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Analysis of single-point test to determine skin factor

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ANALYSIS OF SINGLE-POINT TEST TO DETERMINE SKIN FACTOR

Abbas Belyadi

Thesis submitted to the
College of Engineering and Mineral Resources
at West Virginia University
in Partial fulfillment of the requirements
for the degree of

Master of Science
in
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ABSTRACT

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Abbas Belyadi

Single-point test results can be used to obtain information regarding the degree of damage in gas wells in the gas storage reservoirs. Single-point test is neither time-consuming nor costly to determine the productivity of a well. Furthermore, flow stabilization times would be short in high permeability gas storage reservoirs. Generally, a four-point test is conducted first to establish the deliverability relation. After some period of time, namely one year, a single-point test could be conducted. The results of the single-point and four-point tests can then be compared in order to identify any alteration in well performance.

The objective of this research is to develop a methodology to determine skin factor by using a single-point test. In this work, the impact of formation permeability on determination of skin factor is studied for two cases, including transient radial and linear flow. The impact of non-Darcy flow is also considered in these cases.

The results of this study are summarized by a series of correlation to evaluate skin factor from a single-point test.

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TABLE OF CONTENTS

	Page
ACKNOWLEDGMENTS...	iii
TABLE OF CONTENTS...	iv
LIST OF FIGURES...	vi
LIST OF TABLES...	vii
NOMENCLATURE...	viii
 CHAPTER 1. INTRODUCTION...	 1
 CHAPTER 2. LITERATURE REVIEW...	 3
2.1 Single-Point Test...	.3
2.2 Unsteady-State Radial Gas Flow Equation ...	.4
2.2.1 Pseudo-Steady State Gas Flow Equation...	.4
2.3 -factor Correlation...	.5
2.4 Infinite Conductivity Fracture...	.7
2.5 Effect of non-Darcy on Fractured Well...	.8
2.5.1 Linear Flow Regime in Infinite Conductivity Fractures.....	.9
2.5.2 Linear and Bilinear Flow Regime in Finite-Conductivity Fractures...	.10
 CHAPTER 3. METHODOLOGY...	 .12
3.1 Determine Skin Factor from Single-Point Test using Transient Radial Flow Case...	13
3.2 Impact of Formation Permeability on the Determination of the Skin Factor on Transient Radial Flow Case...	.14
3.3 Determine Skin Factor from Single-Point Test using Linear Flow Case...	.15
3.4 Impact of Formation Permeability on the Determination of the Skin Factor on Linear Flow Case...	17
3.5 Impact of Time on Flow Rate for Transient Radial and Linear Flow ...	.18
 CHAPTER 4. RESULTS AND DISCUSSIONS...	 19
4.1 Impact of Formation Permeability on Skin Factor for Transient Radial Flow...	...19
4.2 Impact of Formation Permeability on Skin Factor for Linear Flow ...	20
4.3 Flow Rate versus Time using Linear and Radial Flow ...	.21
 CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS...	 ..24
 REFERENCES...	 25
Appendix A. Determining Skin Factor from a Single-Point Test for Transient Radial Flow Solution Results...	29
Appendix B. Determining Flow Rate using Transient Radial Flow Solution Results...	..37
Appendix C. Determining Skin Factor and Flow Rate using Linear Flow Solution Results...	39

Appendix D. Flow Rate versus Time (Linear Darcy, Linear non-Darcy and Radial non-Darcy)...	42
Appendix E. Impact of Formation Permeability to Determine Skin Factor on Transient Radial Flow Solution Results...	49
Appendix F. Impact of Formation Permeability to Determine Skin Factor on Linear Flow Solution Results...	51

LIST OF FIGURES

	Page
Figure 2.1: Linear Flow Regime...	8
Figure 2.2: Radial Flow Regime...	8
Figure 4.1: Skin Factor vs. Permeability (Transient Radial Flow)...	19
Figure 4.2: Skin Factor vs. Permeability (Linear Flow)...	20
Figure 4.3: Flow Rate vs. Time (P=2000 Psia, K=100 md)...	21
Figure 4.4: Flow Rate vs. Time (P=2000 Psia, K=200 md)...	22
Figure 4.5: Flow Rate vs. Time (P=2000 Psia, K=500 md)...	23
Figure A.1: z factor, Viscosity, and Compressibility Calculation Program	30
Figure D.1: Flow Rate vs. Time (P=1000 psia, K=100 md)...	43
Figure D.2: Flow Rate vs. Time (P=1000 psia, K=200 md)...	44
Figure D.3: Flow Rate vs. Time (P=1000 psia, K=500 md)...	45
Figure D.4: Flow Rate vs. Time (P=1500 psia, K=100 md)...	46
Figure D.5: Flow Rate vs. Time (P=1500 psia, K=200 md)...	47
Figure D.6: Flow Rate vs. Time (P=1500 psia, K=500 md)...	48

LIST OF TABLES

	Page
Table 1: Constant a, b for Cooke's Correlation...	..6
Table 2: z factor Correlation (Single phase case)...	..7
Table 3: Parameters used throughout this study...	..12
Table A.1: z factor, Viscosity, Compressibility Results.....	31
Table A.2: Pseudo-Pressure Calculation using the z factor, Viscosity, Compressibility Values from Stimulator...	..32
Table A.3: Non-Darcy Turbulence Coefficient, Apparent Skin Factor and Flowing Bottomhole Pseudo-Pressure Results ...	..34
Table A.4: Flowing Bottomhole Pressure Results (Time =49.99 hrs)...	35
Table A.5: Skin Factor Results...	36
Table B.1: Flow Rates using Pressure Transient Solution Results ($P_r=1500$ psia and $t =49.99$ hrs)...	38
Table C.1: Skin Factors and Flow Rates Using Linear Flow Equation under non-Darcy Results ($K=100$ md, $P=1500$ psia and Time= 4 hrs)...	..40
Table C.2: Skin Factors and Flow Rates Using Linear Flow Equation under Darcy Flow Results ($K=100$ md, $P=1500$ psia and Time= 4 hrs)...	..41
Table E.1: Impact of Permeability on Skin Factor Results (Radial Flow) ...	50
Table F.1: Impact of Permeability on Skin Factor Results (Linear Flow)...	52

