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# Formulation of New Equation to Estimate Productivity Index of Horizontal Wells

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## Abstract

Significant advances in horizontal well drilling technology have been made in recent years. The conventional productivity equations for single phase flowing at steady state conditions have been used and solved using Microsoft Excel for various reservoir properties and different horizontal well lengths.

The deviation between the actual field data, and that obtained by the software based on conventional equations have been adjusted to introduce some parameters inserted in the conventional equation.

The new formula for calculating flow efficiency was derived and applied with the best proposed values of coefficients $\psi$=0.7 and $\omega$= 1.4. The simulated results fitted the field data.

Various reservoir and field parameters including lateral horizontal length of the horizontal well (L), Skin factor (S), ratio of the vertical to horizontal permeability of the formation ($K_V/K_H$), and the vertical thickness of the productive zone (h) were studied and verified to generalize the suggested equation to estimate the horizontal well productivity indices for various reservoir kinds. This led to creating a new formula of flow efficiency equation that could be applied in AHDEB field.

**Keywords:** Productivity index, AHDAB oil field, Horizontal well, Horizontal well length

## Introduction

Throughout the last decade, horizontal well technology ruled the oil and gas industry with growing success worldwide. It has now been a widely accepted approach for hydrocarbon recovery optimization. The post implementation recovery, in most cases, has been exceptional with the achievement of the following general goals [1]:

a) Reduction of exploitation time by increasing the production rate and thereby improving the cash flow and rate of return on investment.
b) Improving recovery by reaching the by-passed area in an effective way and increasing the drainage area.

The actual productivity of a horizontal well depends on many reservoir and well parameters such as $Kv/K_H$, reservoir thickness, drainage area, fracture patterns and intensity, horizontal well length, etc. [3].

Numerous models are available in the literature to predict the productivity of horizontal wells. These models are applicable directly only to single phase systems and in reservoirs under "steady state" and "pseudo steady state".

The performance of a horizontal well can be strongly influenced by the anisotropy of horizontal to vertical permeability. Thus, modeling of a horizontal well is much more complex than modeling a vertical well. There are basically two categories of methods for calculation of horizontal well productivity: analytical and semi-analytical models.

Borisov [4] developed one of the earliest analytical models for calculating steady state oil production from a horizontal well. The horizontal flow was assumed from an equivalent circular drainage area toward a vertical fracture with drainage radius much larger than the vertical fracture length; he presented the equation below:

$$q_H = F_D \frac{2\pi k_H h \Delta P}{\mu B[\ln\left(\frac{4r_{eH}}{L}\right)+\left(\frac{h}{L}\right)\ln\left(\frac{h}{2\pi r_w}\right)]} \quad \ldots(1)$$

Where $r_{eH}$ is the drainage radius of the horizontal well.

Giger [5] proposed a model similar to Borisov's, but assumed an ellipsoidal drainage area,

$$q_H = F_D \frac{2\pi k_H L \Delta P}{\mu B[\frac{L}{h}\ln\left(\frac{1+\sqrt{1-(L/2r_{eH})^2}}{L}\right)+\ln\left(\frac{h}{2\pi r_w}\right)]} \quad \ldots(2)$$

Karcher, Giger, and Combe [6] summarized the existing productivity-prediction models, and addressed the limiting assumptions and applicability of each model.

Joshi [7] developed a model with elliptical flow in the horizontal plane and radial flow in the vertical plane. The model was modified to take into account the influence of the horizontal well eccentricity from the vertical center of reservoir and the anisotropy of horizontal to vertical permeability,

$$q_H = F_D \frac{2\pi k_H h \Delta P}{\mu B\{\ln\left[\frac{a+\sqrt{a^2-(L/2)^2}}{(L/2)}\right]+\frac{\beta h}{L}\ln\left[\frac{\beta h}{(2r_w)}\right]\}} \quad \ldots(3)$$

where $a$ is the semi-major axis of the drainage ellipse,

$$a = \left(\frac{L}{2}\right)[0.5 + \sqrt{0.25 + \left(\frac{r_{eH}}{L/2}\right)^4}]^{0.5}$$

For $\frac{L}{2} < 0.9 r_{eH}$ …(4)

and β is the permeability anisotropic factor

$$\beta = \sqrt{\frac{k_H}{k_v}} \quad \ldots(5)$$

Economides et al. [8] augmented the Joshi's equation with Peaceman's equivalent wellbore radius in an anisotropic formation:

$$r_{weq} = r_w \frac{(K_x/K_y)^{\frac{1}{4}}+(K_y/K_x)^{\frac{1}{4}}}{2} \quad \ldots(6)$$

Which, with the β variable, becomes

$$r_{weq} = r_w \frac{\beta+1}{2\sqrt{\beta}} \quad \ldots(7)$$

Also, according to Peaceman's transformation, the equivalent vertical height must be:

$$h_{eq} = h\sqrt{\beta} \quad \ldots(8)$$

All these expressions are based on Muskat's [9] original work on permeability anisotropy. Thus, the second logarithmic expression in the denominator of Joshi's equation must be:

$$\frac{h_{eq}}{r_{weq}} = \frac{\beta}{r_w(\beta+1)} \quad \ldots(9)$$

and therefore, more appropriate expression for horizontal well inflow is:

$$q_H = F_D \frac{2\pi k_H h \Delta P}{\mu B\{\ln\left[\frac{a+\sqrt{a^2-(L/2)^2}}{(L/2)}\right]+\frac{\beta h}{L}\ln\left[\frac{\beta h}{r_w(\beta+1)}\right]\}} \quad \ldots(10)$$

Which for β=1 reverts exactly the Joshi's equation.

Renard and Dupuy [10] modified the steady state equation to include the effective wellbore radius:

$$q_H = \frac{2\pi K_H h \Delta P}{\mu B[cosh^{-1}(X) + \left(\frac{\beta h}{L}\right)\ln\left(\frac{h}{2\pi r'_w}\right)]} \quad ...(11)$$

Where X=2a/L, a is the same as state in Eq. 4; $cosh^{-1}(X)$ is the invers hyperbolic cosine function, and effective wellbore radius is:

$$r'_w = \left(\frac{1+\beta}{2\beta}\right) r_w \quad ...(12)$$

Later, a number of models, both analytical and semi-analytical, were developed using the source function method. The well drainage area was assumed to be a parallelepiped or infinite with no-flow or constant pressure boundaries at top, bottom and the sides. In general, the analytical models are asymptotic solutions under some appropriate simplifications and specific conditions, while the semi-analytical models are rigorous solutions of the original boundary value problem but have to be solved numerically.

