KLINKENBERG PERMEABILITY MEASUREMENTS: PROBLEMS AND PRACTICAL SOLUTIONS

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Abstract Conventionally-derived Klinkenberg parameters, obtained on core plugs over a wide range of permeabilities, are shown to be sensitive to the methods, procedures and techniques used to acquire and analyze the data. Practical recommendations are presented which, simply applied, can overcome or minimize many of these experimental problems, and yield more reliable and realistic data. The importance of selecting test flow procedures, optimizing process sensor accuracy, standardizing sleeve and net effective core pressures, and recognizing and correcting data for the effects of non-Darcy flow, are demonstrated. Although concentrating on the practical problems, this study does reveal some limited evidence which questions a fundamental tenet of gas slippage theory related to porous media and its applicability in Klinkenberg permeability determination.

INTRODUCTION

Klinkenberg (1941), in his definitive paper, showed that by taking several measurements of gas permeability over a range of pore pressures and extrapolating the regressed data to infinite mean pressure, the core permeability to an *inert* liquid, k_∞ , could be predicted within "experimental error". Since Klinkenberg permeability data might be obtained relatively simply, some analysts contend that this might obviate the need for more protracted permeability measurements using reservoir fluids at ambient or reservoir conditions. Representative Klinkenberg data are also used to develop transforms which might predict inert liquid permeability from single-point gas permeability measurements.

Unfortunately, since Klinkenberg's work, analysts have tended to place their own interpretation on how best to acquire reliable and repeatable Klinkenberg data. The evidence presented here illustrates that derived Klinkenberg parameters are extremely sensitive to the test methods and procedures used to acquire and analyze the data. We will suggest practical recommendations to overcome some of these problems, and which should establish a route towards the development of rigorous experimental methodologies which yield Klinkenberg data which are unambiguously free from the influence of experimental artifacts, measurement techniques and procedures.

KLINKENBERG THEORY

Muskat (1937) was amongst the first to report large discrepancies between the permeability measured to air and that measured with water. Klinkenberg (1941) found that these discrepancies were due to the nature of the liquid, an observation which appeared to invalidate Darcy's Law. Developing the ideas of Kundt and Warburg (1875), Klinkenberg idealized the porous medium as a bundle of equidimensional pore capillaries of radius, r. He argued that in capillaries with a diameter comparable to the mean free path of the gas (that is, the distance travelled by a gas molecule between successive molecular collisions) then interactions between the gas molecules and the capillary walls help move the gas molecules forward in the direction of flow. This gas slippage reduces "viscous" drag and increases permeability. Klinkenberg noted that the mean free path (λ) is inversely proportional to the mean pressure, P_m, in the pore capillary system, thus:

$$\frac{4c\lambda}{r} = \frac{b}{P_m} \qquad (1)$$

The constant c is "slightly less than 1" (Klinkenberg, 1941), and b is referred to as the gas slippage factor. At lower pressures, the mean free path increases, and the slippage effect (and therefore, gas permeability) is enhanced. At higher mean pressures, the slippage effect is suppressed (and permeability reduces) until, at infinite mean pressure the mean free path is reduced to zero, the gas molecules are considered to behave as a liquid, and the gas and inert liquid permeability, k_∞, should correspond. Klinkenberg combined poiseuille's Law for gas flow in capillaries (modified for gas slippage) with Darcy's Law for flow in porous media, to obtain the relationship:

$$k_g = k_\infty \left(1 + \frac{4c\lambda}{r}\right) \tag{2}$$

Combining Equations 1 and 2, gives the familiar Klinkenberg equation:

$$k_g = k_\infty \left(1 + \frac{b}{P_m}\right) \tag{3}$$

Gas permeability is calculated from Darcy's Law, which for an ideal gas (e.g. nitrogen) and "ambient" conditions, can be expressed as:

$$k_g = \frac{\mu P_b L Q_b}{A \delta p P_m} \tag{4}$$

Klinkenberg demonstrated that, by plotting gas permeability against the inverse mean pressure for a range of porous media samples, the data fell on a straight line. The intercept of the slope extrapolated to zero inverse mean pressure (that is, infinite mean pressure) is the apparent permeability, k_∞. The slope of the best fit line is bk_∞. Klinkenberg also proved that, since slip factor is inversely proportional to pore radius and directly proportional to mean free path, b was smaller for higher permeability samples and, at the same mean pressure in a given porous medium, gas permeability had different values for different molecular weight gases, although their permeabilities at infinite mean pressure were found to correspond. Klinkenberg then measured the permeability of the same samples to inert liquid (isooctane) and found that the extrapolated gas and liquid permeabilities agreed, "within experimental error".

EXPERIMENTAL EQUIPMENT AND PROCEDURES

Measuring Klinkenberg Permeability

Klinkenberg measurements can be made in atmospheric flow mode, or backpressure flow mode; under either constant differential pressure, or constant mass flow rate.

For atmospheric flow measurements, the gas leaving the core is allowed to flow directly to atmosphere. The mean pressure and flow rate can only be controlled by adjusting the injection flow rate.

