Main Index

North Sea
FLOW
Measurement Workshop

Paper 13: 2.7

EUROPEAN CALIBRATION INTER-COMPARISON ON FLOW METERS - HOW ACCURATE CAN ONE EXPECT TO MEASURE FLOW RATES

Authors:
Peter Lau, Swedish National Testing and Research Institute, Sweden

Organiser:
Norwegian Society of Chartered Engineers
Norwegian Society for Oil and Gas Measurement
Co-organiser:
National Engineering Laboratory, UK

EUROPEAN CALIBRATION INTER-COMPARISON ON FLOW METERS - HOW ACCURATE CAN ONE EXPECT TO MEASURE FLOW RATES

Peter Lau
Swedish National Testing and Research Institute, Sweden

ABSTRACT

Results of a calibration inter-comparison are reported that were performed on a flow meter transfer standard between nine primary flow laboratories in Western Europe. The purpose is to ensure that the equipment and methods used do not suffer from systematic errors. This inter-comparisons was performed on kerosene as a typical representative for light oil products. Traceable calibrations are a prerequisite for international trade and inter-comparisons form the base for the reliability in the calibration job performed at the laboratories. The outcome sets a limit for the reliability in flow measurement itself, which also is important to meter users.

The transfer standard consisted of a turbine being sensitive to changes in flow profiles and a displacement (screw) meter being not. A crucial quality for any exercise of that kind is the stability of the meter package in time. For both meters it was found to be within 0,004 %, which is an order of magnitude less than the measurement uncertainties (0.03 to 0,3 %) claimed by the participating laboratories. The inter-comparison revealed reproducibility figures of 0.16 and 0.17 % compared to 0,07 and 0,09 % within the co-ordinating laboratory. A few laboratories faced problems with non-ideal flow profiles in their test site, that could be overcome with a flow straightener in front of the turbine. The remaining differences in the reported calibration results were predominantly caused by differences in the calibration liquids used even though these were within small limits in both viscosity and temperature.

INTRODUCTION

Assume a situation where a tank boat is loading petrol from a storage tank at a refinery. If only one meter determines the volume of the shipment and the payment is based on it probably everyone would be happy. Suspicious people tend to question the correctness of a measurement. A captain on a boat for instance may have independent information on the received load as the changed displacement can be red off from the water level.

A real problem arises if both the deliverer and the receiver of a shipment use their own instrument. Due to various reasons these will seldom exhibit the same figures. As a natural consequence the question is asked which of the two is right and which one is wrong. This is not only a metrological question because immediately after the discovery of a difference in display the involved parties will discuss on which meter the shipment should be paid. The parties then will realise that meters, like every other instrument have errors, which means that non of the two results may be correct. Then probably both parts look up the specification of their respective instrument. There is a certain chance that the difference could be explained by the uncertainty statements given there. On the other hand with the experience from many meter test there is a high probability that the specifications are far to optimistic and definitely do not take into consideration all the facts that disturb a meter. It would be a good idea to involve a metrological institution to solve the discrepancy.

Calibration as a Means of Solving a Measurement Problem

A calibration laboratory would offer a specification telling how wrong a certain instrument will measure, at least under calibration conditions, and how the indication can be corrected. The service hopefully also contains a statement of uncertainty telling that even after a correction there will still be a certain range of values around the stated one that likewise could be appointed to the calibration result. Does this figure limit the accuracy with which the parties can expect to determine the amount of received petrol in a tank boat? If we assume that both parties engage the same calibration laboratory and it does a good job then the uncertainty figure stated in the certificate must be regarded as a lower limit in that sense that a flow or volume measurement at a production site never can give a value with a smaller uncertainty interval.

An important argument for this postulation is that meters most often do not measure flow or volume directly. Instead they sense the speed of the passing medium. If the measuring principle is sensitive to other disturbing effects, which normally is the case or the measuring spot is not really representative for the whole meter area then deviations from more or less ideal calibration situations are likely to arise. It is certainly not incidental that so many different principles have been used to measure flow, which can be regarded as there is no outstanding technique incorporating all demands a user might have.

Calibration Inter-comparison and Measurement Uncertainty

If the two parties in our example are situated in different countries it would be natural that both could show up a calibration certificate each from different institutions, let's say one from Sweden and one from the Netherlands. What to do if the corresponding meter factors and the belonging uncertainties still does not explain the observed differences in the metering of the ship load. One explanation could of course be that one of the meters is heavily disturbed. But how sure can a customer be that he receives the same calibration result from our laboratory than from an other one. Usually a customer is not willing to pay two times for an answer to that question. But in that also lies the question of how accurate he can expect to measure liquid volumes and flow rates. As argued above his measurement uncertainty can never be smaller than the one he receives from the calibration laboratory. But how good is the agreement in the calibration performance between different laboratories? Thinking of the complexity of flow calibration some consecutive questions are the following. How do national flow laboratories agree concerning their stated calibration uncertainty for a meter? How consistent would the outcome of a calibration inter-comparison be with respect to these uncertainties? Are different methods of calibration gravimetric or volumetric ones equivalent? Are there systematic differences due to installation facilities or references used?

EU-PROJECT

The interest in these questions made the European Community to finance the investigation described below (BCR-project 3476/1/0/203/92/9-BCR-S(30)). Problems of systematic differences between laboratories, the comparison between different methods, the skill of the personnel, traceability and quality assurance are not new ones within the metrological society. Concerning flow measurements a crucial problem has been and still is to find good and repeatable meters with a high stability over the time of the comparison, which is necessary to draw essential conclusions.