NOMENCLATURE

K = permeability (md)

t = Time (hrs)

ϕ = Porosity (%)

μ_g = Gas Viscosity (cp)

C_t = Total compressibility (psi^{-1})

r_d = Transient radius of drainage (ft)

r_w = Wellbore radius (ft)

$m(p_i)$ = Initial pseudo-pressure (psi^2/cp)

$m(p_{wf})$ = Bottomhole pseudo-pressure (psi^2/cp)

$m(p_R)$ = Reservoir pseudo-pressure (psi^2/cp)

h = Formation thickness (ft)

T = Temperature (R)

q = Flow rate (Mscf/D)

S = Apparent skin factor

S = Skin factor

μ_{gi} = Initial gas Viscosity (cp)

D = Non-Darcy turbulence coefficient (Mscf/D)⁻¹

$\bar{\mu}_g$ = Average gas Viscosity (cp)

γ_g = Gas specific gravity

t_D = Dimensionless time

P = Pressure (Psia)

z = Gas compressibility factor

$S \quad S_f = S_d$ = Damaged skin

D_f = Non-Darcy flow factor for fractured wells

D_w = Non-Darcy flow factor for nonfractured wells

= Factor

= Coefficient of internal resistance

= Density (lbm/ft³)

L_f = Fracture length (ft)

r_e = Radius of outer boundary (ft)

L_{fd} = Dimensionless fracture half-length (= L_f/r_e)

CHAPTER 1

INTRODUCTION

Single-point test should be conducted generally after a four-point test. The test must be conducted for a minimum flow time of 48 hours but not more than 72 hours. One would use single-point test results to investigate if the well is damaged or stimulated. Some period of time (one year) after a four-point test had been conducted, one could use a single-point test to investigate well conditions (either damage or stimulation). The four-point test results can be plotted as p^2 versus q to establish baseline performance. The single-point test result can then be plotted on the same graph. Therefore it is possible to find out if the well performance has been altered. Single-point flow data are nearly always available on gas wells therefore this makes single-point test to be appealing compare to the build-up test.

The typical gas storage reservoirs are in general high permeability clastics or carbonates and these reservoirs are depleted formations that contain natural gas. Natural gas is mostly stored in porous reservoirs. Natural gas can be either injected into the underground storage reservoirs or removed from the underground storage reservoirs depending on the market demand. Natural gas is injected into the underground storage reservoirs when the pipeline capacity exceed the market demand during the summer however this gas is withdrawn from the underground storage reservoirs when the market demand exceed the pipeline capacity. It is also possible for gas to move from the storage which can be results of many factors such as permeability of the rock, pressure gradient, faults, fractures, operating conditions, integrity of caprock and others (Tek, 1987).

Previous studies have discussed formation permeability determination using single-point test data. In these studies, the value of skin factor had to be estimated to calculate formation permeability from single-point test. Estimating skin factor is the biggest limitation to single-point method and usually the main source of error.

The present study aims to determine skin factor from single-point test for two cases including transient radial and linear flow. In the present work, the permeability is assumed to be available and the skin factor is determined from single point-test data. The impact of formation permeability on the estimated skin factor has been also studied for cases including transient radial and linear flow.

CHAPTER 2

LITERATURE REVIEW

2.1 Single-Point Test

Single-point test on a well will be required in the following two cases first for calculating AOF and flow coefficient, C. Secondly, for calculating skin factor, S, if non-Darcy flow coefficient, D or exponent n are already obtained from the previous test (Chaudry, 2003). Accordingly the non-Darcy flow coefficient can be estimated from different tests data. Single-point test is neither expensive nor time-consuming compare to other tests. Well produces only at one rate in the single-point test. However, well produces at different rates (Typically four) in multi-point test. Build-up and drawdown tests are more accurate than single-point test however one may use single-point test in the absence of drawdown and build-up data. The accuracy of single-point test will be associated with estimating a proper value of permeability to determine skin factor from single-point test data (Lee et al, 1984).

The transient radius of drainage r_d is similar to the radius of investigation and it is given by the following equation:

$$r_d = \left(\frac{kt}{376 c_t} \right)^{\frac{1}{2}} \quad (1)$$

The pseudo steady-state flow equation shows that well can be flowing at pseudo steady-state condition with a drainage radius that is continuously moving outward. The pseudo-steady state is given by the following equation (Houpeurt, 1959):

$$\frac{kh}{1422 q_g T} [m(p_i) - m(p_{wf})] = \ln\left(\frac{r_d}{r_w}\right) - 0.75 S \quad (2)$$

2.2 Unsteady-State Radial Gas Flow Equation

Unsteady-state radial gas flow solution is usually used for pressure drawdown analysis with a constant-rate gas production. Radial unsteady-state gas flow is given by the following equation (Houpeurt, 1959):

$$m(P_i) - m(P_{wf}) = \frac{1637 qT}{kh} \left[\log t - \log \frac{k}{c_i r_w^2} - 3.23 - 0.869 S \right] \quad (3)$$

One can notice that pressure responses as function of time when unsteady-state radial gas flow equation is used.

