Peter Lau
Krister Stolt

Calibration Intercomparison on Flowmeters for Kerosene Synthesis Report

3476/1/0/203/92/9-BCR-S(30)

SP
Swedish National Testing and Research Institute
Weights & Measures
SP REPORT 1995:77

Abstract

The results of a calibration intercomparison on a flowmeter transfer standard are reported. It was performed between nine primary flow laboratories in Western Europe with kerosene as a typical representative for light oil products. The transfer standard consisted of a turbine meter in series with a screw meter. The stability of the meters over the calibration period of 14 months was an order of magnitude less than the measurement uncertainty. The reproducibilities of the meters in the intercomparison were 0.16 and 0.17% respectively. This is about twice the reproducibility from the tests preceding and following the intercomparison exercise at the co-ordinating laboratory. The spread in the reported calibration results was predominantly caused by differences in the liquids used for the calibration.

The meter results were also compared after an attempt was made to equalise the physical properties. For the adjustment of the turbine, the relation between the meter factor and the actual Reynolds number was suggested. The adjustment of the screw meter was based on its viscosity dependence, which was found to be non-linear and flowrate dependent. The techniques are presented. Due to the non-linear behaviour of the turbine characteristic, the quantitative comparison between the laboratory results was largely based on the concept of a representative k-factor. The sensitivity of its construction to viscosity and to the selection of calibration points is studied in detail.

The calibrations, which were performed both with and without a flow straightener in front of the turbine, revealed that at least four sets of calibration results suffered from significant installation effects.

The uncertainty ranges claimed by the flow laboratories for the stated k-factors were in some cases too small to overlap or to cover the average k-factor even after attempts to remove the differences in liquid properties had been made. The uncertainty margins are presented without regard to influences from the liquid or flow profile properties. Thus installation effects may quite clearly exceed the specified uncertainty limits in the case of the turbine meter.

This intercomparison project formed a part of the harmonisation in Western Europe in the field of flow measurement. It was supported by the BCR, arranged as a BCR-project and co-ordinated by the Swedish National Testing and Research Institute. Part I of the report describes the outcome of the intercomparison and Part II presents the basic measurements obtained to characterise the meters of the transfer standard.

Key words: Intercomparison, calibration, flow meter, flow straightener, viscosity, turbine, screw meter.

Sveriges Provnings- och Forskningsinstitut
SP Rapport 1995:77
ISBN 91-7848-606-8
ISSN 0284-5172
Borås 1995

Swedish National Testing and Research Institute
SP REPORT 1995:77

Postal address:
Box 857, S-501 15 BORÅS, Sweden
Telephone + 46 33 16 50 00
Telex 36252 Testing S
Telefax + 46 33 13 55 02

Contents

1 Introduction

The objectives of this calibration intercomparison, using a pair of flowmeters, were threefold. The first was to verify the degree of agreement between the participating laboratories concerning this metrological task. Provided the reference meters are substantially stable and repeatable, the exercise should result in a figure for the reproducibility currently available for a customer turning to any one of the involved laboratories. This also puts a spotlight onto a real calibration uncertainty to be expected for these meters and it further shows if the involved laboratories performed correct dynamic flow and volume measurements.

Secondly, significant differences in the results between the laboratories should reveal existing systematic errors, which are impossible for a laboratory to find out on its own. The analysis of the results should indicate whether these effects come from the test facility or from the calibration method used. If there is a problem with the traceability chain back to the definition of the litre, this, as well, should be possible to see from the results.

And thirdly, as an additional benefit, the intercomparison was expected to produce valuable information to improve the calibration work carried out at the participating laboratories.

The intercomparison could be looked at from the point of view of a customer needing a calibrated flowmeter. Whichever laboratory he chooses in Western Europe, he would expect to get the same value from the calibration or rather a list with identical flow dependent k-factor values for his meter. The realistic metrologist, however, would expect a spectrum of values due to several influencing factors that differ from laboratory to laboratory. Among these the physical properties of the liquid, the pressure and the temperature must be mentioned, as well as the type and size of reference used. Properties of the test facility, like installation effects producing non-ideal flow conditions or unknown problems (leakage, gas content, etc.) might also have a significant effect on the result. The same is true for the applied test method and the corrections used. On top of that, as flow calibration is a delicate profession, even the skill of the operator, whether we like it or not, can influence the result.

The measurement of large quantities of a valuable liquid, performed with different or even equal meters, calibrated at different laboratories, should of course result in values that can be regarded as equal with respect to the measurement uncertainty specified at the different locations.

With the transfer standard, consisting of a turbine meter and a screw meter in series, and two measurement series, one with and one without a flow straightener in front of it, one should be able 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.

2 Organisation

The intercomparison was co-ordinated by the Department for Volume at the Swedish National Testing and Research Institute under contract of the BCR. The co-ordinator was responsible for the preparation of the intercomparison, for the design of the transfer standard, the working out of the guide-lines and the collection and analysis of the results given in this report. Another support from the BCR for this exercise was in the form of the expertise of Dr Spencer, who helped the organiser in all aspects of the experiments.

2.1 Participating Laboratories

The **Table 1** below contains the list of the nine laboratories engaged in this international intercomparison.

Table 1. The participating laboratories

	Institution:	Address:	Laboratory code:
SP	Sveriges Provnings- och Forskningsinstitut - Swedish National Testing and Research Institute	Brinellgatan 10 501 15 Borås Sweden	**Lab 3** cal I **Lab 10** cal II **Lab 11** cal III
NWML	National Weights an Measures Laboratory	Stanton Avenue, Teddington Middlesex TW11 OJZ U K	**Lab 6**
EAM	Eidgenössisches Amt für Messwesen - Swiss Federal Office of Metrology	Lindenweg 50 CH-3084 Wabern Switzerland	**Lab 9** cal I **Lab 12** cal II
IGM	Inspection Generale de la Metrologie	Chaussee de Haecht 1795 B 1130 Brussels Belgium	**Lab 8**
PTB	Physikalisch-Technische Bundesanstalt	Bundesallee 100 D-38116 Braunschweig Germany	**Lab 5**
NEL	NEL Flow Centre	East Kilbride Glasgow G75 OQU United Kingdom	**Lab 4**
NMi	Nederlands Meetinstituut	Hugo de Grootplein 1 NL-3314 EG Dordrecht Netherlands	**Lab 7**
Force	Force Institutterne Dantest	Amager Boulevard 115 DK-2300 København Denmark	**Lab 1**
BEV	Bundesamt für Eich- und Vermessungswesen	Altgasse 35 A-1163 Wien Austria	**Lab 2**

2.2 Time Table

The intercomparison started with the signing of the BCR contract in early 1993. During that spring the transfer standard was constructed and the meters and other material were ordered. Simultaneously the guide-lines were worked out, distributed and revised twice. The package was built in July. The stability tests started during the second half of July and were finished in mid-August directly followed by the first calibration (SP I). The rest of the exercise followed quite nicely the planned route and time schedule. The last calibration before the transfer standard returned to SP was somewhat delayed due to the summer holiday period, but could be balanced by the safety margins within the project. Unfortunately one of the laboratories performed only half the task and so was given the chance to conclude the measurements after the post-tests at SP. A technical hitch with their test facility then resulted in a considerable time delay so that the transfer standard did not return for some complementary measurements until December '94 and so the complete data were not available until the end of 1994.

The figure below gives a schematic picture of the time schedule. The deviation from the plan is indicated.

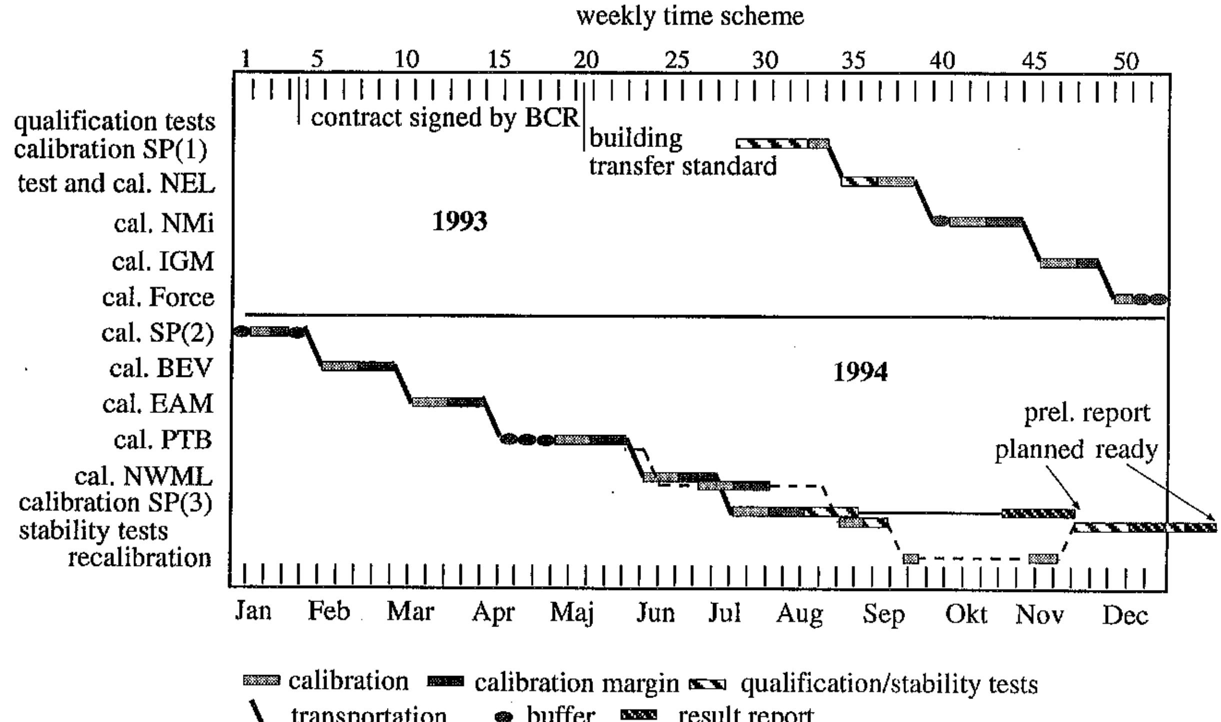


Fig. 1: Route for the transfer standard and time schedule for the intercomparison. A deviation from plan arose in June 94.

The personal transportation of the transfer standard by staff from the laboratories, in several cases from SP, worked out very well. This also offered the possibility to visit each others laboratories and resulted in valuable personal contacts. No problems with damage of the measurement equipment were reported. Nor did the meters indicate any problems that would make the reported results questionable in any way. The travelling route was not the most economic one, but was the most suitable with respect to the different limitations of the participating laboratories.

3 Transfer Standard

3.1 The Meters

To meet the target of the intercomparison, the demands for the flowmeter transfer standard were the following:

1) two different physical measurement principles
2) one sensitive and one insensitive to flow profile disturbances
3) very stable in short and long time terms
4) very linear over a considerable flow range
5) insensitive to liquid properties
6) insensitive to test methods

As the best choice to meet these demands, a turbine meter was selected in series with a screw meter. However, in practice, demands 4) and 5) were not fully met by the turbine. The following table collects the important data of the meters.

Table 2. Primary data of the meters

	Turbine meter	Screw meter
range	500 - 2 500 [l/min]	300 - 2 300 [l/min]
linearity	± 0.3 %	± 0.015 %
pulse output	magn. pick up - sine wave pulses	magn. pick up - rectangular pulses
material	stainless steel	carbon steel
nominal bore	3 inch	4 inch
repeatability from 12 calibration series (1σ-level)	0.0022 [p/l] ⇨ 0.014 %	0.001 [p/l] ⇨ 0.006 %
nominal k-factor delivered	14.51 [p/l]	16.63 [p/l]

The meters had quite comparable k-factors. The nominal values above were given on the reporting forms to all the laboratories. They are significantly, but not unrealistically wrong compared to the real ones. The idea was to give a hint without revealing the correctness of the individually measured values.

The linearity of the turbine was not as good as that of the screw meter. The stability calculations below are therefore based on the concept of a representative k-factor (see **Chapter 15** of **Part II**) rather than on the result at just one flowrate.

Table 2 lists the values found for the average repeatability from the pre- and post- tests (12 calibrations in 2 liquids and 2 different test facilities at several different temperatures, several different volume references - see **Part II** of this report). They indicate a very good short term stability for both meters. The reproducibility calculated from these tests is roughly a factor 3 and 5 larger for the turbine and screw meter respectively. The long term stability can be characterised by the differences in the meter factors from the first (SP I) to the last calibration series (SP III) within the intercomparison. It was 0.003 % and 0.004 % for the turbine and the screw meter. This is well below the measurement uncertainty that is inherent to these meters. It could therefore be assumed that the chosen instruments have a good capability for the intercomparison task.

3.2 The Meter Package

The meter package consisted of three parts: a long section (1755 mm), a short section (871 mm) and a 4" to 3" adapter (100 mm) - see the drawing in **Appendix 1**. For transportation two specially designed wooden boxes were built and the meters fastened in an arrangement supported by shock absorbers to prevent damage on the delicate meter bearings.

The long section was made up of the turbine and two straight pipes of 3" diameter. Both pipes had a length of 10 D. The front pipe housed a flow straightener made up of a tube bundle of 19 thin-walled pipes[1]. It was positioned in a fixed orientation with the help of a guide tab in the pipe wall and a corresponding recess on the back side of the ring to which the pipe bundle was welded. The fitting between the flow straightener and the tube was very fine and the straightener was kept in place with the help of a spring in the circular recess.

The short section consisted of the screw meter with a filter and a 3" to 4" cone in front of it and a short 4" tube with a loose flange behind for easier connection to the test facility. The filter was easily extracted for control and cleaning. This section was also housed in a specially built transportation box.

The different parts of the transfer standard were carefully fixed to each other using pins and dowels in order to preserve their relative orientation. In fact, during the whole exercise there was never a need to disassemble any of the two sections.

The third section comprised just an adapter piece for a 3" and 4" connection to adapt the package entrance to a 4" facility or the outlet to a 3" facility.

In order to easily fit into different installations, hybrid flanges were produced combining four different flange standards. Together with all necessary spare parts accompanying the package this worked very smoothly.

The transportation boxes also included all necessary parts to connect the meters directly to the pulse counters at each laboratory.

3.3 The Temperature Sensor

A Pt-100 temperature sensor was permanently built into the straight pipe behind the turbine meter. It was connected to a temperature instrument THERM 2283-2 having a resolution of 0.01 °C. The idea behind this was to have a common temperature reference between the laboratories. The differences to the thermometers used in the laboratories were, however, insignificant and no corrections were applied.

---

1 ISO 5167-1 : 1991 Measurement of fluid flow by means of pressure differential devices - Part 1: Orifice plates, nozzles and Venturi tubes inserted in circular cross-section conduits running full.

4 Measurement Task

The primary idea of the intercomparison was that each laboratory should perform the calibration as a routine task. For the sake of the comparison, however, certain aspects had to be 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 flowrates. In the first one (configuration A) the 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.

For the sake of comparability the five obligatory flowrates, numbered in order 1 to 5, each with 10 single repetitions, were pre-defined. In contrast to the usual procedure in the laboratories, it was prescribed to start at a middle flowrate 3:1 advancing to the higher ones 4 and 5. Thereafter the lowest 1 and 2 were to be measured and finally the first one repeated (3:2). Thus a simple reproducibility measure was available. Any other additional flowrates were to be run after this series.

Kerosene was recommended as a suitable calibration liquid. 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. No recommendations as to the calibration method, start-up procedure or any other part of the calibration were given but the laboratories were asked for details of their usual routine method of working.

4.1 Reporting

The reporting forms delivered with the guide-lines concentrated only on the most important information from the calibration, namely 1) the result of the 10 single measurements at each flowrate (result form), 2) the collection of the relevant data on one sheet (summary form - see **Appendix 2** for each laboratory), 3) a form for describing the used method (method form), 4) a schematic drawing and some data on the test facility (facility form) and, finally, 5) some information in free form on the uncertainty calculation (uncertainty form).

For an easier and safer exchange of measurement data, the result form and summary form, performed as a spreadsheet application, were distributed on a disk to those laboratories that wished to use such. Some of the laboratories used this possibility, which worked out very well.

Two laboratories did not have the capability of running the highest flowrate, No. 5. Three laboratories could not control the liquid temperature as close to room temperature conditions as was asked. One laboratory did not have its own test facility for this particular liquid and therefore needed to transport the measurement equipment, including a mobile prover, to a flow rig that was not built for primary calibration purposes. The same laboratory was unable to record the flow through both meters simultaneously, which makes the placement of points in the Youden plots (**Figs 1** and **2**) not totally comparable.

5 Intercomparison Results

The information gained in this intercomparison is divided into different aspects, starting with the overall goal. The raw calibration data as presented by the laboratories are contained in **Appendix 2.** They are supplemented with a column for a Reynolds number and some representative meter factors for information reduction. An overview is presented in **Table 3** specifying altogether the 12 calibrations randomly numbered. The numbers 3, 10 and 11 correspond to the first, the intermediate and the last calibration at SP.

Four basically different measuring methods were used. The majority utilise a volumetric technique. Some laboratories used two volume references, a smaller one for the lower flowrates. **Lab 7** used a reference meter that in turn was calibrated via two volume standards.

Without cooling devices it was difficult for some of the laboratories to keep the liquid temperature close to 20 °C. This is especially true for **Lab 1** that did not have its own test facility for this particular liquid and also had only a very small tank (5 m^3) at its disposal.

The viscosity, with respect to the different liquids used, 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. The available straight pipe length upstream of the meter package was between roughly one and seven metres.

The k-factor values listed in **Table 3** are those adjusted to a common temperature and viscosity of 20 °C and 2 cSt. The adjustment tries to equalise the liquid properties. These values should therefore be the best possible ones for a neutral comparison of the metrological overall agreement between the laboratories. The listed k-factors comprise a value which represents a whole calibration curve; the basis for this construction is discussed in detail in **Chapter 15** of **Part II** of this report. The upper one of the two calibration values refers always to the configuration A, i.e. with the flow straightener in place. The lower value is valid for configuration B without the flow straightener. The spread between each set of corresponding values can be used to judge the calibration reproducibility with respect to the used techniques and the test equipment, but disregarding the influence from the liquid properties.

As a simple measure for a laboratory's repeatability the best and worst standard deviation from 10 repeated measurements at the different flowrates are listed. The higher values come predominantly from the calibration without the flow straightener. For comparison the uncertainty estimates given by the laboratories are also listed. These were stated without respect to the actual liquid used in the calibration. Thus the adjusted k-factor values mentioned above and the uncertainty statements should be seen in relation to each other. Only one laboratory made use of the difference between configuration A and B in the specification of its measurement uncertainty.

5.1 Reproducibility of the Intercomparison

The usage of a representative k-factor for an overview, if accepted as such, is quite practicable as a concept. Not only is it often that a user wants to handle just one single value but its use is also very intuitive compared to the unreduced data of a table or the picture of a couple of curves. As a further advantage, the representative k-factors can be used to calculate an inter-series standard deviation (see **Chapter 13**, **Part II**), which is a better measure than just using comparable values at one flowrate. Based on this concept an inter-laboratory reproducibility can be calculated. Then, by comparison with the reproducibility of, for instance, the pre- and post- tests and the calibrations performed by the co-ordinating laboratory SP, the outcome of the exercise can be appreciated in a statistical way. These values, calculated according to the definitions given in **Appendix 3**, are presented in **Table 4**.

Table 4. Reproducibility of intercomparison and reproducibility within one laboratory (σ=2).

	reproducibility intercomparison	reproducibility co-ordinating laboratory	repeatability co-ordinating laboratory	factor inter-comp./ co-ord. lab.	factor reproduc./ repeatab.	units
screw meter (config A)	0.027 *0.16*	0.011 *0.07*	0.002 *0.01*	2.6	5.0	[p/l] *[%]*
turbine (config A)	0.025 *0.17*	0.014 *0.09*	0.005 *0.03*	1.8	3.1	[p/l] *[%]*
screw meter (config B)	0.022 *0.13*	0.017 *0.10*	0.003 *0.02*	1.3	5.0	[p/l] *[%]*
turbine (config B)	0.115 *0.77*	0.183* *1.22*	0.020 *0.13*	0.6	9.2	[p/l] *[%]*

* comment: the high value is due to the first calibration not being in agreement with the two following - compare Chapter 13 part II.

Although the statistical treatment takes care of different sample sizes it can be mentioned that the tabulated values (configuration A with the straightener) for both the intercomparison and the co-ordinating laboratory are based on 12 calibration series each. In the case of configuration B without the straightener the values refer to 11 and 3 series respectively . 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 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, are of course a measure *per se*. However, related to the reproducibility within the co-ordinating laboratory given in column 3 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. The relation between the reproducibility and the repeatability at the co-ordinating laboratory is about a factor of 5 for the screw meter but differs for the turbine depending on the configuration.

5.2 Comparison by Youden plots

A visual way to show the overall agreement of the exercise is to present the values in a Youden plot. This is done in **Figs 1** and **2**. The first of these shows the representative laboratory k-factors calculated on the basis of the submitted calibration data from **Appen-**

Table 3:

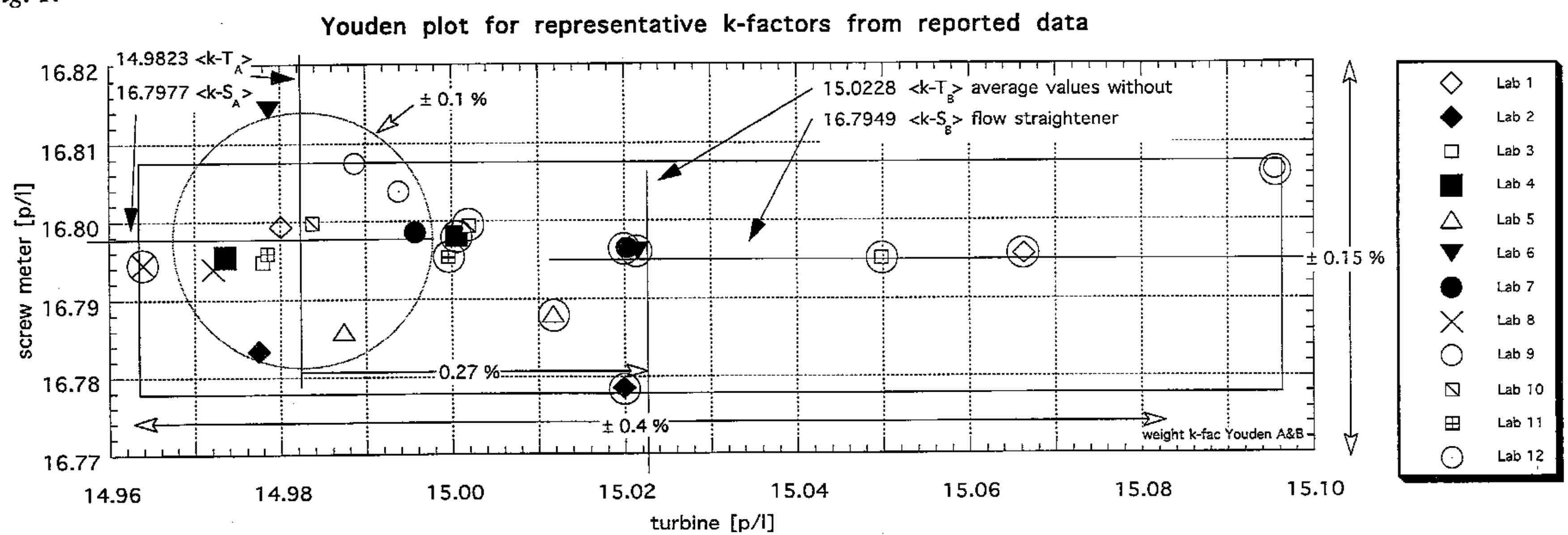
Calibration No: or Lab No:	Method	Reference	Test volume [l]	Liquid temperature [°C]	Liquid viscosity [cSt]	Straight length upstream standard [m]	Turbine k-factor [p/l] *** config A config B	Standard deviation max min [%]	Uncertainty estimated max min ± [%] **	Screw meter k-factor [p/l]*** config A config B	Standard deviation max min [%]	Uncertainty estimated max min ± [%] **
1 Force	volumetric flying s/s	piston prover	60	21.5 - 31.8	1.94 - 1.64	≈ 1	14.9852 15.0777	0.018 0.007	0.04	16.8017 16.8012	0.006 0.002	0.03
2 BEV	volumetric standing s/s	volume standard	1000	15.1 - 21.8	1.19 - 1.08	≈ 2.5	14.9835 15.0252	0.045 0.010	0.07	16.7889 16.7825	0.039 0.008	0.07
3 SP I	volumetric flying s/s	piston prover	60	19.4 - 21.2	2.15 - 2.08	≈ 3.5	14.9765 15.0483	0.030 0.006	0.062 0.055	16.7947 16.7955	0.008 0.001	0.056 0.055
4 NEL	gravimetric standing s/s	2 weigh tanks	variabel 900 - 3600	20.1 - 20.5	2.54 - 2.52	6.8	14.9696 14.9962	0.074 0.010	0.03	16.7957 16.7983	0.044 0.008	0.03
5 PTB	volumetric standing s/s	volume standard	2000	20.0 - 20.6	1.06 - 1.05	≈ 1.3	14.9740 14.9980	0.074 0.011	0.09 0.06	16.7930 16.7949	0.014 0.006	0.064 0.060
6 NWML	volumetric standing s/s	2 volume standards	910 4970	20.2 - 22.8	2.01 - 1.94	≈ 2.3	14.9781 15.0210	0.036 0.005	0.06	16.8154 16.7970	0.027 0.002	0.06
7 NMi	volumetric standing s/s	2 volume standards	2000 5000	20.3 - 25.9	1.52 - 1.40		14.9952 15.0196	0.011 0.003	0.05	16.8009 16.7983	0.011 0.002	0.05
8 IGM	volumetric standing s/s	2 volume standards	3000 10000	20.7 - 22.6	2.02 - 1.96	≈ 1.4	14.9732 14.9646	0.027 0.002	0.07 0.06	16.7951 16.7953	0.013 0.001	0.06
9 EAM I	volumetric flying s/s	ball prover	3000	15.9 - 17.8	2.38 - 2.26	≈ 5	14.9828 15.0894	0.031 0.003	0.31	16.8055 16.8047	0.004 0.001	0.083
10 SP II	volumetric flying s/s	piston prover	60	19.6 - 20.2	2.14 - 2.12	≈ 4	14.9822 15.0004	0.042 0.006	0.095	16.7997 16.7994	0.005 0.001	0.057
11 SP II	volumetric flying s/s	piston prover	60	19.7 - 20.7	2.14 - 2.10	≈ 4	14.9772 14.9980	0.025 0.008	0.081 0.057	16.7959 16.7954	0.005 0.002	0.055
12* EAM II	volumetric flying s/s	ball prover	3000	15.6 - 18.7	2.39 - 2.25	≈ 5	14.9881	0.016 0.001	0.31	16.8022	0.003 0.001	0.083

* Calibration as in 9 but at higher pressure (10 bar)

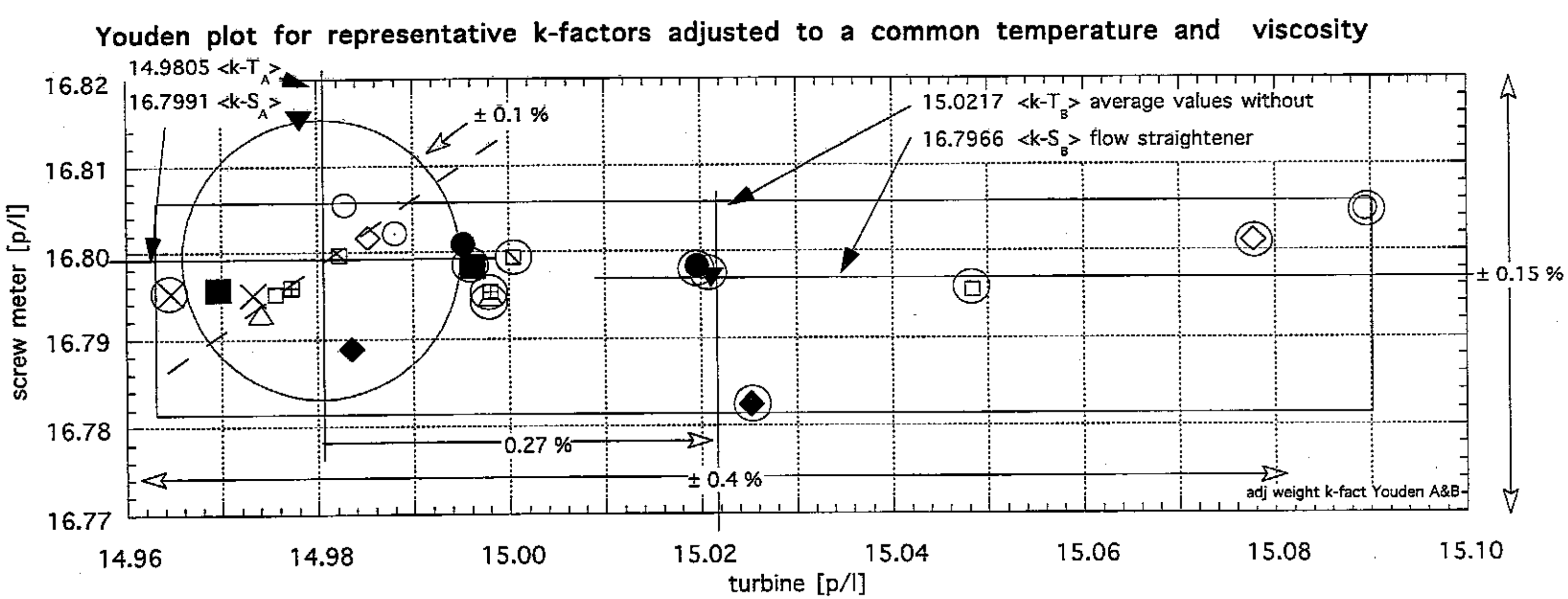
** The figures presented are given with extended resolution to show differences. The third position does not show confidence in a metrological sense

*** The meter factors are the representatives of a whole calibration curve. The values given are adjusted for temperature deviations from 20° C and for viscosity deviations from 2 cSt.

Fig. 1:



Youden plot for representative k-factors from reported data
14.9823 <k-T_A>
16.7977 <k-S_A>
± 0.1 %
15.0228 <k-T_B> average values without
16.7949 <k-S_B> flow straightener
± 0.15 %
0.27 %
± 0.4 %
weight k-fac Youden A&B
screw meter [p/l]
16.82
16.81
16.80
16.79
16.78
16.77
14.96
14.98
15.00
15.02
15.04
15.06
15.08
15.10
turbine [p/l]
Lab 1
Lab 2
Lab 3
Lab 4
Lab 5
Lab 6
Lab 7
Lab 8
Lab 9
Lab 10
Lab 11
Lab 12



Youden plot for representative k-factors adjusted to a common temperature and viscosity
14.9805 <k-T_A>
16.7991 <k-S_A>
± 0.1 %
15.0217 <k-T_B> average values without
16.7966 <k-S_B> flow straightener
± 0.15 %
0.27 %
± 0.4 %
adj weight k-fact Youden A&B
screw meter [p/l]
16.82
16.81
16.80
16.79
16.78
16.77
14.96
14.98
15.00
15.02
15.04
15.06
15.08
15.10
turbine [p/l]

Fig. 2:

dix 2. The calibration series (laboratories) are consequently indicated by the same symbol. Each point represents a pair of k-factors, one for the turbine and one for the screw meter respectively. The plain symbols are valid for configuration A with the flow straightener in front of the turbine whereas the encircled symbols demonstrate the result without the flow straightener. The two pairs of crossing lines mark the global means for the intercomparison with and without the straightener respectively (average of representative k-factors - see **Appendix 3**). At least for the situation including the straightener, $<k(r)T_A>$ and $<k(r)S_A>$ must be regarded as the best possible meter factor choice. Quite clearly there is an offset between the two configurations, which must originate from a superimposition of averaged installation effects and influences of the straightener itself. It can be assumed that the straightener, only 10 D in front of the turbine, will generate a flatter flow pattern.

Fig. 2 is constructed in the same way. The difference from the first one is just that the representative k-factors are calculated from the calibration results adjusted to a common temperature and liquid viscosity as shown in **Chapter 14** of **Part II**. The global mean is slightly changed. The larger the difference of the liquid properties from the adjustment value (temperature 20 °C, viscosity 2 cSt), the larger is the change in position from **Figs 1** to **2** (for example, **Labs 2** and **5**). The axis intervals are constructed to display the length of 1 cm to correspond to the same relative amount in percent on both the x- and y-axis, which makes it easy to compare the spread directly. The circle describes a ±0.1 % range from the global mean and all values from the measurement with the flow straightener are actually covered by it. If some of the observed irregularities were removed the screw meter range would probably amount to ±0.05 % indicating the metrological overall agreement between the laboratories, i.e. when the liquid influence is removed. From **Fig. 2** one can also depict, that the majority of the points fall into the vicinity of a correlation line, which partly might indicate systematic differences in the volume references amongst the participating laboratories.

