OPTIMAL CONFIGURATIONS OF MULTIPLE TUNNELS FOR ACID STIMULATION USING COILED TUBING

Xiaohe Li, Kern Smith and Saleem Chaudhary
Baker Hughes

ABSTRACT

The recent growth in applications of a new carbonate stimulation technique, which involves the construction of numerous tunnels or short laterals out of a main wellbore by using coiled tubing, has yielded excellent production improvements.

A simplified mathematical model to analyze this acid stimulation process is presented in this paper. From the perspective of reservoir properties, this simulation takes into account the reservoir heterogeneity, drainage size, permeability, fluid characteristics, porosity and skin factor. From a tunnel construction perspective, the simulation considers the influence of acid jetting angle, tunnel geometry, tunnel numbers, and eccentricity in different pay zones on well productivity. Meanwhile, from an acidizing viewpoint, the simulation considers effects of acid concentration for tunnel initiation and extension, rock solubility, and acid spending. These capabilities guide job design and reservoir performance analysis in field operations. As an example, a comparative study of different tunnel configurations for optimizing production is provided.

INTRODUCTION

In recent years, a novel acid stimulation with coiled tubing intervention has been successfully used in production enhancement of carbonate reservoirs [1]. In general, this technique creates multiple drainage holes or short laterals (so-called "tunnels") branching from the original wellbore by acid dissolving rock at different pay zones. During the process, a standard coiled tubing unit with a hydraulic kick-off bottom-hole assembly (BHA), is used to pump reactive acid with inclined jetting nozzles. The kick-off tool directs a high efficiency jetting of acid to generate initial holes and extensional tunnels. The BHA is usually located in the open hole section of the well. When this unit reaches the desired formation depth, acid is injected through a nozzle and an initial hole is generated. Then the coiled tubing is slowly run in the hole while jetting acid and dissolving the rocks in front of the tool. As acid continues to dissolve the rock, and leak off, the tunnel is elongated; meanwhile wormholes begin to leave from tunnel and penetrate into the formation. It creates a dendritic structure inside the drainage area, increases reservoir contacts, distributes inflow across more surface area, and ultimately stimulates the well.

There are several benefits from this technology. First, this process does not need a drilling rig and has no fluid return, therefore less impact on environment. Second, unlike other acid stimulation methods, it selectively places the acid at desirable depth and area. Third, it is cost effective. Since it is known where the acid is being placed, the acid can be used more efficiently. As we know, during a traditional bullheaded acid fracturing or matrix acidizing, all of the acid usually goes into the path of least resistance in the formation. Because of selective placement of acid, this new acid tunneling technology is generally less expensive than these traditional acid stimulation methods.

So far, we have implemented this acid stimulation for about 50 wells in Venezuela, Spain, Indonesia, Kuwait, Romania, USA, Brazil, Libya and Saudi Arabia. And we have created about 300 tunnels with over 10,000 feet tunnel length by using1 ½ to 1 ¾" coiled tubing. The tunnel diameter is from 3 to 6 ". The longest tunnel length is about 120 feet. The stimulated well depth ranges from 3000 to 16800 feet and well temperature is from 140 to 300 ^{o}F.

In order to understand this acidizing stimulation process and estimate well productivity with giving tunnel configurations, we present a simplified numerical model to analyze the factors that play an important role in this stimulation process. By integrating reservoir characteristics, fluid and rock properties, acid type and spending and tunnel geometry into this model, we can predict acid simulated well performance. The presented work provides field engineers a useful tool to design this novel acidizing jobs and forecast the production enhancement results.

MODELING

The simplified model is based on the following assumptions: 1) original well is a vertical one; 2) tunnel shape is a cylinder; 3) single phase fluid flow is under steady state condition; 4)effects of non-Darcy flow are not considered.

