World Journal of Engineering and Technology, 2023, 11, 273-280
https://www.scirp.org/journal/wjet
ISSN Online: 2331-4249
ISSN Print: 2331-4222

Establishment of Unstable Flow Model and Well Testing Analysis for Viscoelastic Polymer Flooding

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How to cite this paper: Lv, Z. and Wang, M.N. (2023) Establishment of Unstable Flow Model and Well Testing Analysis for Viscoelastic Polymer Flooding. *World Journal of Engineering and Technology*, **11**, 273-280.
https://doi.org/10.4236/wjet.2023.112019

Received: April 6, 2023
Accepted: May 6, 2023
Published: May 9, 2023

Abstract

At present, the polymer solution is usually assumed to be Newtonian fluid or pseudoplastic fluid, and its elasticity is not considered on the study of polymer flooding well testing model. A large number of experiments have shown that polymer solutions have viscoelasticity, and disregarding the elasticity will cause certain errors in the analysis of polymer solution seepage law. Based on the percolation theory, this paper describes the polymer flooding mechanism from the two aspects of viscous effect and elastic effect, the mathematical model of oil water two-phase three components unsteady flow in viscoelastic polymer flooding was established, and solved by finite difference method, and the well-test curve was drawn to analyze the rule of well test curve in polymer flooding. The results show that, the degree of upward warping in the radial flow section of the pressure recovery curve when considering polymer elasticity is greater than the curve which not considering polymer elasticity. The relaxation time, power-law index, polymer injection concentration mainly affect the radial flow stage of the well testing curve. The relaxation time, power-law index, polymer injection concentration and other polymer flooding parameters mainly affect the radial flow stage of the well testing curve. The larger the polymer flooding parameters, the greater the degree of upwarping of the radial flow derivative curve. This model has important reference significance for well-testing research in polymer flooding oilfields.

Keywords

Polymer Flooding, Viscoelasticity, Well Testing, Mathematical Model, Seepage Law

1. Introduction

Polymer flooding is an important way to improve oil recovery in production oilfields. It has been widely industrialized in China and has achieved good application results and economic benefits [1] [2] [3] [4] [5]. Most experts have conducted a lot of research on the percolation characteristics of polymer in porous media and its impact on oil displacement effect. However, in most analysis of polymer flooding percolation laws, people usually assume that polymer solution is Newtonian fluid or pseudoplastic fluid, without considering its elasticity. A large number of experiments have shown that polymer solutions have viscoelasticity, and disregarding their elasticity will cause certain errors in the analysis of polymer solution seepage law [6] [7] [8] [9] [10]. This article studies the rheological and viscoelastic properties of polymer solution, provides a characterization method for the elastic viscosity of polymer solutions, and proposes a new polymer flooding well testing model which takes into account the viscoelastic properties of polymer, which guiding the study of percolation law in polymer flooding Oilfields.

2. Mathematical Description for the Main Oil Displacement Mechanism of Polymer

Under certain temperature condition, the viscosity of polymer solution increases significantly with increasing concentration. Under static condition, the viscosity of the polymer solution can be expressed as the following equation.

$$\mu_{\mathrm{p}}^{0}=\mu_{\mathrm{w}}\left(1+A_{1}c_{\mathrm{p}}+A_{2}c_{\mathrm{p}}^{2}+A_{3}c_{\mathrm{p}}^{3}+\cdots\right) \tag{1}$$

In which, μ_{p}^{0} is zero shear viscosity of polymer solution, Pa·s; μ_{w} is water viscosity, Pa·s; c_{p} is Polymer solution concentration, mg/L; A_1, A_2, A_3 is coefficient.

Due to the generally low concentration of polymer solutions, $A_3c_{\mathrm{p}}^3$ and its subsequent terms are often overlooked.

$$\mu_{\mathrm{p}}^{0}=\mu_{\mathrm{w}}\left(1+A_{1}c_{\mathrm{p}}+A_{2}c_{\mathrm{p}}^{2}\right) \tag{2}$$

Using the Kerry model to describe the viscoelasticity of polymer solution.

$$\mu_{\mathrm{eff}}=\mu_{\mathrm{p}}^{\infty}+\left(\mu_{\mathrm{p}}^{0}-\mu_{\mathrm{p}}^{\infty}\right)\left[1+\left(\theta_{\mathrm{f}}\cdot\dot{\gamma}\right)^{2}\right]^{(n-1)/2} \tag{3}$$

In which, μ_{eff} is viscoelastic polymer viscosity, Pa·s; $\mu_{\mathrm{p}}^{\infty}$ is ultimate shear rate viscosity, Pa·s; θ_{f} is relaxation time, s; n is power-law index.

