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IMPACT OF SKIN FACTOR ON PERFORMANCE OF GAS RESERVOIRS

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การศึกษานี้เป็นการศึกษาถึงผลกระทบของสกินที่เกิดขึ้นทั้งเชิงกลและนอนดาร์ซีสกินที่ส่งผลต่อประสิทธิภาพในการผลิตและความสามารถในการผลิตจากแหล่งกักเก็บก๊าซธรรมชาติและแหล่งกักเก็บก๊าซธรรมชาติเหลว ในการศึกษานี้ได้ใช้แบบจำลองการไหลของก๊าซจากหลุมผลิต1 หลุม ผลจากการศึกษาโดยใช้แบบจำลองลักษณะการไหลพบว่า สกินที่เกิดขึ้นจากเชิงกลจะทำให้ปริมาณก๊าซที่ผลิตได้จากแหล่งกักเก็บก๊าซธรรมชาติที่มีค่าความซึมผ่านสูง ลดลงเพียงเล็กน้อย แต่จะส่งผลกระทบในระดับปานกลางในแหล่งกักเก็บก๊าซธรรมชาติที่มีค่าความซึมผ่านต่ำ ในการศึกษาแหล่งกักเก็บก๊าซธรรมชาติเหลวพบว่า สกินที่เกิดขึ้นจากเชิงกลจะทำให้ปริมาณก๊าซและก๊าซธรรมชาติเหลวที่ผลิตได้ลดลงในระดับปานกลางในแหล่งกักเก็บก๊าซธรรมชาติเหลวที่มีค่าความซึมผ่านสูงแต่จะส่งผลกระทบมากในแหล่งกักเก็บก๊าซธรรมชาติเหลวที่มีค่าความซึมผ่านต่ำ นอนดาร์ซีสกินจะไม่ส่งผลกระทบต่อปริมาณก๊าซที่ผลิตได้จากแหล่งกักเก็บก๊าซธรรมชาติและแหล่งกักเก็บก๊าซธรรมชาติเหลวเมื่อแหล่งกักเก็บมีค่าสกินแฟคเตอร์น้อยกว่าศูนย์ แต่ผลกระทบจะสูงขึ้นเมื่อค่าสกินแฟคเตอร์มากขึ้น จากการศึกษาพบว่าอัตราการไหลของก๊าซไม่ส่งผลกระทบต่อปริมาณก๊าซและก๊าซธรรมชาติเหลวที่ผลิตได้ แหล่งกักเก็บก๊าซธรรมชาติและก๊าซธรรมชาติเหลวที่มีค่าสกินแฟคเตอร์น้อยกว่าศูนย์จะสามารถรักษาระยะเวลาการผลิตได้นานขึ้นรวมถึงช่วงเวลาที่อัตราการไหลลดลงก็จะสั้นขึ้นด้วย

ผลจากการศึกษาสามารถนำไปใช้เป็นเกณฑ์เบื้องต้นในการประเมินปริมาณก๊าซที่ผลิตได้จากแหล่งกักเก็บแต่ละชนิด นอกจากนี้การประมาณการเพิ่มขึ้นของปริมาณก๊าซที่ผลิตได้สามารถใช้เป็นเกณฑ์ในการประเมินความเหมาะสมของการลงทุนของการกระตุ้นการผลิตในแหล่งกักเก็บดังกล่าวเพื่อลดสกินและเร่งการผลิต ความเข้าใจที่ได้รับจากการศึกษานี้สามารถนำไปประยุกต์ใช้กับแหล่งกักเก็บอื่นๆที่มีลักษณะคล้ายคลึงกันได้

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In this study, the effect of mechanical skin and non-Darcy skin on recovery efficiencies and production performance of dry gas and gas-condensate reservoirs are studied by single well simulation. Results from reservoir simulation runs show that mechanical skin slightly reduces the ultimate gas recovery in dry gas reservoir that have high permeability but have a moderate effect in low permeability reservoir. In gas-condensate reservoir, the mechanical skin moderately reduces the ultimate gas and condensate recoveries in high permeability reservoir but have a large effect in low permeability reservoir. Non-Darcy skin does not have an effect on the ultimate recovery in dry gas and gas-condensate reservoirs when skin factor is negative but the effect is greater when skin factor is high. Gas flow rate does not have an impact on the ultimate gas and condensate recoveries. The reservoir with negative skin factor can maintain longer production plateau period and also shorten the decline period. These effects can be observed in both dry gas and gas-condensate reservoirs.

The result of the study can be used as a preliminary criterion to estimate gas recovery factor of each specific reservoir. In addition, the estimated increment in recovery factor can be used as criteria to justify the investment of stimulation in such reservoir to reduce the skin and accelerate recovery. The understanding gained from this study can be applied to other reservoirs of similar types elsewhere.

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Contents

Page

CHAPTER Page

List of Tables

Page

List of Figures

Page

Page

Page

Page

Page

List of Abbreviations

API	degree (American Petroleum Institute)
bbl	barrel (bbl/d, bpd: barrel per day)
BHP	bottomhole pressure
CGR	condensate gas ratio
D	Darcy
K	kilo- (10^3 or 1,000)
M	thousand (1,000 of petroleum unit),
MSCF/D	thousand standard cubic feet per day
OGIP	Original Gas In-Place
PVT	pressure-volume-temperature
PSIA or psia	pounds per square inch absolute
RF	Recovery Factor
SCAL	special core analysis
SGAS	gas saturation
STB or stb	stock-tank barrel
STB/D	stock-tank barrels per day
SWAT	water saturation
THP	Tubing Head Pressure

Nomenclature

A	cross-section area
B_g	gas Formation Volume Factor
d	differential operator
D	non-Darcy coefficient
h	height
k	permeability
k_{rg}	gas relative permeability
k_{rw}	water relative permeability
p	pressure
q	volumetric flow rate
q_{sc}	volumetric flow rate at standard conditions
r	radial direction
R	universal gas constant
S	Skin factor
T	temperature
V	fluid volume
x	[1]distance in x direction, [2] x direction
y	y direction
z	[1] compressibility factor, [2] z direction

GREEK LETTER

ϕ	porosity
ρ	fluid density (mass/volume)
μ	fluid viscosity
Δ	difference operator
∂	partial differential operator
v	flow velocity
β	high velocity flow constant

SUBSCRIPTS

a	damaged zone
g	gas
i	initial
e	reservoir radius
o	oil
p	perforation
r	radial
s	skin zone
sc	standard condition
w	wellbore radius
$weff$	effective wellbore radius

CHAPTER I

INTRODUCTION

Oil and gas wells may have permeability reduction around the wellbore due to fluid invasion during drilling and completion operations. This is generally referred to as formation damage. Formation damage around the wellbore causes additional pressure drop. The impact of permeability impairment around the wellbore owing to drilling and production operations is quantified in terms of mechanical skin factor due to damage.

Multiphase flow in the formation may evolve because of gas/water coning around the wellbore, gas evaporation from liquid hydrocarbon phase, and liquid drop out from gas-condensate reservoir. Compared to single phase fluid flow, multiphase flow in the formation creates additional pressure drop owing to relative permeability effect. If the multiphase flow is intensified in the near wellbore region only and there exists a nearly single phase flow in the formation away from the wellbore, then the impact of multiphase flow may be formulated in terms of multiphase pseudo skin factor.

When the local fluid velocities are high, the fluid flow in porous media does not obey Darcy's Law. At high flow velocities, the inertia pressure gradients increase quadratically. Hence, high-velocity flow results in additional pressure losses in the formation. The extra pressure drop due to high-velocity flow is quantified as the rate-dependent or non-Darcy skin factor.

In many cases, oil and gas wells are under the influence of several skin factors such as mechanical skin, high-velocity skin, partial penetration skin, condensate blockage skin, etc. The combined effects of all skin factors lead to a total skin factor for the well.

The additional pressure drop in the near wellbore region can be decreased by stimulation operations such as acidizing. The formation permeability around the wellbore will be improved and resulting in the improvement of well productivity.

The main purpose of this study is to investigate the impact of skin damage on recovery efficiencies and production performances in different reservoir fluid systems and to study the relationship between skin factor and gas recovery and production performance from dry gas and gas-condensate reservoirs which will be useful in the industry in terms of productivity improvement, recovery improvement, and reservoir management.

CHAPTER II

LITERATURE REVIEW

Tang *et al.* [1] studied the effects of formation damage and high-velocity flow on the productivity of perforated horizontal wells. The study is based on a 3D semi-analytical model incorporating the effects of selective completion, nonuniform drilling and perforation damages, and high-velocity flow. Their results show that it is important to minimize the extent of the damaged zone around the wellbore. To obtain reasonable well productivity, the perforations need to be extended beyond the damaged zone. It is also found that for openhole oil and gas wells and perforated oil wells, the high-velocity flow effect is small and negligible. However, for perforated gas wells, the high-velocity effect reduces the productivity significantly. Additionally, it is found that small open-to-flow areas caused by poor perforation may cause non-Darcy flow and reduce the well productivity by 10 to 15%.

Tavares *et al.* [2] studied the combined effect of formation damage and non-Darcy flow in naturally fractured reservoirs using simplified analytical solutions and a 2D numerical simulator. The effects of physical skin damage and non-Darcy flow were measured in terms of calculated damage from the drawdown test results. The results showed that the physical skin damage greatly accentuates the non-Darcy effects. For similar flow rates, the calculated effective damage was higher when the physical skin damage was higher.

Ahmed *et al.* [3] studied wellbore liquid blockage in gas-condensate reservoirs and mechanism of gas injection process in improving gas-well productivity due to condensate blocking in the near wellbore region. The effectiveness of lean gas, N_2, and CO_2 Huff 'n' Puff injection technique in removing the liquid dropout accumulation around the wellbore is evaluated. Results of the study show importance of selecting the optimum injection volume and pressure for successful use of the Huff 'n' Puff process in gas condensate reservoirs.

Al-Anazi *et al.* [4] studied the impact of condensate blockage and completion fluid on gas productivity in gas-condensate reservoirs. The results show that reductions of 70% to 95% in gas relative permeability were seen in core samples due to condensate blockage. This study also quantified the required methanol treatment volumes to increase gas relative permeability at lab conditions, which could be extrapolated to field conditions. The reduction in gas relative permeability was more pronounced during two-phase flow in the presence of water saturation due to the dual effect of condensate and water blockage. Methanol was effective in removing water from the cores. A mixture of isopropyl alcohol and methanol yielded similar favorable results as pure methanol. In summary, the evaluated solvents were all effective in removing condensate blockage from the core, delayed condensate accumulation, and enhanced gas productivity.

Whitson and Kuntadi [5] studied gas condensate development from Khuff reservoirs in the Middle East, namely Ghawar Khuff. In this work, they quantified the expected performance of Khuff gas-condensate field and estimated the deliverability impairment from condensate blockage. Results of the study showed that stimulation skin and the magnitude of condensate blockage are the key parameters that determine production performance. Stimulation skin of 0 to -5 was studied. The results showed that 3 years of additional plateau period is achieved for each additional negative-skin unit.

From all the above studies, only a small amount of the reviewed literatures directly addressed the topic of impact of formation damage on different reservoir fluid systems. Therefore, it is decided to investigate this topic in details.

CHAPTER III

THEORY AND CONCEPT

3.1 Assumptions

The main objective of this study is to investigate the impact of skin damage on recovery efficiencies and production performance in different reservoir systems. In order to confine the investigation to a manageable condition, the following assumptions are made:

1. Gas reservoir has a depletion-drive mechanism.
2. The reservoir is homogeneous in flow properties.

3.2 Skin Factor and Related Concepts

Skin factor is a dimensionless form used to describe extra pressure change in a zone around the wellbore in addition to the pressure change caused by natural flow of fluid in the reservoir. There are several reasons that cause the pressure change in the skin zone to be different from the pressure change in the rest of the reservoir. One of the more common reasons is due to the difference in permeability between the reservoir and the skin zone. Fluid invasion during drilling and completion operations cause formation damage near the wellbore resulting in lower value of permeability which in turn results in higher pressure drop from nonideal flow at or near the wellbore. There are different sources of nonideal flow such as:

- Formation damage
- Limited completion interval
- Perforation effects
- High-velocity flow (turbulence)
- Condensate blockage near the wellbore
- Sand control

The skin factor is defined as a dimensionless pressure as follows:

$$S = \frac{2\pi kh}{q_{sc}B\mu}\Delta P_s \ . \tag{3.1}$$

In oil field units,

$$S = \frac{kh}{141.2q_{sc}B\mu}\Delta P_s \ , \tag{3.2}$$

where ΔP_s is a pressure drop due to skin. It is the difference between the actual pressure and the pressure that would have been if there were no skin.

A radial flow is considered when the effect of the altered permeability and radius of the altered zone are studied. From Darcy's law, the flow of fluid in a porous medium can be written as

$$\frac{q_{sc}B}{A} = \frac{k}{\mu}\frac{dp}{dr} \ . \tag{3.3}$$

Substituting the area open to flow at the wellbore, we obtain

$$\frac{q_{sc}B}{2\pi rh} = \frac{k}{\mu}\frac{dp}{dr} \ . \tag{3.4}$$

Integrating both sides, we have

$$\int_{r_1}^{r_2}\frac{q_{sc}B}{r}dr = \frac{2\pi kh}{\mu}\int_{p_1}^{p_2}dp \ . \tag{3.5}$$

$$q_{sc}B\left[\ln r\right]_{r_2}^{r_1} = \frac{2\pi kh}{\mu}\left(p_2 - p_1\right) \ . \tag{3.6}$$

Rearranging the equation, we obtain

$$p_2 - p_1 = \frac{q_{sc}B\mu}{2\pi kh}\ln\frac{r_1}{r_2} \ . \tag{3.7}$$

The pressure drop across the skin zone can be expressed as

$$p_s - p_w = \frac{q_{sc}B\mu}{2\pi k_s h}\ln\frac{r_s}{r_w} \ , \tag{3.8}$$

where

p_s = pressure at r_s

p_w = pressure at r_w

In the reservoir, the pressure drop is

$$p_e - p_s \quad = \quad \frac{q_{sc} B\mu}{2\pi kh} \ln \frac{r_e}{r_s} \ . \tag{3.9}$$

$$p_e - p_w \quad = \quad \frac{q_{sc} B\mu}{2\pi kh} \left[\frac{k}{k_s} \ln r_s - \frac{k}{k_s} \ln r_w + \ln \frac{r_e}{r_s} \right] . \tag{3.10}$$

If there were no skin zone, the pressure drop in the reservoir would be

$$p_e - p_w \quad = \quad \frac{q_{sc} B\mu}{2\pi kh} \ln \frac{r_e}{r_w} \ . \tag{3.11}$$

The difference between the right hand side of Equation (3.10) and the right hand side of Equation (3.11) is the pressure drop caused by the skin, which can be written as

$$\Delta p_s \quad = \quad \frac{q_{sc} B\mu}{2\pi kh} \left[\frac{k}{k_s} \ln r_s - \frac{k}{k_s} \ln r_w + \ln \frac{r_e}{r_s} - \ln \frac{r_e}{r_w} \right] . \tag{3.12}$$

Rearranging the equation, we obtain

$$\frac{2\pi kh}{q_{sc} B\mu} \Delta p_s \quad = \quad \frac{k}{k_s} \ln r_s - \frac{k}{k_s} \ln r_w - \ln r_s + \ln r_w \ . \tag{3.13}$$

The left hand side of Equation (3.13) is actually the definition of the skin factor. Therefore,

$$s \quad = \quad \left(\frac{k}{k_s} - 1 \right) \ln \frac{r_s}{r_w} \ . \tag{3.14}$$

Another way to quantify the skin is to use the concept of effective wellbore radius which can be determined by equating an equation describing the pressure drop with skin and an equation without the skin term as follows:

$$p_e - p_w \quad = \quad \frac{q_{sc} B\mu}{2\pi kh} \ln \frac{r_e}{r_w} + \Delta p_s = \frac{q_{sc} B\mu}{2\pi kh} \ln \frac{r_e}{r_{weff}} , \tag{3.15}$$

where r_{weff} is the effective wellbore radius.

Substituting Δp_s in term of skin s, Equation (3.15) becomes

$$\frac{q_{sc} B\mu}{2\pi kh} \ln \frac{r_e}{r_w} + \frac{q_{sc} B\mu}{2\pi kh} s = \frac{q_{sc} B\mu}{2\pi kh} \ln \frac{r_e}{r_{weff}} \ . \tag{3.16}$$

As a result,

$$r_{weff} \quad = \quad r_w e^{-s} \ . \tag{3.17}$$

The effective wellbore radius is the radius that the wellbore effectively takes in fluid from the reservoir if we do not account for extra pressure drop caused by the skin. If the skin is positive (damaged well), r_{weff} is smaller than the actual wellbore radius. Therefore, it is more difficult to flow reservoir fluid into the wellbore creating a higher pressure drop. If the skin is negative (stimulated well), r_{weff} is larger than the actual wellbore radius. Thus, the reservoir fluid can flow into the wellbore more easily resulting in lower pressure gradient.

3.3 Non-Darcy Skin

At higher flow rates, in addition to the viscous force component represented by Darcy's equation, there is also inertial force acting due to convective accelerations of the fluid particles in passing through the pore spaces. Under these circumstances, the appropriate flow equation is that of Forchheimer [7]. The Forchheimer equation adds a second velocity term to Darcy's equation, giving

$$\frac{dp}{dr} = av + bv^2 . \tag{3.18}$$

At low velocities, bv^2 is neglible and Darcy's law applies. At high velocities av is neglible and pressure drop is proportional to the square of velocity (analogous to turbulent flow in pipe). The constant a is defined by Darcy's law $\left(a = \frac{\mu}{k}\right)$, and the constant b consists of fluid density and an empirical constant β, giving

$$\frac{dp}{dr} = \frac{\mu}{k}v + \beta\rho v^2 . \tag{3.19}$$

The Forchheimer equation is generally expressed as radial Darcy flow equation with a rate-dependent skin Dq, where D is proportional to the high-velocity-flow constant β. The contribution of the high-velocity-flow throughout a reservoir with uniform permeability is expressed by D_R [6], where for gas wells,

$$D_{Rg} = 2.222\times10^{-18}\frac{\nu_g kh}{\mu_g r_w h_p^2}\beta_R , \tag{3.20}$$

where β_R is a property of the reservoir rock, which can be estimated from

$$\beta_R \quad = \quad 2.73\times10^{10}\,k^{-1.1045} \;. \tag{3.21}$$

and k is the formation permeability.

Since most of the pressure drop is localized near the wellbore, a better value of permeability to use for calculating β_R is the effective permeability k_a of the considered phase near the wellbore. If a region near the wellbore has altered permeability to some radius r_a (which can be determined or estimated), then the correct expression for high-velocity flow is $D = D_a + D_R$, where for gas wells,

$$D_{ag} \quad = \quad 2.222\times10^{-18}\,\frac{\nu_g kh}{\mu_g h_p^2}\left(\frac{1}{r_w}-\frac{1}{r_a}\right)\beta_a \;. \tag{3.22}$$

where β_a is given by

$$\beta_a \quad = \quad 2.73\times10^{10}\,k_a{}^{-1.1045} \;. \tag{3.23}$$

The high velocity effect beyond the altered radius is calculated using Equation (3.23) for β_R and the expression $\left(\frac{1}{r_a}-\frac{1}{r_e}\right)$ instead of $\left(\frac{1}{r_w}\right)$ in Equation (3.20). Usually, if a damaged zone exists, the altered zone high-velocity term D_a is much larger than D_R and we can assume $D \cong D_a$. #

3.4 Reservoir simulation

Reservoir simulation is used in this study. In general, it is used to determine reservoir performance and reservoir management. The reservoir model is constructed by an amount of established volume elements namely ‘grid blocks’ that represent the geological reservoir construction. Appropriate equations were used to replace the partial differential equations that describe fluid flow in the reservoirs and can be solved numerically. Input data are required for each grid block. Similarly, well locations and well conditions have to be specified. The required flow in/out rate also has to be specified. The appropriate equations are solved for pressures and saturations for each block as well as the production of each phase from each well.

CHAPTER IV

RESERVOIR SIMULATION MODEL

A single-layered hypothetical reservoir model is set up using reservoir characteristics of a typical reservoir in the Gulf of Thailand. This chapter will describe construction of reservoir model and assumptions used in the study.

4.1 Grid Model

ECLIPSE100 black oil simulation is used as a tool to investigate the impact of skin factor on performance of gas reservoirs. As this study will focus on the impact of skin factor, the hypothetical reservoir model is constructed with radial grid type in order to be able to monitor behavior of reservoir around the wellbore. The model is constructed with homogeneous properties. Sensitivities are performed to identify major uncertainty and impact of the main parameters. Summarized data for reservoir model including phase equilibrium data and reservoir and fluid properties are described below.

a) Case Definition

Simulator:	Black Oil	
Model Dimensions:	Number of cells in r-direction = 50	
	Number of cells in θ-direction = 12	
	Number of cells in z-direction = 50	
Grid type:	Radial Grid	
Geometry type:	Block Centered	

b) Grid

Properties:	Porosity	= 20%
	Permeability	k-r = 150 mD
		k-θ = 150 mD
		k-z = 15 mD

Geometry: r-grid block size follows logarithmic increment

θ-grid block size = 30 º

z-grid block size = 6.56166 ft.

inner radius = 0.2552 ft.

outer radius = 1312.366 ft.

Depth of Top face 4921.25 ft.

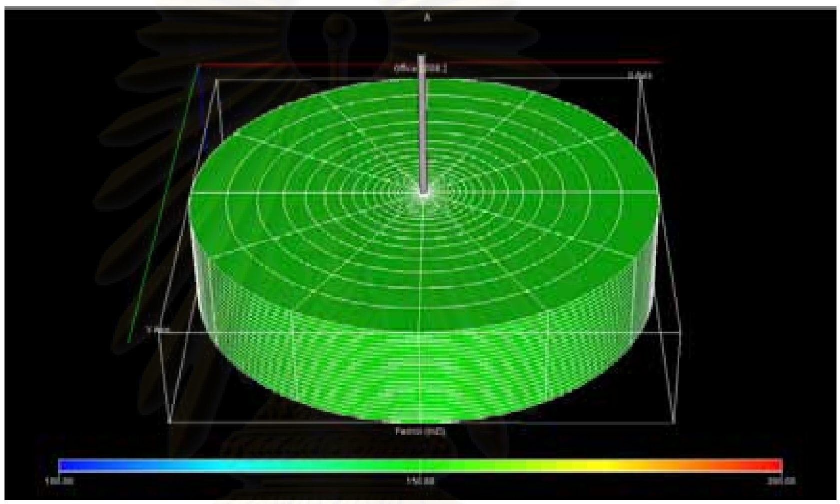


Figure 4.1: Reservoir model

The radii of cells in the r-direction follow a logarithmic increment as shown in Table 4.1.

Table 4.1: Grid block size in the r-direction

NR	DR (ft)	NR	DR (ft)	NR	DR (ft)	NR	DR (ft)	NR	DR (ft)
1	0.04756	11	0.26273	21	1.4513	31	8.0163	41	44.28
2	0.05673	12	0.3117	22	1.7217	32	9.5104	42	52.533
3	0.06695	13	0.36979	23	2.0426	33	11.283	43	62.324
4	0.07942	14	0.43871	24	2.4233	34	13.386	44	73.94
5	0.09423	15	0.52048	25	2.875	35	15.881	45	87.721
6	0.11179	16	0.61748	26	3.4108	36	18.84	46	104.07
7	0.13262	17	0.73257	27	4.0465	37	22.352	47	123.47
8	0.15734	18	0.86911	28	4.8007	38	26.518	48	146.48
9	0.18666	19	1.0311	29	5.6955	39	31.46	49	173.78
10	0.22146	20	1.2233	30	6.757	40	37.324	50	206.17

It is assumed that the radius of damage zone is 1 m. around the wellbore. Based on Equation (3.14), once skin factor is determined, k_s for each scenario can be calculated. The summary of k_s for each scenario is shown in Table 4.2.

Figure 4.2 shows the permeability of the model in case of negative skin factor of -3. The permeability is set to be 392 mD for a distance of 1 m. around wellbore while permeability in the reservoir is set to be 150 mD.

Table 4.2: Summary of k_s in different skin factor scenarios

k **(mD)**	k_s **(mD)**		
	S **= -3**	***S*** **= 5**	***S*** **= 10**
10	26	5	3
50	131	25	16
150	392	74	49

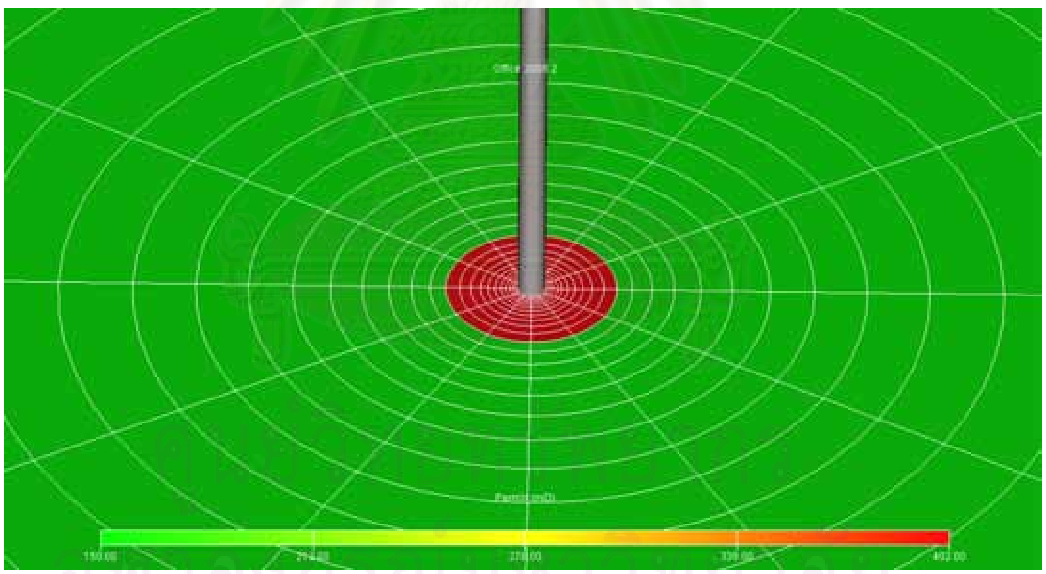


Figure 4.2: Permeability map for reservoir with S = -3

4.2 Fluid, Rock, and SCAL Properties

4.2.1 Fluid and Rock Properties

As this study will focus on the impact of skin factor on gas recovery efficiency and production performance from reservoirs with different reservoir fluid types, the fluids chosen for this study are dry gas and gas-condensate. PVT of dry gas and gas-condensate reservoirs are shown in Figures 4.3 – 4.5.