The productivity index is:

1) for a vertical oil well

$$J_{v,o} = \frac{q_{sc}}{(\bar{P}_r - P_{wf})} = \frac{7.078\times 10^{-3} kh}{\mu_o B_o \ln(\frac{r_e}{r_w'})}$$

Where $J_{v,o}$ is oil productivity index, q_{sc} is oil flow rate in standard condition, k is average reservoir permeability, $k = \sqrt{k_h * k_v}$, k_h is horizontal permeability, k_v is vertical permeability, h is reservoir thickness, $\bar{P}_r$ is average reservoir pressure, P_{wf} is flowing bottom-hole pressure, μo is oil viscosity, B_o is oil formation volume factor, r_e is drainage radius, and r_w' is effective wellbore radius.

2) for a vertical gas well

$$J_{v,g} = \frac{q_{sc}}{(m(\bar{P}_r) - m(P_{wf}))} = \frac{7.03\times 10^{-4} kh}{\mu_g ZT \ln(\frac{r_e}{r_w'})}$$

Where $J_{v,g}$ is gas productivity index, *m(p)* is real gas pseudo pressure, as defined below, μg is gas viscosity, Z is gas compressibility and T is reservoir temperature.

We assume the tunnels are similar to drainholes in horizontal well process [2]; thus the horizontal well productivity index can be used here to calculate the tunnel's productivity index.

The tunnel productivity index is:

3) for oil well

$$J_{h,o} = \frac{q_{sc}}{(\bar{P}_r - P_{wf})} = \frac{7.078\times 10^{-3} kh}{\mu_o B_o \{\ln(\frac{r_{eh}F}{L}) + (\frac{\beta h}{mnL})\ln(\frac{(\beta h/2)^2 + (\beta\delta)^2}{2\pi m r_{wh}'})\}}$$

where $J_{h,o}$ is tunnel productivity index for oil, m is the number of elevations or levels, n is the number of tunnels at same elevation, L is tunnel length, δ is tunnel's eccentricity, β is $\sqrt{k_h/k_v}$, F is a correlation factor depending on tunnel numbers, r_{eh} is tunnel drainage radius and r_{wh} ' is effective tunnel radius.

4) for gas well

$$J_{h,g} = \frac{q_{sc}}{(m(\bar{P}_r) - m(P_{wf}))} = \frac{7.03\times 10^{-4} kh}{T\{\ln(\frac{r_{eh}F}{L}) + (\frac{\beta h}{mnL})\ln(\frac{(\beta h/2)^2 + (\beta\delta)^2}{2\pi m r_{wh}'})\}}$$

Where $J_{h,g}$ is tunnel productivity index for gas. And the pseudo-pressure function is defined as:

$$m(p) = \int_{pb}^{P} \frac{2P}{\mu_g Z}$$

For dry gas reservoir, the compressibility (*Z* factor) is calculated by using Standing-Katz correlation. The gas viscosity is estimated on the basis of gas specific gravity, inorganic compound content, correction factors and reduced temperature and pressure. During z factor and viscosity calculations, the pseudo-critical pressure and temperature are computed by using Standing's curves [3].

Drainage area of tunnels can be calculated by an average method from both horizontal and vertical drainage areas. The tunnel geometry can be calculated from the gravimetric acid dissolving power and material balance during the reaction between acid and minerals.

The productivity index of the acid tunneling stimulated well is calculated by simply adding both the original well's productivity index and the tunnel's production index. The productivity index ratio can be expressed as the stimulated well productivity index divided by the original well productivity index.

NUMERICALSIMULATION AND SOFTWARE IMPLEMENTATION

For a gas well, the Z factors are calculated numerically by solving a high order non-linear equation. This equation is solved by an iteration method. We used a Newton's method to conduct the iteration procedure. For computing the pseudo-pressure function, we also calculate this integration numerically.

The simulator is developed using C++ with object-oriented approaches. The software framework allows engineers to input data using a graphical user interface. It can handle both oil and gas reservoir for this acid tunneling job design. The report is generated with table and charts in order to compare different tunnel configuration in various stimulation scenarios. With this report, engineers can optimize the acid tunneling process in order to maximize the well performance.

CASE STUDY

A vertical dry gas reservoir with a drainage area of 450 acres is used for this study. Each pay zone thickness is 20 feet. The porosity of this reservoir is 20%. The reservoir temperature gradient is 1.2 ^{o}F/100ft. The average reservoir pressure is 5000 psi and the bottom flow pressure in wellbore is 3500 psi.

