EXPERIMENTAL DATA ON THE RELIABILITY OF FLOWMETERS FOR PRESSURE PIPES

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1. Introduction

This paper summarizes the results of a large number of tests carried out about the reliability of discharge measurements given by flowmeters for pressure pipes of different kinds (electromagnetic, ultrasonic and turbine flowmeters), on the basis of the experimental data collected at *Laboratorio di Idraulica* "*G. Fantoli"* of *Politecnico di Milano*.

In fact, since 2002, this laboratory is the seat of the *Settore Portate* of *Centro SIT n. 104,* that is a structure of *Politecnico di Milano* accredited for flowmeters calibration in the discharge range from 3 l/s to 80 l/s, with a so-called "best measurement capability" (*BMC*) equal to 0.2 %.

During these years, a lot of calibrations of different flowmeters have been carried out (61 flowmeters were tested so far: 44 electromagnetic, 9 ultrasonic, 8 turbine flowmeters). So, the tested flowmeters are supposed to give a relevant sample of experimental data, and therefore it seems interesting to carry out some statistical analyses about their performances and reliability. Of course no general consideration can be inferred about the general performances and reliability of other similar instruments not tested.

2. Test method

The calibration method is based on the comparison between on the one hand the discharge Q_M measured by the instrument and on the other hand the discharge Q that is really flowing in the pipe on which the instrument is installed .

The real discharge Q is obtained measuring the volume stored, during a fixed time interval, in a prismatic calibrated tank having a capacity of 9.37 m³ and an height of 1.15 m. This sample tank is referred to a certified primary specimen of unitary volume.

Figure 1 represents the scheme of the accredited laboratory calibration plant.

The calibration phases are the following:

- the discharge that is wanted to flow in the pressure pipe on which the instrument is installed, is diverted from the supplying constant-level tanks;
- the discharge flowing in the pressure pipe is adjusted by a valve placed downstream of the flow meter;
- moving the "start" lever, the flow-diverter starts to divert the flow towards the calibrated tank; before this operation, the discharge went directly to the recirculation system;
- at the same time of moving the "start" lever, a chronometer starts;
- various reading of the discharge indicated by the flowmeter display are carried out;
- at the end of a fixed time interval, the "stop" lever of the flow diverter is moved, in the way that the flow is directed towards the recirculation system; the chronometer stops automatically;
- the tank level raising, due to the water volume flowed into the tank during the fixed time interval, is measured through a staff gauge placed into an appropriate calming water well, and, knowing the tank surface, the real discharge Q is calculated.

The whole procedure is endowed with *SIT* certificated instruments (tank, flow-diverter, chronometer, staff gauge, thermometer), that is checked and subjected to periodic calibrations.

During each calibration, flowmeter behaviour is evaluated for 5 different discharge values at least, comparing the Q_M value showed by the flowmeter with the correspondent real Q evaluated by the calibration tank. In this way the correction $C = Q - Q_M$, is calculated.

Positive corrections ($C > 0$) indicate that the discharge measured by the instrument underestimates the real discharge, while negative corrections ($C < 0$) indicate a flow overestimation.

Each calibration certificate indicates flowmeter data and calibration environmental conditions, the values of the discharges Q_M and Q and of the correction C that represent the various calibration points and, in the end, the measurement extended uncertainties (absolutes and adimensional) associated to the recorded measurements.

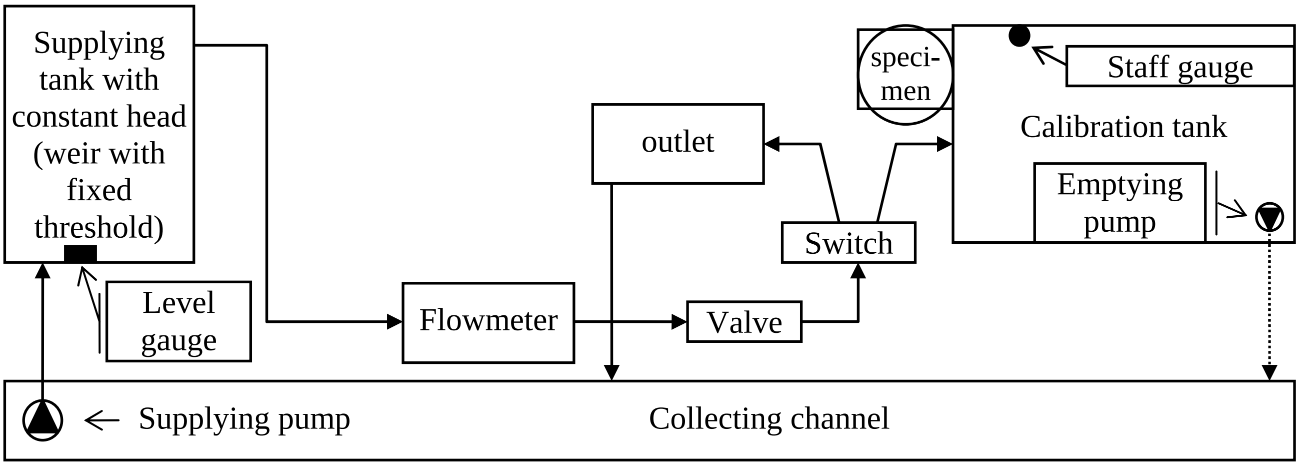

Figure 1 – Scheme of the calibration system in "G. Fantoli" laboratory.

For each instrument a graph was drawn, having on the x-axis the real discharge value divided by the instrument full scale value (Q/Q_{FS}), while on the y-axis the absolute value of the adimensional correction, that is the correction C divided by the real discharge Q:

$$\left|C_{rel}\right| = \frac{\left|Q - Q_M\right|}{Q}$$

It's important to remark that C_{rel} is defined referring to the real circulating discharge and not referring to the instrument full scale value, as it often happens on instrument instructions. This choice has been done because it allows to have a more direct indication about the shifting between the Q_M discharge recorded by the flowmeter and the Q actual circulating value.

Then, it has been defined an average correction $\overline{\left(\frac{|C|}{Q}\right)}_{instrum}$, characteristic of each instrument, that quantifies the measurement "accuracy".

For each instrument the standard deviation $[\sigma_{|C|/Q}]_{instrum}$ can be evaluated, to represent the dispersion of the correction values $\left(\frac{|C|}{Q}\right)_{instrum}$ around the average value $\overline{\left(\frac{|C|}{Q}\right)}_{instrum}$, that is to say the "precision" of the carried out measurements.

In fact, it is known that measurement "accuracy" is the degree of conformity of a measured or calculated quantity to its actual (true) value, while "precision", also called "reproducibility" or "repeatability", is the degree to which further measurements or calculations show the same or similar results.

3. Electromagnetic flowmeters

So far, 44 electromagnetic flowmeters (having diameters from 50 to 100 mm) were calibrated, for a total number of 244 measurements; for each instrument, 5-6 calibration points were carried out, using a discharge included in the operating range of the instrument (from a minimum of about 3 l/s – lower limit of the credited field – up to a maximum of 80 l/s – upper limit of the credited field – or of the instrument full scale discharge, Q_{FS}).

The standard deviation for the tested electromagnetic flowmeters is quite low, with an average value of $4.7 \cdot 10^{-3}$, and this fact means that each instrument is characterized by a quite constant correction for all measurements carried out and it is endowed with a good precision. In particular, 95% of the instruments has a standard deviation $[\sigma_{|C|/Q}]_{instrum}$ less than 1% of the average correction.