In backpressure mode, a pressure is created at the outlet end of the sample and both pressure and flow rate can be controlled independently. In constant differential pressure mode, the pressure drop across the core is maintained constant as mean pressure is increased. To achieve this the mass flow rate through the core (and the outlet volumetric gas flow rate, Q_b) must be increased. In constant mass flow mode, the volumetric flow rate, Q_b, is maintained constant. As the mean pressure in the core is increased, the core differential pressure reduces in response to the reduction in mean gas volumetric flow rate, Q_m.

In principle, measurements should be straightforward, though, in practice, with low permeability samples, the procedures can be tedious and protracted.

Equipment

Klinkenberg determinations were made on both oil and gas reservoir cores, as well as surface outcrop sandstone cores.

All measurements were made under steady-state conditions, using a digital gas permeameter with filtered oxygen-free nitrogen as the test fluid. The permeameter utilises different range digital pressure transducers to record core injection pressure (P_1) and core pressure drop (P_1 - P_2). Gas flow rate, Q_b, is recorded at atmospheric pressure conditions using a digital manometer: the pressure drop created by gas flowing through one of three different range capillary tubes is monitored by an 0-10 mm water gauge digital transmitter, and is calibrated against volumetric rate, using soap film bubble meters. The system backpressure is controlled by a micrometering control valve. The coreholder used to mount the samples utilises a 3 mm thick, 60° Durometer hardness Viton rubber sleeve. Air or hydraulic oil can be used to apply the sleeve confining pressure required to seal the core.

FLOW MODE SELECTION

Atmospheric versus Backpressure Flow Mode

Figure 1 shows the results of Klinkenberg measurements made on the same, 160 mD, core sample, under atmospheric and backpressure flow modes. In atmospheric flow mode, over a narrow range of low mean pressures, the Klinkenberg extrapolation yields a physically meaningless, negative slip factor. It was considered that the pressure regulator used to control injection rate may not have been sufficiently stable to achieve steady-state conditions. The test was repeated using a thermal mass flow controller to improve flow stability. Nevertheless, the data still yield a negative slip factor. Small errors in gas permeability measurements, from whatever source, are accentuated when gas permeability data, obtained over a narrow range of relatively low mean pressures, are extrapolated to infinite mean pressure. Further, under atmospheric flow mode, since flow rate must be increased to yield higher mean pressures, there is a possibility of exceeding the critical velocity required for the onset of non-Darcy flow. This will be discussed in detail, below.

Backpressure flow offers several advantages, namely: improved flow and pressure control; the range of mean pressures can be extended, yielding a less tenuous extrapolation to infinite mean pressure, and; flow can be restricted to a Darcy regime, even at relatively high mean pressures. The derived Klinkenberg data, as illustrated in Figure 2, are more realistic. The variation in predicted values of gas permeability, regressed to exactly 1 atmosphere, k_{abs}, between atmospheric and backpressure flow data is only 3.4% and 4.5%, compared to the equivalent variation in k_{∞} of 25% and 62%. This emphasizes the dangers inherent in Klinkenberg extrapolations from relatively low to infinite mean pressures.

Figure 2 plots slip factor against predicted Klinkenberg permeability for a suite of cores from a Southern North Sea gas reservoir facies. Originally, under atmospheric flow, no meaningful correlation could be obtained. The measurements were repeated using backpressure on randomly selected cores, which cover the range of permeabilities encountered in this particular facies. The application of backpressure now provides data which reveal strong slip factor/ permeability correlations, as summarized in Table 1

Constant Mass Flow Rate versus Constant Differential Pressure

Gas permeability measurements were made on an 160 mD sample of "inert" sintered glass filter material, under backpressure, at constant differential pressure and then at constant mass flow rate. The core was then saturated in synthetic oil (Isopar M) and the permeability of the sample determined at the same value of net effective sleeve pressure.