## Formulation of the Proposed Equations

Estimation of productivity index in horizontal well is directly affected by two key parameters which determine flow direction toward the horizontal well. Joshi [7] developed a widely accepted equation to estimate steady state productivity from a horizontal well. He introduced horizontal and vertical resistances in the Darcy's flow equation and gave the following relationship:

$$q_H = \frac{\alpha(\Delta P)}{R_{Hp} + R_{Vp}} \quad ...(13)$$

Where $\alpha = Kh/\mu B$ and $R_{HP}$ and $R_{VP}$ are horizontal and vertical resistance's to flow.

To simplify the mathematical analysis of the three-dimensional (3D) problem, Joshi [7] subdivided it into two two-dimensional (2D) problems; see Figure1.

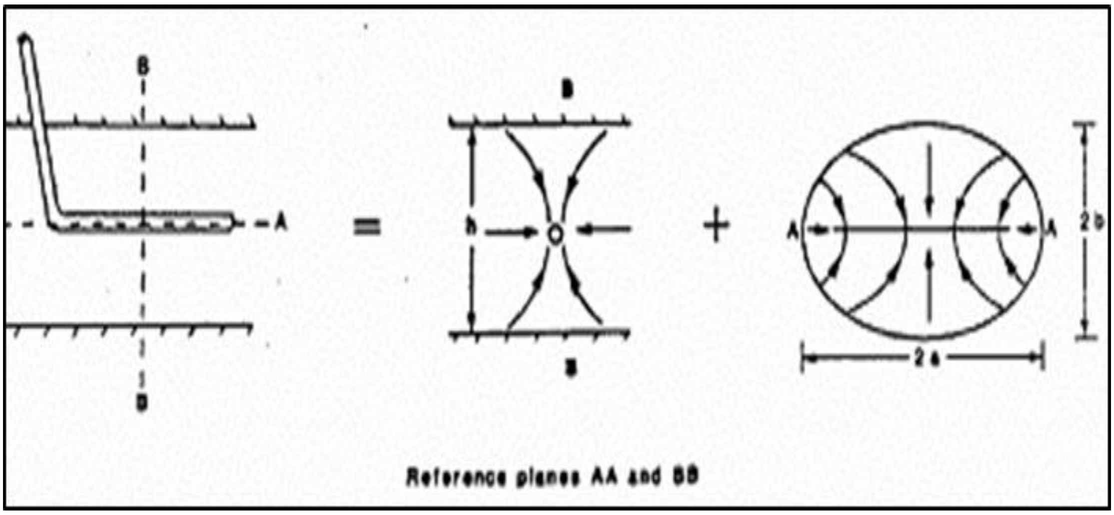


Fig. 1: Division of 3D Horizontal-Well Problem into 2D Problems [7]

The total flow into the horizontal well is having the following components:

1.) Flow into a horizontal well in a horizontal plane.

The pressure at the drainage boundary $P_e$ is:

$$P_e = ln\left[\frac{a+\sqrt{a^2-\Delta r^2}}{\Delta r}\right] \quad ...(14)$$

The pressure drop between the drainage boundary and well ΔP is the same as $P_e$ defined in Eq. 14 because wellbore pressure is assumed to be zero. Substituting this into Darcy's porous-medium equation, we can show it to be:

$$q_1 = \frac{2\pi Kh(\Delta P)/\mu B}{ln\left[\frac{a+\sqrt{a^2-\Delta r^2}}{\Delta r}\right]} \qquad \ldots(15)$$

where Δr is the well half-length (L/2).

$$q_1 = \frac{2\pi Kh(\Delta P)/\mu B}{ln\left[\frac{a+\sqrt{a^2-(L/2)^2}}{(L/2)}\right]} \qquad \ldots(16)$$

Eq. 16 represents flow to a horizontal well from a horizontal plane.

To calculate horizontal-well drainage radius, $r_{eH}$, areas of a circle and ellipse (in a horizontal plane, Fig. 2) are equated. This reduces to:

$$r_{eH} = \sqrt{ab} \qquad \ldots(17)$$

where $a$ and $b$ are major and minor axes of a drainage ellipse. Moreover, +L/2 and –L/2 represent foci of a drainage ellipse. Hence, using properties of an ellipse, we can show that:

$$b = \sqrt{a^2 - (L/2)^2} \qquad \ldots(18)$$

Using an electrical analog concept, flow resistance in a horizontal direction is given as:

$$R_{Hp} = \frac{\Delta P}{q_1} = \frac{\mu B_o}{2\pi Kh} ln\left[\frac{a+\sqrt{a^2-(L/2)^2}}{L/2}\right] \qquad \ldots(19)$$

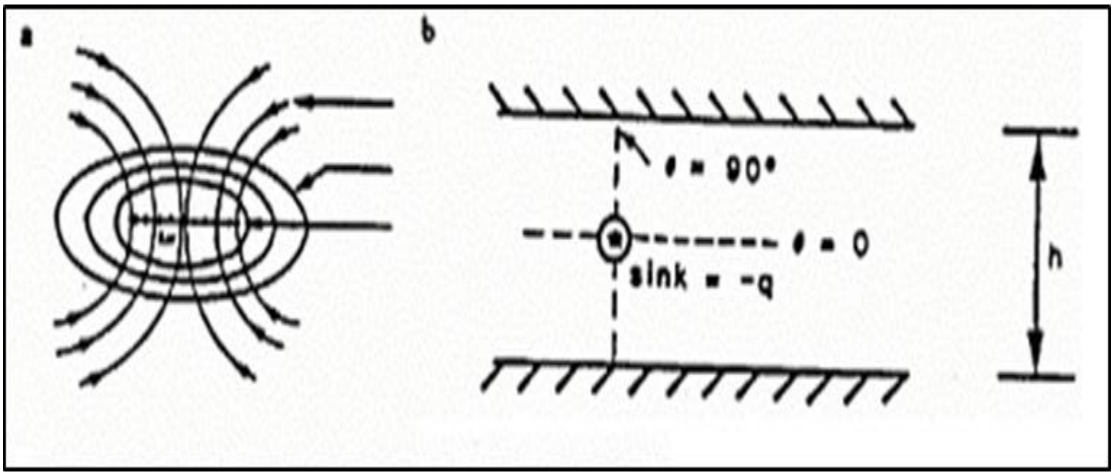


Fig. 2: Schematic Potential Flow to a Horizontal Well: Horizontal Plane and Vertical Plane [3]

2.) Flow into a horizontal well in a vertical plane.