3. Establishment and Solution of a Mathematical Model for Oil-Water Two-Phase Flow in Polymer Flooding

Assuming that polymer flooding is an isothermal displacement process and multiphase flow satisfies the generalized Darcy's law, the fluid consists of oil-water two-phase flow, with only oil components in the oil phase and water and polymer components in the water phase. Ignoring the influence of capillary pressure and gravity, the continuity equation of oil-water two-phase flow can be expressed as the following equations.

$$\nabla\cdot\left[\frac{\rho_{\mathrm{o}}K\cdot K_{\mathrm{ro}}}{\mu_{\mathrm{o}}}\nabla p_{\mathrm{o}}\right]+q_{\mathrm{o}}=\frac{\partial}{\partial t}\left(\rho_{\mathrm{o}}\phi S_{\mathrm{o}}\right) \tag{4}$$

$$\nabla \cdot \left[\frac{\rho_{\mathrm{w}} K K_{\mathrm{rw}}}{\mu_{\mathrm{eff}}} \nabla p_{\mathrm{w}} \right] + q_{\mathrm{w}} = \frac{\partial}{\partial t}\left(\rho_{\mathrm{w}} \phi S_{\mathrm{w}} \right) \tag{5}$$

$$\nabla \cdot \left[\frac{K K_{\mathrm{rw}} c_{\mathrm{p}}}{\mu_{\mathrm{eff}}} \nabla p_{\mathrm{w}} \right] + q_{\mathrm{w}} c_{\mathrm{p}} = \frac{\partial}{\partial t}\left(\phi S_{\mathrm{w}} c_{\mathrm{p}} \right) \tag{6}$$

In which, ρ_{o} is oil phase density, kg/m^3; ρ_{w} is water phase density, kg/m^3; K is absolute permeability, m^2; K_{ro} is oil relative permeability; K_{rw} is water relative permeability; μ_{o} is oil phase viscosity, Pa·s; p_{o} is oil phase pressure, Pa; p_{w} is water phase pressure, Pa; ϕ is porosity; q_{o} is oil recovery intensity, m^3/(s·m^3); q_{w} is water injection intensity, m^3/(s·m^3); S_{o} is oil saturation; S_{w} is water saturation.

From Equations (4) and (5), the pressure differential equations for the oil and water phases can be obtained as the following equations.

$$\begin{aligned} &\frac{\partial}{\partial x}\left(\lambda_{\mathrm{ox}} \cdot \frac{\partial p_{\mathrm{o}}}{\partial x} \right) + \frac{\partial}{\partial y}\left(\lambda_{\mathrm{oy}} \cdot \frac{\partial p_{\mathrm{o}}}{\partial y} \right) + \frac{\rho_{\mathrm{o}}}{\rho_{\mathrm{w}}} \frac{\partial}{\partial x}\left(\lambda_{\mathrm{wx}} \cdot \frac{\partial p_{\mathrm{o}}}{\partial x} \right) + \frac{\rho_{\mathrm{o}}}{\rho_{\mathrm{w}}} \frac{\partial}{\partial y}\left(\lambda_{\mathrm{wy}} \cdot \frac{\partial p_{\mathrm{o}}}{\partial y} \right) \\ &= \phi \rho_{\mathrm{o}} C_{\mathrm{t}} \frac{\partial p_{\mathrm{o}}}{\partial t} - q_{\mathrm{o}} - \frac{\rho_{\mathrm{o}}}{\rho_{\mathrm{w}}} q_{\mathrm{w}} \end{aligned} \tag{7}$$

$$\begin{aligned} &\frac{\partial}{\partial x}\left(\lambda_{\mathrm{wx}} \cdot \frac{\partial p_{\mathrm{o}}}{\partial x} \right) + \frac{\partial}{\partial y}\left(\lambda_{\mathrm{wy}} \cdot \frac{\partial p_{\mathrm{o}}}{\partial y} \right) + q_{\mathrm{w}} \\ &= \phi \rho_{\mathrm{w}} \frac{\partial S_{\mathrm{w}}}{\partial t} + \rho_{\mathrm{w}} S_{\mathrm{w}} \phi C_{\mathrm{f}} \frac{\partial p_{\mathrm{o}}}{\partial t} + S_{\mathrm{w}} \phi \rho_{\mathrm{w}} C_{\mathrm{w}} \frac{\partial p_{\mathrm{o}}}{\partial t} \end{aligned} \tag{8}$$