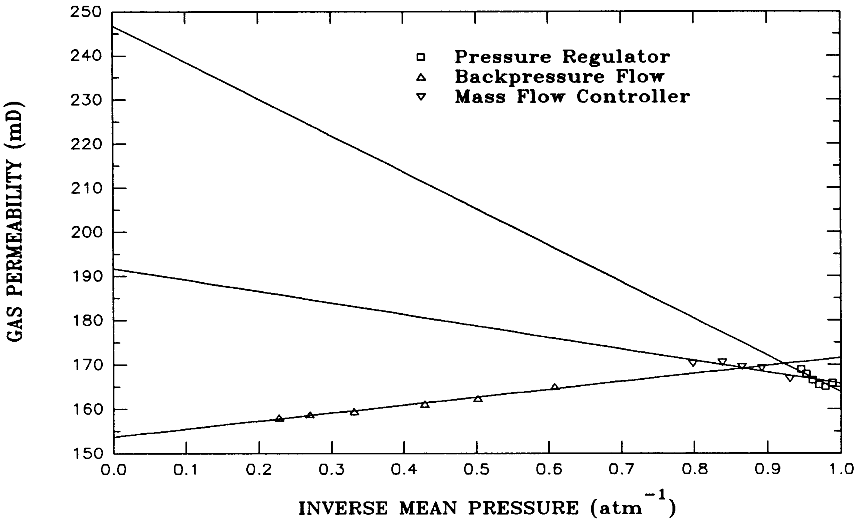

FIGURE 1 Atmospheric versus backpressure flow mode for 160 mD glass core

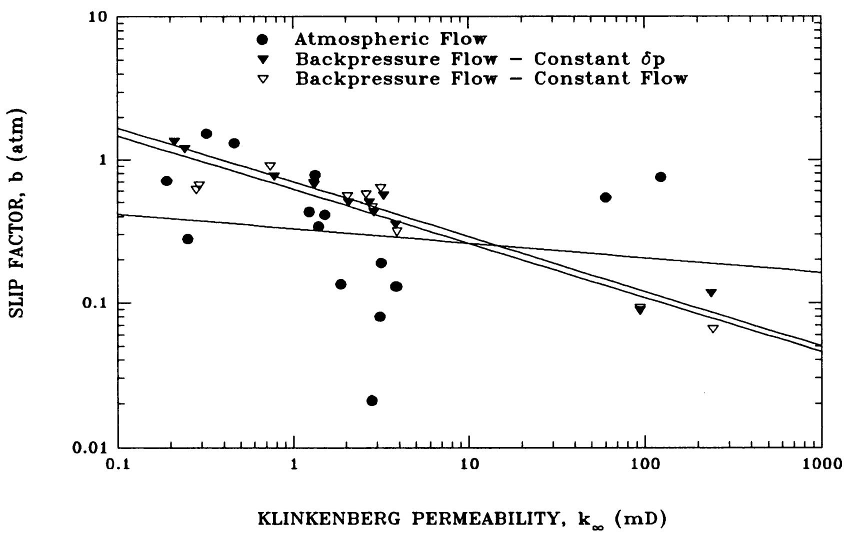

FIGURE 2 Slip factor/permeability relationships for gas reservoir cores

Table 1 Slip Factor/Permeability Correlations for Gas Reservoir Cores

Flow Mode	*Correlation Data* ($b = a k_{\infty}^{-c}$)	*Regression Coefficient*
Atmospheric Flow Mode	$0.328\ k_{\infty}^{-0.10}$	0.158
Backpressure : Constant δp	$0.697\ k_{\infty}^{-0.38}$	0.981
Backpressure : Constant Mass Flow	$0.618\ k_{\infty}^{-0.38}$	0.941
API RP 27 (1956)	$0.777\ k_{\infty}^{-0.39}$	-

Figure 3 and Table 2 compare the Klinkenberg regressions with the regression developed by Heid *et al* (1950), which is reported in API RP27 (1956), and is referenced to the value of oil permeability, k_o. Although the predicted values of k_{∞} are lower than the value of k_o, they nevertheless agree within 2% and 4%, and might be considered to lie within the expected experimental error (Thomas and Pugh, 1989). As with the gas reservoir cores (Figure 2), there appears to be no consistent or significant differences introduced by adopting either backpressure flow mode.

However, the advantages of constant pressure mode must be offset against the increasing mass flow rate in the sample which, in some cases, though not represented here, might possibly result in the onset of non-Darcy flow.

TRANSDUCER ERROR

The relative influence of transducer error on derived gas and Klinkenberg permeability data will depend upon the type, range and resolution of the transducers selected.

Table 3 illustrates the effects of a ± 0.1 psid pressure error (corresponding to an accuracy of ± 0.1% FSD for a 0-100 psid transducer) for an example 100 mD core measured under constant

Table 2 Klinkenberg Data For 160 mD Glass Core

Flow Mode	*Klinkenberg Parameters*		
	k_∞ *(mD)*	*b* *(psi)*	*Regression Coefficient*
Constant Differential Pressure	156.7	1.13	0.986
Constant Mass Flow Rate	153.7	1.70	0.979
Oil (Isopar M)	160.3	1.58*	-

* : $b = 0.777\ k_o^{-0.39}$ (API RP 27, 1956)

differential pressure and constant mass flow rate, at a maximum differential pressure of 5.0 psid. No error in flow rate or injection pressure is assumed. The effects of transducer errors become more significant in the constant mass flow rate mode. The ratio of pressure error to recorded pressure ranges from 2% to nearly 7% as differential pressure reduces at higher mean pressures, in response to the reducing volumetric mean flow rate. The derived slip factor is much more sensitive to error than Klinkenberg permeability : increasing by 72% for a + 0.1 psid error and decreasing by 74% for a - 0.1 psid error. Maintaining differential pressure in backpressure measurements within the optimum range of a higher resolution transducer, with minimal zero and range shift, will minimize the effects of transducer inaccuracy.

SLEEVE PRESSURE

Sleeve confining pressure should be sufficient to allow the sleeve to fill surface irregularities and provide an effective seal against gas bypass, yet low enough, for ambient condition test data, to minimize permeability reduction due to pore volume compaction in response to increasing stress. The extent to which sleeve pressure is transferred to the rock, and to which the sleeve conforms to different core surface textures, is a function not only of the sample surface and grain characteristics, but also of sleeve hardness and thickness.