Darcy's equation for flow through a porous medium to a vertical well is:

$$q_V = \frac{2\pi kh(\Delta P)}{\mu B \ln(\frac{r_e}{r_w})} \qquad ...(20)$$

In this equation, the term in the denominator refers to horizontal flow. Flow in a horizontal well is the same as flow in a vertical well rotated ninety degree. We can state that $r_e$ for vertical well is equivalent to h/2 for a horizontal well. After replacing $r_e$ by h/2 into Eq. 20, it yields:

$$q_2 = \frac{2\pi kh(\Delta P)}{\mu B \ln(\frac{h/2}{r_w})} \qquad ...(21)$$

The influence of vertical flow in horizontal wells is closely linked to relation between reservoir thickness and wellbore length, h/L, which means, the lower h/L is, the lower the influence of this type of flow is. Applying this concept to Eq. 21, we obtain:

$$q_2 = \frac{2\pi kh(\Delta P)}{\mu B(h/L)\ln(\frac{h}{2r_w})} \qquad \ldots(22)$$

The vertical-resistance term represents resistance in a vertical plane in a circular area of radius *h/2* around the wellbore which is:

$$R_{Vp} = \frac{\Delta P}{q_2} = \frac{\mu B_o}{2\pi KL} ln\left[\frac{h}{2r_w}\right] \qquad \ldots(23)$$

Part of this resistance is already accounted for in the horizontal resistance term $R_{Hp}$.

Different methods of combining $R_{Hp}$ and $R_{Vp}$ were considered to calculate effective flow resistance. Horizontal and vertical resistances were added to calculate horizontal-well oil production:

$$R_{Hp} + R_{Vp} = \Delta P\left(\frac{1}{q_1} + \frac{1}{q_2}\right) = \frac{\Delta P}{q_H} \qquad \ldots(24)$$

And

$$q_H = \frac{2\pi kh(\Delta P)}{\mu B\left\{ln\left[\frac{a+\sqrt{a^2-(L/2)^2}}{(L/2)}\right] + \frac{h}{L} ln\left[\frac{h}{2r_w}\right]\right\}}$$

For L>h and L/2< 0.9 $r_{eH}$ …(25)

Where *a*, half the major axis of a drainage ellipse in a horizontal plane in which the well is located Fig. 2, is obtained as shown below:

$$a = \left(\frac{L}{2}\right)\left[0.5 + \sqrt{0.25 + \left(\frac{r_{eH}}{L/2}\right)^4}\right]^{0.5} \qquad \ldots(26)$$

The above relationships were developed for isotropic reservoirs ($K_H = K_v$). In many reservoirs, the vertical permeability is less than the horizontal permeability. In really anisotropic reservoirs, it is possible to have a higher vertical permeability than the effective horizontal permeability. For a horizontal well, a decrease in vertical permeability results in an increase in vertical-flow resistance and a decrease in oil production rates. As Muskat [9] showed, the reservoir anisotropy could be accounted for by modifying the vertical axis as $z^* = \sqrt{K_H/K_v}$ and the average reservoir permeability as $\sqrt{K_H K_v}$. The modification of the z axis makes the wellbore elliptic. If the elliptic wellbore effects are assumed to be negligible, Eq. 25 is modified to account for the reservoir anisotropy:

$$q_H = \frac{2\pi k_H h(\Delta P)}{\mu B\left\{ln\left[\frac{a+\sqrt{a^2-(L/2)^2}}{(L/2)}\right] + \frac{\beta h}{L} ln\left[\frac{\beta h}{2r_w}\right]\right\}}$$

for L>βh and L/2< 0.9 $r_{eH}$ …(27)

Where $\beta = \sqrt{K_H/K_v}$

In Eq. 27, the variable β, which is the measure of reservoir permeability anisotropy [i.e., $(K_H/K_v)^{1/2}$] is particularly important. Obviously, the smaller β is, the larger the inflow performance of a horizontal well is.

Economides et al. [8] augmented the Joshi's [7] equation, with Peaceman's equivalent wellbore radius in an anisotropic formation:

$$r_{weq} = r_w \frac{(K_x/K_y)^{\frac{1}{4}} + (K_y/K_x)^{\frac{1}{4}}}{2} \qquad \ldots(28)$$

This, with the β variable, becomes:

$$r_{weq} = r_w \frac{\beta+1}{2\sqrt{\beta}} \qquad \ldots(29)$$

Also, according to Peaceman's transformation, the equivalent vertical height must be:

$$h_{eq} = h\sqrt{\beta} \qquad \ldots(30)$$

All these expressions are based on Muskat's [9] original work on permeability anisotropy. Thus, the second logarithmic expression in the denominator of Joshi's equation, Eq. 27, must be:

$$\frac{h_{eq}}{r_{weq}} = \frac{\beta}{r_w(\beta+1)} \quad \ldots(31)$$

And therefore, more appropriate expression for horizontal well inflow developed by Economides et al. [8] is:

$$q_H = \frac{2\pi k_H h \Delta P}{\mu B\left\{ln\left[\frac{a+\sqrt{a^2-(L/2)^2}}{(L/2)}\right]+\frac{\beta h}{L}ln\left[\frac{\beta h}{r_w(\beta+1)}\right]\right\}} \quad \ldots(32)$$

Which for β=1 reverts exactly the Joshi's equation, Eq. 27.

There are two terms in the denominator of Eq. 32. The first one (left-hand side) responds for flow in the horizontal direction and the second one is responsible for flow in the vertical direction that can be seen in any of the productivity index correlations (Eqs. (Borisov) [4], (giger) [5], (joshi) [7] and (renared and Dupuy) [10]).

The flow towards horizontal well has been verified for different dependent parameters; the results were compared with the actual well productivity for AHDEB field. We found that the horizontal flow factor proposed by Economides et al. is the same as the one in Josh's correlation. Therefore, we took the correlation factor proposed by Economides et al. to represent this type of flow. It can be concluded a new adjustment for the weighting coefficient that should be done to fit the result of Economides et al. with actual data. Thus:

$$q_H = F_D\frac{2\pi k_H h \Delta P}{\mu B\left\{ln\left(\psi\left[\frac{a+\sqrt{a^2-(L/2)^2}}{(L/2)}\right]\right)+\omega\frac{\beta h}{L}ln\left[\frac{\beta h}{r_w(\beta+1)}\right]\right\}} \quad \ldots.(33)$$

Where ψ and ω are constants (weighting coefficients), which will be determined by using a trial and error procedure.

Where $F_D$ is the unit conversion factor. In field units, $F_D$=0.001127; in metric units, $F_D$=86.4.