Under the condition of uniform grid, the oil phase pressure Equation (7), the water phase saturation seepage Equation (8), and the polymer component concentration Equation (6) are respectively processed by finite difference, and the finite difference model corresponding to the oil-water two-phase seepage mathematical model can be established.

$$c_{i,j} p_{\mathrm{o}i,j-1}^{n+1} + a_{i,j} p_{\mathrm{o}i-1,j}^{n+1} + e_{i,j} p_{\mathrm{o}i,j}^{n+1} + b_{i,j} p_{\mathrm{o}i+1,j}^{n+1} + d_{i,j} p_{\mathrm{o}i,j+1}^{n+1} = f_{i,j} \tag{9}$$

$$\begin{aligned} S_{\mathrm{w}i,j}^{n+1} &= \left(c_{1i,j} p_{\mathrm{o}i,j-1}^{n+1} + a_{1i,j} p_{\mathrm{o}i-1,j}^{n+1} + e_{1i,j} p_{\mathrm{o}i,j}^{n+1} + b_{1i,j} p_{\mathrm{o}i+1,j}^{n+1} + d_{1i,j} p_{\mathrm{o}i,j+1}^{n+1} \right) \frac{\Delta t^n}{\left(\phi \rho_{\mathrm{w}} V \right)_{i,j}} \\ &\quad + \frac{q_{\mathrm{w}} \Delta t^n}{\rho_{\mathrm{w}} \phi} + \left[\phi \rho_{\mathrm{w}} S_{\mathrm{w}} \left(C_{\mathrm{w}} + C_{\mathrm{f}} \right) p_{\mathrm{o}} \right]_{i,j}^{n} + S_{\mathrm{w}i,j}^{n} \end{aligned} \tag{10}$$

$$\begin{aligned} c_{\mathrm{p}i,j}^{n+1} &= \left(c_{2i,j} p_{\mathrm{o}i,j-1}^{n+1} + a_{2i,j} p_{\mathrm{o}i-1,j}^{n+1} + e_{2i,j} p_{\mathrm{o}i,j}^{n+1} + b_{2i,j} p_{\mathrm{o}i+1,j}^{n+1} + d_{2i,j} p_{\mathrm{o}i,j+1}^{n+1} \right) \frac{\Delta t^n}{\left(\phi S_{\mathrm{w}} V \right)_{i,j}} \\ &\quad + \frac{q_{\mathrm{w}} c_{\mathrm{p}i,j}^{n} \Delta t^n}{\left(\phi S_{\mathrm{w}} V \right)_{i,j}} - c_{\mathrm{p}i,j}^{n} \frac{S_{\mathrm{w}i,j}^{n+1} - S_{\mathrm{w}i,j}^{n}}{S_{\mathrm{w}i,j}^{n}} + \left[c_{\mathrm{p}i,j}^{n} C_{\mathrm{f}} p_{\mathrm{o}} \right]_{i,j}^{n} + c_{\mathrm{p}i,j}^{n} \end{aligned} \tag{11}$$

The coefficients in the above equation can be expressed as the following equations.