Table 4.3: Dry gas PVT properties and rock properties

Water Properties	Reference pressure (P_{ref})	2164	psia
	Water FVF at P_{ref}	1.065468	rb/stb
	Water compressibility	4.048251E-6	1/psi
	Water viscosity at P_{ref}	0.1825834	cp
Fluid Specific Gravities	Oil API gravity	45	
	Water specific gravity	0.999014	
	Gas gravity	0.7	
Rock Properties	Reference pressure	3000	psia
	Rock compressibility	8.430027E-6	1/psi

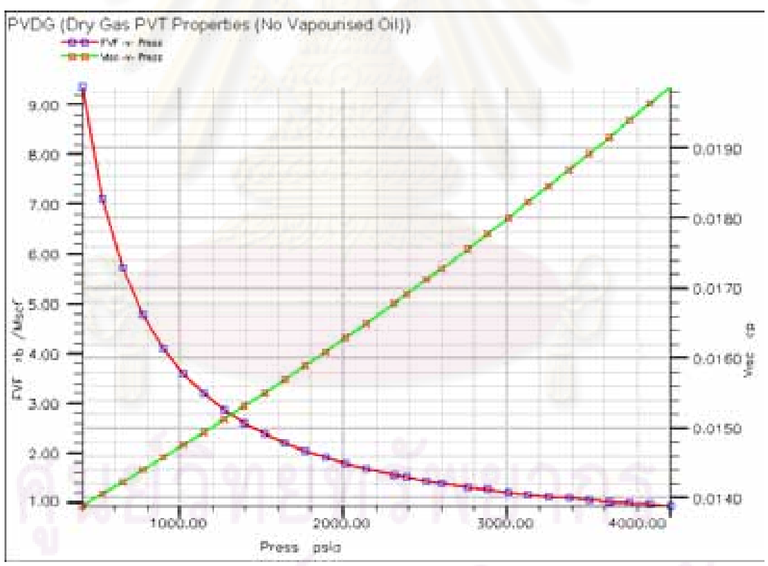


Figure 4.3: Formation volume factor and viscosity of dry gas reservoir

Table 4.4: Gas-condensate reservoir PVT properties and rock properties

Water Properties	Reference pressure (P_{ref})	4440	psia
	Water FVF at P_{ref}	1.03	rb/stb
	Water compressibility	2.8269E-6	1/psi
	Water viscosity at P_{ref}	0.3	cp
Fluid Specific Gravities	Oil density	49.992	lb/ft^3
	Water density	63.801	lb/ft^3
	Gas density	0.061847	lb/ft^3
Rock Properties	Reference pressure	3000	psia
	Rock compressibility	8.430027E-6	1/psi
Fluid Property	Dew point pressure	1996	psia

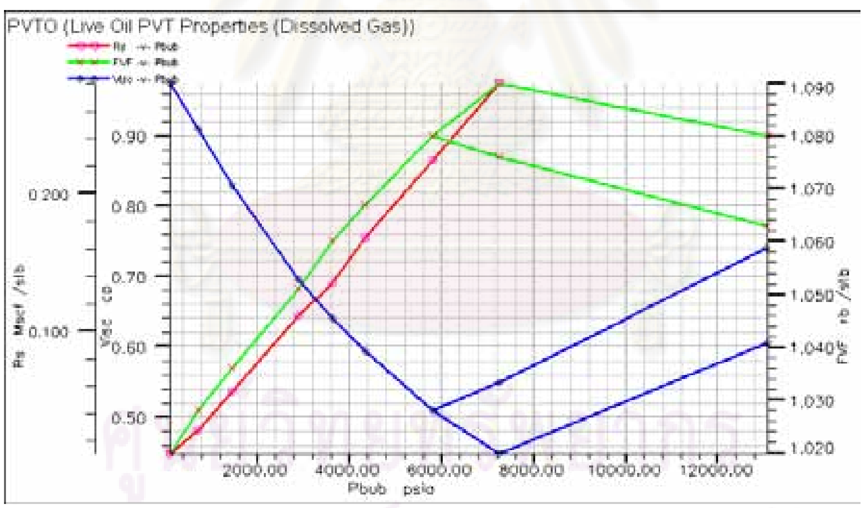


Figure 4.4: Oil PVT properties in gas-condensate reservoir

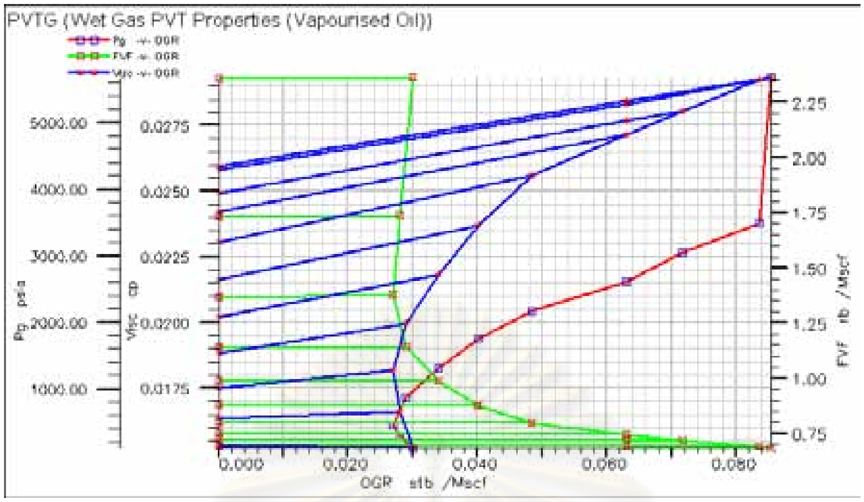


Figure 4.5: Wet gas PVT properties in gas-condensate reservoir

4.2.2 SCAL Properties

Relative permeabilities used in the model are constructed based on SCAL data. Although there is no aquifer present in the reservoir in this study, relative permeabilities are still needed to allow for connate water to expand and flow. In dry gas reservoir, connate water saturation of 0.25 and residual gas saturation of 0.27 are applied. Corey exponent for k_{rg} and k_{rw} curves are determined at 2.5. End points of gas relative permeability (k_{rg}) and water relative permeability (k_{rw}) of 1.00 are applied to the correlation in simulation program. Table 4.5 shows gas-water relative permeability generated based on above information. The gas-water relative permeability curve is shown in Figure 4.6.

Table 4.5: Water saturation versus water and gas relative permeabilities.

S_w	k_{rw}	k_{rg}
0.13	0	1
0.25	0	0.5724
0.31	0.0032	0.41
0.37	0.0183	0.2789
0.43	0.0503	0.1768
0.49	0.1032	0.1012
0.55	0.1803	0.0493
0.61	0.2845	0.0179
0.67	0.4182	0.0032
0.73	0.584	0
1	1	0

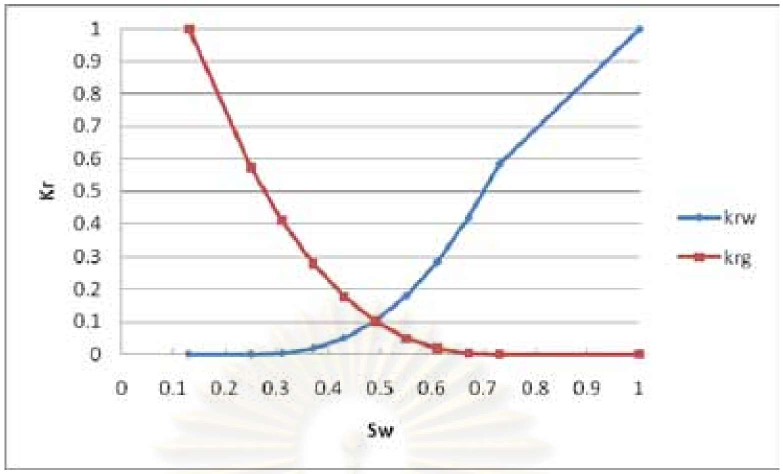


Figure 4.6: Gas-water relative permeability curve

Relative permeabilities for gas-condensate reservoir used in this study are shown in Tables 4.6-4.8 and Figures 4.7-4.10.

Table 4.6: Water saturation versus water relative permeability

S_w	k_{rw}
0.25	0
0.28	0
0.30	0.0060
0.35	0.0270
0.40	0.0675
0.45	0.1260
0.50	0.2055
0.55	0.3075
0.60	0.4320
0.65	0.5790
0.70	0.7500
1.00	1.0000

Table 4.7: Oil saturation versus oil relative permeabilities when oil and water and oil, gas, and connate water are present.

S_0	k_{row}	k_{rowg}
0	0	0
0.2	0	0
0.3	0.05	0.05
0.4	0.15	0.15
0.5	0.25	0.25
0.6	0.45	0.45
0.7	0.70	0.70
0.8	1.00	1.00

Table 4.8: Gas saturation versus gas relative permeability

S_g	k_{rg}
0	0
0.30	0
0.35	0.008
0.40	0.020
0.45	0.030
0.50	0.050
0.55	0.100
0.60	0.150
0.65	0.228
0.70	0.444
0.75	0.800

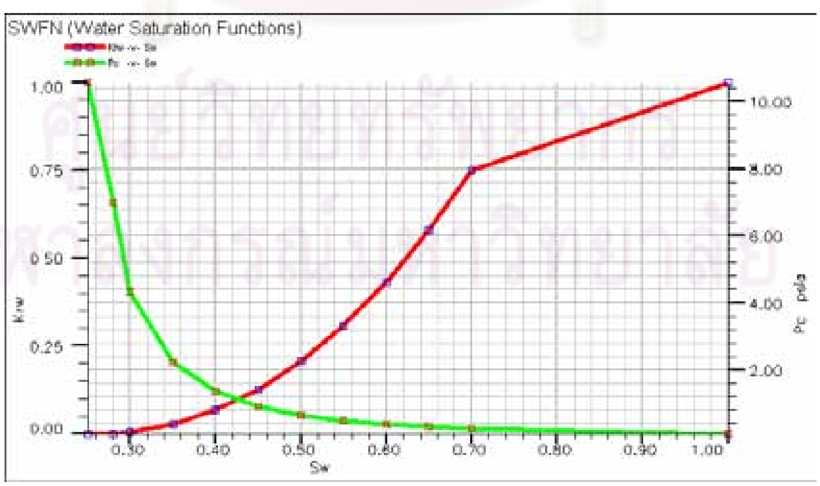


Figure 4.7: Water relative permeability and capillary pressure as a function of water saturation

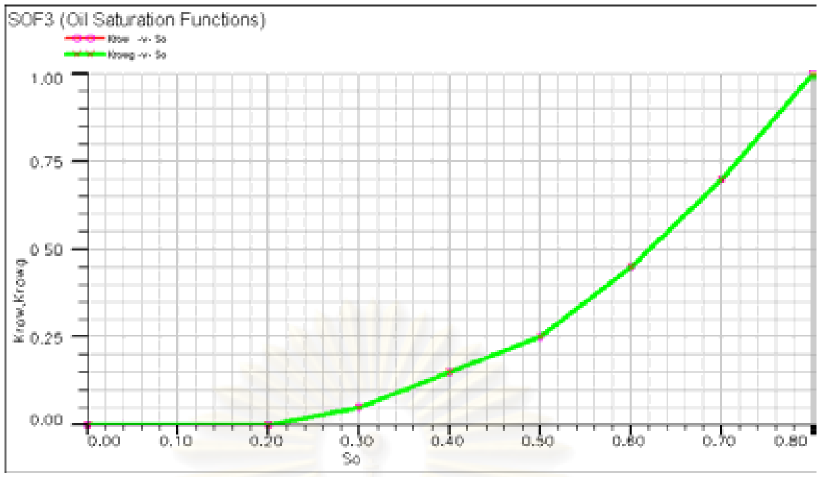


Figure 4.8: Oil relative permeability for a system with oil, water, and gas as a function of oil saturation

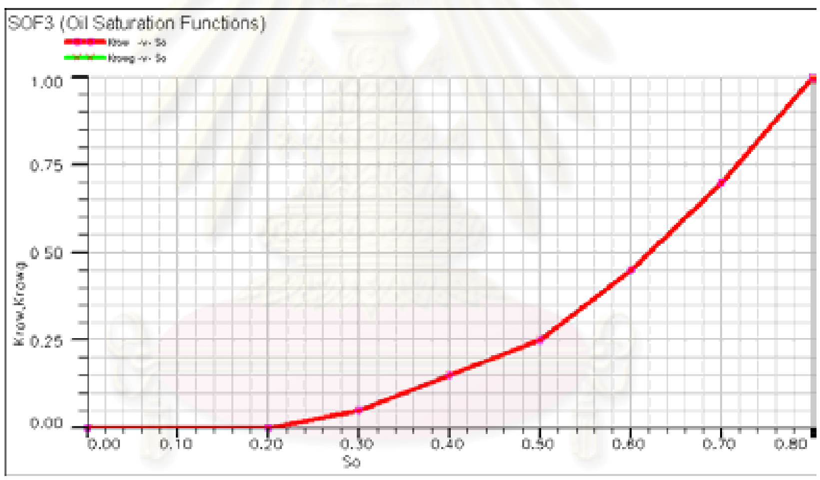


Figure 4.9: Oil relative permeability for a system with oil and water as function of oil saturation

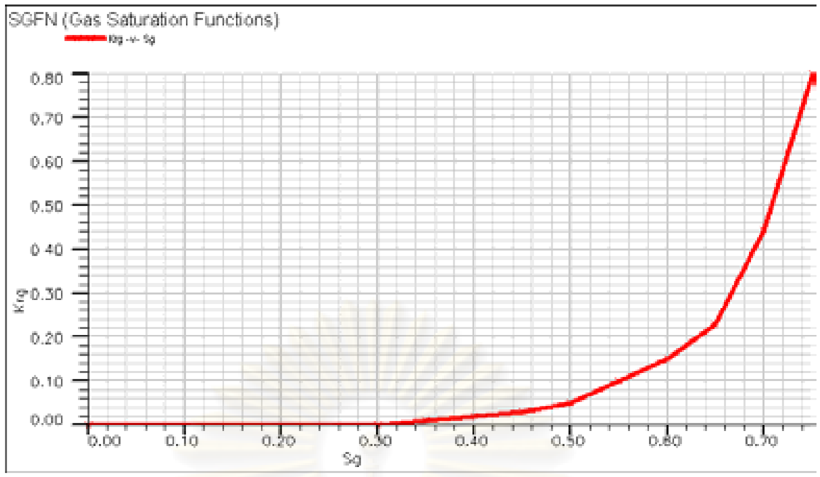


Figure 4.10: Gas relative permeability as a function of gas saturation

4.3 Vertical Lift Performance

Vertical lift performance (VLP) tables which cover possible range of gas flow rate, tubing head pressure, and water-gas ratio were generated from Petroleum Expert 2 correlation in PROSPER software program. The gas flow rate, tubing head pressure, and water-gas ratio are varied as summarized in Table 4.9.

Table 4.9: Range of parameters in Vertical Lift Performance (VLP)

Parameters	**Range**
Gas flow rate (MMscf/d)	0.1-50
Tubing head pressure (psi)	435-1740
Water gas ratio (Stb/MMscf)	1-1000

4.4 Wellbore Completion

One vertical well is placed at the middle of the reservoir to produce gas or condensate. The well is completed with a monobored well design which is widely used in the Gulf of Thailand. The production casing is 3½ inches with an inside diameter of 2.992 inches. The perforation interval is from the top to the bottom of reservoir. The schematic of wellbore is shown in Figure 4.11.

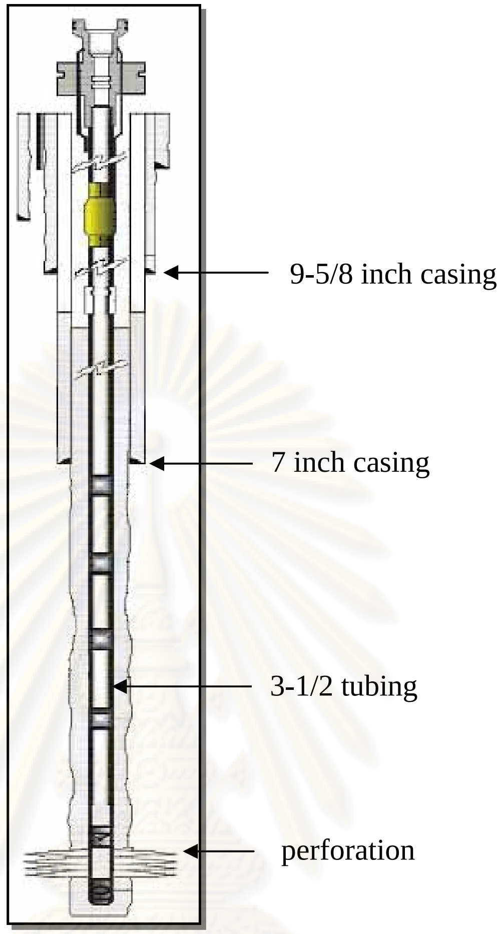


Figure 4.11: Well schematic diagram

4.5 Simulation Cases

The impact of skin factor on gas recovery efficiency and production performances will be investigated from the results of numerous simulation runs with different parameters. The parameters studied can be separated into 2 main groups. The first group is reservoir variables which are the reservoir properties that are given by nature and cannot be controlled (uncontrolled variables). This study will concentrate on three reservoir variables which are mechanical skin, reservoir permeability, and non-Darcy skin. Three mechanical skin factors considered in this study are -3, 5, and 10 which are typical values for stimulated well and damaged wells. Permeability of the reservoir to be investigated in this study is varied from 10, 50, and 150 mD while non-Darcy skin effect is investigated by varying three different values of non-Darcy skin coefficient (*D*-factor).

Non-Darcy skin coefficient applied in the model is calculated based on Equation (3.22) and referred to as “base estimate”. However, the magnitude of calculated non-Darcy skin coefficient (base estimate) is low and the results from the cases with and without non-Darcy skin coefficient are not significantly different. In order to be able to see the effect of non-Darcy skin, a higher non-Darcy skin coefficient is applied. This higher non-Darcy skin coefficient which referred to as “high estimate” is equal to 10 times higher than the calculated non-Darcy skin coefficient from base estimate. With this higher non-Darcy skin coefficient, the effect of non-Darcy skin on production performance can be observed. The summary of non-Darcy skin coefficients for base estimates and high estimates are shown in Table 4.10 and 4.11 These *D*-factors will be used to calculate non-Darcy skin in addition to mechanical skin.

Table 4.10: Summary of base estimates non-Darcy skin coefficients

k **(mD)**	**Non-Darcy skin coefficient, *D* (Day/Mscf)**		
	***S* = -3**	***S* = 5**	***S* = 10**
10	4.9E-05	3.1E-04	4.9E-04
50	4.1E-05	2.6E-04	4.1E-04
150	3.7E-05	2.3E-04	3.7E-04

Table 4.11: Summary of high estimates non-Darcy skin coefficients

k **(mD)**	**Non-Darcy skin coefficient, *D* (Day/Mscf)**		
	***S* = -3**	***S* = 5**	***S* = 10**
10	4.9E-04	3.1E-03	4.9E-03
50	4.1E-04	2.6E-03	4.1E-03
150	3.7E-04	2.3E-03	3.7E-03

The second group is production variables which are the parameters that can be controlled (controlled variables). The production variable that is concentrated in this study is initial gas flow rate because of its importance on the production strategy. Three initial gas flow rates of 2, 10, and 20 MMscf/d are used to see the effect of flow rate on production performance and gas recovery.

In summary, there are a total of 162 cases to be run in this study to see the effect of each parameter on recovery efficiency and production performance of gas and gas-condensate reservoirs. Summary of simulation cases for each permeability value and each reservoir fluid is shown in Table 4.12.

Table 4.12: Summary of simulation cases for each permeability case

S	**Q_i (MMscf/d)**	**Non-Darcy skin coefficient, *D* (Day/Mscf)**
-3	2	None
		Base estimates
		High estimates
	10	None
		Base estimates
		High estimates
	20	None
		Base estimates
		High estimates
5	2	None
		Base estimates
		High estimates
	10	None
		Base estimates
		High estimates
	20	None
		Base estimates
		High estimates
10	2	None
		Base estimates
		High estimates
	10	None
		Base estimates
		High estimates
	20	None
		Base estimates
		High estimates

CHAPTER V

RESULTS AND DISCUSSION

In this chapter, an investigation of the effect of skin damage in dry gas and gas-condensate systems are carried out. The effects of uncontrolled variables (mechanical skin, non-Darcy skin, and permeability) and controlled variable (initial gas production rate) on recovery efficiency and production performance are also investigated. The results are discussed in terms of recovery efficiency and time required to reach the expected ultimate recovery. This will help us to determine the optimized strategy to produce gas from different fluid systems and different reservoir properties.

5.1 Dry Gas Reservoir

5.1.1 Effect of Mechanical Skin

The well production is controlled at tubing head pressure of 500 psia, and the economic rate cut-off is 0.5 MMscf/d. Results of reservoir simulation runs with various mechanical skin factors and reservoir permeabilities are summarized in Table 5.1 and Figures 5.1-5.2.

It can be observed that mechanical skin factor does have effects on both ultimate recovery and time required to reach ultimate recovery for all permeability cases. In 10-mD reservoir, the difference in ultimate recovery between the minimum and maximum mechanical skin factor is 3.7% while the difference in production time required is 7.4 years. Nevertheless, results from simulation runs show that the effect of mechanical skin on ultimate gas recovery cannot be significantly observed in reservoirs with permeabilities of 50 and 150 mD. The difference in ultimate gas recovery between the minimum and maximum mechanical skin factor is less than 1% in reservoirs with permeabilities of 50 and 150 mD cases.

Table 5.1: Recovery factor and time required to reach ultimate recovery for different mechanical skins and reservoir permeabilities

S	*k* (mD)	RF (%)	Time Required (years)
-3	10	73.26	9.4
	50	74.25	6.9
	150	74.45	6.5
0	10	72.43	11.2
	50	74.08	7.4
	150	74.39	6.7
5	10	71.17	13.8
	50	73.82	8.1
	150	74.28	6.9
10	10	69.59	16.8
	50	73.50	8.8
	150	74.17	7.1

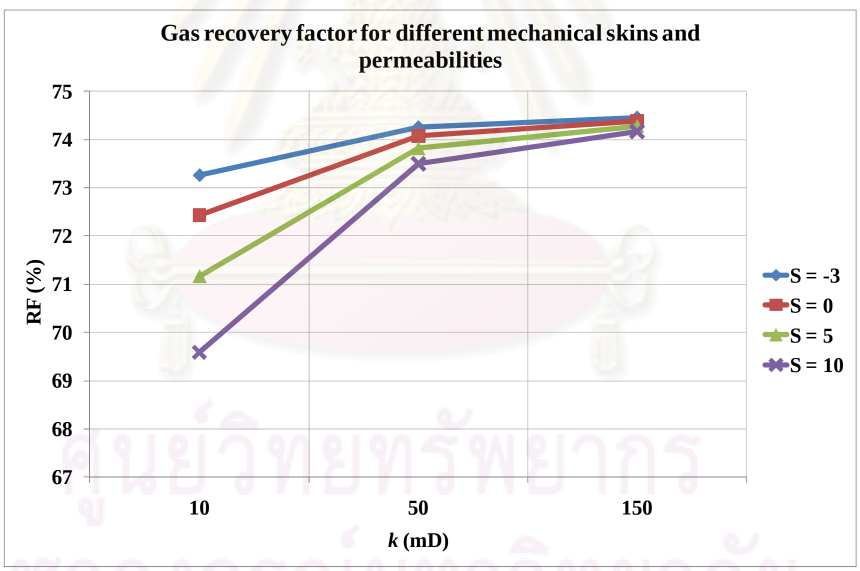


Figure 5.1: Gas recovery factor for different mechanical skins and reservoir permeabilities

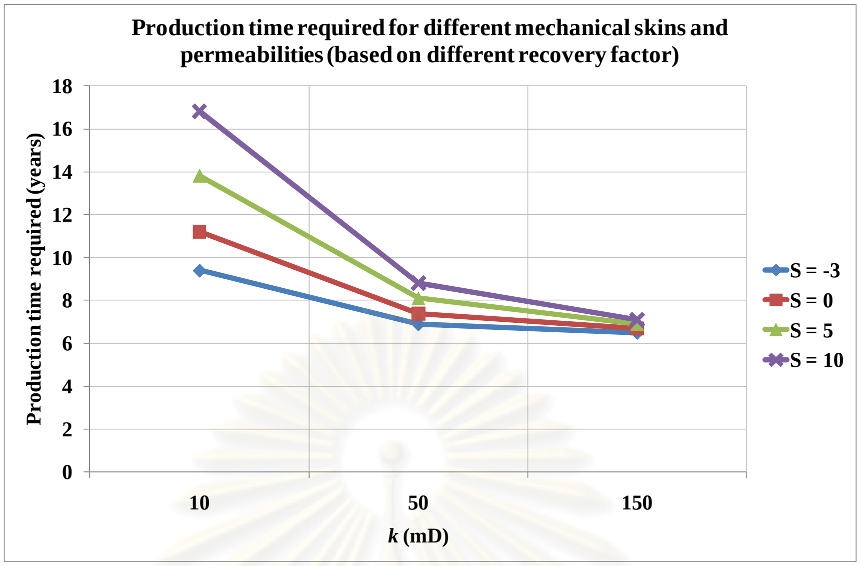


Figure 5.2: Production time required for different mechanical skins and reservoir permeabilities (based on different recovery factor)

Even there is no significant difference in terms of ultimate gas recovery in 50-mD and 150-mD reservoirs, the difference in production time required to reach ultimate recovery is significant. Figure 5.2 shows production time required for different mechanical skins and reservoir permeabilities. It is noted that the results are based on different recovery factor. Thus, the shorter time may not be necessarily good. It can be seen that a reservoir with higher mechanical skin factor requires longer production time in order to reach its ultimate recovery. The largest and smallest difference in production time required to reach ultimate recovery are 1.9 and 0.6 years in reservoirs with permeability of 50 and 150 mD, respectively.

Table 5.2: Reservoir abandonment pressure for different mechanical skins and reservoir permeabilities

S	*k* (mD)	P_R (psia) @ abandonment
-3	10	600
	50	578
	150	574
0	10	618
	50	582
	150	575
5	10	646
	50	588
	150	578
10	10	680
	50	595
	150	580

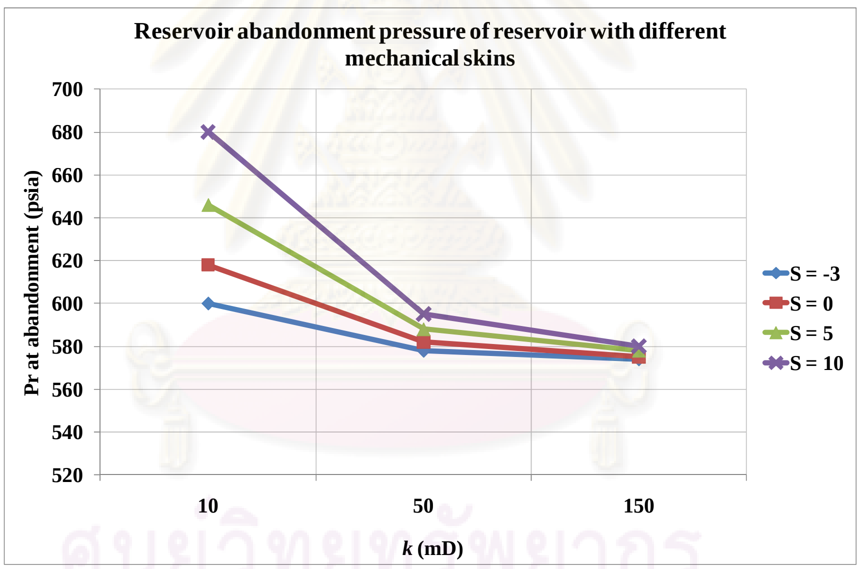


Figure 5.3: Reservoir abandonment pressure for reservoir with different mechanical skins and reservoir permeabilities

Table 5.2 and Figure 5.3 shows reservoir pressure at abandonment condition for different mechanical skins and reservoir permeabilities. The results show that the abandonment pressure for reservoirs with *S* = 10 is greater than reservoirs with *S* = 5, 0, and -3, respectively. It can be explained that the higher abandonment reservoir pressure in reservoirs with higher mechanical skin is caused by the pressure loss across skin zone that occurs in addition to the pressure loss across reservoir. It can be seen that with the same mechanical skin factor, reservoir abandonment pressure for reservoir with permeability of 10 mD is higher than reservoirs with 50 and 150 mD. Since low-permeability sand requires a large pressure drop, the well is abandoned at a higher reservoir pressure. This higher abandonment reservoir pressure leads to lower ultimate gas recovery. In any case, the difference in ultimate gas recovery between 50-mD and 150-mD reservoirs is not significant because the difference in pressure drop across reservoir between 50-mD and 150-mD reservoirs is not high.

Comparing among different mechanical skin factors in each permeability case, it can be seen that there is difference in the magnitude of pressure drop across the skin zone in addition to the pressure drop across the reservoir. The negative skin factor, S = -3, causes less pressure drop while the positive skin factors, S = 5 and 10, create additional pressure drop in zone around the wellbore. As the effect of skin can be described in terms of an effective wellbore radius, the reduction in pressure drop in the case with skin of -3 means that the effective wellbore radius is greater than the actual radius, causing higher well productivity. On the other hand, the additional pressure drops in the cases with skin of 5 and 10 mean that the effective wellbore radius is less than the actual wellbore radius, causing lower well productivity.

The amount of gas recovered in the early and late time of production are compared. Since the longest production time is approximately 18 years, the amount of gas recovered after production for 5 and 15 years are compared. Table 5.3 shows gas recovery for different mechanical skin factors and reservoir permeabilities after producing for 5 and 15 years. It can be seen that the difference between the minimum and maximum gas recovery is significant during gas production of the first 5 years. The difference between the minimum and maximum gas recovery in reservoirs with k = 10, 50, and 150 mD is 15%, 2%, and 1%, respectively. This implies that the effect of mechanical skin on the amount of gas recovered is large in low permeability reservoir. Additionally, it can be seen that gas recovery of each case reaches its ultimate recovery as shown in Table 5.2 before 15 years. There is only one case, S = 10 and k = 10 mD, that gas recovery cannot reach its ultimate recovery even after 15 years of production. The gas recovery in this case is lower than the ultimate recovery by 2%.