**Impact of Skin Effect on Horizontal Well Performance**

The horizontal well skin effect is added to the denominator of Eq. 33, with multiplied it by ωβh/L, and the anisotropic scaled aspect ratio is called in the following manner:

$$q_H = F_D\frac{2\pi k_H h \Delta P}{\mu B\left\{ln\left(\psi\left[\frac{a+\sqrt{a^2-(L/2)^2}}{(L/2)}\right]\right)+\omega\frac{\beta h}{L}\left[ln\left[\frac{\beta h}{r_w(\beta+1)}\right]+S\right]\right\}} \quad \ldots(34)$$

The skin effect, denoted as S, is the characteristic of the shape of damage in horizontal wells, taking into account the permeability anisotropy and the likelihood of larger damage penetration near the vertical section.

The productivity index, $J_H$, for the horizontal well can be estimated by dividing $q_H$ by ΔP as follows:

$$J_H = F_D\frac{2\pi k_H h}{\mu B\left\{ln\left(\psi\left[\frac{a+\sqrt{a^2-(L/2)^2}}{(L/2)}\right]\right)+\omega\frac{\beta h}{L}\left[ln\left[\frac{\beta h}{r_w(\beta+1)}\right]+S\right]\right\}} \quad \ldots(35)$$

Different to other correlations, this correlation includes two constants, ψ and ω, to allow an optimum match with respect to the simulated results.

Using a trial and error procedure [11], the values of constants ψ and ω in Eq. 35 were determined at the lowest deviation error with the simulated results attained. These values were found to be ψ=0.7 and ω= 1.4; Eq. 35 has been arranged to involve (ψ=0.7), (ω= 1.4) and ($F_D$=0.001127) to fit the field results and yield the following equation:

$$J_H = \frac{0.00708 k_H h}{\mu B\left\{ln\left(0.7\left[\frac{a+\sqrt{a^2-(L/2)^2}}{(L/2)}\right]\right)+1.4\frac{\beta h}{L}\left[ln\left[\frac{\beta h}{r_w(\beta+1)}\right]+S\right]\right\}} \quad \ldots(36)$$

The simple Excel Spreadsheet program was developed to calculate the productivity values of horizontal wells using three major available productivity equations. These equations include: Joshi [7] Equation 3, Economides et al. [8] Equation 10 and Renard and Dupuy [10] Equation 11.

Also, the developed spreadsheet program was used to compute the productivity index employing the improved equation, Eq. 34. The stimulated results obtained using FAST WELLTEST software is also presented.

It can be noticed that the productivity index of horizontal well is mainly the function of six parameters of the reservoir: horizontal length (L), anisotropy factor (β), formation thickness (h), drainage radius (re), well radius ($r_w$) and skin factor (s).

To develop a general equation for estimation horizontal well productivity index, various parameter reservoir properties have been made to assist to generate Eq. 36 which can be used to estimate horizontal well productivity index for AHDEB or any other field.

**Effect of Horizontal Well Length (L)**

The improved equation and the stimulated results are used to study the effect of horizontal well length on productivity index of horizontal well for a wide range of horizontal well length in the range of 250 to 6000 ft, as shown in Figures 3 to 11.

Figures 3 to 11 show that the modified equation gives extremely exact results with that obtained from AHDEB field. While original equation and other selected equations give biggest deviation from the field data. This conclusion has been proved for all parameters affecting horizontal well productivity index as shown in Figures 3 to 11. The results of all equations show that horizontal well productivity increases as well length increases.

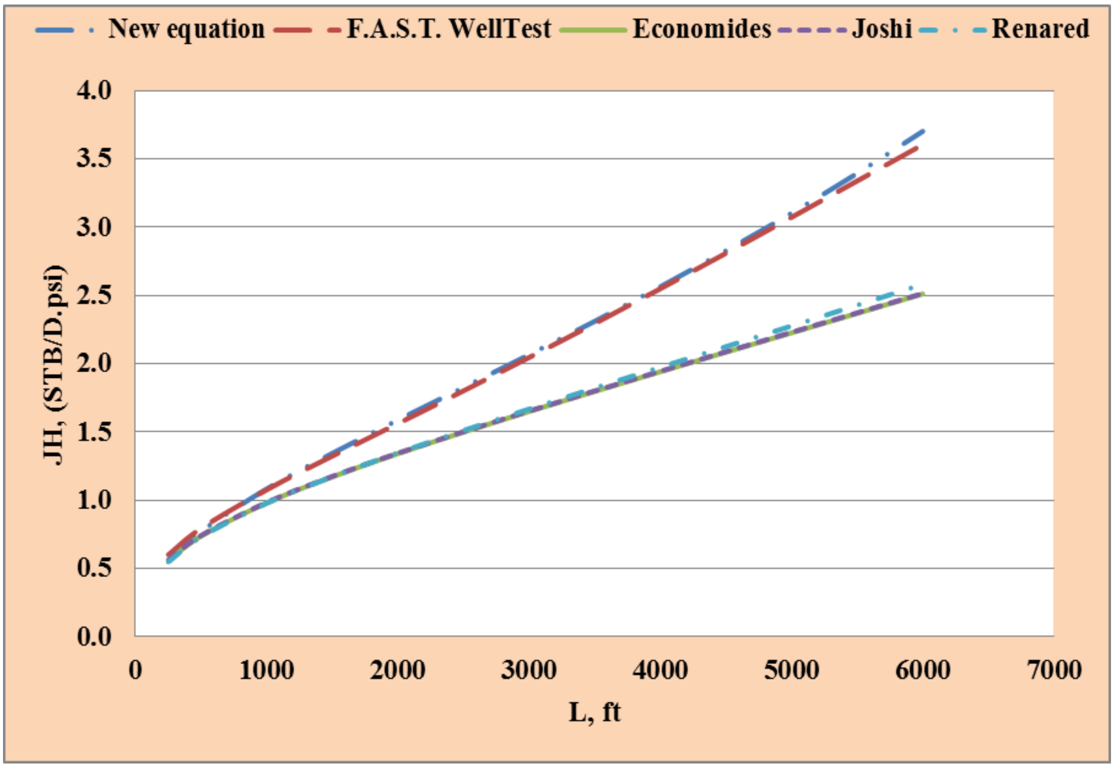


Fig. 3: Effect of Well Length on PI of HW for (s=0) and ($K_V/K_H$=2)