5.3 Calibration Curves of the Screw Meter

A more detailed result of the comparison is presented by showing the actual calibration curves, which were found by the different laboratories. They visualise the screw meter and turbine data from the summary forms of **Appendix 3**.

The screw meter results are shown in **Fig. 3**. With one exception, they are always measured in series and simultaneously with the turbine. The screw meter has a good linear characteristic and its repeatability is in most circumstances better than that of the turbine. More important, however, is its lower susceptibility to changes in fluid parameters and flow properties. The judgement of the metrological agreement between the involved laboratories should therefore mainly be based on the results from this meter. It also makes the comparisons between the laboratories simpler and deviations easier to detect. Thus one can find two results with a deviating curve form at low flowrates (**Labs 4** and 7) and one at high flowrates (**Lab 6**). The **Labs 2** and **5**, working with the lowest viscosity, exhibit the lowest meter factor curve, although no significant sensitivity to viscosity was expected with this meter.

For better comparability the results from **Fig. 3** were first adjusted to a common temperature of 20 °C. This adjustment is simply based on the usual material expansion for positive displacement meters. The resulting data were then used to investigate a possible viscosity dependence. For the two laboratories with the distinctly lower viscosity a

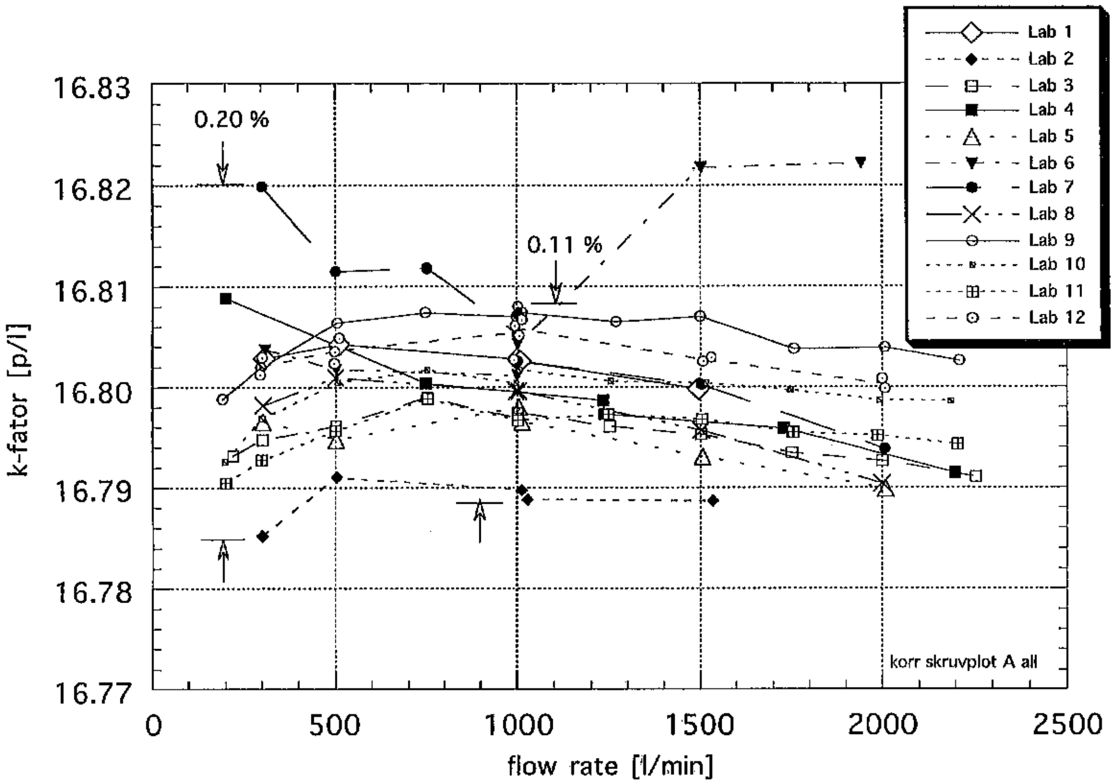


Fig. 4: Comparison of 12 independent calibrations of the screw meter with flow straightener. Adjustment to 20 °C for all and to 2 cSt for two laboratories (2 &5).

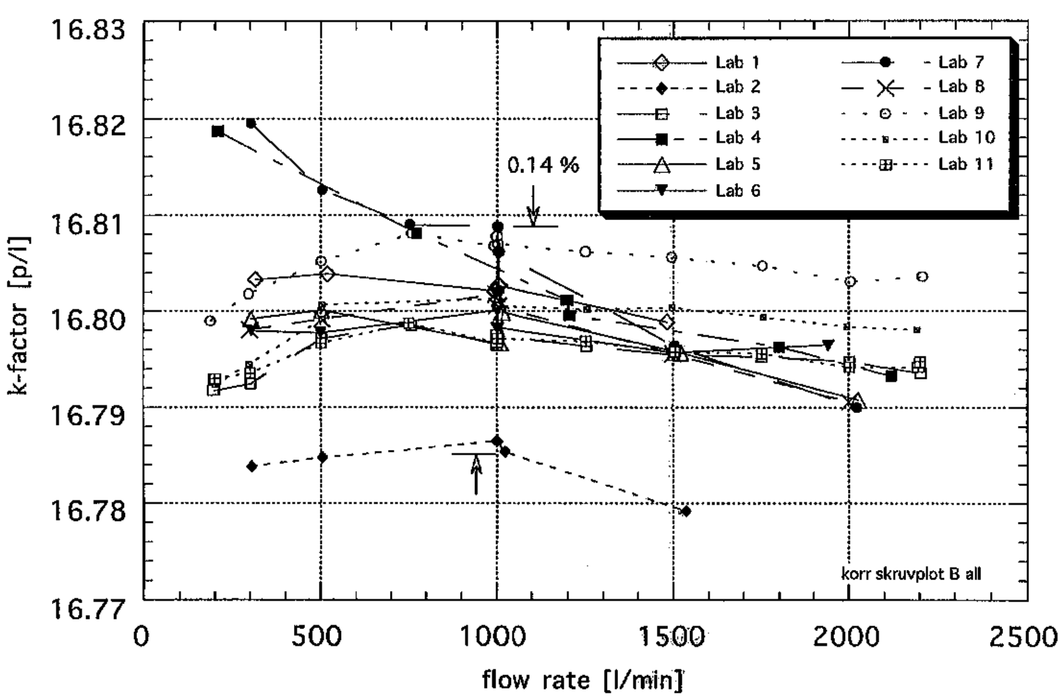


Fig. 5: Comparison of 11 independent calibrations of the screw meter in the package without a flow straightener at the entrance. All curves are adjusted to 20 °C and in case of Labs 2 and 5 also to 2 cSt.

correction was applied. This is discussed in **Chapter 14.2.1** of **Part II**. The adjusted results are presented in **Fig. 4**. Compared to **Fig. 3** the curves in the middle come somewhat closer to each other. The total range, however, is only slightly reduced (0.23 % ⇨ 0.20 % at low flowrates, 0.16 % ⇨ 0.11 % at mid-flow range). Even at high flowrates the adjustment brings the curves closer to each other, which however does not affect the range especially.

The screw meter was expected to be insensitive to flow profile shape. Thus removing the flow straightener was predicted not to affect the overall agreement between the laboratories. This was found to be the case. The curves corrected for temperature and viscosity deviations from 20 °C and 2 cSt are shown in **Fig. 5**. They correspond quite well with those in the **Fig. 4** with the flow straightener. The two somewhat differing results are again from **Labs 4** and **7** at low flowrates; the latter, especially, has also a more steep characteristic. **Lab 2** is still marked by even lower values as before, which leads to a range of 0.14 % at the middle flow. **Fig. 5** presents the magnitude of results a customer with such a positive displacement meter would get from the laboratories involved when all were working with a liquid very close to reference conditions.

5.4 Calibration Curves of the Turbine Meter

The reported turbine results are presented in **Fig. 6**. As can be seen from the legend the curve shape is largely influenced by the viscosity of the liquid used, which is implicitly also a function of the temperature. This is in good agreement with the pre-tests performed with different liquids and temperatures both at SP and NEL. A basic observation drawn from **Fig. 6** is that a higher viscosity generates a higher meter factor on the low-flow side and a lower one at the high-flow side. The results of **Lab 4** and the ones of **Labs 2** and **5** show the extreme examples. The cluster of curves exhibits a crossing region at about 1200 l/min, which also is in good agreement with the pre-test results. The largest spread, of roughly 0.8 and 0.4 %, between the laboratories exist at the lowest and highest obligatory flowrate.

Presenting the meter factor as a function of Reynolds number rather than of the flowrate revealed a much better coincidence (see **Fig. 25**) between calibrations performed with different liquids and temperatures. Furthermore it is possible to fit a curve to this cluster leading to a mathematical description of the Reynolds number dependency, which is typical for this turbine. In turn this can be used to adjust all reported data to a common viscosity and temperature of 2 cSt and 20 °C. The suggested technique is explained in **Chapter 14.3** of **Part II.**

The result of that calculation, performed on all reported turbine data, is displayed in **Fig. 7**. Very clearly the calibration curves now show much better agreement. As indicated the largest spread has now reduced to 0.28 % and 0.2 % at the extreme flowrates. **Fig. 7** gives an image of what the intercomparison would have produced if all the laboratories were to have the same liquid at their disposal and to have kept the temperature very close to 20 °C. For the sake of visual presentation the fitted curve to all the turbine data is given along with the curves for two laboratories with extreme positions.

The effect of the absence of the flow straightener on the turbine is demonstrated in **Fig. 8**. The influence of temperature and viscosity has already been removed using the above-mentioned technique. Compared to the unadjusted data the range at the lowest

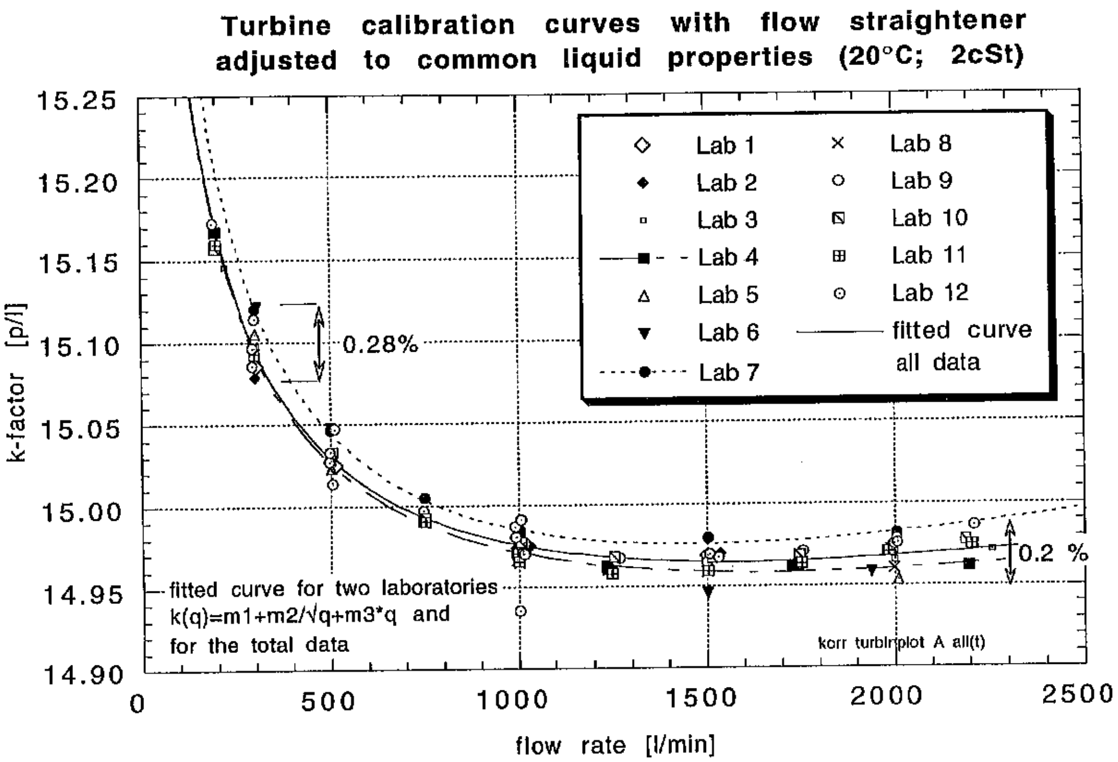


Fig. 7: Turbine results from Fig. 6 after temperature and viscosity adjustment. The thicker line represents the best fit to all points, whereas the broken lines fit the two extreme results.

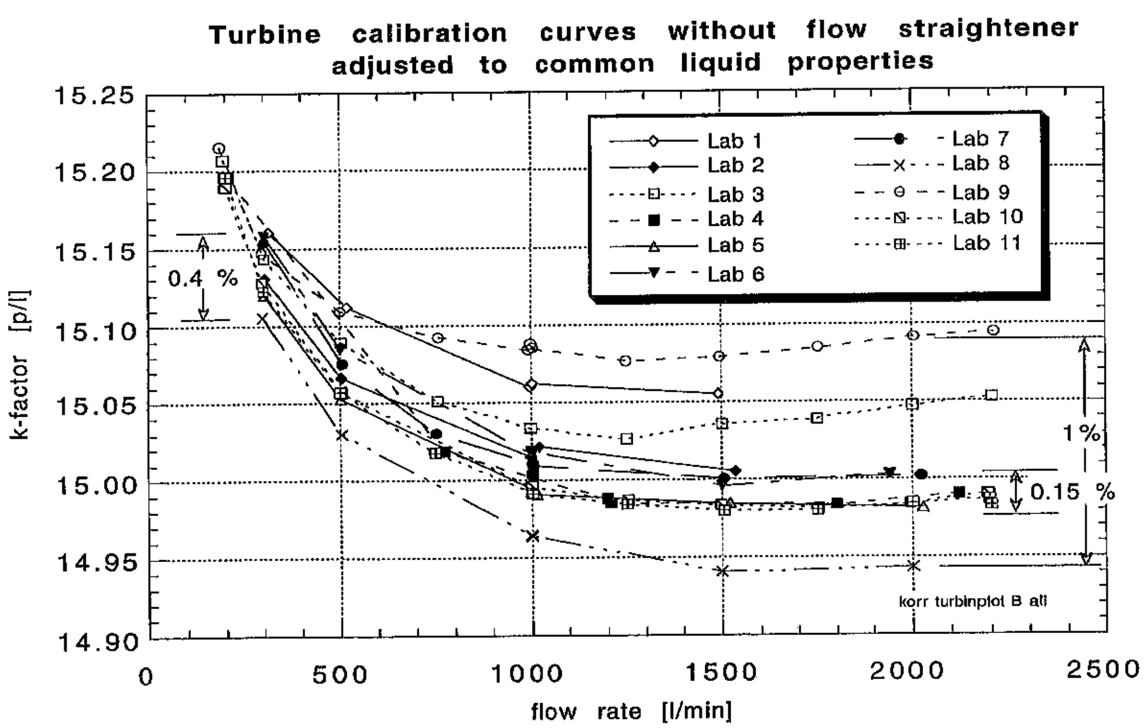


Fig. 8: The turbine calibration results (adjusted for comparable liquid properties) without the flow straightener exhibit a distinct spread due to flow profile disturbances.

flowrate is reduced from 0.96 % to 0.4 %. At high flowrates, however, the spread of 0.96 % before and of 0.99 % after the adjustment is unchanged, which is in contrast to configuration A, where the adjustment almost leads to a 50 % reduction (0.36 % ⇨ 0.2 %). This finding could be explained by flow-profile effects, which are predicted to increase with the energy content in the flow and this was what the measurement in configuration B was intended to reveal. As expected the curves diverge and the relation between them is quite changed compared to **Fig. 7**. Intuitively the three upper and the lowest curve deviate from the rest, especially at high flowrates and this reflects the findings from **Fig. 2**, where the curves are concentrated into just one representative k-factor for each laboratory.

6 Discussion of Results

6.1 Youden plots

The two Youden plots (**Fig. 1** & **2**) show the relation between the results of the laboratories in a visual way. If no installation effects or interference between flow straightener and turbine rotor were present, then the simple and encircled symbols should coincide for all laboratories. This is quite obviously not the case. Furthermore the centres for configurations A and B exhibit a clear offset. This is not significant in the case of the screw meter. Removing for instance the extreme values from **Lab 6** in configuration A and from **Lab 2** in configuration B would cause the global value $\langle k\text{-}S_A \rangle$ to be lower than $\langle k\text{-}S_B \rangle$.

Much more serious is the shift of 0.27 % for the global mean of the turbine after having removed the flow straightener. A closer look at **Fig. 2** also reveals that there are a couple of pairs (from **Labs 4, 5, 7, 10, 11**) that have about the same difference in the turbine factor $(k\text{-}T_B)$ - $(k\text{-}T_A)$ with the two configurations.

Table 5: The change in the turbine meter factor after removing the flow straightener.

Laboratory No:	1	2	3	4	5	6	7	8	9	10	11
Diff config A to config B [%]	0.6	0.28	0.47	0.17	0.16	0.28	0.16	-0.05	0.71	0.12	0.14

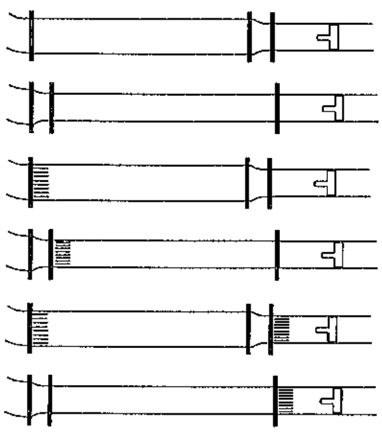
These differences are in the range 0.12 to 0.17 %, which however is significantly less than the offset 0.27 % between both centres. This indicates that the offset could be a superimposition result of an interference effect between the flow straightener and the turbine on the one hand and the averaged installation effects on the other hand.

6.2 Flow Straightener Influence

In order to estimate the suspected interference effect, a couple of calibrations were run after the post-tests and after a repeated calibration at one of the laboratories. In these tests two straight pipes of 3" and 4" diameter about 6 m and 4 m long were flanged between the standard arrangement from the calibration and the unchanged package of meters. For each pipe size three complete runs were performed, one without any straightener, one with the straightener at the entrance of the long pipe and one with the straightener in its original place. For the 3" pipe the straightener of the intercomparison (19 tube bundle) was used in both positions. For the 4" pipe an equivalent one was available and used in its entrance. During these tests the flow from the prover outlet reached the straight pipe via a plain rubber hose that undoubtedly imposed both an asymmetric profile and a swirl. The detailed results of these calibrations will be reported elsewhere. The information, reduced to representative k-factors, is collected in **Table 6**.

Several interesting conclusions can be drawn from the six resulting curves. The important one in this context is that the existence of the straightener reduces the meter-factor curve, as almost all laboratories stated. With a 4" supply pipe the amount is 0.12 %. With a 3" pipe the reduction is as much as 0.17 % if the flow is not rectified by a straightener after the disturbance in the bend hose. However, if a second straightener is introduced, which was possible only in the 4" pipe, then the reduction actually amounts to 0.26 %. The result for the 3" situation of 0.21% is not perfectly comparable as a second straightener in its entrance was lacking.

Table 6: The change in representative meter factor between comparable installations with a 4" and a 3" pipe and between different configurations of the same pipe size.

Straightener placement	code	Difference	Difference	Difference
—— flow direction ——>		[%]	[%]	[%]
	A4" A3"	A4"⇨ A3" 0.015 *0.005*	A4"⇨ B4" -0.123 *0.003*	effect of FS in package profile flattening
	C4" C3"	C4"⇨ C3" -0.085 *0.008*	effect of FS in pipe reduction of swirl	B4"⇨ C4" **0.264** *0.002*
	B4" B3"	B4"⇨ B3" -0.031 *0.005*	A3"⇨ B3" -0.169 *0.004*	B3"⇨ C3" **0.209** *0.000*

upper value for turbine, lower value italic style for screw meter.

The main reason for this behaviour is not fully understood, but could be ascribed to a flatter profile, a higher degree of turbulence produced by the tube bundle a short distance upstream of the turbine rotor and possibly to a generated swirl if the 19 thin-walled tubes are not perfectly in line with the outer pipe. Perhaps if the flattening is the dominating effect and persists to a large extent through the pipe length to the second straightener, then this could explain the large difference between the results of changing straightener placement A ⇨ B and B ⇨ C.

6.3 Installation effects

The figures above (A4"⇨B4" 0.12 % and A3"⇨B3" 0.17 % reduction by the tube bundle) without a straightener in the entrance of the pipe correspond very well with some of the laboratory results mentioned above. On the other hand one would expect the comparison with a second straightener to be the more realistic one. This, however, leads to a reduction of 0.26 % and 0.21 % respectively. The judgement, what reduction the flow straightener in the package really produces, is not simple to draw from the limited measurements and should be studied further. However, whichever value is finally assigned to the reducing interference effect, a larger or smaller difference between configuration A and B must be caused by disturbances from installation effects.

Clearly the findings from **Labs 1, 2, 3, 6** and **9** should, on the basis of this exercise, be interpreted as the result of a swirl supporting the turbine rotation, having a counter clockwise rotation. From the results of **Lab 3** (compare the deviation at the higher flowrates in **Fig. 6**), which were produced in a great hurry and looked upon and analysed after the equipment had already been sent to the first laboratory, it was fairly well established later on that the necessary bends of the used hose produced a swirl, that did not die out despite the fact that the hose was straightened for at least 4 m in front of the package. After the second calibration several extra measurements without the flow straightener were performed at a mid-flowrate revealing a large sensitivity to very small changes in the bending of the hose from the prover. Although the physical changes were too small to be documented in a proper way, the k-factors produced could change noticeably and in certain circumstances become even smaller than with the flow straightener in place.

The opposite deviating result of **Lab 8** (**Fig. 2**) is not easily identified as clockwise swirl effect. It might also be due to a significant deformation of the cylindrical symmetric flow profile.

6.4 Global Means

For the intercomparison the result shown in **Fig. 2**, with all physical differences in the liquid removed, is the most important one. If none of the 12 results is substantially different, then the two means of these 12 representative meter factors should form the best possible value for each instrument and configuration. It might be questioned whether it is correct to use 3 results from the co-ordinating laboratory and 2 from another one to build the global mean of the nine collaborating laboratories. But these calibrations were of course run under totally equivalent circumstances. Still one could argue the mean of the three results from SP together should have the same weight as that from every other laboratory. A calculation removing for instance SP's two first results would lead to a change well below 0.005 % in all cases and for the adjusted global mean an insignificant increase of only 0.0001 p/l for both meters would be found. As to the second calibration (only configuration A) performed by **Lab 9** at 10 bar pressure, it renders further information. Removing this result from the global mean would lower it with 0.007 % and 0.006 % for the turbine (raw data and adjusted data respectively). For the screw meter the global mean would be reduced by 0.002 % in both cases. It is felt that the total of twelve complete calibrations thus forms a balanced result, giving the best information on the meters in question.

Hence, the remaining differences from the global mean must emanate from imperfections in the references used, the techniques and the test facilities. The dashed line in **Fig. 2** indicates a systematic dependence at least for the results in the centre showing for both meters either a somewhat higher or lower value. The distance along this line might be interpreted as the difference in the references used between the laboratories, with the smaller ones in the first quadrant and the larger one in the fourth quadrant. The results of the three laboratories lying away from the dashed line must then have a different cause.

6.5 Observations

The characteristic of the turbine is far too non-linear to observe irregularities in the reported curves. For the screw meter, plotted with much higher resolution, the situation is different. Looking at the cluster of **Figs 4** and **5**, the results of **Labs 4** and **7** differ at the low flow range side, where both use different references, distinctly from the rest. This does not, however, influence the representative k-factor very much. A somewhat deviating characteristic is also seen in the turbine curve of **Lab 7**, behaving as performed in a liquid with a viscosity of 1.9 cSt on the low flow side and rather like one with 1.2 cSt at the high flow side.

A closer look to the relatively high screw meter result of **Lab 6** in **Fig. 2** indicates that it is only due to the two highest flowrates (see **Figs 3 & 4**) in contrast to the repeated measurement without the straightener (see **Fig. 5**). This is believed to be an incidental effect in the first measurement and not at all correlated to the straightener.

To focus on these details a series of cross-correlation plots between the turbine and the screw meter have been constructed. They are contained in **Appendix 5**. The first series comprises 12 plots, one for each calibration (**Lab 1** to **Lab 12**). Here the difference between the adjusted experimental values and a pair of reference values for the six flowrates is presented.

The reference chosen in both series is not the global mean or any other constant pair of values. Any constant reference would, due to the non-linearity of the turbine, hide the interesting details or make the plot totally asymmetric. The reference pair used instead is taken from the theoretically fitted curves for both the turbine and the screw meter, which is based on all the 12 calibration curves for each meter. For each arbitrary flowrate the meter factor calculated from these two curves serves as the best available for a comparison at just the interesting flow. Each point in any of the cross-correlation figures thus represents the difference in percent of the adjusted experimental value from the fitted k-factor for the actual flowrate. This construction has the benefit that measurements performed at other flowrates than the obligatory ones do not interfere with the flow dependence. Thus the centre of each figure defines a different pair in absolute values, but comprises always the best reference for the experimental points contained. This construction is demonstrated with the help of the figure in **Appendix 5** showing the two fitted curves and a cross-correlation plot. The picture visualises how the centre of the correlation plot is made up. Using two arbitrary values at flowrates a and b, the deviation from the fitted curves is explained.

The second series of correlation plots shows, for each of the obligatory flowrates, the position of the laboratories, again with respect to a pair of reference values constructed in the same way.

With this in mind one can more clearly point out some specific observations. One of them is the high values of **Lab 7** in series 2 at flow 1 and 2, which persist to flow 3:2 and which is also seen as a systematic dependency in plot **Lab 7** of series 1. A possible interpretation could be a leakage at the lower flowrates. The opposite is valid for **Lab 2** with a systematic shift to lower k-factors for both meters. Corrections having been made for temperature and viscosity dependency, this could indicate other effects such as: a) not all the liquid collected passes the meters, b) an overestimated volume standard, c) a leakage in the bottom valve of the volume standard, etc. Problems with the pulse registration are not considered to provide an explanation as the pulse preparation was the same for all laboratories.

Quite different is the situation for **Lab 6** with the unmotivated high values for the screw meter at flow 4 and 5. A similar situation is valid for **Lab 4** at flow 1. These might indicate an undetected extra pulse from the screw meter even after the run, which could happen if there are pressure pulses or vibrations in the liquid causing small angular movements of the screw that could induce a false pulse into the magnetic pickup.

The analysis so far does not indicate any behaviour of the results that can be related to the calibration technique or the size of the volume reference used. Comparing the average standard deviations reported from a piston prover of 60 l with those from a 3000 l ball prover or a 10000 l volume standard, one finds very comparable figures for both meters. The repeatability of the screw meter is almost always better than for the turbine. The calibration at 10 bar also supports findings at the co-ordinating laboratory that a higher pressure leads to more stable conditions. A trend seen in the reported data is that the repeatability (standard deviation) is higher at lower flowrates. With the flow straightener removed it also increases at higher flowrates. A reasonable explanation could be the spread in bearing friction at low flowrates. At high flowrates the straightener seems to have a damping effect.

The repetition of a calibration point is not the normal procedure in the laboratories. From all together 35 completed series (20 from the intercomparison) the repeated measurement at flow 3:2 showed a lower k-factor in 22 cases for both meters. In 12 cases the changes in the screw meter and the turbine had a different sign. There are two effects one can think of, if the change is significant and not caused by temperature (viscosity) changes. Pumping kerosene for a long time will saturate it with gas that is not removed in the gas separator. If it has the form of small bubbles then one would expect both meters to overestimate the real liquid volume. If the gas is dissolved, it might cause a reduction of the density, thus lowering the impulse on the turbine. In either case the difference might indicate changes in the calibration conditions that should be taken into consideration in an uncertainty calculation.

6.6 Representative k-factor Construction

As argued in **Chapter 15** of **Part II**, the construction of a representative meter factor is not very sensitive to the selection of calibration points. This means that this construction leads to a comparable value even though a laboratory did not measure at the obligatory flowrates or a calibration point was missed. The comparison of a meter factor taken at necessarily slightly varying flowrates would have meant much larger arbitrariness. In only one case, due to the more U-shaped curve (**Lab 7**) the combination of the representative k-factor was done differently (see **Chapter 15.2**)

6.7 Measurement Uncertainty

Table 2 contains the uncertainty figures estimated by the laboratories. Some of them gave one value for all flowrates while others made a calculation for each of them. These estimates lie, with two exceptions, in the range 0.03 to 0.09 %. The way these values have been judged differs of course due to the test method chosen. In some cases the repeatability of the meters forms a part of the uncertainty contribution, in some it does not and the given figures rather point to the contribution from the test facility alone. No-one has however specified contributions due to expected installation effects, which of course are not easy to know. Neither has there been any reservation due to contributions arising from the meter sensitivity to the used liquid. Of course no reproducibility aspects could influence the uncertainty calculation as this aspect was outside the perspective of the individual laboratories. At this level of flowmetering the non-random uncertainty contributions are usually the dominating ones. They also differ with the equipment and the method. Thus no efforts were undertaken within this project to find a common description for a better comparison.

What do the stated uncertainty figures imply? They probably tell that the given meter factors would, with a confidence level of approximately 95 % , be repeated within this margin if the meters were exactly the same and all other conditions under total control. They don't specify a range within which a customer can rely on this calibrated factor, a range that, to a large extent, would overlap with the ranges specified by the other laboratories. Applying the uncertainty figures to the representative values of **Fig. 2**, with the difference in liquid largely equalised, one would expect to find the uncertainty margins for the respective meter to cover at least the global means. This does not seem to be the case for all laboratories as is shown in **Fig. 9**.

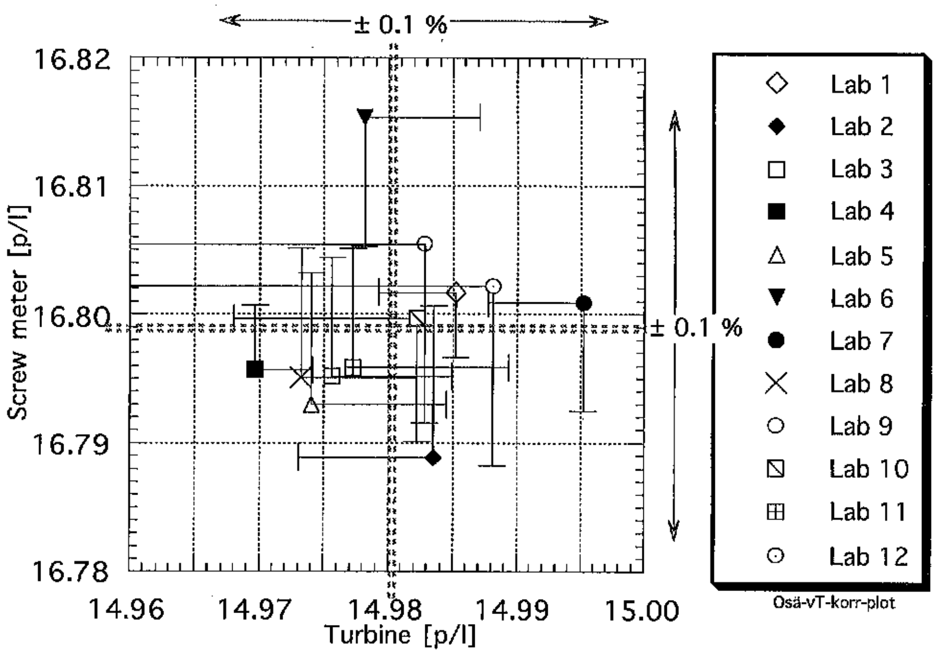


Fig. 9: *Youden-plot with adjusted values for the representative meter factors, the global means and the associated uncertainty limits.*

A conclusion the project co-ordinator might draw, when looking at the available information, is that one should include uncertainties for unknown effects. One of these is particles in the liquid that might cling to the turbine blades and both increase or reduce the meter factor. Another could be rust, which is a deposit on the inside of the screw meter, increasing the tightness to slippage. In other words the calibration object itself, although there is no redundant or primary information about it, should include a reproducibility or stability contribution, perhaps based on intra-laboratory or inter-laboratory comparison experience.