Table 5.3: Gas recovery at different periods of time for different mechanical skins and reservoir permeabilities

S	***k* (mD)**	**Gas Recovery (%)**	
		5 years	**15 years**
-3	10	61.64	73.26
	50	65.39	74.25
	150	65.52	74.45
0	10	58.03	72.43
	50	64.92	74.08
	150	65.51	74.39
5	10	52.73	71.17
	50	63.93	73.82
	150	65.41	74.28
10	10	46.52	68.24
	50	62.65	73.50
	150	65.20	74.17

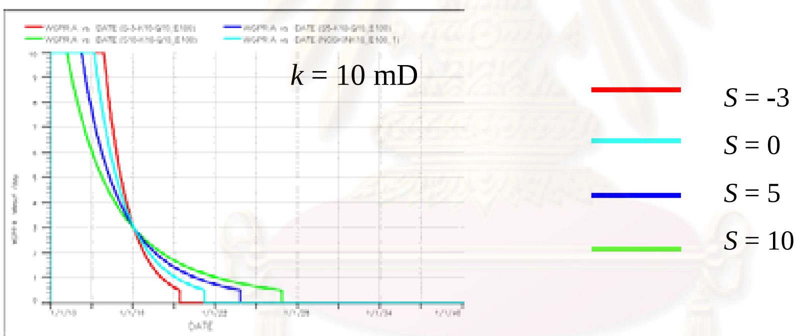


Figure 5.4: Gas production rate for different mechanical skin factors in reservoir with k = 10 mD

Figure 5.4 shows gas production rate for different mechanical skin factors in dry gas reservoir with permeability of 10 mD. It can be seen that gas flow rate in the case of negative skin factor, S = -3, can be maintained at 10 MMscf/d longer than other cases, and the decline period is shorter than the cases with S = 0, 5, and 10. Comparison among different mechanical skin factors shows that gas flow rate during the decline period of S = -3 is the highest. It can be observed that in the case that S = -3, the time required to produce the ultimate recovery is less than the other cases while the ultimate gas recovery is the highest when compared with S = 0, 5, and 10.

Figures 5.5 and 5.6 show gas flow rate for different mechanical skin factors in reservoir with permeability of 50 and 150 mD, respectively. The results show similar trend with those shown in reservoir with permeability of 10 mD in Figure 5.4. It can be seen that the gas production rate for a reservoir with higher permeability can be kept constant longer than that for a reservoir with lower permeability due to lower pressure loss across the reservoir in addition to pressure loss across the skin zone.

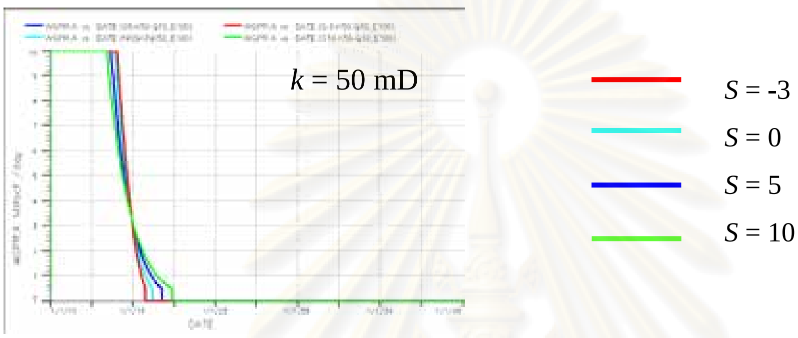


Figure 5.5: Gas production rate for different mechanical skin factors in reservoir with k = 50 mD

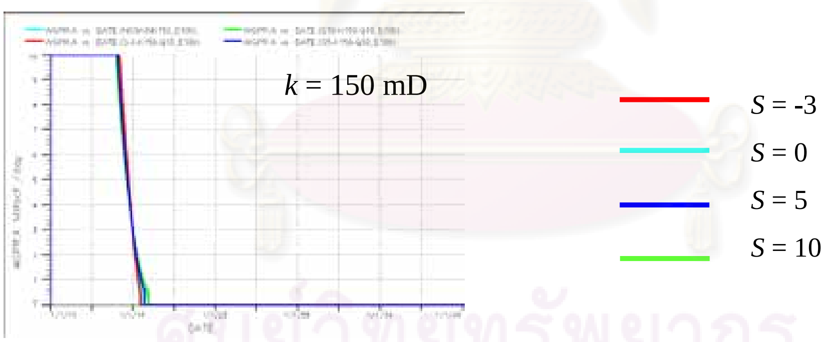


Figure 5.6: Gas production rate of different mechanical skin factors in reservoir with k = 150 mD

From the above analysis, it can be concluded that mechanical skin does have effects on both ultimate recovery and production time required to reach ultimate recovery, especially in 10-mD reservoir. With the same reservoir permeability, a lower skin factor leads to higher ultimate gas recovery and shorter time required to reach the ultimate recovery. The difference on the ultimate recovery for different skin factors in reservoir with permeability of 10 mD is high because of large pressure drop across the reservoir and skin zone. In addition, production acceleration by well stimulation to create negative skin can increase gas recovery significantly, especially in the 10-mD reservoir.

5.1.2 Effect of Permeability

Permeability is considered as one of the highest impact parameters on the recovery efficiency. Three permeabilities to be investigated in this study are 10, 50, and 150 mD. The effect of permeability in different mechanical skin factor systems is investigated.

Results from Table 5.1 show that the difference in ultimate gas recovery among various permeabilities is obviously seen for the case with higher mechanical skin factor. The difference in ultimate recovery between 10-mD reservoir and 150-mD reservoir in the case with skin of -3, 0, 5, and 10 are 1%, 2%, 3%, and 4%, respectively. In terms of reservoir abandonment pressure, it can be observed that for each mechanical skin factor, reservoir abandonment pressure for 10-mD reservoir is the highest when compared with 50-mD and 150-mD reservoirs as shown in Table 5.2. This high reservoir abandonment pressure in 10-mD reservoir occurs due to a large pressure drop across the reservoir. In addition to the large pressure drop across the reservoir in 10-mD reservoir, if a mechanical skin occurs in the area around the wellbore, the well productivity would be impaired.

The effect of permeability on gas recovery in different periods of time can be observed in Table 5.3. Within the first 5 years of production, permeability does have a significant effect on gas recovery. The difference in gas recovery between 10-mD reservoir and 150-mD reservoir when the skin equals -3, 0, 5, and 10 is 4%, 8%, 12%, and 18%, respectively. It is noticed that the effect of permeability is significantly observed for a system with higher mechanical skin factor because of the impact from both pressure loss across the reservoir and the skin zone.

5.1.3 Effect of Non-Darcy Skin

A comparison between a system having only mechanical skin factor and a system containing both mechanical skin and non-Darcy skin is performed in this part of the study. Initial gas flow rate of 2, 10, and 20 MMscf/d is applied to reservoirs having different mechanical skin factors and permeabilities to investigate the effect of non-Darcy skin.

Results of simulation run for systems that contain both mechanical and non-Darcy skins are shown in Tables 5.4-5.9. Table 5.4 and Figures 5.7-5.8 show results of simulation runs for 10-mD reservoir. It can be seen that non-Darcy skin does not have an effect on ultimate gas recovery when S = -3. The ultimate gas recoveries for different gas flow rates and various non-Darcy skin coefficients are the same at 73%. However, when the skin is 5, the ultimate gas recoveries for most cases are the same at 71% except for the cases with high non-Darcy skin coefficients which have an ultimate recovery of 70%. For higher mechanical skin, S = 10, it can be noticed that the cases with high non-Darcy skin coefficient have an ultimate recovery lower than the cases without non-Darcy skin by 2%.

Besides the observation mentioned above, it can be observed that gas flow rate does not have an effect on the ultimate gas recovery. The ultimate gas recoveries in cases that have the same mechanical skin factor and non-Darcy skin are the same for all three different gas flow rates.

Results from simulation runs also show that the effect of non-Darcy skin on time required to reach the ultimate recovery is not significant for cases with negative skin of -3. However, this effect is more significant for cases with higher mechanical skin factors. Table 5.5 and Figures 5.9-5.10 show the comparison between gas recovery after production for 5 and 15 years in reservoir with permeability of 10 mD. It can be seen that for gas flow rate of 2 MMscf/d, non-Darcy skin does not have an effect on gas recovery after 5 years of production. The effect of non-Darcy skin on gas recovery can be seen when gas flow rate is 10 or 20 MMscf/d. This effect cannot be seen in the case of negative skin of -3 but it become significant when the skin is 5 or 10.

Table 5.4: Recovery factor and production time required for 10-mD reservoir

S	***Q***	**Non-Darcy skin coefficient, *D* (Day/Mscf)**	**RF (%)**	**Production time (years)**
		None	73.28	29.2
	2	Base estimates	73.28	29.2
		High estimates	73.25	29.2
		None	73.26	9.4
-3	10	Base estimates	73.25	9.4
		High estimates	73.22	9.9
		None	73.27	7.8
	20	Base estimates	73.24	7.9
		High estimates	73.24	8.7
		None	71.17	30.1
	2	Base estimates	71.14	30.3
		High estimates	70.47	31.8
		None	71.17	13.8
5	10	Base estimates	71.13	15.1
		High estimates	70.44	21.7
		None	71.18	13.2
	20	Base estimates	71.13	14.9
		High estimates	70.44	21.7
		None	69.60	30.7
	2	Base estimates	69.41	31.2
		High estimates	67.75	34.1
		None	69.59	16.8
10	10	Base estimates	69.39	19.3
		High estimates	67.74	28.9
		None	69.60	16.7
	20	Base estimates	69.39	19.3
		High estimates	67.74	28.9

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

Comparison among different mechanical skin factors shows that after 5 years of production with gas flow rate of 10 and 20 MMscf/d, gas recoveries for the case when skin is -3 are greater than the cases with skin of 5 and 10 for all values of non-Darcy skin. The difference in gas recovery becomes smaller after producing for 15 years due to low gas flow rate in the decline period.

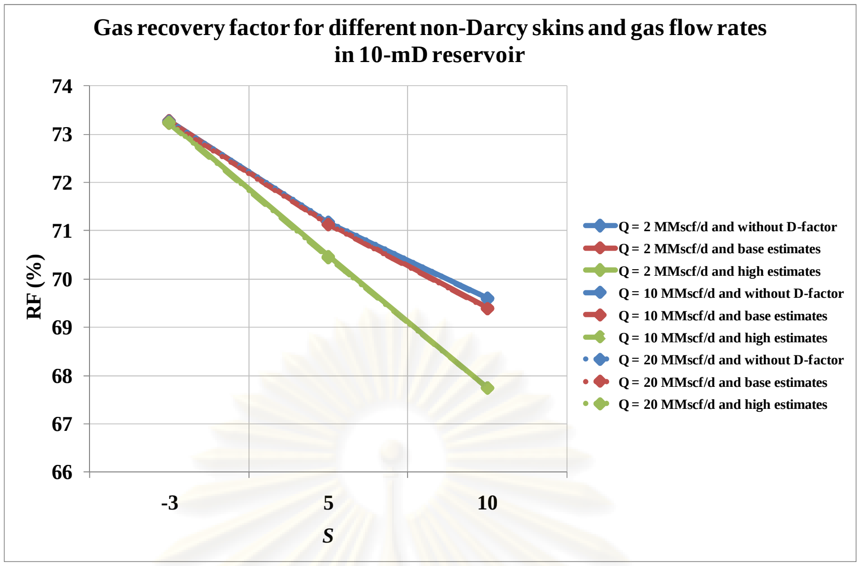


Figure 5.7: Gas recovery factor for different non-Darcy skins and gas flow rates in 10-mD reservoir

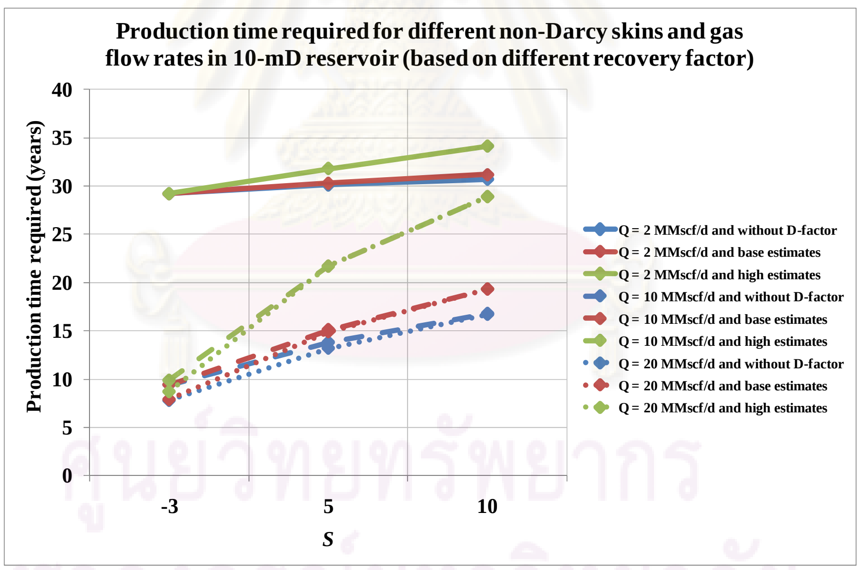


Figure 5.8: Production time required for different non-Darcy skins and gas flow rates in 10-mD reservoir (based on different recovery factor)

From the above results, it can be concluded that non-Darcy skin has a slightly effect on the amount of gas recovered. A higher non-Darcy skin leads to slightly lower amount of gas recovered. It can be explained that in the late period of production, when gas flow rate is low, non-Darcy skin will be less. Therefore, when gas flow rate is low enough and the production period is long enough, the amount of gas recovered in all cases are similar. Additionally, it can be noticed that the effect of non-Darcy skin is small in the cases with low mechanical skin factor. Therefore, reducing mechanical skin can also reduce the effect of non-Darcy skin.

Table 5.5: Gas recovery at different periods of time for 10-mD reservoir

S	***Q_i* (MMscf/d)**	**Non-Darcy skin coefficient, *D* (Day/Mscf)**	**Gas Recovery (%)**	
			@ 5 yrs	**@ 15 yrs**
-3	2	None	13.10	39.32
		Base estimates	13.10	39.32
		High estimates	13.10	39.32
	10	None	61.64	73.26
		Base estimates	61.47	73.25
		High estimates	60.09	73.22
	20	None	69.00	73.27
		Base estimates	68.75	73.24
		High estimates	66.56	73.24
5	2	None	13.10	39.32
		Base estimates	13.10	39.32
		High estimates	13.10	39.32
	10	None	52.73	71.17
		Base estimates	49.25	71.09
		High estimates	33.54	63.44
	20	None	55.75	71.18
		Base estimates	50.25	71.13
		High estimates	33.54	63.44
10	2	None	13.10	39.32
		Base estimates	13.10	39.32
		High estimates	13.10	39.32
	10	None	46.52	68.24
		Base estimates	39.65	65.64
		High estimates	23.29	51.24
	20	None	47.35	68.39
		Base estimates	39.65	65.64
		High estimates	23.29	51.24

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

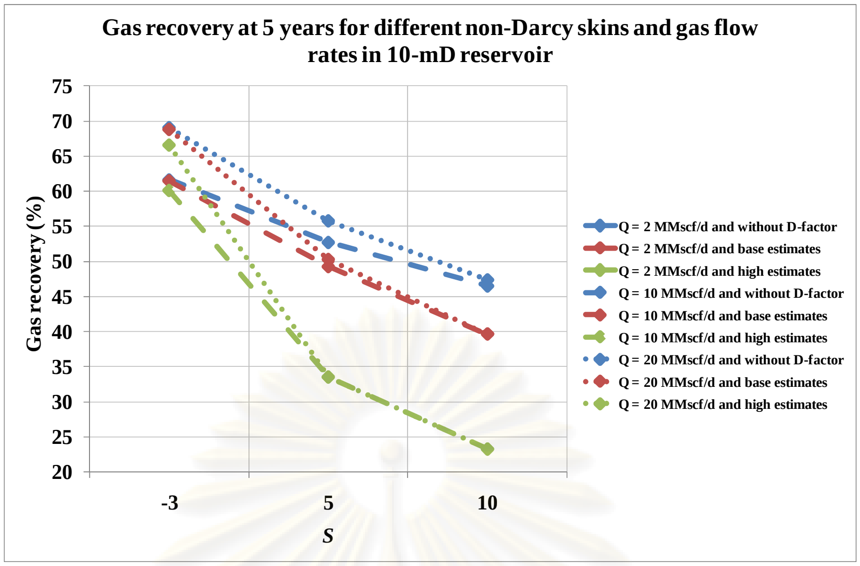


Figure 5.9: Gas recovery at 5 years for different non-Darcy skins and gas flow rates in 10-mD reservoir

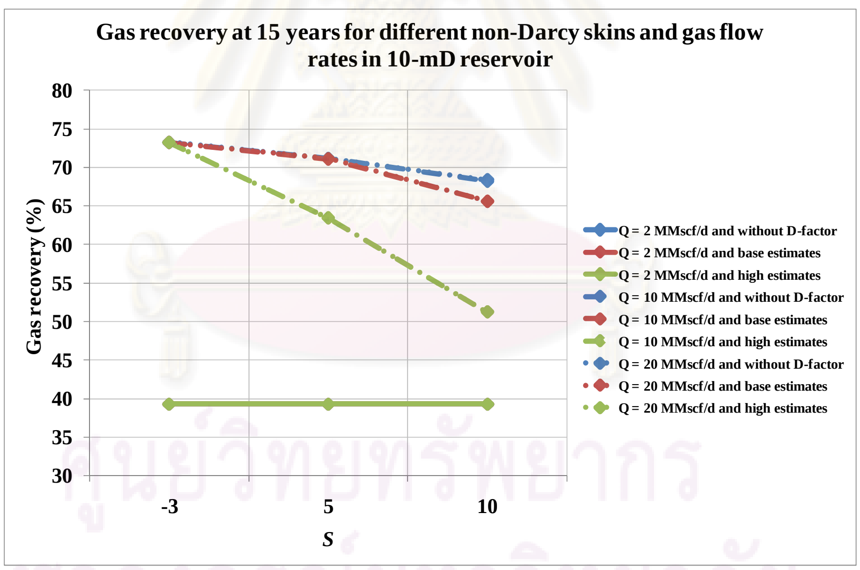


Figure 5.10: Gas recovery at 15 years for different non-Darcy skins and gas flow rates in 10-mD reservoir

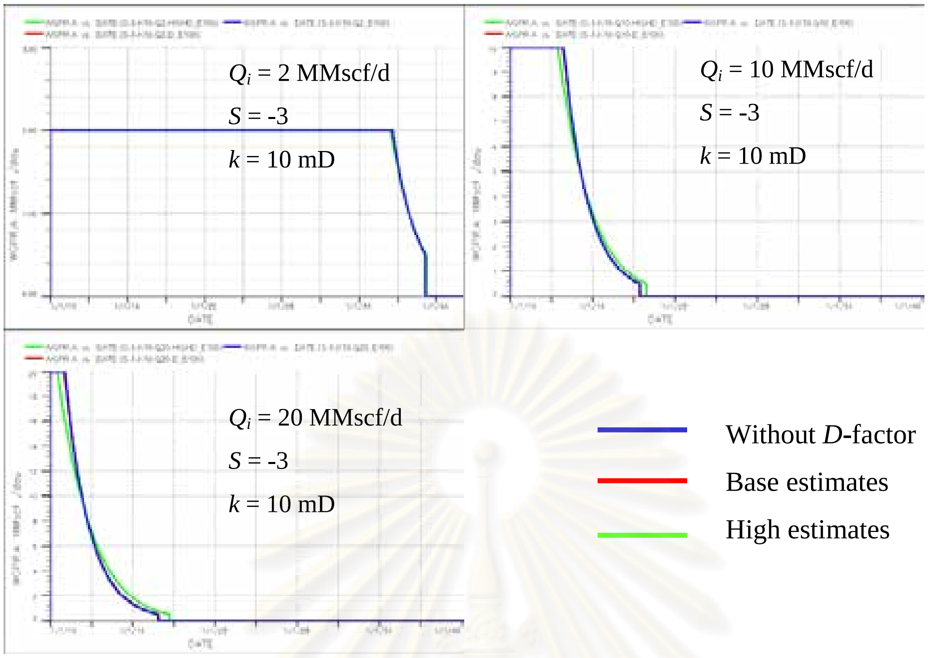


Figure 5.11: Gas production profiles for different initial gas flow rates and D-factors in reservoir with S = -3 and k = 10 mD

Figure 5.11 shows gas production profiles for 10-mD reservoir with different initial gas flow rates in the case of negative skin, S = -3. It can be observed that for each initial gas flow rate, gas production profiles for different values of non-Darcy skin are similar except for the cases with high non-Darcy skin which tend to decline more rapidly and have longer production time than the cases without or with low-non-Darcy skin.

Figures 5.12 and 5.13 show gas production profiles for 10-mD reservoirs with different initial gas flow rates when skin is 5 and 10, respectively. The results show similar trend with those shown in cases with S = -3. Cases with high non-Darcy skin cannot maintain the plateau as long as cases without or with low non-Darcy skin. However, the plateau period for cases with S = 5 and 10 are shorter than that for cases with S = -3 when compared case by case. Additionally, it can be noticed that cases with high non-Darcy skin with gas flow rate of 10 MMscf/d (S = 5 and 10, Q_i = 10, and high D-factor) and all cases with gas flow rate of 20 MMscf/d cannot produce gas at the required initial rate due to a large pressure drop caused by mechanical skin, non-Darcy skin, and also pressure loss across the reservoir due to low permeability.

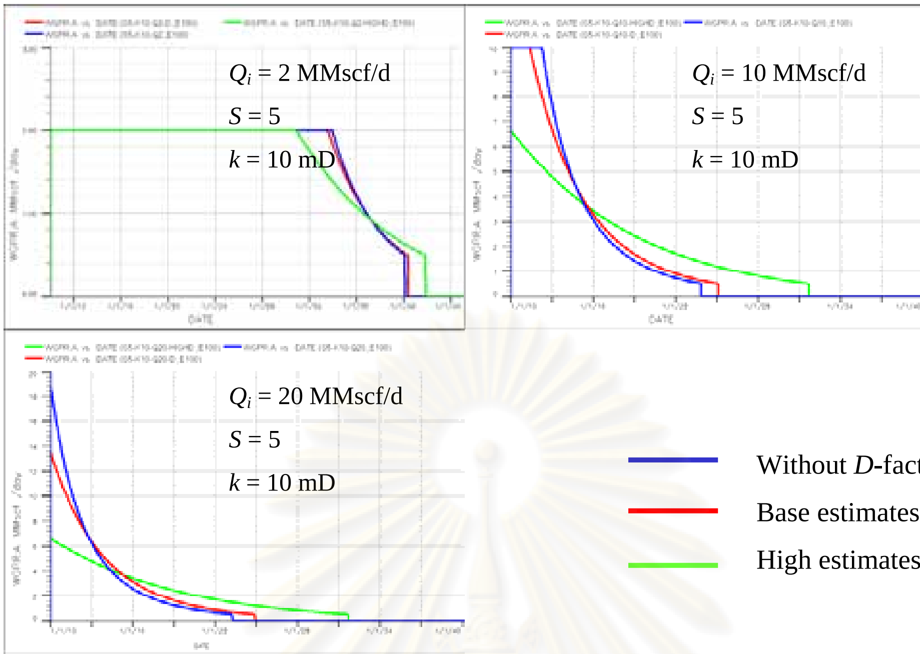


Figure 5.12: Gas production profiles for different initial gas flow rates and D-factors in reservoir with S = 5 and k = 10 mD

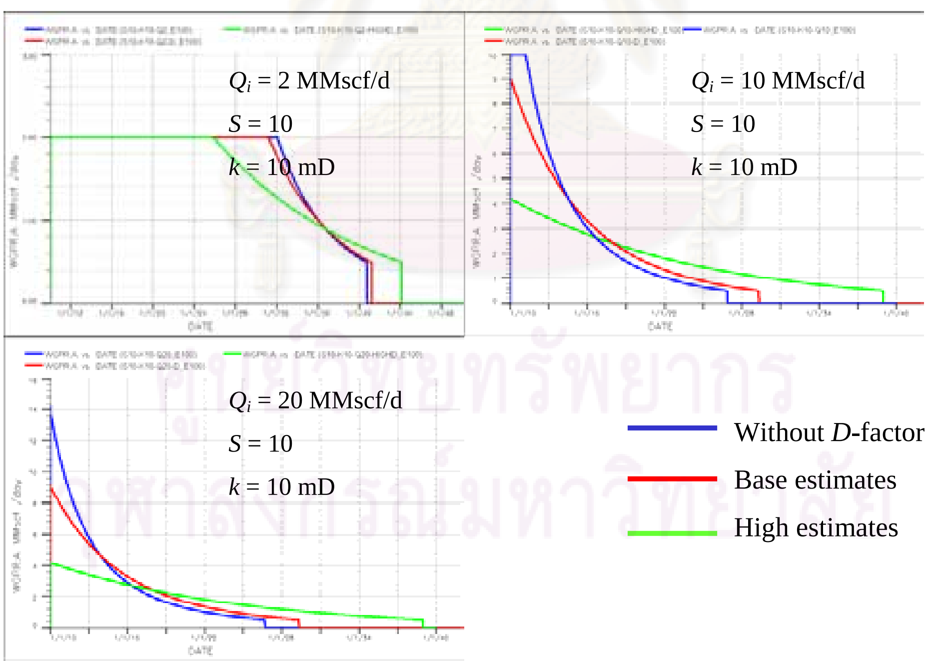


Figure 5.13: Gas production profiles for different initial gas flow rates and D-factors in reservoir with S = 10 and k = 10 mD

Table 5.6: Recovery factor and production time required for 50-mD reservoir

S	**Q_i (MMscf/d)**	**Non-Darcy skin coefficient, *D* (Day/Mscf)**	**RF (%)**	**Production time (years)**
-3	2	None	74.27	28.7
		Base estimates	74.30	28.7
		High estimates	74.26	28.7
	10	None	74.25	6.9
		Base estimates	74.30	6.9
		High estimates	74.30	6.9
	20	None	74.25	4.8
		Base estimates	74.30	4.8
		High estimates	74.25	4.8
5	2	None	73.83	28.9
		Base estimates	73.85	29.0
		High estimates	73.72	29.3
	10	None	73.82	8.1
		Base estimates	73.79	8.4
		High estimates	73.72	10.7
	20	None	73.81	6.2
		Base estimates	73.78	6.7
		High estimates	73.71	10.1
10	2	None	73.55	29.1
		Base estimates	73.52	29.2
		High estimates	73.21	30.0
	10	None	73.50	8.8
		Base estimates	73.50	9.6
		High estimates	73.21	14.0
	20	None	73.52	7.2
		Base estimates	73.52	8.3
		High estimates	73.21	13.9

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

Table 5.6 and Figures 5.14-5.15 show results from simulation runs with the same parameters as in previous series except that the permeability of the reservoir is increased to 50 mD. It can be observed that cases with higher mechanical skin factors require longer times to reach the ultimate recovery than cases with lower mechanical skin factors. There is no significant difference between the ultimate gas recoveries among different mechanical skin factors, gas flow rates, and non-Darcy skins. The ultimate recoveries of all cases are in the range of 73 – 74%. It can be noticed that the ultimate gas recoveries of all cases in this set of parameters is higher than those for 10-mD reservoir when compared on a case by case basis. The production times required are shorter than those for 10-mD reservoir, and their differences for different non-Darcy skins are also less than those for 10-mD reservoir.