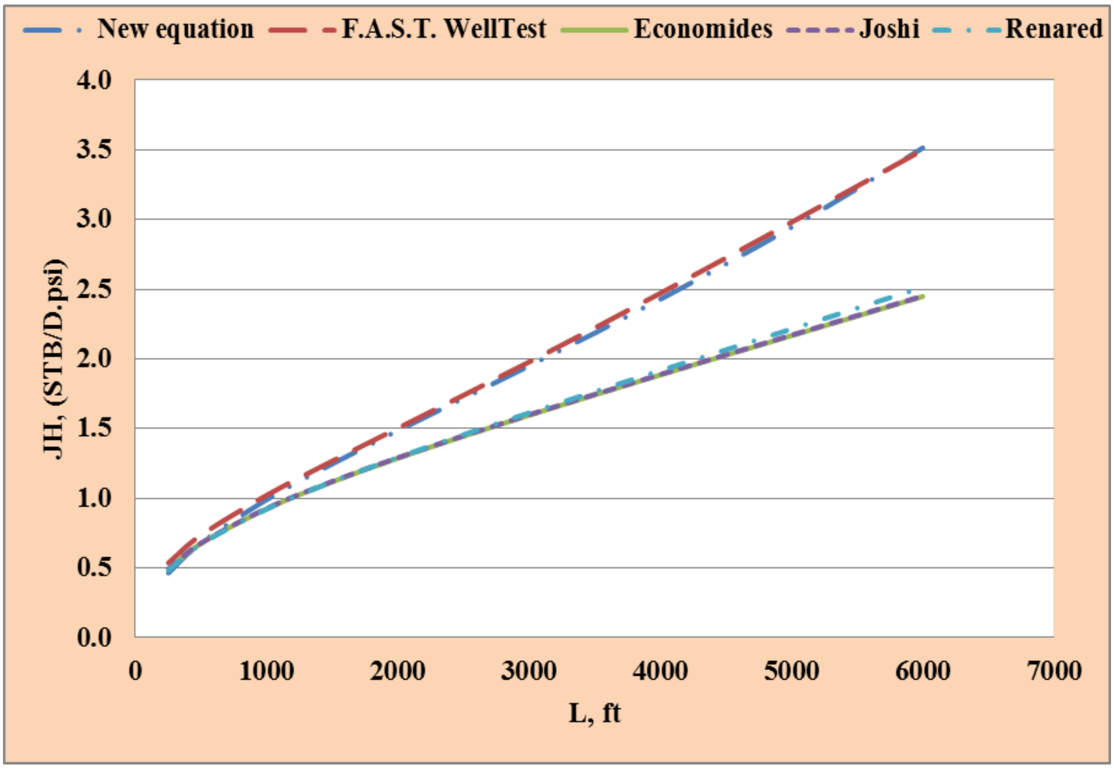


Fig. 4: Effect of Well Length on PI of HW for (s=+3) and ($K_V/K_H$=2)

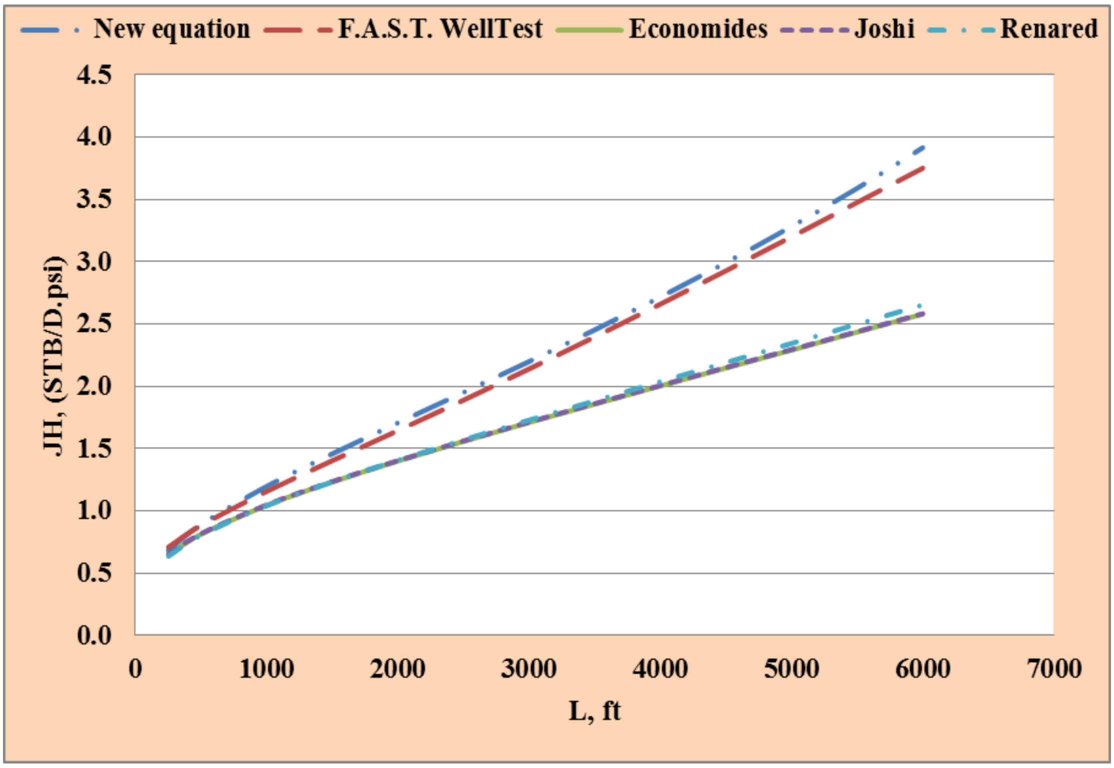


Fig. 5: Effect of Well Length on PI of HW for (s=-3) and ($K_V/K_H$=2)