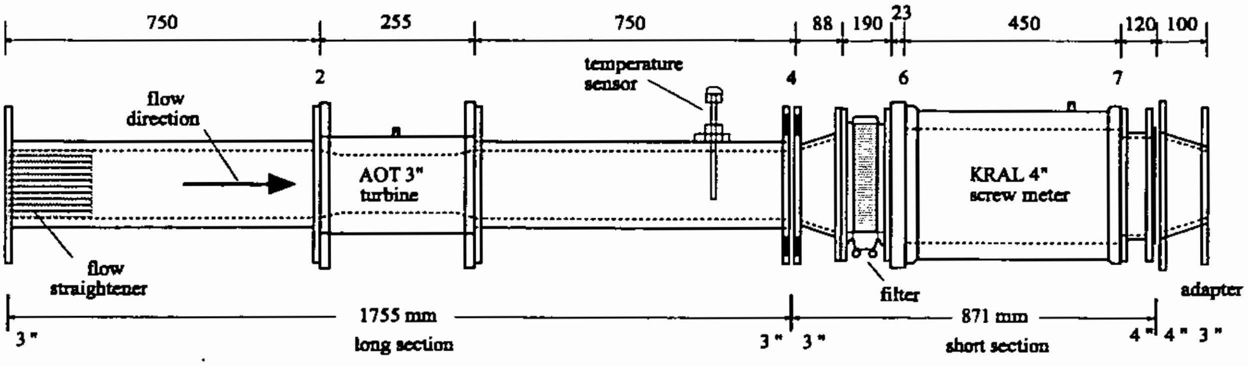
A proposal for an inter-comparison with a suitable transfer standard and certain test procedures for evaluation were send to all national flow calibration laboratories in Western Europe. A total of nine laboratories responded positively for this special work. They are listed below. The limitations for others were either the lack of a test rig within the specified flow range or kerosene, which was the liquid agreed upon. It is frequently used for testing purposes in the laboratories and is a good representative for a lot of different light oil products in the petrochemical industry. A viscosity of approximately 2 cSt and a temperature close to 20 °C were other parameters asked for.

Table 1. The participating laboratories

	Calibration institutions:	Laboratory code:
SP	Swedish National Testing and Research Institute	**Lab 3** cal I
		Lab 10 cal II
		Lab 11 cal III
NWML	National Weights an Measures Laboratory	**Lab 6**
EAM	Eidgenössisches Amt für Messwesen	**Lab 9** cal I
		Lab 12 cal II
IGM	Inspection Generale de la Metrologie	**Lab 8**
PTB	Physikalisch-Technische Bundesanstalt	**Lab 5**
NEL	NEL Flow Centre	**Lab 4**
NMi	Nederlands Meetinstituut	**Lab 7**
Force	Force Institutterne Dantest	**Lab 1**
BEV	Bundesamt für Eich- und Vermessungswesen	**Lab 2**

The Meter Package

The following demands were put upon a suitable flow meter transfer standard. It should consist of two meters with different physical measurement principles. On should be sensitive and one insensitive to flow profile disturbances. Both should be very stable in short and long time terms. Further both should be linear and insensitive to liquid properties and test methods. Using a turbine meter and a screw meter in series and performing two measurement series, one with and one without a flow straightener in front of it, the expectation was to detect installation induced effects. This is because the turbine meter is sensitive to swirl or asymmetric flow profiles whereas the screw meter is not.



The schematic drawing is not correctly scaled! total length 4"-3"-adapter included 2726 mm total weight appr. 150 kg

Fig.1: Schematic drawing of the transfer standard.

The Measurement Task

The primary idea of the inter-comparison was that each laboratory should perform the calibration as a routine task. For the sake of the comparison, however, certain aspects had to be in common. Thus the measurement task, as described in detail in the guide-lines, consisted of two separate, but simultaneous calibrations of both meters in a package arrangement at five obligatory flow rates. In the first one (configuration A) a flow straightener was placed in a specified position 10 D in front of the turbine. This configuration was thought to produce a well-defined and repeatable flow characteristic, thus equalising possible installation effects. The second calibration was a repetition without the flow straightener in place. In this configuration (B) the influence of non-ideal flow properties like swirl, asymmetric flow profiles etc. would be observed as a turbine is sensitive to these disturbances.

For the sake of comparability five obligatory flow rates, numbered 1 to 5, each with 10 single repetitions, were pre-defined and run in the order 3(1), 4, 5, 1, 2, 3(2). Any other additional flow rates were to be run after this series. No recommendations as to the calibration method, start-up procedure or any other part of the calibration were given.

The inter-comparison started and ended at SP as the co-ordinator. SP also performed a calibration at an intermediate state. Although this increased the costs it was accepted to secure the outcome if any technical failure should happen to the equipment. To characterise the meters special tests were run both before and after the inter-comparison measurements. The total project was actively run during 20 month and ended in 1995 with a meeting where the results were presented and discussed.