Calculating the value $[\sigma_{|C|/Q}]_{instrum}$ for all the instruments tested, the mass frequency distribution showed in.

It must be noted that in Figure 2, as in the followings, absolute frequencies are indicated instead of adimensional frequencies, to give a direct idea of sample size, and that each class is identified by the upper limit of its own interval.

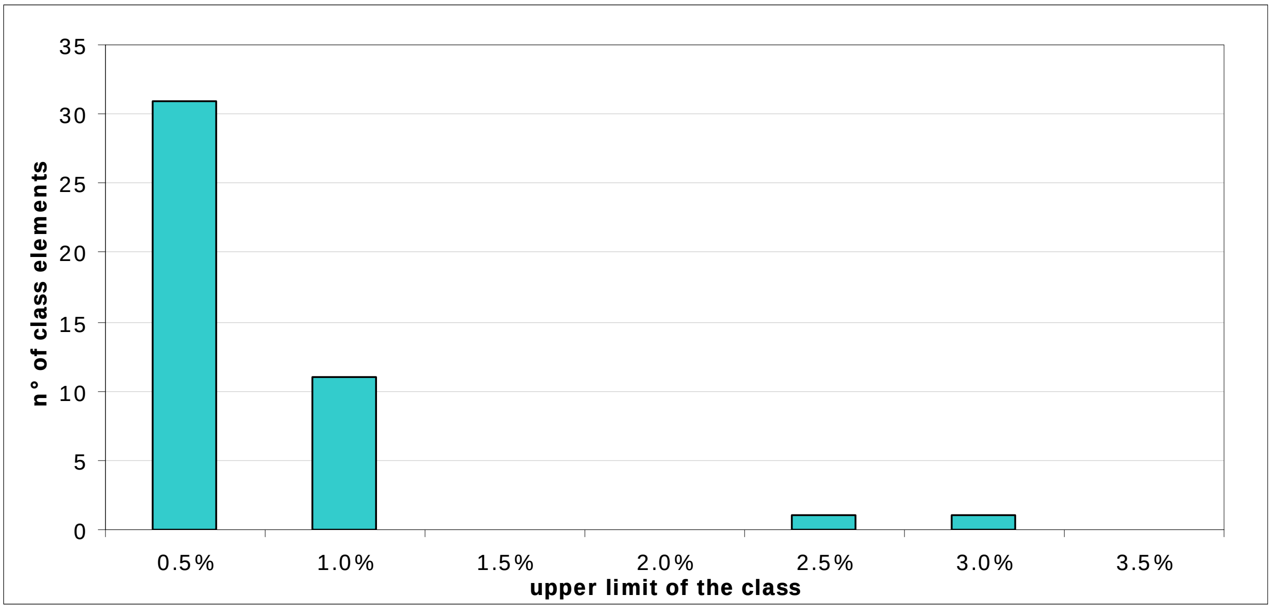

Figure 2 –Mass frequency distribution $[\sigma_{|C|/Q}]_{instrum}$ for electromagnetic flowmeters.

The $[\sigma_{|C|/Q}]_{instrum}$ low value is not an index of instrument accuracy, because it may happen that the correspondent $\overline{\left(\frac{|C|}{Q}\right)}_{instrum}$ is very high and so it would give a Q_M discharge value far from the real Q circulating in the pipe.

The results of statistical analysis carried out for the 244 calibration points sample are showed in Table 1; all the different electromagnetic flowmeters are considered to belong to the same population, in order to characterize the correction of this family of flowmeters.

$\overline{\left(\frac{\lvert C \rvert}{Q}\right)}$	$\sigma_{\lvert C \rvert/Q}$	$\left(\frac{\lvert C \rvert}{Q}\right)_{max}$	$\left(\frac{\lvert C \rvert}{Q}\right)_{min}$	$\left(\frac{C}{Q}\right)_{min}$
1.39%	2.17%	14.33%*	0.00%**	-6.80%

* This value refers to a flowmeter that has much higher correction values, in all its calibration points, than those of the other tested instruments.
** Value registered in 3 cases on 244.

Table 1 – Average correction and its standard deviation, maximum and minimum correction, in absolute value or not.

Graphs in Figure 3, Figure 4 and Figure 5 show mass and cumulated frequency distribution of measurements carried out, subdivided in classes 1% wide. In Figure 3 it is noticeable a certain tendency of the measurements to underestimate the discharge: in fact the mode is positive (correction class *C/Q* between 0 and 1 %), as the mean too (0.08 %).

In Figure 5 it is noticeable that the 95% of the instruments has a correction less than 7% of actual discharge; only one instrument (5 measurements) has corrections very far from the rest of the sample (more than 13% of the actual discharge).

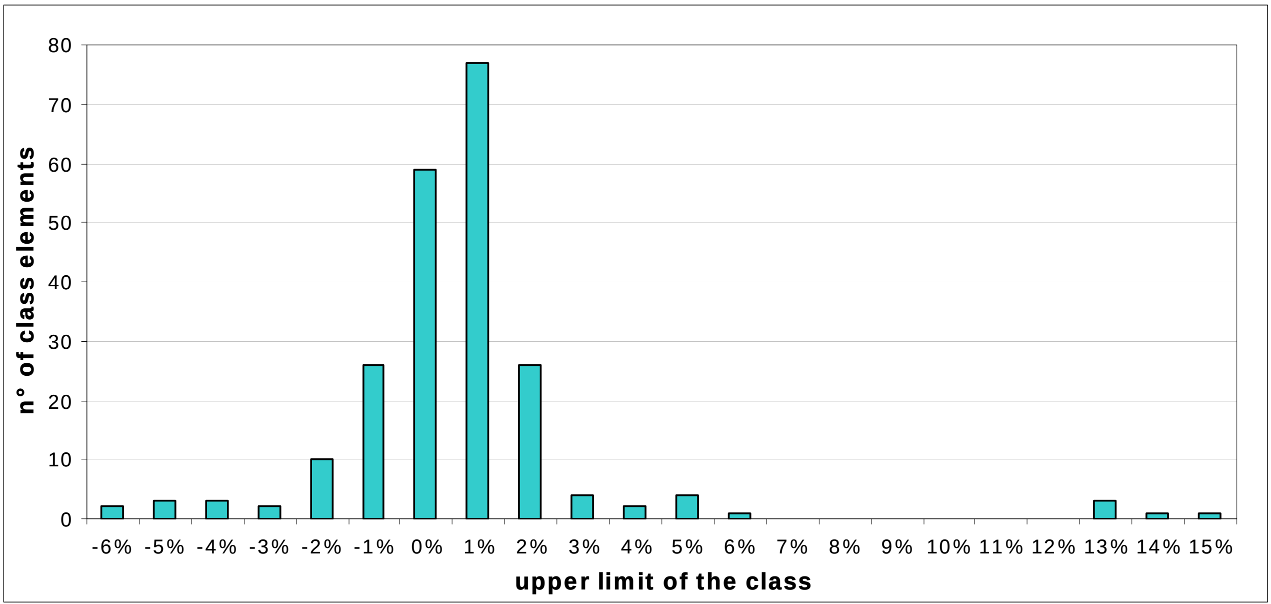

Figure 3 – Mass frequency distribution of *C/Q* for tested electromagnetic flowmeters.

