DANMARKS OG GRØNLANDS GEOLOGISKE UNDERSØGELSE RAPPORT 2007/11

Routine laboratory measurement of gas permeability in rock samples:

On the possible occurrence of turbulent flow in reservoir chalk samples under standard laboratory conditions

Niels Springer

GEOLOGICAL SURVEY OF DENMARK AND GREENLAND
MINISTRY OF THE ENVIRONMENT

GEUS

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Core Laboratory

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1. Summary

In an e-mail dated 29.11.2006 from Mr. Christian Høier, GEUS Core Laboratory was asked to conduct routine gas permeability measurements on a range of low permeable samples covering the Danian and Maastrichtian chalk reservoirs in the Danish North Sea. The objective was to look for possible turbulent flow conditions that may affect the calculated gas permeability.

Nine chalk samples having model gas permeabilities in the range 1-5 mD were selected from the two reservoir formations and measured for gas permeability at a range of upstrean gas pressures from 100 to 960 [mbarg]; downstream pressure was kept at ambiemt conditions. Klinkenberg corrected gas permeability was measured later at 3 different upstream gas pressures ≥ 2000 [mbarg] using a suitable downstream back pressure. It was found that routine gas permeability varies inversely with the pressure drop across the sample. The difference is 10-20% for differential pressures between 100 and 960 [mbarg]. This is attributed to the Klinkenberg slip effect as no correction for slip is carried out in the calculation of routine gas permeability. Effects due to inertial or turbulent flow are considered unlikely with the present instrument configuration and measurement procedure.

Raw data in an Excel spreadsheet have been forwarded to DONG Energy by e-mail.

2 Sampling and analytical procedures

2.1 Sample material

Nine plug samples, 4 from the Danian and 5 from the Maastrichtian chalk were selected from old released wells, table 1. The samples had previously been analyzed for porosity and gas permeability. The samples were re-cleaned in methanol, trimmed and dried at 110 ˚C before analysis.

2.2 Experimental programme

The objective was to search for deviations in the measured gas permeability as a function of varying upstream gas pressure, given ambient (atmospheric) downstream pressure conditions. Traditionally the gas permeability for low permeability core material has been measured at GEUS Core Laboratory using an upstream pressure (= differential pressure) of 960 [mbarg]. An experimental design was agreed covering the following 9 upstream pressure steps:

100, 200, 300, 400, 500, 600, 700, 800 and 960 [mbarg]

The laboratory was later asked to measure Klinkenberg corrected gas permeability on the same set of plugs. Three readings are taken at upstream pressures of:

2000, 4000 and 7000 [mbarg]

and the back pressure regulated to obtain a differential pressure of ~ 300 [mbarg] at all three pressure steps. The Klinkenberg corrected gas permeability then appears from a regression analysis of measured gas permeability vs. the reciprocal mean gas pressure.

Confining radial sleeve stress in the core holder was set at 27 [barg], and temperature was approx. 23 ˚C in the air conditioned laboratory. A massive steel plug was initially placed in the core holder to test for gas leaks in the upstream line of the gas permeameter. No leaks were observed. To minimize experimental scatter it was attempted to use the same mass flowmeter for all measurements recorded on the same plug sample. It was inevitable that a few flow readings fell slightly outside the linear range for the subject flowmeter, ref. table 1. A calibration check had to be carried out for flowmeter 1, and the new set of constants was applied to all measured data.

3 Analytical Methods

The following is a short description of the methods used by GEUS Core Laboratory. For a more detailed description of methods, instrumentation and principles of calculation the reader is referred to API recommended practice for core-analysis procedure (API RP 40, 2nd ed. 1998).

4.1 Gas permeability

The plug is mounted in a Hassler core holder, and a confining pressure of 27 [barg] applied to the sleeve. The specific permeability to gas is measured by flowing nitrogen gas through a plug of known dimensions at differential pressures between 0 and 1 [barg]. No back pressure is applied. The readings of the digital gas permeameter are checked regularly by measurement of permeable steel reference plugs.

QC check: As a calibration check, two porous and permeable steel reference plugs from Core Laboratories® were measured during this study and data found to compare well with the figure given by Core Laboratories® :

Plug no.	**kg std [mD]**	**kg meas [mD] ***
625A	**3.17**	3.34
625B	**6.64**	6.44

* measured by GEUS Core Laboratory using a dif. P of 300-400 [mbarg]

4.2 Klinkenberg permeability

The Klinkenberg corrected gas permeability, sometimes termed the equivalent liquid permeability, is calculated from gas permeability measurements performed at 3 different mean pressures in the plug sample. The plug is mounted in a Hassler core holder, and a confining pressure of 27 [barg] is applied to the sleeve. Nitrogen gas pressures of 2, 4 and 7 [barg] (3, 5 and 8 [bara]) are applied at the upstream end of the plug, and the downstream pressure is regulated until a suitable flow is obtained. The differential pressure is kept approx. constant in order to maintain a similar flow regime during the 3 measurements. When a steady state is reached, the upstream pressure, the differential pressure across the plug and the flow reading is recorded. A linear regression of permeability on inverse mean pressure is performed for the 3 measurements, and the intercept on the permeability axis is the Klinkenberg corrected gas permeability.

Klinkenberg corrected gas permeabilities are only reported down to approx. 0.1 mD on normal routine terms. However, on request measurements can be carried out to a lower limit of 0.01 mD. The performance of the digital gas permeameter is checked regularly by measurements of permeable steel reference plugs.