Muskut (1937), Katz (1959), and Wattenbarger and Ramey (1968), all describe non-Darcy flow close to the wellbore depend on skin. Total skin factor is given by the following equation:

$$S' = S + Dq_g \quad (4)$$

The non-Darcy turbulence coefficient is given by the following equation (Katz et al 1959):

$$D = \frac{2.22 \cdot 10^{-15} k}{hr_w} \quad (5)$$

2.2.1 Pseudo-Steady State Gas Flow Equation

Pseudo-steady state constant rate solution is usually used for the deliverability test analysis and is given by the following equation (Houpeurt, 1959):

$$m(\bar{p}_R) - m(p_{wf}) = \frac{1422 Tq_{sc}}{kh} \left[\ln \left(\frac{0.472 r_e}{r_w} \right) - S - Dq_{sc} \right] \quad (6)$$

2.3 -factor Correlation

Darcy's law describes the linear proportionality developed by Henry Darcy in 1856 as shown by the following equation:

$$\frac{P}{L} = \frac{v}{K} \quad (7)$$

Darcy's law is however inadequate for describing high flow of gas through porous media as identified for more than one century. Forchheimer proposed a second order equation as shown by the following equation :

$$\frac{P}{L} = \frac{v}{K_d} + v^2 \quad (8)$$

Forchheimer equation introduces a pressure drop term due to high flow velocities.

-factor Correlation for fractures and non-fractures

Janicek and Katz (1955) were the first to develop a correlation for (The non-Darcy coefficient) as a function of permeability and porosity of the porous medium. A correlation was proposed by Tek et al (1962) after analyzing both Janicek and Katz data. This correlation is given by the following equation:

$$\frac{5.5 \cdot 10^9}{k^{5/4}} \quad (9)$$

The non-Darcy flow effect for several fluids in different sizes of fracture propping agents at various temperature was considered by Cooke (1973). This correlation is given by the following equation:

$$\frac{b}{k^a} \quad (10)$$

Depending on propped type, the constant values of Cooke's correlation are shown in table below:

Table 1: Constant a, b for Cooke's Correlation

Sand size	a	b
8-12 mesh	1.24	2.32
10-20 mesh	1.34	2.63
20-40 mesh	1.54	2.65
40-60 mesh	1.6	1.1

Cooke's correlation was only used for single-phase flow. Regarding to Cooke's conclusion, it is very important to consider the non-Darcy effects in designing fracture treatment for gas reservoirs. Cooke's correlation is an application that was derived for fracture system. Another correlation for gas flow in porous media was developed by Geertsma (1974). This correlation is given by the following equation:

$$\frac{0.005}{k^{0.5} \cdot 0.5} \quad (11)$$

Geertsma (1974) also developed a correlation for for formation with an immobile liquid saturation. This correlation is given by the following equation:

$$\frac{0.005}{k^{0.5} \cdot 0.5} \left(\frac{1}{(1 - s_w)^{5.5} k_{re}^{0.5}} \right) \quad (12)$$

New correlation for factor at both mobile and immobile liquid saturation was afterward offered by Frederick and Graves.

-factor Correlation for Single-Phase Case

There are a number of correlations for predicting and permeability is the key parameter for all these correlations. Some of these correlations are listed in the table below (Li et al, 2001):

Table 2: Factor Correlation (Single-Phase Case)

Author name	Equation	Unit
Thauvin and Mohant (1998)	$1.75 \cdot 150^{1/2} (10^{-8} K)^{1/2} \cdot 3/2$	k, d, and , 1/cm
Janicek and Katz (1955)	$1.82 \cdot 10^8 K^{5/4} \cdot 3/4$	k, md, and , 1/cm
Pascal et al. (1980)	$\frac{4.8 \cdot 10^{12}}{k^{1.176}}$	k, md, and , 1/m
Jones (1987)	$\frac{6.15 \cdot 10^{10}}{k^{1.55}}$	k, md, and , 1/ft
Coles and Hartman (1998)	$\frac{1.07 \cdot 10^{12} \cdot 0.449}{k^{1.88}}$	k, md, and , 1/ft
Coles and Hartman (1998)	$\frac{2.49 \cdot 10^{11} \cdot 0.537}{k^{1.79}}$	k, md, and , 1/ft
Li et al. (1995)	$\frac{11500}{K}$	k, d, and , 1/cm

Table above for predicting is only for single-phase condition and these equations can not be used for multi-phase flow. Coles and Hartman (1998) proposed two methods, same porosity and simultaneous, to calculate as shown in the table above.

2.4 Infinite Conductivity Fracture

There are three types of fracture behavior that can be observed in a well test: (1) Low (Finite) conductivity fracture (2) high (Infinite) conductivity fracture (3) uniform flux fracture. In infinite conductivity fracture linear flow starts first, then followed by radial flow.

Infinite conductivity fracture has different flow regimes, which are shown by the following figures.

Figure 2.1: Linear Flow Regime

Figure 2.1 shows flow is occurring toward fracture. Pressure drop inside the fracture during production is zero in infinite-conductivity fracture.

Figure 2.2: Radial Flow Regime

Figure 2.2 shows flow is occurring toward fracture. Radial flow regime will occur after linear flow in infinite conductivity fracture.

2.5 Effect of non-Darcy on Fractured Well

Non-Darcy flow will play an extremely significant role for pressure drop in the hydraulically fractured gas wells, where high velocity occurs in the fracture. This will result in pressure distribution in the entire reservoir following pressure distribution in the

fracture. Non-Darcy flow would be less important in the formation than inside of the fracture (Alvarez et al 2002). Hydraulic fractures will reduce the effect of non-Darcy flow (Hagoort, 2002). Millheim and Cichowicz (1968) were first to observe the effect of non-Darcy flow on vertically fractured well. Holditch and Morse (1976) also discussed the effect of non-Darcy flow in both reservoir and fracture system by using numerical models.