RESULTS AND DISCUSSION

Several important parameters in job design have been studied. The relationship between productivity index ratio (i.e., (Jh+Jv)/Jv) and tunnel length is shown in Figure 1. In this case, we set up one tunnel in the centerline of a 20 feet pay zone. This figure shows that the production increases as the tunnel length increases. The main reason for this is when acid dissolves more rock and diffuses and penetrates deeper in the pay zone, it creates more contact area and more wormholes and connections between formation and wellbore.

At the same elevation with zero eccentricity, we also have investigated the influence of tunnel numbers on the stimulated well performance. The results are presented in Figure 2. As the tunnel number increases the stimulated well production also increase. However, the increase is not proportional to the tunnel number increase. For example, when tunnel number changes from 1 to 4 (i.e., 4 times), the production increases only about 2.8 times. In reality, it is difficult to create four tunnels at the same elevation.

Meanwhile, eccentricity is an important factor to determine the tunnel's production performance. Figure 3 shows the relationship between productivity index ratio and eccentricity. As eccentricity increases, the production contributed from the tunnel decreases. As we know, the top and bottom locations inside the pay zone are reservoir boundaries. If a tunnel is placed near these locations (in other words, the eccentricity is high), then fluid flow is close to the drainage limits, this will decrease the flow rate. In order to maximize the tunnel production, we should generate tunnels in the centerline of the pay zone.

The acid-rock solubility efficiency is also related to the acid tunnel well performance. Figure 4 describes the relationship between solubility efficiency and stimulated well productivity. In this study, we keep the other parameters the same and only solubility efficiency changes. The productivity increases slightly as solubility efficiency increases from 75% to 95%.

Figure 5 shows the relationship between stimulated well productivity index ratio and the ratio of reservoir horizontal permeability (k_h) to vertical permeability (k_v). It shows that the productivity index ratio of acid tunneling well to original well decreases as and the ratio of k_h to k_v. This is because the original well productivity is related to $\sqrt{k_h * k_v}$ (the effective permeability) and the stimulated well productivity is related to both $\sqrt{k_h * k_v}$ and $\sqrt{k_h / k_v}$. Figure 6 shows that the increasing degrees and slopes of these two curves are not the same. This results in the final productivity index ratio decreases as k_h / k_v increases.

The software can allow the users to compare five different job designs in one run. This enables engineers to optimize the well productivity with considerations of reservoir heterogeneity, drainage size, permeability, fluid characteristics, porosity and skin factor, acid jetting angle, tunnel geometry, tunnel numbers, eccentricity, rock and acid properties and acid spending.

SUMMARY

A simplified mathematical model is established to describe an acid stimulation with coiled tubing intervention. Multiple short laterals or tunnels can be generated in this acidizing process to increase the well productivity. On the basis of this model, we have created a numerical simulator with a user-friendly graphical interface. This software provides engineers a useful design tool.

REFERENCES

1. Strasburg, J., Clark J., Acid Tunneling Stimulation in Oklahoma Limestone Using Coiled Tubing, SPE 120772, presented at 2009 Production Operations Symposium in Oklahoma, USA, 2009.