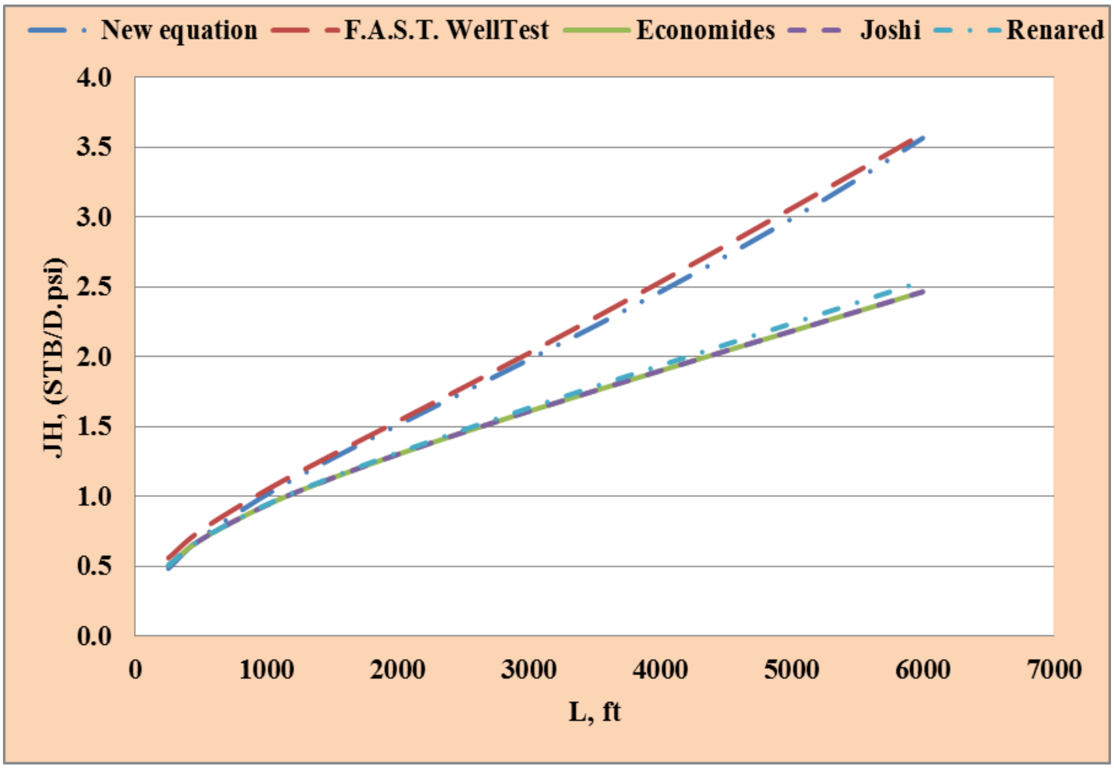


Fig. 6: Effect of Well Length on PI of HW for (s=0) and ($K_V/K_H$=1)

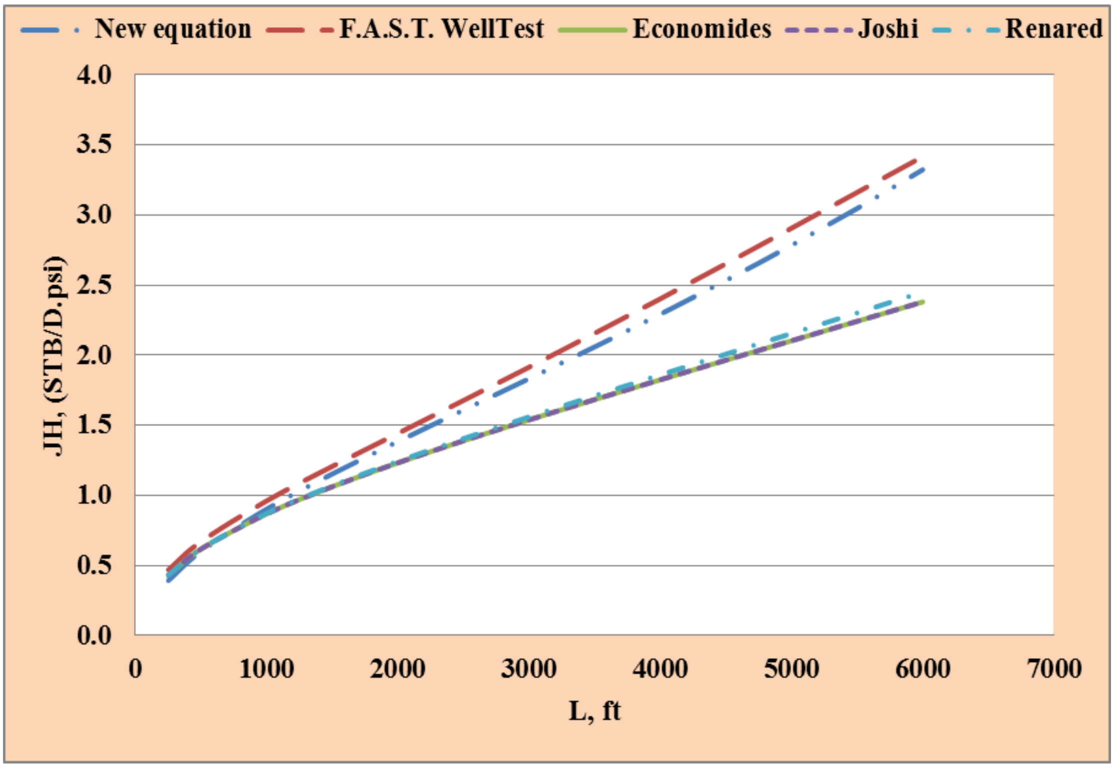


Fig. 7: Effect of Well Length on PI of HW for (S=3) and ($K_V/K_H$=1)

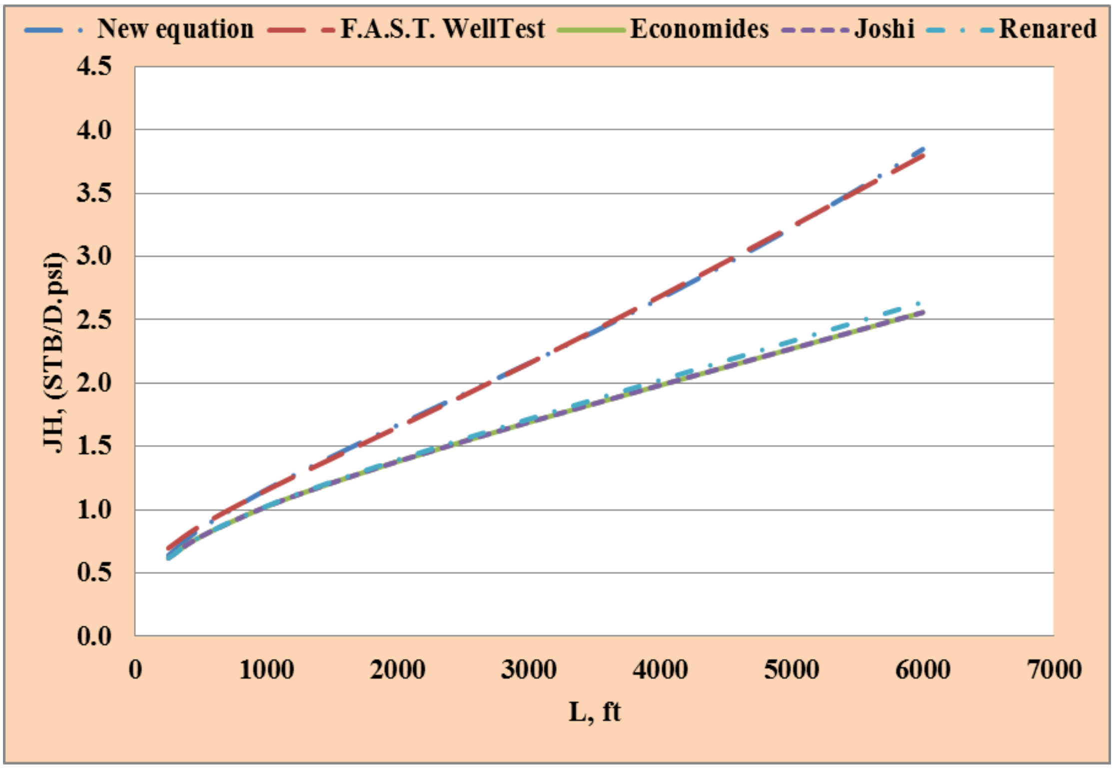


Fig. 8: Effect of Well Length on PI of HW for (S=-3) and ($K_V/K_H$=1)