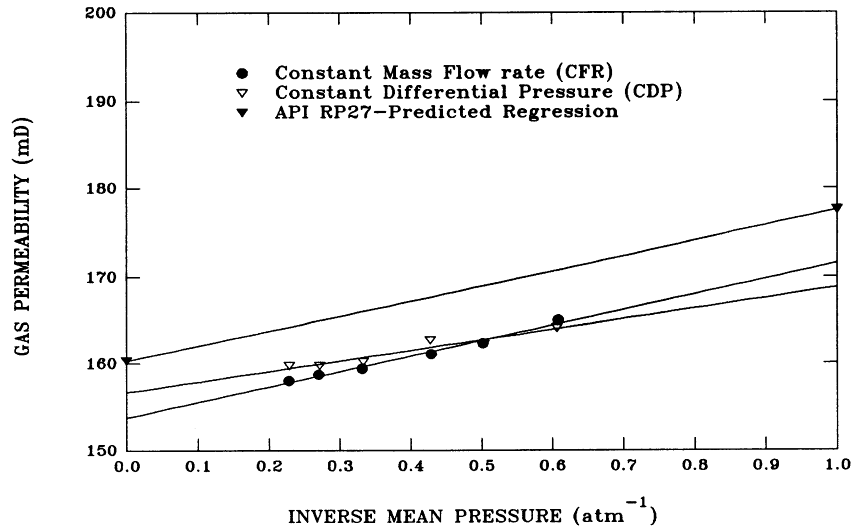

FIGURE 3 Klinkenberg and oil permeability data for 160 mD glass core

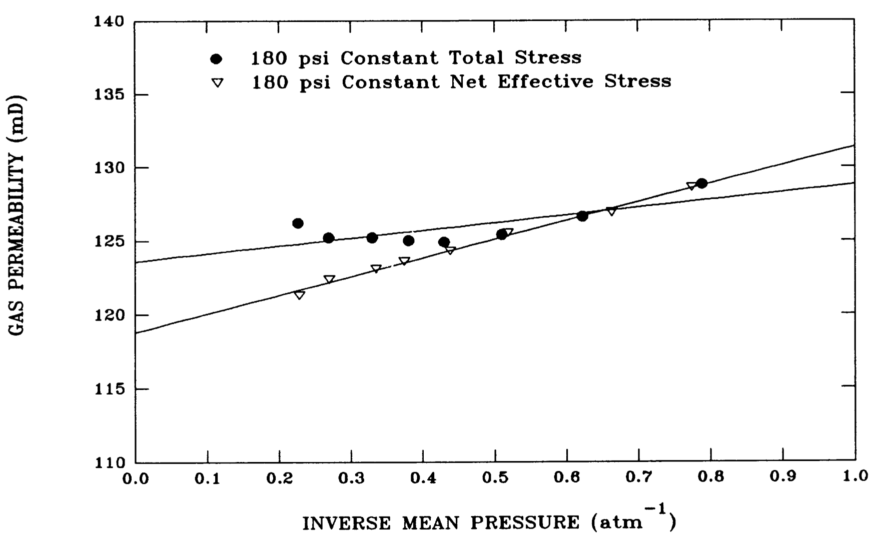

FIGURE 4 Effect of non-constant effective stress

Table 3 Pressure Error Analysis for 100 mD Core Sample

Flow Mode	Pressure Error (psid)	Klinkenberg Parameters: k_∞ (mD)	b (psi)	Regression Coefficient
Constant δp	0.0	100.4	1.70	0.996
	+0.1	98.43	1.75	0.996
	-0.1	102.4	1.65	0.995
Constant Flow	0.0	100.4	1.70	0.996
	+0.1	93.30	2.93	0.986
	-0.1	108.8	0.45	0.816

Typically the sleeve pressure for so-called "ambient" tests ranges from about 150 psi to 800 psi. It is often difficult therefore, to reconcile both gas and Klinkenberg permeabilities measured by different laboratories using different sleeve specifications and confining pressures.

Net effective pressure is defined as the difference between the sleeve (or confining) pressure and the pore (or mean) pressure developed within the sample. As the net confining pressure is increased, so permeability reduces. Sample stress sensitivity is comparatively greater at lower net confining pressures, so that conventional "ambient" measurements are therefore most affected by small changes in effective stress. Figure 4 shows the derived Klinkenberg relationships for a 120 md oil reservoir core sample measured at constant *total* confining and constant *net* confining pressures. In the former example, the sleeve pressure was maintained at 180 psi throughout the experiment. The net effective pressure acting on the sample therefore progressively *reduces* as mean pressure *increases*. In the latter case, the sleeve pressure was *increased* to compensate for the *increase* in mean pressure. Thus the net effective pressure is maintained *constant* during the experiment. The data at lower mean pressures exhibit similar Klinkenberg trends, though the data soon begin to deviate as gas permeability increases and sleeve conformance becomes progressively poorer, in response to a progressive reduction in net effective pressure. Thus non-constant permeability and gas bypass, not gas slippage effects, dominate this data set.

Additional, representative core samples were then tested at 180 psi, 290 psi and 400 psi constant net effective pressures; covering the range of test pressures often specified for "ambient" condition tests. The test data indicate that, even within this narrow range of sleeve pressures, there are significant differences in the derived Klinkenberg permeability. The reduction in k_∞ in response to increasing effective stress is a strong function of permeability - lower permeability cores experience a comparatively greater permeability reduction - and, the relative influence of higher confining pressures becomes progressively greater with decreasing permeability (Figure 5).

It can be difficult to isolate the influence of pore volume compaction from sleeve conformance effects on derived Klinkenberg data. This re-emphasizes the need for a sufficiently rigorous experimental database which might be used to standardize sleeve pressures in relation to different sleeve specifications and core surface textural properties. Pressures below 400 psi may not be sufficient to achieve total sleeve conformance on many cores.