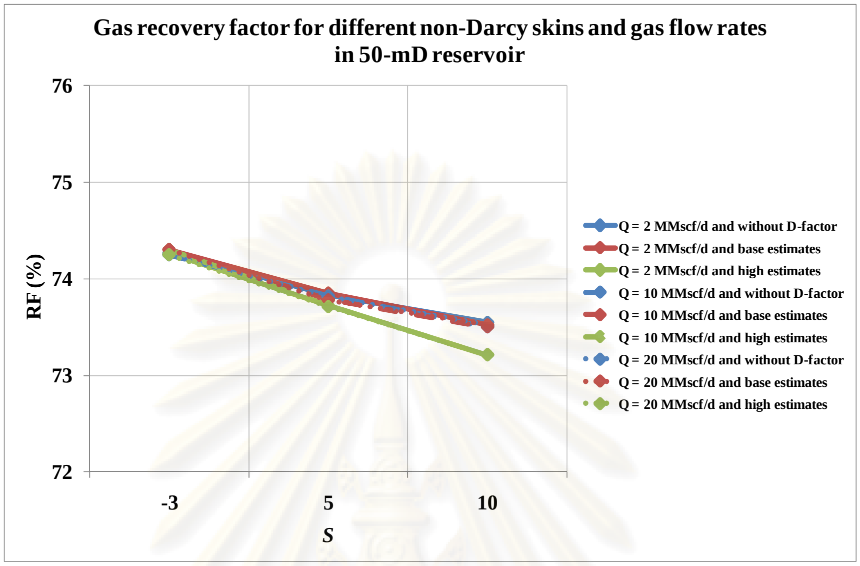


Figure 5.14: Gas recovery factor for different non-Darcy skins and gas flow rates in 50-mD reservoir

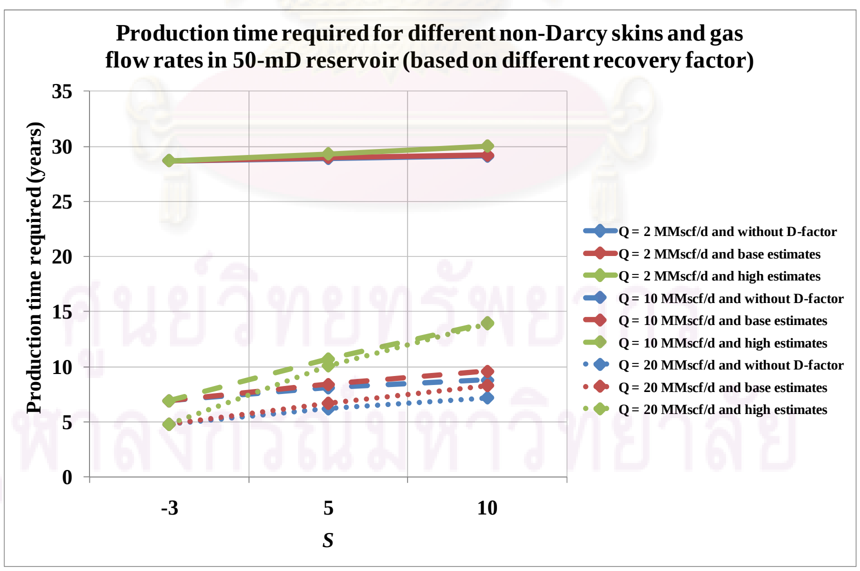


Figure 5.15: Production time required for different non-Darcy skins and gas flow rates in 50-mD reservoir (based on different recovery factor)

Table 5.7 and Figures 5.16-5.17 show gas recovery at different periods of time for 50-mD reservoir. It can be seen that non-Darcy skin has an effect on the amount of gas recovered during the first 5 years of production. However, the effect of non-Darcy skin cannot be seen when skin is -3. Even without, low, and high non-Darcy skin, gas recoveries are the same for each gas flow rate. In the case when skin is 5, the effect of non-Darcy skin leads to the difference in gas recovery of 7% and 12% when gas flow rate is 10 and 20 MMscf/d, respectively. This effect is more significant when mechanical skin is 10 as seen from the difference in gas recovery of 14% and 21% when gas flow rate is 10 and 20 MMscf/d, respectively.

Table 5.7: Gas recovery at different periods of time for 50-mD reservoir

S	**Q_i (MMscf/d)**	**Non-Darcy skin coefficient, *D* (Day/Mscf)**	**Gas Recovery (%)**	
			@ 5 yrs	**@ 15 yrs**
-3	2	None	13.10	39.32
		Base estimates	13.10	39.32
		High estimates	13.10	39.32
	10	None	65.39	74.25
		Base estimates	65.36	74.25
		High estimates	65.19	74.23
	20	None	74.25	74.25
		Base estimates	74.24	74.24
		High estimates	74.25	74.25
5	2	None	13.10	39.32
		Base estimates	13.10	39.32
		High estimates	13.10	39.32
	10	None	63.93	73.82
		Base estimates	63.03	73.79
		High estimates	56.85	73.72
	20	None	72.36	73.81
		Base estimates	71.24	73.78
		High estimates	60.23	73.71
10	2	None	13.10	39.32
		Base estimates	13.10	39.32
		High estimates	13.10	39.32
	10	None	62.65	73.50
		Base estimates	60.59	73.50
		High estimates	48.57	73.21
	20	None	70.49	73.52
		Base estimates	67.31	73.52
		High estimates	48.74	73.21

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

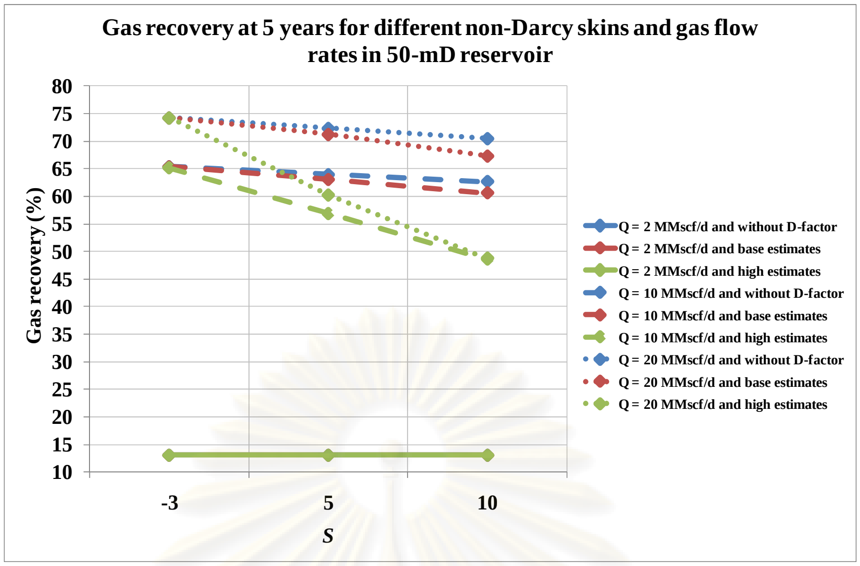


Figure 5.16: Gas recovery at 5 years for different non-Darcy skins and gas flow rates in 50-mD reservoir

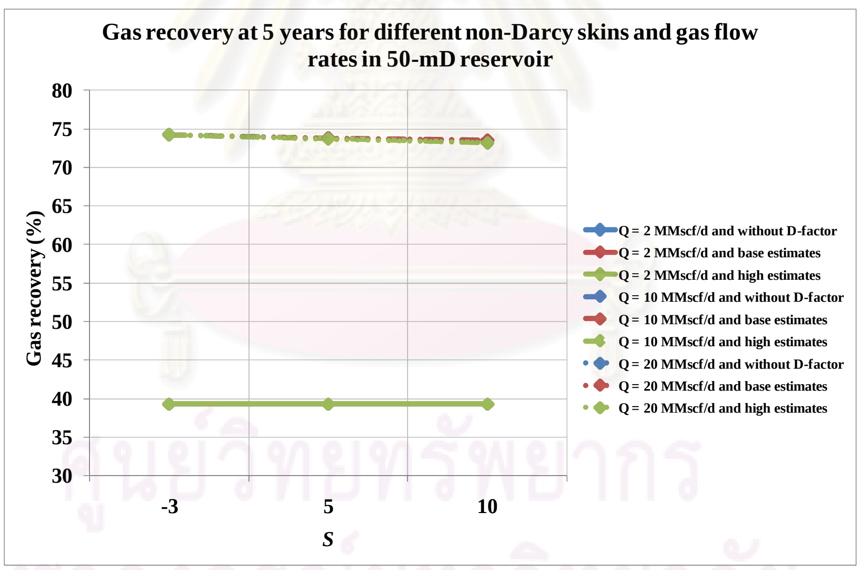


Figure 5.17: Gas recovery at 15 years for different non-Darcy skins and gas flow rates in 50-mD reservoir

The effect of non-Darcy skin is not significant after producing for 15 years because gas flow rate is low in the decline period. It can be noticed that the effect of non-Darcy skin is small when mechanical skin is low. Therefore, reducing mechanical skin can reduce the effect of non-Darcy skin.

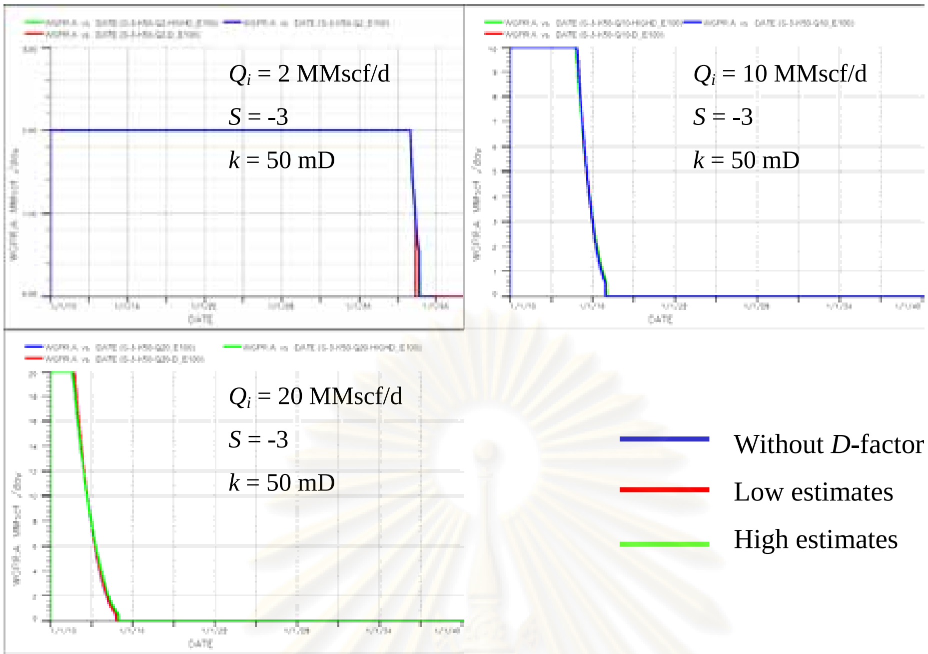


Figure 5.18: Gas production profiles for different initial gas flow rates and D-factors in reservoir with S = -3 and k = 50 mD

Figure 5.18 shows the comparison of gas production profiles among different initial gas flow rates and D-factors in the reservoir with S = -3 and k = 50 mD. The results show that the effect of non-Darcy skin cannot be seen in all gas flow rates when permeability is 50 mD.

Figures 5.19 and 5.20 show the comparison of gas production profiles among different initial gas flow rates and D-factors when the skin is 5 and 10, respectively. The results show similar trends with those shown in the case of S = -3. However, it is clearly seen that the production plateau period of high non-Darcy skin in cases of S = 5 and 10 is shorter than that in cases of S = -3. Additionally, the decline period in cases of high non-Darcy skin when S = 10 and 5 are significantly longer than the case with S = -3 when compared case by case.

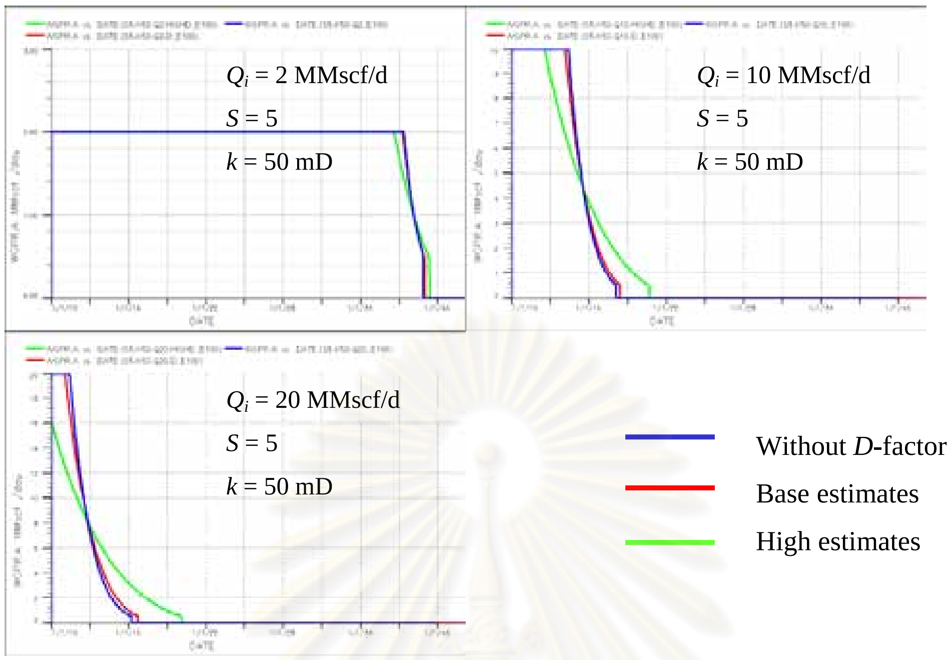


Figure 5.19: Gas production profiles for different initial gas flow rates and D-factors in reservoir with S = 5 and k = 50 mD

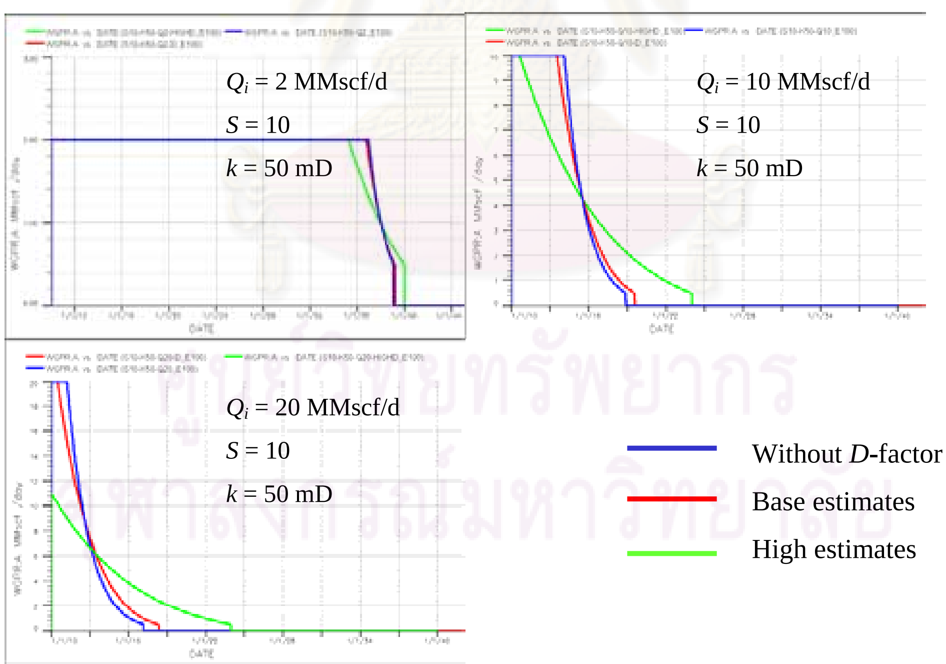


Figure 5.20: Gas production profiles for different initial gas flow rates and D-factors in reservoir with S = 10 and k = 50 mD

Table 5.8 and Figures 5.21-5.22 show results of simulation runs with the same parameters as in previous series except that the reservoir permeability is increased to 150 mD. It can be noticed that non-Darcy skin and gas flow rate do not have effects on the ultimate gas recovery. All cases have the same ultimate recovery of 74%. In terms of production time required to reach the ultimate recovery, non-Darcy skin does have an effect on production time only when *S* equals 5 and 10. However, this effect is less when compared with reservoirs with permeability of 50 and 10 mD.

Table 5.8: Recovery factor and production time required for 150-mD reservoir

S	**Q_i (MMscf/d)**	**Non-Darcy skin coefficient, *D* (Day/Mscf)**	**RF (%)**	**Production time (years)**
-3	2	None	74.44	28.6
		Base estimates	74.44	28.6
		High estimates	74.44	28.6
	10	None	74.45	6.5
		Base estimates	74.43	6.5
		High estimates	74.40	6.5
	20	None	74.44	4.3
		Base estimates	74.43	4.3
		High estimates	74.32	4.2
5	2	None	74.27	28.6
		Base estimates	74.29	28.7
		High estimates	74.28	28.8
	10	None	74.28	6.9
		Base estimates	74.29	7.0
		High estimates	74.28	7.9
	20	None	74.27	4.7
		Base estimates	74.26	4.9
		High estimates	74.27	6.3
10	2	None	74.18	28.7
		Base estimates	74.22	28.8
		High estimates	74.13	29.1
	10	None	74.17	7.1
		Base estimates	74.13	7.4
		High estimates	74.13	9.2
	20	None	74.20	5.1
		Base estimates	74.17	5.4
		High estimates	74.13	8.3

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

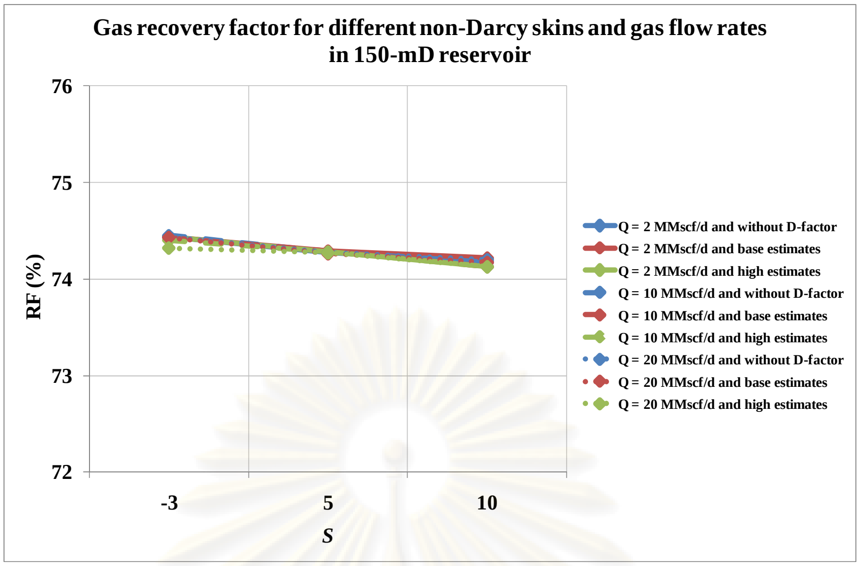


Figure 5.21: Gas recovery factor for different non-Darcy skins and gas flow rates in 150-mD reservoir

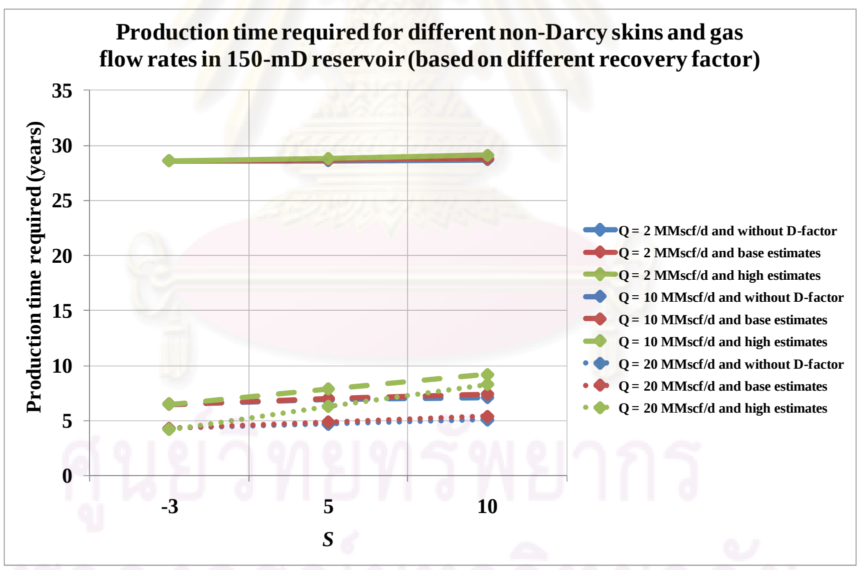


Figure 5.22: Production time required for different non-Darcy skins and gas flow rates in 150-mD reservoir (based on different recovery factor)

Table 5.9 and Figures 5.23-5.24 show gas recovery at different periods of time for 150-mD reservoir. It can be seen that within the first 5 years, the effect of non-Darcy skin cannot be seen when *S* equals to -3. In the cases with skin equals to 5, the effect of non-Darcy skin leads to the difference in gas recovery of 2% when gas flow rate is 10 and 20 MMscf/d. This effect is more significant when skin equals to 10 as seen from the difference in gas recovery of 5% and 8% when gas flow rate is 10 and 20 MMscf/d, respectively. It can be concluded that the effect of non-Darcy skin becomes more significant in case of high mechanical skin. Therefore, reducing mechanical skin can reduce the effect of non-Darcy skin on gas recovery.

Table 5.9: Gas recovery at different periods of time for 150-mD reservoir

S	**Q_i (MMscf/d)**	**Non-Darcy skin coefficient, *D* (Day/Mscf)**	**Gas Recovery (%)**	
			@ 5 yrs	**@ 15 yrs**
-3	2	None	13.10	39.32
		Base estimates	13.10	39.32
		High estimates	13.10	39.32
	10	None	65.52	74.45
		Base estimates	65.52	74.43
		High estimates	65.52	74.40
	20	None	74.44	74.44
		Base estimates	74.43	74.43
		High estimates	74.32	74.32
5	2	None	13.10	39.32
		Base estimates	13.10	39.32
		High estimates	13.10	39.32
	10	None	65.41	74.28
		Base estimates	65.24	74.29
		High estimates	63.26	74.28
	20	None	74.27	74.27
		Base estimates	74.26	74.26
		High estimates	71.98	74.27
10	2	None	13.10	39.32
		Base estimates	13.10	39.32
		High estimates	13.10	39.32
	10	None	65.20	74.17
		Base estimates	64.66	74.18
		High estimates	59.92	74.13
	20	None	74.16	74.20
		Base estimates	73.74	74.17
		High estimates	65.59	74.13

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

From the above results, it is noticed that well stimulation (negative skin) can improve the ultimate recovery for 10-mD reservoir from 70% to 73%. In addition, the amount of gas recovered during the production period can be improved while the effect of non-Darcy skin on gas recovery is reduced. This can be used as a preliminary criterion to justify the investment of stimulation to reduce skin and accelerate recovery.

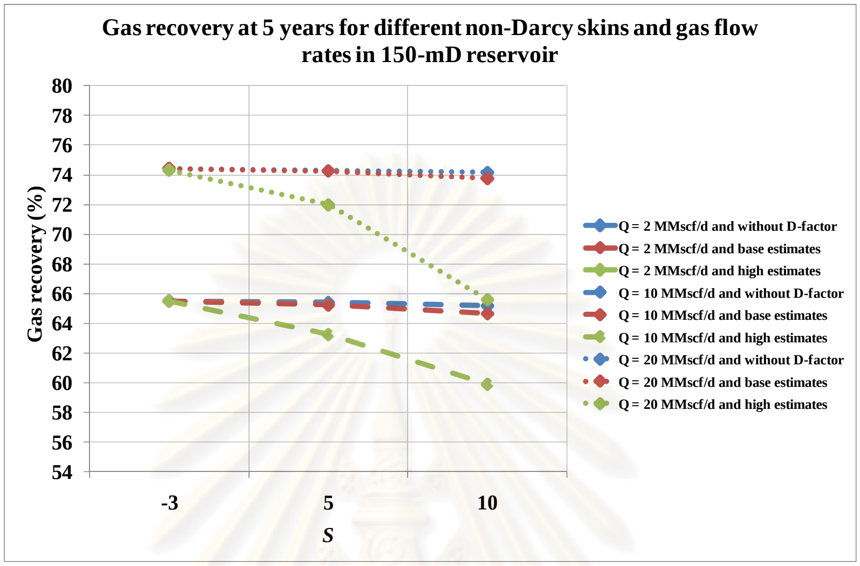


Figure 5.23: Gas recovery at 5 years for different non-Darcy skins and gas flow rates in 150-mD reservoir

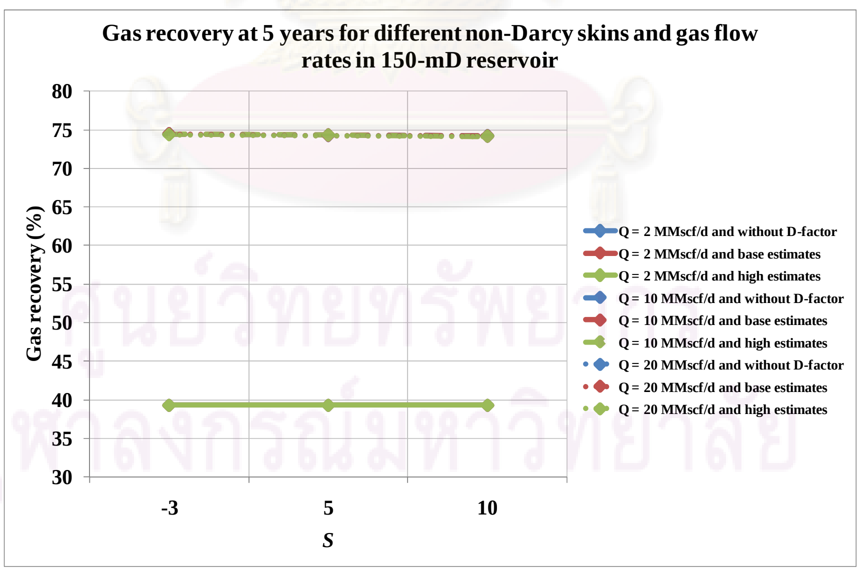


Figure 5.24: Gas recovery at 15 years for different non-Darcy skins and gas flow rates in 150-mD reservoir

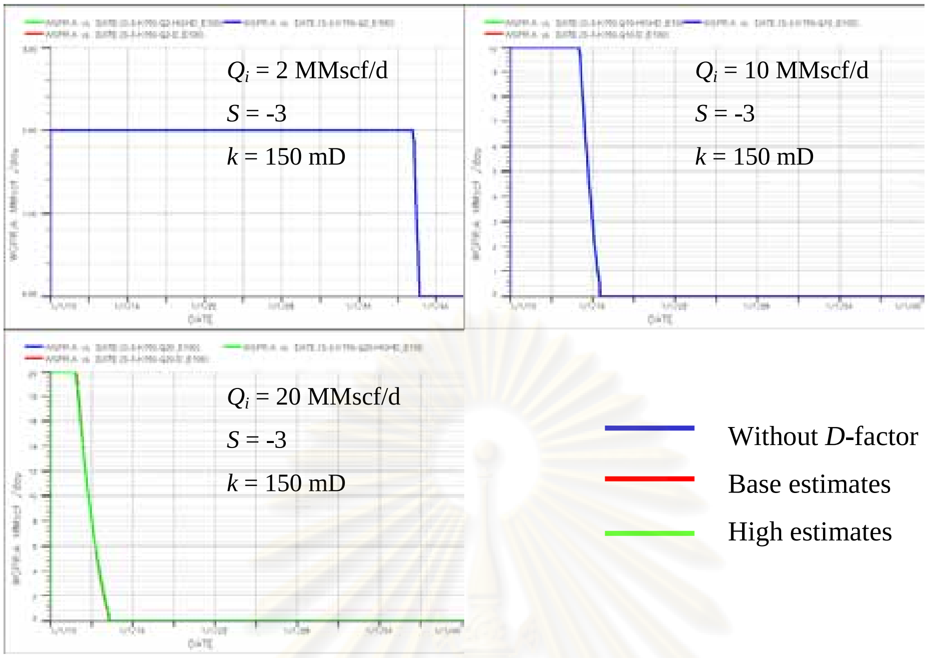


Figure 5.25: Gas production profiles for different initial gas flow rates and D-factors in reservoir with S = -3 and k = 150 mD

Figure 5.25 shows the comparison of gas production profiles among different initial gas flow rates and D-factors in the reservoirs with S = -3 and k = 150 mD. It can be observed that the effect of non-Darcy skin cannot be seen in all gas flow rates. Gas production profiles are the same for cases without, low, and high non-Darcy skin.

Figures 5.26-5.27 show the comparison of gas production profiles among different initial gas flow rates and D-factors as the same as Figure 5.25 except that the skin are 5 and 10, respectively. The results show similar trends with those shown in the reservoir with permeaiblities of 10 and 50 mD. It is significantly observed that the cases with high non-Darcy skin cannot maintain plateau period as long as the cases without and low non-Darcy skin. Additionally, the decline period in the cases with high non-Darcy skin are longer than the case without and low non-Darcy skin. These effect becomes more significant in S = 10.