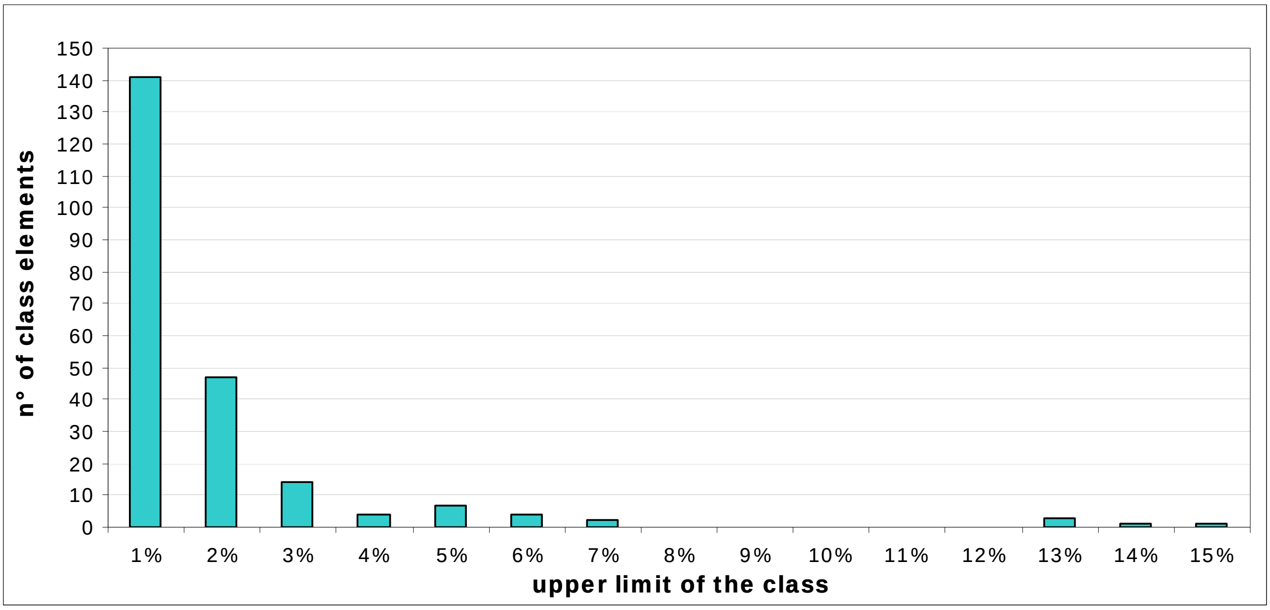

Figure 4 – Mass frequency distribution of $|C|/Q$ for tested electromagnetic flowmeters.

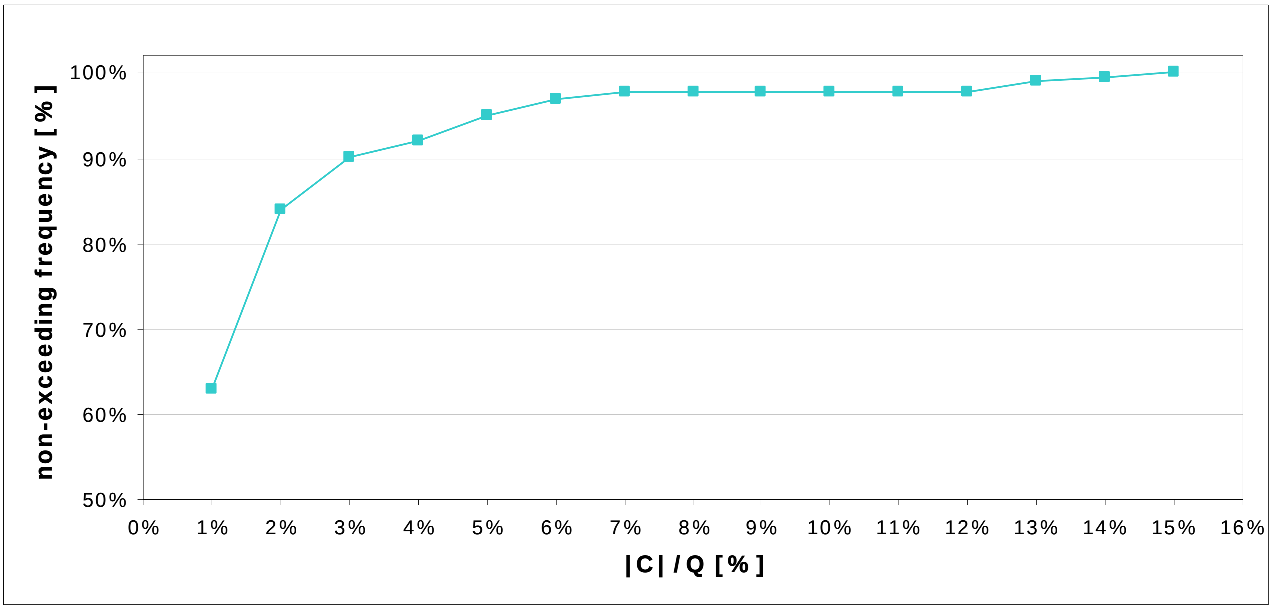

Figure 5 – Cumulated non-exceeding frequency distribution of $|C|/Q$ for tested electromagnetic flowmeters.

It was investigated if correction size is linked to some physical quantities such as the actual discharge Q (Figure 6), or the ratio between actual discharge and full scale discharge Q/Q_{FS} (Figure 7), or the velocity V in the pipe (Figure 8), or the instrument diameter D (Figure 9). All measured values were used in these analysis.

However, these investigations, showed by following Figure 6, Figure 7, Figure 8, Figure 9, gave negative results, that is to say that there isn't any kind of correlation between correction C and considered physical quantities. Only in the graph about $|C|/Q$ - Q relationship (Figure 6), a rough decreasing trend for the correction $|C|/Q$ can be assumed.

In Figure 6, the 5 calibration points very distant from the others, and surrounded by a red line, are those concerning the only flowmeter that has anomalous correction values compared to the rest of the sample. For this reason, in the other graphs, the calibration points of this flowmeter weren't showed, in favour of a better visualization of the rest of the other data.