For a customer with a totally different liquid, which probably is the standard situation and not the exception, the uncertainty should be clearly limited to the specified calibration liquid. Concerning a user liquid with different properties, the possible uncertainty contribution compared to the given calibration values should be added.

Flow calibration is a quite delicate profession and probably an operator doing everything right in all circumstances cannot be expected. Perhaps a contribution for the human factor should be included in the uncertainty judgement.

The most striking effect, however, comes from imperfections in the test facility. Only one of the laboratories has taken into account the difference between configurations A & B, i.e. with and without the straightener. A separate analysis by each laboratory of its result on the background of the intercomparison could improve this situation.

7 Conclusions

There are some important statements and conclusions that can be drawn from this intercomparison exercise.

1 The meters were stable enough throughout the calibration series, making this intercomparison worthwhile and informative. Overall changes of less than 0,01 % for both the turbine and the screw meter were found between the first and last calibration. This is clearly less than the possible measurement uncertainty. These figures were also confirmed by one of the laboratories, which repeated its first calibration.

2 A lot of additional information can be deduced by the laboratories studying their results on the basis of the overall picture (especially the plots in **Appendix 5** and **6**).

3 At least 5 calibration runs suffered from installation effects, the amount of which should be read from **Fig. 2** in conjunction with **Table 5**. The size of this effect does not exhibit a simple relation to the distance of upstream straight pipe before the test section (given in **Table 3**). A large pipe diameter may despite its length allow swirl and asymmetric profiles to partly persist. On the other hand the experiment also demonstrates that the chosen flow conditioner worked effectively.

4 The overall reproducibility of the intercomparison, liquid properties equalised, was 0.17 % for the turbine with upstream flow straightener. Without the straightener the reproducibility increased to 0.77 %. For the screw meter the reproducibility lay between 0.13 and 0.16 %. The intercomparison reproducibility concerning different methods and test facilities was about twice as large as the intra-laboratory reproducibility, i.e. within the co-ordinating laboratory, which should be regarded as an excellent result.

5 Even though the reproducibility (different liquid conditions etc) for these meters showed to be only roughly a factor 3 to 5 larger than the average calibration repeatability one may not forget that it affected the characteristic of the turbine considerably.

6 With single questionable values corrected, the adjusted results would very well be within a range of ± 0.07 % for both meters (configuration A), which at least for the screw meter also would be in good agreement with the mean of the estimated uncertainty figures.

7 Without any corrections being made, the result of the ordinary calibration, which a customer could expect, would be one of the curves of **Figs 3** or **6**. This would mean a range of up to almost 1 % for the turbine at low flowrates despite the flow conditioner and still around 0.2 % for the screw meter.

8 From the analysis of the results the conclusion is drawn, that it is primarily the absence of a flow straightener in the first and the liquid properties in the second place that cause the spread between the laboratories.

9 If measurement uncertainties of less than 0.5 % are asked for one would recommend always to calibrated and run a turbine in a field installation with an associated flow straightener. Otherwise much larger differences must be expected at varying customer

realistic to expect. Thus what should be required of a calibration laboratory is to ensure that its test section has a fully developed flow profile being the equivalent of a long upstream pipe installation.

10 The cross-correlation technique used is quite a powerful tool in detecting anomalies in a calibration. Therefore one would always recommend having at least one well-known reference meter in series with the calibration object.

11 The concept of a representative k-factor is suitable for several aspects of such an intercomparison and should be applicable also for a customer, who cannot use electronic linearisation techniques.

12 The knowledge that turbines are very sensitive to viscosity is not new. Calibrations are rarely run at the customer's facility and with its liquid at the usual temperature. This therefore demands two things. Firstly, an uncertainty estimation would be needed that also includes the customer's measurement situation. Secondly, a practical translation of the calibration result to the liquid properties of the customer is needed. The adjustments performed in this report to make the results more comparable might be a suitable technique, which needs to be applied, however, to different turbine meters and a larger viscosity range in order to see its applicability. An interesting study, if the technique should hold, would be to find the minimal amount of information about the turbine meter to be able to perform such a translation.

8 Experience and Comments

From the organisers point of view the intercomparison worked very well following the time table for the project almost to the end. All practical aspects, like the handling of the carnet, the packing details, installation, meter registration etc., obviously did not cause any problems. Transportation damages, breakdowns, de-mounting and rebuilding, etc. known from preceding flow calibration intercomparisons, were thankfully absent. It is not unlikely that organising the transport with one's own entrusted personnel and making personal contact between the laboratories contributed to that result. Another contributing effect to keep to the time schedule was undoubtedly the buffer periods that obviously were needed especially around vacation periods. If a larger failure had happened, they would clearly not have been long enough.

The contact between the participants and the organising laboratory is felt to have been adequate. The guide-lines, thought to contain all necessary information, were obviously, however, too exhaustive to be read carefully and completely, otherwise some elementary information would not have been missed. A principle problem could also arise from the involvement of at least two persons in the intercomparison at participating laboratories, the one with more administrative responsibilities and the other the operator performing the actual job. As a consequence, a note containing the obligatory flowrates was put directly with the meters and a separate copy of the guide-lines followed the package.

The reporting was in most cases suitable, both concerning the amount of information and delivery time. However, from the point of putting together all data, a faster delivery would have made this work more effective.

Acknowledgements

The results from this comparison have embedded our calibration work within those of our colleagues. It is only in relation to others that confidence into one's own measurements can be found. For this co-operation the organisers from SP want to express their gratefulness to the persons from the engaged laboratories who contributed with their work and to the BCR for the support given. Special thanks are also made to Dr Spencer, who helped us to structure the exercise, accompanied it with great enthusiasm and continued to be of great help in discussing the different aspects of the results.

Calibration Intercomparison on Flowmeters for Kerosene Synthesis Report
Part II

Summary

The tests performed prior and after the intercomparison exercise are described and the associated results are reported. The main objective was to characterise the chosen meters in the transfer standard and to reveal their stability and sensitivity to different parameters. The tests at SP utilised two different calibration facilities with two different liquids, three different temperatures, several different volume standards and two different volumetric methods. At NEL the tests were extended to higher viscosities and temperatures and a gravimetric method. The outcome of these tests showed a viscosity dependence that is very different for the two meters. It was studied in detail. From this a correction technique was deduced and used to adjust the international results to a common basis for a fair comparison.

The concept of a representative k-factor, a practical measure for the comparison of non-linear calibration curves between the laboratories, is presented. The calculation of the intra- and inter-laboratory reproducibility as well as the judgement of the meter stability in time was based on this representative k-factor. After an initial change of the turbine, probably due to bearing friction, the turbine and the screw meter were stable through out the whole intercomparison.

Contents

Part II

10 Purpose of the Pre- and Post-Tests

The aim of the pre-test programme for the calibration intercomparison was to establish a measure for the stability of the transfer standard, to characterise the meters by their repeatability and reproducibility concerning variations in the physical parameters as well as different measurement techniques, transportation and reinstallation. Furthermore, two operators working independently of each other, were thought to add a supplementary parameter. Of equally important concern was to reveal the sensitivity of the meters to temperature and viscosity, and if necessary find a suitable correction technique to equalise them. As the resources at SP to vary the temperature and viscosity were limited to a range of roughly 10 °C and two liquids at 1.3 and 2.1 cSt, several extended tests were performed at the National Engineering Laboratory (NEL) in Scotland. There the temperature could be changed between 5 and 50 °C and the liquid viscosity between 2.5 and 4.7 cSt.

In the post-tests several of the sequences of the pre-tests were repeated in order to check whether some of the meter characteristics had changed during the round robin series. During the intercomparison period a 12 " Brooks Compact Prover (BCP 12), the volume reference predominantly used, was re-calibrated twice and several of the fixed volume standards were re-calibrated once between the pre- and post-tests. These measures, the use of a second prover (BCP 24) connected at a different place in the rig and two supplementary calibration runs in the low viscosity rig, were expected to generate an intra-laboratory reproducibility, which should be equivalent to that between the participating laboratories.

Tests for revealing the sensitivity of the turbine to flow distortions could not be performed during the pre-tests. Neither was it possible to explore the effect of the existence of the flow straightener on the turbine as the time schedule was too tight just before the start of the intercomparison. These tests with 6 complete calibration runs were postponed until the end of the exercise

11 Test Programme

The pre-test programme, which contained several test sequences, was performed during three weeks from mid-July to mid-August 1993. The post-tests were performed during three weeks in September 1994. They directly preceded and followed the first and last calibrations, SP I & SP III, belonging to the intercomparison. The last tests to evaluate the influence of the flow straightener on the turbine could not be accomplished before the beginning of January 1995.

Table 7 below summarises the different tests. They are identified by capital letters. Only those that contain a complete curve are listed. Minor tests, omitted in the list of series, refer to rechecking of some observations, variations in pump pressure or concern about the straightness of the hoses, but did not provide additional information in this context. Besides temperature and viscosity, **Table 7** also specifies the volume reference, the method and an alternative flow path used.

Table 7. The pre- and post- test program

Test	Liquid	Temp. [°C]	Visc. [cSt]	Volume reference	Method	Op.	Bench config	Comment
A	D 80	19.5	2.16	prover	flying start/stop	KS/ JEB	FM1 [I]	basic calibration curve, single meter in bench
B	D 80	20.0	2.13	prover	flying start/stop	JEB	FM1 [III]	simultaneous measurement meter in package
C	D 80	19.9	2.14	prover	flying start/stop	JEB	FM1 [III]	repeatability measurement meter in package
D	D 80	24.9	1.93	prover	flying start/stop	JEB	FM1 [III]	temperature increase
E	D 80	15.4	2.34	prover	flying start/stop	JEB	FM1 [III]	temperature decrease
F	D 80	23.3	2.0	vol normal 1000,2000 and 5000 l	standing start/stop	JEB	FM1 [II]	change in method and test volume
G	D 40	19.8	1.31	prover	flying start/stop	KS	BM1 [III]	mounting in new rig lower viscosity
H	D 40	14.8	1.4	prover	flying start/stop	KS	BM1 [III]	temperature decrease viscosity increase
I	D 40	25.1	1.2	prover	flying start/stop	KS	BM1 [III]	temperature increase viscosity decrease
J	D 80	20.3	2.12	prover	flying start/stop	JEB	FM1 [III]	mounting in new rig with higher viscosity
K	D 80	20.0	2.13	prover	flying start/stop	JEB	FM1 [III]	demounting - transport - remounting
Intercomparison with calibration SP (I)								
I	kerosene	5.8	3.29	weigh tanks 1.5 & 6 t	standing start/stop	RB	NEL	different test method extended viscosity range
II	gas oil	20.3	4.68	two weigh tanks	standing start/stop	RB	NEL	different test method high viscosity range
III	gas oil	48.6	2.66	two weigh tanks	standing start/stop	RB	NEL	comparable viscosity but different liquid
IV	kerosene	20.4	2.52	two weigh tanks	standing start/stop	RB	NEL	different test method comparable viscosity
Intercomparison with intermediate and final calibration SP (II) and (III)								
W(I)	D 40	20.1	1.3	BCP 12	flying start/stop	KS	BM1 [III]	new mounting rig BM1 reproducibility test
W(II)	D 40	19.9	1.3	BCP 12	flying start/stop	KS	BM1 [III]	repeatability in lower viscosity
X	D 80	20.1	2.12	vol. normal 5000 l	standing start/stop	KS	FM1 [I]	new mounting in rig FM1
Y	D 80	20.3	2.13	BCP 12 stand. inst.	flying start/stop	KS	FM1 [III]	different installation of BCP12 as in pre-test
Z	D 80	19.6	2.17	BCP 24 stand. inst.	flying start/stop	KS	FM1	different prover size different connection
AA - BC	D 80	20	2.12	BCP 12	flying start/stop	KS	FM1 [III]	6 tests to check flow straightener influence

11.1 Test of the Individual Meters

After adjustments of the turbine to improve its linearity, the pre-test program comprised a basic calibration of each meter (test A) over its specified range. This was done in SP's standard flow rig (FM1) using kerosene (commercial name Exxsol D 80) and a piston prover (Brooks BCP 12"; 60 l, in a special installation) as a volume reference.

The basic calibration procedure was as follows. After mounting the meter in the bench, the liquid was pumped through the meter at a high flowrate (≈ 2000 l/min) to get rid of trapped air in the pipe work and to stabilise the temperature at ≈20 °C. Thereafter the meter-factor was measured at different flowrates starting in the middle of the curve at 1000 l/min and advancing in steps to the maximum flowrate. If necessary the test was interrupted until the temperature had stabilised again. Then the k-factors were measured starting from low flowrates and finishing with a repetition of the first flowrate at 1000 l/min. Each k-factor was determined as the mean value of 10 single results each referring to one stroke (60 l) of the piston prover.

11.2 Test of the Meters as a Package

The rest of the pre-test program (tests B to K) was always performed with both meters built together in the transfer standard configuration and with the flow straightener in place. However, as the meter package was too long to fit into the ordinary test section, it was connected via a pair of rubber hoses. These had a smooth and plane inner surface and a length of 6 m each.

In all but two tests the piston prover was installed with hoses in a special position in the rig. A flying start and stop technique was used and the same measurement scheme was applied. Only for the test runs F and X a standing start-and-stop technique was chosen to reveal the sensitivity of the meters to this calibration method. In order to keep the testing time reasonably equal (170 s ± 50 %) three different volume standards (1000 l, 2000 l and 5000 l) were used as reference for the different flowrates. This technique showed good repeatability but is rather time consuming. Therefore only five repetitive measurements were performed per flowrate.

The tests E, C, D and G, H, J were run in the same manner at 15, 20 and 25 °C respectively. But whereas the first group refer to rig FM1 with D 80 the second group was carried out in a similar calibration rig, BM1, but with a kerosene of lower viscosity (commercial name Exxsol D40).

Due to practical reasons, the tests at NEL were done between the first and second calibrations of the intercomparison. NEL worked with a gravimetric method and could run two of the tests in two liquids of different temperature but approximately the same viscosity.

Immediately after the concluding calibration SP(III), some of the tests were repeated in both calibration rigs and with different volume standards, but without any further temperature changes. The test W(II) is just a repetition of W(I) in order to check the repeatability with D40. The run X (standing start/stop) corresponds to F in the pre-tests, but is limited to one volume standard (5000 l) to exclude influences from several volume sizes or eventual systematic differences in their calibration. Test Z over Y finally adds the influsence of a larger prover volume (BCP 24") and, due to a different installation, a much larger buffer volume between meter package and volume reference. In test Y the small prover was connected at its standard place in the test facility in contrast to all other tests.

11.3 Test Facility

A schematic drawing of the main calibration facility is given in **Fig. A4, Appendix 4**. As indicated different flow situations can be arranged. Altogether six pumps moved the liquid from the tank in the basement via a gas separator directly to the meter in the test section [I] or to the transfer standard [II] connected to the test section with hoses. In the standing start/stop method (tests F and X) the liquid was then directed to one of a set of different volume standards. After filling, the synchronised diverter valves were triggered manually stopping the flow through the meters to the volume standard and redirecting it to the tank.

In the test of the single meter in the ordinary test section (test A) the prover was used as reference and flow path [III] applied (but without the transfer standard). In that case the liquid first passed the prover (with the block and bleed valve closed) and then the meter in the test bench [I].

In the majority of tests the flow path [III] with the block and bleed valve closed (piston prover - transfer standard - tank) was used as indicated in **Fig. A4, Appendix 4**. An analogous flow configuration also applied for the series G, H, I, W(I) and W(II) in the test bench BM1. A fourth configuration, including a large prover BCP 24" connected at a different place in the pipe work, is not shown here.

The control and data acquisition system, producing automated measurements with the help of the prover, is the same as in earlier flow intercomparison projects using water and has been reported earlier[1].

The double chronometry technique makes it possible to register parts of pulses, resulting in a high resolution and a very good repeatability despite the low volume of 60 litres and the low k-factor of the two meters.

The reported temperature values refer to the temperature sensor in the prover, which is read off by the data acquisition system. The sensor in the meter package was read manually and reported three times per flowrate, before, after and in the middle of the 10 piston strokes. Its resolution is 0.01 °C and the difference was always below 0.3 °C. In tests F and X both the temperatures in the package and in the volume standards were documented. Only a few differences exceeded 0.2 °C. During the tests most of them were below 0.1 °C.

11.4 Test Evaluation

One important result to be gained from the different test stages is the repeatability and the reproducibility of the meters. Concerning the time difference between the series also a stability judgement may be deduced. The other important result to be extracted is the response of the meters to variations in calibration parameters as temperature, viscosity, calibration technique, test equipment, test volume etc.

---

1 Börjesson B., Lau P., Stolt K.; Hot water meter calibration intercomparison, Large package, SP-AR 1991:49

A simple method to evaluate 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 technique has considerable limitations. The main reason lies in the large change of the turbine meter characteristic with liquid viscosity.

As the NEL tests were mainly performed to extend the temperature and viscosity range, the corresponding results were evaluated for temperature and viscosity corrections together with the SP results. Concerning an intra-laboratory repeatability and reproducibility reference, with which to compare the outcome of intercomparison, only SP data are used, as these correspond closer to the other laboratories own physical parameters. Further the three SP calibrations belonging to the intercomparison are included in these calculations as seen from **Table 8.**

The laboratory repeatability r_l is based on the average in-series variance observed in the tests. The reproducibility R_l is calculated from both the mean in-series and the inter-series variance. The definition follows the intention of ISO 5725[2] and the necessary formulae are found in **Appendix 3**. The inter-series variance is calculated with the help of the representative k-factor for each series, the concept of which is presented in **Chapter 15** and **Appendix 3.**

[2] ISO 5725 Precision of test methods - Determination of repeatability and reproducibility by inter-laboratory test.

12 Results

The test results are presented in a series of figures. They are put together in different ways to exhibit certain findings. A total picture of the behaviour of the transfer standard is shown in **Figs 10** and **11**. The open symbols represent the results collected in D 80 (higher viscosity). The black symbols give the results in D 40 (lower viscosity).

The observation from both figures, which is also supported by the tests at NEL, is that both meter factors decrease with increasing temperature. The dependence on liquid temperature is, however, not a simple function as liquid viscosity changes along with temperature.

The screw meter factor increases with viscosity. For a change of $\Delta v = +0.8$ cSt (same temperature) an increase of 0.03 % is found while a change of $\Delta v = +1.2$ cSt together with $\Delta t = +10$ °C corresponded to an increase 0.07 % (**Fig. 10**). The threshold as well is increased with viscosity, which physically is understandable, as this is expected to reduce the slippage. The characteristic screw meter curve, however, seems fairly unchanged.

For the turbine a change in viscosity leads to a totally changed characteristic of the meter curve (**Fig. 11**). The viscosity difference between D40 and D80 in combination with a temperature change of 10 °C leads to an 0.6 % increase of the meter factor at low flowrates and to a 0.45 % decrease and more at high flowrates.

In both figures the implicit influence from the viscosity seems to have a stronger effect than the temperature change alone, but this behaviour is much more pronounced in the turbine meter.

Compared to the effect of temperature and liquid viscosity 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 even with the flow straightener in place.

In **Figs 12a** and **12b** a reduced selection of comparable screw meter results from two liquids at three temperatures is shown. As a complement the overall result from the intercomparison is given as well, serving as reference. Further the results of the repeated measurements at the mean temperature of 20 °C (**Fig. 12b**) are added. These (Y and W(II)) follow quite well the ones from the pre-tests. Only a slight change can be observed in W(II) (D40) having generally somewhat higher values and a clearly higher threshold.

A corresponding picture for the turbine is displayed in **Fig. 13a**. Again the overall turbine curve (20° C and 2 cSt) from the intercomparison is used as a reference. The systematic dependence on the viscosity both explicit and implicit via the liquid temperature is clearly observed. The repeated curves (**Fig. 13b**) show the same behaviour. However a closer look reveals that the curve from test W(II) and the corresponding one from H (same symbols) are very similar, whereas Y has a distinctly higher k-factor than curve C especially at higher flowrates, which leads to a shift of the intersection flowrate from 850 to 1250 l/min.

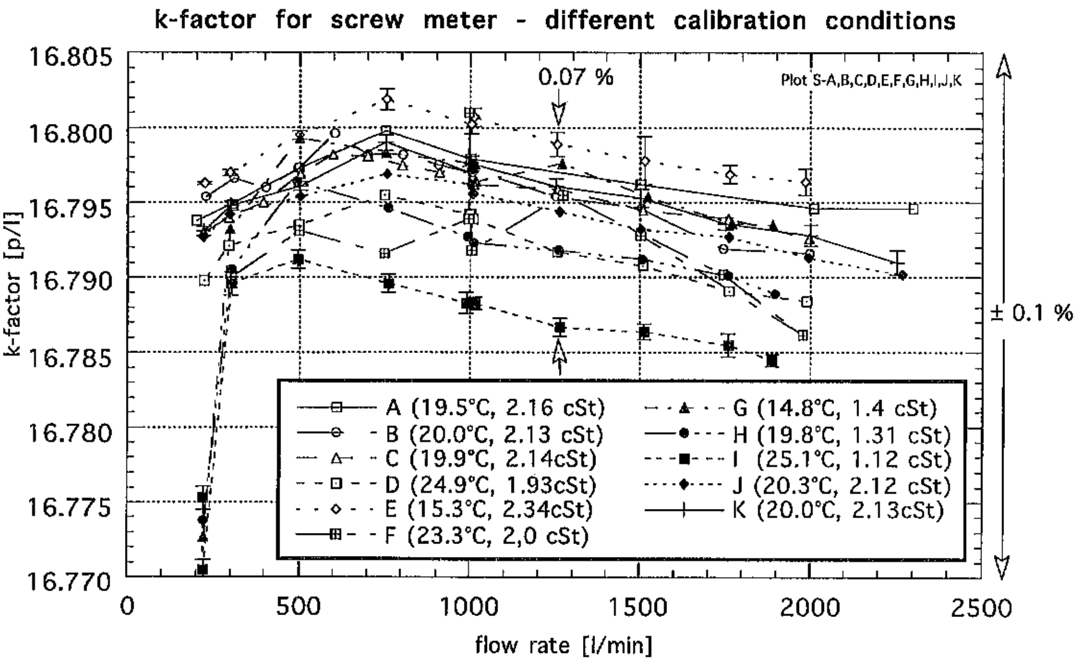


Fig. 10: Result of pre-tests at SP on the screw meter in two liquids and three temperatures each. The black symbols correspond mainly to the results in the lower viscosity of D40.

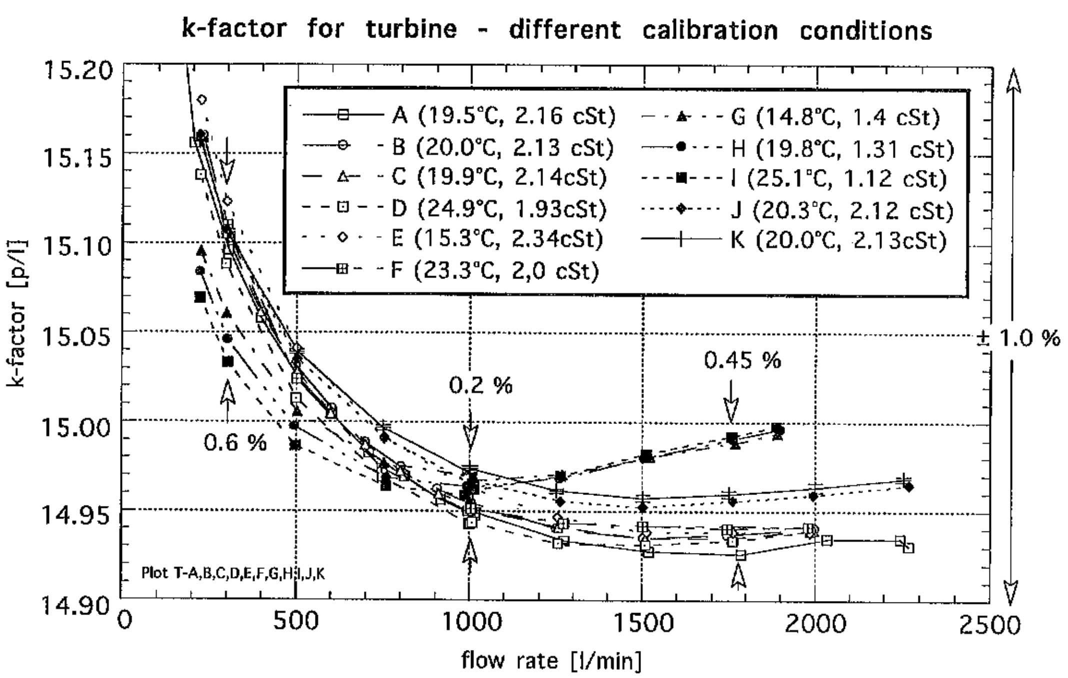


Fig. 11: Calibration curves from all pre-tests at SP on the turbine meter performed in two liquids and at three temperatures.The black symbols give the results from tests in D40 (exception run J).

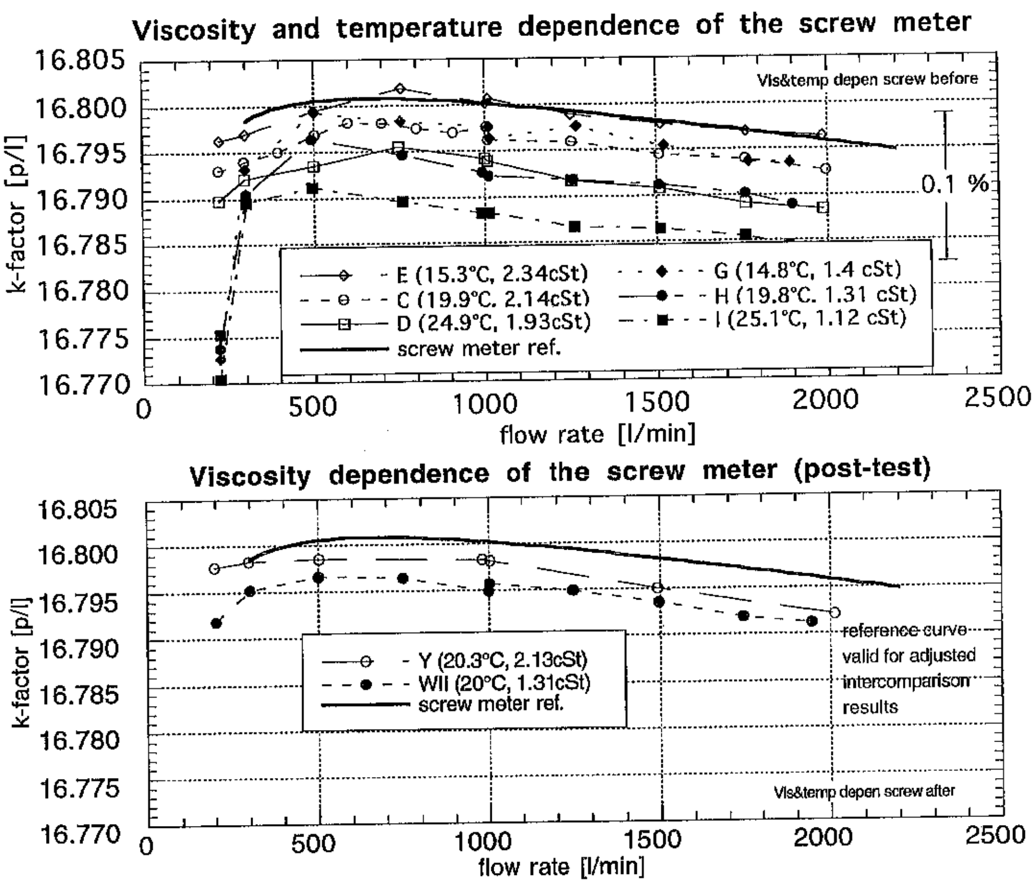


Fig. 12a, 12b: Calibration curves for the screw meter before and after the intercomparison - two liquids - three temperatures. (Black symbols D40)

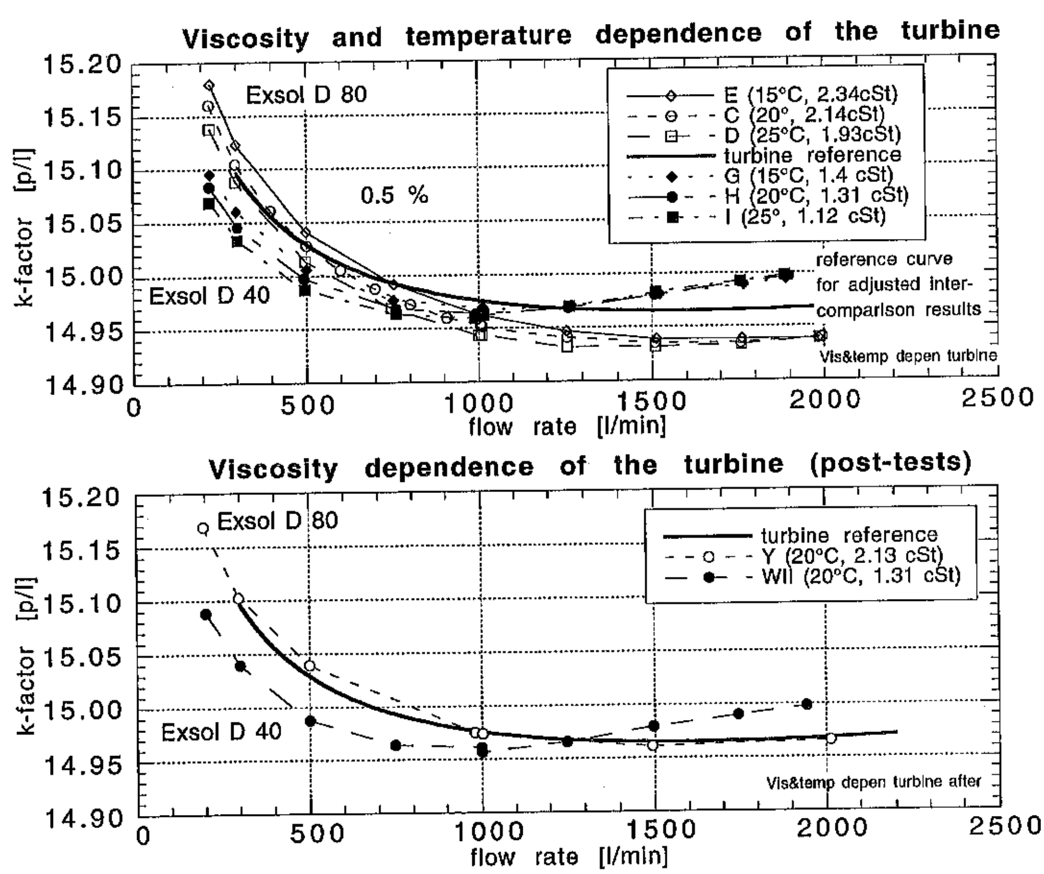


Fig. 13a, 13b: Calibration curves for the turbine before and after the intercomparison - two liquids - three temperatures. (Black symbols D40

A probable explanation for this behaviour could be a grounding in the ball bearings of the turbine after having been run in D40 (initial wear), which has a markedly reduced lubricity. **Fig. 14** attempts to expose this effect. Here a close-up of those results is given that refer to measurements in D80 at 20°C both before and after the pre-tests in D40, i.e. before test G and after test I. The two fitted lines characterise the two categories of curves. Run J was the first after the measurement in D40. It looks like the turbine had shifted about 0.2 % comparing the two groups. This shift is significant having a size twice the range found in the second group, i.e. most tests after those in D40 (see also **Chapter 16**).

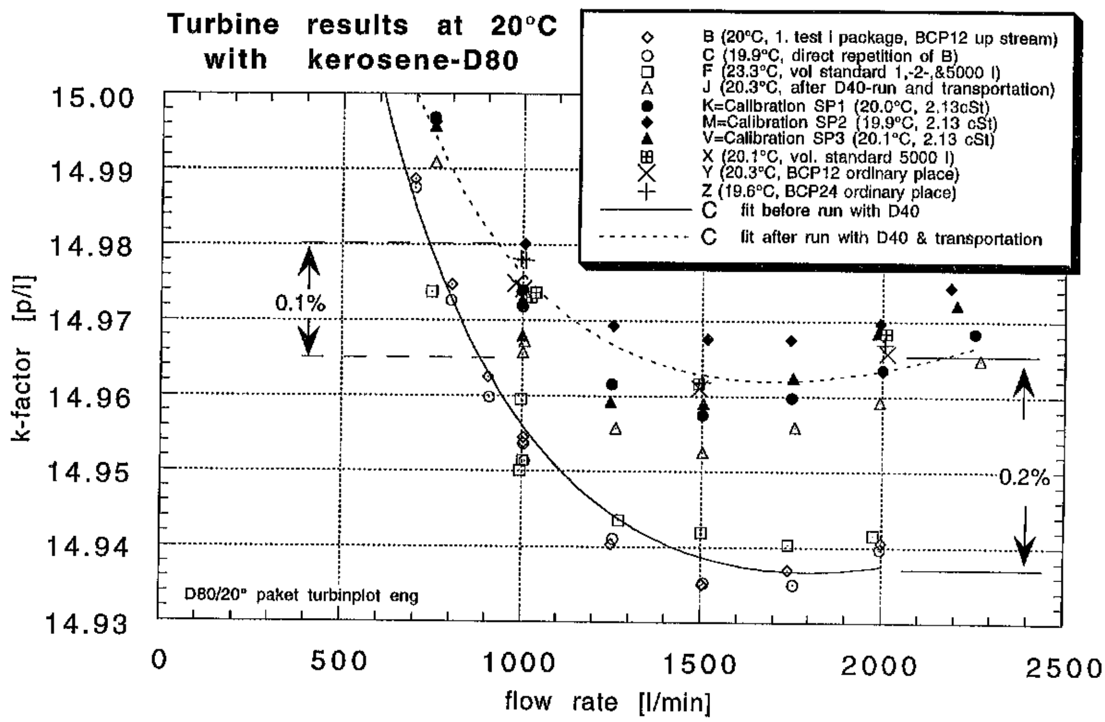


Fig. 14: Calibration curves under comparable conditions in D80. Significant change of characteristic after tests performed in D40, having lower lubricity.