Instrumental: GEUS digital gas permeameter M 1989 is a steady-state instrument using nitrogen as the measuring gas. It is designed and built by the laboratory. The instrument is equipped with Druck Ltd.® pressure transducer and Brooks Instruments® thermal mass flowmeters; for all flowrates a facility exist to measure gas flow downstream with a range of soap film flowmeters. This is used for calibration purpose or whenever the present flow rate is outside the limits of the thermal mass flowmeters. Each mass flowmeter has a dynamic range of approx. 30 and the output is given in mV. Readings are normally confined to the linear part of the calibration curve within 200 – 6000 mV. Zero offset is corrected for. The net mV-reading is converted to a flow reading in ml/s from the relevant flowmeter calibration found in the laboratory calculation and database program "WinPOPE".

4 Results

4.1 Gas and Klinkenberg permeability data

Conventional gas perm data are shown in table 1. All samples were measured in the direction of decreasing upstream pressure, ie. 960 > 800 > … > 100 [mbarg]. Sample T227 was re-measured at a later date (by the same operator) under increasing upstream pressure (100 > 960 [mbarg]) to check for reproducibility. It was difficult to reproduce data for sample A84E between different days probably due to a partly open micro stylolite in one plug end. Klinkenberg corrected gas perm data are presented in table 2. A conventional reading at 960 [mbarg] is also taken during Klinkenberg measurements; a direct comparison with the earlier measured 960 [mbarg] data to assess the reproducibility of the gas perm data is therefore possible, cf. tables 1 and 2. A visual presentation of measured gas permeability data vs. the reciprocal mean pressure for each plug sample is given in the diagrams below.

4.2 Fluid flow theory

In the mid nineteenth century Darcy established an empirical relationship for fluid flow in porous media stating that the volumetric flowrate per unit cross-sectional area is direct proportional to the potential gradient, ie. displays a linear trend in figure 1 below. Later Forchheimer showed that Darcy's law was not valid at high flowrates and he introduced the concept of inertial resistance to explain the deviation from linearity as illustrated by the orange curve in the diagram below (turbulent flow). In the mid twentieth century Klinkenberg observed that even when inertial effects was accounted for, gas permeability depends on gas pressure. He introduced the concept of slippage and showed that gas permeability k_g calculated from Darcy's or Forchheimer's equations was higher than obtained using a liquid. Klinkenberg showed that a slip corrected gas permeability k_∞, equivalent to a liquid permeability, could be obtained from the expression:

$$k_g = k_\infty \left(1 + \frac{b}{P}\right)$$

b is the Klinkenberg slip factor, and
P is the absolute gas pressure

By conducting a number of gas permeability measurements at different mean pore pressures P_m the Klinkenberg corrected gas permeability k_∞ can be obtained from a regression analysis of k_g vs. $1/P_m$, ref. the section on permeability in API RP 40 (1998).

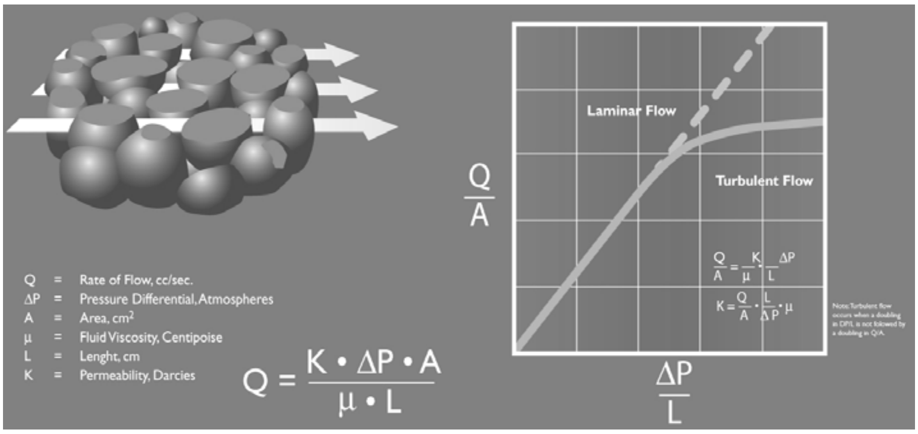

Figure 1. Darcy's equation for non-reactive liquid flow through porous media. At high flow rates inertial and turbulence effects cause the flux vs. pressure gradient to deviate from a linear trend.

Credits: Core Laboratories® Fundamentals of core analysis, 1984.

4.3 Observations

The gas permeabilities measured in this study at upstream pressures between 100 and 960 [mbarg] are conventional steady-state axial nitrogen gas permeabilities calculated without Klinkenberg (slip) correction. It is believed that the gas flux is kept so low that the inertial resistance term in Forchheimer's equation can be neglected and the Darcy equation therefore be applied in calculation of the gas permeability. Measurements at elevated mean gas pressures between ~ 2000 and 7000 [mbarg] have been Klinkenberg (slip) corrected according to the equation given above, and data have been plotted in scatter diagrams with accompanying regression line and regression constants.

Also shown in the Klinkenberg scatter diagrams are the uncorrected gas permeabilities measured at upstream (=differential) pressures between 100 and 960 [mbarg]. It is observed that the uncorrected gas permeabilities plot closely along the extension of the Klinkenberg regression line and that no systematic deviation is observed that could be attributed to inertial or turbulent flow conditions. The pressure dependance observed for the uncorrected gas permeabilities in table 1 can therefore be explained solely as due to the Klinkenberg gas slippage effect.