NON-DARCY FLOW

Forchheimer (1901) observed that Darcy's Law failed to adequately describe flow at high rates, and described flow through a porous medium by the model:

$$-\frac{dp}{dL} = \frac{\mu v}{k} + \beta \rho v^2 \qquad (5)$$

The first term on the right hand side of this equation is equivalent to Darcy's law. The second term predicts the additional pressure drop resulting from non-Darcy flow. If $\beta\rho v^2$ approaches zero, Darcy's law will adequately describe flow.

Analysis of Klinkenberg permeability tests must take account of non-Darcy flow influencing the derived data. It becomes important to either:

a) adjust test procedures to ensure flow is within a Darcy regime, or;

b) isolate the contribution to overall core pressure drop arising from non-Darcy flow, to enable the prediction of Klinkenberg parameters from non-Darcy flow data.

Many attempts to provide a criterion for non-Darcy flow limitation have hinged upon identifying a critical Reynold's Number, defined by Green and Duwez (1951) as:

$$Re = \frac{\rho v \beta k}{\mu} \tag{6}$$

Although the assumption that transition from viscous-dominated to inertially-dominated flow occurs at a Reynold's Number of 1, is theoretically valid for flow in capillaries, Noman and Kalam (1990) report that the critical value may be much lower for complex gas flow in tortuous porous media. In the data illustrated by Noman and Kalam (1990), the Klinkenberg plots exhibit abrupt and distinct deviations from linearity. However, in many cases, deviation may be much more subtle, as measurements made on a 0.1 mD permeability core (Table 4 and Figure 6) illustrate.

So how do we define the onset of non-Darcy flow in this example? According to Darcy's law, a plot of the pressure term, $(P_1^2 - P_2^2)$, against Q_b, will yield a straight line with slope proportional to k/μ. Inertially-dominated gas flow however, will produce a concave upwards deviation from Darcy linearity as shown in Figure 7. The pressure term in this equation does not allow for gas slippage. However, if initial estimates for the Klinkenberg parameters, k_∞ and b, are calculated from the data which falls on the initial straight line section, then the value of initial slip factor can be used to modify pressure drop. The term $(P_1^2 - P_2^2)(1 + b/P_m)$ plotted against Q_b, is shown overlain in Figure 7. The Klinkenberg parameters can now be recalculated from slip-modified Darcy data, and the procedure repeated until acceptable convergence is achieved. In this example, the onset of non-Darcy flow appears to occur above about 0.1 ml/s.

Obviously analysis by this graphical approach can be tedious and time consuming. Many authors, such as Tiss and Evans (1989), Noman and Kalam (1990), and Morrison and Duggan (1991) have therefore derived correlations which might predict critical or limiting velocities for non-Darcy flow for a range of core permeabilities and porosities. These correlations have been developed for particular facies or reservoirs and predicted critical flow velocities can vary by at least an order of magnitude.