The screw meter also exhibits a small change in the same direction, i.e. to higher k-factors with time (see **Chapter 16**). But the effect is much smaller. After this initial jump both meters seem fairly stable and it therefore makes sense to take this "ageing" into consideration when calculating a reproducibility for the meters as is done in the following chapter.

13 Repeatability and Reproducibility Evaluation

Table 8 below summarises the representative k-factors for both meters before any corrections are applied and also gives the average standard deviation for each series.

Table 8:	representative k-factors [p/l]				average standard deviations [p/l]			
Test series	Turbine A	Turbine B	Screw A	Screw B	Turbine A	Turbine B	Screw A	Screw B
A	14.9522		16.7959		0.0022		0.0007	
B	14.9588		16.7943		0.0013		0.0009	
C	14.9574		16.7946		0.0012		0.0005	
D	14.9515		16.7909		0.0012		0.0006	
E	14.9629		16.7978		0.0014		0.0007	
F	14.9607		16.7901		0.0010		0.0012	
G	14.9865		16.7951		0.0018		0.0011	
H	14.9843		16.7911		0.0016		0.0007	
I	14.9839		16.7867		0.0016		0.0006	
J	14.9730		16.7933		0.0018		0.0006	
K=SP I	14.9779		16.7952		0.0015		0.0005	
L=SP I		15.0498		16.7945		0.0036		0.0005
M=SP II	14.9837		16.7998		0.0015		0.0004	
N=SP II		15.0019		16.7994		0.0033		0.0003
S=SP III	14.9784		16.7959		0.0017		0.0005	
T=SP III		14.9995		16.7954		0.0024		0.0008
W(I)	14.9806		16.7935		0.0014		0.0006	
W(II)	14.9878		16.7934		0.0015		0.0008	
X	14.9812		16.797		0.0013		0.0008	
Y	14.9797		16.795		0.0015		0.0008	
Z	14.9821		16.7955		0.0008		0.0003	

The table below lists mean values of the representative k-factors and an inter-series standard deviation calculated from the above values with respect to either all series, or those after grounding of the turbine bearings, measured in both D80 and D40 or just in D80.

Table 9:	Turbine config A	Turbine config B	Screw meter config A	Screw meter config A	
SP mean k-factor (all series D80 & D40)	14.9735	15.0171	16.7941	16.7964	[p/l]
SP mean k-factor (in D80 &D40 after series I)	14.9816		16.7943		[p/l]
SP mean k-factor (only in D80 after series I)	14.9794		16.7960		[p/l]
SP intra laboratory standard deviation (all series)	0.0117	0.0284	0.0031	0.0026	[p/l]
SP intra laboratory standard dev. (after series I, D80 &D40)	0.0041		0.0032		[p/l]
SP intra laboratory standard dev. (after series I only in D80)	0.0035		0.0020		[p/l]

For the same selection of test series the laboratory reproducibility was calculated and compared to the outcome of the intercomparison, which was calculated in the same manner (for definitions and statistical weighting see **Appendix 3**).

Table 10:	Turbine config A	Turbine config B	Screw meter config A	Screw meter config B	
SP repeatability (all series D80 & D40)	**0.0045**	0.0199	**0.0021**	0.0034	[p/l]
SP reproducibility (all series D80 & D40)	0.0361	0.1829	0.0098	0.0171	[p/l]
SP reproducibility (D80 &D40 after series I)	**0.0138**		**0.0105**		[p/l]
SP reproducibility (only D80 after series I)	0.0142		0.0080		[p/l]
Intercomparison repeat-ability	**0.0060**	0.0105	**0.0038**	0.0040	[p/l]
Intercomparison repro-ducibility	**0.0250**	0.1152	**0.0273**	0.0224	[p/l]

The figures for the standard deviations in **Table 9** and for the repeatability and reproducibility in **Table 10** exhibit remarkable differences between the two meters and the two configurations. One reason is that there are different numbers of tests, which contribute to the statistical weighting. Another reason is a larger variety of experimental parameters, when two liquids are involved. A third is a noticeable change in turbine characteristic, which is believed to be the result of an initial wear effect on its bearings as mentioned above. Finally the configuration B without the flow straightener introduced flow profile effects, which shifted the turbine curve distinctly. From the different intra-laboratory (SP) values the ones in bold style are used for comparison with the inter-laboratory result presented in **Chapter 5.1** of **Part I**. Thus the intercomparison rendered repeatability and reproducibility figures that are roughly twice as large as the intra-laboratory results at otherwise comparable variations in calibration conditions.

The repeatability figures of the intercomparison above state that the average meter factor only in few cases (5 %) will change more than 0.04 or 0.07 % (turbine) and 0.022 or 0.024 % (screw meter) at repeated conditions. On the other hand a customer must be prepared that the representative calibration value that he could receive from an arbitrary laboratory, due to the used liquid and test facility, may with a large probability (95 %) vary by up to 0.17, 0.77, 0.16 and 0.13 % for the turbine and screw meter with the appropriate configuration.

14 Temperature and Viscosity Effects

As stated earlier the viscosity effect is the more important one for the meter behaviour (at least for the turbine). The change in liquid temperature and in consequence in viscosity is more pronounced at low viscosities. **Figs 15** and **16** give the result from three pre- and two post-tests with the meter package. In the case of the screw meter a temperature change of 10 °C corresponds to a range in meter factor of almost 0.07 %, which is twice the expected effect from the expansion of the meter housing (compare **Fig. 19**). The curves in **Fig. 19** are fitted to the temperature corrected values. They indicate the remaining sensitivity to viscosity. It can also be seen, that the correction effect is different on both sides of the maximum. From **Fig. 15** one can also see an increase of approximately 0.02 % with time at otherwise comparable measurements.

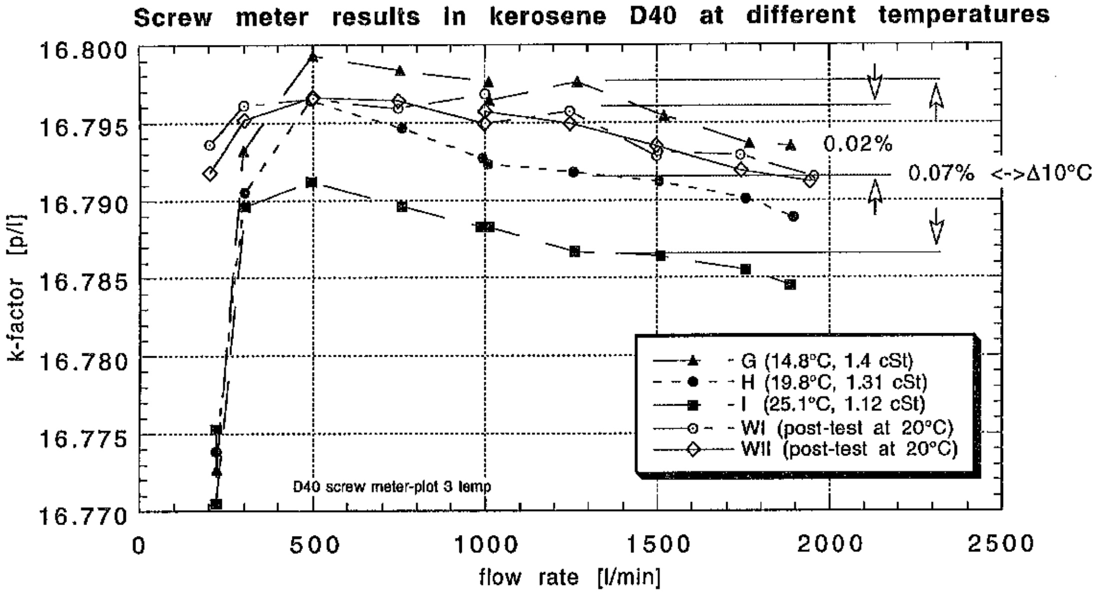


Fig. 15: The change in screw meter curve within a given range of liquid temperature and time (15 months between pre- and post-tests).

The corresponding figures for the turbine (**Fig. 16**) are 0.2 % and 0.08 % at most. To cancel out viscosity effects in the intercomparison is thus much more crucial for the turbine.

The tests at different temperature/viscosity conditions can be used to evaluate the sensitivity to the respective parameter. Attempts to plot the dependence of the k-factors separately for each flowrate as a function of the temperature has shown a good linear correlation ($k_t^S = k_{to} + \gamma \cdot t$; coefficient > 0.99) for both meters. The values for the temperature coefficient γ are found using a least square technique.

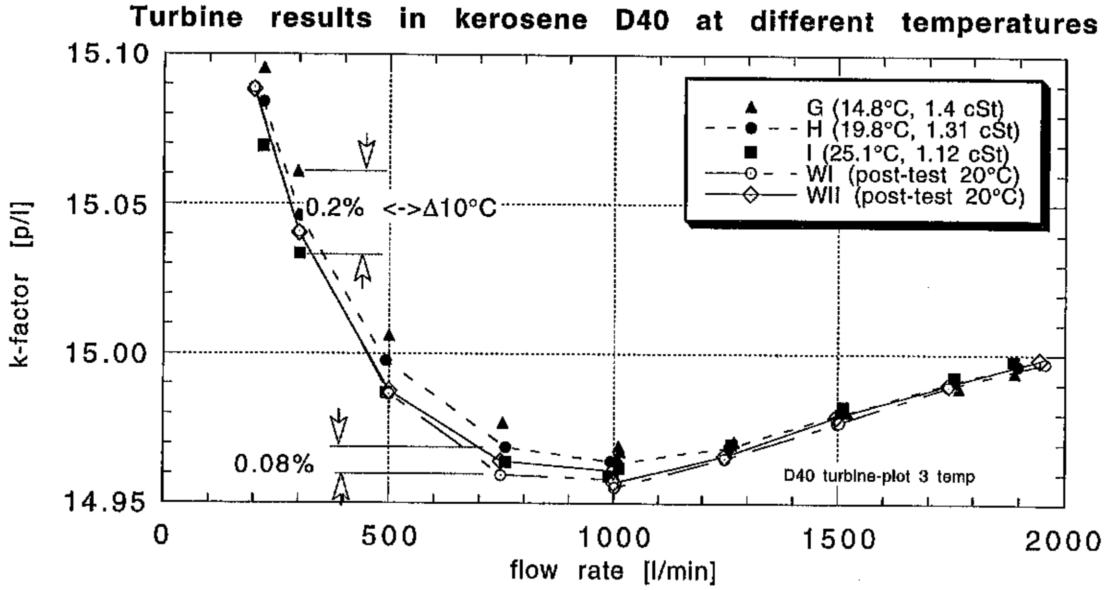


Fig. 16: The shift in turbine meter curve within a range of 10°C in liquid temperature and comparison with repeated measurements after 15 months.

The temperature coefficient γ, however, seems also to be a function of the flowrate, the temperature itself, and even more complex, of the viscosity, as is exemplified in **Table 11** below.

Table 11: Temperature dependence of the meter factors valid at 1000 l/min.

Liquid	Screw meter	Turbine meter
D 80; 1.9-2.4 cSt	$k_t^S = 16.811 - 6.728 \cdot 10^{-4} \cdot t$	$k_t^T = 14.993 - 1.98 \cdot 10^{-3} \cdot t$
D 40; 1.2-1.4 cSt	$k_t^S = 16.809 - 8.368 \cdot 10^{-4} \cdot t$	$k_t^T = 14.979 - 7.54 \cdot 10^{-4} \cdot t$

As long as there is only one liquid the flowrate dependence then can be found by using a least square fit technique on the temperature coefficients at the different flowrates. Unfortunately in the case of the screw meter, due to its slope, one also has to distinguish between two flow ranges (below and above 500 l/min).

As an example **Fig. 17** shows the results of this correction to a temperature of 20 °C. The left- and right-hand scales are shifted with respect to each other to visualise the difference. The result, which gives a convincing congruence, is in fact even an implicit correction for the viscosity. The problem arises, however, when one tries to manage this for both liquids simultaneously.

The effort to make a regression analysis of the viscosity dependence by plotting the k-factors at different flowrates from two liquids or even including the NEL data (from two further liquids) as a function of the viscosity rather than the temperature was not successful. The meter behaviour is obviously more complex and other liquid quantities like lubricity and also pressure effects as well as the flowrate are important parameters and no acceptable correlation could be found.

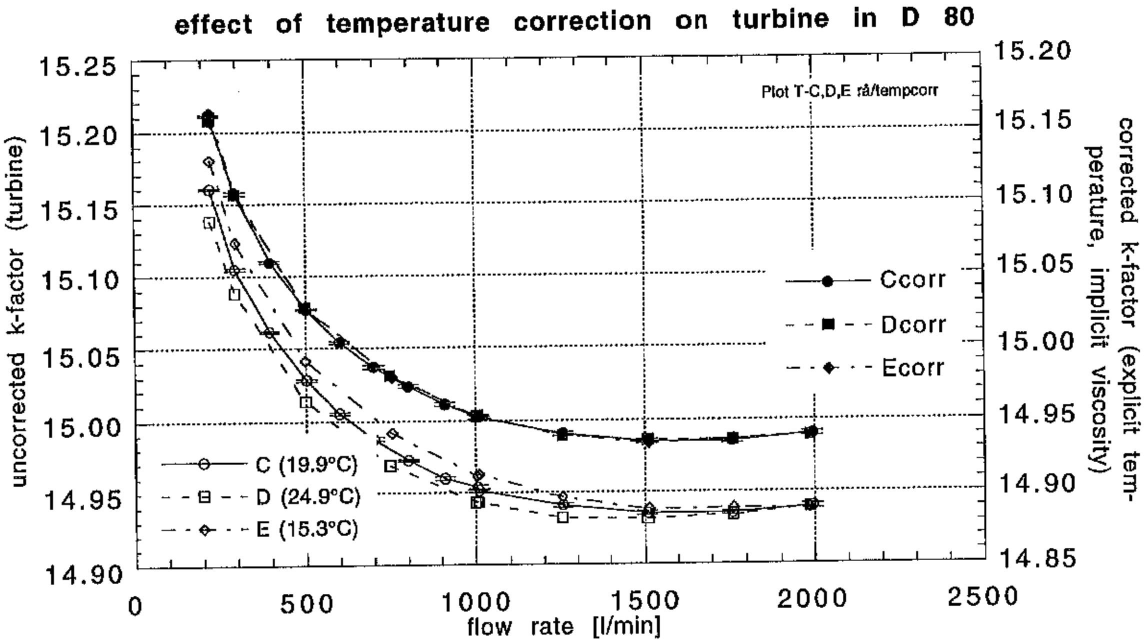


Fig. 17: Example for an applied temperature (implicit viscosity) correction from the regression analysis valid in D80. The scales for raw (left) and corrected data (right) are shifted for clearness.

14.1 Temperature correction

For the temperature and viscosity correction a quite different attempt was therefore tried. In a first step, a temperature adjustment to 20 °C was performed, where only the expansion of the meter itself was concerned.

In the case of the screw meter, being a positive displacement meter, a simple volume expansion model was chosen using the expansion coefficient for carbon steel:

$3\alpha_{cs} = 33 \cdot 10^{-6}/°C$

Thus the adjusted value k_{20}^S for 20°C followed from the measured one k_t^S at a temperature t using equation:

$$k_{20}^S = (1+3\alpha_{cs}(t-20)) \cdot k_t^S$$

A corresponding idea was applied for the turbine. But only the circular area expansion for a stainless steel pipe was considered:

$2\alpha_{ss} = 34 \cdot 10^{-6}/°C$

Hence the following equation for the temperature correction of the turbine was used:

$$k_{20}^T = (1+2\alpha_{ss}(t-20)) \cdot k_t^T$$

The difference between these two attempts of correction is seen from **Fig. 18**, again with shifted scales at left- and right-hand side (pure temperature expansion - upper curves, even implicit for viscosity correction - lower curves). Although the implicit technique seems to give a better result (black symbols), it is not a good correction model for viscosity differences when different liquids must be considered.

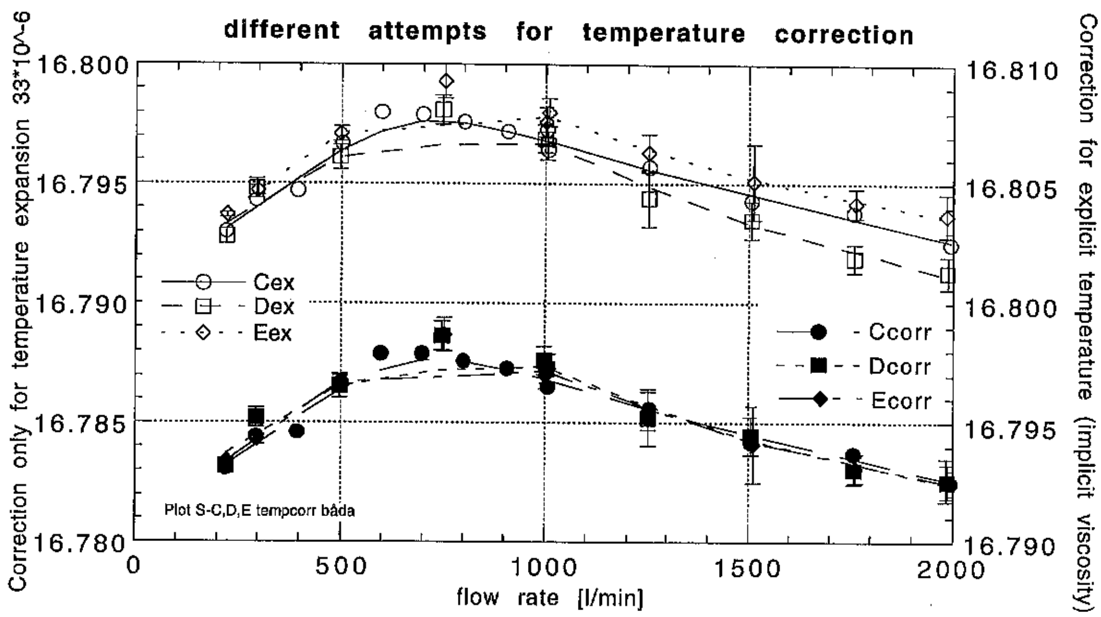


Fig. 18: Comparison of two temperature correction methods. Open symbols - solely temperature expansion of screw meter housing; dark symbols - taking care of the implicit viscosity dependence (however not used). Left and right hand scales shifted.

14.2 Viscosity Dependence of the Screw Meter

The possibility that the NEL and SP results also might reflect some differences due to different calibration methods, brings about a further difficulty for a consistent analysis. The attempt to adjust a calibration result to a common viscosity was therefore mainly based on the SP results from two very similar liquids in the interesting temperature and viscosity range of 15 to 25 °C and 1.2 to 1.4 and 1.9 to 2.3 cSt respectively.

In a first step of the analysis the temperature influence was eliminated as mentioned before. At 25 °C the meter body will contain 0.017 % (vol) more liquid compared to the situation where the liquid temperature is the same but the meter has a wall temperature of 20 °C. Thus, due to the temperature correction from 25 to 20 °C, the meter factor would increase by this amount, meaning a smaller liquid volume would have produced the same number of pulses per time interval given a constant flowrate and pressure drop. The effect of this temperature correction is shown in **Fig. 19**. The remaining difference among the three curves is assumed to reflect the inherent viscosity difference.

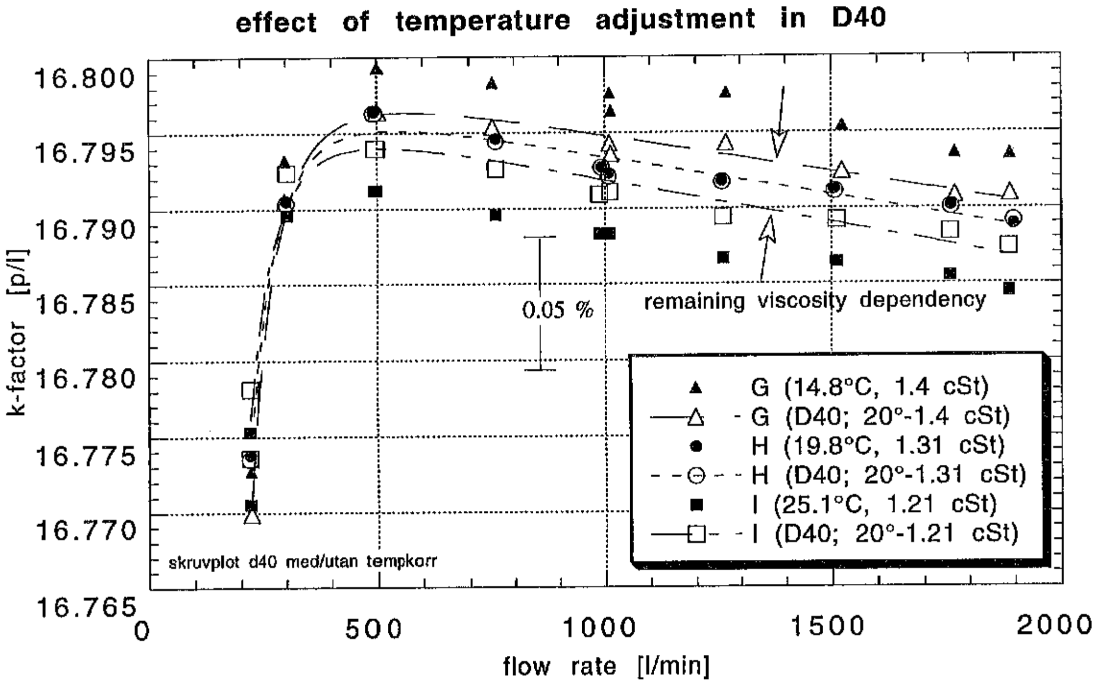


Fig. 19: Screw meter without (black symbols) and with adjustment (open symbols) for temperature expansion.

In the next step the temperature adjusted calibration points (20°C) representing six different viscosities are plotted (**Fig. 20**). First of all the picture reveals that there is hardly a linear relationship between the meter factor and viscosity. Secondly the difference between the curves is also dependent on the flowrate. This is very pronounced at low flowrates where the slippage and thus the threshold seems very sensitive to small changes in viscosity. Thirdly, taking the experimental values from different flowrates directly and plotting them as a function of the corresponding viscosity would create a confusing spread. The following evaluation is therefore based on fitted curves to the experimental values leading to better representativeness.

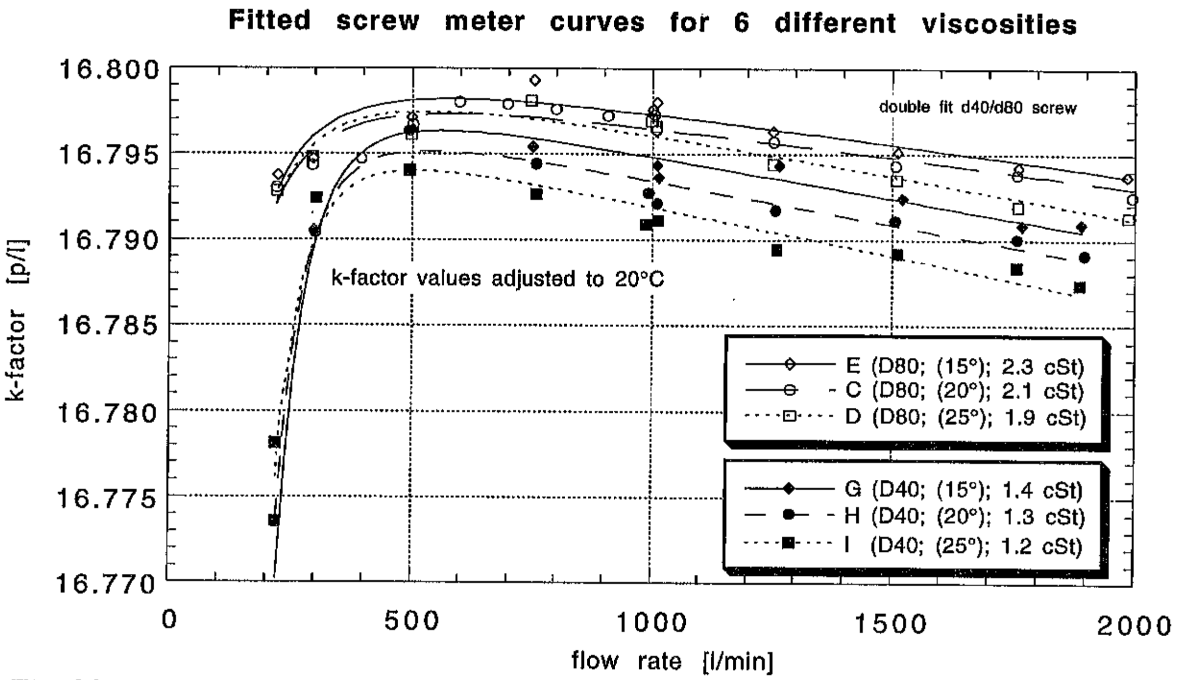


Fig. 20: *Fitted curves to the experimental data for better representativeness of the viscosity dependence at different flowrates.*

The best fit is given by the equation

$k_1(q) = a_{1i}+b_{1i}\cdot q^{-2}+c_{1i}\cdot q$ for the three curves $1 \leq i \leq 3$ in Exxsol D80 and

$k_2(q) = a_{2j}+b_{2j}\cdot q^{-4}+c_{2j}\cdot q$ for the three curves $1 \leq j \leq 3$ in Exxsol D40.

In **Fig. 21** a linear regression to a number of derived k-factors at the flowrates given in the legend is plotted against the corresponding viscosity. For comparison the treatment also takes into account two NEL calibrations at the most comparable liquid conditions.

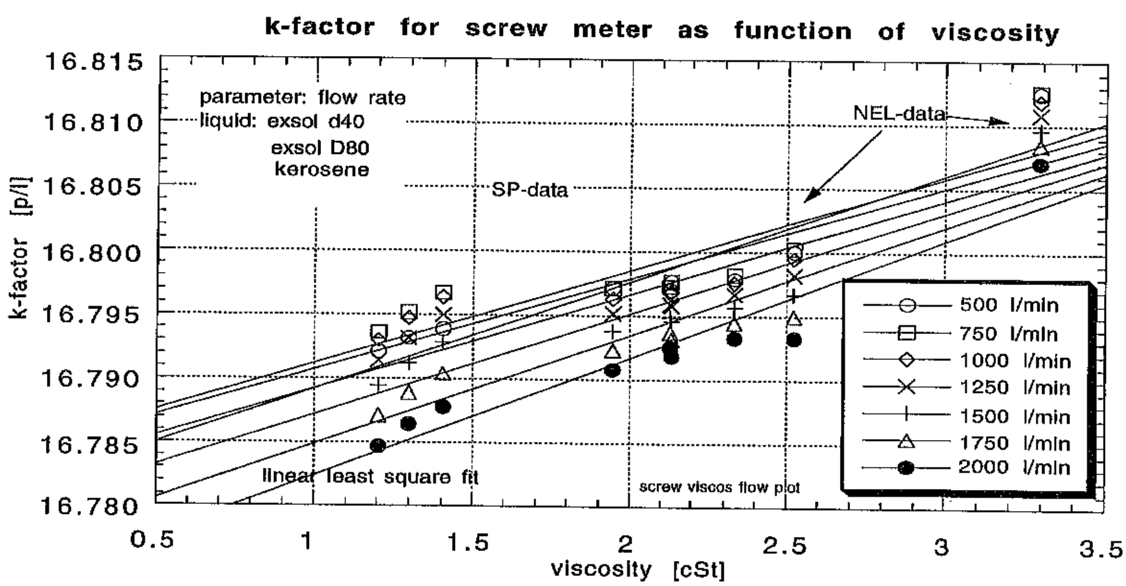


Fig. 21: *Extracted k-factors plotted against associated viscosity at different flowrates q > 500 l/min. Poor correlation for a linear regression attempt concerning the viscosity dependence.*

As can be seen the linear least square fit is not a good model for the viscosity behaviour; not even for q>500 l/min or if the NEL-data were ignored. The fit therefore uses again an additional term proportional to ν^{-2}. The result is exemplified in **Fig. 22.** The symbols at roughly the viscosities 1.2, 1.3, 1.4, 1.9, 2.1 and 2.3 are again the SP data extracted from the fitted curves after having been adjusted to 20 °C (**Fig. 20**). The four lines shown indicate the expected viscosity dependence. They are calculated as a fitting to the SP-data only. Other data are just used for demonstration. For a steeper dependence at 1 cSt, terms proportional to ν^{-3} and ν^{-4} were tested as well. However the attempt with only a ν^{-2} term leads to a dependence that lies between the linear one shown in **Fig. 21** and another linear one based solely on the three SP-results at the low viscosities (1,2 to 1,4 cSt with D40).

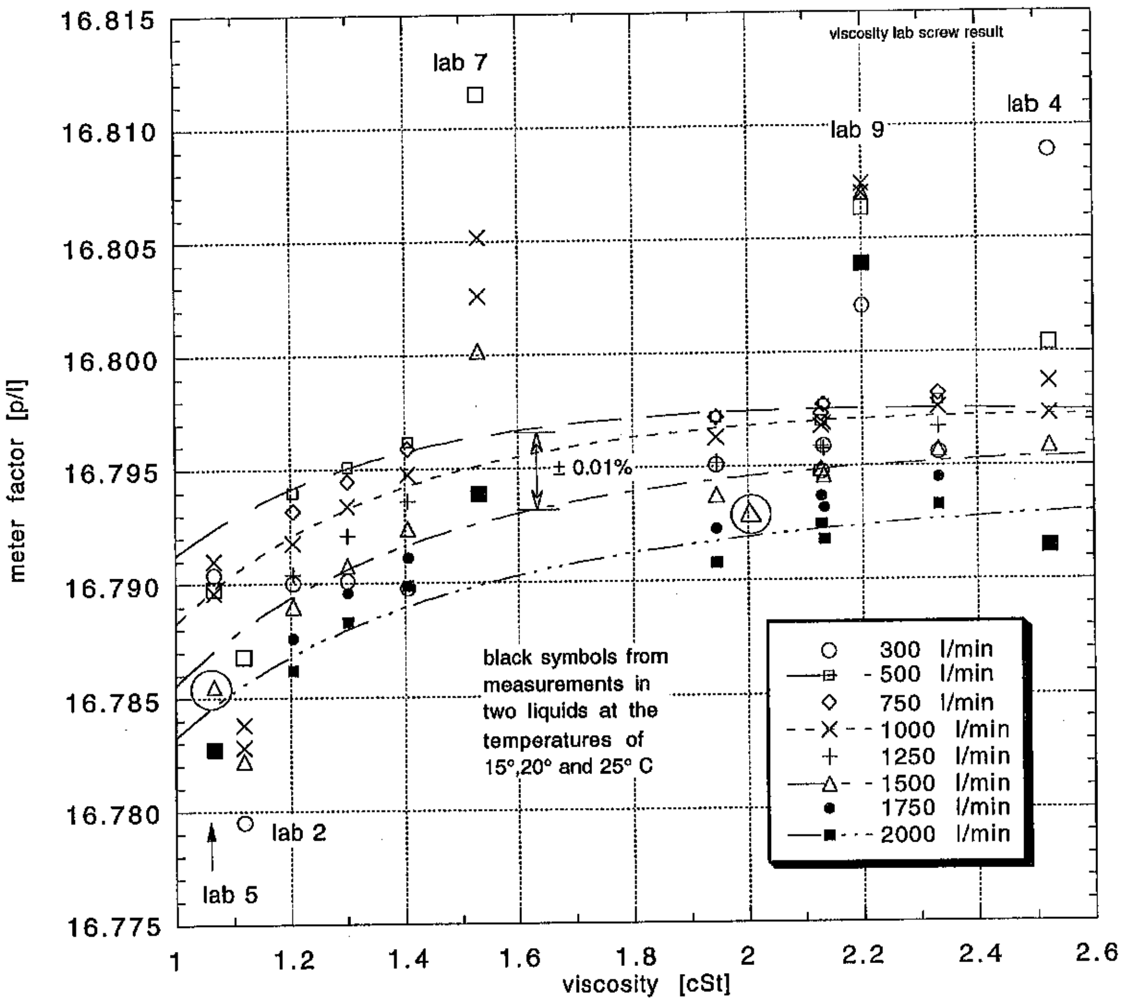


Fig. 22: Non-linear viscosity dependence (~ ν^{-2}) of the screw meter. It is used for a correction that varies with flowrate. Only 4 fitted lines are shown and one transformation example (encircled Δ, see text) is given.