2.5.1 Linear Flow Regime in Infinite Conductivity Fractures

The following technique is based on the analytical expressions of linear flow regime in infinite conductivity fractures (Hagoort, 2002). Non-Darcy flow factor, D_f for a fractured well is defined by following equation:

$$D_f = \frac{k}{2 h L_f} \quad (13)$$

For comparison, Non-Darcy flow factor, D_w for non-fractured well can be defined by following equation:

$$D_w = \frac{k}{2 h r_w} (1 - r_w / r_e) \quad (14)$$

Except for fracture half-length, L_f and r_e , equation 13 is similar to the one that is used for radial flow. r_e can be expressed as shown below (Hagoort, 2002):

$$\frac{2L_f}{r_e} = \frac{L_f}{r_w} \quad (15)$$

Fracture skin can also be calculated and is given by the following equation for infinite conductivity fracture:

$$S_f = \ln \frac{2r_w}{L_f} \quad (16)$$

2.5.2 Linear and Bilinear Flow Regime in Finite-Conductivity Fractures

Linear-Flow

The following technique is based on the analytical expressions of linear regime in finite conductivity fractures (Gringarten et al, 1974). The dimensionless pseudo-pressure is defined, in field units, by:

$$m_D(t_d) = \frac{Kh}{1422 qT} [m(p_i) - m(p_{wf})] \quad (17)$$

In the above equation, the dimensionless time, t_D is defined by

$$t_D = \frac{2.637 \cdot 10^4 k}{(c_i)_i L_f^2} t \quad (18)$$

According to Camacho (1984), the pseudo-pressure responses of finite conductivity fractures during the reservoir's linear-flow period, could be expressed for Darcy and non-Darcy using equations below respectively:

$$m_{wD}(Darcy) = \sqrt{t_D} \frac{a}{C_{fD}} \quad (19)$$

$$m_{wD}(non \ Darcy) = \sqrt{t_D} \frac{a}{C_{fD,app}} \quad (20)$$

$$a = 1/3 \text{ for } C_{fD} \geq 25$$

$$a = 0.944 \text{ for } C_{fD} = 10$$

$$a = 0.902 \text{ for } C_{fD} = 5$$

Bilinear-Flow

According to Cinco and Samaniego (1978), the pseudo-pressure responses of finite conductivity fractures during the reservoir's bilinear-flow period, could be expressed for Darcy using equation below:

$$m_{wD}(Darcy) = \frac{t_D^{1/4}}{(5/4)\sqrt{2C_{fD}}} \quad (21)$$

According to Guppy et al. (1982), the pseudo-pressure responses of finite conductivity fractures during the reservoir's bilinear-flow period, could be expressed for non-Darcy using equation below:

$$m_{wD}(non \ Darcy) = \frac{t_D^{1/4}}{(5/4)\sqrt{2C_{fD,app}}} \quad (22)$$

CHAPTER 3

METHODOLOGY

The objective of this study was to analyze single-point test to determine skin factor. To achieve the objective, the following 3 steps were employed:

1. A methodology to determine skin factor from single-point test data, using transient radial and linear flow solutions.
2. Study the impact of formation permeability on the determination of the skin factor for both cases.
3. Impact of time on flow rate using linear and radial flow cases under study.

Table 3 shows the parameters that were used throughout this study.

Table 3: Parameters used, throughout this study

q (Mscf/D)	150450
r_w (ft)	0.33
T (°F)	80
h (ft)	100
k (md)	100
(%)	20
Gas Gravity	0.6

3.1 Determine Skin Factor from Single-Point Test using Transient Radial Flow Case

Parameters such as gas viscosity, compressibility and z factor were calculated at reservoir pressure of 1000 psia, 1500 psia and 2000 psia respectively from fluid properties and reservoir program. In this research, the following correlation was used, which is very similar to Jones (1987) to determine s -factor and is given by the following equation:

$$\frac{2.33 \cdot 10^{10}}{k^{1.2}} \quad (23)$$

Where

k = Permeability (md)
= 1/ft

The non-Darcy turbulence coefficient, D is determined and is given by the following equation:

$$D = \frac{5.18 \cdot 10^{-5}}{h r_w k^{0.2}} \quad (24)$$

Total skin factor (Using eq.4) is afterward determined. Next the flowing bottomhole pseudo-pressure is determined using unsteady-state radial gas flow that is given by the following equation:

$$m(P_{wf}) - m(P_R) = \left[\frac{1637 q T}{k h} \left\{ \log t - \log \frac{k}{i C_{ti} r_w^2} - 3.23 - 0.869 S \right\} \right] \quad (25)$$

Therefore skin factor can be determined from single-point test data. Initially transient radius of drainage (Using eq.1) is determined. Then apparent skin factor is determined using pseudo-steady state flow and is given by the following equation:

$$S' = \frac{k h}{1422 q_g T} [m(p_i) - m(p_{wf})] - \ln\left(\frac{r_d}{r_w}\right) - 0.75 \quad (26)$$

Finally, skin factor is determined for transient radial flow using equation below (Refer to Appendix A):

$$S = S' - Dq_g \quad (27)$$

In this section, our first step is to calculate flowing bottomhole pressure using constant flow rate. Formation permeability is assumed to be available to determine skin factor from single-point test data.

3.2 Impact of Formation Permeability on the Determination of the Skin Factor on Transient Radial Flow Case

Flowing bottomhole pressure for reservoir pressure of 1000 psia, 1500 psia and 2000 psia is provided using equation $p^2 = P_R^2 - P_{wf}^2 = 10^6$ where p^2 is taken as 10^6 , as it is a common practice in gas storage. In addition well test is generally done taking $p^2 = 10^6$. Flow rate is determined using radial unsteady-state flow equation (Using eq.3), after replacing apparent skin factor equation (Using eq.4) and the non-Darcy turbulence coefficient equation (Using eq.5). Therefore these expressions become:

$$m(p_i) - m(p_{wf}) = \frac{1637qT}{kh} \left[\log t - \log \frac{k}{c_{ti}r_w^2} - 3.23 - 0.869S - 0.869 \frac{5.18 \times 10^{-5} q}{hr_w k^{0.2}} \right] \quad (28)$$

Quadratic equation is developed to determine flow rate for a given reservoir pressure on transient radial flow case (Refer to Appendix B).