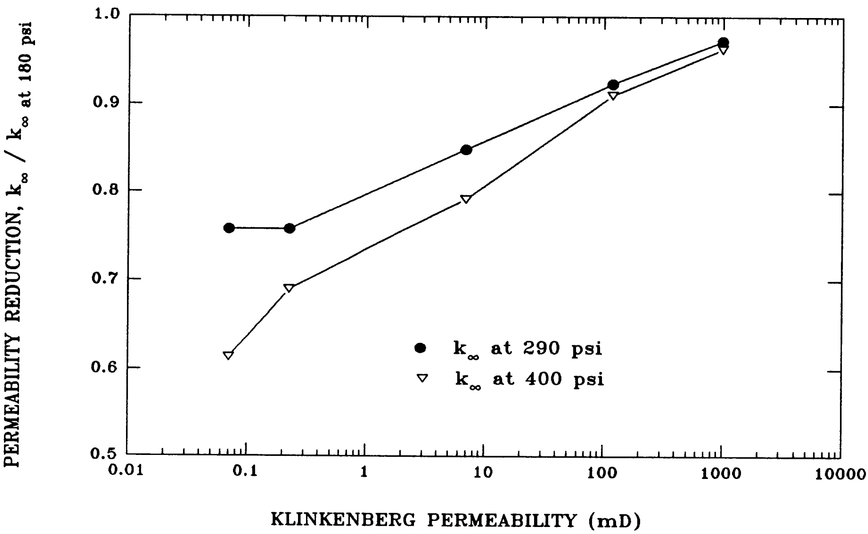

FIGURE 5 Permeability reduction as a function of effective stress

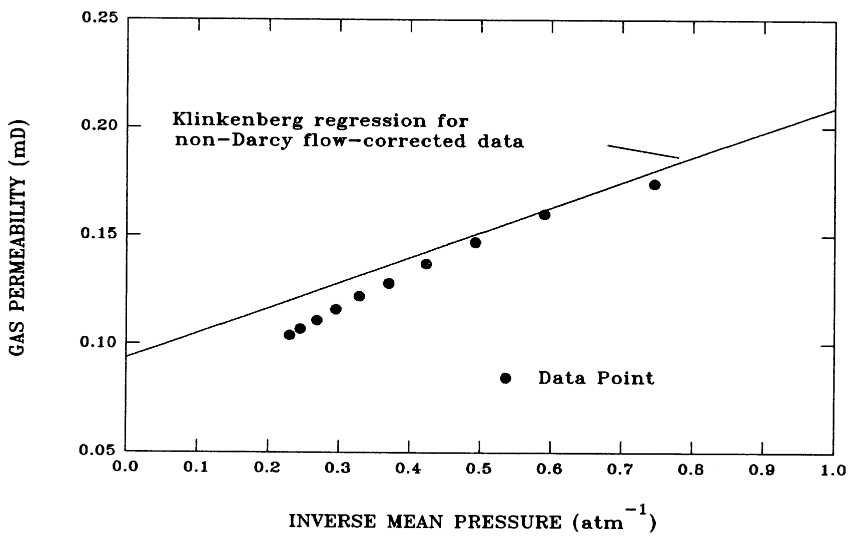

FIGURE 6 Effects of non-darcy flow on Klinkenberg linearity: 0.1 mD Core

The increasing power of personal computers encourages the application of more rapid *numerical* solutions for non-Darcy flow models. The solution method we have adopted is an iterative technique, based on non-linear optimization of the parameters, k_∞, b and ß, calculated using the Forchheimer equation modified to account for gas slippage, as follows:

$$-\frac{dp}{dL} = \frac{\mu v}{k_\infty\left(1 + \frac{b}{P_m}\right)} + 3.238 \times 10^{-8}\,\beta\rho v^2 \qquad (7)$$

where, ß has the units, ft^{-1}

Table 4 Non-Darcy Flow Data For 0.1 mD Core[a]

P_1 (atm)	δP (atm)	Q_b (ml/s)	$1/P_m$ (atm^{-1})	k_g (mD)	b/P_m	Re^*	$\beta\rho v^2L$ (psi)
1.681	0.681	0.018	0.7461	0.174	1.026	0.058	0.11
2.386	1.386	0.043	0.5907	0.160	0.812	0.139	0.48
3.056	2.056	0.070	0.4931	0.147	0.678	0.226	1.07
3.724	2.724	0.100	0.4234	0.137	0.582	0.322	1.90
4.399	3.399	0.134	0.3704	0.128	0.509	0.432	2.98
5.084	4.084	0.171	0.3287	0.122	0.452	0.551	4.34
5.766	4.766	0.212	0.2956	0.116	0.406	0.683	5.97
6.442	5.442	0.256	0.2688	0.111	0.369	0.825	7.91
7.155	6.155	0.306	0.2453	0.107	0.337	0.986	10.33
7.688	6.688	0.343	0.2302	0.104	0.316	1.106	12.18

[a] L = 2.487 cm; D = 2.518 cm; ϕ = 0.098 ; μ = 0.0176 cP; P_b = 1.000 atm

$$Re = \frac{\rho_m Q_m\, \beta\, k_\infty}{A\, \phi\, \mu}$$

Initial estimates of the Klinkenberg parameters, k_∞ and b, are derived from conventional linear regression analysis, assuming all data have been measured in a Darcy flow regime. The value of ß is estimated from a correlation suggested by Jones (1987). These values are now entered into the Forchheimer equation, which is successively iterated until convergence on k_∞, b and ß is achieved, or a pre-set number of iterations is exceeded. Table 5 compares the Klinkenberg data obtained by the graphical and numerical solutions. The non-Darcy flow-corrected Klinkenberg regression is shown overlain on Figure 6, and the pressure drop term, modified for gas slippage and corrected to account for the contribution to core pressure drop from non-Darcy flow ($\beta\rho v^2L$) is plotted on Figure 8. The numerical solution is not rigorously exact, since the model apparently fails to predict pressure drop at higher flow rates. This illustrates the sensitivity of this numerical solution to often quite small fluctuations in data.

Table 5 Comparison of Graphical and Numerical Solutions for 0.1 mD Core

Method	*Flow Regime*	k_∞ *(mD)*	*b (psi)*	*ß (ft^{-1})*
Graphical	Viscous	0.096	16.06	-
Numerical	Viscous + Inertial	0.090	20.20	8.207×10^{12}

Ruth and Kenny (1979) contest that if inertial effects are not present, or can only be barely captured, yet an analytical model allows for them, then any minor experimental errors (such as transducer inaccuracy) can cause calculated values of ß to arise, which have nothing to do with inertial effects. They suggest that derived values for b and ß should only be accepted if they lead to experimental Reynold's Numbers and Klinkenberg Numbers (b/P_m) greater than 0.1.

The numerical solution strives to find a value for ß which best describes the pressure and flow rate behaviour. In our experience, analysis of data wholly obtained in a Darcy regime can force the solution method to return physically untenable values for b and ß. In this case, data are analyzed using the Klinkenberg-modified Darcy equation.

