metrology is nowadays close to issue a specific decree on this relevant item. By the proof circulating, it seems probable that the maximum permissible errors (mpe) in subsequent verification and in service could be double in respect to the corresponding errors in the initial conformity assessment, as fixed in 5.3.3 of OIML R137-1:2006 [5]; that is for a domestic meter (MID class 1,5) the maximum permissible errors in subsequent verifications could be the following in table 1:

Table 1 – Maximum Permissible Error (MPE) for domestic gas meters (MID class 1,5) in initial conformity assessment and in subsequent verification*

	Flowrate range	*MPE for the EU MID (class 1,5) in force after 2007*	*MPE for the Italian legal metrology law in force before 2007*
in initial conformity assessment	$Q_{min} < Q < Q_t$	± 3 %	± 3 %
	$Q_t < Q < Q_{max}$	± 1,5 %	± 2 %
*in subsequent verification**	$Q_{min} < Q < Q_t$	± 6 %	-
	$Q_t < Q < Q_{max}$	± 3 %	-

*fixed equal to twice the MID MPE (to be confirmed in a specific italian decree).

In the table 1 the transition flowrate Q_t is the flowrate occurring between the maximum and minimum flowrates at which the flowrate range is divided into two zones, the 'upper zone' and the 'lower zone'. Each zone has a different characteristic MPE. For diaphragm gas meters Q_t has been considered equal to $0{,}1Q_{max}$, as fixed in OIML R137-1:2006 par. 5.2.

3 Methods

Four samples of minimum 60 gas meters each have been withdrawn in 2011 directly from the natural gas distribution network of the city of Genoa: the first two samples with animal diaphragm meters manufactured before 1990 and two further samples with synthetic diaphragm meters manufactured after 1990 .

The following sampling criteria have been adopted, when possible: i) year of construction (up to 1965 and further groups of five years each), ii) manufacturer, iii) type of gas consumptions (kitchen, water heater, boiler), iv) consumptions ramges (<100, 100÷500, >500 $m^3/year$), v) installation (indoor/outdoor). After their removal all the meters have been immediately filled with humidified gas, sealed and stored in a conditioned room before their transportation to the laboratory.

The tests for the <u>*error of indication*</u> and <u>*pressure absorption*</u> have been conducted at LAMI (accredited calibration laboratory number 105) in an ambient in which both temperature and humidity were controlled, respectively at (20±1) °C and (50±10) %UR. The tests have been conducted by means of a 550 L bell prover test bench (see fig.1), whose traceability rises from a 50 L first line volume standard, calibrated at INRIM, the Italian National Metrology Primary Institute, with an expanded uncertainty of 3,3 mL (i.e about 0,007%), with a coverage factor k=2 corresponding to a probability of about 95%.

Fig.1 – Test Layout for the error of indication and pressure absorption tests

Auxiliary calibrated devices for the measurement of the main influence entities for the tests(ambient temperature, humidity and pressure) have been used during the tests. The typical relative expanded overall uncertainty of the bell prover test bench is less than ± 0,3% with a coverage factor k=2 corresponding to a probability of about 95%, so conforming to the general legal metrology rule that the overall expanded uncertainty of the test bench normally shall not exceed 1/3 to 1/5 of the maximum permissible errors of the meter under test.
The test have been conducted at the nominal flowrates Q_{min}, $0,2 \cdot Q_{max}$ and Q_{max}, in compliance to the Italian legal metrology law in force before 2007, with a further verification point at $0,5 \cdot Q_{max}$. Furthermore, according to OIML R137-1:2006 [5] par. 2.2.8, a weighted mean error of indication (WME) has been calculated by the following equation (1) as a function of the errors and of the flowrates at which the errors have been measured:

$$WME = \frac{\sum_{i=1}^{n} \frac{Q_i}{Q_{\max}} \cdot E_i}{\sum_{i=1}^{n} \frac{Q_i}{Q_{\max}}} \qquad (1)$$