Where

$$a = \frac{1637T}{kh} [0.869D] - \frac{1422TD}{kh}$$

$$b = \frac{1637T}{kh} \left[\log t - \log \frac{k}{c_{ti}r_w^2} - 3.23 - 0.869S \right]$$

$$c = m(p_i) - m(p_{wf})$$

First step is to study the impact of formation permeability to determine skin factor on transient radial flow case. We can calculate a_i and a_{new} from four-point test and single-point test respectively:

$$a_i = \frac{1637 T}{kh} \left[\log t - \log \frac{k}{c_{ti} r_w^2} - 3.23 - 0.869 S_i \right] \text{ (Four-point test)} \quad (29)$$

$$a_{new} = \frac{1637 T}{kh} \left[\log t - \log \frac{k}{c_{ti} r_w^2} - 3.23 - 0.869 S_{new} \right] \text{ (Single-point test)} \quad (30)$$

$$\frac{a_i}{a_{new}} = \frac{\frac{1637 T}{kh} \left[\log t - \log \frac{k}{c_{ti} r_w^2} - 3.23 - 0.869 S_i \right]}{\frac{1637 T}{kh} \left[\log t - \log \frac{k}{c_{ti} r_w^2} - 3.23 - 0.869 S_{new} \right]}$$

The above equation is solved for S_{new} once a_i and a_{new} are estimated from the procedure above. One needs to estimate permeability and skin factor in order to determine a_i and a_{new} (Refer to Appendix E).

$$S_{new} = \frac{1}{0.869} \left[\left(\log t - \log \frac{k}{c_{ti} r_w^2} - 3.23 - 0.869 S_i \right) * \left(\frac{a_{new}}{a_i} \right) - \log \frac{k}{c_{ti} r_w^2} - 3.23 \right] \quad (31)$$

3.3 Determine Skin Factor from Single-Point Test using Linear Flow Case

Linear Flow non-Darcy Flow Case

In this section, the dimensionless pseudopressure, m_{wD} for linear flow with non-Darcy effect in infinite-conductivity fractures is given by the following equation:

$$m_D(\text{Non Darcy}) = \sqrt{t_d} (S - S_f) - D_f q \quad (32)$$

Factor can be determined (Using eq.15). The non-Darcy flow factor, D_f for a fracture well is also determined (Using eq.13). Fracture skin, S_f is determined for infinite-conductivity fracture (Using eq.16). Finally, the flow rate is determined using linear flow with non-Darcy effect and is shown by the following procedures:

$$\frac{Kh}{1422 qT} [m(p_i) - m(p_{wf})] = \sqrt{t_d} [(S + S_f) + D_f q] \quad (33)$$

Then a quadratic equation was developed to determine flow rate for a given reservoir pressure for linear flow case (Refer to table C.1).

Where

$$a = 1422 TD_f$$

$$b = 1422T\sqrt{t_d} - 1422T(S + S_f)$$

$$c = Kh[m(p_i) - m(p_{wf})]$$

Finally a methodology was developed to determine skin factor from single-point test data for linear flow case.

Linear Flow Darcy Flow Case

The dimensionless pseudopressure equation for gas flow in infinite conductivity fracture is determined similar to Camacho equation (Using eq.19). Therefore pseudopressure is obtained by the following equation:

$$m_{wD}(\text{Darcy}) = \sqrt{t_D} \quad (34)$$

Flow rate for linear flow of infinite conductivity fracture is determined using the following procedures (Refer to table C.2):

$$\begin{aligned}
& \frac{kh}{1,422qT} [m(p_i) - m(p_{wf})] \sqrt{t_D} \\
& \frac{kh}{1,422qT} [m(p_i) - m(p_{wf})] (t_D)^{0.5} \\
& q = \frac{kh}{1,422T} \frac{[m(p_i) - m(p_{wf})]}{(t_D)^{0.5}} \quad (35)
\end{aligned}$$

3.4 Impact of Formation Permeability on the Determination of the Skin Factor on Linear Flow Case

Second step is to study the impact of formation permeability to determine skin factor on linear flow case (Refer to Appendix F). One can calculate a_i and a_{new} from four-point test and single-point test respectively.

$$a_i = 1422T\sqrt{t_d} - 1422T(S - S_f)_i \quad (\text{Four-point test}) \quad (36)$$

$$a_{new} = 1422T\sqrt{t_d} - 1422T(S - S_f)_{new} \quad (\text{Single-point test}) \quad (37)$$

$$\frac{a_i}{a_{new}} = \frac{1422T\sqrt{t_d} - 1422T(S - S_f)_i}{1422T\sqrt{t_d} - 1422T(S - S_f)_{new}}$$

The above equation is solved for $(S - S_f)_{new}$ once a_i and a_{new} are calculated from procedure above. One needs to estimate permeability and fracture skin factor in order to calculate a_i and a_{new} (Refer to Appendix F).

$$(S - S_f)_{new} = \frac{a_{new}[\sqrt{t_d} - (S - S_f)_i]}{a_i} \sqrt{t_d} \quad (38)$$

3.5 Impact of Time on Flow Rate for Transient Radial and Linear Flow

It is important to study if time has a significant impact on non-Darcy flow in different cases including transient radial and linear flow. It is possible to illustrate this impact once flow rate is determined in these cases, one can plot flow rate versus time to illustrate this impact (Refer to Appendix D).

CHAPTER 4

RESULTS AND DISCUSSION

The objective of this research was to determine skin factor from single-point test data. The impact of formation permeability to determine skin factor was studied using different cases including transient radial and linear flow. Finally, the non-Darcy flow effects were also considered in all mentioned cases.