To estimate, whether the model leads to reasonable k-factors at viscosities between 1 and 1.2 cSt, the experimental values from **Lab 5** (1.07 cSt) and **Lab 2** (1.12 cSt) were temperature adjusted and included in the figure as well. Whereas the low screw meter values of **Lab 5** seem to be totally in accordance with the viscosity effect, the even lower values of **Lab 2** are only partly explained by the relatively low viscosity of the test liquid. Taking into account that the experimental data of **Lab 4** at the highest viscosity belong to flowrates quite different to those in the legend, even this result is in good agreement with the assumed viscosity dependence. On the other hand this is not true for the relatively high results of **Labs 7** and **9**. These cannot be explained by viscosity differences.

14.2.1 Correction Technique (Screw Meter)

The modelling equations for the curves in **Fig. 22** can now be used to transform the meter factor from one viscosity to another. The suggested technique starts from the experimentally determined meter factor $k(q_i)\big|_{Va}^{exp}$ at flowrate q_i and actual viscosity ν_a. The relation between a meter factor at this viscosity and a reference viscosity ν_r is for each flowrate q_i found from the fitting equation (1)

$$k(\nu;q_i)=m_1(q_i)+\frac{m_2(q_i)}{\nu^2}+m_3(q_i)\cdot\nu \qquad (1)$$

by inserting values for the actual and reference viscosity respectively. The two meter factors produced by this model are denoted $k(q_i)\big|_{Va}^{mod}$ and $k(q_i)\big|_{Vr}^{mod}$ and the adjustment assumes that their relation also holds for any other k-factor at that actual and reference viscosity. A correction to another viscosity thus implies a movement along one of the fitted curves (or parallel ones) from the measured value to the one at reference conditions (2 cSt). The encircled triangular symbol (**Fig. 22**) exemplifies the transformation result for the flowrate of 1500 l/min of **Lab 5**. The transformation equation for this is:

$$k(q_i)\big|_{V_r}^{exp}=\frac{k(q_i)\big|_{V_r}^{mod}}{k(q_i)\big|_{V_a}^{mod}}\cdot k(q_i)\big|_{Va}^{exp} \qquad (2)$$

The relation factor for correction in equation (2) is larger than 1 as long as $\nu_r > \nu_a$ and varies with flowrate. This is shown in Fig. 23.

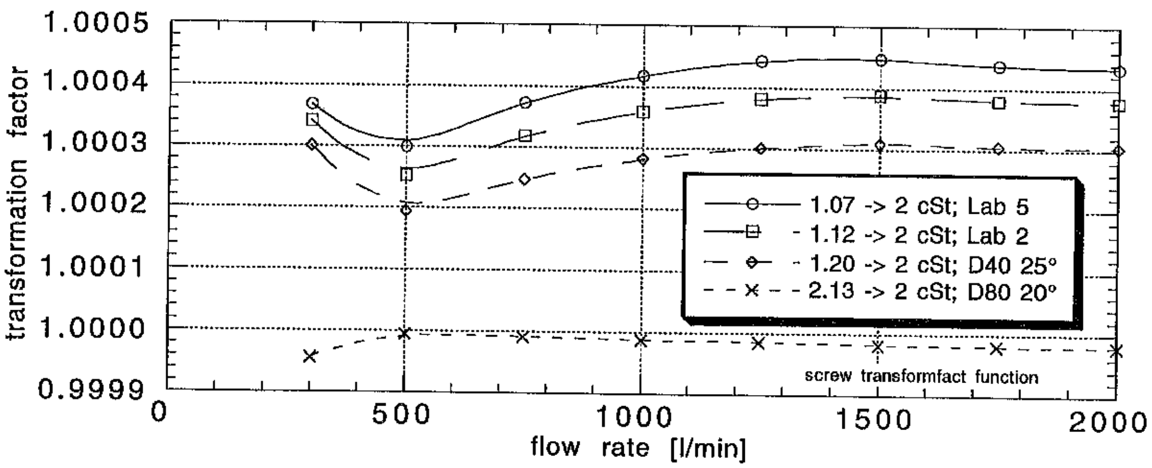


Fig. 23: Flowrate dependence of the correction factor for the viscosity adjustment of the screw meter.

As can be seen, transformations from 2.2 cSt or higher values to 2 cSt have very little effect (within the height of the symbols used in the calibration curves).

The conclusion drawn from this finding is only to adjust the two laboratory results (**Labs 2 & 5**) at the especially low viscosities and not to apply any viscosity correction to the screw meter results of all other laboratories.

14.3 Viscosity Dependence of the Turbine Meter

For the turbine meter a very different approach was tried. In order to get rid of liquid dependent qualities it was suggested to display the calibration curves not as k-factor versus flowrate but versus Reynolds number for comparison. The transformation is performed using equation (3).

$$\mathrm{Re} = \frac{\rho \cdot V \cdot D}{\mu} = \frac{q \cdot D}{\nu \cdot A} = \frac{q \cdot D}{\nu \cdot \left(\frac{D}{2}\right)^2 \cdot \pi} = \frac{4 \cdot q}{\nu \cdot D \cdot \pi} \qquad (3)$$

Re	Reynolds number
ρ	density of liquid
V	linear speed (bulk speed - mean value in pipe)
D	inside pipe diameter
μ	dynamic viscosity

The quotient μ/ρ is replaced by the kinematic viscosity ν and the linear speed is defined by the flow q passing through the pipe area A. Collecting some of the constants for the transformation between units into one single constant f leads to equation (4)

$$\mathrm{Re} = \frac{q_i \cdot f}{\nu(t_i) \cdot D(t_i)}; \quad \text{with} \quad f = \frac{4 \cdot 1000}{60 \cdot \pi} \qquad (4)$$

Here the viscosity and the pipe diameter are given as a function of the temperature to take care of measurements at different liquid temperatures. The temperature dependence of the viscosity is assumed to be a polynomial of degree n=2, equation (5).

$$\nu(t_i) = \nu_0 + m_1 \cdot t_i + m_2 \cdot t_i^2 \qquad (5)$$

Fig. 24 shows the fitted curves for the liquids used in the intercomparison. The constants ν_0, m_1 and m_2 differ from liquid to liquid. For each laboratory they are determined by a least square fit based on at least 3 viscosity values in the range 15° to 50°.

The index i above is incorporated for the following reason. During the ten repeated runs at each flowrate the temperature is quite stable. From flowrate to flowrate, however, the temperature can shift several degrees centigrade. Thus an individual correction for the temperature at each flowrate is more advantageous than for the mean temperature of the entire calibration curve. The temperature effect on the pipe diameter D is already considered (see 14.1).

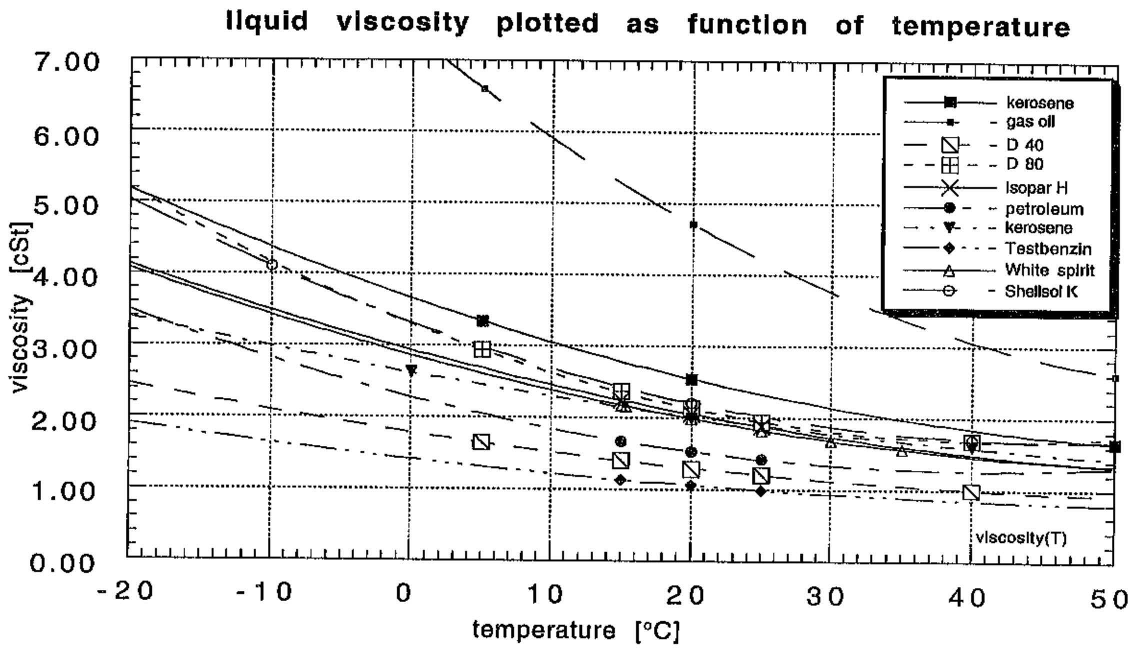


Fig. 24: Temperature dependence of the liquid viscosity. The fit is performed with a second order polynomial (equation 5). The actual viscosity is calculated for each test temperature (i.e. each flowrate) and used in the viscosity adjustment of the turbine results and in two cases for the screw meter.

14.3.1 Reynolds Number Dependence

The **Fig. 25** displays the temperature corrected (t_{ref}=20°C) points from several calibrations taken at NEL and SP in different liquids and at several temperatures. They were performed with the whole meter package and the flow straightener in place. The result is rearranged as a function of Reynolds number according to the concept above. It can be seen, that the curves in this representation coincide quite well (compare to **Fig. 27**). The drawn line in **Fig. 25** indicates the best fit to all experimental points (corr. coeff. 0.996). It's mathematical form is expressed by equation (6).

$$k(\mathrm{Re}) = n_0 + \frac{n_1}{\sqrt{\mathrm{Re}}} + n_2 \cdot \mathrm{Re} \qquad (6)$$

Other possible attempts, amongst them polynomials with varying degree n from 2 to 10, do not give a fit as good as (6). A polynomial fit for n=5 indeed revealed a correlation coefficient very close to 1. The resulting curve, however, exhibited details that intuitively contrasted with the very simple and smooth dependence of the experimental data. The fitting constants n_0 to n_2 for equation (6) should be valid for all liquids within the range of the viscosities, temperatures and flowrates that contributed to the experimental data.

Theoretical models for turbine meters (Hutton[3]) also suggest terms proportional to Re^{-1} or Re^{-2} for the bearing friction at very low flowrates. Within the tested region, however,

[3] Hutton, S.P. The effects of fluid viscosity on turbine meter calibration, Flow Measurement the Mid-80s, NEL, HMSO, Paper 1.1, June 1986

none of these give a significant contribution. According to Salami[4] the term $Re^{-1/2}$ can explain the drag of the blade profile. The term ~Re dominates the curve shape on the high flowrate side and is influenced mainly by the linearising efforts laid down on the support and the rotor itself.

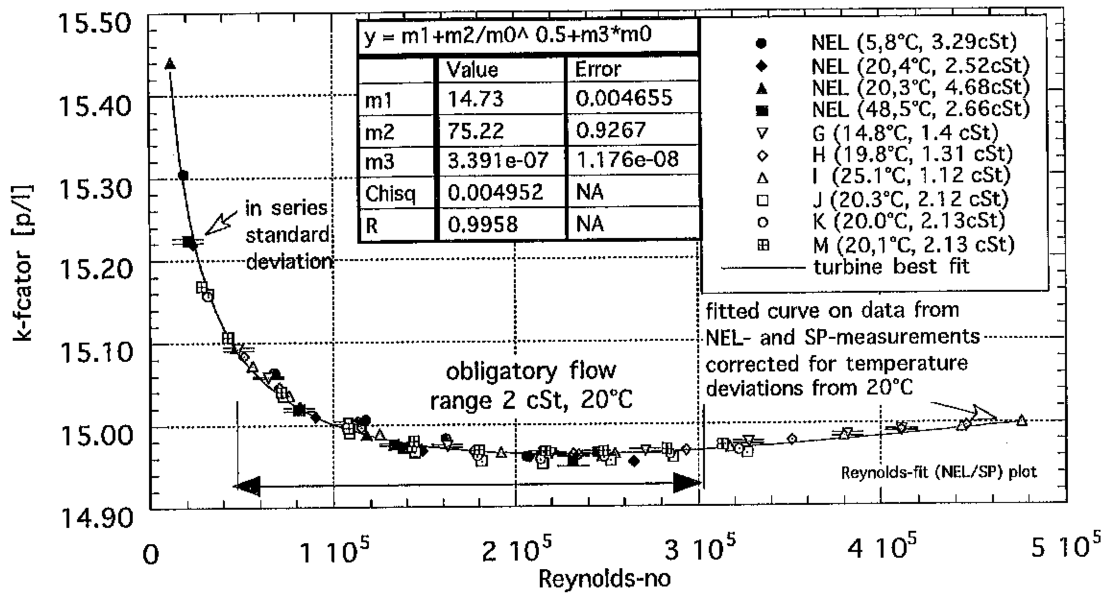


Fig. 25: Reynolds number dependence of the turbine exemplified with 4 tests at NEL and 6 tests at SP at several different temperatures and viscosities together with the best fit for all data points.

The model to rearrange reported measuring data as a function of Reynolds number allows the results of the different laboratories to be compared on a common basis. However, if one believes in a stable functional relationship between k-factor and Reynolds number for this particular turbine, one is also able to transform a whole calibration curve (k-factor as a function of flowrate) measured at one actual viscosity (temperature) to a common reference viscosity.

14.3.3 Correction Technique for Viscosity Effects (Turbine Meter)

The technique proposed for the viscosity correction is the following. Starting from an actual meter factor value $k(q_i)\big|_{V_a}^{t_a}$ at flowrate q_i with values V_a and t_a for the actual viscosity and temperature, a Reynolds number Re_a is calculated with equation (4). The theoretical meter factor $k(Re_a)$ follows from equation (6). This equation can also give a value $k(Re_r)$ for the same flowrate but reference values V_r and t_r, i.e. a k-factor for this turbine in a different liquid. One just moves along the fitted curve from Re_a to Re_r. If one assumes that the relation between $k(Re_a)$ and $k(Re_r)$ also holds for the measured value $k(q_i)\big|_{V_a}^{t_a}$ and the interesting one at a reference liquid $k(q_i)\big|_{V_r}^{t_r}$, then all individual k-fac-

---

[4] Salami, L. A. Analysis of swirl, viscosity and temperature effects on turbine flowmeters Trans. Inst Meas. Control 7(4) (1985) 183 -202

tors can be transformed to a common viscosity, for instance 2 cSt. This can possibly be accomplished using equation (7):

$$k(q_i)\Big|_{V_r}^{t_r} = \frac{k(\mathrm{Re}_r)}{k(\mathrm{Re}_a)} \cdot k(q_i)\Big|_{V_a}^{t_a} \qquad (7)$$

The transformation was tested with good results on seven calibration curves, four from NEL and three from SP at large viscosity differences. Thus the resulting calibration curves, reflecting the same physical conditions, do lie much closer to each other. Going from a high viscosity to a lower one reduces the k-factor at the low flow side. In contrast, going from a low viscosity to a higher one increases the k-factor at the low flow side; on the high flow side it is instead reduced. This effect follows from the turbine characterisation (**Fig. 25**). At the low flow side a lower viscosity means higher Re-number and thus a lower k-factor (shift to the right along the curve). At the high flow side a higher viscosity means a lower Re-number also leading to a lower k-factor. The effect on the high flow side is of course much less pronounced.

The conformation found was not so good for the curves at the extreme temperatures 5 ° and 50°C as for those at intermediate temperatures, which all lie very well within ± 0.1 % (**Fig. 26**). This, however, is already due to the selection of the points for the fitting. In the low flow range the turbine repeatability is poorer and the number of fitting points low.

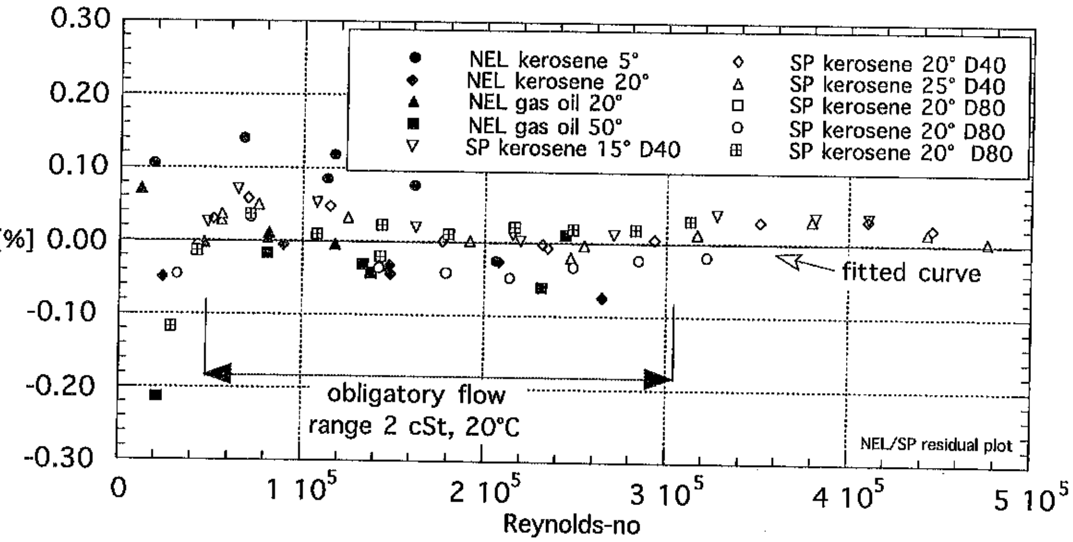


Fig. 26: The difference between the individual values and the fitted curve is a measure for the quality of the curve fitting.

But within the temperature and viscosity range for the intercomparison, the technique seems to be a promising one to perform corrections. And quite clearly one could expect that the differences in calibration results, depending on the liquid properties, can be reduced making the comparison between the involved laboratories more objective. The effect of the viscosity and temperature transformation is demonstrated by the comparison of **Figs 27, 28** and **29**. It should be noted that the effect of the viscosity adjustment is larger than intuitively seen due to the factor 2 in increased resolution of the scale in **Figs 28** and **29**.

Although the viscosity correction seems promising, it must be observed that it has so far been tested only for this particular turbine meter.

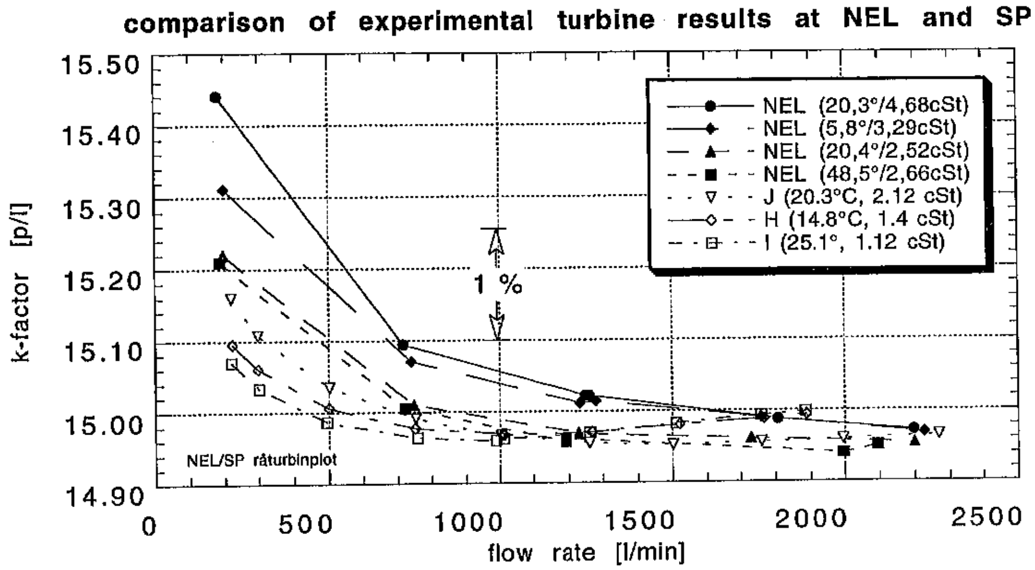


Fig. 27: Turbine results plotted in order of falling viscosity. The drawn interpolation lines exaggerate the differences between the curves due to the few flow points.

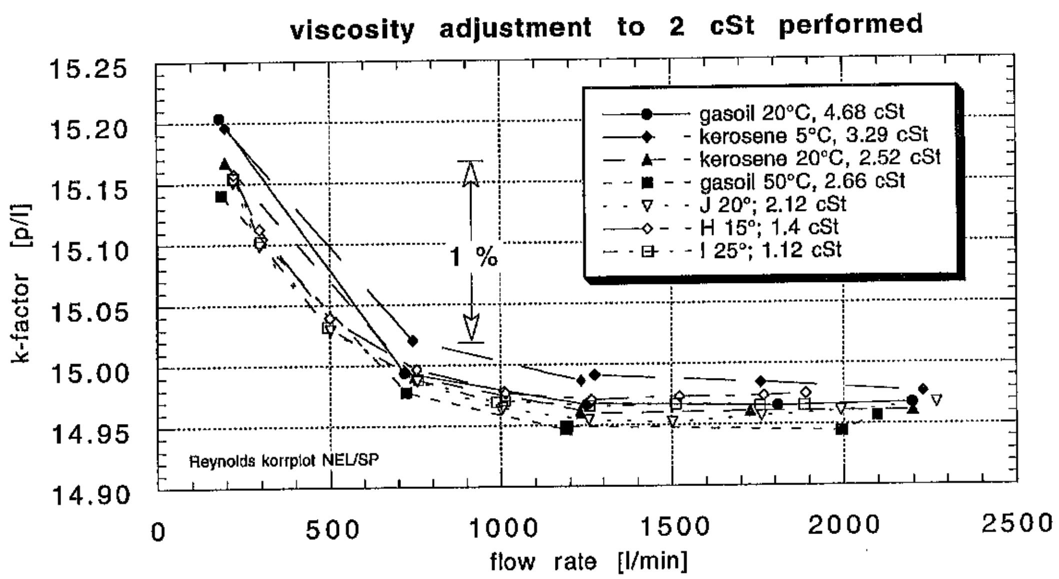


Fig. 28: The viscosity adjustment brings the curves much closer to each other.

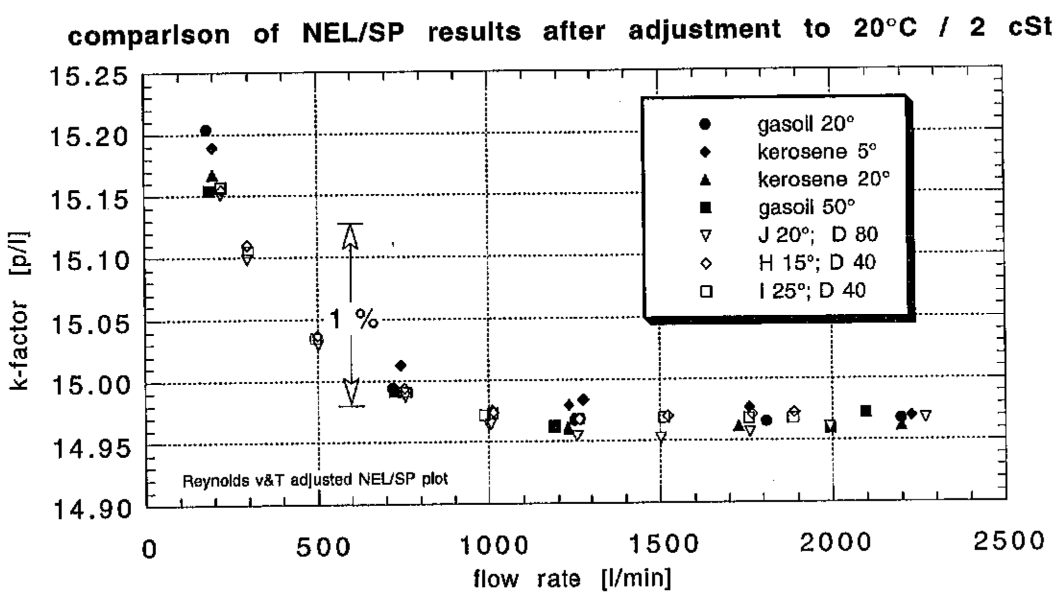


Fig. 29: The temperature correction finally equalises the results even more.

15 Non-linearity and Representative k-factor $<k_{rep}>$

Flowmeters are usually delivered commercially with one k-factor rather than with a list of k-factors for different flowrates. Due to practical reasons, users often want to handle just one single value from a meter calibration despite the flow dependency. Even when comparing results from different calibrations with varying conditions it is more intuitive to try to do this on the basis of just one value, i.e. a representative k-factor. This is especially true for a quantitative comparison between different laboratories because there is a wish to relate the reproducibility of the intercomparison to the repeatability or reproducibility within one laboratory.

The question, however, is how to construct this k-factor in a representative way. If the flowrate dependence were strictly linear, a mean value over the measured k-factor values would be acceptable, as long as one does not know anything about the probability for the different flowrates to occur. If the meter is not linear, and that is especially true for the turbine, then a simple average is insufficient. Concerning the turbine in question, the volume passing through the meter during a given time interval would be overestimated at low flowrates and underestimated at high flowrates. If we assume that the meter will face all flowrates within a given range and we do not know anything about the probability for them to occur, a possible way to build a mean value is by weighting each k-factor k_j with the corresponding flowrate q_j according to the definition:

$$k_{rep} = \frac{\frac{1}{m}\sum_{j=1}^{m} q_j \cdot k_j(q_j)}{\frac{1}{m}\sum_{j=1}^{m} q_j}$$, m is the number of tested flowrates

Even this construction will still depend on the selected values for that average as an unequal spreading of the flowrates will influence the result in the direction of too low or too high values, compared with the best possible selection.

Concerning the intercomparison as a whole, there is not much of a choice as there are only values from six flowrates available. But as the calibration curves can change shape considerably with viscosity, it is not self-evident that a good choice for one calibration liquid is good for another one.

15.1 Sensitivity of $<k_{rep}>$ to the Selection of Calibration Points

The sensitivity of the representative k-factor as a measure with respect to the selected flowrates was studied for two calibration curves at two different viscosities. As the experimental values are still few, the study was extended to the mathematically fitted curve as well, where representative k-factors were then calculated with several combinations of selected flowrates.

A result of this study is shown in the **Figs 30** and **31** below. The first exemplifies two combinations of calibration points, one from the obligatory flowrates (Ae) and one with an arbitrary selection (M) from the fitted curve. The second exhibits the resulting $<k_{rep}>$ for these combinations. In the lower part of **Fig. 31**, valid for 2 cSt, the different symbols indicate the result of $<k_{rep}>$, if different curve fittings are used. For the upper part of the figure (1 cSt) the few data points from **Lab 5** were used.

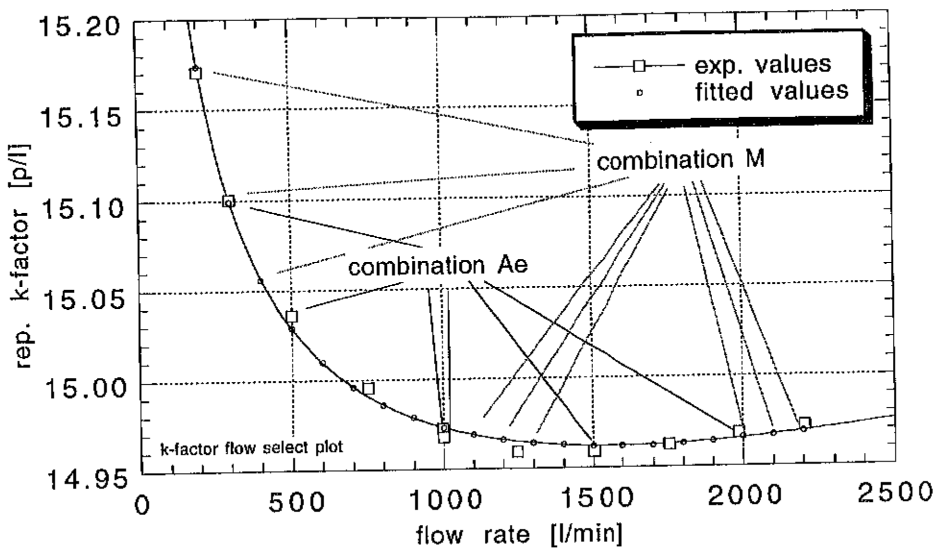


Fig. 30: Example how the representative k-factor can be based on two different combinations of flow points selected from the calibration curve.

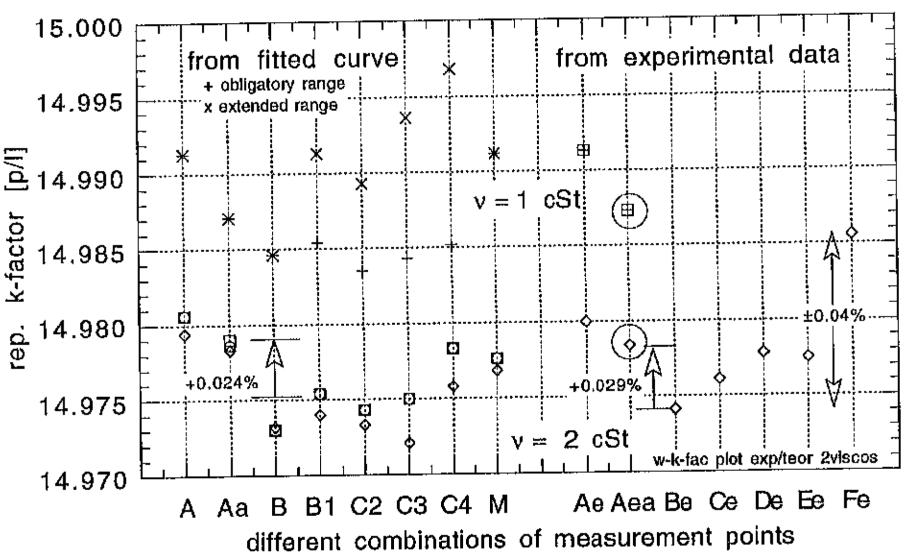


Fig. 31: Example for the sensitivity of the representative k-factor to the selection of flow points both from a fitted curve and from experimental data directly. The upper part is valid for the lower viscosity results.

The legend for the various combinations is the following:

- Ae based on five obligatory intercomparison flowrates using the mean values of the repeated flowrates 3:1 and 3:2 (k-factor and flowrate) as one of them.
- Be based on all available values (11 flow points) from the calibration.
- Ce based on all complementary values compared to Ae.
- De based on a combination with a majority of optional flowrate values.
- Ee based on an equal combination of obligatory and optional flowrate values.
- Fe based on the three lowest and the three highest measured values.
- Aea based on the six points from five obligatory flowrates counting the repeated middle one with the same weight (1/6).

Fitted data for 21 equidistant flow points between 200 l/min and 2200 l/min:

A based on obligatory flowrates (corresponding to Ae)
B based on all points within the interesting flow range 300 - 2000 l/min
B1 based on all available equidistant points within the larger flow range
C2 based on every second value.
C3 based on every third value.
C4 based on every forth value.
M based on the three lowest, three highest values and three flow points in the middle.
Aa based on the six points from five tested obligatory flowrates counting the repeated middle one with the same weight.