where Q_i/Q_{max} is the wheighting factor and E_i is the error of indication at the flowrate Q_i. As regarding the MPE of the WME, the recommendation fixes a value of ±0,6% in initial verification. The other tests (external leak tightness, resistance to internal pressure and planarity) have been conducted at Palmer, accredited testing and calibration laboratory (number 273 and 85). Here below a brief description of these tests is reported:

i) *External leak tightness*:
In compliance to the par 6.2.2 of EN 1359:2006, the meter under test is pressurized at normal laboratory temperature with air to 1,5 times the declared maximum working pressure. The test is performed by means of a leak tightness test bench (with a calibrated air flowmeter and a digital manometer) by immersing the meter, without its index, in water and observing for leakage for about 30 s after any external trapped air has been dispersed (see fig.2).


[redacted]

Fig. 2 – External leak tightness test of gas meter

ii) *Disassembly and visual check*
After the external leak tightness tests the meters have been disassembled and visually checked in order to detect:

- the integrity of couplings and of the exit pipe;
- the presence of evident defects on the body of the meter;
- the possible leakages from the coupling grid-distributing valve and their wear conditions (see fig. 3 and 4).

Figure 3 – Meters disassembled waiting for dimensional check and internal leak test

Figure 4 – Gas meter completely disassembled for the visual check

iii) *Resistance to internal pressure*
In compliance to the par 6.2.3 of EN 1359:2006, the case of the meter under test is pressurized progressively with air to 1,5 times the maximum working pressure. The test is performed by means of the internal pressure test bench in fig.5 (equipped with a calibrated digital manometer) and the test pressure is maintened for 30 min and then released, also ensuring that the rate of pressurization or depressurization does not exceed 350 mbar/s.

Figure 5 – Test layout for the internal pressure test

iv) *Planarity of grid and distributing valve*
In order to check the presence of leakages and their possible correlation with the error of indication, the planarity of the respective contact surfaces of grid and distributing valve has been checked by means of a calibrated coordinate measuring machine. The planarity has been measured in a controlled environment (20±0,5 °C and 50±10 %UR) as the maximum height difference between 12 points in the coupling area (see fig.6 and 7).
As concerning to the planarity acceptance limits, a tolerance of 0,020 mm is fixed both for grid and distributing valve, in compliance to the planarity tolerances usually given by the main diaphragm gas meters manufacturers.