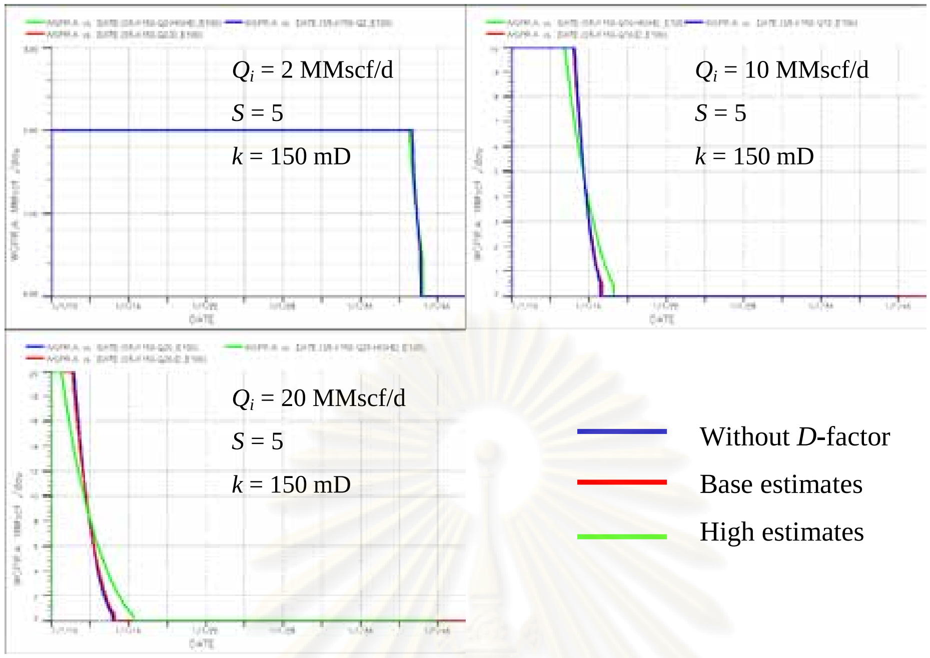


Figure 5.26: Gas production profiles for different initial gas flow rates and D-factors in reservoir with S = 5 and k = 150 mD

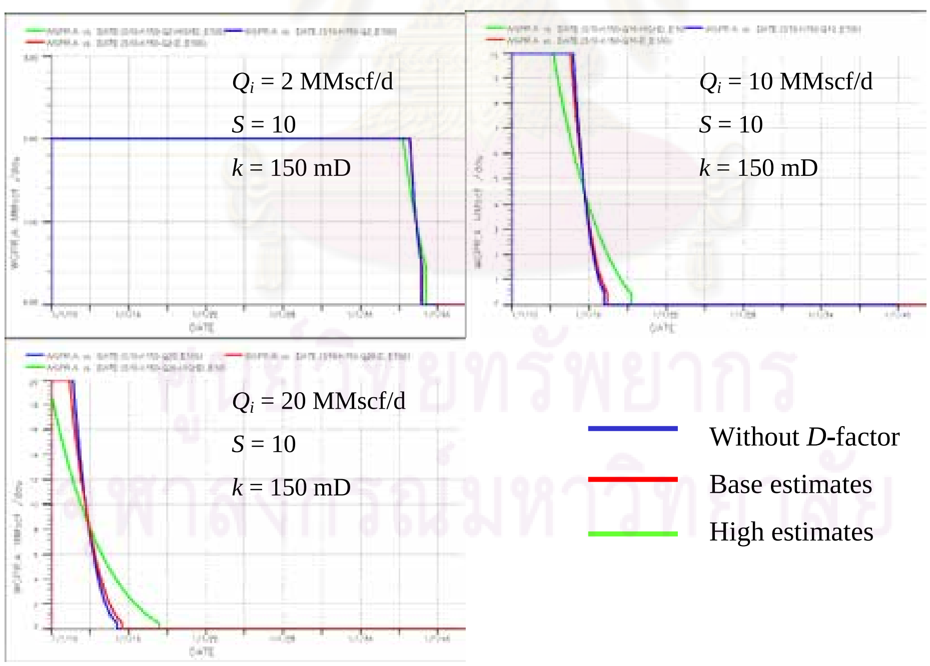


Figure 5.27: Gas production profiles for different initial gas flow rates and D-factors in reservoir with S = 10 and k = 150 mD

5.2 Gas-Condensate Reservoirs

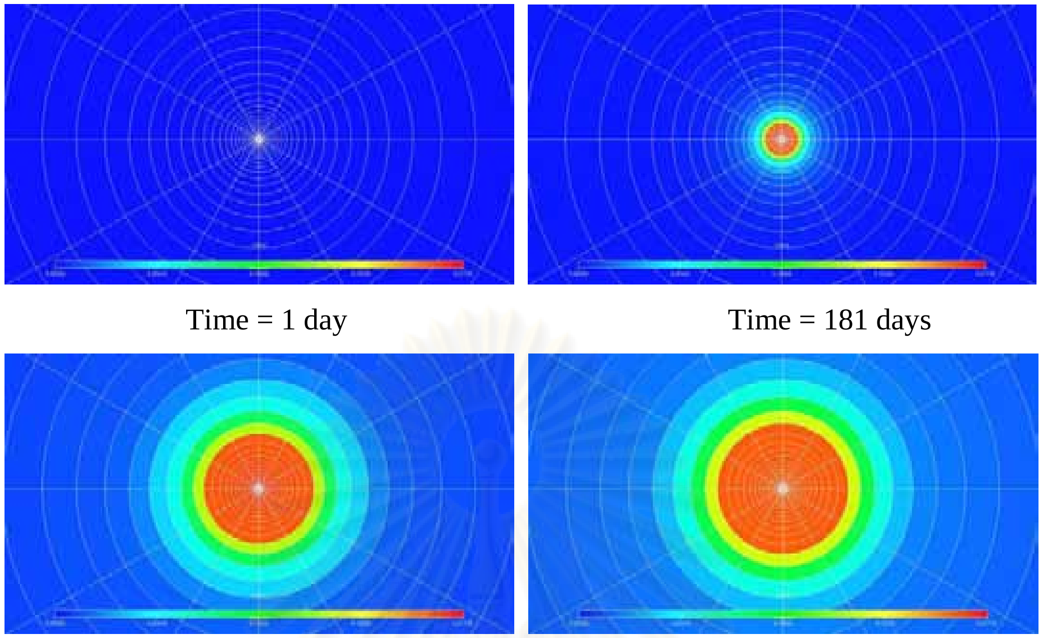
Gas-condensate presents a challenging production problem because when the reservoir pressure drops below dewpoint pressure, condensates begin to drop out from the vapor phase into liquid in the reservoir. A region of high condensate saturation build up around the wellbore causing lower gas deliverability, due to the reduction in the gas permeability. The presence of the additional liquid saturation in the reservoir also causes the gas rate drop from the initial rate. The pore space for the gas to flow is basically reduced when liquid saturation increases, hence the relative permeability to gas (k_{rg}) will also drop.

The combination effects of condensate blockage skin, mechanical skin, and non-Darcy skin are investigated in this part of the study.

5.2.1 Effect of Mechanical Skin

The impact of mechanical skin on gas recovery efficiency in gas-condensate reservoir is investigated from the results of numerous simulation runs. It can be observed that condensate banking occurs after reservoir pressure decreases below the dew point pressure. The amount of the condensate drop-out is rather limited near the well during the early production period, but as the pressure continues to drop due to continued production, the area where the liquid saturation increases continues to grow larger. Figure 5.28 shows the condensate drop-out near the well, where the pressure drop is the highest, for 4 production times with skin factor of 5 in 150-mD reservoir.

The condensate saturation from the well going outward in case with skin factor of 5 in 150-mD reservoir is plotted in Figure 5.29. The condensate saturation profile shows expected high saturation near the wellbore where the pressure drop is the highest, and drops at location away from the well. There are two phases (gas and condensate) flowing in Region 1, where condensate saturation is above S_{oc}. In Region 2, condensate saturation is below S_{oc}; therefore, there is only gas that can flow while condensate is left behind. Figure 5.30 shows pressure profile from the well going outward in case with skin factor of 5 in 150-mD reservoir at time = 181 days. It is noticed that the reservoir pressure of all grid block along the r-direction drops below dew point pressure of 1996 psia which confirms condensate drop out when pressure is below dew point pressure.



Time = 1 day　　Time = 181 days

Time = 365 days　　Time = 730 days

Figure 5.28: Condensate drop out near the wellbore in case with S = 5 and k = 150 mD

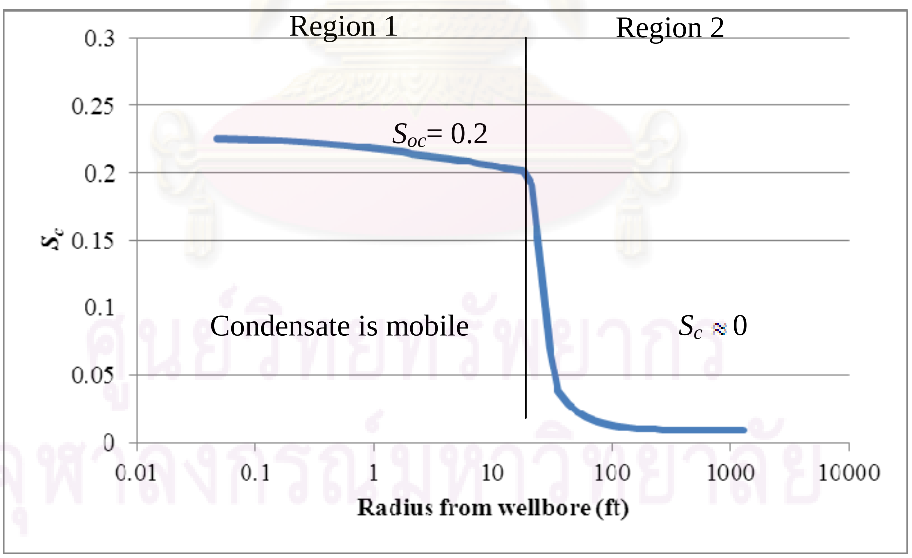


Figure 5.29: Condensate saturation profile in case S = 5 and k = 150 mD at time = 181 days

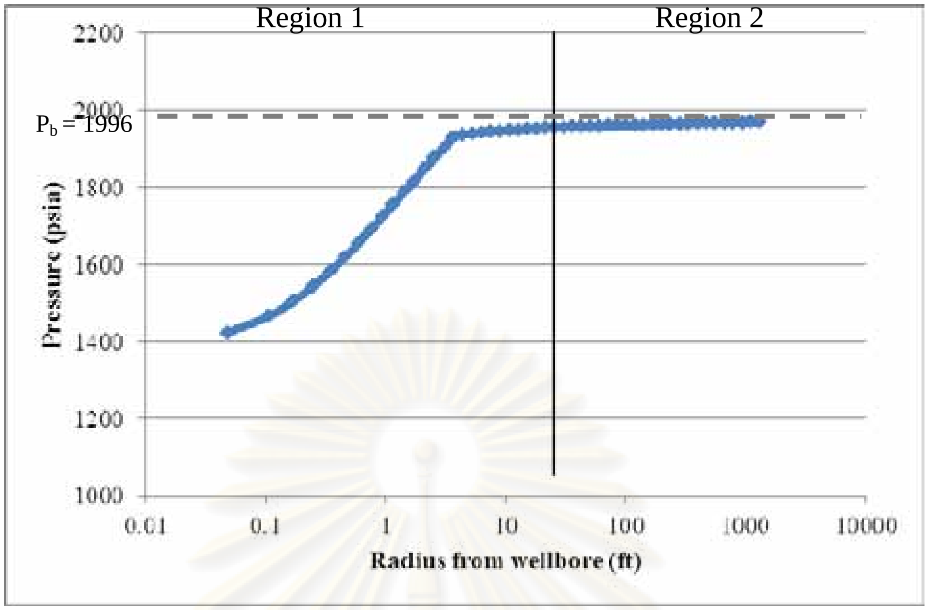


Figure 5.30: Pressure profile along r-direction in case with S = 5 and k = 150 mD at time = 181 days

Table 5.10 and Figures 5.31-5.33 show results of reservoir simulation runs with various mechanical skin factors and reservoir permeabilities. It can be observed that in gas-condensate reservoir, the effect of mechanical skin on gas recovery have similar trend with those for dry gas reservoir. The effect of mechanical skin on ultimate gas and condensate recoveries is clearly observed in the case with permeability of 10 mD. As seen in Table 5.10, the difference of ultimate gas and condensate recoveries between the minimum and maximum mechanical skin factor in 10-mD reservoir are 23% and 17%, respectively. The difference in ultimate gas recovery between the minimum and maximum mechanical skin in gas-condensate reservoir is greater than that of dry gas reservoir due to the additional effect from condensate blockage skin. The presence of additional liquid saturation around the wellbore when the pressure drops below the dew point pressure also causes the gas rate to drop from the initial rate. The pore space for gas to flow is reduced when liquid saturation increases; hence, the relative permeability to gas (k_{rg}) also drops.

Table 5.10: Recovery factor and production time required to reach ultimate recovery for different mechanical skins and reservoir permeabilities

S	*k* (mD)	Gas RF (%)	Condensate RF (%)	Time Required (years)
-3	10	43.39	35.98	6.1
	50	46.17	38.02	2.7
	150	46.60	38.52	2.1
0	10	38.76	33.41	9.2
	50	45.18	37.48	4.1
	150	46.28	38.30	2.5
5	10	30.47	27.80	9.6
	50	43.64	36.63	6.0
	150	45.75	37.96	3.3
10	10	19.75	19.24	5.8
	50	41.90	35.57	7.4
	150	45.19	37.63	4.1

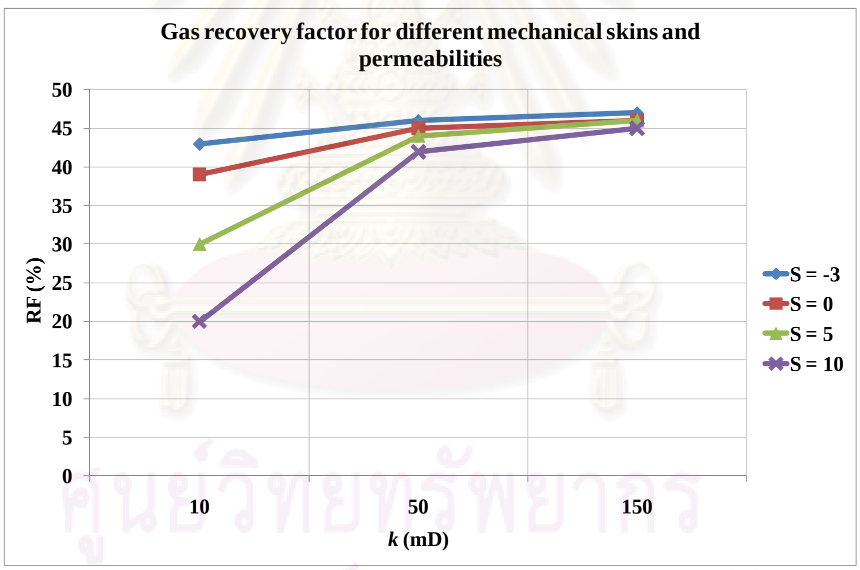


Figure 5.31: Gas recovery factor for different mechanical skins and reservoir permeabilities

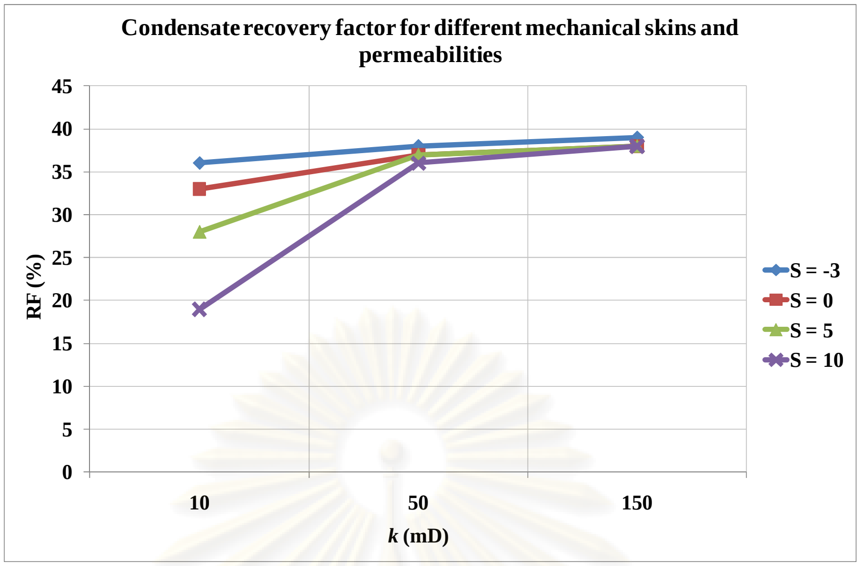


Figure 5.32: Condensate recovery factor for different mechanical skins and reservoir permeabilities

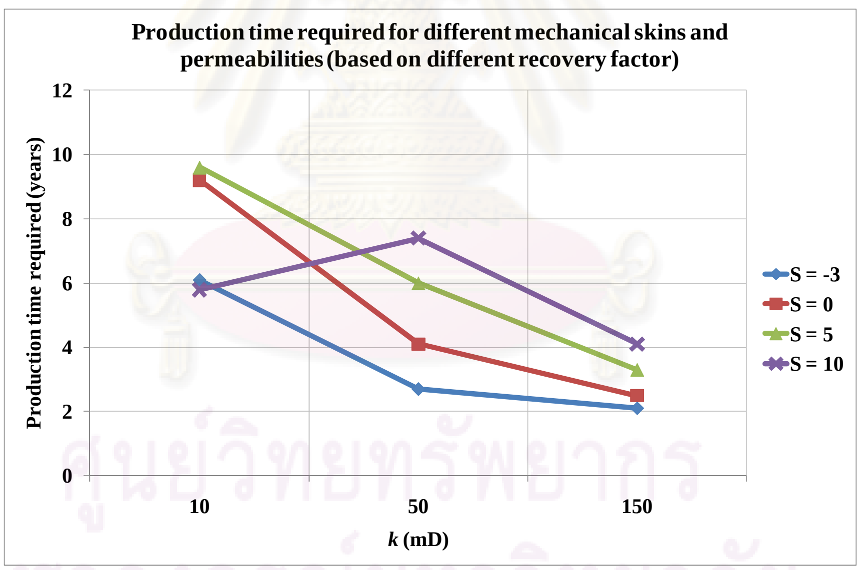


Figure 5.33: Production time required for different mechanical skins and reservoir permeabilities (based on different recovery factor)

Figure 5.33 shows production time required for different mechanical skins and reservoir permeabilities. It is noted that the results are based on different recovery factor. Thus, the shorter time may not be necessarily good. It can be observed that cases with higher mechanical skin factors require longer time to reach the ultimate recovery than cases with lower mechanical skin factors except only in the case with skin of 10 for 10-mD reservoir. In this case, the high skin causes a large pressure drop around the wellbore, and the well is not able to produce the economic limit at 500 psi tubing head pressure limit.

Figure 5.34 shows gas production rate for different mechanical skin factors in gas-condensate reservoir with permeability of 10 mD. It can be seen that gas flow rate in the case of negative skin factor, *S* = -3, can be maintained at 10 MMscf/d longer than other cases, and the decline period is shorter than the cases with *S* = 0 and 5. Comparison among different mechanical skin factors shows that gas flow rate during the decline period of *S* = -3 is the highest. In the case with *S* = 10, the plateau period cannot be maintained since the first day of production due to a large pressure drop around the wellbore. It can be observed that in the case that *S* = -3, the time required to produce the ultimate recovery is less than the other cases while the ultimate gas and condensate recoveries are the highest.

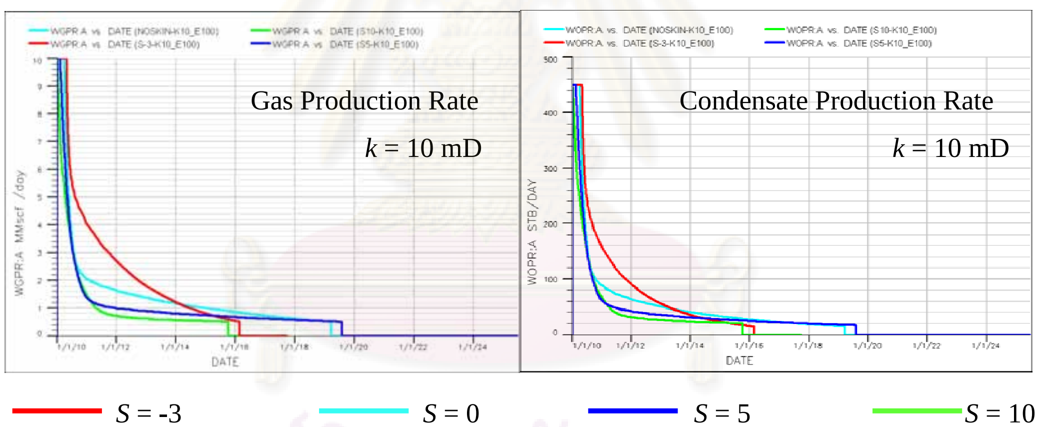


Figure 5.34: Gas and condensate production profiles for different mechanical skin factors in reservoir with *k* = 10 mD

Figures 5.35 and 5.36 show similar trend of gas flow rates for different mechanical skin factors in 50-mD and 150-mD reservoirs as those shown in Figure 5.34. However, it can be noticed that gas flow rate for a reservoir with higher permeability can be kept constant longer than that for a reservoir with lower permeability due to lower pressure loss across the reservoir in addition to the pressure loss across the skin zone.

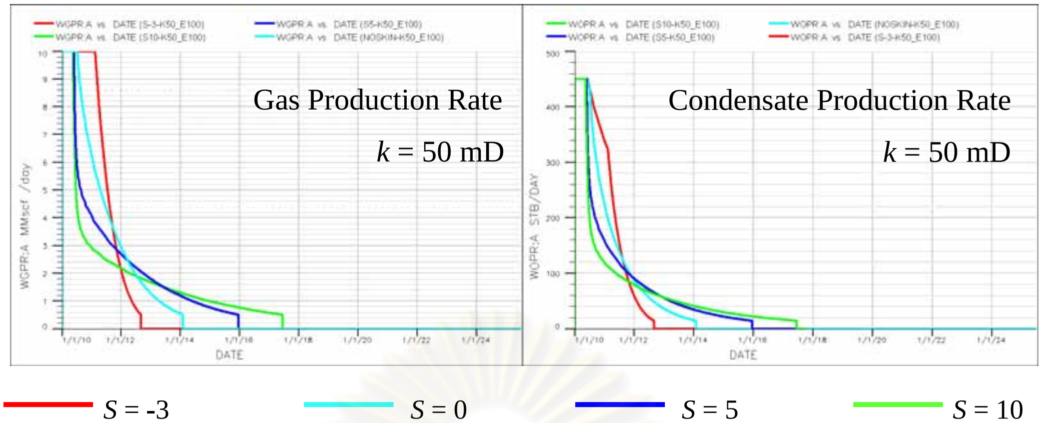


Figure 5.35: Gas and condensate production rates for different mechanical skin factors in reservoir with k = 50 mD

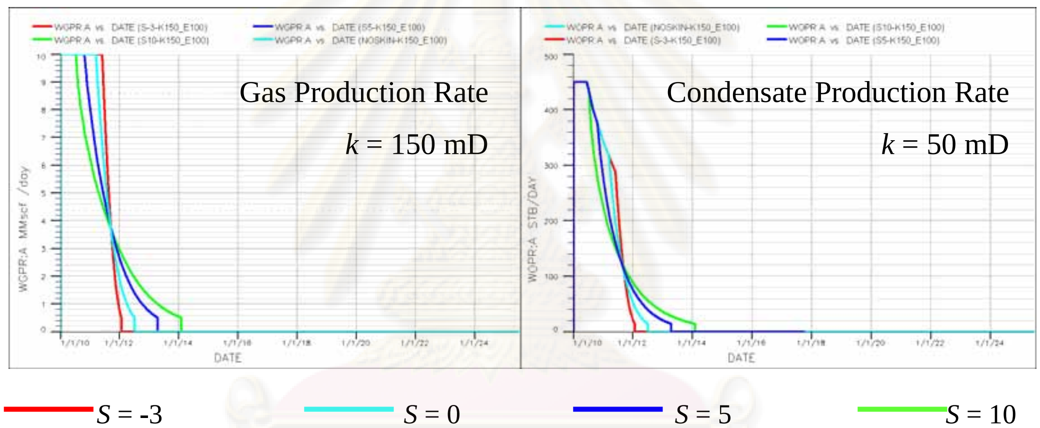


Figure 5.36: Gas and condensate production profiles for different mechanical skin factors in reservoir with k = 150 mD

The above results lead to a conclusion that the effect of mechanical skin does have effects on ultimate gas and condensate recoveries and production profiles (time required to reach its ultimate recoveries). Negative skin factor can maintain a longer production plateau period and provide a high gas flow rate with a shorter decline period when compared with cases with positive skins. This is an advantage in terms of economics because the NPV and IRR will be high.

5.2.2 Effect of Reservoir Permeability

The effect of reservoir permeability for gas-condensate reservoir with different mechanical skin factors are investigated in this part of the study. Results from Table 5.10 show that the difference in ultimate gas and condensate recoveries among various permeabilities is obviously seen for the case with higher mechanical skin factor. The difference in ultimate gas recovery between 10-mD reservoir and 150 mD-reservoir in the case with skin of -3, 0, 5, and 10 are 4%, 7%, 16%, and 25%, respectively. The difference in ultimate condensate recovery has similar trend with gas recovery. The difference in ultimate condensate recovery between 10-mD reservoir and 150-mD reservoir in the case with skin of -3, 0, 5, and 10 are 3%, 5%, 10%, and 18%, respectively. It can be noticed that the difference in ultimate gas recovery for each skin factor of gas-condensate reservoir is significantly higher than that of dry gas reservoir because of the effect of additional skin caused by condensate drop out near the wellbore.

Table 5.11 and Figure 5.31 show the reservoir pressure at abandonment condition for different mechanical skins and reservoir permeabilities. The results show that the abandonment pressure for 10-mD reservoir is higher than that for 50-mD and 150-mD reservoirs for all values of mechanical skin. This observation is similar with dry gas reservoir. It can be noticed that the reservoir abandonment pressure of gas-condensate reservoir is higher than that of dry gas reservoir when compared case by case, especially in the case of permeability of 10 mD. As seen in Table 5.11, the abandonment reservoir pressure in the case with skin of 5 and 10 in the 10-mD reservoir is high (1236 and 1700 psi). It can be explained that, in gas-condensate reservoir, the presence of additonal liquid around the wellbore significantly reduce the gas relative permeability and consequently the well productivity. Therefore, there is a large amount of gas and condensate remained in the reservoir and cannot be produced, causing the reservoir to be abandoned at a higher reservoir pressure.

Based on the above results, it is noticed that the effect of permeability is clearly observed for a system with higher mechanical skin factor. Therefore, reducing the effect of mechanical skin factor will also reduce the effect of permeability on gas and condensate recoveries in gas-condensate reservoir.

Table 5.11: Reservoir abandonment pressure for different mechanical skins and reservoir permeabilities

S	*k* (mD)	P_R (psia) @ abandonment
-3	10	705
	50	593
	150	575
0	10	890
	50	632
	150	587
5	10	1236
	50	694
	150	609
10	10	1700
	50	763
	150	631

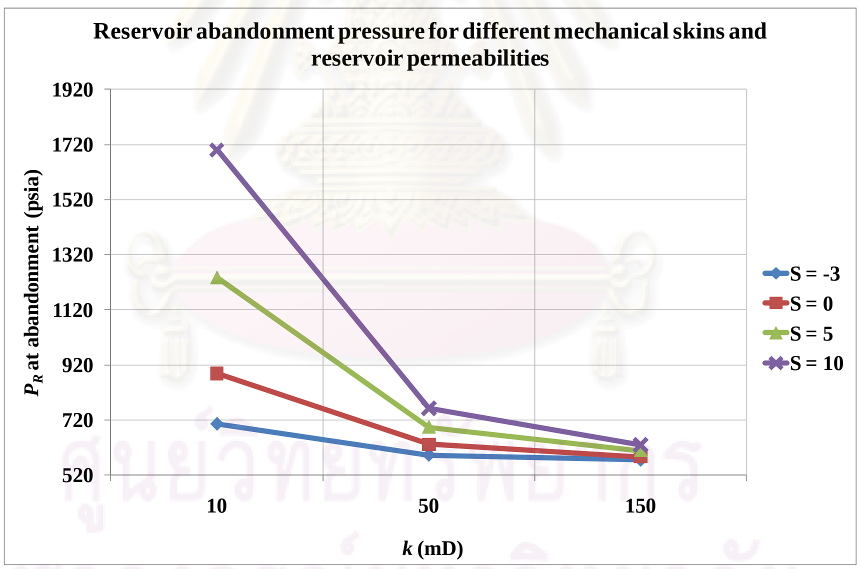


Figure 5.37: Reservoir abandonment pressure for different mechanical skins and reservoir permeabilities

5.2.3 Effect of Non-Darcy Skin

Results of reservoir simulation run for systems that contain both mechanical and non-Darcy skins are shown in Tables 5.12-5.17.