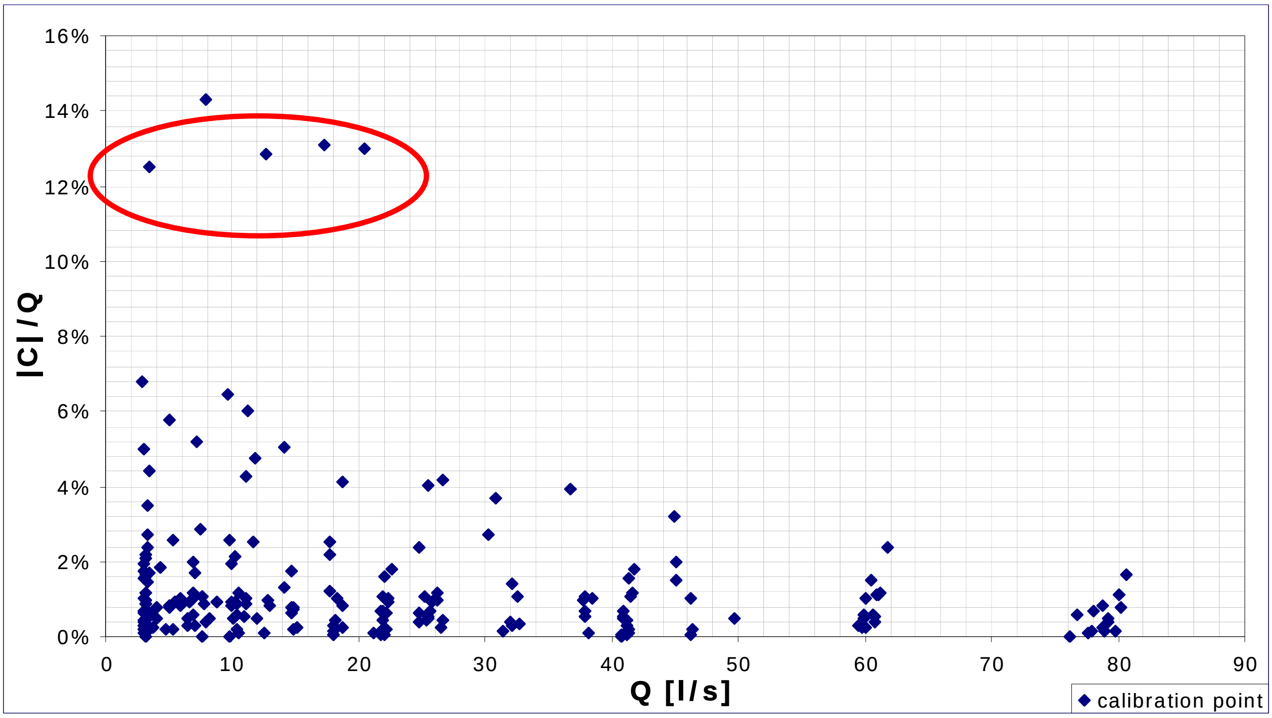

Figure 6 – Relationship between the absolute value of adimensional correction |*C*|/*Q* and the real discharge *Q*.

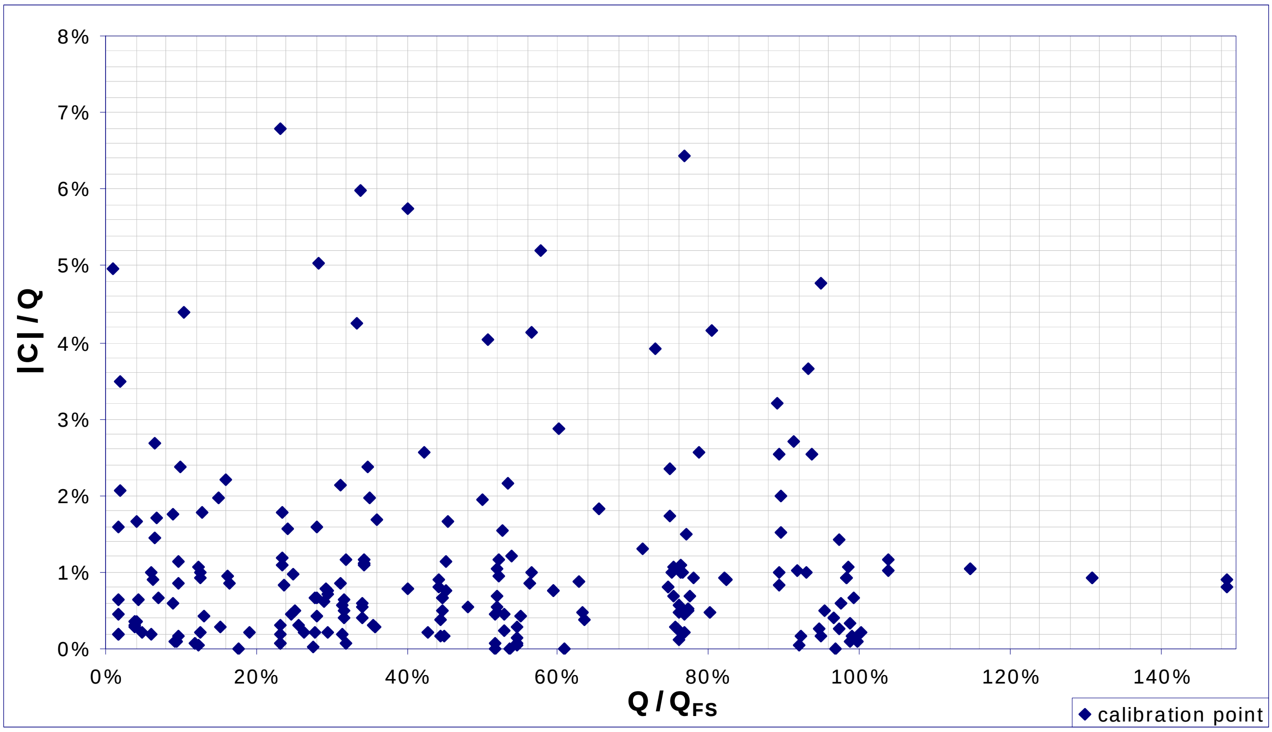

Figure 7 – Relationship between the absolute value of adimensional correction |*C*|/*Q* and Q/Q_{FS} ratio.

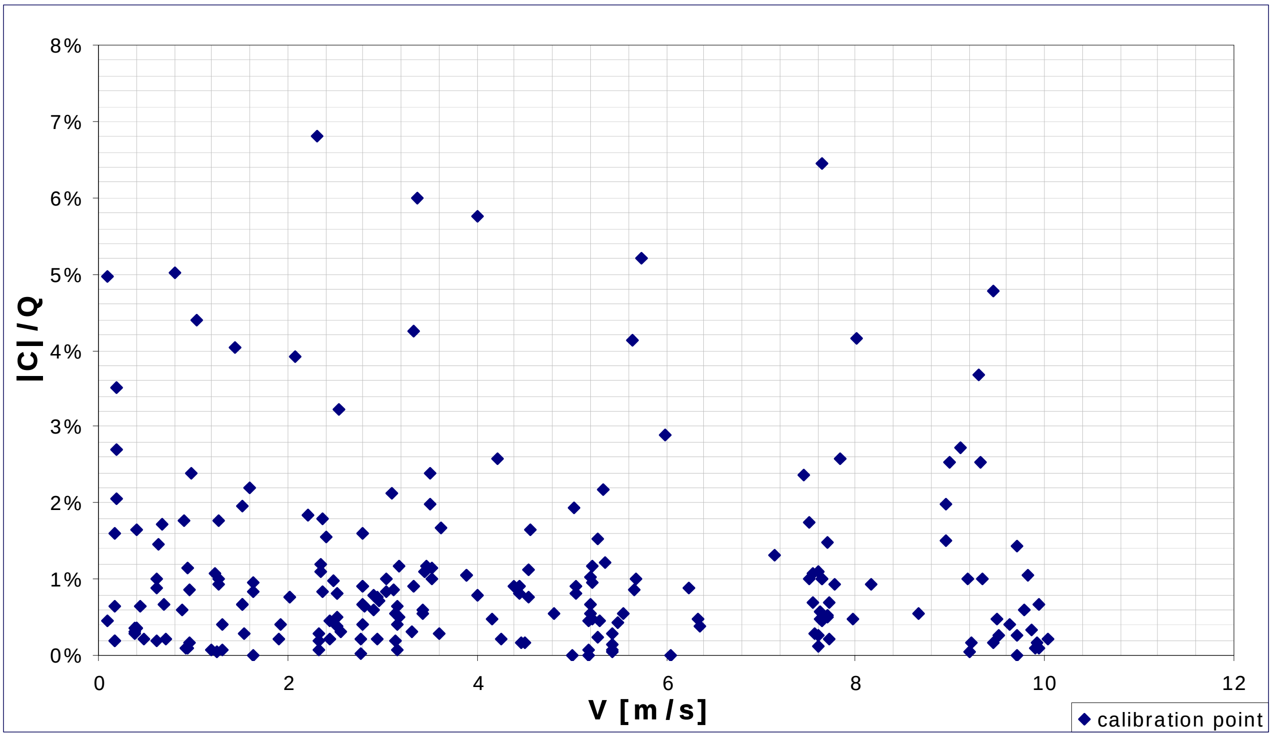

Figure 8 – Relationship between the absolute value of adimensional correction |*C*|/*Q* and flow velocity *V*.