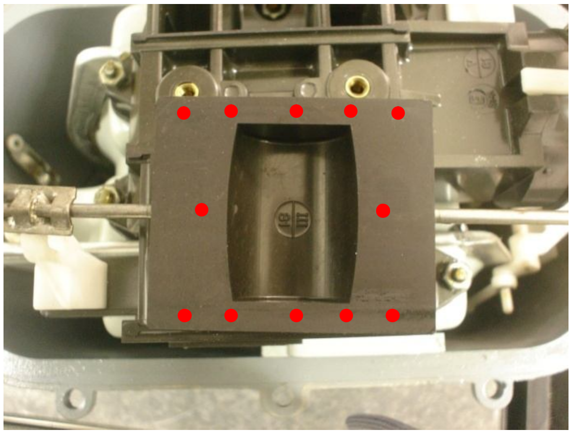

Figure 6 – Measuring points for planarity on the distributing valve

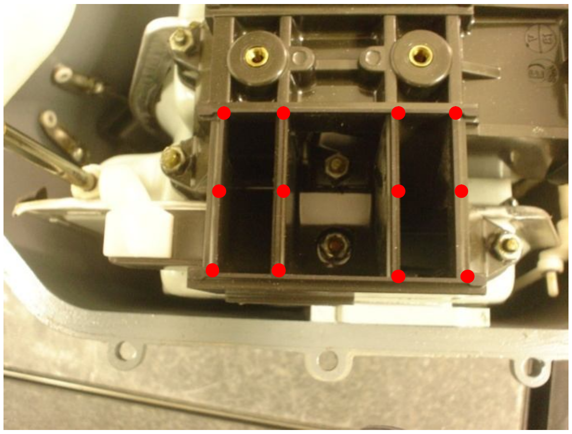

Figure 7 – Measuring points for planarity on the grid

4 Results

The results of the above described tests are here reported, grouped by animal and synthetic diaphragms. A wider emphasis has been given to the error of indication tests, because of their criticality both in consumer protection and integrity of supplying and, moreover, in the correct estimation of UAG. Furthermore the possible correlation between significant errors of indication and other metrological faults of the meter is presented.
In the following tables and graphs only the errors of indication lying under 50% form the statistical basis of the whole analysis, that is the errors higher than 50% were considered as

outliers data and they don’t contribute to the results presented, even if they have been considered as failed meters.

The average results of the diaphragm meters, both animal and synthetic, show a quite regular behaviour, with not significant faults, especially if compared to their age.

The error of indication test show a significant negative error (i.e. for consumer advantage) only at minimum flowrate, Q_{min}. In particular:

a) for the animal diaphragm meters (117 meters tested):
   - 8 meters (i.e. about the 7 % of the sample) present significant errors (in particular at minimum flowrate) and 14 meters (i.e. about the 12 % of the sample) present a negative error of indication at minimum flowrate higher than 50%;
   - 2 meters (i.e. about the 2 % of the sample) were blocked.

b) for the synthetic diaphragm meters (130 meters tested):
   - 6 meters (i.e. about the 5 % of the sample) present significant errors, especially at minimum flowrate and 2 meters (i.e. about the 2 % of the sample) present a negative error of indication at minimum flowrate higher than 50%;
   - 2 meters (i.e. about the 2 % of the sample) were blocked.

In the following tables 2a and 2b and in figures 8 and 9 the average errors of indication of the 247 diaphragm meters tested are reported, grouped by year and manufacturer, respectively (the failures have been evidenced with red ink).

Table 2a – Average errors of indication of the meters grouped by year.

Year		*Number of meter tested*	*Average E%*				*WME*	*% of meters presenting at all the test flowrates*	
			Q_{min}	*0,2 Q_{max}*	*0,5 Q_{max}*	*Q_{max}*		*negative errors*	*positive errors*
Synthetic d.	from 2001 to 2006	33	-2,8%	0,3%	-0,2%	-1,2%	-0,8%	27,3%	9,1%
	from 1996 to 2000	56	-2,6%	0,9%	0,2%	-0,8%	-0,3%	19,6%	8,9%
	from 1991 to 1995	41	-4,0%	0,8%	0,3%	-0,4%	-0,1%	14,6%	9,8%
	synthetic diaph. meters average	130	-3,1%	0,7%	0,1%	-0,8%	-0,4%	20,0%	9,2%
Animal diaphragm	from 1986 to 1990	20	-0,8%	1,8%	1,2%	0,8%	1,1%	5,0%	30,0%
	from 1981 to 1985	21	-4,0%	2,3%	2,5%	1,6%	**1,9%**	9,5%	19,0%
	from 1976 to 1980	17	0,1%	2,2%	2,6%	2,3%	**2,4%**	0,0%	52,9%
	from 1971 to 1975	19	**-6,0%**	-0,6%	1,1%	1,4%	1,1%	5,3%	21,1%
	from 1966 to 1970	21	**-9,1%**	-1,0%	0,6%	0,7%	0,4%	14,3%	4,8%
	up to 1965	19	**-18,8%**	0,3%	0,1%	0,8%	0,3%	15,8%	0,0%
	animal diaphragm meters average	117	-5,3%	0,9%	1,4%	1,3%	**1,2%**	8,5%	20,5%
Overall average**		247	-4,1%	0,8%	0,7%	0,2%	0,4%	14,6%	14,6%
MPE in subsequent verification-*			*±6,0%*	*±3,0%*	*±3,0%*	*±3,0%*	*±1,2%*	-	-