The experience from this exercise can be summarised in the following:

1. An equal weighting of all values (B) within the specified test range renders a relatively low value.
2. To use all available information from the larger range (B1) seems intuitively to be the best approximation and it falls in the middle of the spread.
3. The range of constructed values for reasonable combinations is within 0.05 %, which is less than the measurement uncertainty that can be claimed for any of the measured single k-factors. As a consequence of that it can be stated, that any five flowrate values, that are not totally skew-distributed, will have no substantial influence on the weighted k-factor. This is important when comparing the results between laboratories that did not measure in total conformity with the obligatory flowrates.
4. The most obviously constructed k-factor from the five obligatory flowrates, with the average of the two repeated middle flowrates as one value (A and Ae), yields a relatively high value.
5. The different possible combinations of the experimental data points show the same behaviour as from the fitted points.
6. A combination with an over representation of large flowrates yields a relative low value and vice versa, which is to be expected from the formula with the calibration curve in mind. An unreasonable combination of just low and high flowrates leads to an extremely high value, which is 0.08 % too high. This figure, however, should be related to the total non-linearity within the obligatory measurement range which is as much as 1.27 %.

The conclusion that can be drawn from this study is that the constructed k-factor for the turbine based on five flowrates (A, Ae) is representative but somewhat too high with respect to the most neutral selection (B, Be). A better combination, which is also simpler to achieve, would be the one based on six values from five obligatory flowrates (Aa and Aea), counting both the repeated middle flowrates with 1/6 weight each. This value is encircled in the figure. It is still a little bit too high (0.024 - 0.029 % valid for $\nu = 2$ cSt), but it is actually the best available with the limited information.

15.2 The Sensitivity of $<k_{rep}>$ to Viscosity

Even if, due to the limited data, there is not much choice, an important question when comparing the results on the basis of a constructed k-factor is whether this construction is neutral to the form of the calibration curve due to the used liquid, or if one flowrate is lacking, as was the case for **Lab 1** and **Lab 2** (highest flowrate). To answer this question both possible combinations Ae and Aea were performed on all non-corrected calibration data. With one exception, the combination Aea leads to a lower k-factor. For six calibrations the reduction is in the range 0,006 - 0,011 %, i.e. no significant change. For three laboratories (**Lab 7**, **Lab 5** and **Lab 2**) the reduction is 0,057, 0,027 and 0,024 %. Except for **Lab 7** this also is acceptable in relation to the results from the theoretically fitted curve. For **Lab 7** with the middle viscosity the curve shape is much more U-like, which leads with a double weight for the middle flowrate to a less representative result. For configuration B without the flow straightener the reduction in the k-factor is even less than the numbers given above, except for **Lab 7**, where it results in as much as 0,083 %.

The decision based on these observations is to use the weighting with six values at five flowrates according to combination Aea, with the exception of **Lab 7** where combination Ae is chosen. This combination is relatively insensitive to viscosity effects, i.e. a different curve shape due to a lower viscosity gives a very comparable representative k-factor value, even before the correction for the viscosity effects is performed.

15.3 The Representative k-factor for the Turbine After Viscosity Correction

After the adjustment of all calibration curves for the turbine to a common viscosity and temperature, the curves from the laboratories come much closer to each other. For laboratories with somewhat higher viscosities than 2 cSt the representative k-factor is reduced by between 0,008 to 0,026 % (config. A) and 0,009 and 0,029 % (config. B). For laboratories with lower viscosity it is instead increased. The values are in the range 0,001 to 0,043 % (config. A) and 0,001 and 0,049 % (config. B). However, this picture is not fully complete. For **Lab 5** for example with quite a low viscosity the representative k-factor increases with 0,089 and 0,091 % respectively due to the dominating influence of the high flowrates. For **Lab 2** the highest flowrate is missing otherwise even here an increase could have been expected.

15.4 Representative k-factor for the Screw Meter

Concerning the weighting for the screw meter due to its good linearity there should not be a large effect due to the combination chosen. Still it might be interesting to see how big the effect can be. As the screw meter exhibits a maximum near the middle flowrate a double weighting should increase the k-factor. This is, in fact, also the case with an effect of 0 - 0,004 %. For one laboratory (**Lab 7**) it is significantly larger 0,009 and 0,014 % (configurations A and B). The main reason for this is the relatively large inclination of this calibration result. For just one laboratory (**Lab 6**, configuration A) the double weighting leads to a 0,011 % reduction. In this case the reason is due to two unnaturally high values on the high flowrate side of the calibration curve.

The conclusion for the screw meter is the following. The most representative combination is Ae with five points, using the mean between the two repeated mid-flowrates as one of them.

15.5 The Influence of a Missing Result at High Flowrates on the Global Mean of the Representative k-factors

When calculating a reference mean for the representative k-factor and plotting the result of all laboratories in relation to this, another important question is, how a missing calibration point influences the global mean. Generally, due to the missing values at the highest flowrate from **Labs 1** and **2** both would have a slightly higher representative k-factor (**Lab 1** < 0,01 %, **Lab 2** < 0,06 %) for the turbine and an unimportant decrease (0,01 %) for the screw meter. Together with the weight of 1/12 each the total effect on the global mean would be less than 0.005 % and could therefore be disregarded.

16 Meter Stability

An important aspect of the intercomparison exercise is whether the transfer standard has been stable enough, or if varying results could be the effect of changes in the meters themselves. As the repeatability and reproducibility measures also contain other parameters (reference standards, test methods etc.) a stability judgement should be based on almost identical measurements. The three complete calibrations at the start, in the middle and at the end of the intercomparison (SPI to SPIII) can be used for this task.

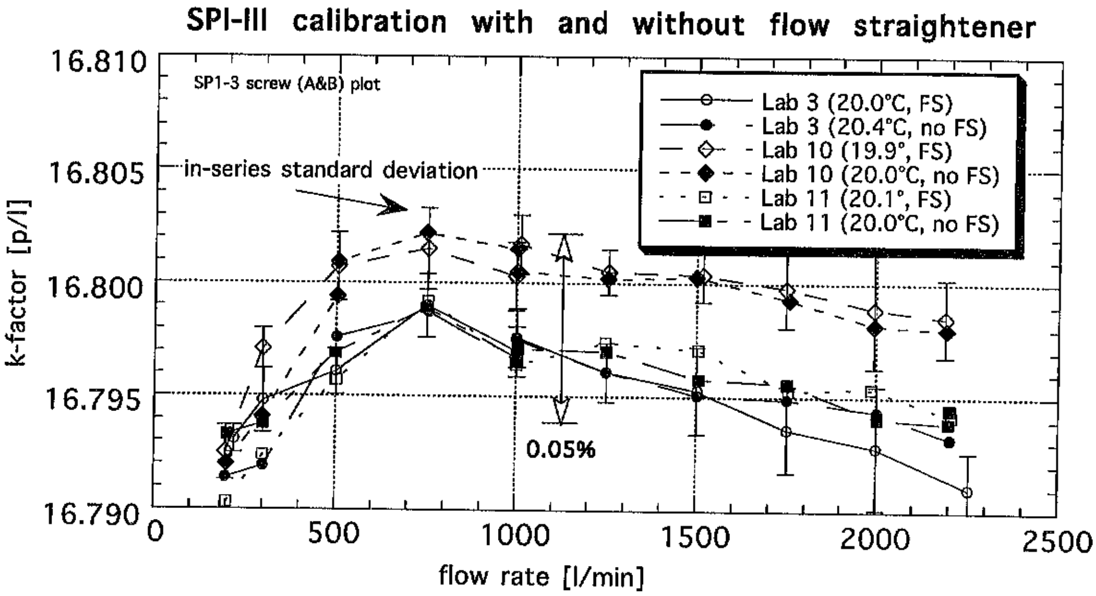


Fig. 32: Three repeated complete screw meter calibrations after 5 and 13 months respectively. White and black symbols denote the presence of a flow straightener - no flow straightener.

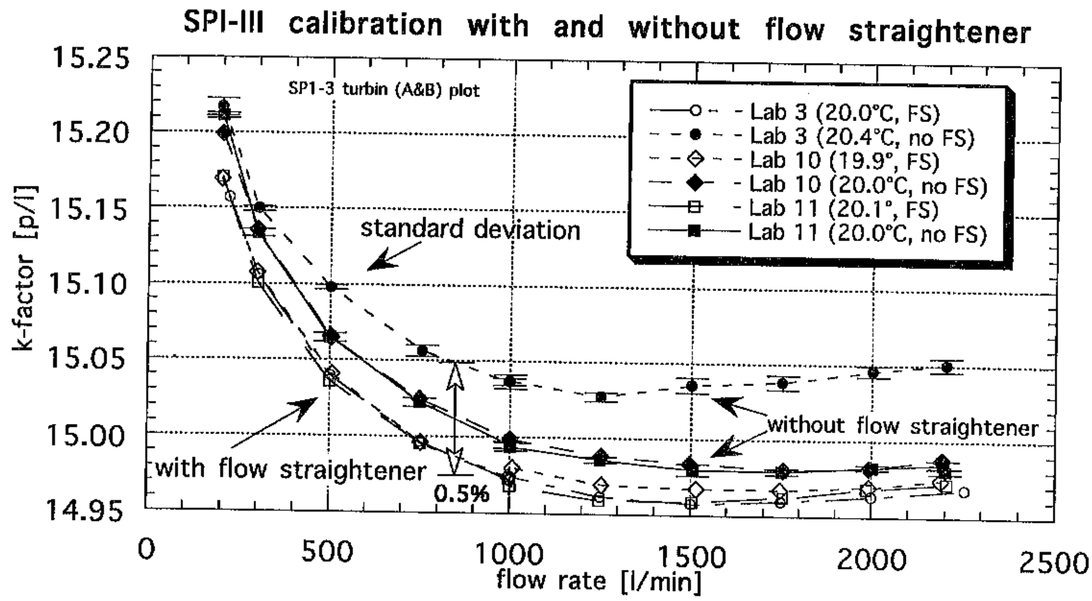


Fig. 33: Three complete turbine meter calibrations - open symbols with, dark symbols without flow straightener in place.

With respect to the measurement uncertainty (±0.06 %) no difference can be seen in the result of the screw meter (**Fig. 32**) whether there is a flow straightener or not. Further the results from SPI and SPIII (**Lab 3** and **Lab 11**) are very close to each other (metrologically identical), whereas the SPII curve lies 0.025 % above the others over the whole flow range.

Even the turbine results (**Fig. 33,** uncertainty ±0.08 %), disregarding the effect of the flow straightener, show a much closer relation (same difference) between SPI and SPIII, whereas the SPII values were 0.03 % higher.

The first reaction after the intermediate calibration, with the results from **Labs 4, 7** and **8** at hand, was that of a trend for both meters. On the other hand a significant amount of rust particles was found trapped in the filter prior to re-mounting and the calibration SP II. A closer investigation, when removing the flow straightener for running configuration B, revealed a very thin rust layer on the inside of the meter package that afterwards was removed. No such problem arose at the last calibration SPIII. This finding is also supported by the fact that the calibration preceding SPII was performed in a rig of carbon steel not built for calibration purposes. With the picture more complete the thin rust layer thus could serve as an explanation for the higher values in SPII. In the screw meter this layer could tighten against the meter walls and reduce slippage, especially at higher pressure drop, i.e. higher flowrates. In the turbine the clearance can be reduced also leading to higher k-factors. Rust in the form of a layer or particles fastening on the rotor blades could work both ways, but from our experience mostly to give higher meter factors.

This explanation also seems acceptable when looking at the representative k-factor of the two meters concerning all relevant series (even from the other laboratories) as is shown in **Figs 34** and **35**. They can serve as a histogram over the meter package. The SP calibrations I, II and III are marked. Five series (G,H,I,WI;WII, low viscosity, no correction) in D40 gave lower values. The figure shows a very stable screw meter, with the SPII-value as an outlier preceded by even a higher one, probably causing the rust layer.

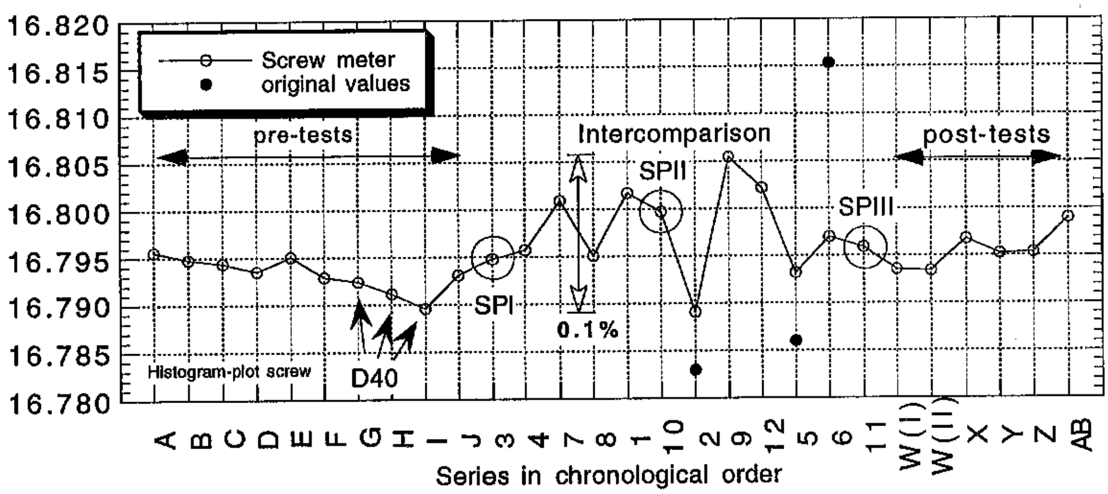


Fig. 34: Histogram of the representative screw meter factor over a period of 1.5 years. The values are adjusted for temperature deviations from 20°C and for viscosity in two cases (•). One value (6) has been exchanged against the one from the configuration without flow straightener.

For the turbine (**Fig. 35**) the picture is a little more difficult. Again a drastic change happening in D40 is seen. But after that the high value of SPII forms the exception.

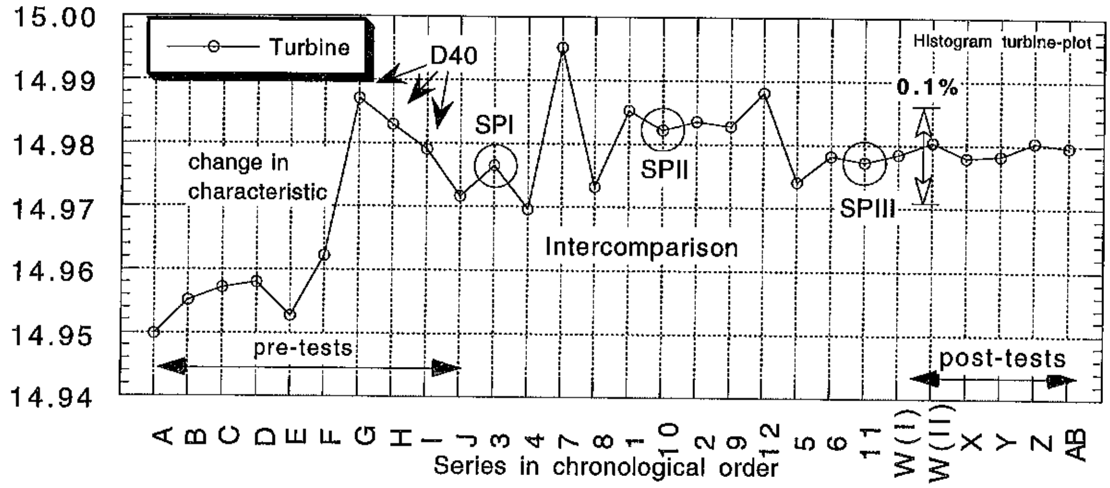


Fig. 35: Histogram of the representative turbine meter factor over a period of 1.5 years. All values are adjusted for temperature and viscosity deviations from 20°C and 2 cSt respectively.

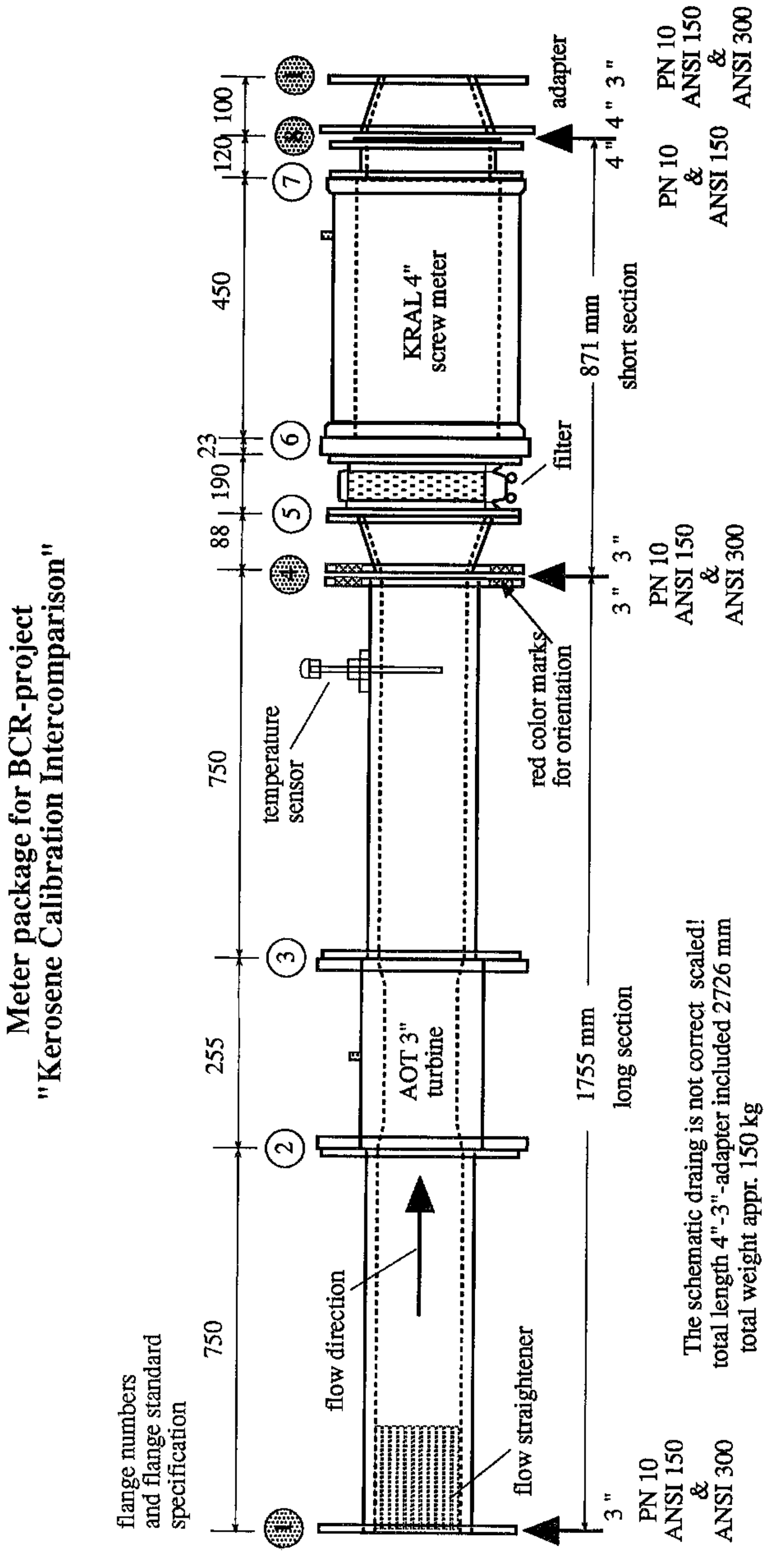
The histograms above support the assumption that the SPII measurement is an exception and that the difference between SPI and SPIII gives the real measure for the stability of the meters in the transfer standard. The differences, based on the representative k-factor as measure for a whole calibration curve, are given in Table 12 below.

Table 12	k(S)A [p/l]		Δk(S)A [%]	k(T)A [p/l]		Δk(T)A [%]
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**

The difference between SP I and SP III, with a recalibration of the volume reference, is only about 0.004 % for both meters. With an uncertainty estimate for the meter factor (constant calibration conditions assumed), being of the order of 0.08 % for the turbine and 0.06 % for the screw meter, this result is even better than expected from earlier experience with those meters.

The result of **Table 12** is also verified by the good congruence between the calibrations before SP I with those after SP III demonstrating a very good stability of both meters for the intercomparison exercise.

Appendix 1 Drawing of the Transfer Standard



Appendix 2

Summary form

Laboratory:	**Lab 1**		
Liquid:	**White spirit**		
Viscosity (20 °C):	**1.984 cSt**	**Density (20 °C):**	808.7 kg/m3

Configu-ration	mean values				meter factors						other related quantities		comments
	flow rate [No]	flow rate [l/min]	tempera-ture [°C]	test pressure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncertainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncertainty Us [%]	nominal volume used [l]	Reynolds no	
A	3:1	1000.000	21.50	230	14.9714	0.0117	0.04				60	*156672*	weighted k-factor
	4	1501.667	22.80	230	14.9671	0.0128	"				"	*240603*	for turbine meter
	5	-											14.9800
	1	305.000	24.10	350	15.0715	0.0085	"				"	*49962*	weighted k-factor
	2	511.667	25.30	320	15.0119	0.0066	"				"	*85521*	for screw meter
	3:2	1008.333	26.10	260	14.9638	0.0106	"				"	*170785*	16.7994
	3:1	998.333	21.70	170				16.8019	0.0038	0.03	"	*156954*	after adjustment
	4	1495.000	23.40	100				16.7979	0.0029	"	"	*242002*	14.9852
	1	305.000	24.40	340				16.8005	0.0019	"	"	*50215*	16.8017
	2	510.000	25.60	300				16.8012	0.0041	"	"	*85669*	
	3:2	1008.333	26.40	190				16.7991	0.0062	"	"	*171630*	
B	3:1	1003.333	27.00	260	15.0579	0.0148	0.04				"	*172464*	weighted k-factor
	4	1491.667	29.20	230	15.0567	0.0181	"				"	*265604*	for turbine meter
													15.0663
	1	315.000	30.10	350	15.1349	0.0109	"				"	*56882*	weighted k-factor
	2	516.667	30.90	320	15.0937	0.0148	"				"	*94454*	for screw meter
	3:2	996.667	31.60	260	15.0534	0.0168	"				"	*184149*	16.7957
	3:1	1003.333	27.50	200				16.7985	0.0045	0.03	"	*173869*	after adjustment
	4	1481.667	29.60	120				16.7936	0.0038	"	"	*265484*	15.0777
	1	315.000	30.40	340				16.7975	0.0029	"	"	*57147*	16.8012
	2	518.333	31.10	300				16.7977	0.0050	"	"	*95048*	
	3:2	995.000	31.80	200				16.7956	0.0056	"	"	*184394*	

Summary form

Laboratory:	**Lab 2**		
Liquid:	**Testbenzin**		
Viscosity (20 °C):	**1.109 cSt**	**Density (20 °C):**	**774.4 kg/m3**

Configu-ration	mean values				meter factors						other related quantities		comments
	flow rate [No]	flow rate [l/min]	tempera-ture [°C]	test pressure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncertainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncertainty Us [%]	nominal volume used [l]	Reynolds number	flow straightener in front of turbine ?
A	3:1	1027	16.94	204	14.9691	0.020	0.07	16.7845	0.017	0.07	1000	*268649*	weighted k-factor
	4	1535	18.67	250	14.9921	0.023	"	16.7829	0.008	"	1000	*411957*	for turbine meter
	5	-											14.9774
	1	301	18.63	140	15.004	0.022	"	16.7803	0.039	"	1000	*80735*	weighted k-factor
	2	503	21.09	150	14.9642	0.013	"	16.7862	0.008	"	1000	*139461*	for screw meter
	3:2	1010.7	21.77	200	14.9623	0.017	"	16.7828	0.011	"	1000	*282590*	16.7834
													after adjustment
													14.9835
													16.7889
	3	1012	14.18	150	14.9842	0.033		16.789	0.020		1000	*253204*	flow geometry - variant 2

B	3:1	999.3	15.1	150	15.0059	0.022	0.07	16.7832	0.016	0.07	1000	*253880*	weighted k-factor
	4	1534.8	16.97	251	15.0251	0.017	"	16.7744	0.013	"	1000	*401667*	for turbine meter
	5	-											15.0199
	1	304.6	17.94	150	15.0568	0.045	"	16.7793	0.019	"	1000	*80886*	weighted k-factor
	2	503.5	15.4	150	15.0215	0.010	"	16.7831	0.008	"	1000	*128545*	for screw meter
	3:2	1019.4	16.03	150	15.0138	0.015	"	16.7816	0.007	"	1000	*262900*	16.7786
													after adjustment
													15.0252
													16.7825
	3	1007.6	16.08	150	15.0344	0.014		16.7836	0.013		1000	*260063*	flow geometry - variant 2

Laboratory:	Lab 3		
Liquid:	Exxsol D80		
Viscosity (20 °C):	2.13 cSt	Density (20 °C):	796 kg/m3

Summary form

I. Calibration

Configu-ration	mean values				meter factors						other related quantities		comments
	flow rate [No]	flow rate [l/min]	tempera-ture [°C]	test pressure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncertainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncertainty Us [%]	nominal volume used [l]		
A	3:1	1000.828	19.81	231	14.9740	0.0089	0.061	16.7976	0.0030	0.055	60	*142296*	weighted k-factor
	4	1501.485	19.87	288	14.9575	0.0126	0.062	16.7953	0.0033	"	"	*213730*	for turbine meter
	5	1999.616	19.83	417	14.9635	0.0180	0.062	16.7928	0.0040	"	"	*284440*	14.9779
	1	300.450	20.09	220	15.1060	0.0092	0.061	16.7948	0.0015	"	"	*42951*	weighted k-factor
	2	500.365	20.22	398	15.0394	0.0063	0.061	16.7961	0.0020	"	"	*71699*	for screw meter
	3:2	999.515	19.83	378	14.9718	0.0076	0.061	16.7970	0.0041	"	"	*142172*	16.7948
		1250.341	20.07	223	14.9616	0.0085		16.7961	0.0030		"	*178660*	after adjustment
		1749.641	19.82	407	14.9598	0.0125		16.7936	0.0023		"	*248820*	14.9765
		2253.433	20.08	523	14.9684	0.0109		16.7910	0.0048		"	*322067*	16.7947
		220.035	20.16	213	15.1568	0.0042		16.7931	0.0019		"	*31492*	
		750.546	20.02	315	14.9968	0.0095		16.7990	0.0031		"	*107137*	
B	3:1	999.373	20.13	269	15.0368	0.0297	0.059	16.7975	0.0028	0.056	"	*142959*	weighted k-factor
	4	1501.457	20.71	424	15.0359	0.0327	0.059	16.7951	0.0028	0.056	"	*217138*	for turbine meter
	5	2001.779	20.81	422	15.0461	0.0231	0.059	16.7944	0.0075	0.057	"	*290071*	15.0498
	1	301.624	21.15	309	15.1498	0.0106	0.055	16.7919	0.0013	0.056	"	*43983*	weighted k-factor
	2	501.316	19.40	194	15.0980	0.0114	0.055	16.7976	0.0011	0.056	"	*70721*	for screw meter
	3:2	998.534	19.99	402	15.0365	0.0160	0.056	16.7966	0.0019	0.056	"	*142471*	16.7952
		1250.911	20.63	327	15.0276	0.0191		16.7961	0.0017		"	*180635*	after adjustment
		1750.716	20.73	407	15.0384	0.0316		16.7949	0.0028		"	*253298*	15.0483
		2202.347	20.76	510	15.0508	0.0293		16.7932	0.0036			*318842*	16.7955
		196.445	20.75	168	15.2170	0.0370		16.7914	0.0030			*28431*	
		756.061	19.78	214	15.0566	0.0257		16.7987	0.0010			*107443*	

Summary form

Laboratory:	Lab 4		
Liquid:	Kerosene		
Viscosity (20 °C):	2.3 cSt	Density (20 °C):	797.232 kg/m3

Configu-ration	mean values				meter factors						other related quantities		comments
	flow rate [No]	flow rate [l/min]	tempera-ture [°C]	test pressure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncertainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncertainty Us [%]	nominal volume used [l]		Used liquid : Kerosene 15°C Density : 797.232 kg/m3
A	3:1	1231.26	20.337		14.9702	0.0103	0.03	16.7985	0.0081	0.03	3521.410	*147841*	weighted k-factor
	4	1728.00	20.383		14.9608	0.0140	"	16.7957	0.0112	"	3556.723	*207656*	for turbine meter
	5	2198.58	20.484		14.9540	0.0118	"	16.7912	0.0115	"	3607.499	*264683*	14.9735
	1	197.16	20.240		15.2191	0.0741	"	16.8088	0.0437	"	903.621	*23633*	weighted k-factor
	2	747.66	20.348		15.0099	0.0162	"	16.8002	0.0163	"	949.355	*89791*	for screw meter
	3:2	1234.44	20.377		14.9683	0.0100	"	16.7971	0.0130	"	1370.098	*148328*	16.7955
													after adjustment
													14.9696
													16.7957
B	3:1	1197.80	20.390		14.9970	0.0133	0.03	16.8010	0.0103	0.03	3532.353	*143959*	weighted k-factor
	4	1800.60	20.500		14.9823	0.0154	"	16.7960	0.0158	"	3586.347	*216833*	for turbine meter
	5	2119.60	20.470		14.9840	0.0291	"	16.7930	0.0060	"	3600.047	*255111*	15.0005
	1	206.80	20.057		15.2480	0.0066	"	16.8187	0.0150	"	902.827	*24707*	weighted k-factor
	2	771.60	20.253		15.0377	0.0366	"	16.8080	0.0259	"	945.927	*92509*	for screw meter
	3:2	1205.40	20.483		14.9937	0.0139	"	16.7993	0.0069	"	1361.153	*145113*	16.7981
													after adjustment
													14.9962
													16.7983

Laboratory:	Lab 5	
Liquid:	White spirit	
Viscosity (20 °C):	1.066 mm^2/s	Density (20 °C):

Summary form

Configu-ration	mean values				meter factors						other related quantities		comments
	flow rate [No]	flow rate [l/min]	tempera-ture [°C]	test pressure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncertainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncertainty Us [%]	nominal volume used [l]	Reynolds number	Used liquid: Testbenzin
A	3:1	1010.9	20.00	109	14.9655	0.013	0.060	16.7896	0.011	0.060	2000.0	*289110*	weighted k-factor
	4	1504.8	20.24	218	14.9873	0.013	0.061	16.7854	0.008	0.060	2000.0	*431741*	for turbine meter
	5	2008.8	20.10	277	15.0072	0.027	0.063	16.7826	0.014	0.061	2000.0	*575269*	14.9873
	1	300.7	20.18	115	15.0226	0.074	0.077	16.7903	0.013	0.061	2000.0	*86205*	weighted k-factor
	2	501.8	20.64	114	14.9715	0.011	0.060	16.7894	0.008	0.060	2000.0	*144738*	for screw meter
	3:2	1004.2	20.00	110	14.9669	0.021	0.062	16.791	0.006	0.060	2000.0	*287194*	16.7859
													after adjustment
													14.9740
													16.7930
B	3:1	1014	19.5	109	14.9846	0.061	0.072	16.7932	0.020	0.061	2000.0	*288061*	weighted k-factor
	4	1521	19.9	219	15.0111	0.065	0.073	16.7882	0.031	0.063	2000.0	*434414*	for turbine meter
	5	2024	19.8	275	15.0363	0.103	0.090	16.7836	0.024	0.062	2000.0	*577303*	15.0117
	1	303	19.5	112	15.0388	0.031	0.063	16.7933	0.024	0.062	2000.0	*86077*	weighted k-factor
	2	502	19.0	113	15.0023	0.029	0.063	16.7956	0.019	0.061	2000.0	*141653*	for screw meter
	3:2	1008	18.9	108	14.9873	0.069	0.075	16.790	0.037	0.064	2000.0	*284050*	16.7881
													after adjustment
													14.9980
													16.7949

Summary form

Laboratory:	**Lab 6**		
Liquid:	**Kerosene**	**Viscosity (50 °C):**	**1.432 cSt**
Viscosity (20°C):	**2.12 cSt**	**Density (15 °C):**	797.5 kg/m3