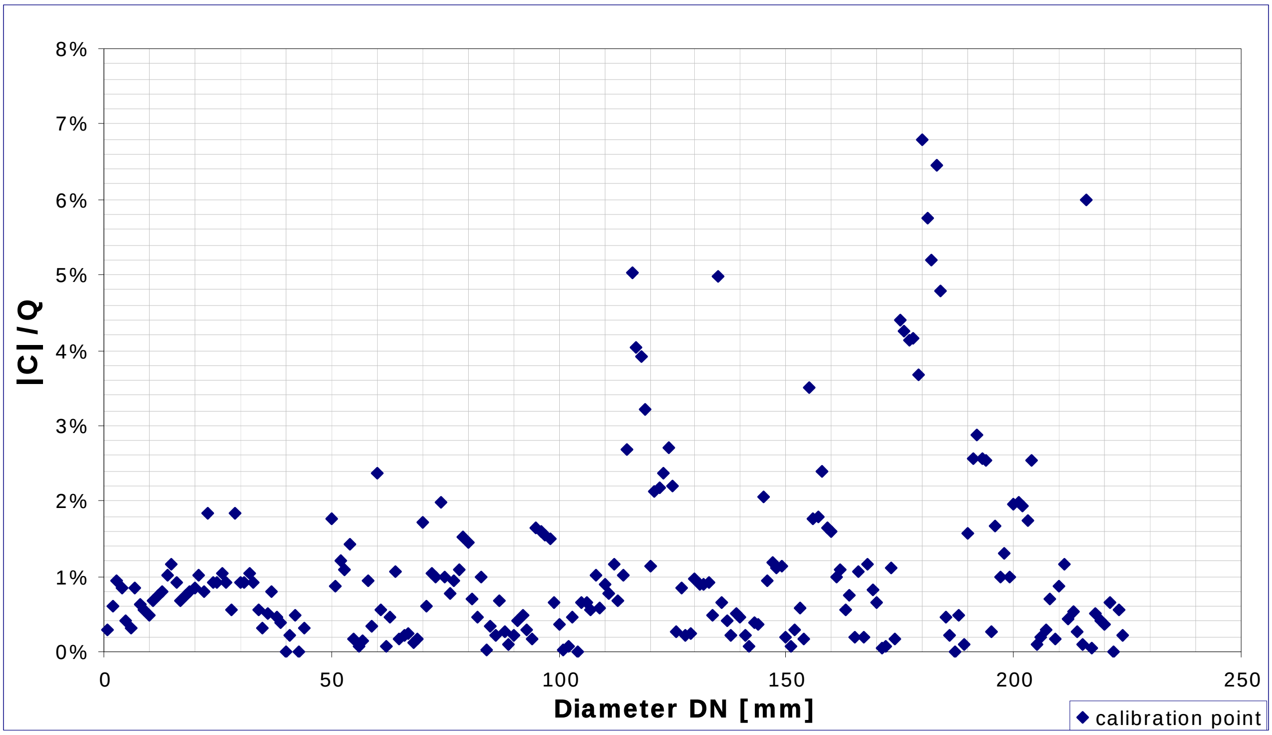

Figure 9 - Relationship between the absolute value of adimensional correction |*C*|/*Q* and instrument diameter *D*.

Figura 10 shows, in relationship with discharge Q, the $|C|/Q$ value for each calibration point, indicating with the same colour and symbol the calibration points referring to each single instrument, in the way that is possible to visualize the behaviour of each single tested flowmeter.

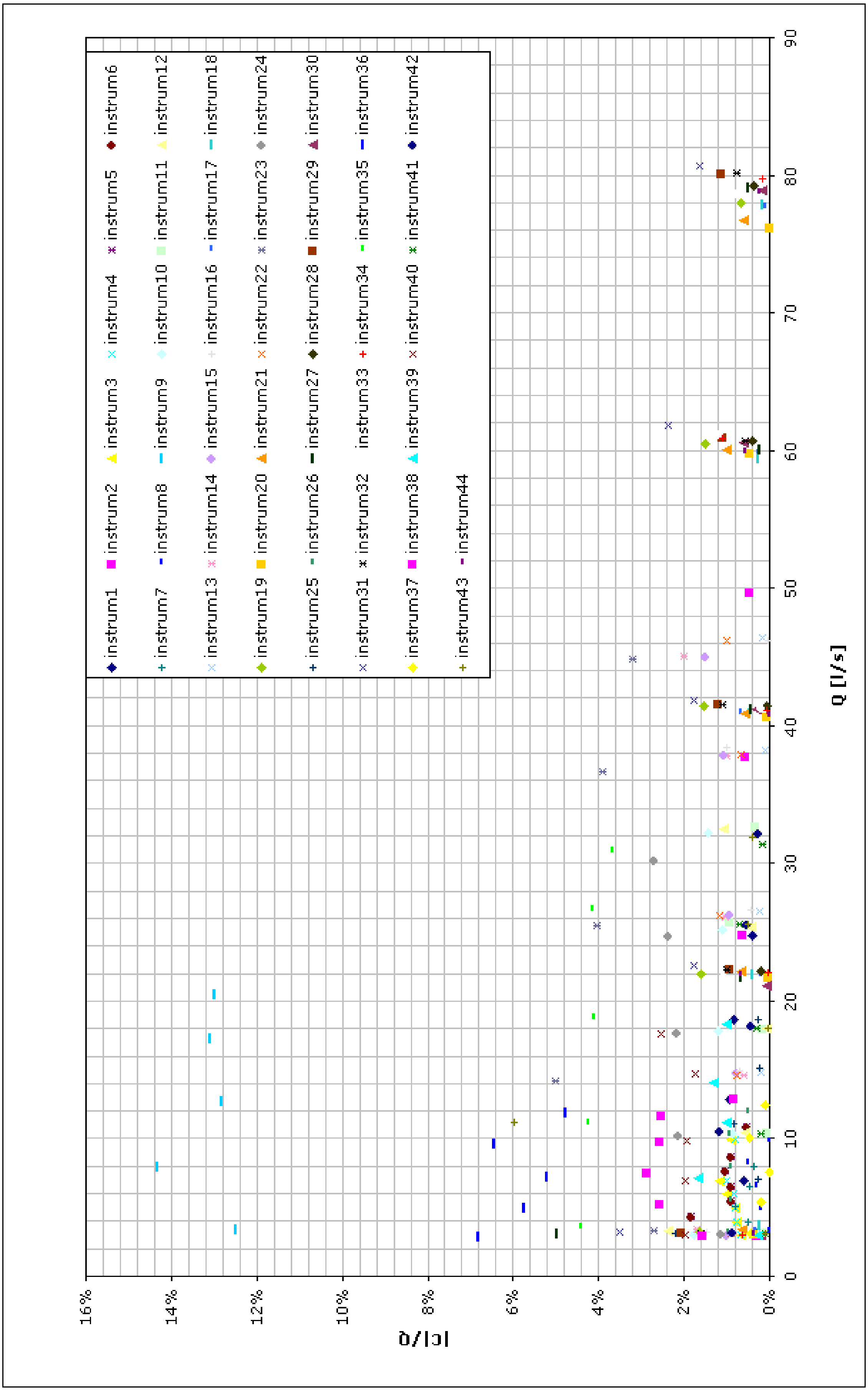

Figura 10 – Relationship between the absolute value of adimensional correction |*C*|/*Q* and real discharge *Q*, underlining the behaviour of each tested instrument.