* equal to twice the MID MPE (to be confirmed in a specific italian decree)

** weighted in function of the number of meters tested

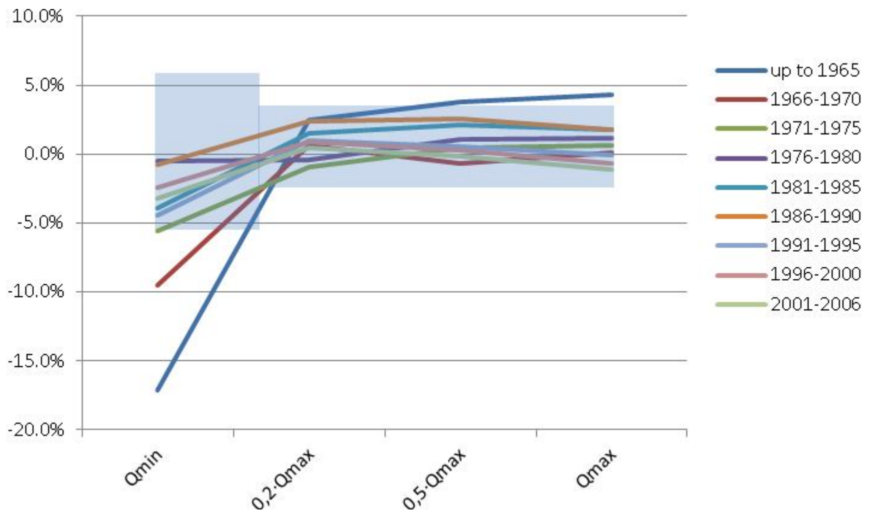

Fig.8 – Average error of indication of the gas meters tested, grouped by year and compared to the conformity area in subsequent verification*

From the above results it can be pointed out that all the synthetic diaphragm meters present a negative *WME* whereas all the animal ones present always positive *WME*. Furthermore the percentage of the meters presenting a systematic drift at all the flowrates is quite low (about 15% both in consumer advantage and disadvantage).

Table 2b – Average error of indication of the meters grouped by manufacturer.

	Manufacturer	*Number of meter tested*	*Average E%*				*WME*	*% of meters presenting at all the test flowrates*	
			Q_{min}	0,2 Q_{max}	0,5 Q_{max}	Q_{max}		*negative errors*	*positive errors*
synthetic diaphragm	Man.#1	22	-1,2%	1,4%	1,2%	0,9%	1,0%	36%	5%
	Man.#2	66	-4,4%	0,4%	1,5%	1,1%	1,1%	2%	9%
	Man.#3	4	0,2%	1,7%	0,7%	-1,0%	0,2%	25%	0%
	Man.#4	13	**-7,1%**	0,1%	0,1%	-0,3%	-0,2%	15%	31%
	Man.#5	13	**-8,2%**	0,1%	-0,6%	-1,3%	-1,0%	0%	38%
	Man.#6	6	-4,9%	0,4%	-0,5%	0,1%	-0,1%	17%	67%
	Man.#7	5	-5,8%	0,9%	0,9%	1,7%	**1,4%**	0%	0%
animal d.	Man.#1	41	-2,2%	1,7%	2,0%	1,8%	**1,7%**	32%	7%
	Man.#2	49	-1,5%	0,6%	-0,2%	-1,6%	-0,9%	18%	4%
	Man.#3	9	**-6,6%**	3,3%	1,6%	2,6%	**2,4%**	11%	0%
	Man.#4	14	**-21,0%**	-1,8%	-0,7%	-0,7%	-0,9%	0%	36%
*MPE in subsequent verification**			*±6,0%*	*±3,0%*	*±3,0%*	*±3,0%*	*±1,2%*	-	-

* equal to twice the MID MPE (to be confirmed in a specific italian decree).