$$a_{i,j} = T_{\mathrm{o}xi-\frac{1}{2}} + \frac{\rho_{\mathrm{o}}}{\rho_{\mathrm{w}}} T_{\mathrm{w}xi-\frac{1}{2}};\quad b_{i,j} = T_{\mathrm{o}xi+\frac{1}{2}} + \frac{\rho_{\mathrm{o}}}{\rho_{\mathrm{w}}} T_{\mathrm{w}xi+\frac{1}{2}};\quad c_{i,j} = T_{\mathrm{o}yi-\frac{1}{2}} + \frac{\rho_{\mathrm{o}}}{\rho_{\mathrm{w}}} T_{\mathrm{w}yi-\frac{1}{2}};$$

$$d_{i,j} = T_{\mathrm{o}yi+\frac{1}{2}} + \frac{\rho_{\mathrm{o}}}{\rho_{\mathrm{w}}} T_{\mathrm{w}yi+\frac{1}{2}};\quad e_{i,j} = -\left[a_{i,j} + b_{i,j} + c_{i,j} + d_{i,j} + \frac{\left(\phi \rho_{\mathrm{o}} C_{\mathrm{t}} V \right)_{i,j}}{\Delta t^n} \right];$$

$$f_{i,j}=-\frac{\rho_o}{\rho_w}q_wV_{i,j}-q_oV_{i,j}-\frac{\left(\phi\rho_oC_tV\right)_{i,j}}{\Delta t^n}p_{i,j}^n;\ a_{1i,j}=T_{wxi-\frac{1}{2}};$$

$$b_{1i,j}=T_{wxi+\frac{1}{2}};\ c_{1i,j}=T_{wyi-\frac{1}{2}};\ d_{1i,j}=T_{wyi+\frac{1}{2}};$$

$$e_{1i,j}=-a_{1i,j}-b_{1i,j}-c_{1i,j}-d_{1i,j}-\frac{\left[\phi\rho_wS_w\left(C_w+C_f\right)V\right]_{i,j}}{\Delta t^n};$$

$$a_{2i,j}=T_{wxi-\frac{1}{2}};\ b_{2i,j}=T_{wxi+\frac{1}{2}};\ c_{2i,j}=T_{wyi-\frac{1}{2}};\ d_{2i,j}=T_{wyi+\frac{1}{2}};$$

$$e_{1i,j}=-a_{1i,j}-b_{1i,j}-c_{1i,j}-d_{1i,j}-\frac{\left[\phi S_wc_p^nC_fV\right]_{i,j}}{\Delta t^n};\ T_{oxi\pm\frac{1}{2}}=\frac{2\Delta y_jh\lambda_{oxi\pm\frac{1}{2}}}{\Delta x_i+\Delta x_{i\pm1}};$$

$$T_{oyj\pm\frac{1}{2}}=\frac{2\Delta x_ih\lambda_{oyj\pm\frac{1}{2}}}{\Delta y_j+\Delta y_{j\pm1}};\ T_{wxi\pm\frac{1}{2}}=\frac{2\Delta y_jh\lambda_{wxi\pm\frac{1}{2}}}{\Delta x_i+\Delta x_{i\pm1}};\ T_{wyj\pm\frac{1}{2}}=\frac{2\Delta x_ih\lambda_{wyj\pm\frac{1}{2}}}{\Delta y_j+\Delta y_{j\pm1}};$$

$$V_{i,j}=\Delta x_i\Delta y_jh;\ \lambda_o=\frac{\rho_oKK_{ro}}{\mu_o};\ \lambda_w=\frac{\rho_wKK_{rw}}{\mu_{eff}};\ \lambda_p=\frac{KK_{rw}c_p}{\mu_{eff}}$$

The finite difference method is used to solve the problem, and the IMPES method is used to solve the pressure implicitly, the saturation explicitly, and the polymer concentration explicitly. The solution process is as follows: Firstly, starting from the initial conditions, the pressure value at time n can be obtained from the pressure equation. After obtaining the pressure at each time step, the obtained node pressure is substituted into the saturation equation to obtain the water saturation value of each node at time n. Then, the water saturation value is substituted into the polymer seepage equation to obtain the polymer concentration value of each node at time n. In this way, the reservoir pressure, oil saturation, water saturation, and polymer concentration values at different time steps can be obtained. Record the bottom hole pressure values at different times and the pressure values at any point in the formation, draw a well testing curve, and analyze the curve.

4. Analysis of Polymer Flooding Well Testing Curve

After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command, and use the naming convention prescribed by your journal for the name of your paper. In this newly created file, highlight all of the contents and import your prepared text file. You are now ready to style your paper. The viscoelastic polymer flooding mathematical model of the inverse five point method well pattern has been established, the basic parameter variables being are as follow, $C_t = 5.2 \times 10^{-4}$ MPa^{-1}, $\phi = 0.3$, $n = 0.4$, $K = 0.375$ μm^2, $c_p = 2.0 \times 10^3$ mg/L, $p_e = 20$ MPa, $h = 10$ m, $S_{wi} = 0.4$. The shut-in pressure recovery test curve of the central polymer injection well was drawn.