4. Turbine and ultrasonic flowmeters

The results of the same statistical analysis carried out for electromagnetic flowmeters, but now referring to tested turbine and ultrasonic flowmeters, are schematically presented hereby.

However the sample of these two kinds of instruments is much smaller than the electromagnetic flowmeters sample. So, in these cases, of course the results and the frequency distributions obtained up to now have a lower statistical consistency.

	Turbine flowmeters	**Ultrasonic flowmeters**
Number of calibrated instruments	9	9
Measurements carried out for each instrument	5*	5**
Total number of carried out measurements	45	55
Flow range	from 1.35 l/s to 21.72 l/s	From 3.05 l/s to 79.02 l/s
Instrument diameter	from 40 to 100 mm	from 50 to 200 mm
Kind of correction	3 instruments with $C < 0$ 4 instruments with $C > 0$ 2 instruments C </> 0	3 instruments with $C < 0$ 5 instruments with $C > 0$ 1 instruments with C </> 0

* Except for one flowmeter that has 10 calibration points.
** Except for two flowmeters that have 10 calibration points.
° This flowmeter has only a calibration point with $C < 0$.

Table 2 – Data about turbine and ultrasonic flowmeters calibration.

Kind of flowmeter	$\overline{\left(\frac{\|C\|}{Q}\right)}$	$\sigma_{\|C\|/Q}$	$\left(\frac{\|C\|}{Q}\right)_{max}$	$\left(\frac{\|C\|}{Q}\right)_{min}$	$\left(\frac{C}{Q}\right)_{min}$
Turbine	5.10%	2.80%	11.00% °	0.00% °°	-11.00%
Ultrasonic	6.20%	4.10%	16.90%*	0.30%**	-10.70%

° This value refers to a flowmeter that, in all its 5 calibration points, showed correction values of about 11 %.
°° Value registered in 2 cases on 45.
* This value refers to a flowmeter that, all its 5 calibration points, showed correction values > 13%.
** For ultrasonic flowmeters only, correction is never = 0.00%

Table 3 – Characterization of the correction for turbine and ultrasonic flowmeters.

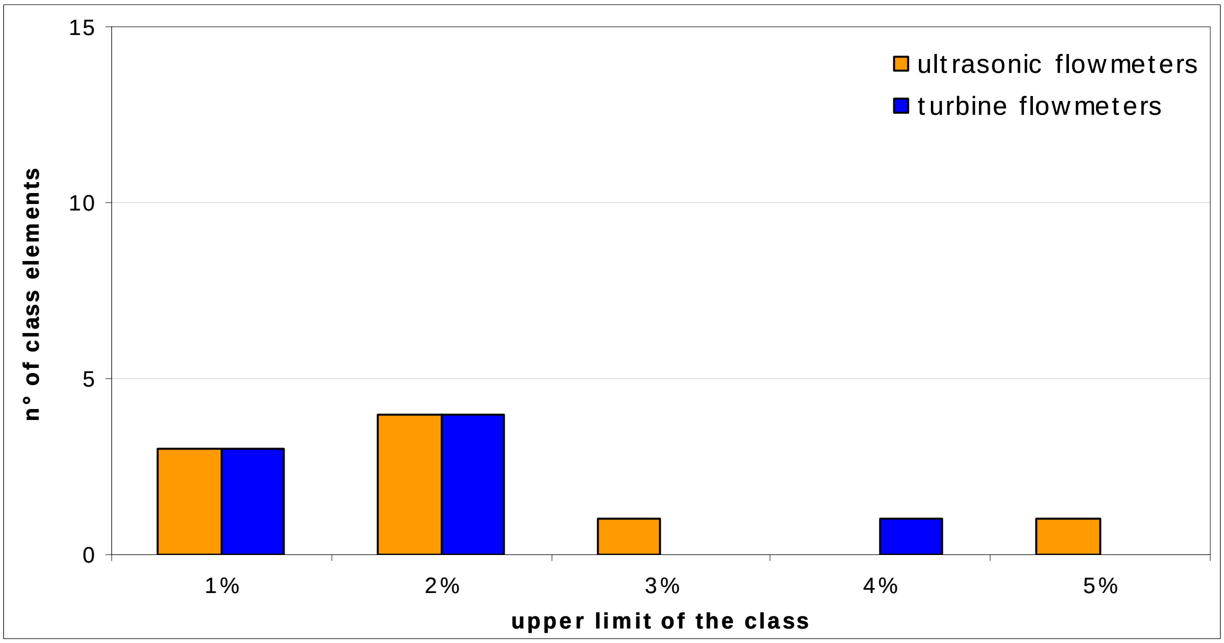

Figura 11 – Mass frequency distribution of $[\sigma_{|C|/Q}]_{instrum}$ for turbine and ultrasonic flowmeters.

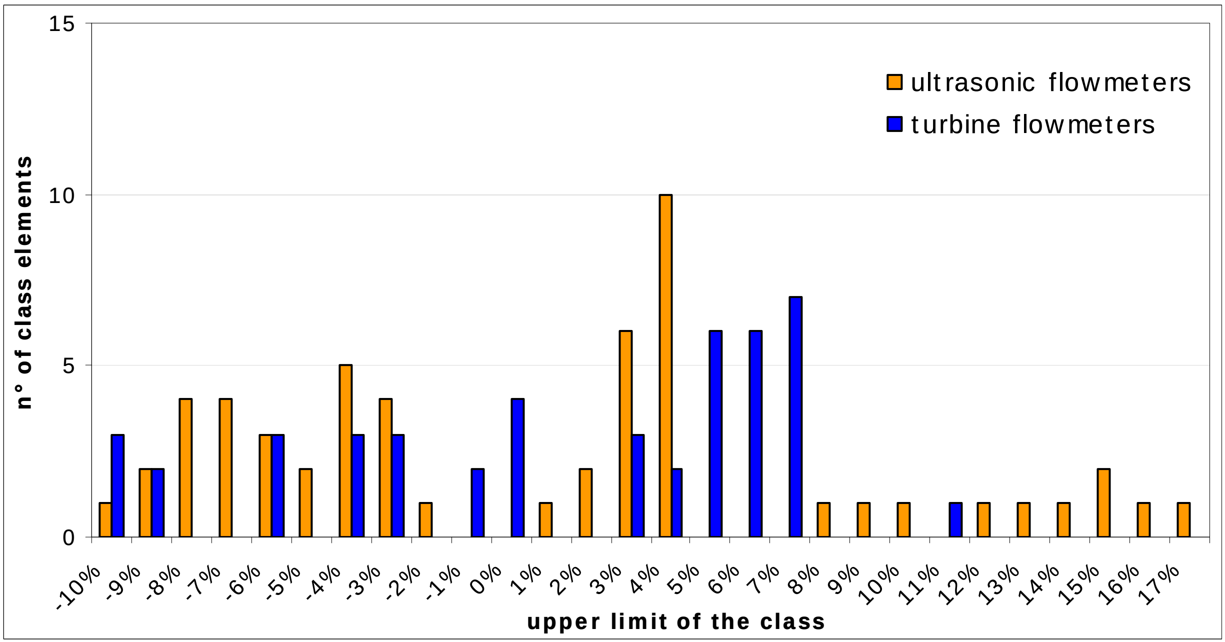

Figura 12 – Mass frequency distribution of C/Q for turbine and ultrasonic flowmeters.