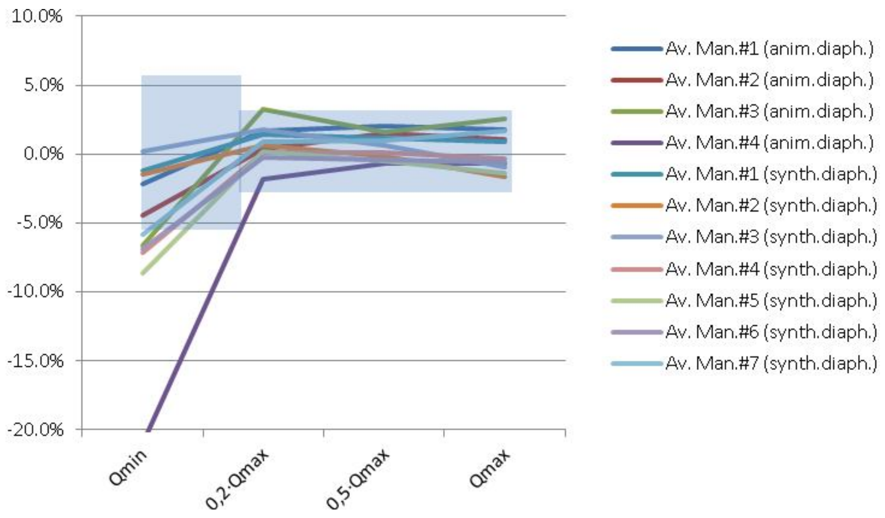

Fig.9 – Average error of indication of the animal diaphragm gas meters tested, grouped by manufacturer and compared to the conformity area in subsequent verification*

From the above results, the different performance at Q_{min} of manufacturers are demonstrated. In particular 3 synthetic diaphragm manufacturers and 2 animal diaphragm manufacturers show relevant error at Q_{min} and a single manufacturer (#4 in table 2b and figure 9) failed at Q_{min} both in animal and synthetic diaphragm meters.

Furthermore, a significant trend of the error of indication of the meter is demonstrated only at the minimum flowrate for animal diaphragm meters (see fig.10). The figure shows that an average error in consumer advantage occurs at Q_{min} and this become significant as the age of the meter becomes higher. On the other hand, no significant behaviour has been demonstrated at higher flowrates, even if the meters show a very small increasing trend at $0,5Q_{max}$ and Q_{max} also remaining within their legal limits.