The comparison of pressure dynamic curves between water flooding and polymer flooding is shown in **Figure 1**.

Before polymer injection, the radial flow section of the water drive derivative curve is basically horizontal, and the recovery speed is stable. After polymer injection, a hump appears in the radial flow stage of the curve, and the pressure and pressure conductivity values are higher than those of water drive. The degree of warping in the radial flow section of the well testing curve when considering polymer elasticity is greater than the curve which not considering polymer elasticity. After polymer injection, the viscosity of the displacement fluid increases, and the flow resistance within the formation increases, resulting in an upward trend in the radial flow section of the curve compared to water flooding. Compared with water flooding, polymer flooding has a higher viscosity of the displacement fluid, greater resistance to fluid flow in the formation, and higher injection pressure required. Therefore, the pressure and pressure derivative values of polymer flooding well testing curves are higher than those of water flooding. Considering the elasticity of the polymer, in addition to shear viscosity, elastic viscosity is also taken into account. As the viscosity of the polymer increases, the flow resistance increases, resulting in a greater degree of upward warping in the radial flow section.

The polymer flooding oil-water two-phase well test curves corresponding to different relaxation times are shown in Figure 2.

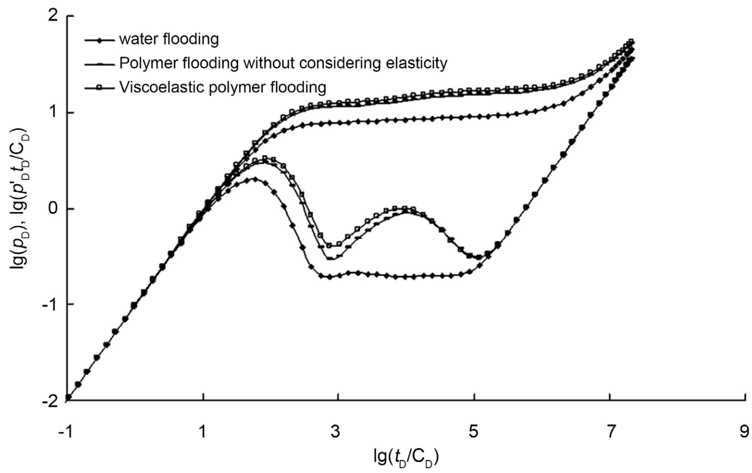

Figure 1. Comparison of well testing curves between water flooding and polymer flooding.

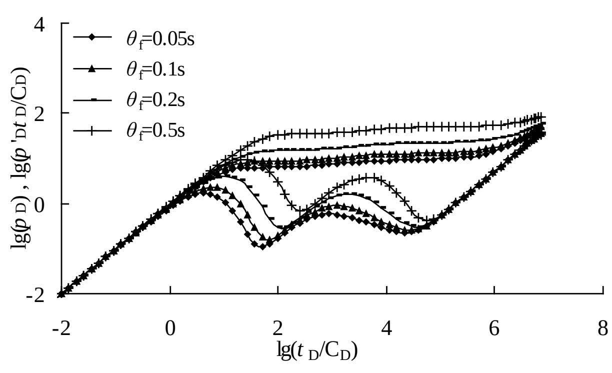

Figure 2. Effect of relaxation time on pressure test curve of injection well.

Relaxation time is a physical quantity that measures the elasticity of a polymer solution. From the graph, it can be seen that the relaxation time mainly affects the transition section and radial flow section of the well testing curve. The larger the relaxation time, the greater the pressure and pressure derivative values. The higher the "hump" of the transition section and radial flow section, and the greater the degree of upward warping of the radial flow section. Due to the consideration of the elastic viscosity of the polymer solution, the relaxation time affects the elastic viscosity of the polymer. As the relaxation time increases, the influence of elasticity on the well testing curve gradually increases; The larger the relaxation time, the greater the elastic viscosity at the same shear rate, the greater the apparent viscosity, and the greater the seepage resistance of the fluid during the seepage process, resulting in a greater degree of upward warping of the radial flow section.