2. Joshi, S.D., Horizontal Well Technology, PennWell Books, 1991.

3. Dake, L.P., Fundamentals of Reservoir Engineering, Elsevier, 1978.

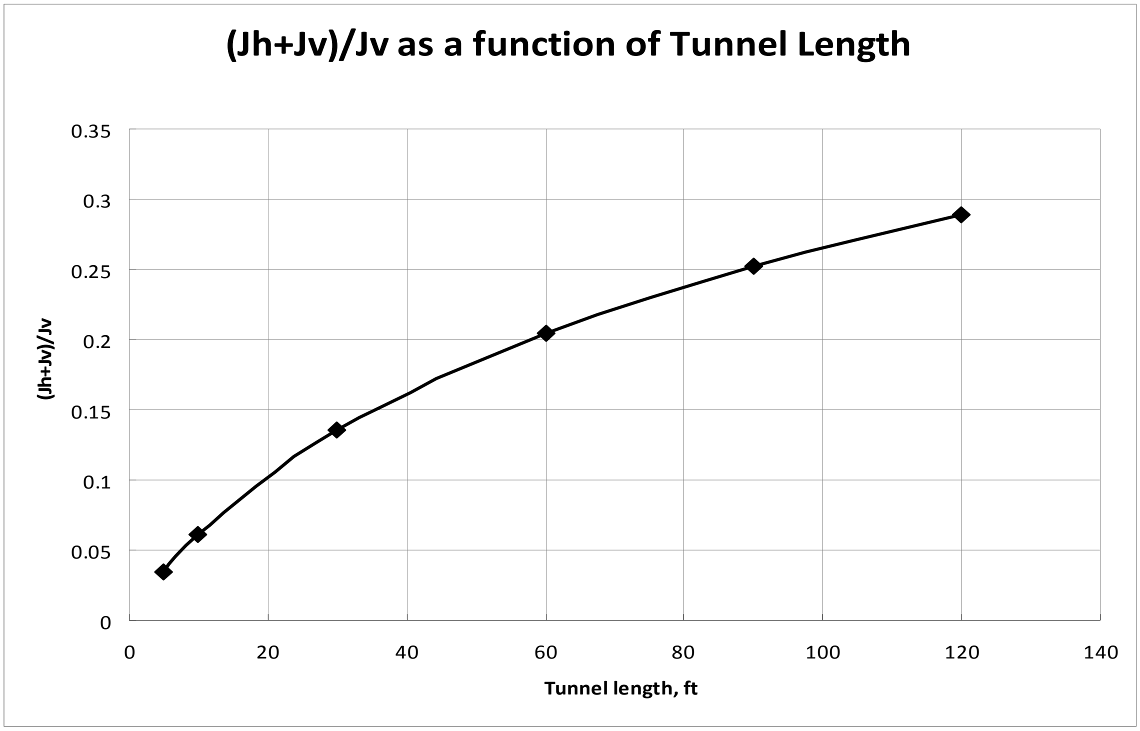