CHARACTERISTICS OF THE TRANSFER-STANDARD

Flow meter inter-comparisons often suffer from instabilities. The figures 2 and 3 are typical calibration results for the two meters in question, i.e. the meter factor as a function of the flow rate. Six curves, three with and three without a flow straightener, represent the SP-result at the start, in the middle and at the end of the intercomparison (corresponding to Lab3, Lab10 and Lab11 in the diagram). A stability judgement should be based on almost identical measurements, which is the case in these curves, where a long hose was used to connect the meter package with a Brooks piston prover as reference.

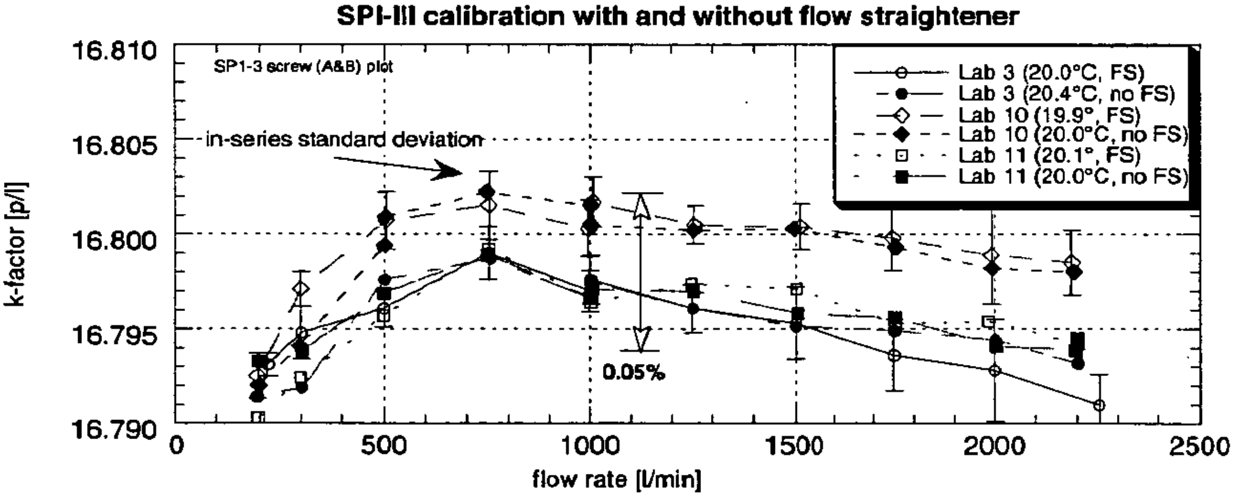


Fig. 2: Three repeated complete screw meter calibrations after 5 and 13 months respectively

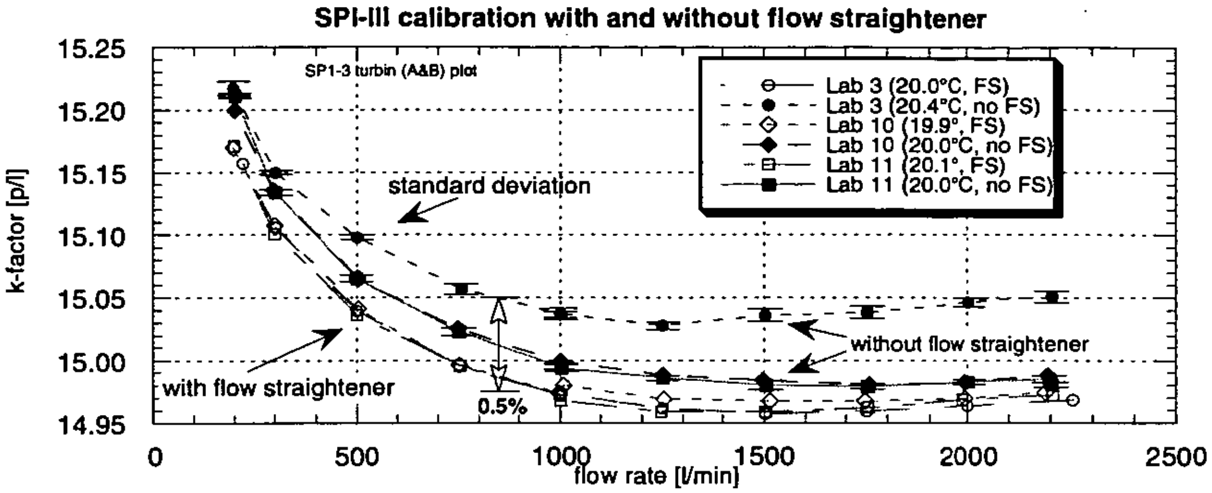


Fig. 3: Three complete turbine meter calibrations - open symbols with, dark symbols without flow straightener in place.

As expected the screw meter does not exhibit systematic differences between respective series with (white symbols) and without the flow straightener (black symbols). But so does the turbine. The existence of the straightener influences the flow profile, an effect that was found in all laboratories. The difference was largest in the first calibration in spite of the straightness over roughly 4 m of the hose upstream of the turbine.

A look on just those curves measured at identical situations i.e. with the flow straightener in front (white symbols) shows a much better agreement. Among these the intermediate result SPII or Lab 10 tends to have a generally higher meter factors, an observation which is better exposed when compared with measurements taken earlier and later. A very truly explanation is the fine and temporary layer of rust that was found on the inside pipe wall coming from a preceding calibration site with ordinary steel pipes. During the immediately following tests this difference had already disappeared.