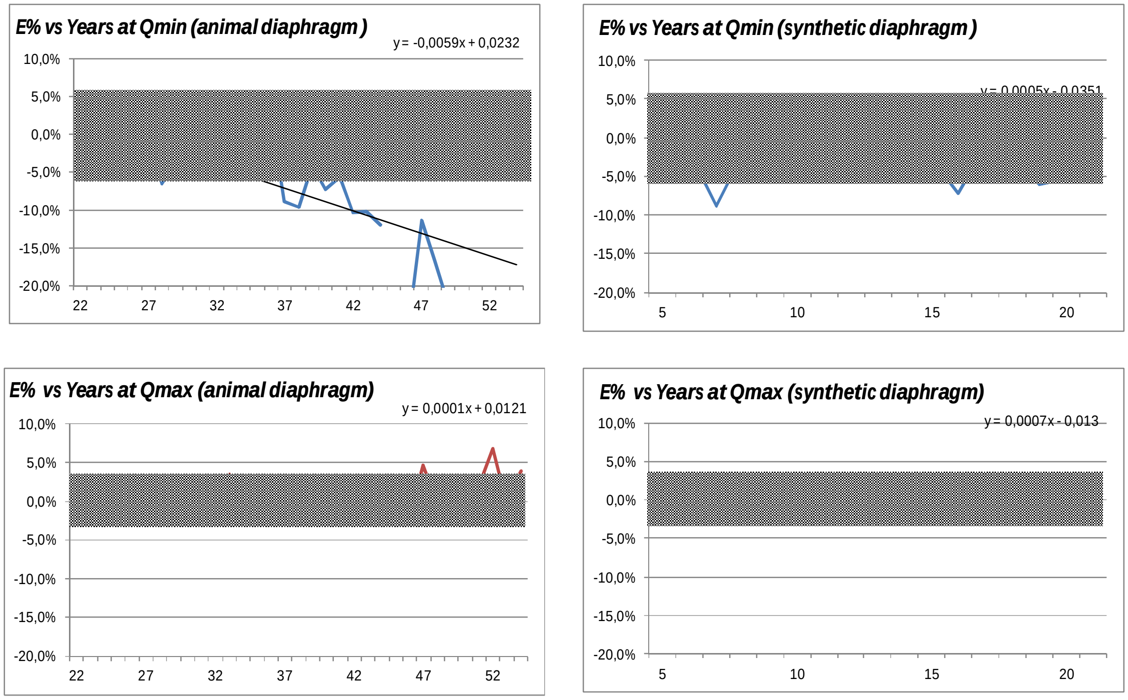

Fig.10 – Trend of the average error of indication at Q_{min} and Q_{max} as a function of the age of the meters

No significant results have been found as a function of the installation of the meter (indoor/outdoor), whereas the average year consumption of the meter seems to influence the error of indication of the only animal diaphragms meters (however generally within the values of MPE in subsequent verification): in fact, the average errors increase as the yearly consumptions decrease (see table 3 and fig.11).

Table 3 – Average error of indication of the diaphragm meters grouped by class of yearly consumptions

Average year consumptions (m^3/year)		*Number of meter tested*	*Average E%*				*WME*	*% of meters presenting at all the test flowrates*	
			Q_{min}	*$0{,}2 \cdot Q_{max}$*	*negative errors*	*negative errors*		*negative errors*	*positive errors*
synth	<100	33	*-2,5%*	*1,0%*	*0,4%*	*-0,5%*	*-0,1%*	*24,2%*	*9,1%*
	100<C<500	57	*-4,0%*	*0,5%*	*-0,1%*	*-1,0%*	*-0,5%*	*17,5%*	*10,5%*
	>500	40	*-2,4%*	*0,8%*	*0,2%*	*-0,9%*	*-0,4%*	*20,0%*	*7,5%*
animal	<100	37	***-9,2%***	*-0,8%*	*0,7%*	*0,6%*	*0,4%*	*16,2%*	*16,2%*
	100<C<500	38	*-3,7%*	*1,3%*	*1,3%*	*1,5%*	***1,4%***	*2,6%*	*23,7%*
	>500	42	*-3,8%*	*1,8%*	*2,1%*	*1,6%*	***1,7%***	*7,1%*	*21,4%*
overall	<100	70	-5,6%	0,1%	0,5%	0,1%	0,2%	20,0%	12,9%
	100<C<500	95	-3,9%	0,8%	0,5%	0,0%	0,2%	11,6%	15,8%
	>500	82	-3,0%	1,3%	1,1%	0,4%	0,7%	13,4%	14,6%
*MPE in subsequent verification**			*±6,0%*	*±3,0%*	*±3,0%*	*±3,0%*	*±1,2%*	-	-

* equal to twice the MID MPE (to be confirmed in a specific italian decree).