4.4 Reference and abbreviations

API RP 40, Recommended Practice for Core Analysis, second edition. 1998.
Washington DC: American Petroleum Institute.

[barg] = bar gauge; to obtain the absolute pressure add the atmospheric pressure.
[bara] = bar absolute.

k_g = uncorrected gas (nitrogen) permeability
$k_\infty = k_{el}$ = slip corrected gas permeability = equivalent liquid permeability also termed Klinkenberg corrected gas permeability

Table 1. List of plug samples and routine gas permeabilities measured for the selected plugs. Plug no. T227 was measured twice at decreasing and increasing upstream gas pressure to check the reproducibility. Plug no. A84E was also measured twice but returned a poor reproducibility probably due to fracturing.

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Chalk unit: Danian and Maastrichtian
Routine gas permeability data k_g @ 27 bar confining stress

GEUS Core Laboratory
Date: 02/2007

Formation	Well no.	Plug no.	depth	Ø$_{He}$ [%]	k_g [mD] @ spec. differential N_2 pressure									Comment
			feet		960 mb	800 mb	700 mb	600 mb	500 mb	400 mb	300 mb	200 mb	100 mb	
Danian	**Anne-3**	**A19E**		27.7	1.68	1.69	1.70	1.72	1.74	1.74	1.78	1.78	1.77	
	M-10X	**007E**	6347	35.0	1.42	1.45	1.48	1.50	1.52	1.55	1.57	1.62	1.69	
	Anne-3	**A10E**	6194	36.4	2.04	2.08	2.08	2.11	2.14	2.15	2.21	2.26	2.26	
	TWC-2	**T227**	7549	~ 42	+ 4.15	4.27	4.32	4.40	4.49	4.53	4.63	4.67	4.79	→ decreasing dP
	TWC-2	**T227**	7549	~ 42	+ 4.12	4.25	4.33	4.41	4.46	4.56	4.63	4.66	4.82	← increasing dP
Maastrichtian	**Nana-1XP**	**10**	7144	23.5	0.92	0.94	0.95	0.97	0.99	1.01	1.05	1.08	1.17	
	M-10X	**281E**	6626	26.1	1.35	1.39	1.40	1.40	1.44	1.47	1.50	1.53	1.54	
	M-10X	**241E**	6586	30.2	2.36	2.42	2.45	2.48	2.51	2.54	2.56	2.58	2.63	
	M-10X	**291E**	6636	32.6	3.50	3.53	3.57	3.61	3.66	3.70	3.80	3.81	* 4.09	
	Anne-3	**A84E**	6377	32.7	7.96	8.02	8.00	8.03	8.09	8.15	8.21	8.24	* 8.41	
	Anne-3	**A84E**	6377	32.7	6.25	6.23	6.35	6.47	6.65	6.73	6.87	7.07	* 7.24	

Re-measured during Klinkenberg gas perm.

\+ slightly above linear range for flm. 1

* below linear range for flm. 2

Table 2. Klinkenberg corrected gas permeability data for the same set of plugs measured at another day by the same operator. A repeat routine gas permeability at ~ 960 [mbarg] upstream pressure is listed as well.

DONG Energy: Turbulence study

Req. no.: 09201-558

Chalk unit: Danian and Maastrichtian
Klinkenberg corrected gas permeability data k_{el} @ 27 bar confining stress

GEUS Core Laboratory
Date: 02/2007

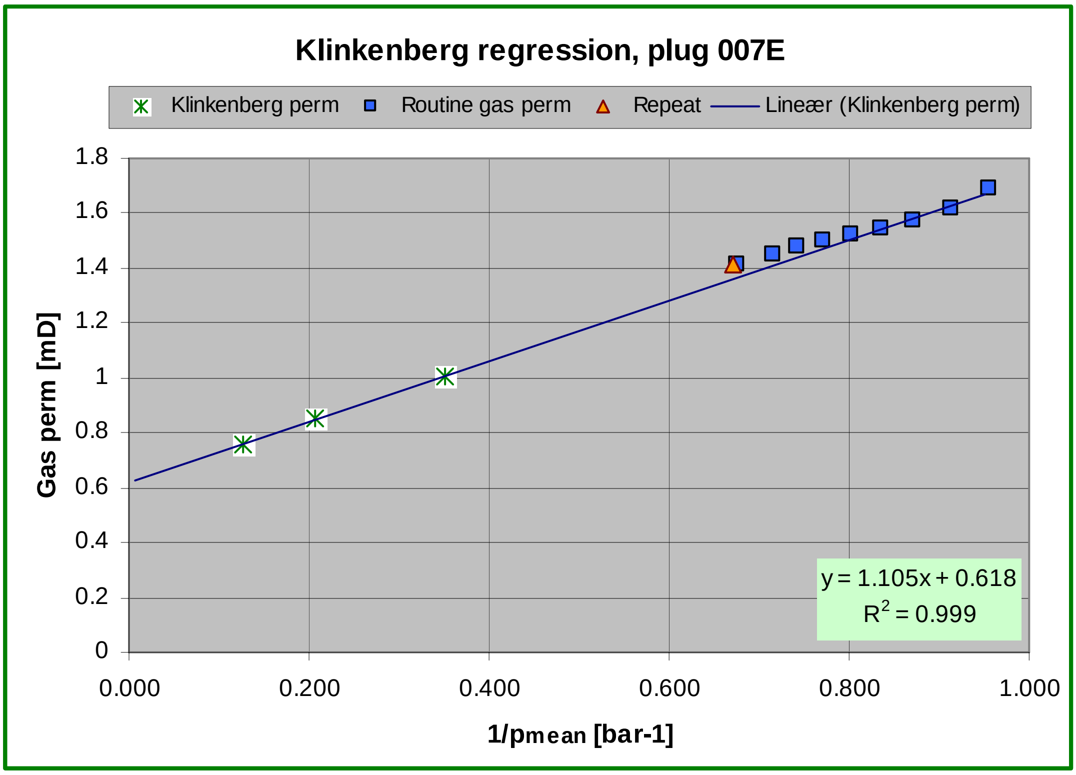
Formation	Well no.	Plug no.	depth	ØHe [%]	k_g [mD] @ spec. upstream gauge pressure				k_{el} [mD]	Corr. coef.	b [bar]
			feet		960 mb *	2000 mb	4000 mb	7000 mb	**	**	**
Danian	**Anne-3**	**A19E**		27.7	1.57	1.17	1.02	0.92	0.78	0.9989	1.43
	M-10X	**007E**	6347	35.0	1.41	1.00	0.85	0.76	0.62	0.9996	1.79
	Anne-3	**A10E**	6194	36.4	1.98	1.51	1.32	1.21	1.04	0.9996	1.30
	TWC-2	**T227**	7549	~ 42	4.11	3.30	2.99	2.59	2.26	0.9698	1.36
Maastrichtian	**Nana-1XP**	**10**	7144	23.5	0.90	0.64	0.55	0.49	0.41	0.9960	1.69
	M-10X	**281E**	6626	26.1	1.35	1.00	0.86	0.79	0.67	0.9999	1.41
	M-10X	**241E**	6586	30.2	2.29	1.77	1.57	1.42	1.24	0.9972	1.24
	M-10X	**291E**	6636	32.6	3.18	2.65	2.33	2.12	1.83	0.9985	1.29
	Anne-3	**A84E**	6377	32.7	6.39	5.75	5.21	4.71	4.18	0.9896	1.10