Figure 1 - (Jh+Jv)/Jv as a function of Tunnel Length

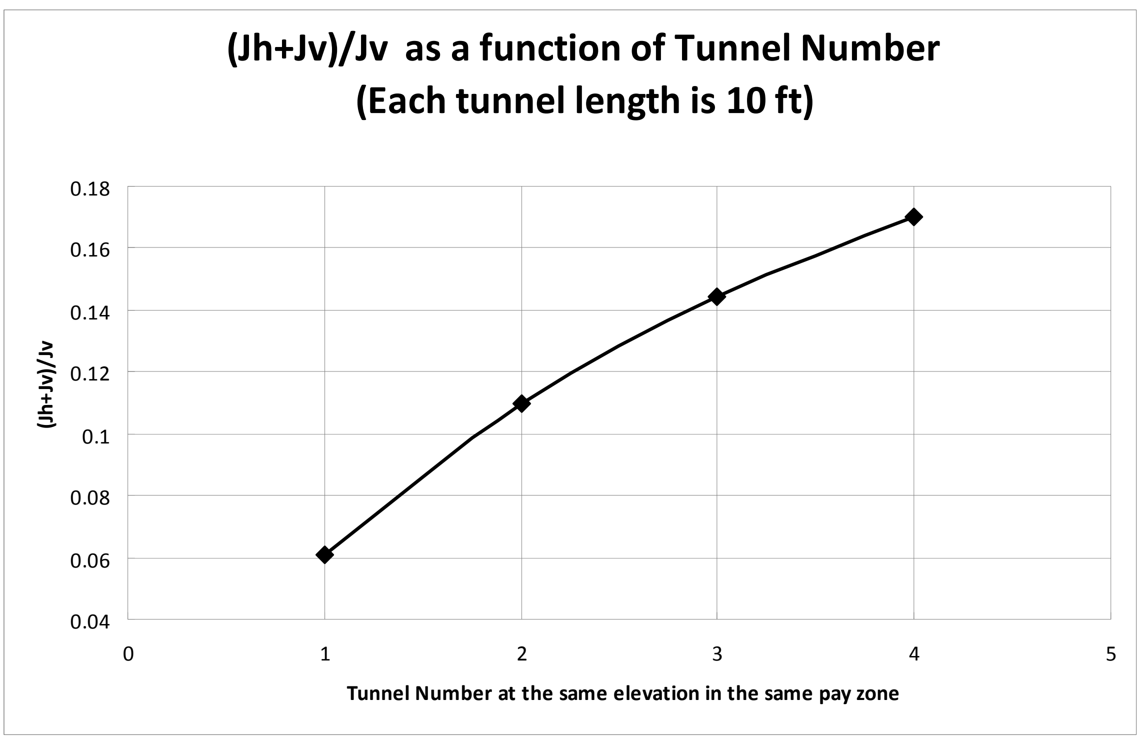

Figure 2 - (Jh+Jv)/Jv as a function of Tunnel Number

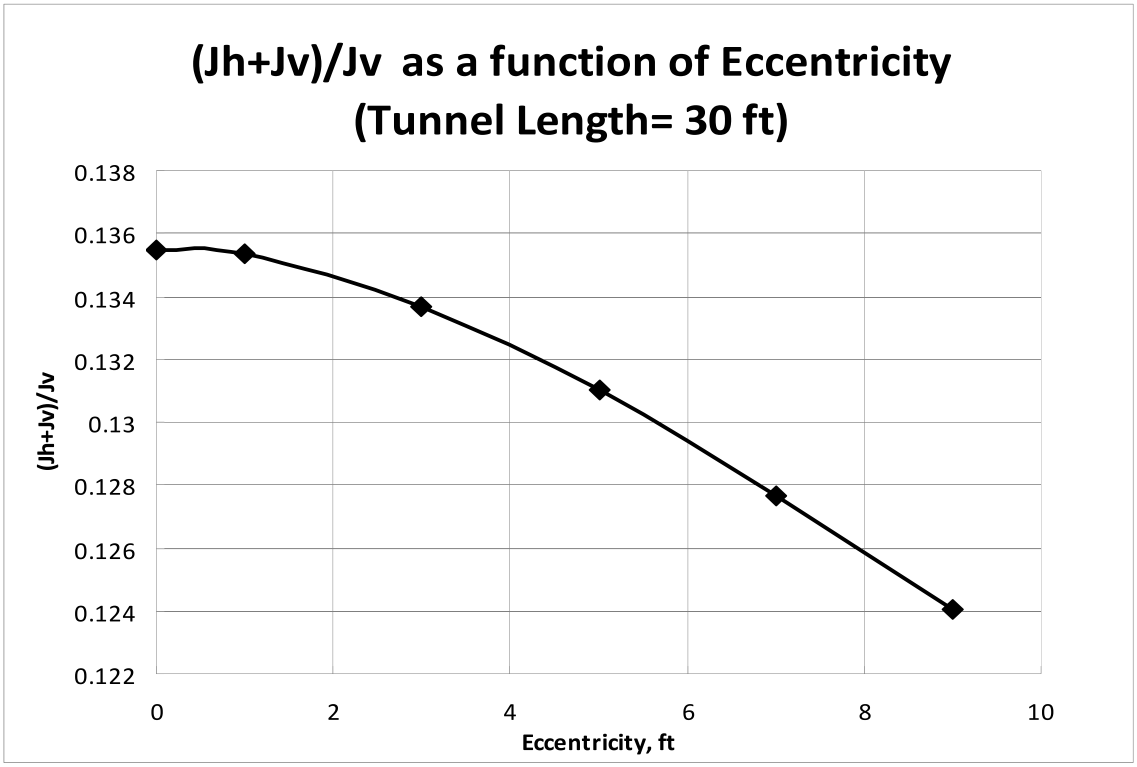