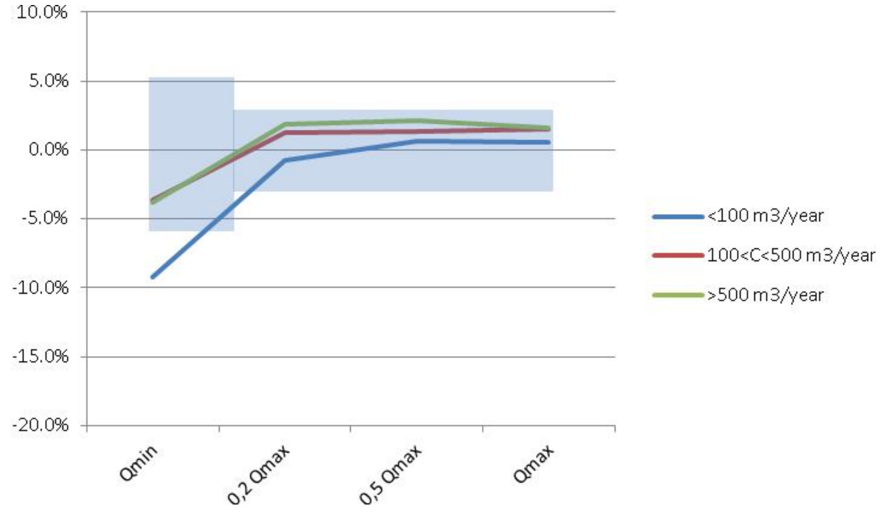

Fig.11 – Average error of indication of the animal diaphragm gas meters tested, grouped by class of average yearly consumptions and compared to the conformity area in subsequent verification*.

All the meters tested for the <u>pressure absorption</u> have been found largely within the predicted limit of 2 mbar given in table 3 of EN 1359:2006, even if the synthetic diaphragms meters present average pressure absorption values higher than the animal diaphragms ones and this is probably due to the lower cyclic volume of the synthetic diaphragms in respect to the animal diaphragm one. Furthermore, during disassembly and visual inspection no tampering have been found.

Only few animal diaphragm meters failed the <u>external leak tightness</u> and the <u>resistance to internal pressure</u> tests. In particular:

- 5 meters (i.e. about the 4 % of the sample) failed the external leak tightness test;
- 14 meters (i.e. about the 12 % of the sample) failed the resistance to internal pressure test (see fig.12 and 13).

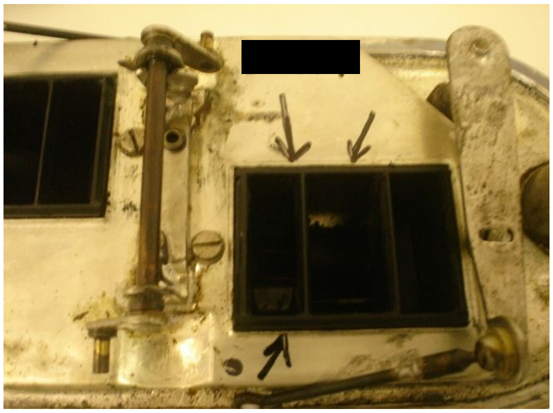
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Figure 12 – Leakage from the grid of an animal diaphragm meter.

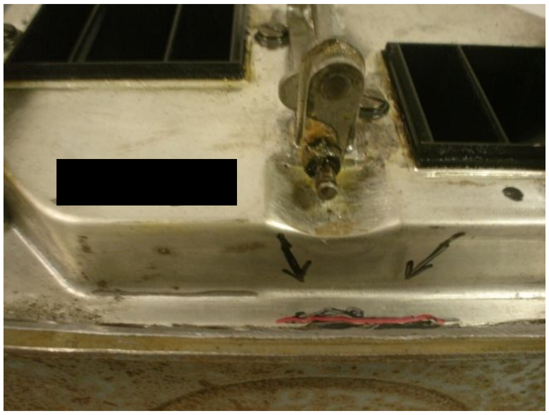
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Figure 13 – Leakage from the internal case of an animal diaphragm meter

No synthetic diaphragm meters failed the external leak tightness and the resistance to internal pressure test. This is probably due to the improved technologies developed by manufacturers, especially for the welding of the external case (instead of usual mechanical joints) and of the leaking parts of the internal body of the meters.

As concerning the <u>planarity test</u> of grid and distributing valve, the results of the measurements show a very significant percentage of animal diaphragms meters (more than the 50%) out of the usual tolerance in production (0,020 mm) and, normally, when a planarity failure is found, it occurrs both on the grid and the distributing valve contemporarily.