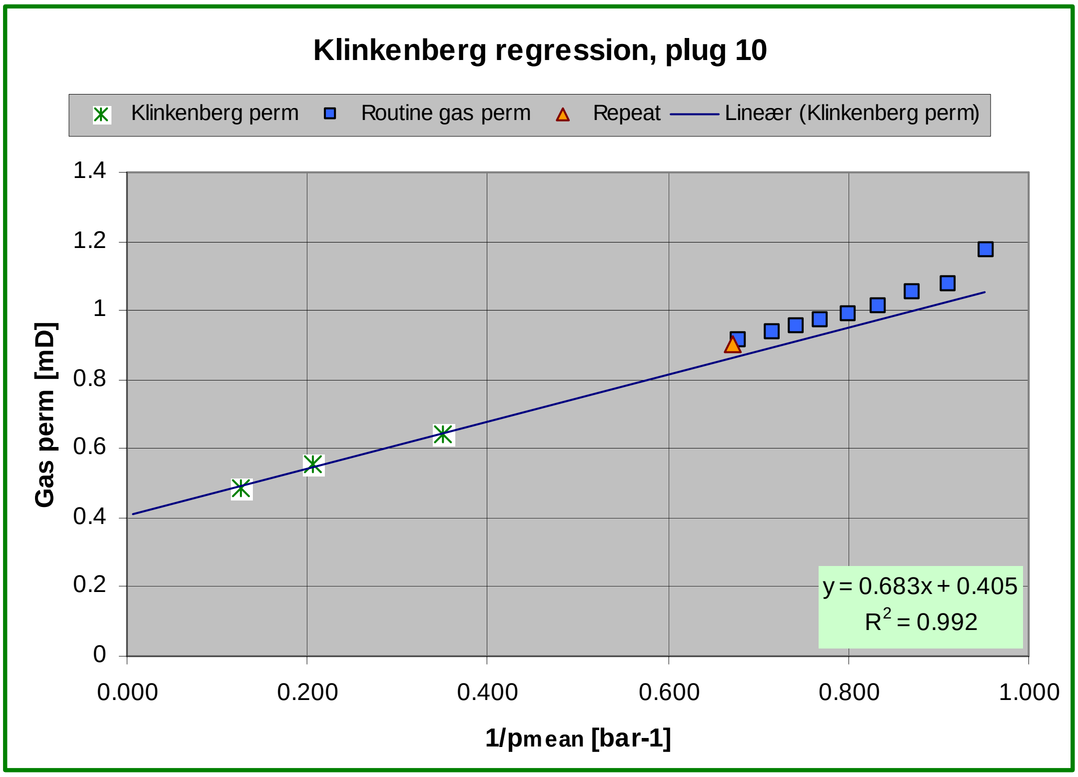
Notice:

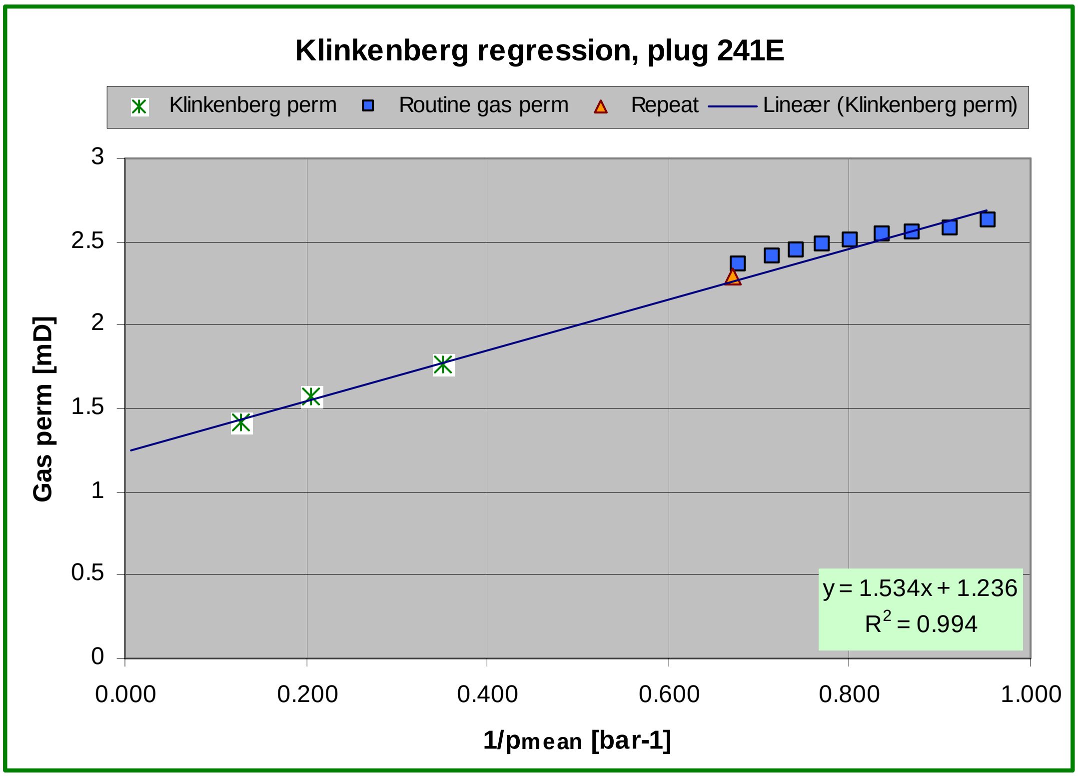
* A conventional gas perm is routinely measured @ 960 mbar upstream P during Klinkenberg gas permeability measurement; this figure should conform with the previous measured result for the subject plug, listed in the sub-sheet 'Gas perm'

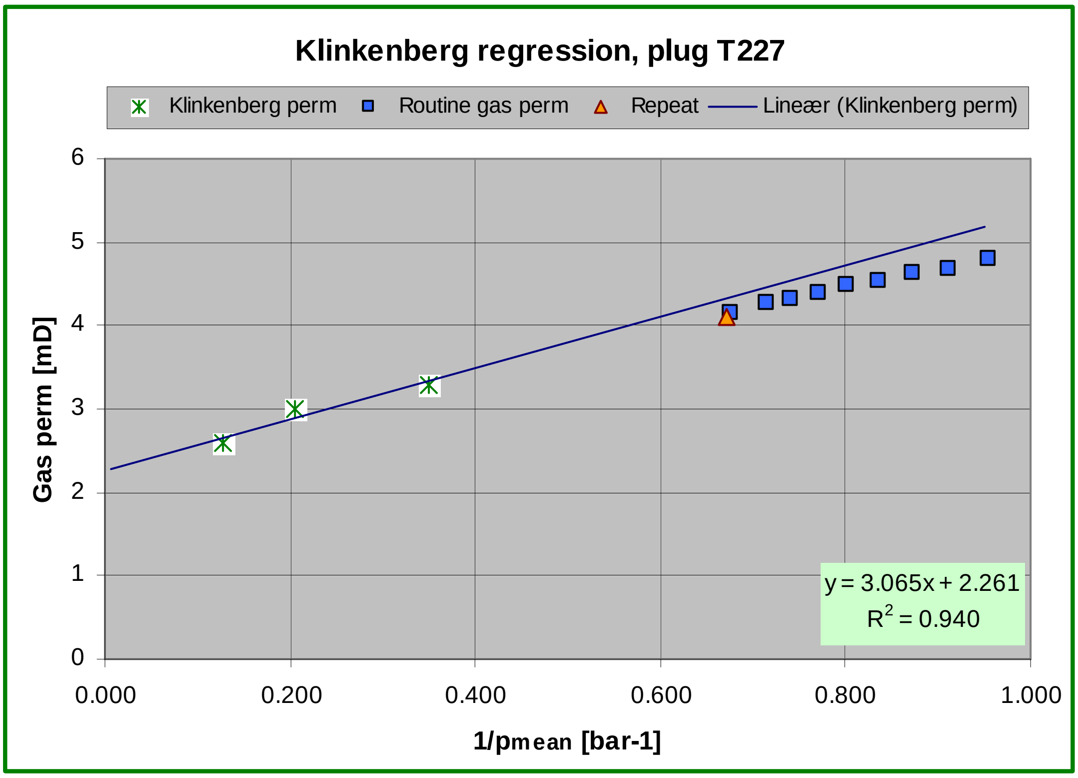
** Klink regression is solely based on 2, 4 and 7 bar (g) upstream P measurements. 'b' is the Klinkenberg gas slippage factor