Representative k-factor

A valuable concept to compare curves on a quantitative basis especially during the intercomparison was to extract a representative k-factor. Flowmeters are usually delivered with one k-factor rather than with a list of k-factors for different flow rates.

The question is, however, how to construct this k-factor in a representative way. If the flow rate dependence were strictly linear, a mean value over the measured k-factor values would be acceptable. If the meter is not linear, and that is especially true for the turbine, this is insufficient. Concerning the turbine in question, the volume passing through the meter during a given time interval would be overestimated at low flow rates and underestimated at high flow rates. The best suggestion was to construct a mean value by weighting each k-factor k_j with the corresponding flow rate q_j according to the following definition:

$$k_{rep} = \frac{\frac{1}{m}\sum_{j=1}^{m} q_j \cdot k_j(q_j)}{\frac{1}{m}\sum_{j=1}^{m} q_j}$$

where m is the number of tested flow rates

Applied on the curves in figures 2 and 3 the results are listed in the following table.

Table 2: Stability of meter-factors over 13 month.

	k(S) [p/l]		Δk(S) [%]	k(T) [p/l]		Δk(T) [%]
SP I	16.7952	I ⇨ II	0.027	14.9779	I ⇨ II	0.039
SP II	16.7998	II ⇨ III	-0.023	14.9837	II ⇨ III	-0.035
SP III	16.7959	I ⇨ III	**0.004**	14.9784	I ⇨ III	**0.003**

With this classification the differences Δk(S) and Δk(T) between two results for both the screw meter and turbine results are all below 0.04 %. This is less than the estimated uncertainty in the measurement being of the order of 0.08 % for the turbine and 0.06 % for the screw meter. The two situations I and III are most alike concerning the preconditions for the meters and the difference over 13 month and thus the stability over the inter-comparison period is even an order of magnitude better, which makes it worthwhile to look into details of the results from the different laboratories.

Repeatability and Reproducibility

Besides stability an other important precondition for an international comparison is a good reproducibility of the meters that make up the transfer standard. In order to assess eventual differences between laboratories with respect to test equipment, test volume or calibration technique, it is essential to know the response of the meters to variations in calibration parameters as temperature, liquid viscosity or pressure.

A simple method to determine the reproducibility is to plot the corresponding calibration curves into a common figure and to depict the minimum, maximum and average differences between these. This is done in the following figures 4 and 5, where the simultaneous calibration of both meters in the package in two liquids Exsol D80 and D40 at different temperatures are shown.

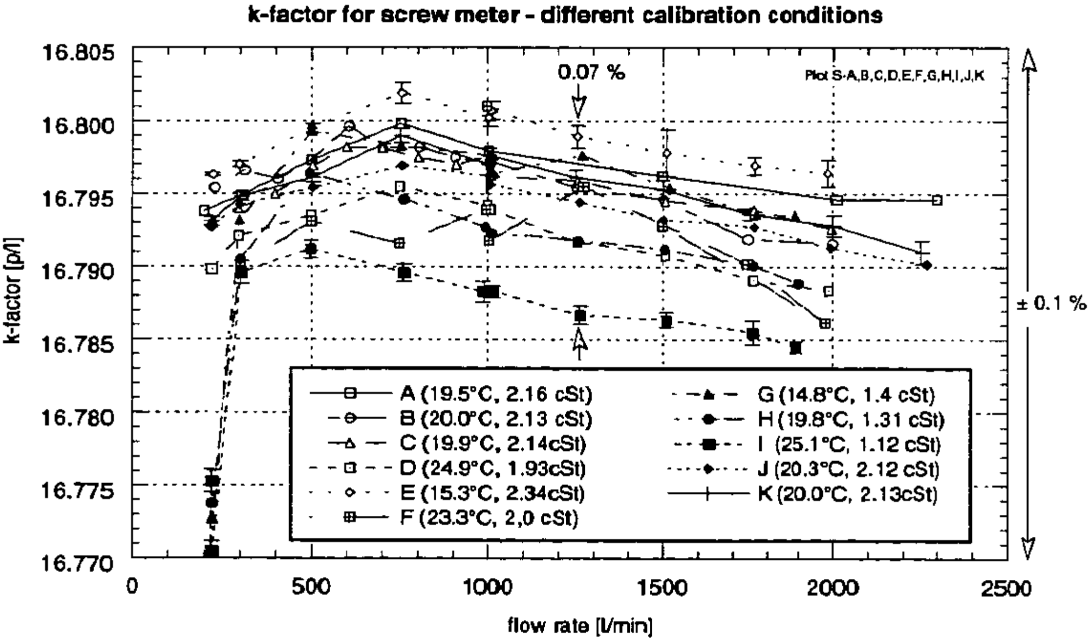


Fig. 4: Result of pre-tests at SP to reveal repeatability and reproducibility of the screw meter