About all the animal diaphragms meters which failed the internal leakage test (13 on the overall 14) and the external (3 on the overall 5) present a significant planarity error on the coupling grid-valve. Furthermore, the single animal diaphragm meter which failed both the internal and external leakage test failed the planarity test too, both on grid and distributing valve and showed a very relevant error of indication (-100,0%, -62,9%, -25,4% and -16,6% at Q_{min}, 0,2 Q_{max}, 0,5 Q_{max} and Q_{max} respectively).

Finally, the possibility that a significant error of indication of the animal diaphragm meters could be induced by a failure in the internal and external leakage or in planarity have been also investigated by the authors. The only significant behaviour which can be pointed out is that a relevant error of indication, especially at low flowrates and for the very old meters, is almost always present in the meters with a significant planarity error of the coupling grid-distributing valve and which failed the internal leakage test.

No planarity faults have been found for the synthetic diaphragm meters at all and this is probably due to also to the smaller dimension of the actual synthetic diaphragm meters (especially for the coupling grid-distributing valve) in respect to the old animal ones.

5 Summary/Conclusions

The results of the tests performed are particularly encouraging both in terms of consumers protection and of integrity of supplying, as the average error of the meters tested is normally close to zero and the weighted mean error of the overall population is significantly lower than the permissible value in initial verification.

In fact, considering the average error of indication at different flowrates, all the old animal diaphragm meters (more than 20 years old) lie within the range ±6% at high flowrates ($0{,}2 \cdot Q_{max}$, 0,5·Q_{max} and Q_{max}) and up to -30% (i.e. in consumer advantage) only at Q_{min}. Furthermore, the synthetic diaphragm meters show a very regular behaviour, with average errors very close to 0 except at Q_{min} with scattered errors (generally negative in consumer advantage) up to -15%. Some manufacturers present, moreover, a significant negative error at Q_{min}, which seems to be the most critical flowrate (the average negative error at Q_{min} is significantly high, in consumer advantage and with an increasing error of indication as a function of the age of the meter). Furthermore, the possible drift of the meters has been investigated by the authors and the results presented seems to be encouraging also at unaccounted for gas level. In such scenario, with a very large number of similar meters (for size and measuring principle) installed in the distribution networks, the reduction strategies for UAG can rely on generally good metrological performance of the meters in terms of overall average error and systematic drift.

6 References

[1] Italian law n.99/2009 on date 23/07/2009, art.30.21, 2009
[2] AEEG Resolution 155/08, 2008
[3] G.Buonanno, “*On field characterization of static domestic gas flowmeters*”, Measurement, 27 (2000), 277-285
[4] G.Buonanno, A.Carotenuto, M.Dell'Isola, "*The influence of reference condition correction on natural gas flow measurement*", Measurement, vol 23, pp. 77-91, 1998.
[5] P.Vigo, F.Cascetta, "*The future domestic gas meter review of current developments*", Measurement No.13, pp. 129-145, 1993.
[6] P.Vigo, F.Cascetta, "*Sensor-A Comprehensive Book Series Vol. 7: Sensor for measuring flow*": Edited by VCH Verlagsgessellschaft mbH, Weinheim, Germany 1993.
[7] P.Vigo, F.Cascetta, "*Flowmeters A Comprehensive Survey and Guide To Selection*" Instrument Society of America ISA Research Triangle Park NC 1988
[8] P.Vigo, M.Dell’Isola, F.Arpino, G.Ficco, “*Some metrological considerations on natural gas metering in city networks*” 20th meeting of Marcogaz SCGI WG Distribution, 21st June 2011 – Genova
[9] AEEG Resolution VIS 93/10, 2010
[10] EN 1359, *Gas meters. Diaphragm meters*, 2006
[11] EU Directive 2004/22/EC on *Measuring Instruments* (MID Directive), 2004.
[12] OIML R137-1, *Gas meters*, 2006