Figure 3 - (Jh+Jv)/Jv as a function of Eccentricity

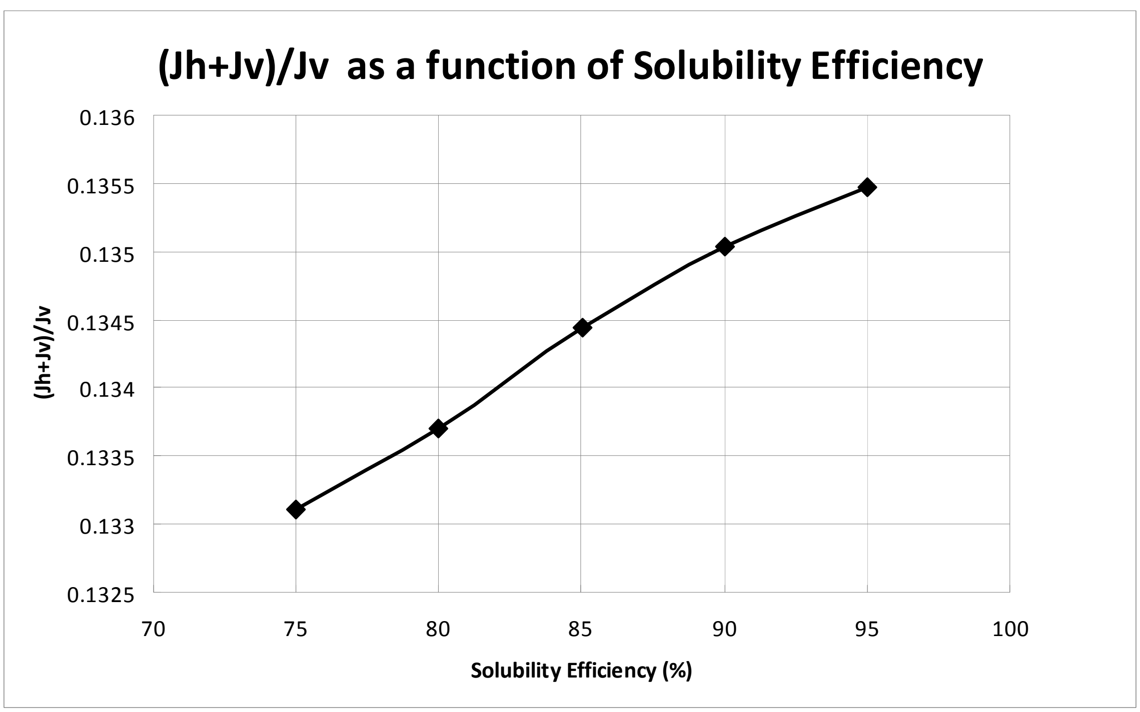

Figure 4 - (Jh+Jv)/Jv as a function of Solubility Efficiency