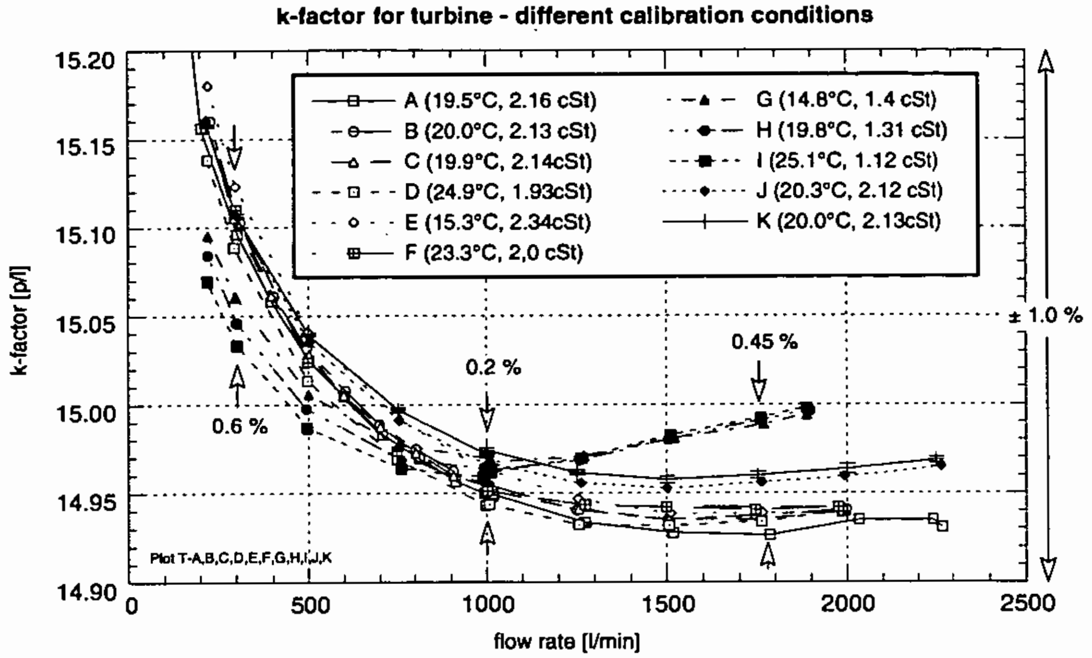


Fig. 5: Result from pre-tests on the turbine meter performance in two liquids and different temperatures involving variations in viscosity.

The figures 4 and 5 demonstrate two things. In the case of the screw meter the k-factor over the range of viscosities and temperatures is within 0.07 %. In the case of the turbine it is very obvious that both temperature and especially viscosity changes have a large influence on the meter behaviour. Thus corrections for both had to be worked out.

Compared to these effects all other factors like test method (gravimetric, volumetric, standing or flying start-stop), density changes of the liquid, size of test volume or testing time, type of reference and its installation etc., seem to be of second order. On the basis of the representative k-factors from the different curves the following numbers were calculated.

Table 3. Reproducibility of intercomparison and reproducibility within pilot laboratory (σ=2).

no flow straightener	reproducibility inter-comparison	reproducibility co-ordinating laboratory	repeatability co-ordinating laboratory	units
screw meter	0.16	0.07	0.01	[%]
turbine	0.17	0.09	0.03	[%]

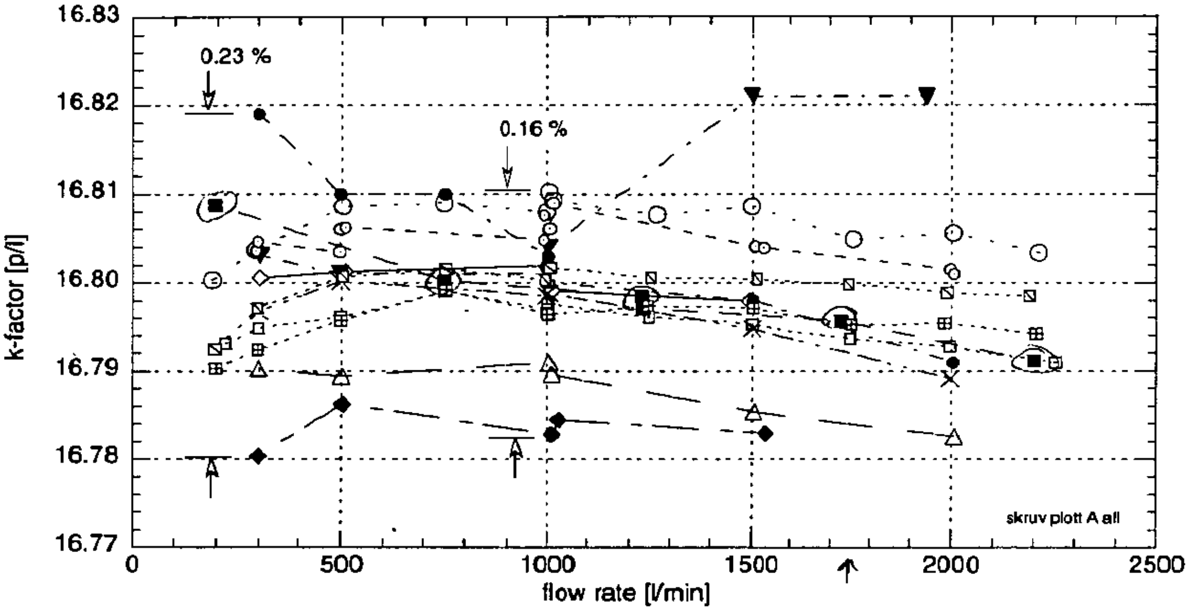
Although the statistical treatment takes care of different sample sizes it can be mentioned that the tabulated values for both the inter-comparison and the co-ordinating laboratory are based on 12 calibration series each. The information is given on a 95 % confidence level, stating that any two results (representative k-factors) between the participating laboratories are within 0.027 and 0.025 p/l for the screw meter and the turbine respectively, corresponding roughly to 0.16 % in both cases. Removing the flow straightener results in a comparable reproducibility for the screw meter, whereas it increases by a factor of 4 to 5 for the turbine.