The analysis curve of the influence factors of power law index on polymer flooding oil-water two-phase well testing is shown in **Figure 3**.

The power-law index is a parameter to characterize the non-newtonian property of polymer solution, and the power-law index of Newtonian fluid is 1. The power-law index mainly affects the degree of upwarping in the radial flow section. The closer the power-law index is to 1, the higher the pressure and pressure derivative curve, and the greater the degree of upwarping in the radial flow section of the pressure derivative curve. Near the injection well, the closer the power law index is to 1, the weaker the non-newtonian property of the polymer solution is, the lower the shear thinning degree is at the same shear rate, the higher the viscosity of the polymer solution is, the greater the seepage resistance is, and the greater the upward warping degree of the radial flow section of the pressure derivative curve is.

The analysis curve of the influencing factors of polymer injection concentration on polymer flooding oil-water two-phase well testing is shown in **Figure 4**.

From the figure, it can be seen that the higher the injection concentration of the polymer solution, the greater the pressure and pressure conductivity values,

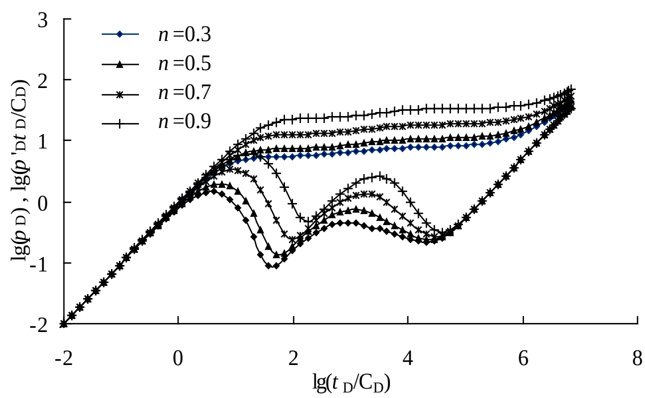

Figure 3. Influence of power-law index on bottom hole pressure test curve of injection well.

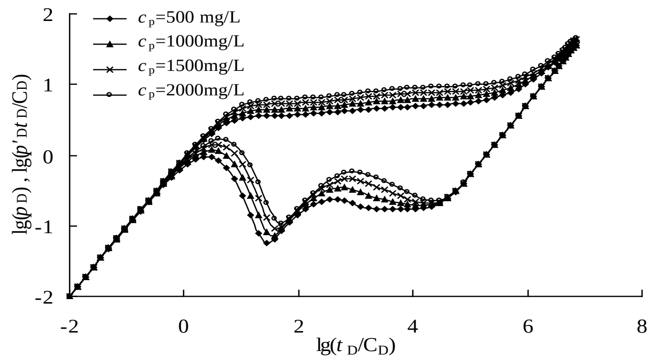

Figure 4. Influence of polymer injection concentration on pressure test curve of Injection well.

and the greater the degree of upwarping in the radial flow section, while the radial flow section is shorter. The viscosity of polymer solution is greatly affected by concentration. The higher the concentration of polymer solution, the greater its viscosity, the greater the injection pressure required, the greater the flow resistance, and the greater the degree of upward warping in the radial flow section; The higher the viscosity of the polymer, the smaller the range of influence during the same production time, and the shorter the radial flow section.

5. Conclusions

1) Compared with water flooding, the radial flow section of the pressure recovery curve of polymer flooding will appear upward in the early stage, resulting in greater flow resistance in the formation and higher injection pressure required; The degree of upward warping in the radial flow section of the pressure recovery curve when considering polymer elasticity is greater than the curve which not considering polymer elasticity.

2) Through the analysis of the influencing factors on the pressure recovery curve of polymer flooding, it can be concluded that each factor mainly affects the radial flow stage. The larger the relaxation time, power law exponent, and polymer injection concentration, the greater the degree of upward warping of the radial flow derivative curve.

3) The existence of viscoelasticity in polymer solutions is one of the reasons for the increasing in injection pressure. It is necessary to consider the viscoelasticity of polymer solutions in the flow theory and flow pattern analysis of polymer flooding.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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