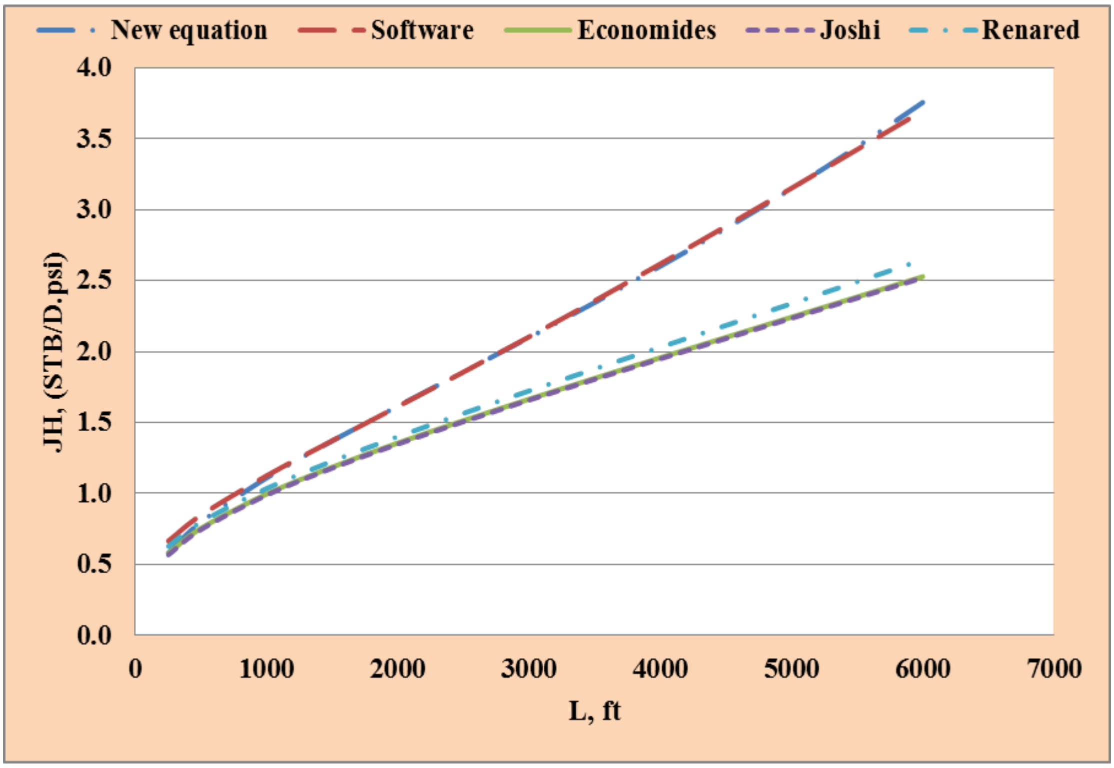


Fig. 9: Effect of Well Length on PI of HW for (S=0) and ($K_V/K_H$=0.5)

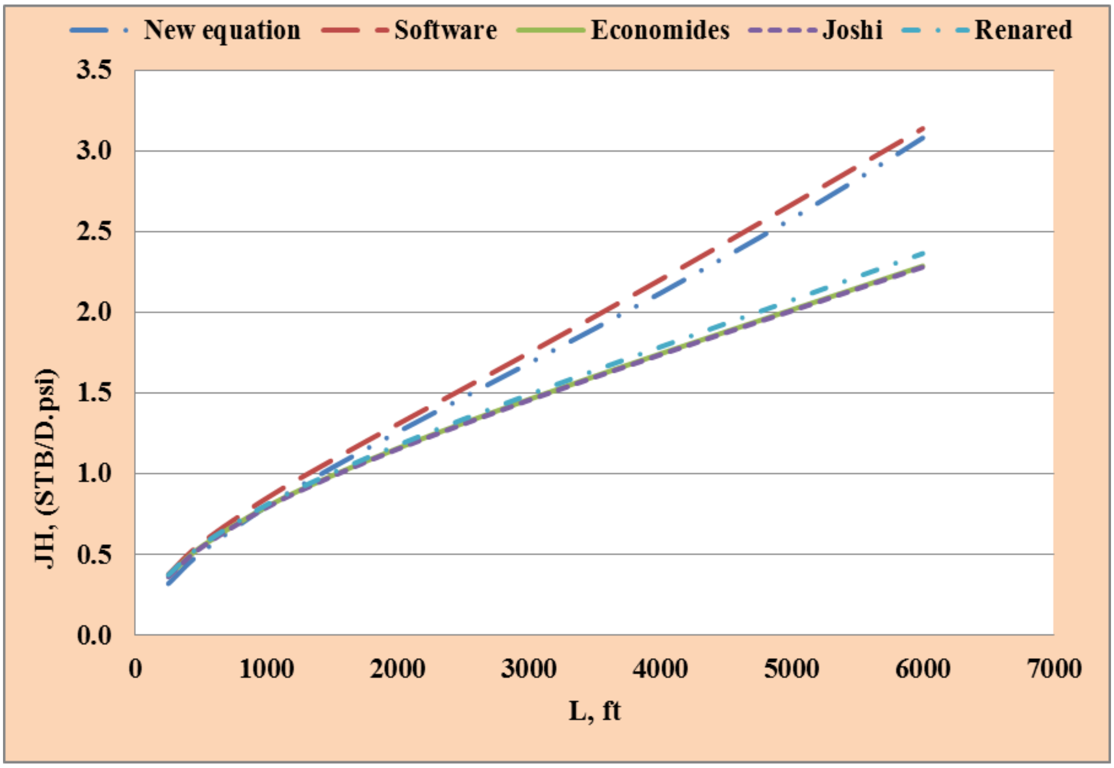


Fig. 10: Effect of Well Length on PI of HW for (S=3) and ($K_V/K_H$=0.5)