These values, which actually exceed the estimated uncertainty intervals by the participants, are of course a measure *per se*. However, related to the reproducibility within the co-ordinating laboratory they seem very satisfactory being only twice as large. The tests in the co-ordinating laboratory covered a temperature interval of 15 - 25 °C, a viscosity range of 1.3 - 2.4 cSt, 2 methods, 2 test facilities, different installations of the meters in one of them, 6 volume references and 2 operators. Thus the comparison of reproducibility figures should be valid.

RESULTS FROM THE INTER-COMPARISON

At the participating laboratories four basically different measuring methods were used. The majority utilised a volumetric technique. Some laboratories used two volume references, a smaller one for the lower flow rates. At one laboratory a reference meter was used that in turn was calibrated via two volume standards and one used a gravimetric technique. The result before any corrections were undertaken is shown in figure 6 and 7 below.

Screw meter calibration curves with flow straightener as reported by the laboratories



Turbine calibration curves with flow straightener as reported by the laboratories

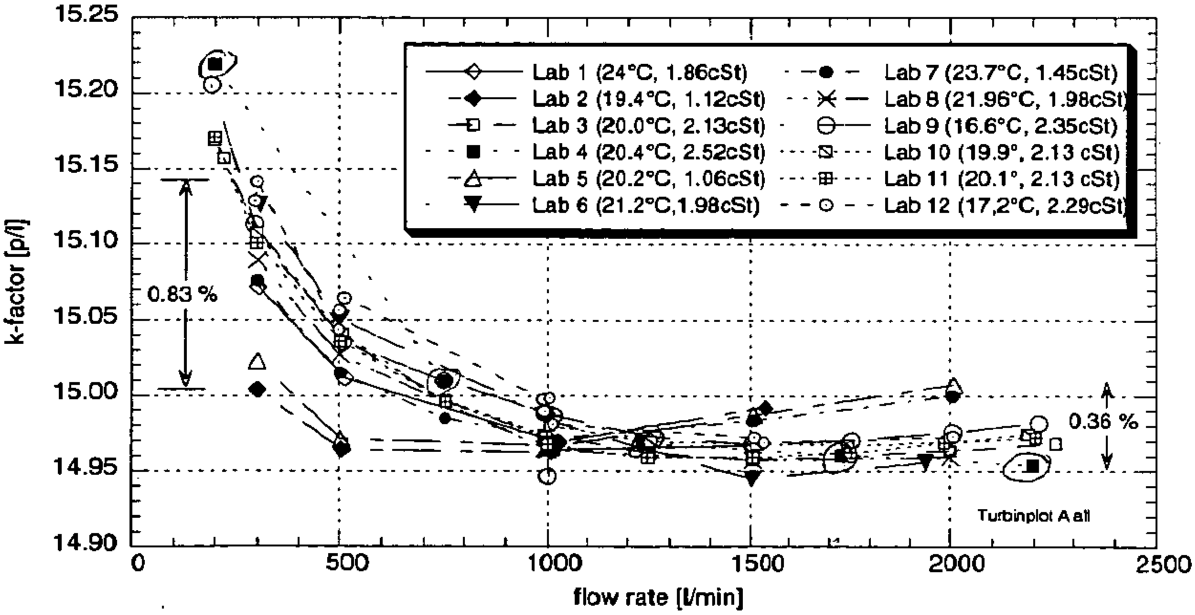


Fig. 6, 7: The calibration curves from the inter-comparison when the flow straightener was inserted. Each point represents the mean of 10 repeated measurements

Compared with the corresponding tests at SP (figure 4 and 5) the spread between the resulting curves is even larger, which is mainly due to a larger range in liquid viscosity, which was in the range 1.05 to 2.54 cSt. This does not seem very much, but was found to have a significant effect on the results of the turbine meter and also influenced the screw meter.

It was considered necessary to work out a correction for both the temperature and viscosity deviations. Different techniques were tried. Finally for the temperature just the expansion of the pipe wall with temperature was calculated. And for the viscosity a correction was suggested that is based on a forward translation from a k-factor as a function of the flow rate to a dependence of the Reynolds number *Re*. Using the reference viscosity instead of the actual one implied a movement to a different Reynolds number and belonging k-factor. The following diagram contains the Reynolds number dependency.