Table 5.12: Recovery factor and production time required for 10-mD reservoir

S	Q_i (MMscf/d)	*D*-factor (Day/Mscf)	Gas RF (%)	Condensate RF (%)	Production time (years)
-3	2	None	43.69	36.48	9.2
		Base estimates	43.67	36.47	9.3
		High estimates	43.53	36.39	9.4
	10	None	43.39	35.98	6.1
		Base estimates	43.39	36.00	6.2
		High estimates	43.37	36.09	6.7
	20	None	43.39	35.98	6.0
		Base estimates	43.39	36.00	6.1
		High estimates	43.37	36.09	6.6
5	2	None	30.47	27.80	10.9
		Base estimates	30.03	27.48	10.8
		High estimates	26.60	24.91	10.1
	10	None	30.47	27.80	9.6
		Base estimates	30.03	27.48	9.6
		High estimates	26.61	24.91	9.0
	20	None	30.47	27.80	9.6
		Base estimates	30.03	27.48	9.6
		High estimates	26.61	24.91	9.0
10	2	None	19.75	19.24	6.8
		Base estimates	18.97	18.57	6.4
		High estimates	14.48	14.44	4.0
	10	None	19.75	19.24	5.8
		Base estimates	18.97	18.57	5.5
		High estimates	14.48	14.44	3.3
	20	None	19.75	19.24	5.8
		Base estimates	18.97	18.57	5.5
		High estimates	14.48	14.44	3.3

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

Table 5.12 and Figure 5.38-5.40 show results of simulation runs for 10-mD reservoir. It can be observed that non-Darcy skin does not have an effect on ultimate gas and condensate recoveries in the case with negative mechanical skin, *S* = -3. The ultimate gas recoveries for different gas flow rates are in the range of 43 – 44 % while the ultimate condensate recoveries are the same at 36%. The effect of non-Darcy skin becomes larger in the system that has higher mechanical skin (*S* = 5 and 10). When skin is 5, the ultimate gas and condensate recoveries in the case with high non-Darcy skin are lower than the case without non-Darcy skin both by 3%. For higher skin, S = 10, the case with high non-Darcy skin has an ultimate gas and condensate recoveries lower than the case without non-Darcy skin by 6% and 5%, respectively.

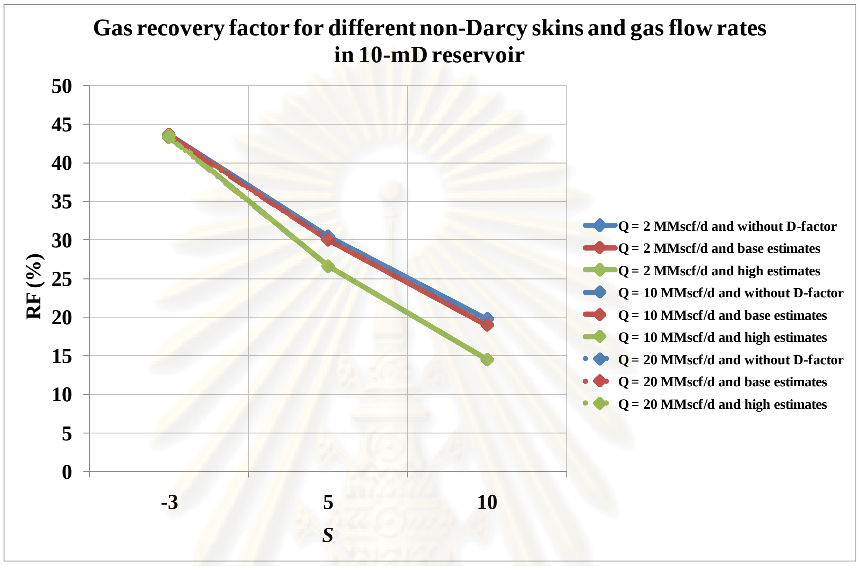


Figure 5.38: Gas recovery factor for different non-Darcy skins and gas flow rates in 10-mD reservoir

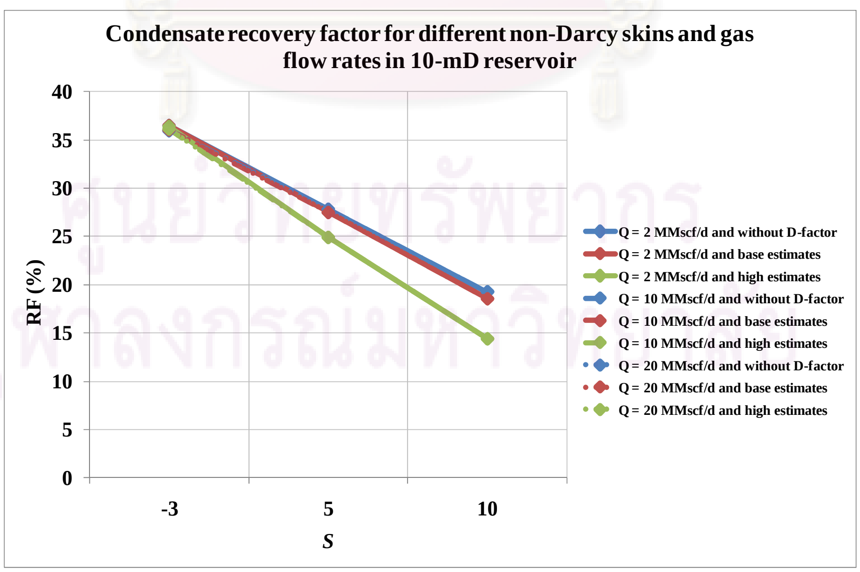


Figure 5.39: Condensate recovery factor for different non-Darcy skin and gas flow rate in 10-mD reservoir

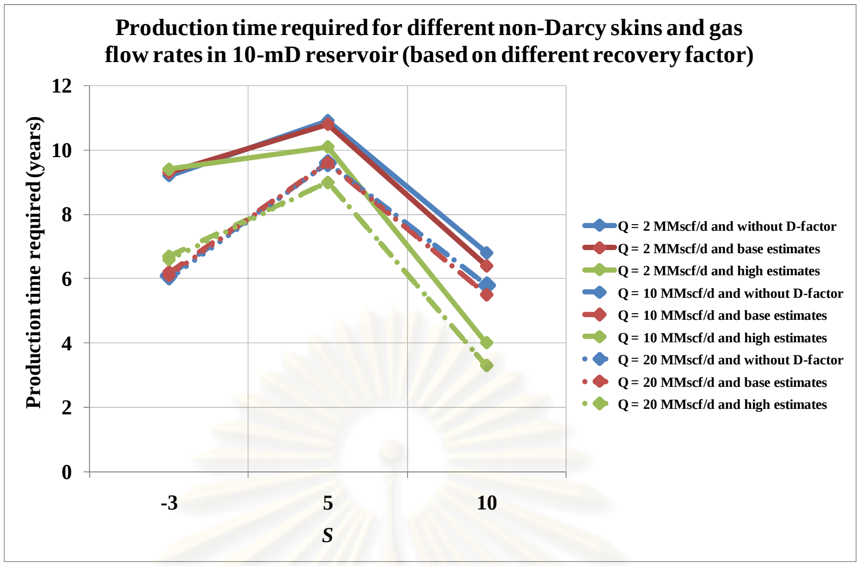


Figure 5.40: Production time required for different non-Darcy skins and gas flow rates in 10-mD reservoir (based on different recovery factor)

The comparison between the amount of gas and condensate recovered in the early and late production time period are performed. Since the longest production time is approximately 11 years, the amount of gas and condensate recovered after production for 3 and 7 years are compared. Table 5.13 and Figures 5.41-5.44 show the comparison between gas and condensate recoveries after production for 3 and 7 years in reservoir with permeability of 10 mD. It can be seen that the amount of gas and condensate recovered after producing for 3 years in the case with S = -3 are significantly higher than those of the cases with positive skins, S = 5 and 10, especially when the initial gas flow rate is 10 or 20 MMscf/d. It can be observed that in the case with S = -3 and initial gas flow rate of 20 MMscf/d, within the first 3 years, the amount of gas and condensate recovered are higher than that for S = 10 approximately 20% and 15%, respectively. It can be seen that the difference in gas recovery among different non-Darcy skin is less when S = -3 and becomes higher when S = 5 and 10. However, the effect of non-Darcy skin becomes more significant after producing for 7 years because the effect of condensate blockage is more significant when reservoir pressure is highly depleted.

Table 5.13: Gas and condensate recoveries at different periods of time for 10-mD reservoir

S	***Q_i*** **(MMscf/d)**	***D*-factor (Day/Mscf)**	**Gas Recovery (%)**		**Condensate Recovery (%)**	
			@ 3 yrs	**@ 7 yrs**	**@ 3 yrs**	**@ 7 yrs**
-3	2	None	16.78	38.34	16.58	33.08
		Base estimates	16.78	38.29	16.58	33.04
		High estimates	16.78	37.81	16.58	32.74
	10	None	34.47	43.39	30.20	35.98
		Base estimates	34.23	43.39	30.05	36.00
		High estimates	32.30	43.37	28.81	36.09
	20	None	35.12	43.39	30.64	35.98
		Base estimates	34.88	43.39	30.49	36.00
		High estimates	32.94	43.37	29.26	36.09
5	2	None	14.87	24.15	14.80	22.92
		Base estimates	14.75	23.83	14.69	22.67
		High estimates	14.04	21.86	14.01	21.06
	10	None	18.30	26.48	17.95	24.78
		Base estimates	17.97	26.06	17.66	24.45
		High estimates	16.50	23.70	16.34	22.58
	20	None	18.36	26.52	18.01	24.81
		Base estimates	18.02	26.09	17.70	24.48
		High estimates	16.50	23.70	16.34	22.58
10	2	None	13.69	19.75	13.67	19.24
		Base estimates	13.57	18.97	13.55	18.57
		High estimates	12.97	14.48	12.97	14.44
	10	None	15.53	19.75	15.43	19.24
		Base estimates	15.24	18.97	15.16	18.57
		High estimates	14.13	14.48	14.10	14.44
	20	None	15.53	19.75	15.43	19.24
		Base estimates	15.24	18.97	15.16	18.57
		High estimates	14.13	14.48	14.10	14.44

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

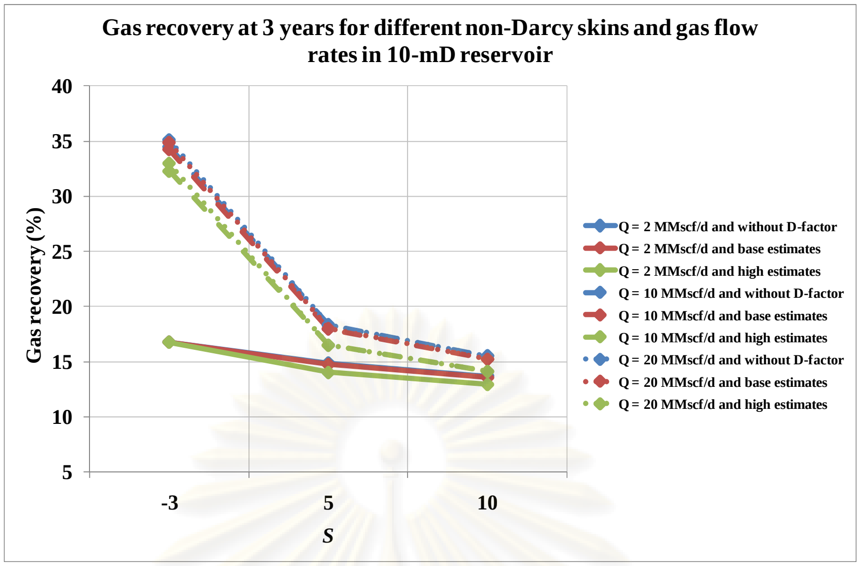


Figure 5.41: Gas recovery at 3 years for different non-Darcy skins and gas flow rates in 10-mD reservoir

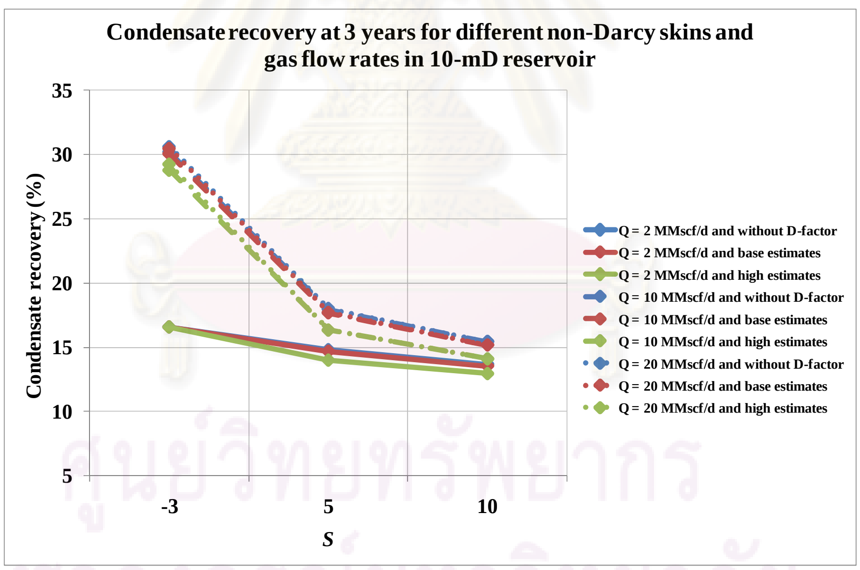


Figure 5.42: Condensate recovery at 3 years for different non-Darcy skins and gas flow rates in 10-mD reservoir

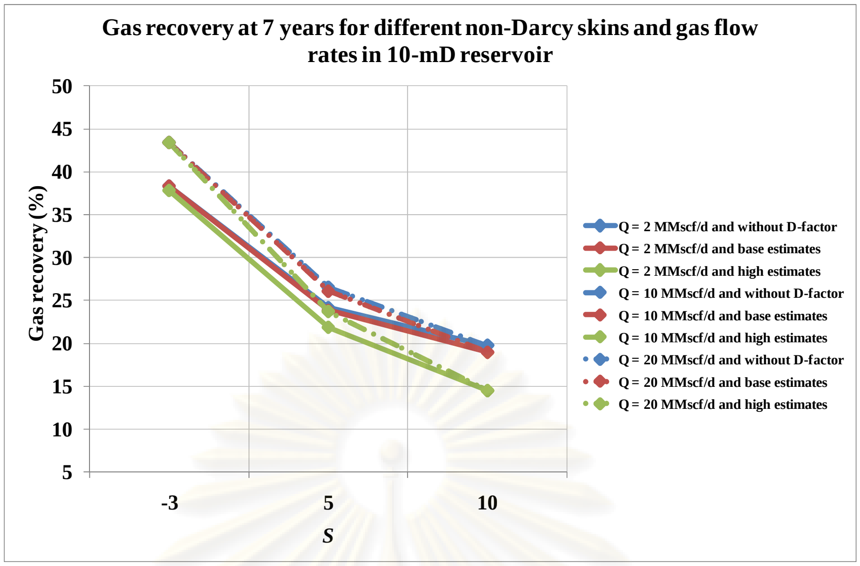


Figure 5.43: Gas recovery at 7 years for different non-Darcy skins and gas flow rates in 10-mD reservoir

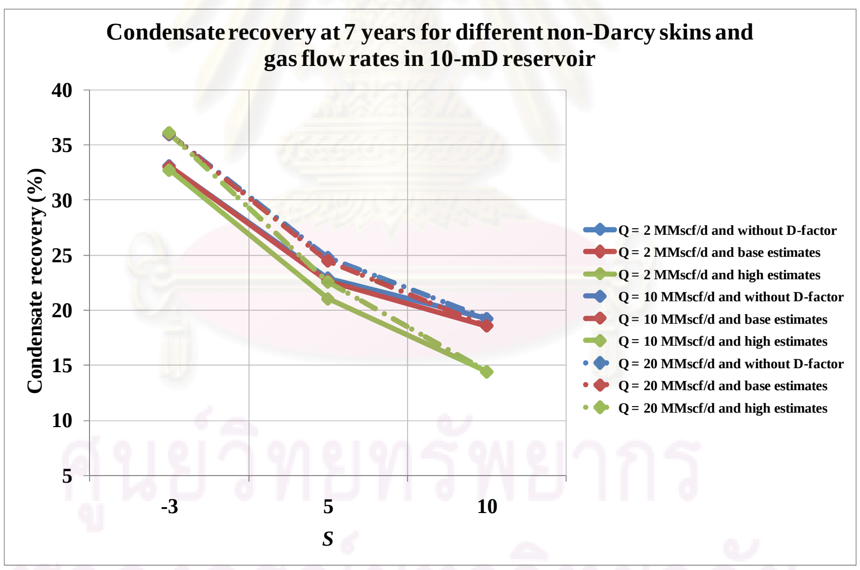


Figure 5.44: Condensate recovery at 7 years for different non-Darcy skins and gas flow rates in 10-mD reservoir

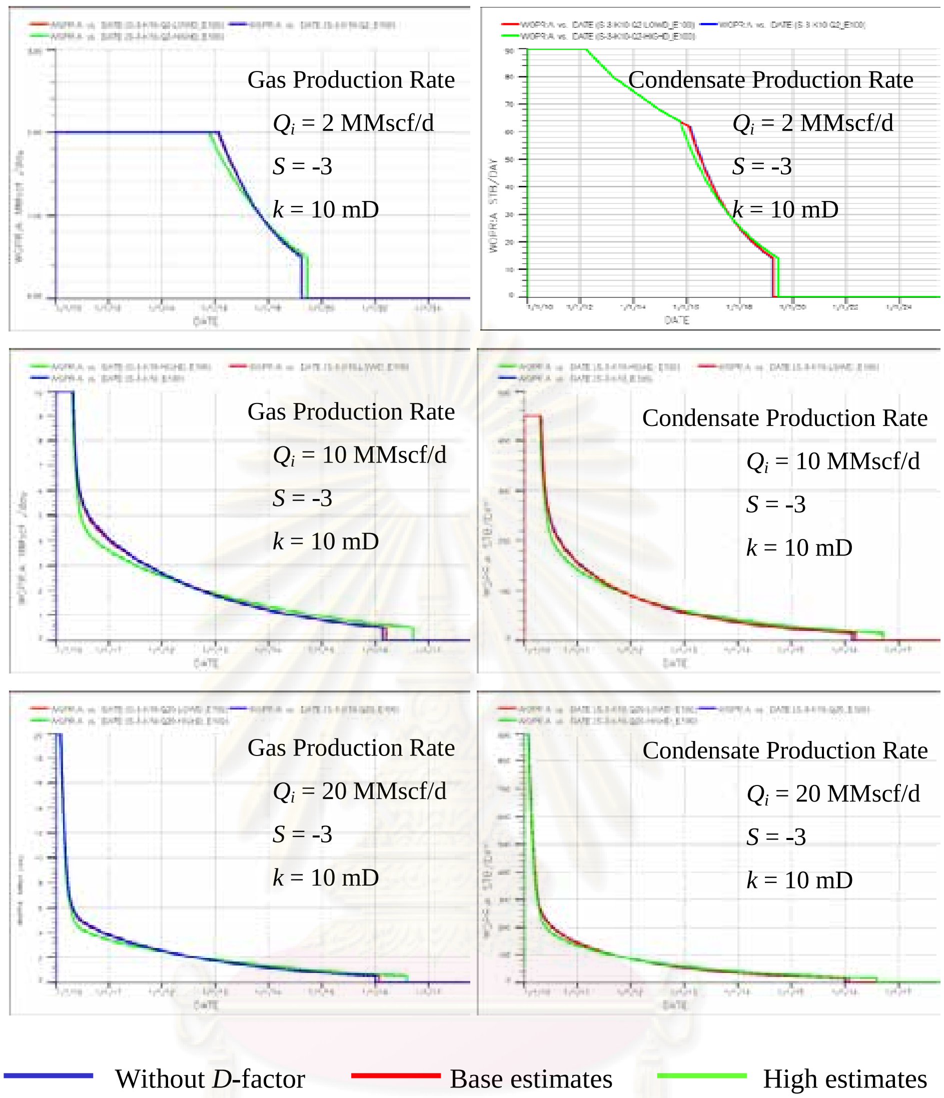


Figure 5.45: Gas and condensate production profiles for different initial gas flow rates and D-factors in reservoir with S = -3 and k = 10 mD

Figure 5.45 shows gas and condensate production profiles for 10-mD reservoir with different initial gas flow rates in the case of negative skin, S = -3. It can be observed that for each initial gas flow rate, gas production profiles for different values of non-Darcy skin are similar except for the cases with high non-Darcy skin which tend to decline more rapidly and have longer production time than the cases without or with low non-Darcy skin.

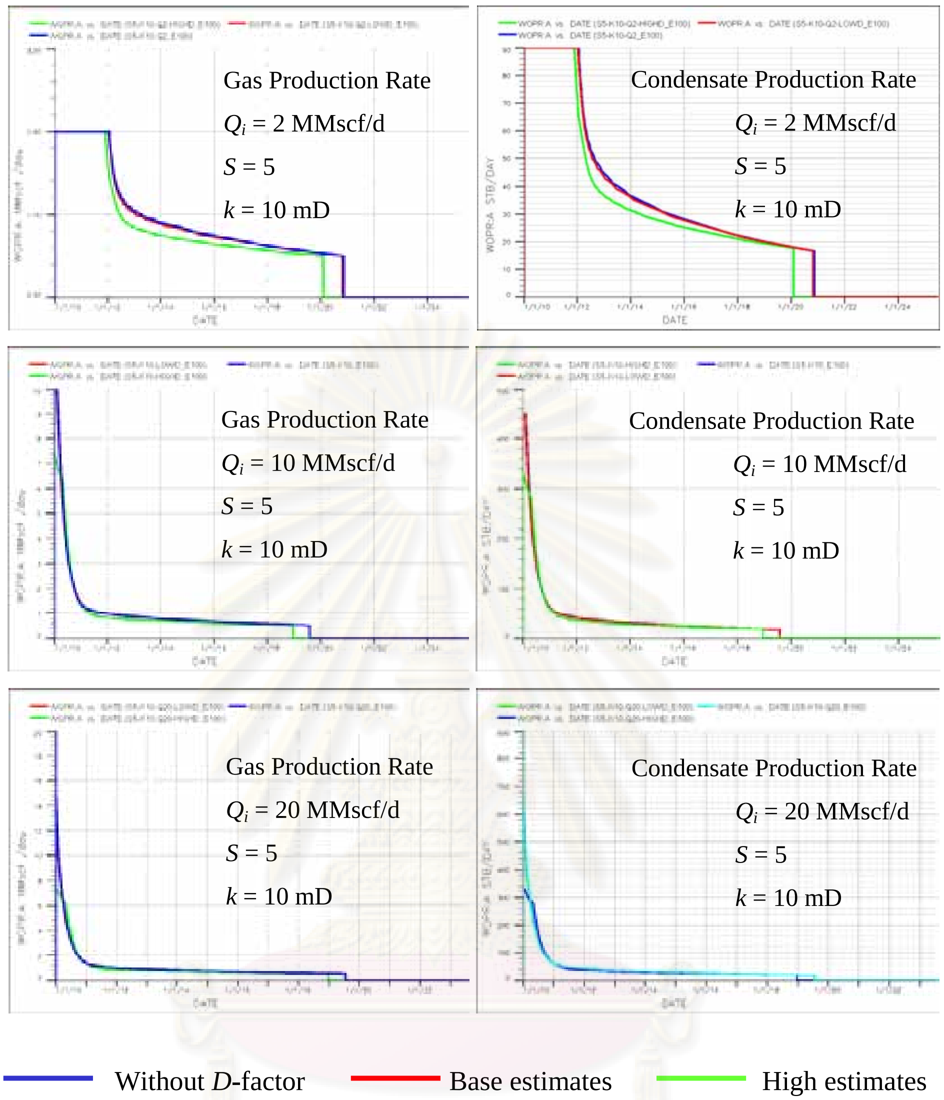


Figure 5.46: Gas and condensate production profiles for different initial gas flow rates and D-factors in reservoir with S = 5 and k = 10 mD

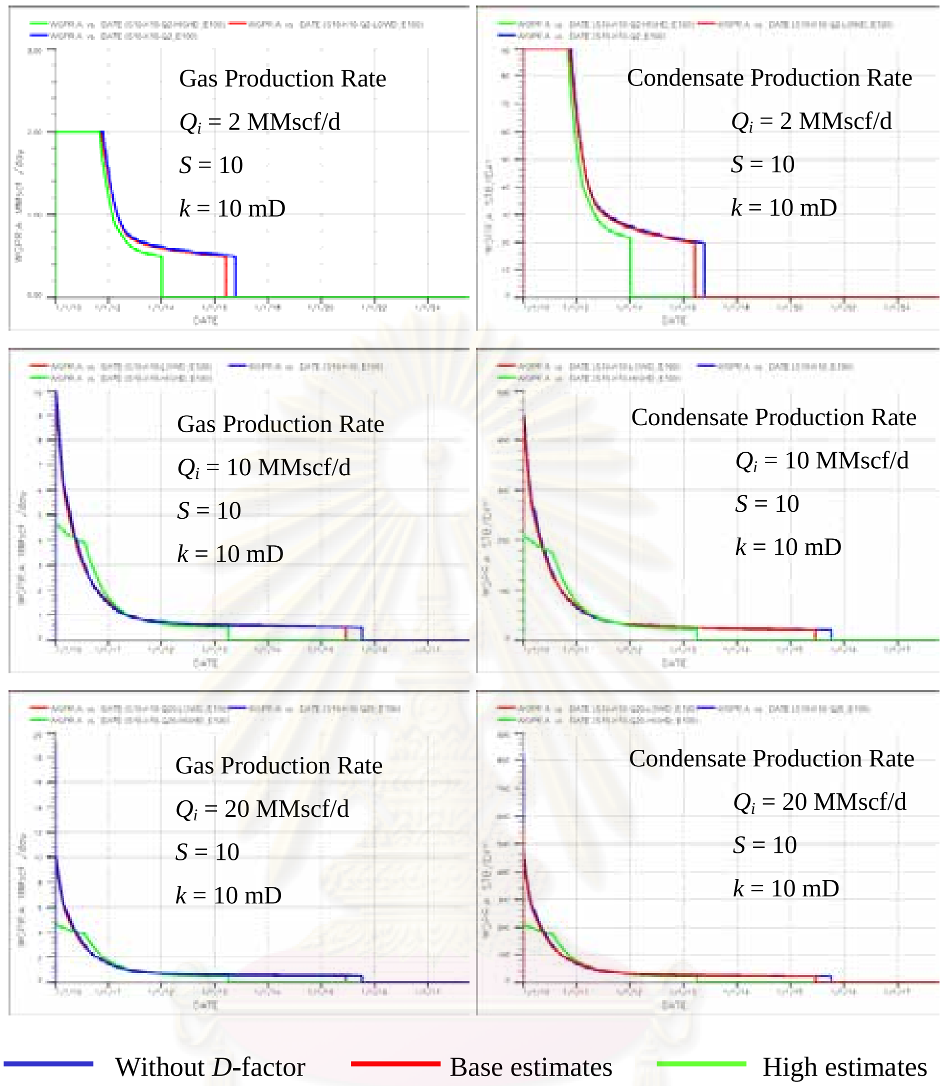


Figure 5.47: Gas and condensate production profiles for different initial gas flow rates and D-factors in reservoir with S = 10 and k = 10 mD

Figures 5.46 and 5.47 show gas and condensate production profiles for 10-mD reservoirs with different initial gas flow rates when skin is 5 and 10, respectively. The results show similar trend with those shown in case with S = -3. Cases with high non-Darcy skin cannot maintain the plateau as long as cases without or with low non-Darcy skin. However, the plateau period for cases with S = 5 and 10 are shorter than that for cases with S = -3 when compared case by case. Additionally, it can be noticed that cases with high non-Darcy skin with gas flow rate is 10 MMscf/d (S = 10, Q_i = 10, and high D-factor) and all cases with gas flow rate of 20 MMscf/d cannot produce gas at the required initial rate due to a large pressure drop caused by mechanical skin, non-Darcy skin, and condensate blockage skin and also pressure loss across the reservoir due to low permeability.