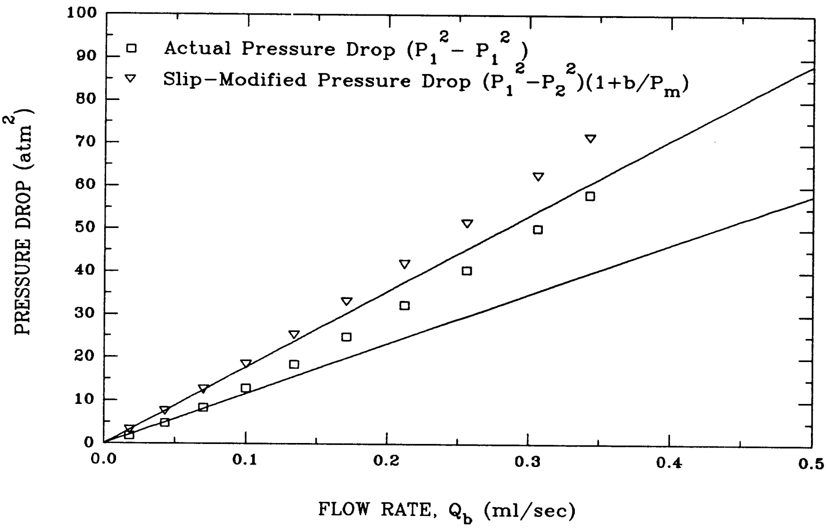

FIGURE 7 Actual and slippage-modified pressure drop : 0.1 mD core

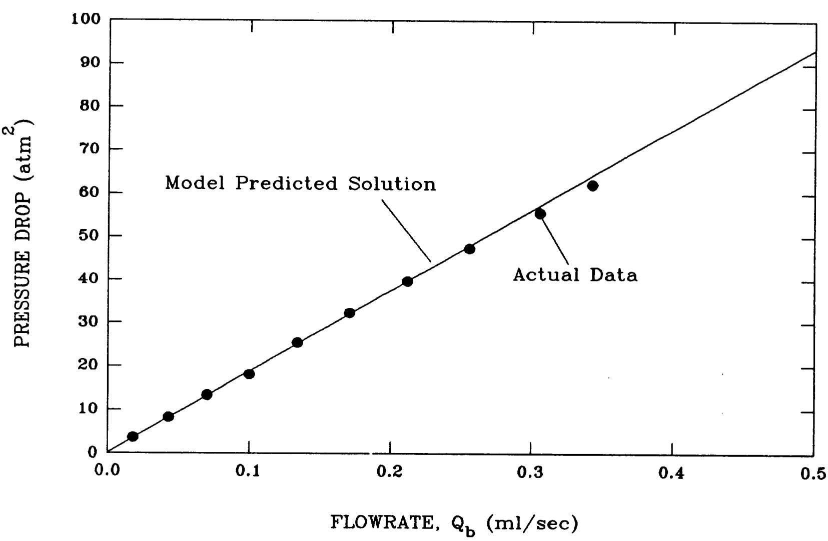

FIGURE 8 Slippage and non-Darcy flow-modified pressure drop : 0.1 mD core

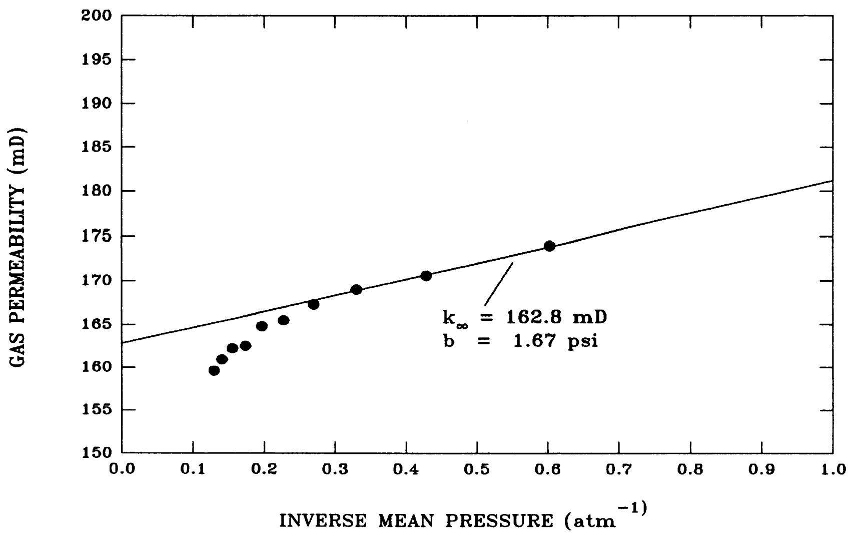

FIGURE 9 **Effects of possible non-constant gas slippage : 160 mD Core**

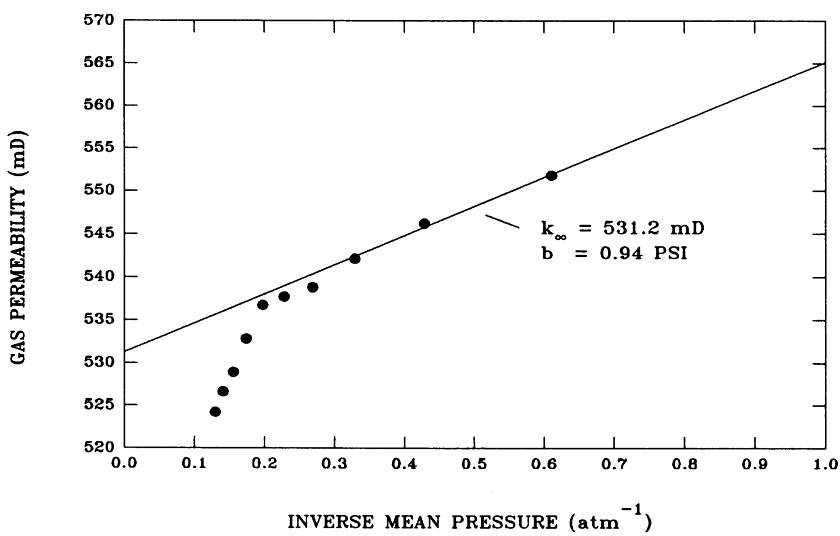

FIGURE 10 **Effects of possible non-constant gas slippage : 530 mD Core**

NON-CONSTANT SLIP FACTOR

Interpretation of Klinkenberg data hinges on the assumption that the slip factor is constant, and does not vary with mean pressure. In fact, Klinkenberg (1941) comments that "the value of the constant, b, increases with increasing pressure": a most significant statement which has been overlooked by many analysts. Klinkenberg convincingly argues that the concept of slippage was developed for gas flow in capillaries and is unlikely to be valid for flow in tortuous pore systems.

Figures 9 and 10 illustrate just two examples, for a 160 mD and a 530 mD core, respectively, measured under constant mass flow mode, which suggest that the concept of constant slip factor *may* not be valid for higher permeability porous media, at higher mean pressures. Despite the fact that non-Darcy flow effects, or progressively influential transducer error could reproduce similar behaviour, the data were obtained in a Darcy flow regime (Reynold's numbers are constant at 0.004 and 0.009), and the differential transducer was re-zeroed at each mean pressure increment. The apparent *unit* rate of reduction of gas permeability with mean pressure is greater for the higher permeability sample, presumably having a greater mean pore dimension. This data also tends to confirm Klinkenberg's experimental observations (Klinkenberg, 1941). Although further work will be required to satisfactorily isolate the cause of this behaviour, it does suggest that the theory of gas slippage in porous media may only be applicable within certain, though as yet poorly defined, boundary conditions.

CONCLUSIONS

1) Measurements of Klinkenberg permeability should, as far as possible, be made under backpressure. Backpressure provides improved control of gas flow rate and core differential pressure, and assists in maintaining viscous flow at higher mean pressures.
2) Measurements under backpressure at progressively higher mean pressures, at constant core differential pressure, suffer less from the effects of transducer error than under constant mass flow mode. However, maintenance of constant core pressure drop at higher mean pressures might introduce the possibility of inducing non-Darcy flow in the sample. Ensuring pressure drop is within the range of higher resolution, carefully calibrated transducers optimizes experimental accuracy.