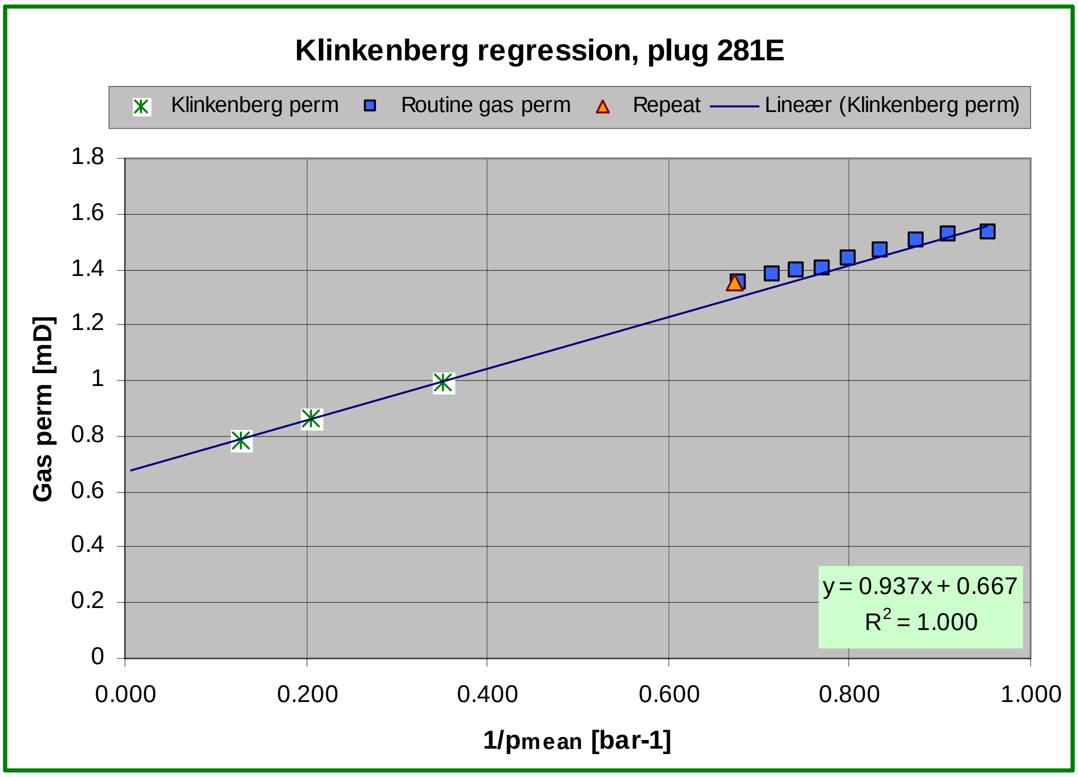
During Klinkenberg corrected permeability measurement, a differential pressure of ~ 300 mbar was used for all plugs and at all pressure steps

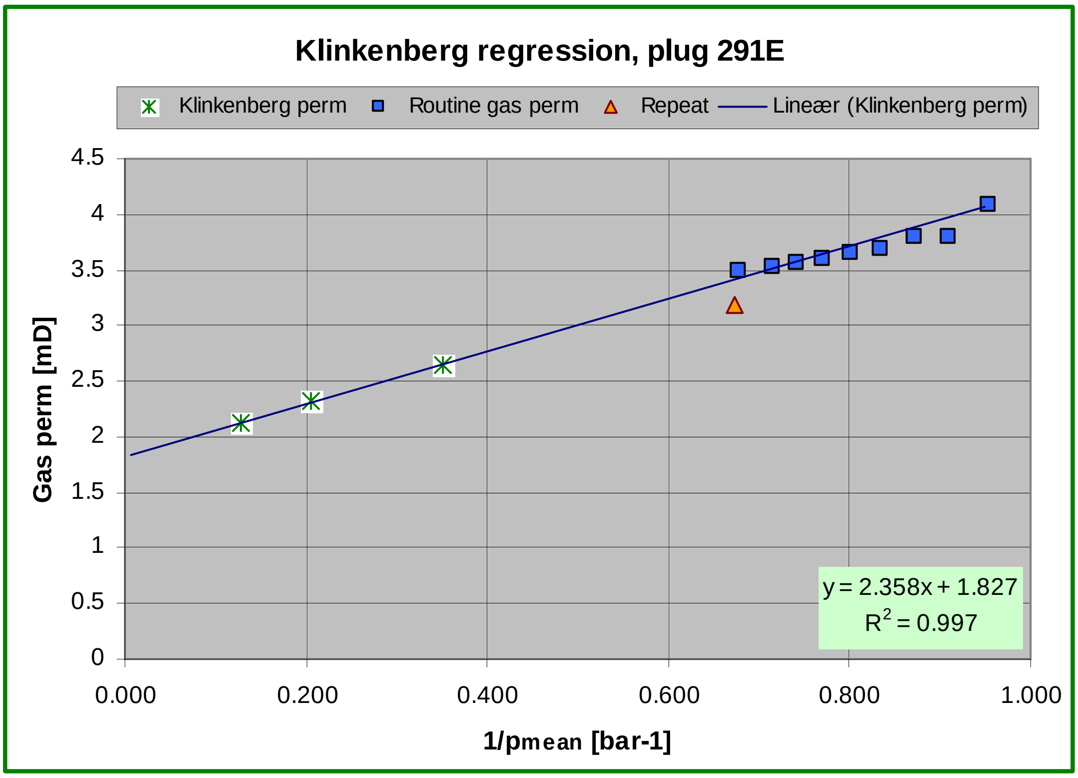

Klinkenberg regression, plug 007E
Klinkenberg perm
Routine gas perm
Repeat
Lineær (Klinkenberg perm)
Gas perm [mD]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.000
0.200
0.400
0.600
0.800
1.000
1/pmean [bar-1]
y = 1.105x + 0.618
R2 = 0.999