4.1 Impact of Formation Permeability on Skin Factor for Transient Radial Flow

Figure 4.1 illustrates the impact of formation permeability to determine skin factor for transient radial flow case.

Figure 4.1: Skin Factor vs. Permeability (Transient Radial Flow)

One can observe that formation permeability will not have a significant impact to determine skin factor for transient radial flow case.

4.2 Impact of Formation Permeability on Skin Factor for Linear Flow

Figure 4.2 illustrates the impact of formation permeability to determine skin factor for linear flow case.

Figure 4.2: Skin Factor vs. Permeability (Linear Flow)

One can observe that formation permeability will have a significant impact to determine skin factor for linear flow case.

4.3 Flow Rate versus Time using Linear and Radial Flow

Flow rate versus time for reservoir pressure of 2000 psia and permeability of 100 md is shown below.

Figure 4.3: Flow Rate vs. Time (P=2000 Psia, K=100 md)

Flow rate versus time for reservoir pressure of 2000 psia and permeability of 200 md is shown below.

Figure 4.4: Flow Rate vs. Time (P=2000 Psia, K=200 md)

Flow rate versus time for pressure of 2000 psia and permeability of 500 md is shown below.

Figure 4.5: Flow Rate vs. Time (P=2000 Psia, K=500 md)

Figures 4.3, 4.4 and 4.5 all illustrate that non-Darcy does not show a considerable change between the time intervals of $t=1$ and $t=4$. This concludes that time does not have a significant impact on linear (Non-Darcy) and radial flow (Non-Darcy) solution. One also can conclude that time will have a significant impact on linear flow (Darcy) solution.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATION

The following conclusions were obtained based on the work done in this study:

1. A methodology to determine skin factor from single-point test data for transient radial and linear flow case were developed.
2. Formation permeability does not have a significant impact in determining skin factor using transient radial flow solution.
3. Formation permeability has a significant impact in determining skin factor using linear flow solution.
4. Time does not have a significant impact on linear and radial flow solution.

It is recommended to study, what causes formation permeability to have a significant impact on the determination of skin factor from single-point test data for linear flow case.

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**APPENDIX A- Determining Skin Factor from a Single-Point Test for Transient
Radial Flow Solution Results**

Figure A.1- z factor, Viscosity, and Compressibility Calculation Program (Aminian, 2003).

Table A.1- z factor, Viscosity, Compressibility Results

	program	program	program	program
t, hrs	C	p, psia	z	μ , cp
0	1.01E-02	100	0.9888498	1.15E-02
0.09	5.11E-03	200	0.9778506	1.16E-02
0.19	3.44E-03	300	0.9670271	1.17E-02
0.29	2.61E-03	400	0.9564064	1.19E-02
0.39	2.53E-03	500	0.9460179	1.20E-02
0.49	1.77E-03	600	0.9358935	1.22E-02
0.99	1.53E-03	700	0.9260672	1.23E-02
1.99	1.35E-03	800	0.9165752	1.25E-02
2.99	1.21E-03	900	0.9074554	1.27E-02
4.99	1.09E-03	1000	0.8987471	1.29E-02
5.99	9.99E-03	1100	0.8904899	1.32E-02
6.99	9.18E-03	1200	0.8827233	1.34E-02
9.99	8.49E-03	1300	0.8754857	0.0136592
11.99	7.88E-03	1400	0.8688135	1.39E-02
13.99	7.33E-03	1500	0.8627393	1.42E-02
15.99	6.85E-03	1600	0.8572918	1.44E-02
17.99	6.41E-03	1700	0.8524943	0.0147049
19.99	6.00E-03	1800	0.848364	0.0149649
21.99	5.63E-03	1900	0.8449116	1.52E-02
23.99	5.29E-03	2000	0.8421413	1.55E-02
25.99	7.85E-03	2100	0.8400503	1.58E-02
27.99	7.53E-03	2200	0.83863	1.61E-02
29.99	4.40E-04	2300	0.8378659	0.0164531
31.99	4.10E-04	2400	0.8377392	1.68E-02
33.99	3.91E-04	2500	0.8382268	1.71E-02
35.99	3.68E-04	2600	0.839303	1.74E-02
37.99	3.48E-04	2700	0.8409398	1.78E-02
47.99	3.28E-04	2800	0.8431082	1.81E-02
48.99	3.10E-04	2900	0.8457785	1.85E-02
49.99	2.94E-04	3000	0.8489212	1.88E-02

Table A.2- Pseudo-Pressure calculation using the z factor, Viscosity, Compressibility**Values from Stimulator**

2p/μz	avg(2p/μz)	dP	avg(2p/μz) x dp	m(p _r), (psi ² /cp)
12292.83149	6146.415745	100	614641.5745	614641.5745
24376.28826	18334.55987	100	1833455.987	2448097.562
3.63E+04	30320.60355	100	3032060.355	5480157.917
47970.58322	42117.75104	100	4211775.104	9691933.021
59500.95612	53735.76967	100	5373576.967	15065509.99
1.05E+05	82338.46626	100	8233846.626	23299356.61
123050.7353	114113.3558	100	11411335.58	34710692.2
139592.4511	131321.5932	100	13132159.32	47842851.52
156084.2471	147838.3491	100	14783834.91	62626686.42
172167.9061	164126.0766	100	16412607.66	79039294.08
187788.9995	179978.4528	100	17997845.28	97037139.36
203015.5071	195402.2533	100	19540225.33	116577364.7
217419.7676	210217.6373	100	21021763.73	137599128.4
231440.1819	224429.9747	100	22442997.47	160042125.9
245140.5117	238290.3468	100	23829034.68	183871160.6
258408.3056	251774.4086	100	25177440.86	209048601.4
271222.277	264815.2913	100	26481529.13	235530130.6
283560.9682	277391.6226	100	27739162.26	263269292.8
295405.2167	289483.0924	100	28948309.24	292217602.1
306737.5189	301071.3678	100	30107136.78	322324738.8
316493.8367	311615.6778	100	31161567.78	353486306.6
325371.1615	320932.4991	100	32093249.91	385579556.5
333684.1505	329527.656	100	32952765.6	418532322.1
341438.5016	337561.3261	100	33756132.61	452288454.8
348644.2979	345041.3998	100	34504139.98	486792594.7
355313.7821	351979.04	100	35197904	521990498.7
361453.2641	358383.5231	100	35838352.31	557828851
366724.1437	364088.7039	100	36408870.39	594237721.4
371515.2057	369119.6747	100	36911967.47	631149688.9
375848.3187	373681.7622	100	37368176.22	668517865.1