3) Failure to maintain constant net effective pressure during the experiment may result in non-constant permeability as a result of progressive pore volume expansion, and gas bypass due to poor sleeve conformance with the sample's surface texture.

4) More data is required to assess the effectiveness of different sealing pressures for a range of sample surface textures, sleeve specifications and thicknesses. In the absence of such data, we suggest that pressures higher than those currently specified may be necessary. The effects of increasing "ambient" sleeve pressures must be offset against the effects on permeability reduction from pore volume compaction.

5) The effects of non-Darcy flow in any Klinkenberg measurement must be recognised. Deviation from a viscous flow regime may be more subtle than often realized. Numerical solutions to the Forchheimer Equation offer greater speed and resolution than graphical solutions, although derived data are sensitive to experimental influences. Solutions which return physically untenable values of b or ß should be rejected, and the data analyzed conventionally. Alternatively, experimentalists should ensure that data are obtained in a Darcy flow regime.

6) The crucial assumption that the Klinkenberg slip factor, b, is constant and independent of mean pressure may not be valid for gas flow through higher permeability porous media at higher mean pressures.

7) Given these problems, a search for an "indisputable", reliable base value of permeability might better focus on the value of gas permeability, extrapolated to a mean pressure of 1 atmosphere, k_{abs}. This value is more realistically attainable, involves less tenuous extrapolation, avoids the problems inherent in tests at higher mean pressures, and is less sensitive to experimental procedures. In many cases, it may be preferable, although more protracted, to measure permeability under more realistic conditions using real or synthetic reservoir fluids.

ACKNOWLEDGEMENTS

The authors wish to thank Peter Whattler, Enterprise Oil plc and, in particular, Stuart Morrison, Sun Oil, for several "stimulating" discussions on Klinkenberg measurements. Thanks also to Alastair Dodds, Mattheus Suthe and Elaine Blackie who performed the majority of the experimental work and crunched the numbers.

NOMENCLATURE

Parameters

A core cross sectional area (cm^2)
b gas slippage factor (atm)
ß inertial resistance coefficient ($atm.s^2/gm$)
c dimensionless gas slippage parameter
ϕ core porosity fraction
k permeability (mD)
L core length (cm)
λ gas molecular mean free path (microns)
P absolute pressure (atm)
δp core differential pressure (atm)
Q gas volumetric flow rate (ml/s)
r mean pore radius (microns)
ρ gas density (g/ml)
μ gas viscosity (cP)
v gas velocity (cm/s)

Subscripts

1 inlet
2 outlet
b atmospheric pressure
m mean pressure
abs atmospheric pressure = 1.00 atm
g gas
∞ infinite pressure
o oil

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