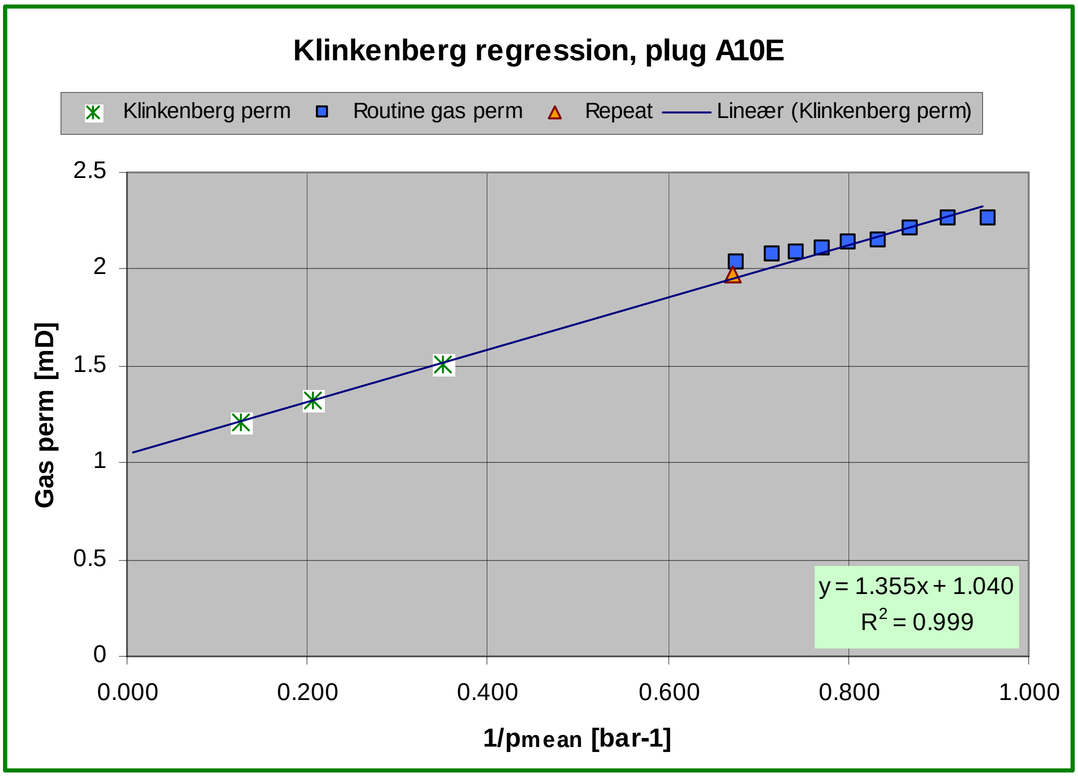

Klinkenberg regression, plug 10
Klinkenberg perm
Routine gas perm
Repeat
Lineær (Klinkenberg perm)
Gas perm [mD]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.000
0.200
0.400
0.600
0.800
1.000
1/pmean [bar-1]
y = 0.683x + 0.405
R2 = 0.992

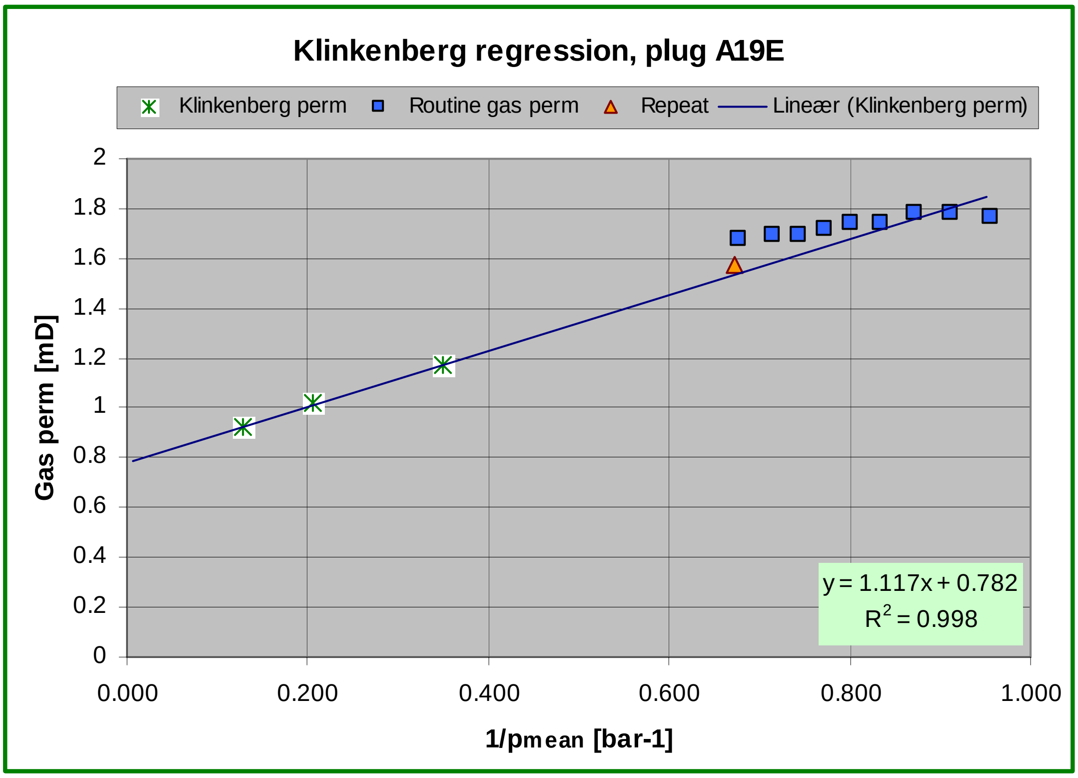

Klinkenberg regression, plug 241E
Klinkenberg perm
Routine gas perm
Repeat
Lineær (Klinkenberg perm)
Gas perm [mD]
3
2.5
2
1.5
1
0.5
0
0.000
0.200
0.400
0.600
0.800
1.000
1/pmean [bar-1]
y = 1.534x + 1.236
R2 = 0.994