Table 5.14: Recovery factor and production time required for 50-mD reservoir

S	**Q_i (MMscf/d)**	***D*-factor (Day/Mscf)**	**Gas RF (%)**	**Condensate RF (%)**	**Production time (years)**
-3	2	None	46.26	38.38	8.5
		Base estimates	46.26	38.38	8.5
		High estimates	46.23	38.36	8.6
	10	None	46.17	38.02	2.7
		Base estimates	46.17	38.02	2.7
		High estimates	46.15	38.04	3.0
	20	None	46.15	37.83	2.3
		Base estimates	46.15	37.86	2.3
		High estimates	46.14	38.00	2.7
5	2	None	43.83	36.83	9.2
		Base estimates	43.75	36.77	9.3
		High estimates	42.96	36.30	10.3
	10	None	43.64	36.63	6.0
		Base estimates	43.60	36.62	6.3
		High estimates	42.94	36.27	8.2
	20	None	43.64	36.63	5.8
		Base estimates	43.60	36.62	6.7
		High estimates	42.94	36.27	8.1
10	2	None	42.04	35.69	9.8
		Base estimates	41.83	35.56	10.0
		High estimates	40.07	34.47	11.8
	10	None	41.90	35.57	7.4
		Base estimates	41.77	35.50	7.9
		High estimates	40.07	34.47	10.1
	20	None	41.90	35.57	7.3
		Base estimates	41.77	35.50	7.8
		High estimates	40.77	34.47	10.1

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

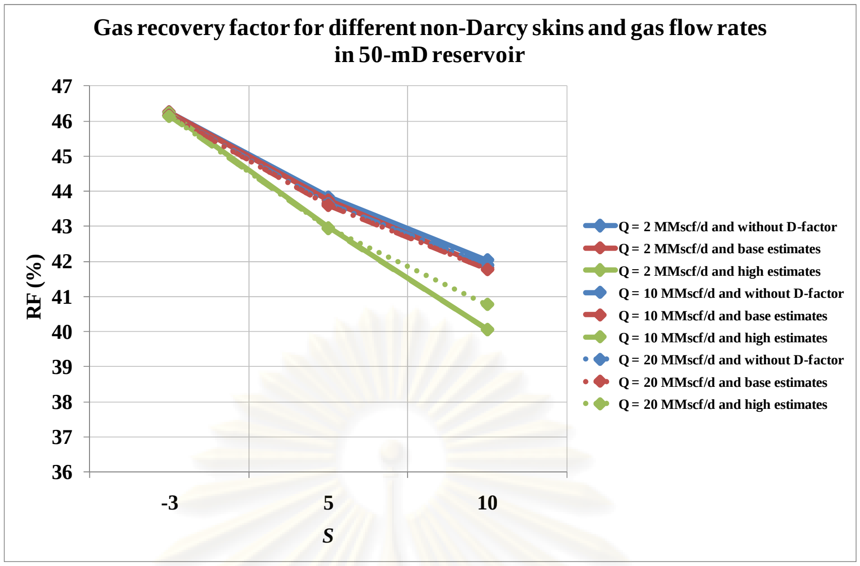


Figure 5.48: Gas recovery factor for different non-Darcy skin and gas flow rate in 50-mD reservoir

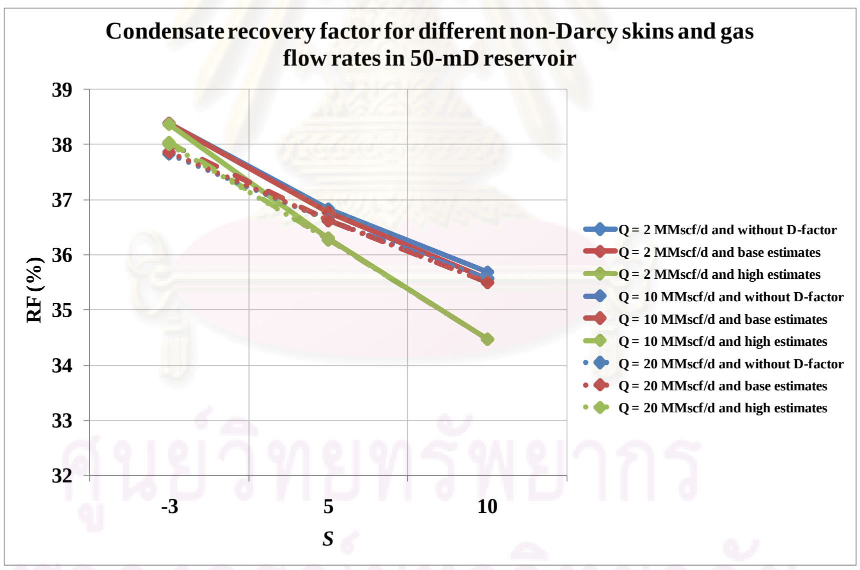


Figure 5.49: Condensate recovery factor for different non-Darcy skin and gas flow rate in 50-mD reservoir

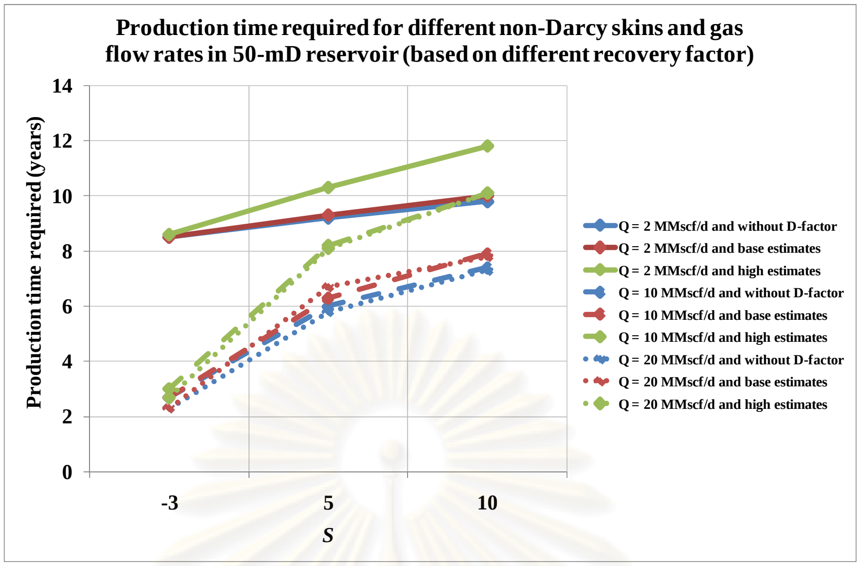


Figure 5.50: Production time required for different non-Darcy skins and gas flow rates in 50-mD reservoir (based on different recovery factor)

Table 5.14 and Figures 5.48-5.50 show results from simulation runs with the same parameters as in previous series except that the permeability of the reservoir is increased to 50 mD. It can be seen that non-Darcy skin does not have an effect on ultimate gas and condensate recoveries for cases with *S* = -3. The ultimate gas and condensate recoveries for different gas flow rates and various non-Darcy skins are the same at 46% and 38%, respectively. When *S* = 5, the ultimate gas and condensate recoveries for most cases are the same at 44% and 37%, respectively, except for the case with high non-Darcy skin which have ulitmate gas and condensate recoveries of 43% and 37%. For higher mechanical skin factor, *S* = 10, it can be noticed that cases with high non-Darcy skin have an ultimate recovery lower than cases without non-Darcy skin by 2%.

Table 5.15: Gas and condensate recoveries at different periods of time for 50-mD reservoir

S	Q_i (MMscf/d)	*D*-factor (Day/Mscf)	Gas Recovery (%)		Condensate Recovery (%)	
			@ 3 yrs	@ 7 yrs	@ 3 yrs	@ 7 yrs
-3	2	None	16.78	39.16	16.65	33.91
		Base estimates	16.78	39.16	16.65	33.91
		High estimates	16.78	39.16	16.65	33.91
	10	None	46.17	46.17	38.02	38.02
		Base estimates	46.17	46.17	38.02	38.02
		High estimates	46.15	46.15	38.04	38.04
	20	None	46.15	46.15	37.83	37.83
		Base estimates	46.15	46.15	37.86	37.86
		High estimates	46.14	46.14	38.00	38.00
5	2	None	16.78	38.44	16.63	33.40
		Base estimates	16.78	38.15	16.63	33.21
		High estimates	16.78	35.68	16.63	31.57
	10	None	35.22	43.64	31.16	36.63
		Base estimates	33.88	43.60	30.25	36.62
		High estimates	27.98	40.89	26.01	34.97
	20	None	36.10	43.64	31.76	36.63
		Base estimates	34.74	43.60	30.85	36.62
		High estimates	28.59	41.14	26.47	35.13
10	2	None	16.78	36.11	16.62	31.84
		Base estimates	16.78	35.39	16.62	31.35
		High estimates	16.29	30.49	16.17	27.90
	10	None	29.71	41.25	27.26	35.16
		Base estimates	28.27	40.30	26.20	34.57
		High estimates	23.10	34.60	22.14	30.83
	20	None	30.44	41.49	27.80	35.31
		Base estimates	28.94	40.56	26.71	34.74
		High estimates	23.18	34.64	22.20	30.87

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

The production time required to reach ultimate recovery among different values of non-Darcy skin in cases for *S* = -3 is not different for all gas flow rates. However, the difference becomes more significant when the mechanical skin is 5 and 10.

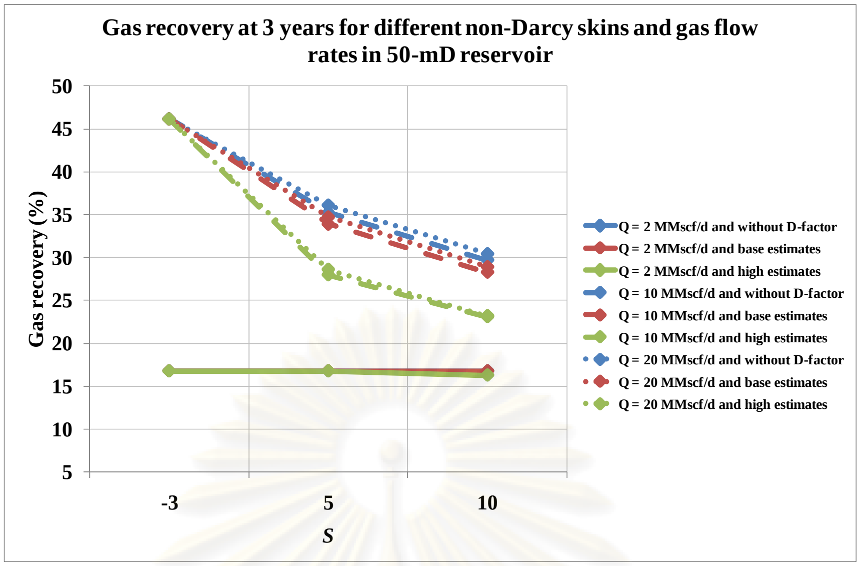


Figure 5.51: Gas recovery at 3 years for different non-Darcy skins and gas flow rates in 50-mD reservoir

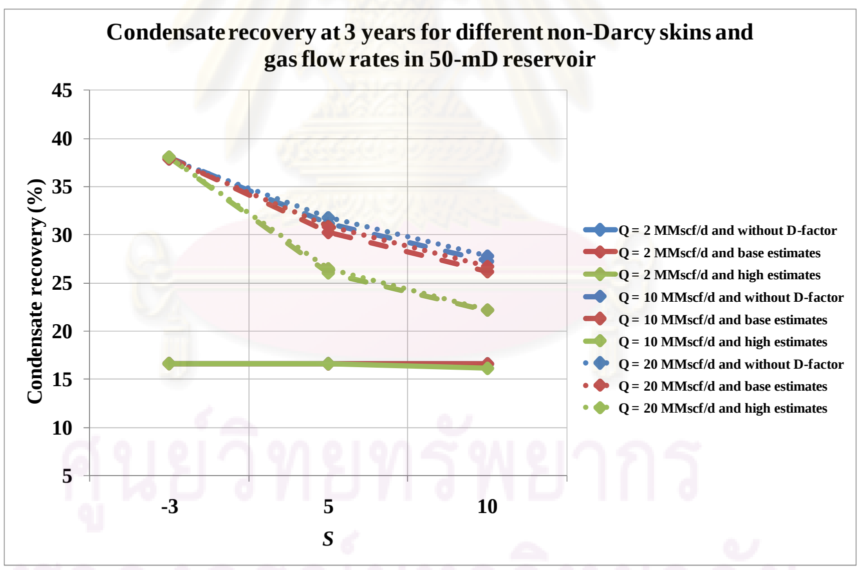


Figure 5.52: Condensate recovery at 3 years for different non-Darcy skins and gas flow rates in 50-mD reservoir

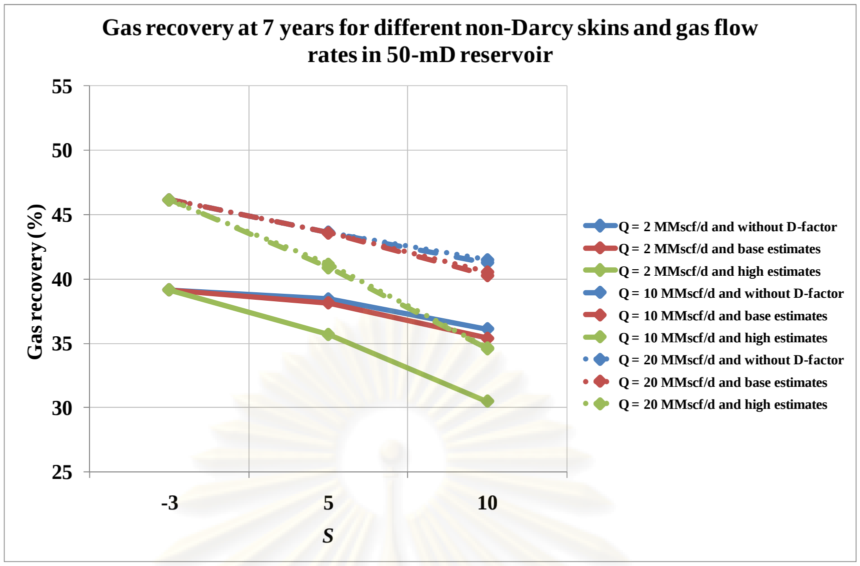


Figure 5.53: Gas recovery at 7 years for different non-Darcy skins and gas flow rates in 50-mD reservoir

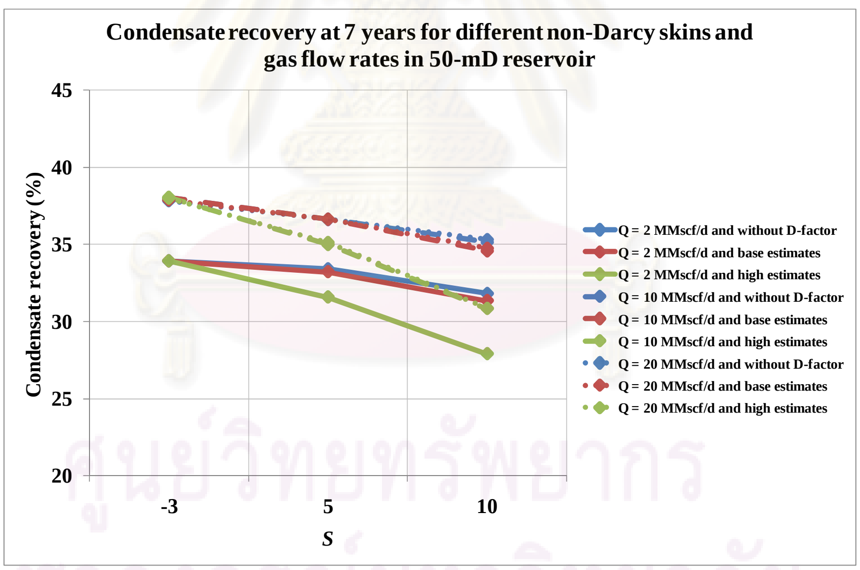


Figure 5.54: Condensate recovery at 7 years for different non-Darcy skins and gas flow rates in 50-mD reservoir

Table 5.15 and Figures 5.51-5.54 show gas and condensate recoveries at different periods of time for 50-mD reservoir. It can be seen that non-Darcy skin has an effect on the amount of gas recovered during the first 3 years of production when the skin is 5 and 10. However, the effect of non-Darcy skin cannot be seen when skin is -3. The gas and condensate recoveries are the same for each gas flow rate. When skin factor is 5 or 10, non-Darcy skin does have an effect on gas recovery after 3 years of production. The effect of non-Darcy skin on gas recovery can be seen when gas flow rate is 10 or 20 MMscf/d. Gas and condensate recoveries for cases without non-Darcy skin are approximately 7% and 5% greater than the cases with high non-Darcy skin, respectively. However, the effect of non-Darcy skin becomes more significant after producing for 7 years because the effect of condensate blockage is greater when reservoir pressure is highly depleted.

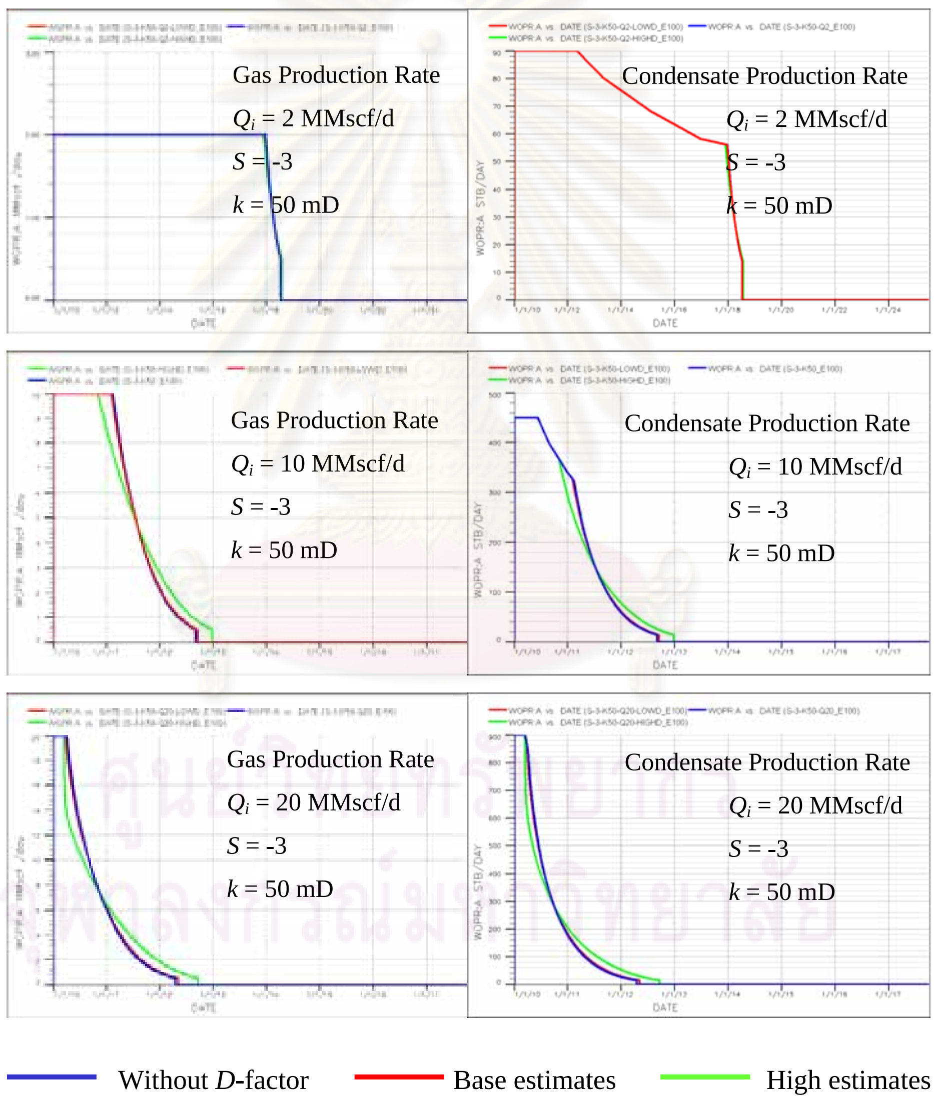


Figure 5.55: Gas and condensate production profiles for different initial gas flow rates and *D*-factors in reservoir with S = -3 and k = 50 mD

Figure 5.55 shows the comparison of gas production profiles among different initial gas flow rates and D-factors in the reservoir with S = -3 and k = 50 mD. The effect of non-Darcy skin cannot be observed when gas flow rate is 2 MMscf/d. The effect of non-Darcy skin can be seen when gas flow rate is 10 or 20 MMscf/d. Gas flow rate in case of high non-Darcy skin cannot be maintained as a plateau as long as cases without or with low non-Darcy skin. The gas flow rate in cases of high non-Darcy skin rapidly declines after the end of production plateau period. Additionally, the decline period in the cases of high non-Darcy skin is longer than that for the cases without or with low non-Darcy skin.

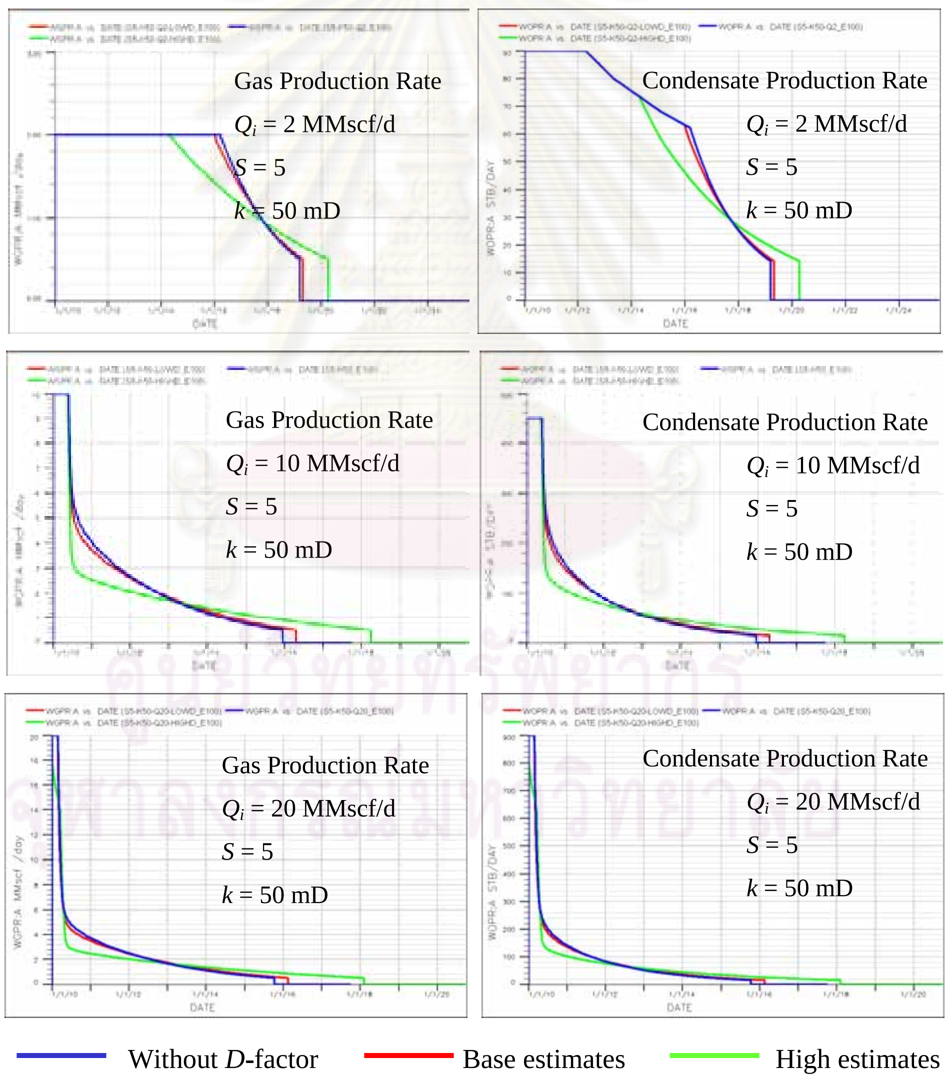


Figure 5.56: Gas and condensate production profiles for different initial gas flow rates and *D*-factors in reservoir with S = 5 and k = 50 mD

Figures 5.56 and 5.57 show the comparison of gas production profiles among different initial gas flow rates and *D*-factors when the skin is 5 and 10, respectively. The results show similar trends with those shown in the case of S = -3. However, it is clearly seen that the production plateau period of high non-Darcy skin in cases of S = 10 is shorter than that in cases of S = 5 and -3. Additionally, the decline period in cases of high non-Darcy skin when S = 10 and 5 are significantly longer than the case with S = -3 when compared case by case.

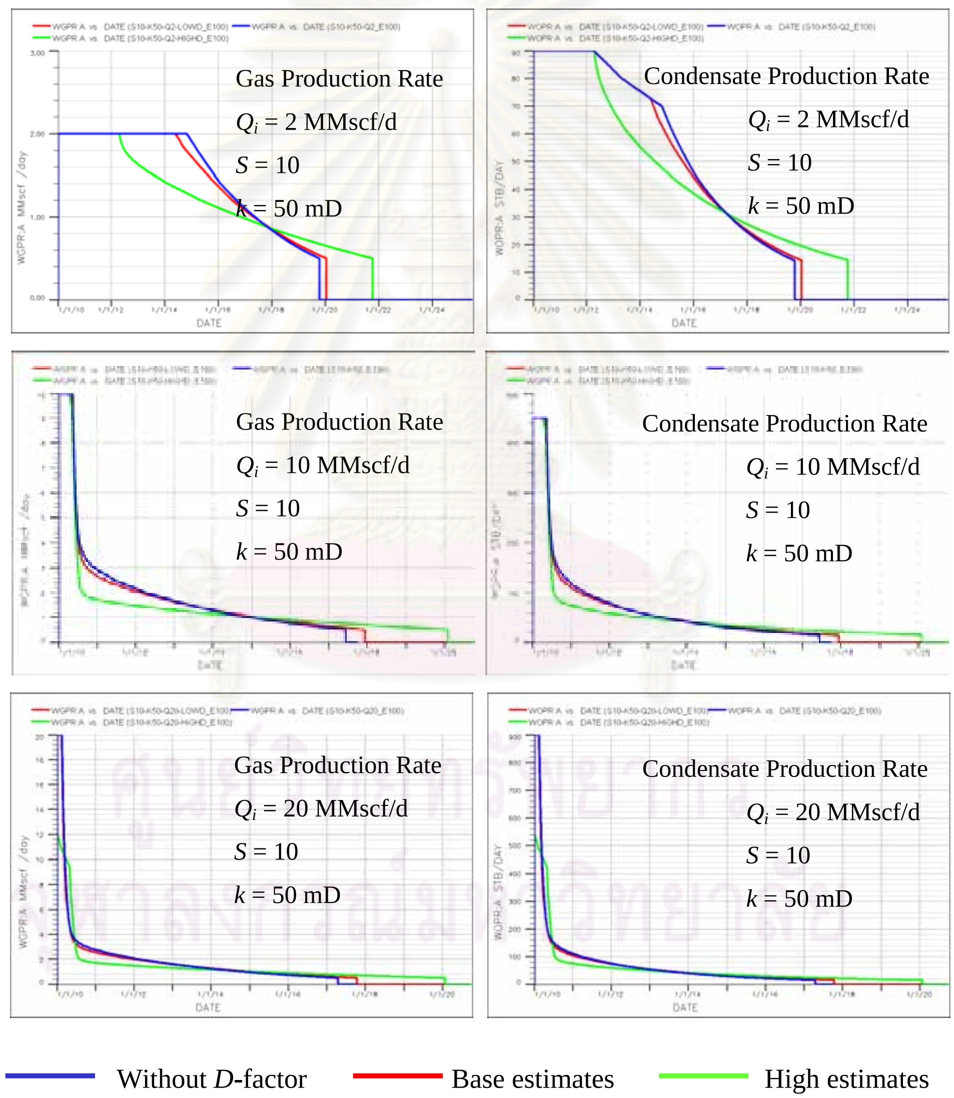


Figure 5.57: Gas and condensate production profiles for different initial gas flow rates and *D*-factors in reservoir with S = 10 and k = 50 mD

From the above results, it can be concluded that non-Darcy skin has an effect on the production performance of both gas and condensate. Higher non-Darcy skin leads to lower amount of gas and condensate recovered, shorter production plateau period, and longer decline period. The effect of non-Darcy skin is small when there is low mechanical skin. Therefore, reducing mechanical skin can reduce the effect of non-Darcy skin.