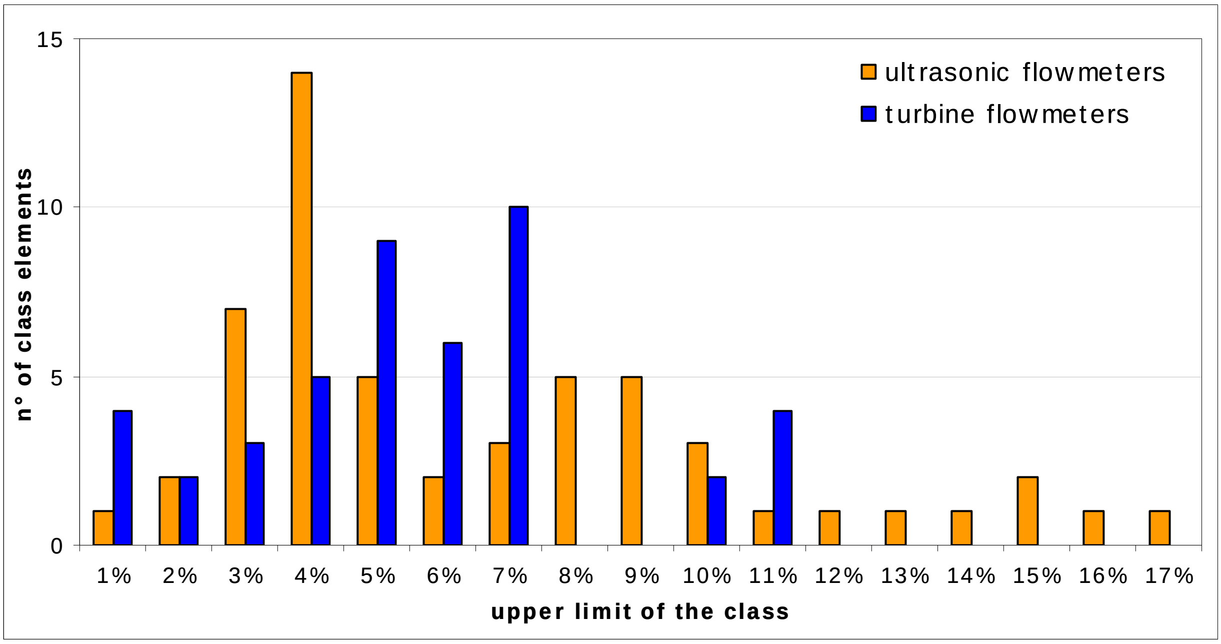

Figura 13 – Mass frequency distribution of $|C|/Q$ for turbine and ultrasonic flowmeters.

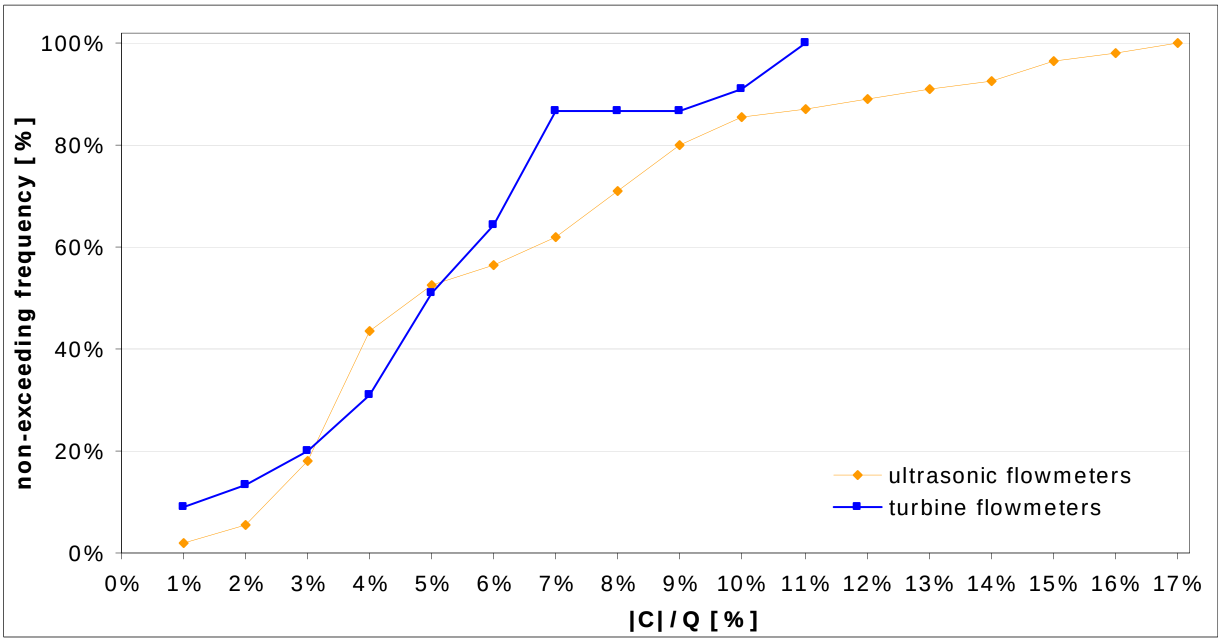

Figura 14 – Cumulated non-exceeding frequency distribution of $|C|/Q$ for turbine and ultrasonic flowmeters.