Configuration	mean values				meter factors						other related quantities		comments
	flow rate [No]	flow rate [l/min]	temperature [°C]	test pressure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncertainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncertainty Us [%]	nominal volume used [l]	Reynolds no	
A	3:1	998.85	20.37	181	14.987	0.025	0.06	16.801	0.016	0.06	4963.81	*143548*	weighted k-factor
	4	1501.05	21.45	250	14.945	0.010	0.06	16.821	0.018	0.06	4967.67	*220107*	for turbine meter
	5	1940.40	22.10	225	14.956	0.014	0.06	16.821	0.027	0.06	4968.94	*287911*	14.9786
	1	306.20	21.52	198	15.126	0.005	0.06	16.803	0.006	0.06	909.79	*44957*	weighted k-factor
	2	500.60	21.39	198	15.051	0.011	0.06	16.801	0.020	0.06	4967.19	*73325*	for screw meter
	3:2	1001.45	20.57	181	14.983	0.012	0.06	16.804	0.018	0.06	4964.00	*144466*	16.8145
													after adjustment
													14.9781
													16.8154
B	3:1	1000.65	20.16	182	15.020	0.028	0.06	16.800	0.0161	0.06	4964.12	*143235*	weighted k-factor
	4	1499.95	21.27	250	14.996	0.017	0.06	16.795	0.0018	0.06	4967.38	*219218*	for turbine meter
	5	1939.80	22.79	230	15.003	0.018	0.06	16.795	0.0024	0.06	4969.14	*291377*	15.0215
	1	303.20	21.83	198	15.162	0.036	0.06	16.797	0.0054	0.06	909.56	*44769*	weighted k-factor
	2	498.95	21.46	200	15.089	0.018	0.06	16.797	0.0024	0.06	4966.03	*73177*	for screw meter
	3:2	1001.10	20.51	184	15.021	0.021	0.06	16.798	0.0190	0.06	4963.61	*144252*	16.7961
													after adjustment
													15.0210
													16.7970

Summary form

Laboratory:	Lab 7		
Liquid:	Petroleum		
Viscosity (20 °C):	1.53 cSt	Density (20 °C):	786.6 kg/m3

Configuration	mean values				meter factors						other related quantities		comments
	flow rate [No]	flow rate [l/min]	tempera-ture [°C]	test pressure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncertainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncertainty Us [%]	nominal volume used [l]		
A	3:1	1002.6	24.75		14.971	0.011	0.05	16.800	0.010	0.05	5000	*213358*	weighted k-factor
	4	1502.9	23.95		14.983	0.009	"	16.798	0.011	"	5000	*316302*	for turbine meter
	5	2006.0	25.20		15.000	0.008	"	16.791	0.007	"	5000	*429474*	14.9957
	3:2	1001.4	25.87		14.972	0.011	"	16.802	0.008	"	5000	*216278*	weighted k-factor
	3:3	1002.4	22.08		14.973	0.005	"	16.806	0.002	"	2000	*205256*	for screw meter
	1	300.6	21.71		15.076	0.007	"	16.819	0.002	"	2000	*61204*	16.7986
	2	500.4	22.69		15.015	0.004	"	16.810	0.004	"	2000	*103410*	
	2a	751.8	23.18		14.985	0.004	"	16.810	0.002	"	2000	*156488*	after adjustment
	3:4	1001.0	23.93		14.973	0.003	"	16.803	0.003	"	2000	*210612*	14.9952
													16.8009
B	3:1	1002.0	23.13		14.993	0.005	0.05	16.799	0.004	0.05	5000	*208415*	weighted k-factor
	4	1504.7	24.41		15.007	0.009	"	16.794	0.007	"	5000	*318720*	for turbine meter
	5	2021.5	23.62		15.021	0.008	"	16.788	0.007	"	5000	*423458*	15.0203
	3:2	1003.0	23.86		14.996	0.009	"	16.800	0.006	"	5000	*210825*	weighted k-factor
	3:3	1004.4	20.28		15.001	0.004	"	16.806	0.003	"	2000	*199921*	for screw meter
	1	301.9	22.70		15.109	0.008	"	16.818	0.003	"	2000	*62398*	16.7965
	2	503.8	21.17		15.048	0.004	"	16.812	0.003	"	2000	*101716*	
	2a	751.7	21.82		15.013	0.004	"	16.808	0.003	"	2000	*153310*	after adjustment
	3:4	1001.5	21.49		15.002	0.005	"	16.808	0.003	"	2000	*203217*	15.0196
													16.7983
													Reference A and B
													Avery Hardoll meter

Summary form

Laboratory:	Lab 8		
Liquid:	ISOPAR H		
Viscosity (20 °C):	2.05 cSt	Density (20°C):	752.6 kg/m3

Configu-ration	mean values				meter factors						Other related quantities		Comments
	flow rate [No]	flow rate [l/min]	tempera-ture [°C]	test pressure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncertainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncertainty Us [%]	nominal volume used [l]	Reynolds number	Used liquid : ISOPAR H 15°C Density : 0.7562 kg/dm3
A	3:1	995	21.95	80	14.9649	0.003	0.06	16.7985	0.001	0.06	10000	*152252*	weighted k-factor
	4	1501	21.80	105	14.9574	0.002	0.06	16.7947	0.002	0.06	10000	*229079*	for turbine meter
	5	1999	22.18	120	14.9595	0.008	0.06	16.7892	0.002	0.06	10000	*307108*	14.9721
	1	301	22.59	80	15.0889	0.002	0.06	16.7968	0.003	0.06	3000	*46573*	weighted k-factor
	2	500	21.68	115	15.0270	0.005	0.06	16.8001	0.002	0.06	3000	*76149*	for screw meter
	3:2	1002	21.53	111	14.9637	0.005	0.06	16.7988	0.001	0.06	10000	*152204*	16.7940
													after adjustment
													14.9732
													16.7951
B	3:1	999	20.74	97	14.9650	0.027	0.07	16.8014	0.005	0.06	10000	*149665*	weighted k-factor
	4	1499	20.78	84	14.9409	0.018	0.06	16.7952	0.003	0.06	10000	*224731*	for turbine meter
	5	2000	21.60	122	14.9433	0.008	0.06	16.7897	0.002	0.06	10000	*304172*	14.9639
	1	299	21.59	114	15.1051	0.016	0.06	16.7972	0.003	0.06	3000	*45466*	weighted k-factor
	2	503	21.75	146	15.0295	0.012	0.06	16.7982	0.001	0.06	3000	*76700*	for screw meter
	3:2	1001	22.01	133	14.9635	0.046	0.07	16.7995	0.013	0.06	10000	*153330*	16.7945
													after adjustment
													14.9646
													16.7953

Summary form

Laboratory:	**Lab 9**		
Liquid:	**Kerosene (Shellsol K)**		
Viscosity (20°C):	**2.2 mm^2/s**	**Density (20°C):**	787.23 kg/m3

	mean values				meter factors						Other related quantities			Comments
Con-figu-ration	flow rate [No]	flow rate [l/min]	tem-pera-ture [°C]	test pres-sure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncer-tainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncer-tainty Us [%]	nominal volume used [l]	THERM 2283-2 via ADC [°C]	Reynolds number	
A	3:1	1002.02	15.86	85	14.9466	0.014	0.31	16.8103	0.004	0.083	2998.20	15.92	*127618*	weighted k-factor
	4	1500.41	17.21	97	14.9672	0.004	0.31	16.8086	0.003	0.083	2998.20	17.28	*196155*	for turbine meter
	1	294.32	16.96	82	15.1134	0.014	0.31	16.8037	0.004	0.083	2998.20	16.89	*38295*	14.9887
	2	504.38	15.99	87	15.0360	0.012	0.31	16.8086	0.004	0.083	2998.20	15.98	*64392*	weighted k-factor
	3:2	1013.68	16.63	89	14.9867	0.003	0.31	16.8093	0.002	0.083	2998.20	16.64	*131058*	for screw meter
	5	2006.52	16.95	276	14.9757	0.003	0.31	16.8056	0.002	0.083	2998.20	17.09	*261032*	16.8072
	0107	190.27	17.38	78	15.2057	0.005	0.31	16.8003	0.004	0.083	2998.20	17.27	*24956*	
	0108	747.70	17.19	89	15.0101	0.006	0.31	16.8090	0.001	0.083	2998.20	17.16	*97711*	after adjustment
	0109	1267.77	17.72	188	14.9723	0.001	0.31	16.8077	0.002	0.083	2998.20	17.80	*167370*	14.9828
	0110	1755.77	18.10	216	14.9704	0.001	0.31	16.8049	0.001	0.083	2998.20	18.12	*233496*	16.8055
	0111	2210.70	18.54	346	14.9821	0.001	0.31	16.8034	0.001	0.083	2998.20	18.68	*296475*	
	0112	996.30	18.13	113	14.9886	0.001	0.31	16.8080	0.001	0.083	2998.20	18.13	*132580*	
B	3:1	999.55	16.34	93	15.0972	0.029	0.31	16.8098	0.004	0.083	2998.20	16.40	*128502*	weighted k-factor
	4	1494.66	17.78	209	15.0806	0.016	0.31	16.8068	0.002	0.083	2998.20	17.90	*197545*	for turbine meter
	5	2003.70	16.60	253	15.0877	0.031	0.31	16.8049	0.001	0.083	2998.20	16.74	*258876*	15.0955
	1	296.16	17.02	82	15.1731	0.010	0.31	16.8035	0.002	0.083	2998.20	16.94	*38578*	weighted k-factor
	2	500.39	16.72	86	15.1282	0.012	0.31	16.8070	0.002	0.083	2998.20	16.69	*64803*	for screw meter
	3:2	993.93	17.10	165	15.0923	0.017	0.31	16.8085	0.001	0.083	2998.20	17.11	*129672*	16.8064
	0206	187.93	17.27	78	15.2481	0.006	0.31	16.8005	0.003	0.083	2998.20	17.18	*24599*	
	0207	757.13	17.22	89	15.1047	0.032	0.31	16.8097	0.001	0.083	2998.20	17.20	*99001*	
	0208	1248.47	17.53	163	15.0811	0.013	0.31	16.8076	0.001	0.083	2998.20	17.60	*164244*	after adjustment
	0209	1753.17	15.78	196	15.0839	0.012	0.31	16.8071	0.000	0.083	2998.20	15.90	*222916*	15.0894
	0210	2207.47	16.34	267	15.0885	0.003	0.31	16.8056	0.001	0.083	2998.20	16.50	*283759*	16.8047
	0211	1001.57	16.67	90	15.0940	0.006	0.31	16.8088	0.001	0.083	2998.20	16.67	*129585*	

Laboratory:	Lab 10		
Liquid:	Exxsol D80		
Viscosity (20 °C):	2.13 cSt	Density (20 °C):	0.796 g/ml

Summary form

II. Calibration

Configu-ration	mean values				meter factors						other related quantities		comments	
	flow rate [No]	flow rate [l/min]	tempera-ture [°C]	test pressure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncertainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncertainty Us [%]	nominal volume used [l]			
A	3:1	1006.371	20.00	217	14.9801	0.0090	0.095	16.8017	0.0021	0.057	60	*143627*	weighted k-factor	
	4	1514.324	20.04	230	14.9676	0.0079	"	16.8004	0.0027	"	"	*216261*	for turbine meter	
	5	1992.323	19.70	347	14.9697	0.0173	"	16.7989	0.0048	"	"	*282677*		14.9837
	1	298.487	19.68	151	15.1075	0.0062	"	16.7971	0.0010	"	"	*42333*	weighted k-factor	
	2	504.713	19.61	232	15.0407	0.0098	"	16.8007	0.0007	"	"	*71485*	for screw meter	
	3:2	995.945	20.18	356	14.9738	0.0100	"	16.8003	0.0017	"	"	*142607*		16.7998
		1253.530	20.25	231	14.9693	0.0067		16.8005	0.0017		"	*179739*	after adjustment	
		1746.023	19.84	272	14.9675	0.0113		16.7998	0.0029		"	*248429*		14.9822
		2187.610	20.13	435	14.9745	0.0114		16.7985	0.0047		"	*312987*		16.7997
		196.707	20.21	194	15.1692	0.0080		16.7925	0.0011		"	*28183*		
		752.126	20.27	346	14.9963	0.0121		16.8015	0.0011		"	*107879*		
B	3:1	999.852	19.61	277	14.9989	0.0323	0.095	16.8015	0.0018	0.056	"	*141631*	weighted k-factor	
	4	1496.905	20.13	299	14.9841	0.0185	"	16.8003	0.0022	"	"	*214144*	for turbine meter	
	5	1993.418	20.29	453	14.9823	0.0158	"	16.7982	0.0037	"	"	*286029*		15.0019
	1	297.412	20.72	445	15.1356	0.0154	"	16.7941	0.0007	"	"	*43025*	weighted k-factor	
	2	502.821	19.60	188	15.0648	0.0217	"	16.8009	0.0016	"	"	*71209*	for screw meter	
	3:2	999.946	20.05	357	14.9990	0.0421	"	16.8005	0.0020	"	"	*142845*		16.7994
		1252.574	19.92	330	14.9883	0.0184		16.8002	0.0022		"	*178482*	after adjustment	
		1755.305	20.27	412	14.9806	0.0259		16.7993	0.0025		"	*251798*		15.0004
		2192.577	20.15	538	14.9879	0.0221		16.7980	0.0028			*313766*		16.7994
		199.842	20.70	320	15.1995	0.0135		16.7920	0.0014			*28901*		
		502.160	19.60	289	15.0656	0.0143		16.7994	0.0012			*71116*		
		747.991	19.85	233	15.0248	0.0172		16.8022	0.0015			*106438*		

Laboratory:	**Lab 11**		
Liquid:	**Exxsol D80**		
Viscosity (20 °C):	**2.13 cSt**	**Density (20 °C):**	796 kg/m3

Summary form

III. Calibration

Configu-ration	mean values				meter factors						other related quantities		comments
	flow rate [No]	flow rate [l/min]	tempera-ture [°C]	test pressure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncertainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncertainty Us [%]	nominal volume used [l]	Reynolds no	
A	3:1	1000.275	20.55	298	14.9679	0.0077	0.081	16.7964	0.0031	0.055	60	*144245*	weighted k-factor
	4	1503.745	19.59	285	14.9590	0.0132	"	16.7971	0.0032	"	"	*212908*	for turbine meter
	5	1985.907	19.66	368	14.9685	0.0169	"	16.7954	0.0027	"	"	*281581*	14.9784
	1	299.406	20.69	212	15.1004	0.0195	"	16.7924	0.0015	"	"	*43288*	weighted k-factor
	2	500.131	20.04	364	15.0360	0.0071	"	16.7957	0.0029	"	"	*71423*	for screw meter
	3:2	997.510	20.02	382	14.9727	0.0130	"	16.7966	0.0026	"	"	*142392*	16.7959
		1246.960	19.66	285	14.9592	0.0112	"	16.7974	0.0028	"	"	*176808*	after adjustment
		1753.473	20.28	360	14.9624	0.0135	"	16.7953	0.0028	"	"	*251567*	14.9772
		2205.171	20.22	439	14.9722	0.0074	"	16.7942	0.0062	"	"	*316011*	16.9759
		199.436	20.33	343	15.1708	0.0093	"	16.7903	0.0020	"	"	*28637*	
		752.308	19.47	184	14.9957	0.0054	0.082	16.7992	0.0015	"	"	*106281*	

B	3:1	999.774	20.05	400	14.9950	0.0156	0.058	16.7967	0.0022	0.055	"	*142817*	weighted k-factor
	4	1504.825	19.92	377	14.9801	0.0253	0.059	16.7958	0.0026	"	"	*214405*	for turbine meter
	5	2001.432	20.13	436	14.9827	0.0124	0.057	16.7941	0.0046	"	"	*286333*	14.9995
	1	300.719	19.68	236	15.1337	0.0160	0.058	16.7938	0.0015	"	"	*42649*	weighted k-factor
	2	499.338	19.67	186	15.0652	0.0183	0.058	16.7969	0.0010	"	"	*70806*	for screw meter
	3:2	1001.267	20.21	334	14.9938	0.0175	0.058	16.7971	0.0019	"	"	*143468*	16.7954
		1249.666	19.97	314	14.9858	0.0117	0.057	16.7970	0.0017	"	"	*178221*	
		1750.721	19.94	354	14.9794	0.0140	0.057	16.7956	0.0023	"	"	*249575*	after adjustment
		2200.870	20.60	476	14.9807	0.0124	0.057	16.7945	0.0321	0.059	"	*317657*	14.9980
		2196.112	20.62	478	14.9848	0.0179	0.058	16.7939	0.0028	0.055	"	*317076*	16.7954
		199.740	19.48	228	15.2112	0.0120	0.057	16.7933	0.0043	"	"	*28219*	
		749.265	19.83	213	15.0227	0.0196	0.058	16.7989	0.0011	"	"	*106581*	

Laboratory:	Lab 12	
Liquid:	Kerosene (Shellsol K)	
Viscosity (20°C):	2.2 mm^2/s	Density (20°C): 787.23 kg/m3

Summary form

II. Calibration

elevated pressure

Con-figu-ration	mean values				meter factors						Other related quantities			Comments
	flow rate [No]	flow rate [l/min]	tem-pera-ture [°C]	test pres-sure [kPa]	turbine meter Kt [p/l]	standard deviation s(Kt) [%]	uncer-tainty Ut [%]	screw meter Ks [p/l]	standard deviation s(Ks) [%]	uncer-tainty Us [%]	nominal volume used [l]	THERM 2283-2 via ADC [°C]	Reynolds number	
A 1000 kPa Centrifugal Pumps	3:1	992.32	17.30	989.4	14.9896	0.012	0.31	16.8076	0.002	0.083	2998.20	17.37	*129947*	weighted k-factor
	4	1529.97	18.08	1007.3	14.9691	0.004	0.31	16.8039	0.000	0.083	2998.20	18.14	*203380*	for turbine meter
	5	1999.20	18.73	1021.3	14.9723	0.001	0.31	16.8015	0.001	0.083	2998.20	18.83	*269025*	14.9938
	1	299.10	17.00	999.7	15.1416	0.012	0.31	16.8046	0.003	0.083	2998.20	17.05	*38947*	weighted k-factor
	2	510.33	17.67	1003.3	15.0644	0.004	0.31	16.8062	0.002	0.083	2998.20	17.68	*67315*	for screw meter
	3:2	1005.14	18.33	1006.4	14.9984	0.016	0.31	16.8061	0.001	0.083	2998.20	18.39	*134255*	16.8038
														after adjustment
1000 kPa Centrifugal Pumps	2	497.40	15.62	1009.7	15.0566	0.002	0.31	16.8060	0.002	0.083	2998.20	15.59	*63048*	14.9881
	1	293.63	15.88	1003.3	15.1286	0.005	0.31	16.8036	0.003	0.083	2998.20	15.83	*37408*	16.8022
	3:1	989.90	16.29	1007.7	14.9977	0.013	0.31	16.8048	0.003	0.083	2998.20	16.30	*127118*	
	4	1507.30	17.06	1009.3	14.9721	0.002	0.31	16.8041	0.001	0.083	2998.20	17.15	*196489*	
	5	2006.70	17.81	1007.7	14.9733	0.012	0.31	16.8010	0.002	0.083	2998.20	17.86	*265401*	
	2	496.50	17.99	1009.0	15.0437	0.001	0.31	16.8035	0.002	0.083	2998.20	17.92	*65883*	
	3:2	1013.34	15.84	995.8	14.9810	0.006	0.31	16.8090	0.003	0.083	2998.20	15.99	*128994*	

Appendix 3

Definitions of Representative k-factor, Global Mean, Repeatability and Reproducibility.

Repeatability and reproducibility are defined here in accordance with ISO 5725 and given on a probability level of 95%. The repeatability defines the statistical range of values produced by repeating a measurement without changing any parameter other than the time for the measurement. If one should succeed totally in that, then this would define the meter repeatability in question. Normally, parameters like temperature, gas content in the liquid, pressure drop, or flowrates, are not in perfect control so that repeatability comprises both the meter and the facility. The term reproducibility refers to planned changes in those parameters influencing the meter performance like changes of temperature, liquid, test method, operator, test facility, volume references, etc. Thus the reproducibility is the important measure for the judgement of an intercomparison outcome. The figures presented in the report are based on the following definitions.

Indices used in the definitions:

i	to indicate a single measurement within a series at one flowrate
j	to distinguish a selected flowrate (only the obligatory ones are used)
l	to identify one of the co-operating laboratories
t	to mark the result from the test laboratory organising the intercomparison, i.e. SP
h	to distinguish between different calibrations at the test laboratory SP

$k_i(q_j)$: k-factor for a single measurement i at flow q_j $\quad 1 \le j \le m$; $m = 6$ obligatory

$\bar{k}_j(q_j)$: mean value for a series at flowrate j (this is stated in the summary form of each laboratory)

$$\bar{k}_j(q_j) = \frac{1}{n}\sum_{i=1}^{n} k_i(q_j) \qquad 1 \le i \le n; \qquad n = 10 \text{ (standard)}$$

$k(r)$: **representative k-factor** for a calibration result, i.e. one calibration curve

$$k(r) = k_{rep} = \frac{\frac{1}{m}\sum_{j=1}^{m} q_j \cdot \bar{k}_j(q_j)}{\frac{1}{m}\sum_{j=1}^{m} q_j}$$

$m = 5 / 6$ for screw-/turbine meter - see **Chapter 15.1**

$k_l(r)$: **representative k-factor** for the calibration of **laboratory** l

$< k(r) >$: **global mean** value for the representative k-factor from participating laboratories

$$< k(r) > = \frac{1}{p}\sum_{l=1}^{p} k_l(r) \quad 1 \le l \le p; \quad p = 12 \text{ (comparable calibrations)}$$

$k_t(r)_h$: **representative k-factor** for calibration number h of **test laboratory** (SP)

$< k_t(r) >$: mean representative k-factor from all relevant calibrations at SP at different conditions

$$< k_t(r) > = \frac{1}{z}\sum_{h=1}^{z} k_t(r)_h \qquad 1 \leq h \leq z; \quad z = 12$$

s_j^2: variance of $\overline{k}_j$ from repeated measurements at flowrate qj

$$s_j^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left(k_i - \overline{k}_j\right)^2$$

$\overline{s}_l{}^2$: average calibration variance of participating laboratory l, i.e. mean value for the obligatory flowrates ($m = 6$, j=1 and j=6 mid flowrate)

$$\overline{s}_l{}^2 = \frac{1}{m}\sum_{j=1}^{m} s_{lj}^2$$

$\overline{s}^2$: global mean calibration variance, i.e. average over the variances from all laboratories

$$\overline{s}^2 = \frac{1}{p}\sum_{l=1}^{p}\overline{s}_l^2 \qquad 1 \leq l \leq p; \quad p = 12 \text{ (comparable calibrations)}$$

s_C^2: inter-laboratory variance, i.e. from the inter-comparison of representative k-factors between laboratories

$$s_C^2 = \frac{1}{p-1}\sum_{l=1}^{p}\left[k_l(r) - < k(r) >\right]^2$$

$\overline{s}_{t\,h}^2$: variance of test laboratory t *(SP)* for calibration number h

$\overline{s}_t{}^2$: mean calibration variance for test laboratory (SP)

$$\overline{s}_t{}^2 = \frac{1}{z}\sum_{h=1}^{z}\overline{s}_{t\,h}^2 \qquad 1 \leq h \leq z; \text{ z number of test series}$$

$s_t{}^2{}_{is}$: intra-laboratory (SP) test-series variance for representative k-factor

$$s_t{}^2{}_{is} = \frac{1}{z-1}\sum_{h=1}^{z}\left[k_t(r)_h - < k_t(r) >\right]^2$$

r_e : **test laboratory** (SP) **repeatability** stating that the possible difference in variance from any test series will, with a 95% probability, be less than the value r_e (factor t^{95} from Students t-distribution).

$$r_e = t^{95}_{(n-1)} \sqrt{2} \sqrt{\bar{s}_t^{\,2}}$$

R_{et} : **test laboratory** (SP) **reproducibility** stating that the absolute difference between any two of the representative k-factors from all test series will never exceed the value R_{et} within a 95% probability.

$$R_{et} = t^{95}_{(n-1)} \sqrt{2} \sqrt{s_t^{\,2}{}_{is} + \bar{s}_t^{\,2}}$$

R_{eC} : **reproducibility for the total intercomparison** defining the probable maximum difference between any two laboratory results concerning the representative k-factor.

$$R_{eC} = t^{95}_{(n-1)} \sqrt{2} \sqrt{s_C^{\,2} + \bar{s}^2}$$

r_{eC} : **intercomparison repeatability** giving the statistical range of variances at the different laboratories.

$$r_{eC} = t^{95}_{(n-1)} \sqrt{2} \sqrt{\bar{s}^2}$$

Appendix 4

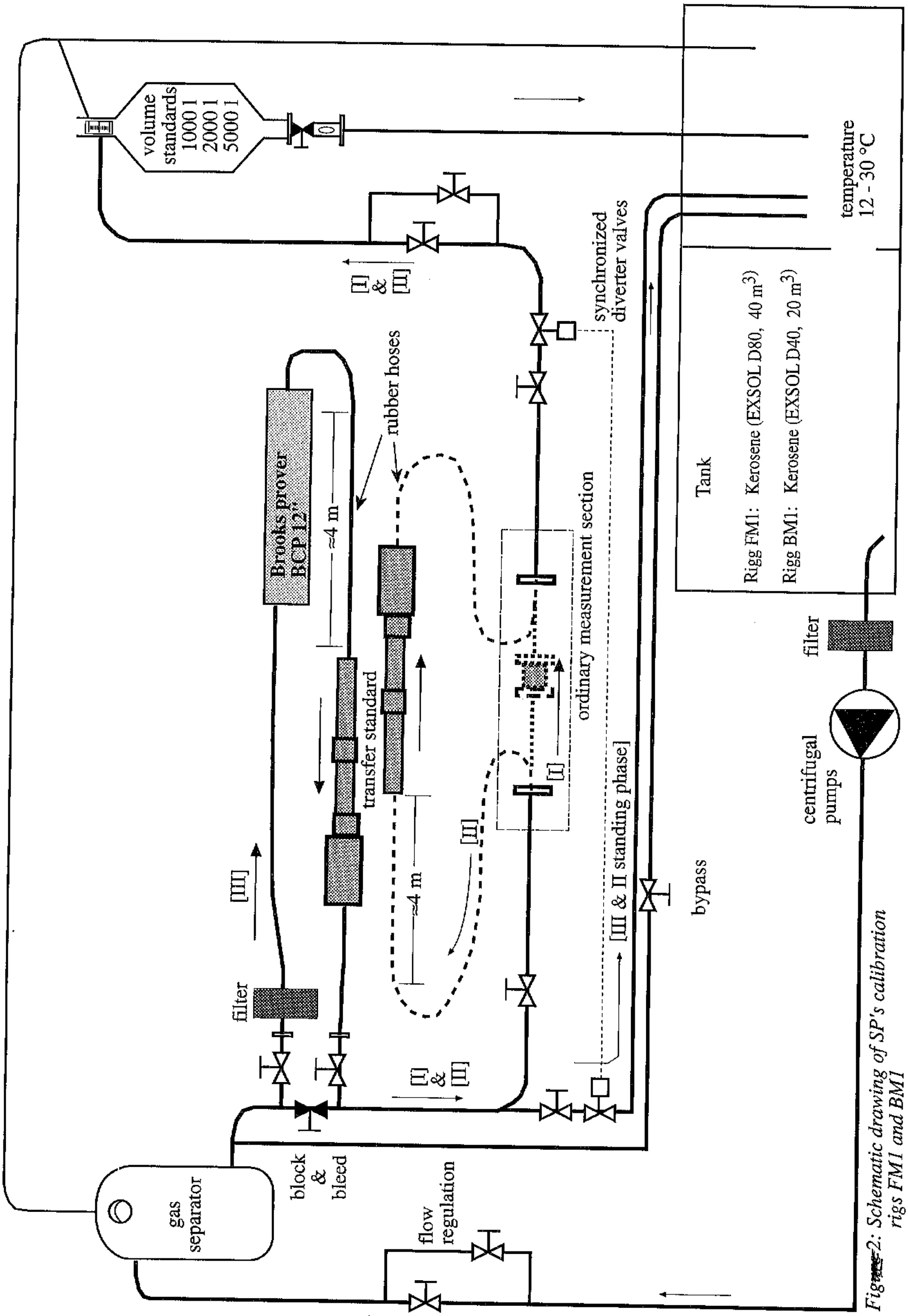
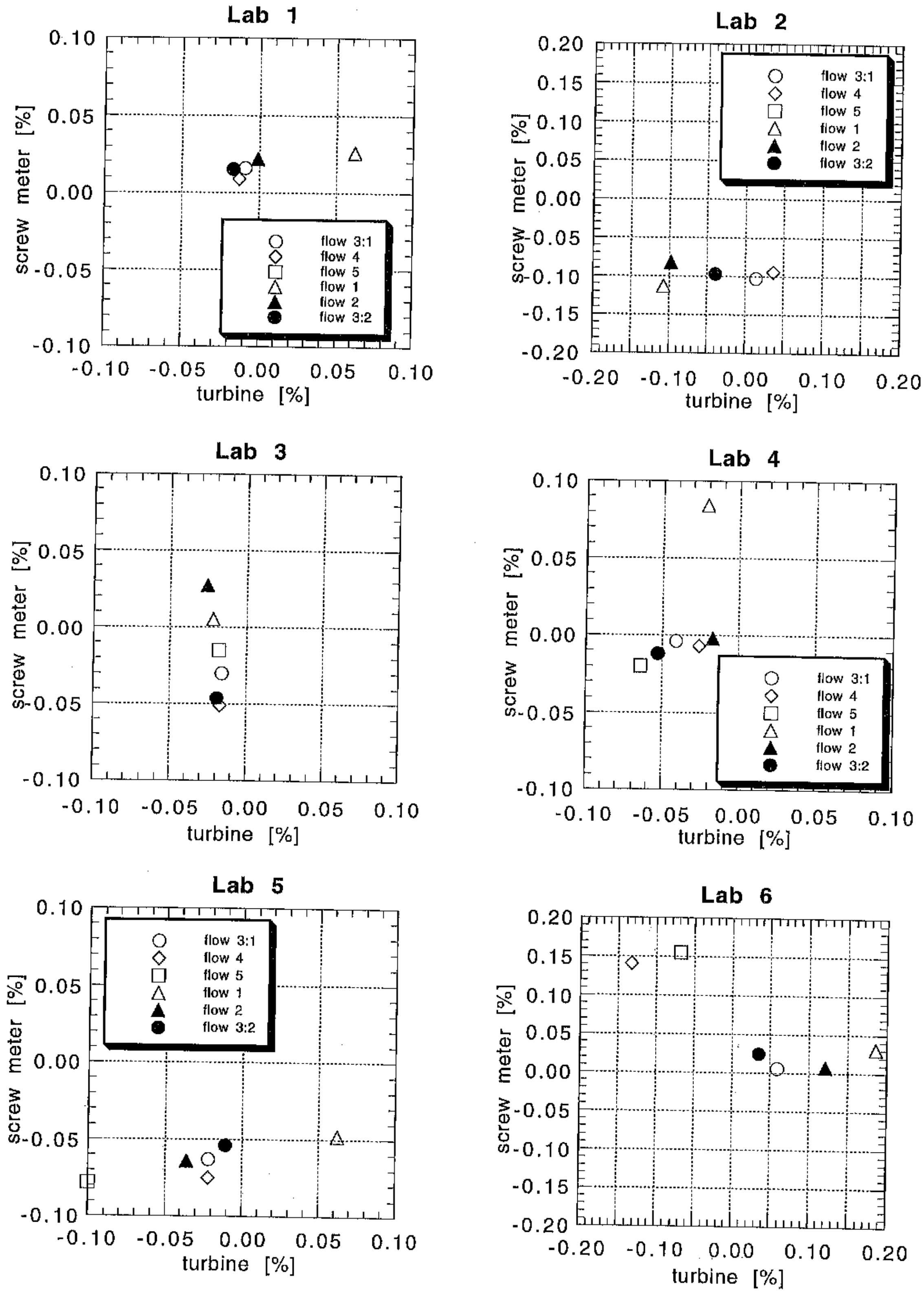


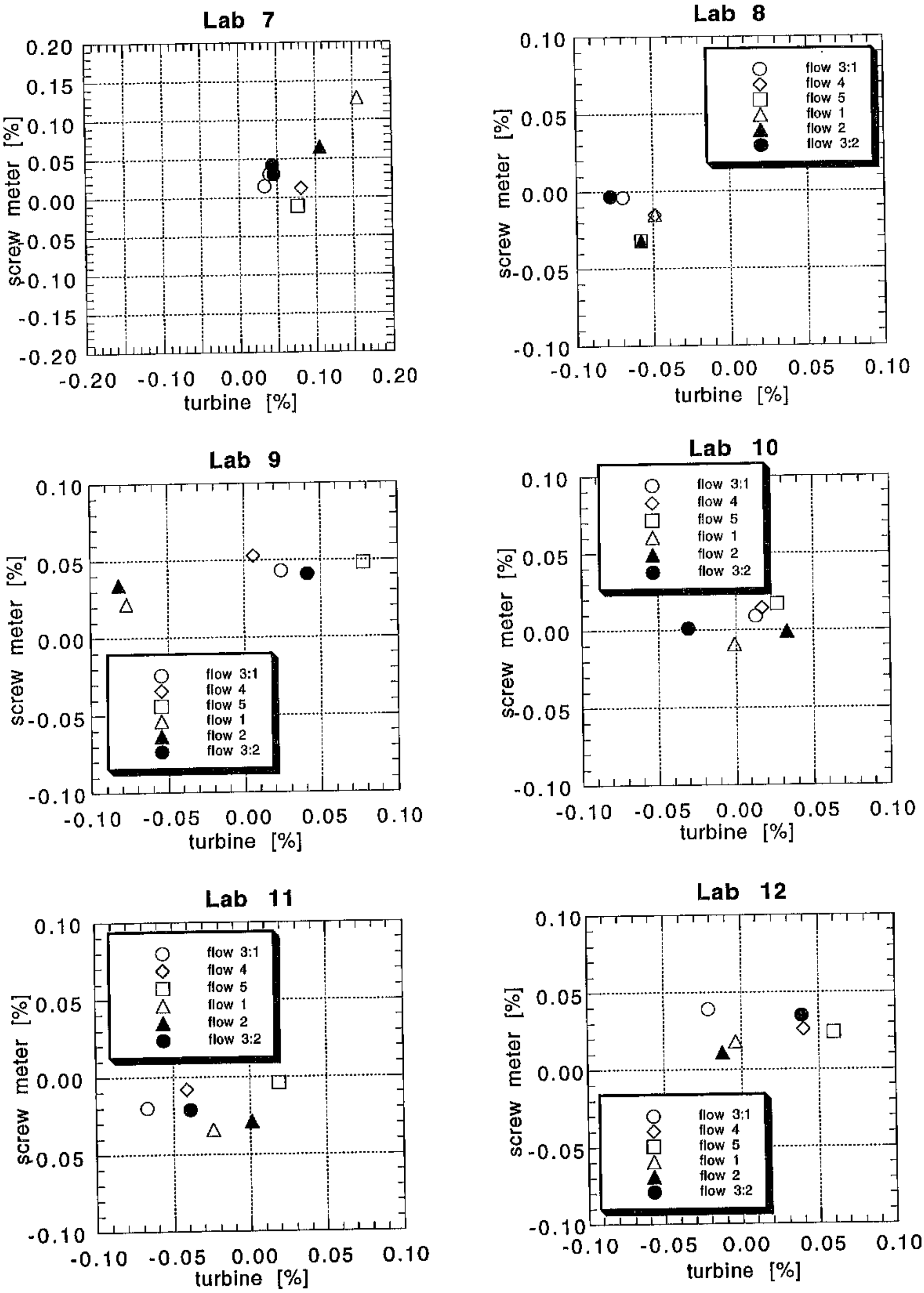
Figure 2: Schematic drawing of SP's calibration rigs FM1 and BM1

Appendix 5 - Cross correlation plots - series 1

Series of cross correlation plots, one for each calibration (laboratory). For each flow rate a symbol indicates the relative position that the corresponding laboratory has with respect, not to a global mean for respective meter, but the best reference (fitted curve) for this flow rate.