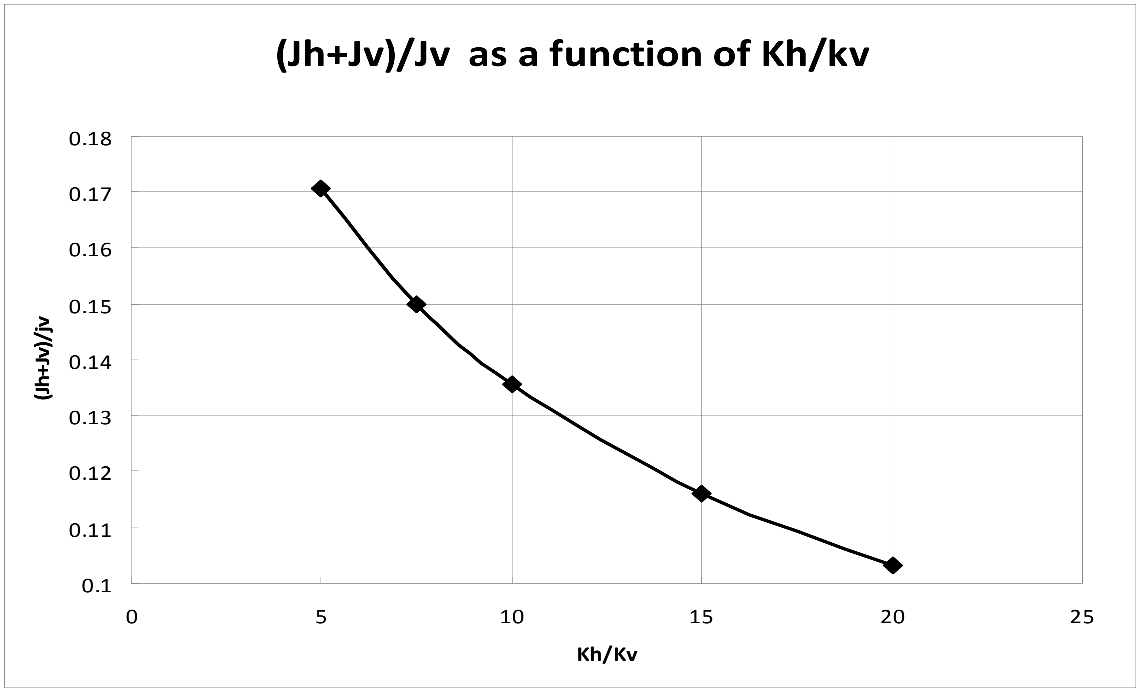

Figure 5 - (Jh+Jv)/Jv as a function of k_h/k_v

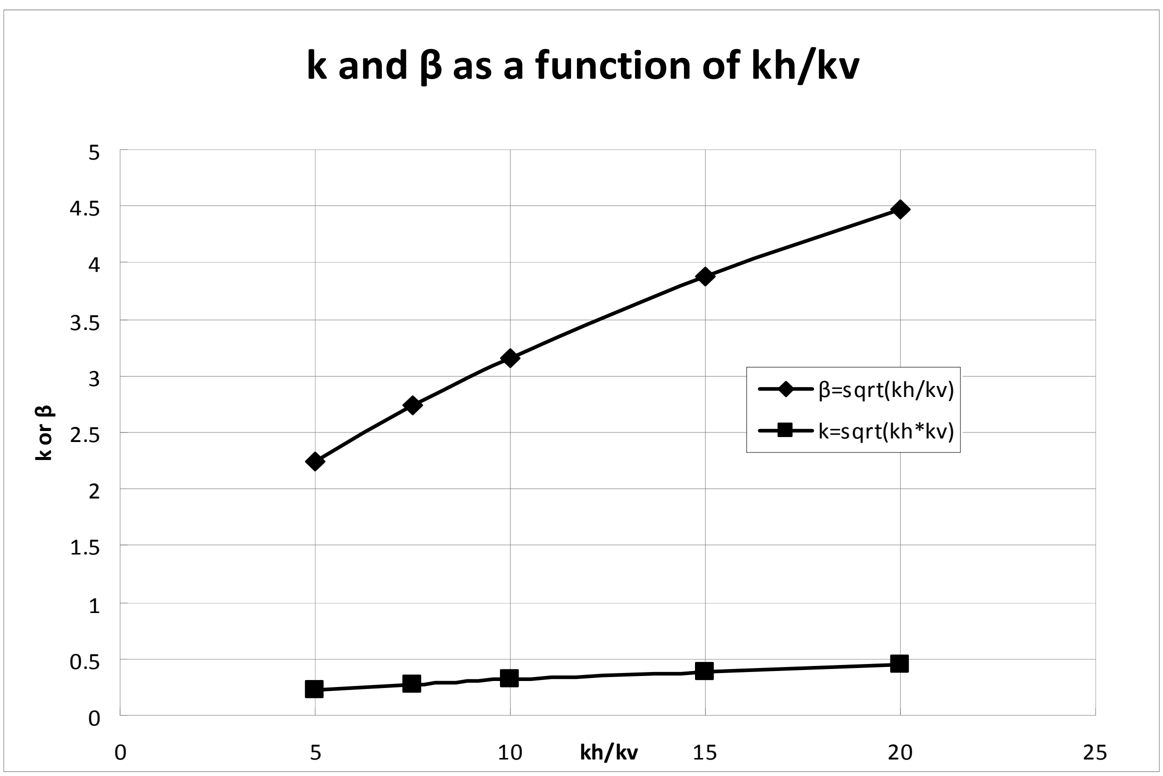

Figure 6 - k and β as a function of k_h/k_v