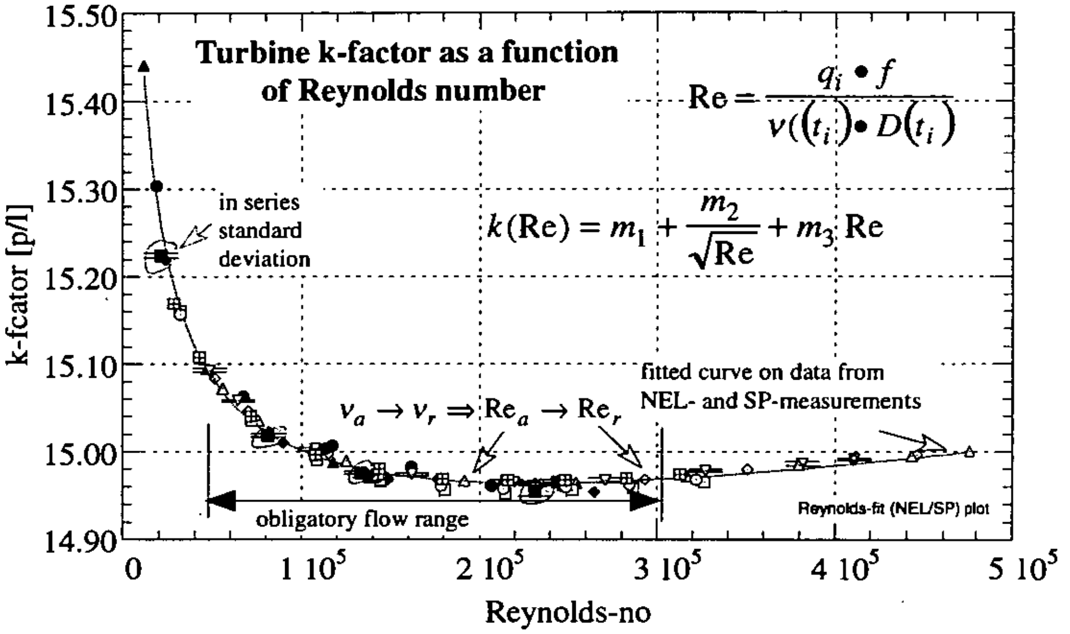


Fig. 8: The Reynolds number Re dependency as a translation help from one viscosity to an other. The experimental data is based on measurements at NEL and SP.

In order to extend the range of temperatures and viscosities several tests were repeated at NEL. The results from both laboratories fit well together.

The main task and most interesting question from the beginning was to reveal possible installation effects due to flow profile disturbances. Although the detailed curves from the measurements without a flow straightener are not shown here it should be mentioned that the spread for the screw meter, as expected, only increased very little from 0,11 to 0,14 % at mid flow rates. Concerning the turbine results, however, the curves diverged especially at higher flow rates from 0,36 to over 1 %. Although the available straight pipe length upstream of the meter package was between roughly one and seven meters at least 4 test sites faced problems with the flow profile. The following Youden plot summarises the problem. It is constructed by plotting a representative k-factor for the two simultaneously measured meter curves against each other. Figure 9 shows the original turbine and the screw meter factor on the x- and y-axis respectively, i.e. before any corrections were performed.

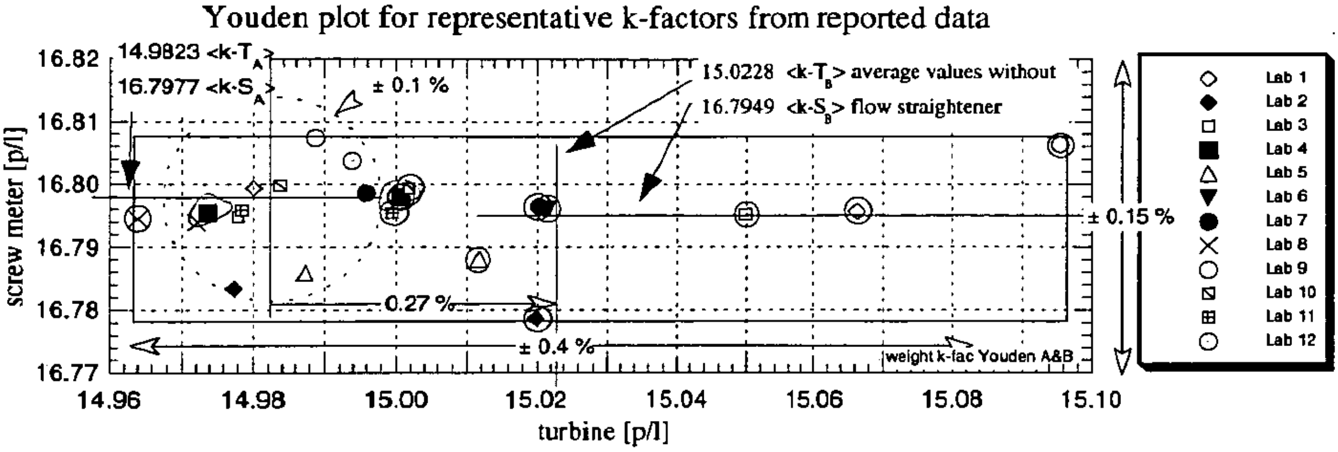


Fig. 9: Values of the representative k-factors with and without (encircled) a flow straightener to minimise flow profile disturbance. Definition of global values as the respective average from all laboratories.

One can distinguish between two groups of results. The encircled ones represent the configuration without the flow straightener. They are wide spread with more than ± 0,4 % on the x-axis. The same symbols without the circle give the corresponding result with the flow straightener in place. One can observe that, in contrast to the turbine, the results and the range of spread for the screw meter, i.e. with respect to the y-axis, is almost the same.

Inter-comparison Result and Measurement Uncertainty

The two pairs of crossing lines define two global mean values for respective meter and test configuration. They present as an overall outcome from the inter-comparison the most probable meter factor result. The large shift of 0,27 % between the two situations with and without the flow straightener in place is mainly due to the large overestimation in some test rigs. As an other effect the physical existence of the straightener has a strong influence on the turbine creating its own flow profile.