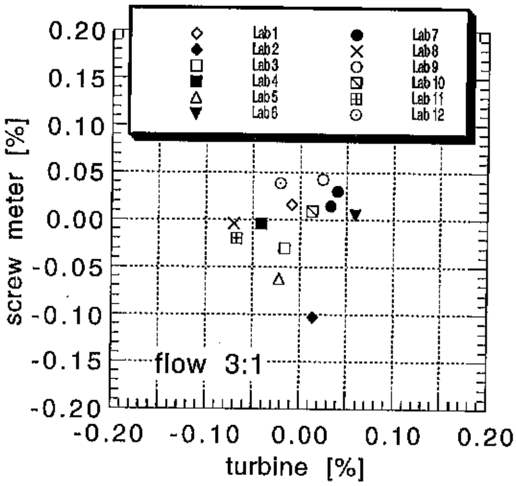


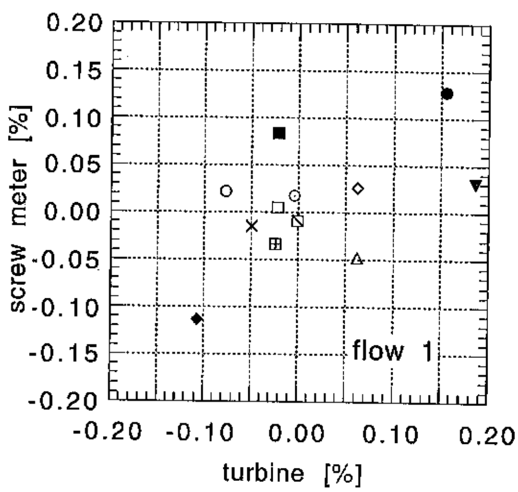
The best choice of flow rate is constructed by using a fitted curve for both meters and calculate the deviation of a k-factor at the actual measured flow rate from the fitted one. In that way the cross correlation plots do not suffer from meter non-linearity. The construction is shown in the following **Fig. A5**.

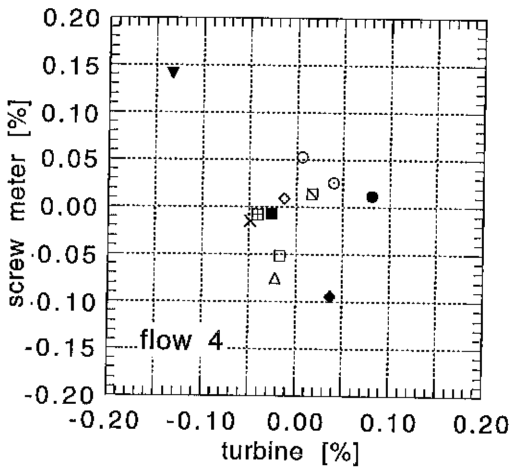


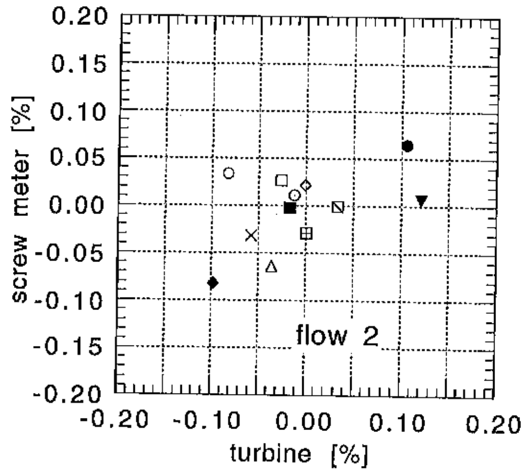
Appendix 5 Cross correlation plots - series 2

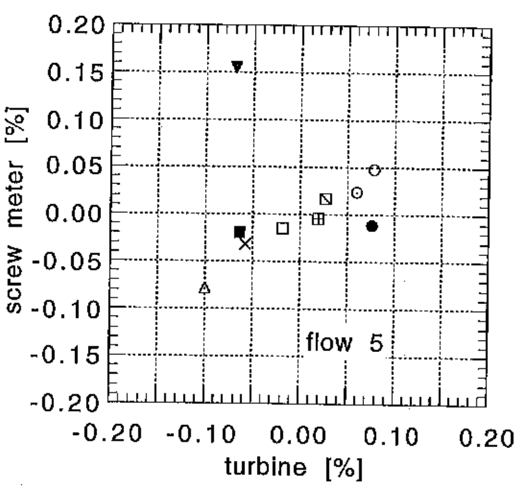
Series of cross correlation plots, one for each flow rate, that collect the deviation of the laboratory results from the best reference. The best reference is constructed according to **Fig. A5.**

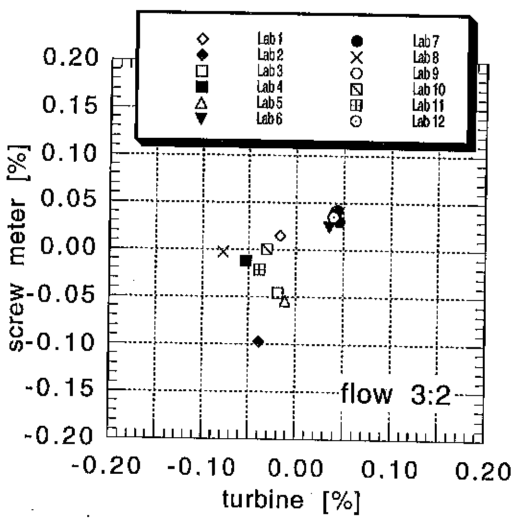












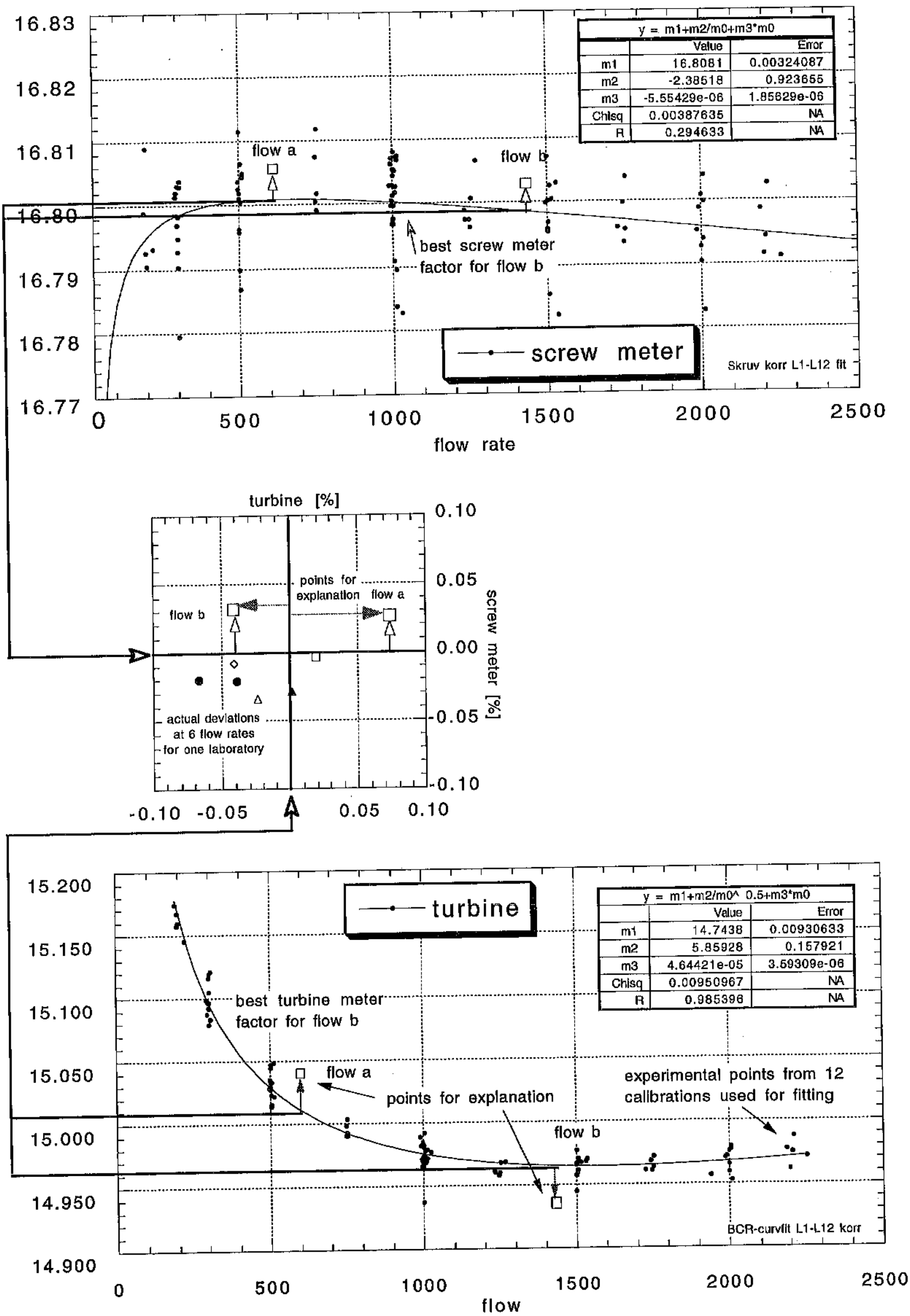
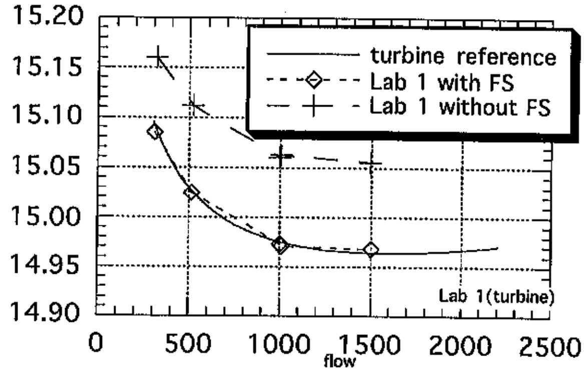
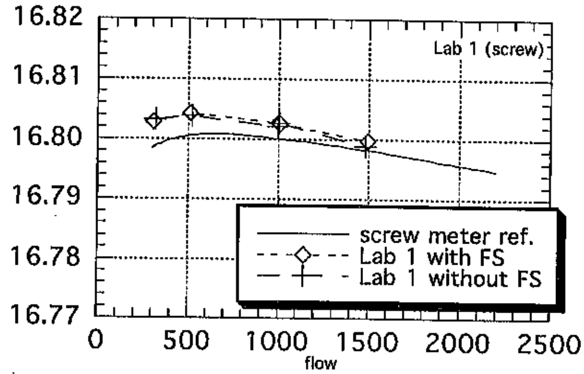
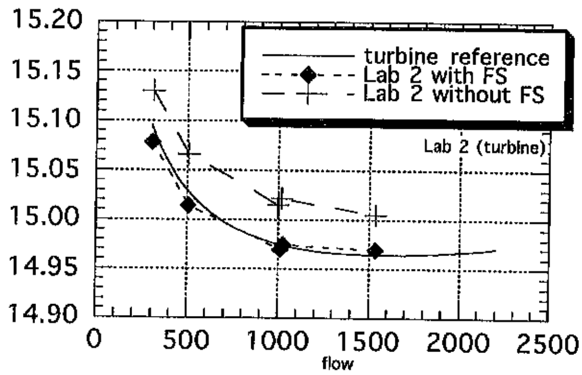


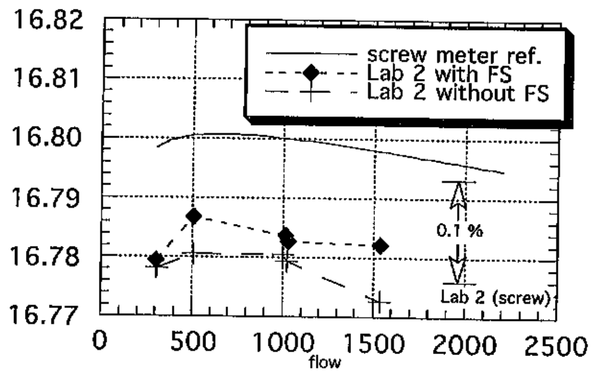
Fig. A5: Construction of best reference value using the fitted curves for both the screw meter and the turbine meter.

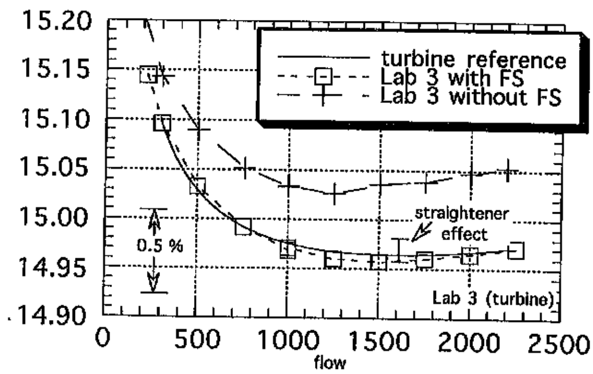
Appendix 6: Individual calibration results (with and without flow straightener) in comparison with the mean curves for the intercomparison. The mean curves are the ones that are fitted to all data from the intercomparison.

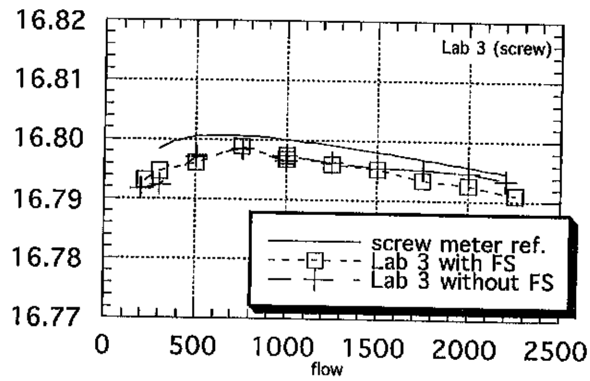


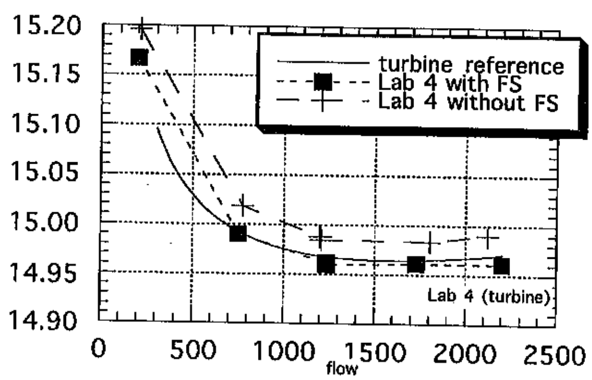


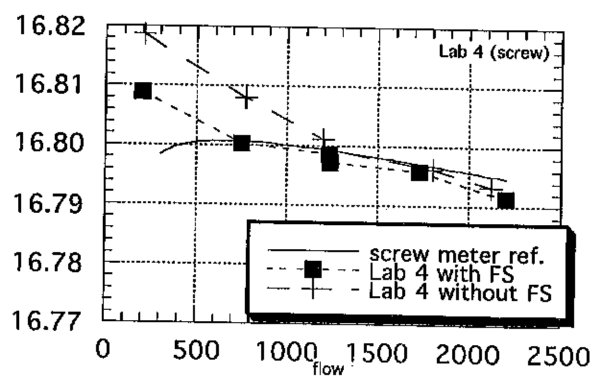


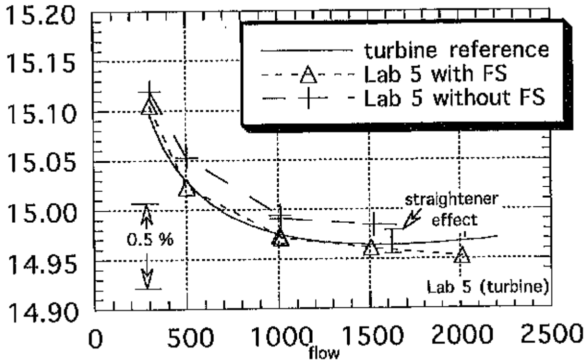


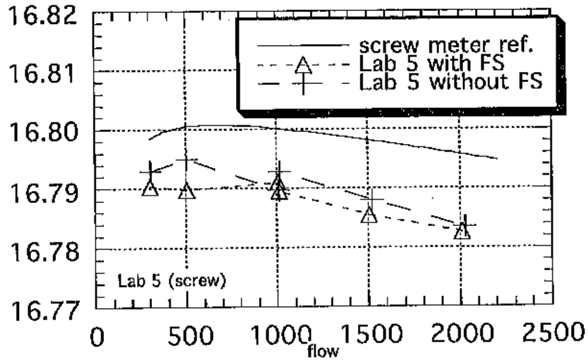


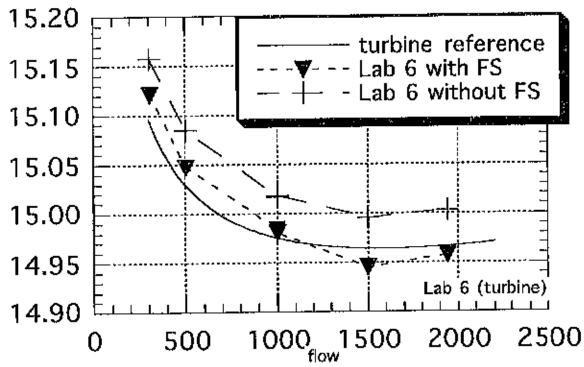


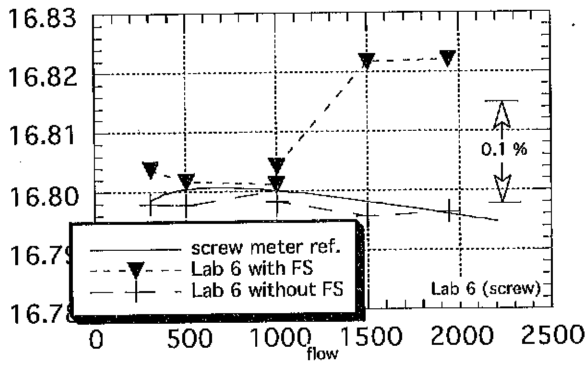


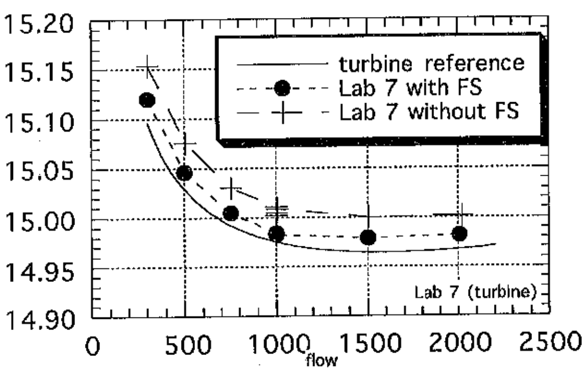


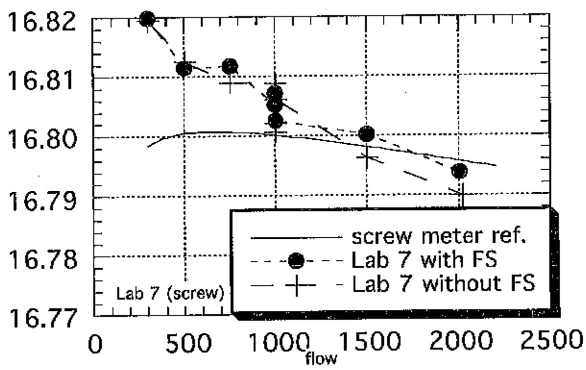

15.20
15.15
15.10
15.05
15.00
14.95
14.90
0
500
1000
1500
2000
2500
flow
turbine reference
Lab 5 with FS
Lab 5 without FS
straightener effect
0.5 %
Lab 5 (turbine)

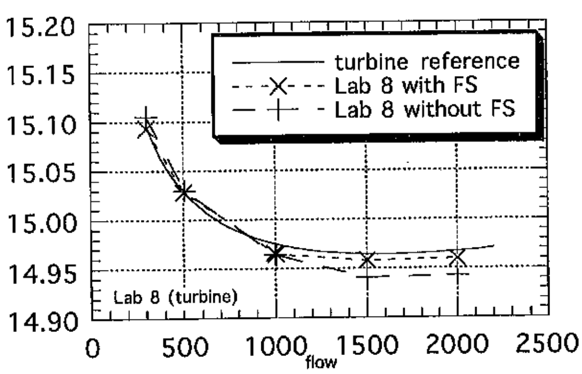

16.82
16.81
16.80
16.79
16.78
16.77
0
500
1000
1500
2000
2500
flow
screw meter ref.
Lab 5 with FS
Lab 5 without FS
Lab 5 (screw)

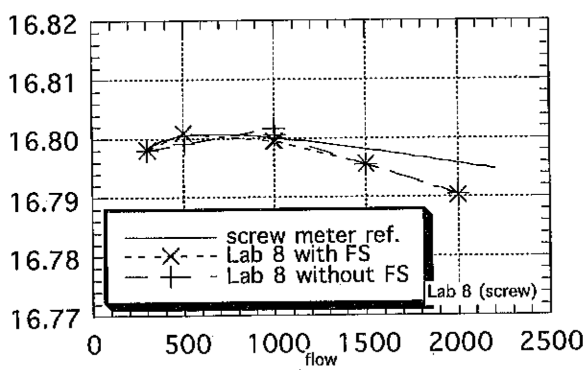

15.20
15.15
15.10
15.05
15.00
14.95
14.90
0
500
1000
1500
2000
2500
flow
turbine reference
Lab 6 with FS
Lab 6 without FS
Lab 6 (turbine)

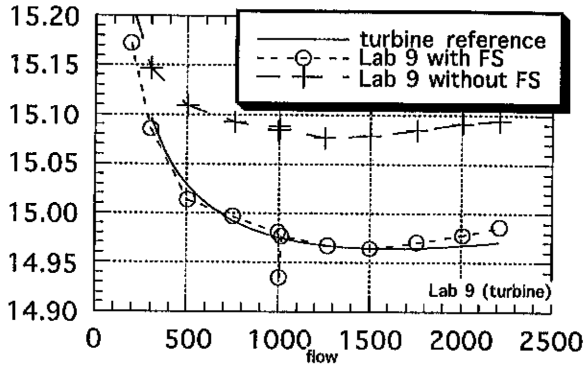

16.83
16.82
16.81
16.80
0
500
1000
1500
2000
2500
flow
0.1 %
screw meter ref.
Lab 6 with FS
Lab 6 without FS
Lab 6 (screw)

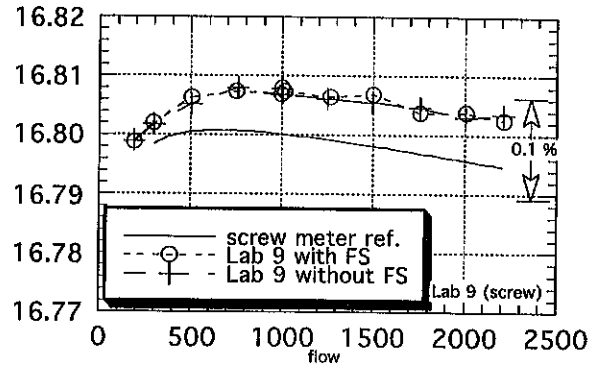

15.20
15.15
15.10
15.05
15.00
14.95
14.90
0
500
1000
1500
2000
2500
flow
turbine reference
Lab 7 with FS
Lab 7 without FS
Lab 7 (turbine)

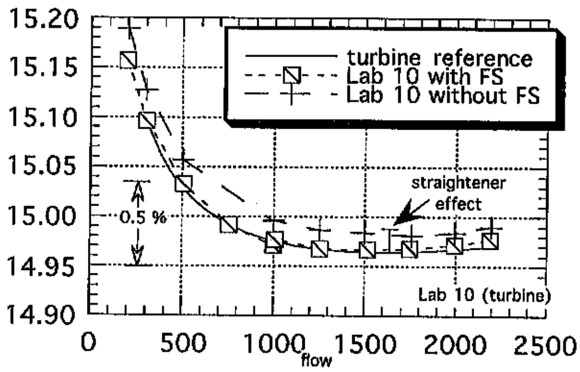

16.82
16.81
16.80
16.79
16.78
16.77
0
500
1000
1500
2000
2500
flow
screw meter ref.
Lab 7 with FS
Lab 7 without FS
Lab 7 (screw)

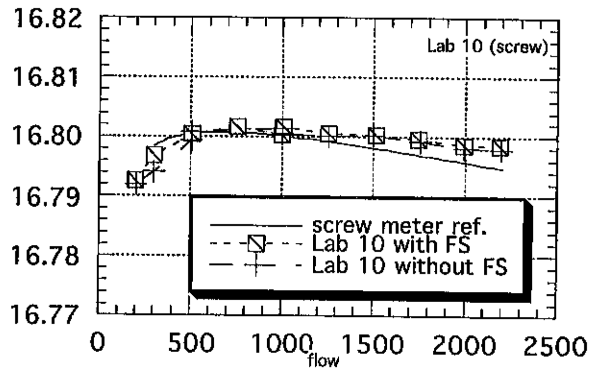

15.20
15.15
15.10
15.05
15.00
14.95
14.90
0
500
1000
1500
2000
2500
flow
turbine reference
Lab 8 with FS
Lab 8 without FS
Lab 8 (turbine)

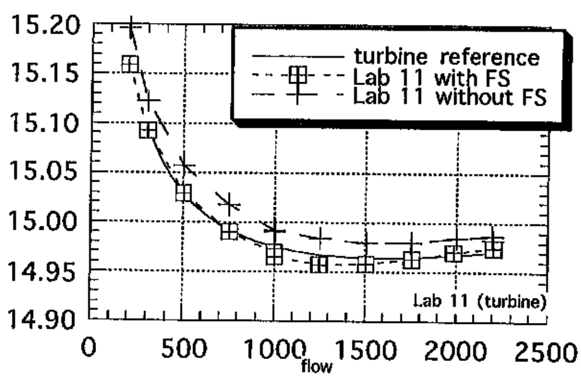

16.82
16.81
16.80
16.79
16.78
16.77
0
500
1000
1500
2000
2500
flow
screw meter ref.
Lab 8 with FS
Lab 8 without FS
Lab 8 (screw)

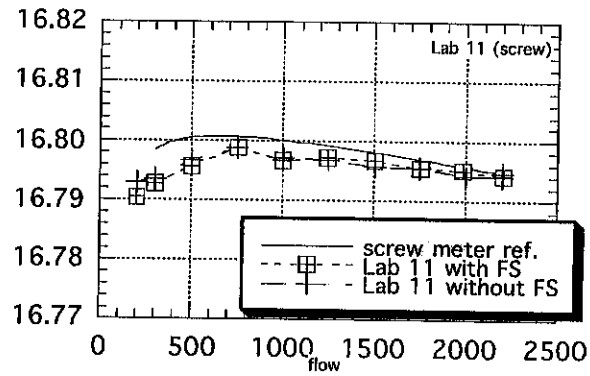

turbine reference
Lab 9 with FS
Lab 9 without FS
Lab 9 (turbine)
15.20
15.15
15.10
15.05
15.00
14.95
14.90
0
500
1000
1500
2000
2500
flow

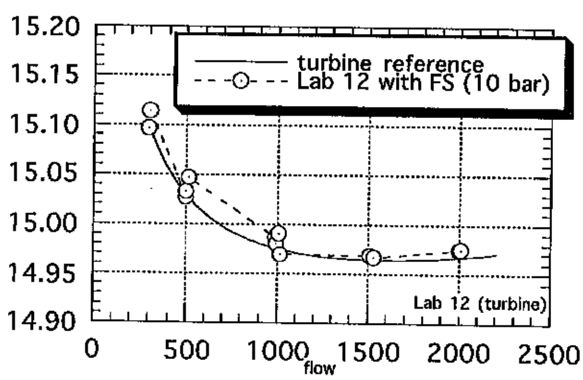

screw meter ref.
Lab 9 with FS
Lab 9 without FS
Lab 9 (screw)
0.1 %
16.82
16.81
16.80
16.79
16.78
16.77
0
500
1000
1500
2000
2500
flow

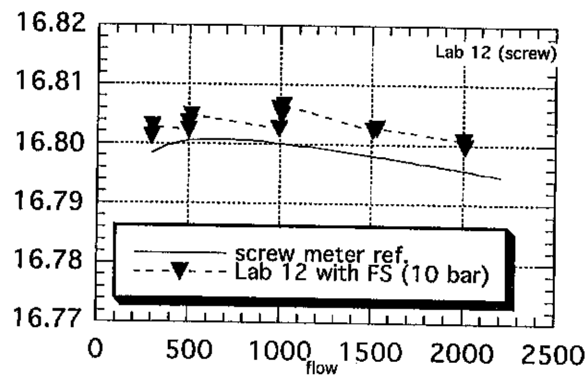

turbine reference
Lab 10 with FS
Lab 10 without FS
straightener
effect
0.5 %
Lab 10 (turbine)
15.20
15.15
15.10
15.05
15.00
14.95
14.90
0
500
1000
1500
2000
2500
flow


Lab 10 (screw)
screw meter ref.
Lab 10 with FS
Lab 10 without FS
16.82
16.81
16.80
16.79
16.78
16.77
0
500
1000
1500
2000
2500
flow


turbine reference
Lab 11 with FS
Lab 11 without FS
Lab 11 (turbine)
15.20
15.15
15.10
15.05
15.00
14.95
14.90
0
500
1000
1500
2000
2500
flow


Lab 11 (screw)
screw meter ref.
Lab 11 with FS
Lab 11 without FS
16.82
16.81
16.80
16.79
16.78
16.77
0
500
1000
1500
2000
2500
flow


turbine reference
Lab 12 with FS (10 bar)
Lab 12 (turbine)
15.20
15.15
15.10
15.05
15.00
14.95
14.90
0
500
1000
1500
2000
2500
flow


Lab 12 (screw)
screw meter ref.
Lab 12 with FS (10 bar)
16.82
16.81
16.80
16.79
16.78
16.77
0
500
1000
1500
2000
2500
flow