Table 5.16: Recovery factor and production time required for 150-mD reservoir

S	**Q_i (MMscf/d)**	***D*-factor (Day/Mscf)**	**Gas RF (%)**	**Condensate RF (%)**	**Production time (years)**
-3	2	None	46.63	38.67	8.4
		Base estimates	46.63	38.67	8.4
		High estimates	46.62	38.66	8.4
	10	None	46.60	38.52	2.1
		Base estimates	46.60	38.52	2.1
		High estimates	46.59	38.52	2.2
	20	None	46.59	38.40	1.5
		Base estimates	46.59	38.40	1.5
		High estimates	46.58	38.43	1.7
5	2	None	45.90	38.19	8.7
		Base estimates	45.87	38.18	8.7
		High estimates	45.62	38.02	9.0
	10	None	46.19	37.63	4.1
		Base estimates	46.17	37.65	4.6
		High estimates	45.69	37.41	6.9
	20	None	45.73	37.94	3.0
		Base estimates	45.73	37.97	3.3
		High estimates	45.55	37.93	4.9
10	2	None	45.39	37.87	8.8
		Base estimates	45.33	37.83	8.9
		High estimates	44.74	37.46	9.6
	10	None	45.19	37.63	4.1
		Base estimates	45.17	37.65	4.6
		High estimates	44.69	37.41	6.9
	20	None	45.19	37.63	3.9
		Base estimates	45.17	37.65	4.4
		High estimates	44.69	37.41	6.7

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

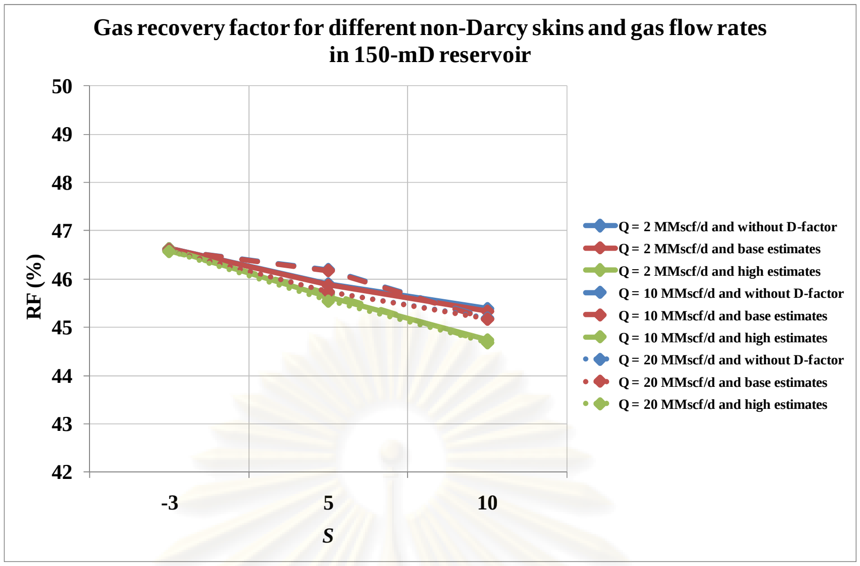


Figure 5.58: Gas recovery factor for different non-Darcy skins and gas flow rates in 150-mD reservoir

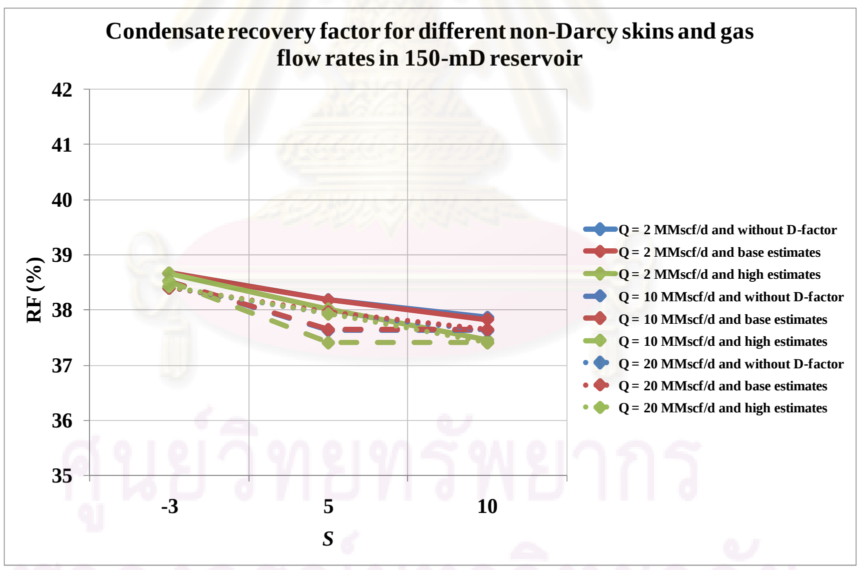


Figure 5.59: Condensate recovery factor for different non-Darcy skin and gas flow rate in 150-mD reservoir

Table 5.16 and Figures 5.58-5.60 show results of simulation runs with the same parameters as previous series except that the reservoir permeability is increased to 150 mD. It can be noticed that the non-Darcy skin and gas flow rate do not have effects on the ultimate gas and condensate recoveries for each mechanical skin factor.

The ultimate gas recovery is 47%, 46%, and 45% while ultimate condensate recovery is 39%, 38%, and in the range of 37-38% when *S* equals to -3, 5, and 10, respectively.

In terms of production time required to reach ultimate recovery, non Darcy skin does have an effect on production time only when *S* equals 5 and 10. However, this effect is less when compared with reservoirs with permeability of 50 and 10 mD.

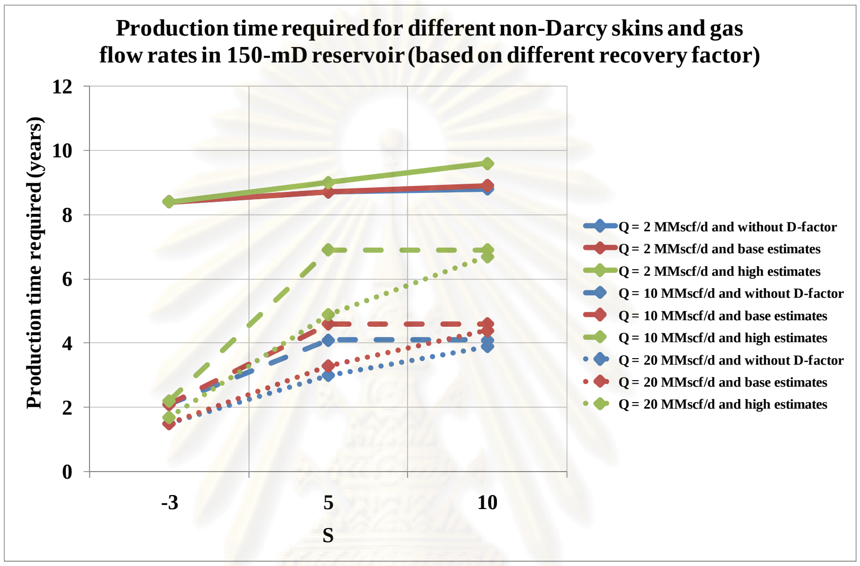


Figure 5.60: Production time required for different non-Darcy skins and gas flow rates in 150-mD reservoir (based on different recovery factor)

Table 5.17 and Figures 5.61-5.64 shows the comparison between gas and condensate recoveries after production for 3 and 7 years in reservoir with permeability of 150 mD. It can be seen that within the first 3 years, the effect of non-Darcy skin cannot be seen when *S* equals to -3. In cases with skin equals to 5, the effect of non-Darcy skin leads to the difference in gas recovery of 7% and 6% and condensate recovery of 5% and 4% when gas flow rate is 10 and 20 MMscf/d, respectively. This effect is more significant when skin equals to 10 as the difference in gas recovery is 11% and 10% and the difference in condensate recovery is 7% and 7% when gas flow rate is 10 and 20 MMscf/d, respectively. However, the effect of non-Darcy skin is not significant after producing for 7 years because the production time required to reach ultimate recovery for most of the cases are less than 7 years.

Table 5.17: Gas and condensate recoveries at different periods of time for 150-mD reservoir

S	Q_i (MMscf/d)	*D*-factor (Day/Mscf)	Gas RF (%)		Condensate RF (%)	
			@ 3 yrs	@ 7 yrs	@ 3 yrs	@ 7 yrs
-3	2	None	16.78	39.16	16.66	33.97
		Base estimates	16.78	39.16	16.66	33.97
		High estimates	16.78	39.16	16.66	33.97
	10	None	46.60	46.60	38.52	38.52
		Base estimates	46.60	46.60	38.52	38.52
		High estimates	46.59	46.59	38.52	38.52
	20	None	46.59	46.59	38.40	38.40
		Base estimates	46.59	46.59	38.40	38.40
		High estimates	46.58	46.58	38.43	38.43
5	2	None	16.78	39.16	16.65	33.94
		Base estimates	16.78	39.16	16.65	33.94
		High estimates	16.78	39.16	16.65	33.94
	10	None	45.28	45.75	37.67	37.96
		Base estimates	44.60	45.73	37.27	37.97
		High estimates	38.41	45.55	33.41	37.93
	20	None	45.71	45.73	37.92	37.94
		Base estimates	45.16	45.73	37.61	37.97
		High estimates	39.58	45.55	34.16	37.93
10	2	None	16.78	39.16	16.65	33.93
		Base estimates	16.78	39.16	16.65	33.93
		High estimates	16.78	38.06	16.65	33.22
	10	None	42.71	45.19	36.08	37.63
		Base estimates	40.89	45.17	34.96	37.65
		High estimates	32.16	44.69	29.14	37.41
	20	None	43.42	45.19	36.52	37.63
		Base estimates	41.77	45.17	35.52	37.65
		High estimates	33.15	44.69	29.85	37.41

Note: Low estimates of non-Darcy skin coefficients for different mechanical skins are obtained from Table 4.10 while high estimates are obtained from Table 4.11.

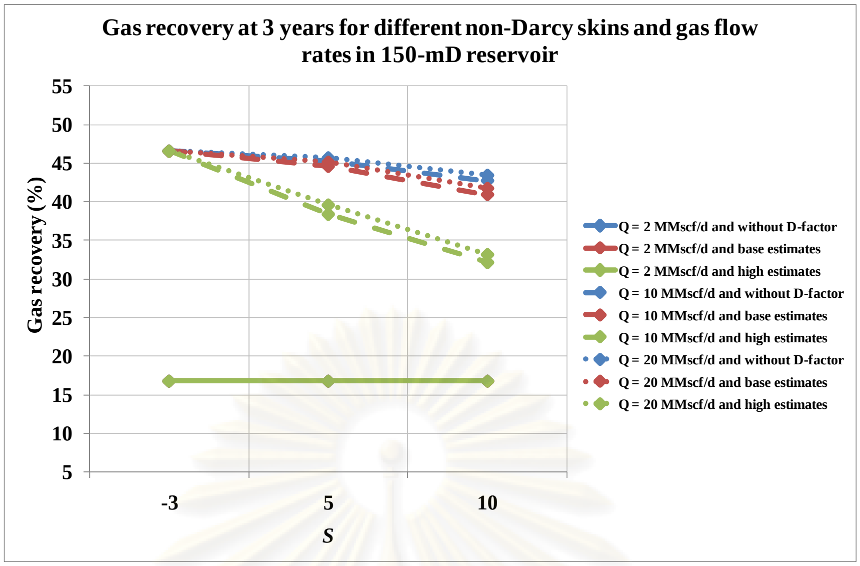


Figure 5.61: Gas recovery at 3 years for different non-Darcy skins and gas flow rates in 150-mD reservoir

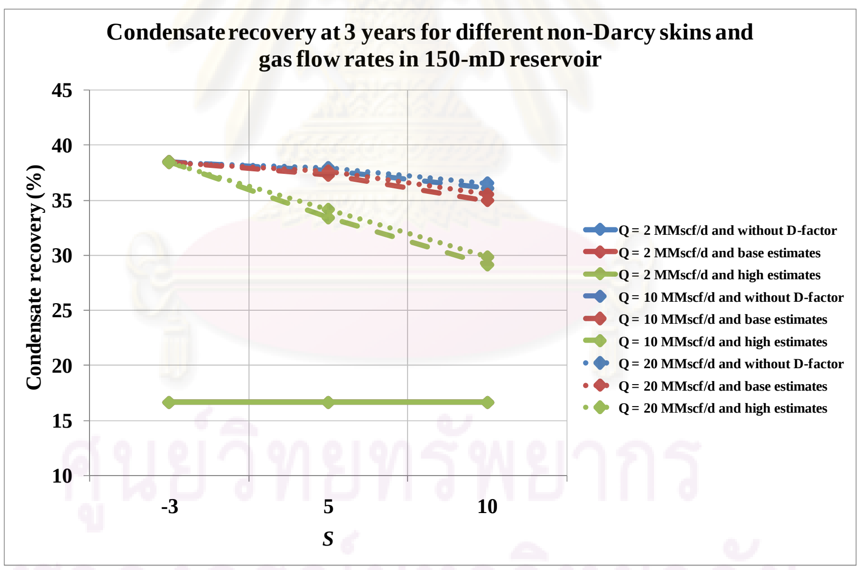


Figure 5.62: Condensate recovery at 3 years for different non-Darcy skins and gas flow rates in 150-mD reservoir

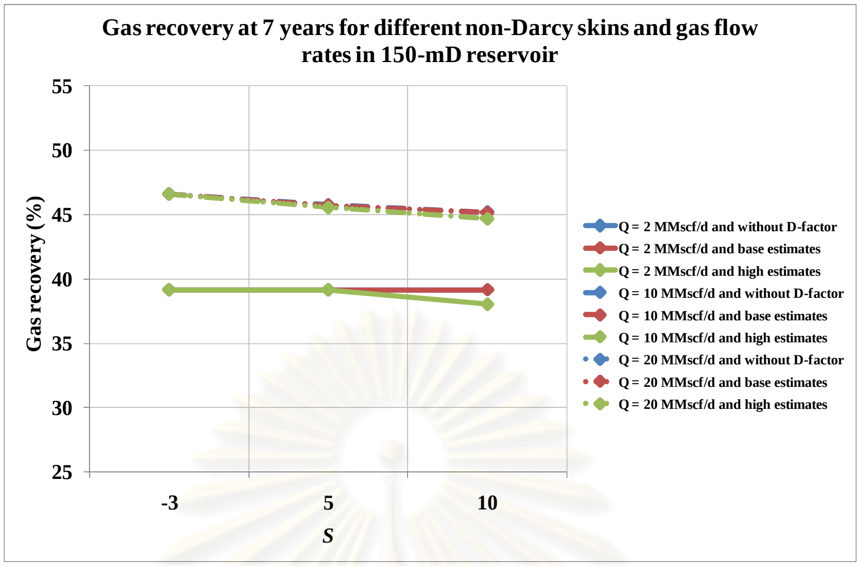


Figure 5.63: Gas recovery at 7 years for different non-Darcy skins and gas flow rates in 150-mD reservoir

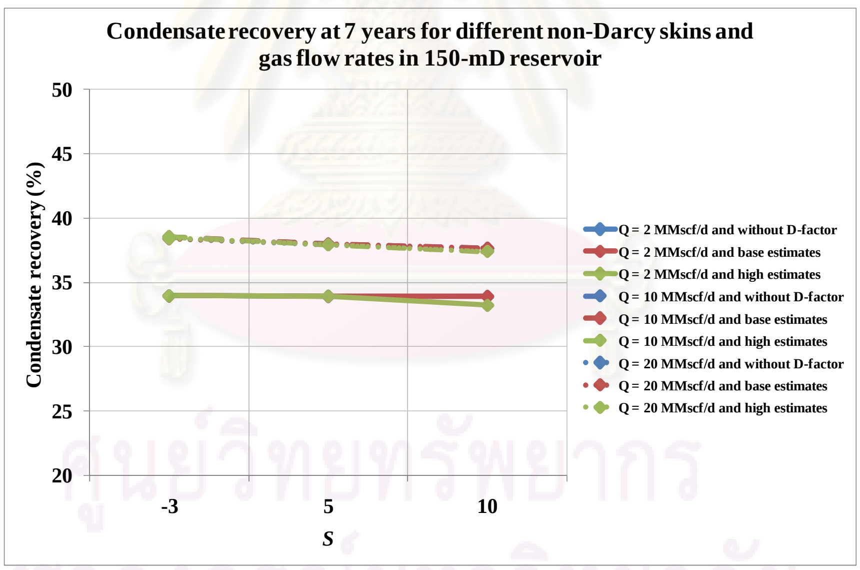


Figure 5.64: Condensate recovery at 7 years for different non-Darcy skins and gas flow rates in 150-mD reservoir

Figure 5.65 shows the comparison of gas production profiles among different initial gas flow rates and D-factors in the reservoir with S = -3 and k = 150 mD. It can be observed that the effect of non-Darcy skin cannot be seen in when initial gas flow rate is 2 MMscf/d. Gas production profiles are the same for cases with no, low, and high non-Darcy skin. In cases with high gas flow rate of 10 and 20 MMscf/d, the effect of non-Darcy skin on the production plateau period and the decline period becomes more evident than cases with initial gas flow rate of 2 MMscf/d. However, these effects are less when compared with cases that S = 5 and 10 in Figures 5.66 and 5.67.

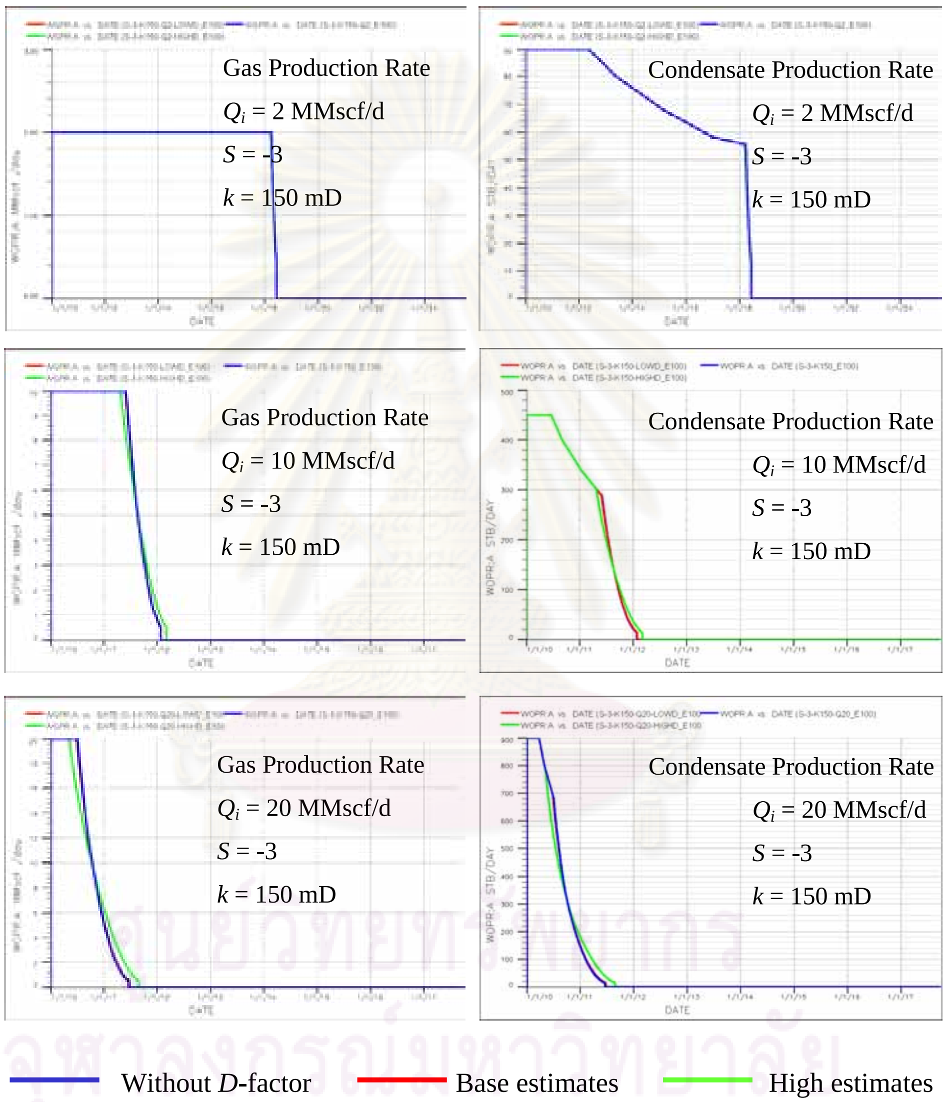


Figure 5.65: Gas and condensate production profiles for different initial gas flow rates and D-factors in reservoir with S = -3 and k = 150 mD

Figures 5.66 and 5.67 show the comparison of gas production profiles among different initial gas flow rates and D-factors as the same as Figure 5.47 except that the skin are 5 and 10, respectively. The results show similar trends with those shown in the reservoir with permeabilities of 10 and 50 mD. It can be observed that in all cases of gas flow rates with skin of 5, gas flow rate in the cases with high non-Darcy skin declines rapidly after end of plateau period. The decline period in the cases with high non-Darcy skin are longer than the case without and low non-Darcy skin. These effect becomes more significant in S = 10.

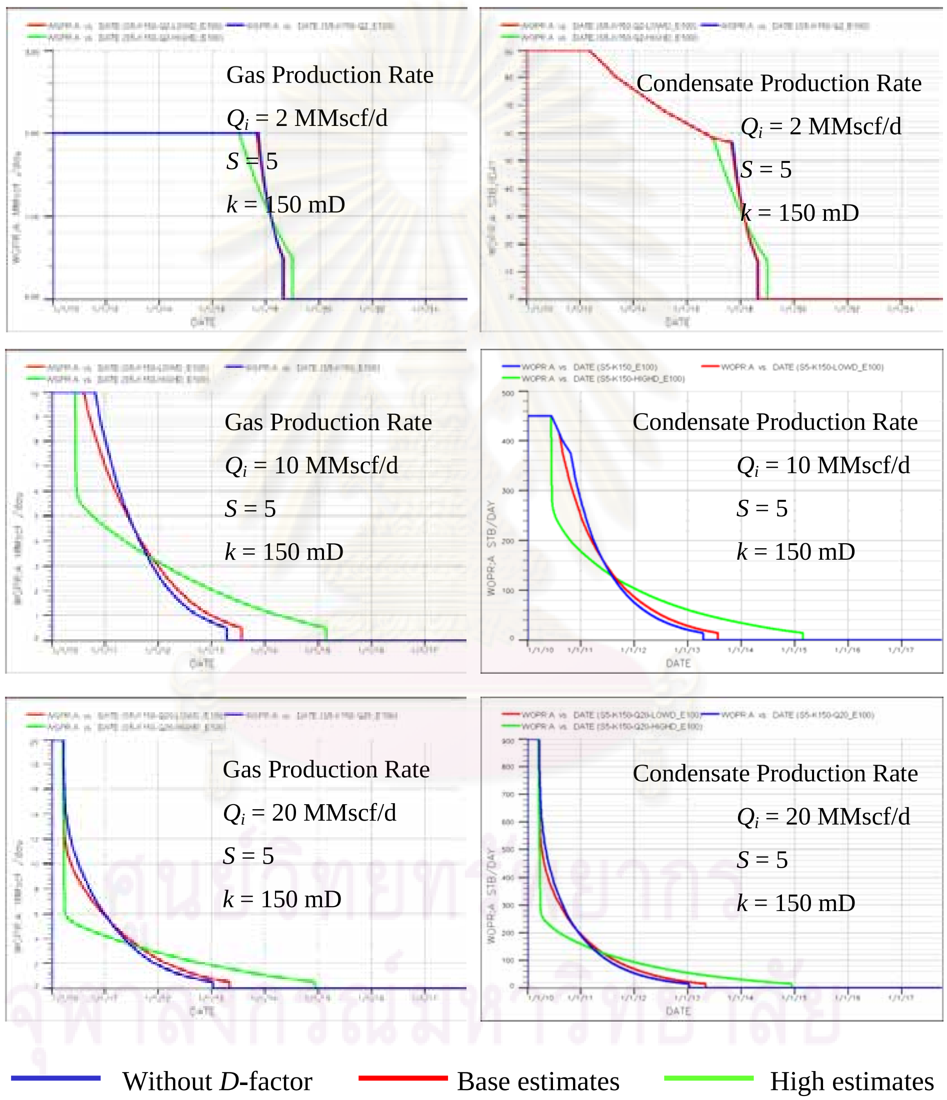


Figure 5.66: Gas and condensate production profiles for different initial gas flow rates and D-factors in reservoir with S = 5 and k = 150 mD

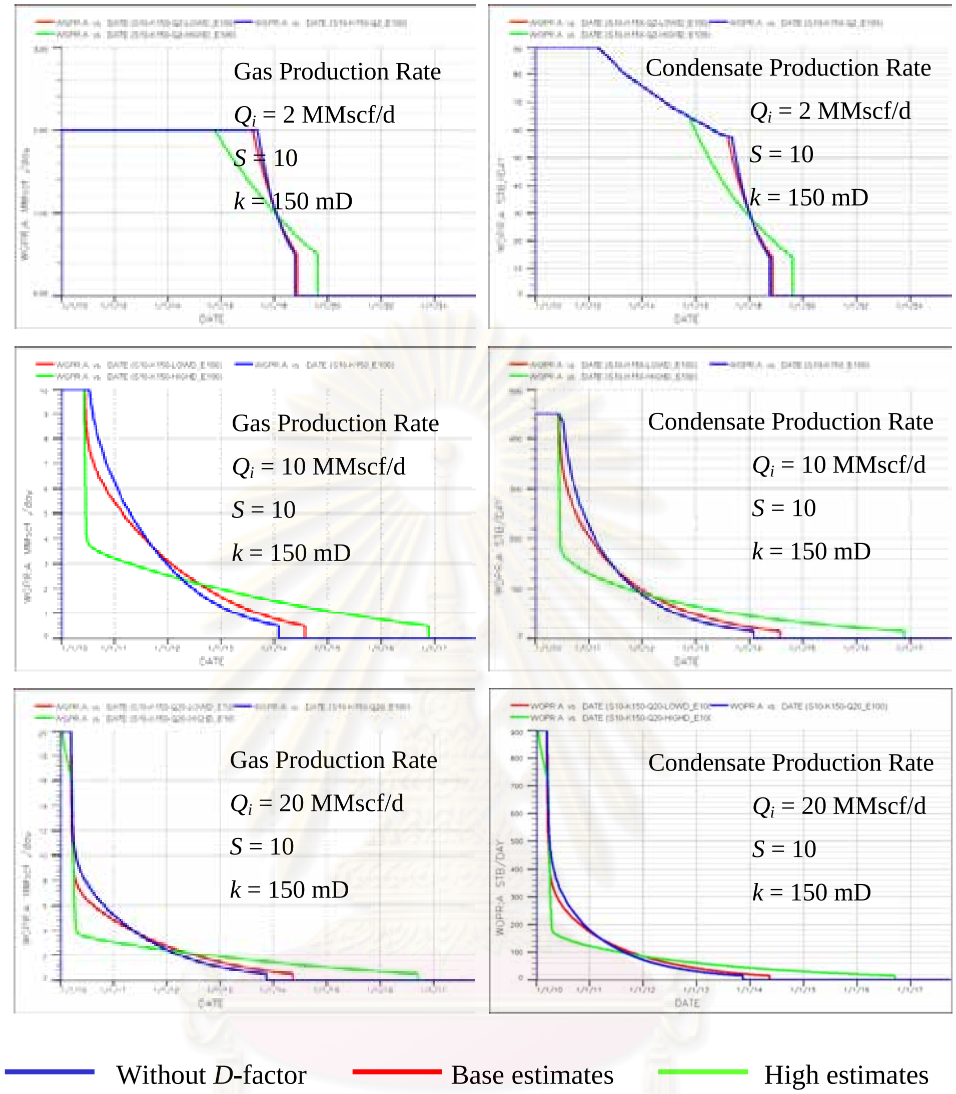


Figure 5.67: Gas and condensate production profiles for different initial gas flow rates and *D*-factors in reservoir with S = 10 and k = 150 mD

CHAPTER VI

CONCLUSIONS

This study is intended to investigate the effect of mechanical skin and non-Darcy skin on recovery efficiency and production performance of gas and gas-condensate reservoirs. A single-layered hypothetical reservoir model is set up using reservoir characteristics of a typical reservoir in the Gulf of Thailand. Based on the results of this study, the effects of mechanical skin, non-Darcy skin, reservoir properties, and gas flow rate on recovery efficiency and production performance in gas and gas-condensate reservoirs can be summarized as follows:

1. In dry gas reservoir, mechanical skin moderately reduces the ultimate gas recovery for a 10-mD reservoir but has a slight impact on the ultimate gas recovery for 50-mD and 150-mD reservoirs.
2. In gas-condensate reservoir, mechanical skin considerably reduces the ultimate recovery for a 10-mD reservoir but moderately reduces the ultimate recovery for 50-mD and 150-mD reservoirs.
3. The difference in ultimate recovery between the minimum and maximum mechanical skin in gas-condensate reservoir is greater than that of in dry gas reservoir due to the additional effect from condensate blockage skin.
4. The production time required to reach the ultimate recovery in dry gas and gas-condensate reservoirs is affected by mechanical skin for all reservoirs in this study (permeability of 10, 50, and 150 mD). The reservoir with higher mechanical skin requires longer production time to reach ultimate recovery. The effect will be greater in low permeability reservoir.
5. In dry gas reservoir, non-Darcy skin does not have an effect on the ultimate gas recovery when skin factor is -3 for all gas flow rates. This effect can be observed in all reservoirs in this study (permeability of 10, 50, and 150 mD). However, non-Darcy skin slightly reduces the ultimate gas recovery when the skin factor is 5 and 10 for all gas flow rates only in the 10-mD reservoir.

6. In gas-condensate reservoir, non-Darcy skin does not have an effect on the ultimate recovery when skin factor is -3 for all gas flow rates. This effect can be observed in reservoirs with permeability of 10, 50, and 150 mD. For skin of 5 and 10, non-Darcy skin moderately reduces the ultimate recovery when reservoir permeability is 10 mD but slightly reduces the ultimate recovery in 50-mD and 150-mD for all gas flow rates.
7. Gas flow rate does not have an impact on the ultimate recovery in dry gas and gas-condensate reservoirs in this study (permeability of 10, 50, and 150 mD). The ultimate recoveries in cases that have the same mechanical skin factor and non-Darcy skin coefficient are the same for all three different gas flow rates.
8. Negative skin factor, S = -3, can maintain the longer production plateau period and shorten the decline period when compared with S = 0, 5, and 10. This effect can be observed in dry gas and gas-condensate reservoirs. Therefore, doing well stimulation to create negative skin will be beneficial in terms of economics because the NPV and IRR will be high.

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Vitae

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