Table A.2- Pseudo-Pressure calculation using the z factor, Viscosity, Compressibility**Values from Stimulator (Cont)**

$m(p) \times 10^{-6}$	p/z
0.614641574	101.1275929
2.448097562	204.5302217
5.480157917	310.2291549
9.691933021	418.2322494
15.06550999	528.5312255
23.29935661	641.0985865
34.7106922	755.8846701
47.84285152	872.8143637
62.62668642	991.7842794
79.03929408	1112.660058
97.03713936	1235.2751
116.5773647	1359.429393
137.5991284	1484.890044
160.0421259	1611.393009
183.8711606	1738.648048
209.0486014	1866.342359
235.5301306	1994.148231
263.2692928	2121.730767
292.2176021	2248.755965
322.3247388	2374.898369
353.4863066	2499.850307
385.5795565	2623.326139
418.5323221	2745.069348
452.2884548	2864.853405
486.7925947	2982.486363
521.9904987	3097.808539
557.828851	3210.69356
594.2377214	3321.044677
631.1496889	3428.793709
668.5178651	3533.896904

Table A.3- Non-Darcy Turbulence Coefficient, Apparent Skin Factor and Flowing Bottomhole Pseudo-Pressure Results

D, (Mscf/D) ⁻¹	s'	m(p _{wf}), (psi ² /cp)
3.74945E-05	8.641041079	0.00E+00
3.74945E-05		3.14E+08
3.74945E-05		3.10E+08
3.74945E-05		3.07E+08
3.74945E-05		3.05E+08
3.74945E-05		3.04E+08
3.74945E-05		2.99E+08
3.74945E-05		2.95E+08
3.74945E-05		2.93E+08
3.74945E-05		2.89E+08
3.74945E-05		2.88E+08
3.74945E-05		2.87E+08
3.74945E-05		2.85E+08
3.74945E-05		2.84E+08
3.74945E-05		2.83E+08
3.74945E-05		2.82E+08
3.74945E-05		2.82E+08
3.74945E-05		2.81E+08
3.74945E-05		2.80E+08
3.74945E-05		2.80E+08
3.74945E-05		2.79E+08
3.74945E-05		2.79E+08
3.74945E-05		2.78E+08
3.74945E-05		2.78E+08
3.74945E-05		2.78E+08
3.74945E-05		2.77E+08
3.74945E-05		2.77E+08
3.74945E-05		2.75E+08
3.74945E-05		2.75E+08
3.74945E-05		2.75E+08

Table A.4- Flowing Bottomhole Pressure Results (Time =49.99 hrs)

p_{wf} , psia
1468.42
1471.01
1472.28
1473.08
1473.65
1475.12
1476.16
1476.58
1476.90
1476.96
1476.98
1476.97
1476.91
1476.85
1476.77
1476.69
1476.61
1476.53
1476.45
1476.37
1476.28
1476.21
1476.13
1476.05
1475.97
1475.90
1475.55
1475.52
1475.48

Table A.5- Skin Factor Results

r_d , ft	s'	s
133.8238	8.640078476	2.999037
194.4414	8.640046983	2.999006
240.221	8.640029161	2.998988
278.5764	8.640016674	2.998976
312.2555	8.640007054	2.998966
443.8432	8.639977412	2.998936
629.2722	8.639947985	2.998907
771.3431	8.639930826	2.99889
996.4655	8.639909239	2.998868
1091.756	8.639901541	2.99886
1179.371	8.639895034	2.998854
1409.921	8.639879983	2.998839
1544.62	8.639872292	2.998831
1668.479	8.63986579	2.998825
1783.759	8.639860158	2.998819
1892.028	8.639855191	2.998814
1994.428	8.639850748	2.99881
2091.822	8.639846729	2.998806
2184.878	8.63984306	2.998802
2274.129	8.639839685	2.998799
2360.008	8.639836561	2.998795
2442.869	8.639833652	2.998793
2523.011	8.639830931	2.99879
2600.684	8.639828375	2.998787
2676.104	8.639825965	2.998785
2749.455	8.639823686	2.998783
3090.206	8.639813837	2.998773
3122.236	8.639812968	2.998772
3153.941	8.639812116	2.998771