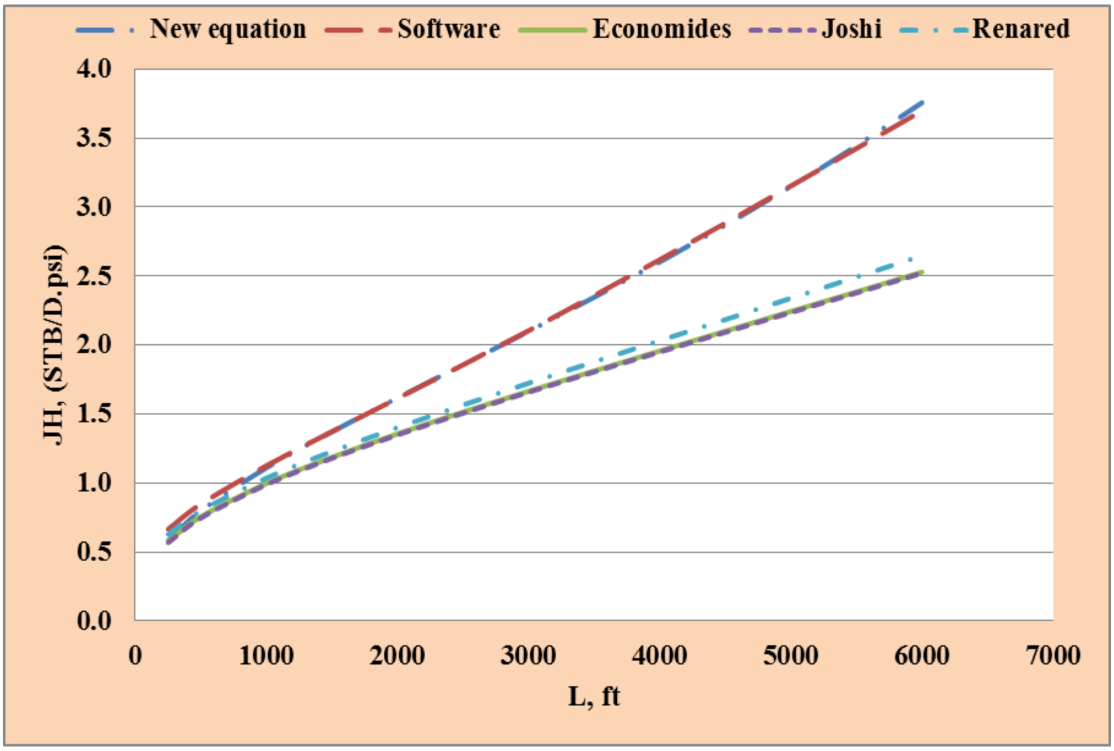


Fig. 11: Effect of Well Length on PI of HW for (S=-3) and ($K_v/K_H$ =0.5)

**Brief Description of the Field**

AHDEB oil field is located between Nomina town and Kut town of Wasit Province, 180km southeast away from Baghdad.

The AHDEB oil field is an anticline elongated trending NWW-SEE. There are three heights which are AD-1, AD-2, and AD-4 within the anticline.

Based on testing data, the main oil-bearing formations in the AHDEB field are Khasib formation of upper Cretaceous, Mishrif, Rumaila and Mauddud formations of middle Cretaceous. The cover depth of the oil reservoirs is from 2600m to 3300m. Horizontally, the oil-bearing formations of Khasib is distributed all over the field, the oil-bearing formations of Mishrif, Rumaila and Mauddud mainly are distributed in the eastern part.

The average core porosity is 17.3%; the average permeability is 25 mD. The AHDEB reservoirs have moderate porosity with lower permeability. Pressure coefficient is 1.135 averagely. Reservoir temperature is 71-85 ℃.

## Conclusions

1. A new formula for calculating flow efficiency is derived and applied in AHDEB field. This equation takes into consideration the proposed values of $\psi$=0.7 and $\omega$= 1.4.
2. The factors (well length, permeability ratio, reservoir thickness, skin factor, drainage radius, and well radius) affect the pressure drop between the wellbore and the reservoir affect productivity index in horizontal wells.
3. The productivity index of horizontal well results obtained for well AD10-H show very close agreement with other results obtained for other wells drilled by Chinese Company.
4. The simulation of AHDEB field indicates that the reservoir is affected by the existence of a partial edge water drive. This conclusion agreed also with that of the Chinese Company.
5. The horizontal well productivity index is highly affected by the lateral horizontal well section and the net pay thickness of the reservoir. Since studying the net, production thickness for each well is very important to estimate the horizontal well productivity index.

## Recommendations

1. Prediction of the reservoir performance when the reservoir pressure declines below the bubble point pressure and multiphase flow of fluid is an important future case of study.
2. A study of water and gas injection to increase the productivity of horizontal wells can be taken into consideration.
3. A study of forecast for the horizontal well productivity index of previous drilled wells in AHDEB oil field is important to maximize the production of the field.
4. For reservoirs with small vertical permeability value, $K_V$ can be increased by fracturing the reservoirs to reduce the anisotropy value and as a result increasing horizontal well productivity idex.

## Nomenclature

A = Drainage area, acres
a = Semi-major axis of the drainage ellipse, (ft), (m)
$B_o$ = Oil formation volume factor (BBL/STB)
$F_D$ = unit conversion factor. In field units (0.001127); and in metric units (86.4).
h = Formation thickness (ft), (m)
J = productivity index (STB/d/psi)
$J_H$ = Oil productivity index for horizontal well (STB/d/psi)
K = Permeability (millidarcy)
$K_H$ = Horizontal Permeability (millidarcy)
$K_v$= Vertical permeability (millidarcy)
L = Horizontal lateral length, ft
q = Flow rate, (STB/d)
$q_H$ = flow rate for horizontal well, (STB/d)
$q_V$ = flow rate for vertical well, (STB/d)
P = Pressure, (psi)
$P_b$ = Bubble point pressure, (psi)
$P_e$ = Bounded pressure (psi)
$P_r$ = Reservoir pressure (psi)

$P_{wf}$ = Bottom hole flowing pressure (psi)
$r_e$ = Drainage radius (ft), (m)
$r_{eH}$ = Drainage radius for horizontal well (ft), (m)
$r_{eV}$ = Drainage radius for vertical well (ft), (m)
$r_w$ = Wellbore radius (ft), (m)
S = Skin Factor (dimensionless)
STB =Stock tank barrel
β = Anisotropy ratio ($\sqrt{K_H/K_V}$)
$\mu_o$ = Oil viscosity, (cp)
Ø = porosity (percentage)

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