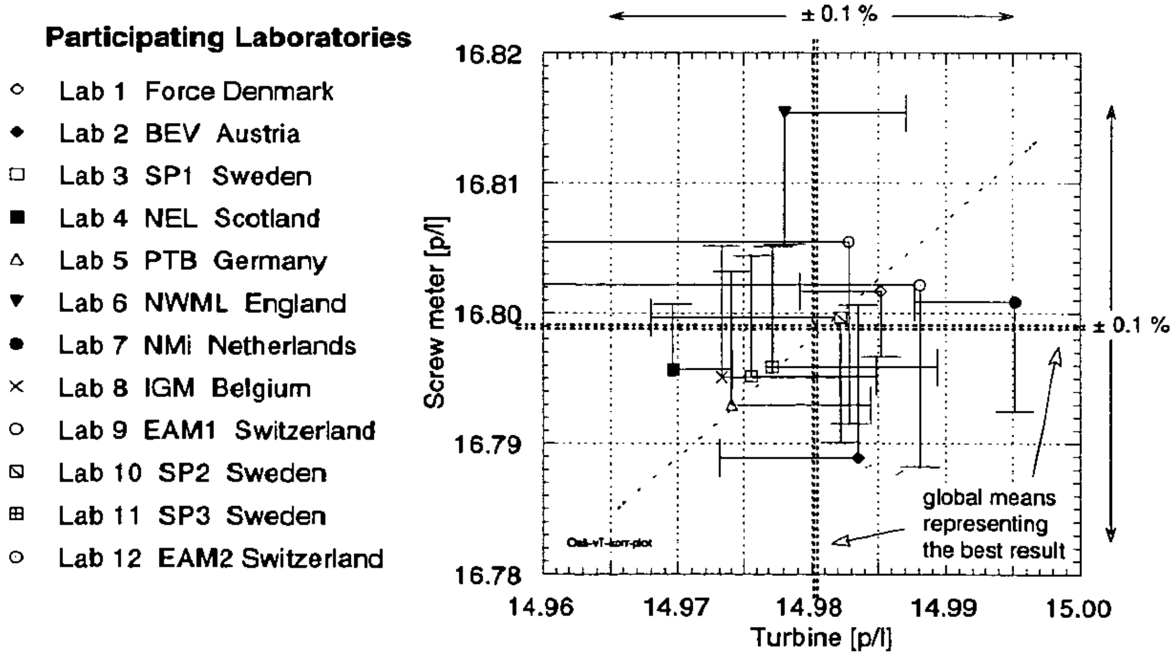


Fig. 10: The inter-comparison result adjusted with respect to temperature and viscosity together with the corresponding uncertainty judgements.

Figure 10 presents the most essential part of the inter-comparison. Here installation effects are effectively blocked of by the flow straightener and corrections both for temperature and viscosity deviations are applied for both meters. Thus the diagram represents a couple of results from very stable meters all taken at idealised measurement conditions but at different test sites. The results are further completed with the uncertainty estimations delivered by each laboratory, which range from ±0,03 to ±0,3 % with an average at about 0,06 %. The uncertainty bars given above cover in most cases the global mean values but do not necessary overlap with each other, which means that some estimations are too optimistic. From figure 10 one could state an uncertainty of the global mean itself of roughly ±0,08 % for the turbine and somewhat better for the screw meter.

A further observation from figure 10 is that the majority of results seem to fall into the vicinity of a correlation line. This might be interpreted as systematic differences in the volume references used at the participating laboratories.

Considering the situation that a number of national flow laboratories working at optimal calibration conditions with repeated measurements with a stable meter of good repeatability can agree to a common meter factor with an uncertainty of lets say ±0,06 to ±0,08 % means that the individual calibration uncertainties hardly can be much better. If a laboratory deviates from the well selected conditions and allows for a small change in temperature (±3 °C) and viscosity (±1cSt) then the new k-factor and the belonging uncertainty figure in that calibration certificate may still apply on the same level but it will not cover the earlier conditions without increasing the uncertainty to ±0,1 % or more. The same is true if the meter after calibration is run in somewhat different conditions, which is generally the case. Thus the owner of the meter cannot expect to be able to measure with the same low uncertainty as long as the calibration is not performed in the actual installation and at actual conditions. The whole discussion, however, still would demand that the flow profile conditions must be under full control. Otherwise as seen in figure 9 uncertainties of ±0,4 % are not unrealistic and the problem tends to increase for higher flow rates.

CONCLUSIONS FOR A USER OF FLOW METERS

A user of turbine meters and this is probably even true for other types of meters should first of all prepare for a good installation if accurate flow or volume measurements are of interest. Preferably a flow straightener should be used not only in the measurement installation. It is recommendable to send the meter with preceding and following pipe work including a straightener and keep everything unchanged in one package. A third recommendation, as a result of this work, would be to inform the calibration laboratory about the measurement conditions for the particular meter in terms of temperature and viscosity range and if ever possible to simulate those conditions during the calibration as close as possible. One also should consider to perform transformations between different liquid properties. Finally and this is most easily to accomplish a linearising equipment should be used. The uncertainty numbers given above concern just one k-factor chosen as a representative value for a whole curve. It is preferable to work with varying k-factors or different corrections along a meter curve in order to keep a god uncertainty even at low and high flow rates.

References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.