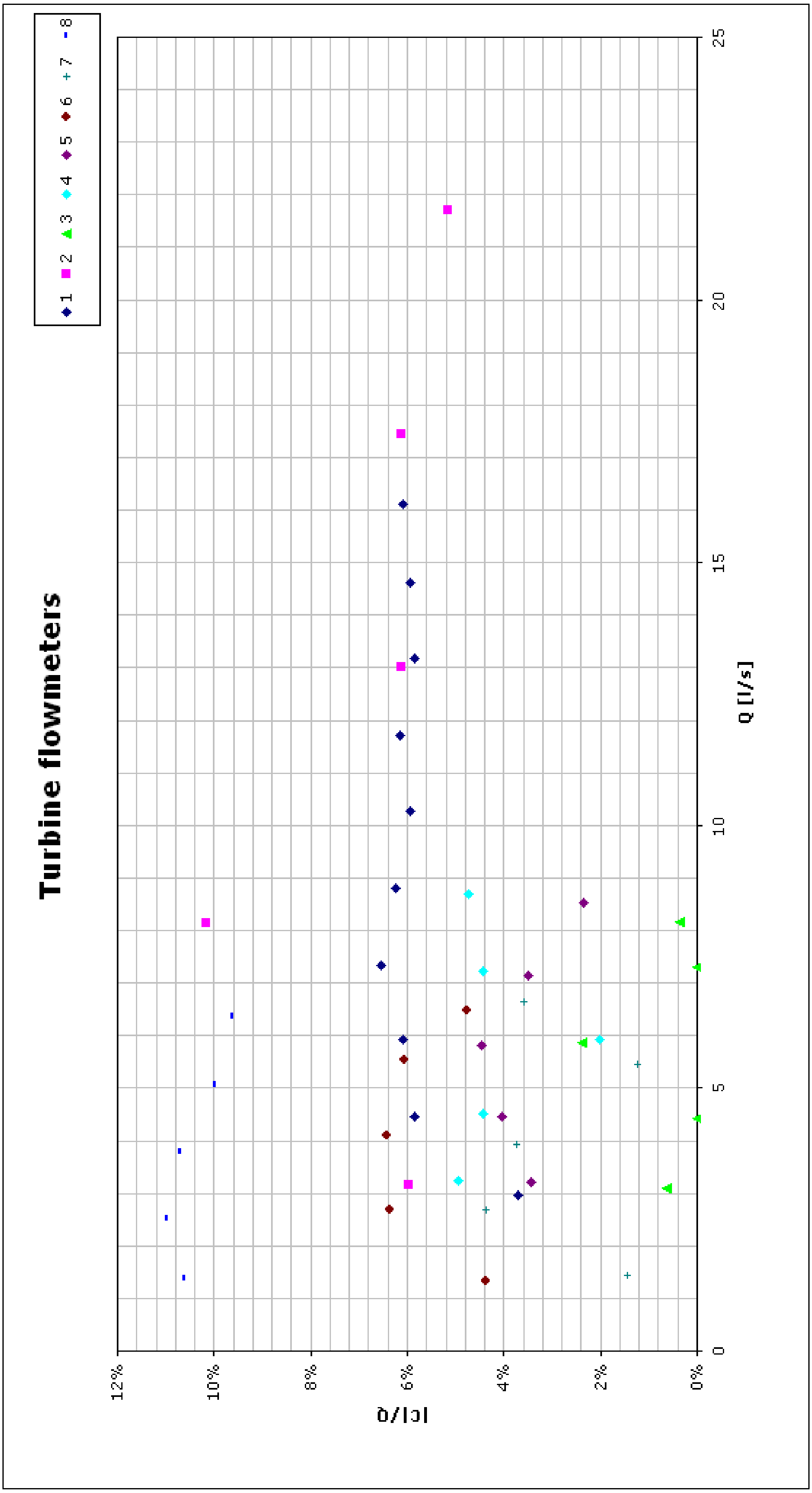

Figure 15 – Relationship between the absolute value of adimensional correction |*C*|/*Q* and real discharge *Q*, underlining the behaviour of each tested turbine flowmeter, indicated by a different number.

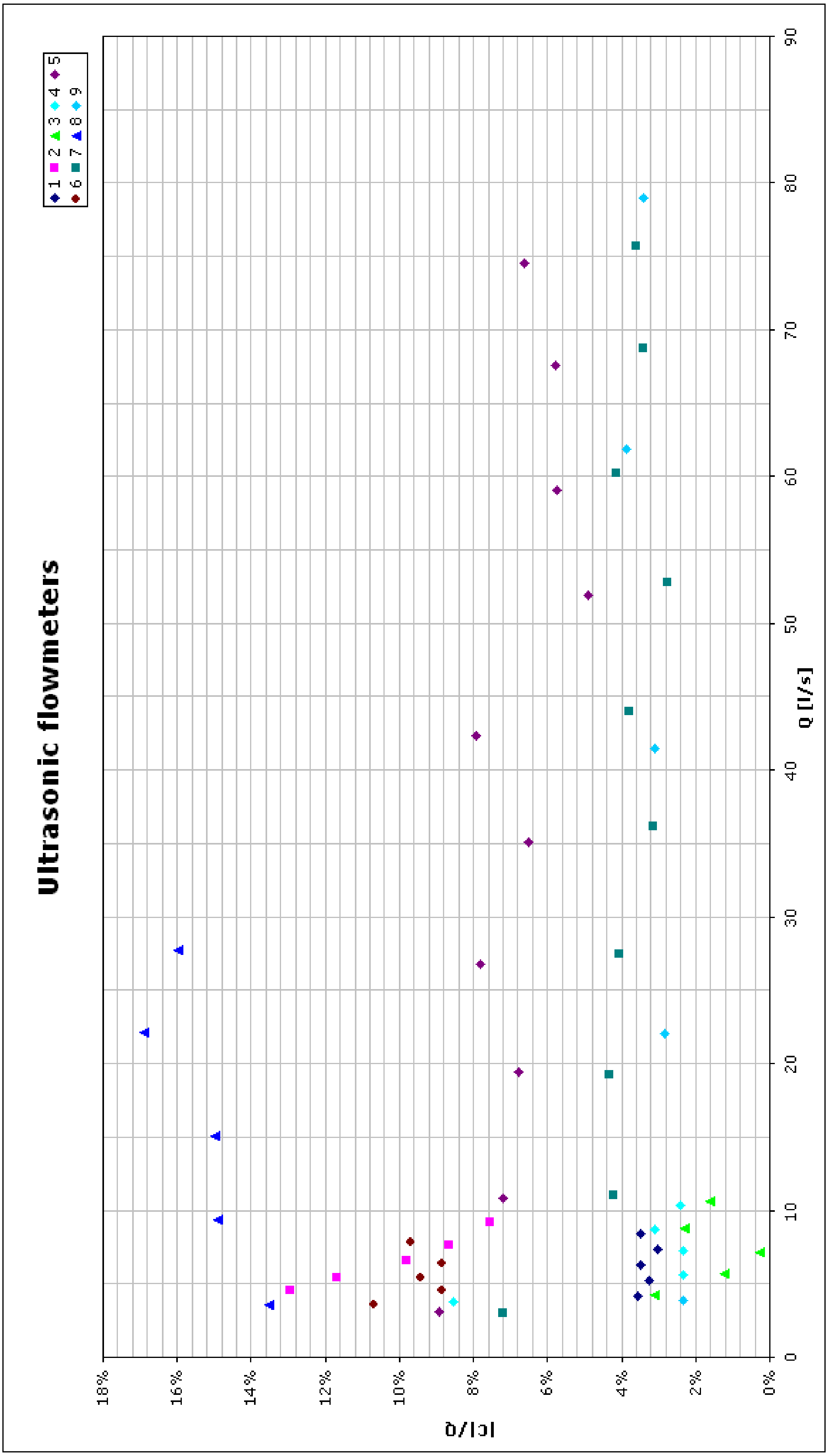

Figure 16 – Relationship between the absolute value of adimensional correction |*C*|/*Q* and real discharge *Q*, underlining the behaviour of each tested ultrasonic flowmeter, indicated by a different number.

5. Conclusions

Calibration measurements carried out allowed to evaluate the "accuracy" and the "precision" of a large number of tested flowmeters.

In particular, it can be asserted that the results obtained for the tested electromagnetic flowmeters are characterized, on average, by a correction of 1.4% referred to the actual flow.

About the other two kinds of tested instruments, that is turbine and ultrasonic flowmeters, collected data seem to show an average correction higher than electromagnetic flowmeters average correction, in particular it's respectively about 5% and 6 % of the actual flow.

Of course no general consideration can be inferred about the general performances and reliability of other similar instruments not tested.

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Monographies

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