APPENDIX B- Determining Flow Rate using Transient Radial Flow Solution

Results

**Table B.1- Flow Rates using Pressure Transient Solution Results (Pr=1500 psia and
t =49.99 hrs)**

a	b	c	q , Mscf/D
0.0028791	528.8340093	-86680376.58	104479.1817
0.0028791	557.5201408	-86680376.58	101876.7261
0.0028791	573.7539382	-86680376.58	100446.3942
0.0028791	585.1278091	-86680376.58	99462.09596
0.0028791	593.8908331	-86680376.58	98713.60632
0.0028791	620.8910399	-86680376.58	96460.27469
0.0028791	647.6948942	-86680376.58	94300.13717
0.0028791	663.3252617	-86680376.58	93074.7091
0.0028791	682.987572	-86680376.58	91567.98379
0.0028791	689.9998562	-86680376.58	91039.83205
0.0028791	695.9269734	-86680376.58	90597.12834
0.0028791	709.63647	-86680376.58	89586.02873
0.0028791	716.6423381	-86680376.58	89076.19036
0.0028791	722.5648743	-86680376.58	88648.76162
0.0028791	727.6946765	-86680376.58	88281.16695
0.0028791	732.2191248	-86680376.58	87958.95668
0.0028791	736.2661294	-86680376.58	87672.33008
0.0028791	739.9269058	-86680376.58	87414.33746
0.0028791	743.2687938	-86680376.58	87179.87414
0.0028791	746.3429255	-86680376.58	86965.08179
0.0028791	749.1890422	-86680376.58	86766.97414
0.0028791	751.8386456	-86680376.58	86583.1932
0.0028791	754.3171288	-86680376.58	86411.84502
0.0028791	756.6452602	-86680376.58	86251.38571
0.0028791	758.8402429	-86680376.58	86100.54044
0.0028791	760.9164862	-86680376.58	85958.24452
0.0028791	769.887244	-86680376.58	85347.75327
0.0028791	770.6789974	-86680376.58	85294.20689
0.0028791	771.4547515	-86680376.58	85241.79501

**APPENDIX C- Determining Skin Factor and Flow Rate using Linear
Flow Solution Results**

Table C.1- Skin Factors and Flow Rates using Linear Flow Equation under non-Darcy Results (K=100 md, P=1500 psia and Time= 4 hrs)

s_d	L_f , ft	t_D		D_f
3.00	50.00	2.03E+00	1.35E+00	2.35E-07
3.00	45.00	2.50E+00	1.37E+00	2.66E-07
3.00	40.00	3.17E+00	1.39E+00	3.04E-07
3.00	35.00	4.14E+00	1.42E+00	3.53E-07
3.00	30.00	5.64E+00	1.44E+00	4.18E-07
3.00	25.00	8.12E+00	1.46E+00	5.09E-07
3.00	20.00	1.27E+01	1.48E+00	6.46E-07
3.00	15.00	2.25E+01	1.50E+00	8.74E-07
3.00	10.00	5.07E+01	1.53E+00	1.33E-06
3.00	5.00	2.03E+02	1.55E+00	2.70E-06

a	b	C	q, Mscf/D
1.81E-01	4.24E+06	-8.67E+11	2.03E+05
2.04E-01	4.46E+06	-8.67E+11	1.93E+05
2.33E-01	4.73E+06	-8.67E+11	1.82E+05
2.71E-01	5.07E+06	-8.67E+11	1.69E+05
3.21E-01	5.53E+06	-8.67E+11	1.55E+05
3.91E-01	6.18E+06	-8.67E+11	1.39E+05
4.96E-01	7.15E+06	-8.67E+11	1.20E+05
6.71E-01	8.76E+06	-8.67E+11	9.82E+04
1.02E+00	1.20E+07	-8.67E+11	7.18E+04
2.07E+00	2.17E+07	-8.67E+11	3.98E+04

Table C.2- Skin Factors and Flow Rates using Linear Flow Equation under Darcy

Flow Results (K=100 md, P=1500 psia and Time= 4 hrs)

L_f , ft	t_D	q , Mscf/D	$m(p_{wf})$	L_f , ft
50.00	2.03E+00	4.47E+05	97190784.00	50.00
45.00	2.50E+00	4.03E+05	97190784.00	45.00
40.00	3.17E+00	3.58E+05	97190784.00	40.00
35.00	4.14E+00	3.13E+05	97190784.00	35.00
30.00	5.64E+00	2.68E+05	97190784.00	30.00
25.00	8.12E+00	2.24E+05	97190784.00	25.00
20.00	1.27E+01	1.79E+05	97190784.00	20.00
15.00	2.25E+01	1.34E+05	97190784.00	15.00
10.00	5.07E+01	8.94E+04	97190784.00	10.00
5.00	2.03E+02	4.47E+04	97190784.00	5.00

APPENDIX D- Flow Rate versus Time (Linear Darcy, Linear non-Darcy and Radial non-Darcy)

Figure D.1- Flow Rate vs. Time (P=1000 psia, K=100 md)

Figure D.2- Flow Rate vs. Time (P=1000 psia, K=200 md)

Figure D.3- Flow Rate vs. Time (P=1000 psia, K=500 md)

Figure D.4- Flow Rate vs. Time (P=1500 psia, K=100 md)

Figure D.5- Flow Rate vs. Time (P=1500 psia, K=200 md)

Figure D.6- Flow Rate vs. Time (P=1500 psia, K=500 md)

**APPENDIX E- Impact of Formation Permeability to Determine Skin Factor on
Transient Radial Flow Solution Results**

Table E.1- Impact of Permeability on Skin Factor Results (Radial Flow)

s	k, md	b_i	b_n	S_{new}
0	100	390.278	467.1	0.9988506
0	200	390.278	467.1	1.0669555
0	300	390.278	467.1	1.1067943
0	400	390.278	467.1	1.1350604
0	500	390.278	467.1	1.1569853

**APPENDIX F- Impact of Formation Permeability to Determine Skin Factor on
Linear Flow Solution Results**

Table F.1- Impact of Permeability on Skin Factor Results (Linear Flow)

s_d	s_f	x_f , ft	t_d	s	k , md	b_i	b_n
0	-3	50	5.07E-01	-3	100	1.26203	3.26203
0	-3	50	5.07E-01	-3	200	1.26203	3.26203
0	-3	50	5.07E-01	-3	300	1.26203	3.26203
0	-3	50	5.07E-01	-3	400	1.26203	3.26203
0	-3	50	5.07E-01	-3	500	1.26203	3.26203

$(s_d)_{new}$
2
2.828427125
3.464101615
4
4.472135955