Klinkenberg regression, plug T227
Klinkenberg perm
Routine gas perm
Repeat
Lineær (Klinkenberg perm)
Gas perm [mD]
6
5
4
3
2
1
0
0.000
0.200
0.400
0.600
0.800
1.000
1/pmean [bar-1]
y = 3.065x + 2.261
R2 = 0.940


Klinkenberg regression, plug 281E
Klinkenberg perm
Routine gas perm
Repeat
Lineær (Klinkenberg perm)
Gas perm [mD]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.000
0.200
0.400
0.600
0.800
1.000
1/pmean [bar-1]
y = 0.937x + 0.667
R2 = 1.000


Klinkenberg regression, plug 291E
Klinkenberg perm
Routine gas perm
Repeat
Lineær (Klinkenberg perm)
Gas perm [mD]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
0.000
0.200
0.400
0.600
0.800
1.000
1/pmean [bar-1]
y = 2.358x + 1.827
R2 = 0.997


Klinkenberg regression, plug A10E
Klinkenberg perm
Routine gas perm
Repeat
Lineær (Klinkenberg perm)
Gas perm [mD]
2.5
2
1.5
1
0.5
0
0.000
0.200
0.400
0.600
0.800
1.000
1/pmean [bar-1]
y = 1.355x + 1.040
R2 = 0.999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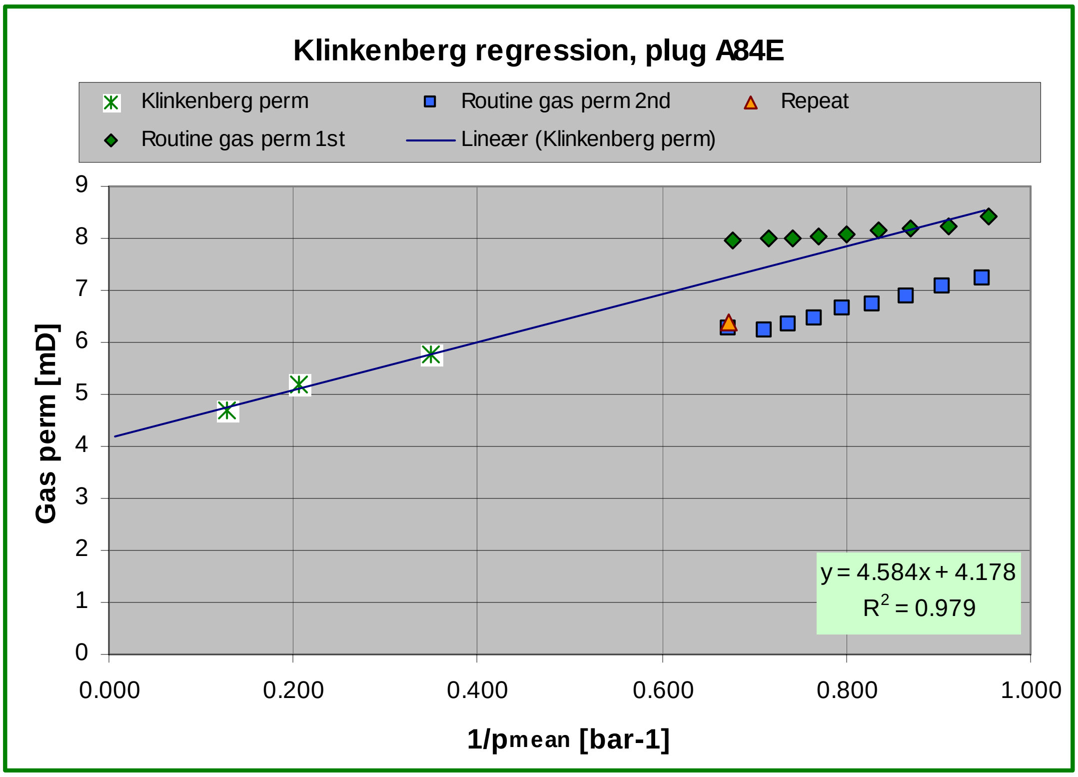
Klinkenberg perm
Routine gas perm
Repeat
Lineær (Klinkenberg perm)
Gas perm [mD]
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.000
0.200
0.400
0.600
0.800
1.000
1/pmean [bar-1]
y = 1.117x + 0.782
R2 = 0.998


Klinkenberg regression, plug A84E
Klinkenberg perm
Routine gas perm 2nd
Repeat
Routine gas perm 1st
Lineær (Klinkenberg perm)
Gas perm [mD]
0
1
2
3
4
5
6
7
8
9
0.000
0.200
0.400
0.600
0.800
1.000
1/pmean [bar-1]
y = 4.584x + 4.178
R2 = 0.979