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DESIGN OF A SELF-ADAPTIVE DOWN-HOLE LAYERED STEAM INJECTOR AND ITS APPLICATION

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ABSTRACT

Layered steam injection, widely used in Liaohe Oilfield at present, is an effective recovery technique to heavy oil reserves, which makes the steam front-peak push forward uniformly, the amount of steam injection be assigned rationally, and the effect of injection steam be obtained as expected. To maintain a fixed ratio of layered steam injection and solve the problem of nonadjustable hole diameter with the change of layer pressure in the existing injectors, a new method is proposed in this paper to design layered steam injectors based on the dynamic balance theory. According to gas-liquid two-phase flow theory and heat transfer theory, the energy equation and the heat conduction equation in boreholes are developed. By analyzing the energy equilibrium of water-steam passing through the injector hole, we find an expression to describe the relation between the cross-sectional area of injector hole and the layer pressure. With this expression, we provide a new set of calculation methods and write the corresponding computer program to design and calculate the main parameters of a steam injector. The actual measurement data show that the theoretically calculated results are accurate, the software runs reliably, and they provide the design of self-adjustable layered steam injectors with the theoretical foundation.

Keywords: Thermodynamic Oil Exploitation, Layered Steam Injector, Multi-Phase Flow, Theoretical Model, Design and Calculation

INTRODUCTION

Thermodynamic oil exploitation by injecting steam is an effective method for heavy oil. Formerly we usually used general steam injection mode, i.e. injecting steam into several layer synchronously [1]. However, the difference of layer pressure, permeate rate, oil physical properties among different layers causes irrational assignment of steam injection amount, it even can cause rapid push of some layer's steam band, so the expected effect of steam injection can not be achieved[2]. Layered steam injection can push the steam front-peak uniformly, avoid the appearance of "tongue-advance" phenomenon and assign the amount of steam injection rationally, so it can improve the effect of steam injection.

Layered steam injection is performed by down-hole tools. Rational recovery by injecting steam is a dynamic equilibrium process of the steam injection amount and pressure. However the existing layered steam injectors can not adjust dynamically. Based on the dynamic equilibrium principle of layer and well bore, a new self-adaptive down-hole layered steam injector is designed in this paper, it can adjust the amount of steam injection automatically with the layer pressure changing according to the steam injection ratio needed by production.

The key problem in designing the self-adaptive down-hole layered steam injector is how to decide the configuration of steam injector, the figure and area of the orifice's cross-section, the physical and mechanical parameters of the auto controlling spring scientifically and rationally. The steam flowing along the well bore is gas-liquid two-phase flow with unstable heat transfer process. Based on the gas-liquid two-phase flow mechanics and heat transfer theory, the characteristics about how the pressure, temperature, dryness faction and the loss of heat quantity changing are studied in this paper, then every layer's steam injecting pressure and dryness fraction are established. According to the requests of layer number, layer pressure and designed injection amount, the calculation equation of injection orifice's cross-sectional area is developed through analyzing the energy balance of the water-steam two-phase fluid passing through the injector hole. After that the needed parameters of hole and spring can be calculated, and the new down-hole layered steam injector with automatic adjustment function can be designed.

THE MATHEMATICAL MODEL OF THE MULTIPHASE FLOW IN WELL BORE

The Eqution of Pressure Gradient

The wet steam flowing along the well bore belongs to downward gas-liquid two-phase flow, and the well trace is a continuous and smooth line of deflection. The research indicates that the Beggs-Brill method can be used to calculate the pressure distribution in the well bore [3].

Assuming that the gas-liquid mixture in well bore is a closed system, and based on the mechanical energy conservation law of the steady flow, the total pressure gradient of the unit mass gas-liquid mixture is

$$\frac{dp}{dz}=-\frac{\left[\rho_l H_l+\rho_g(1-H_l)\right]g\sin\theta+\lambda Gv/2DA}{1-\left[\rho_l H_l+\rho_g(1-H_l)\right]v\,v_{sg}/p} \qquad (1)$$

where p denotes the mixture pressure (absolute), Pa; z denotes the distance of axial flow, m; ρ_l denotes the gas phase density, kg/m^3; H_l denotes the liquid hold-up ratio, m^3/m^3; g denotes gravity acceleration, m/s^2; θ denotes the angle between pipe and horizontal direction, °; λ denotes the friction factor of two-phase flow; G denotes the mass flow rate of mixture, kg/s; v denotes the mixture velocity, m/s; v_{sg} denotes the converted velocity of gas phase, m/s; D denotes the pipe diameter, m; A denotes the pipe cross-sectional area, m^2.

The Energy Equilibrium Equation in Well Bore

Assumed conditions:

1. The velocity, pressure and dryness fraction of the injection steam at well head are constants.
2. The steam flow inside well bore is treated as one-dimensional homogeneous flow.
3. The heat transfer process from well bore to the external edge of cement ring is one-dimensional stable heat transfer, and the heat transfer process from the external edge of cement ring to layer is one-dimensional unstable heat transfer. The heat transfer along the well direction is neglected.

Taking a tiny element cube dz along the well direction, the special solution of the energy equilibrium equation in well bore can be obtained based on the first law of thermodynamics and boundary conditions:

$$x=e^{b}\left(\frac{C_3}{C_2}\left(1-e^{k}\right)+x_0\right) \qquad (2)$$

Where $b=-\frac{C_2}{C_1}z$; $k=\frac{C_2}{C_1}z$;

$$C_1=G(h_s-h_w);\quad C_2=G\left[\frac{dp}{dz}\left(\frac{dh_s}{dp}-\frac{dh_w}{dp}\right)\right];$$

$$C_3=\frac{dQ}{dz}+G\left(\frac{dp}{dz}\right)\left(\frac{dh_w}{dp}\right)+\frac{G^3}{(A\upsilon_m)}\frac{d\left(\rho_m^{-1}\right)}{dz}-Gg\,.$$

And x denotes dryness fraction; z denotes the depth of any point, m; G denotes the mass flow rate of injection steam, kg/s; h_w denotes the enthalpy of saturated water, J/kg; h_s denotes the enthalpy of dry saturated steam, J/kg.

The parameters C_1, C_2 and C_3 are related with h_w and h_s, and h_w, h_s are usually the function of pressure. They can be computed by computer interpolation according to the steam table. It is discussed detailedly in the reference about well bore heat loss dQ[4], so we do not discuss it anymore.

We must point out that to keep the physical parameters and flow characteristics of flow in every pipe portion not change, the calculation need divide well bore into several portions because ρ、λ、Q_g、h_m are all functions of pressure and dryness fraction.

THE DESIGN CALCULATION OF THE SELF-ADAPTIVE DOWN-HOLE LAYERED STEAM INJECTOR

The Structure of Self-Adaptive Down-Hole Layered Steam Injector

The down-hole layered steam injector is composed of short pipe, upper and subjacent injector orifice, guide rod, piston, spring, etc (Figure 1).

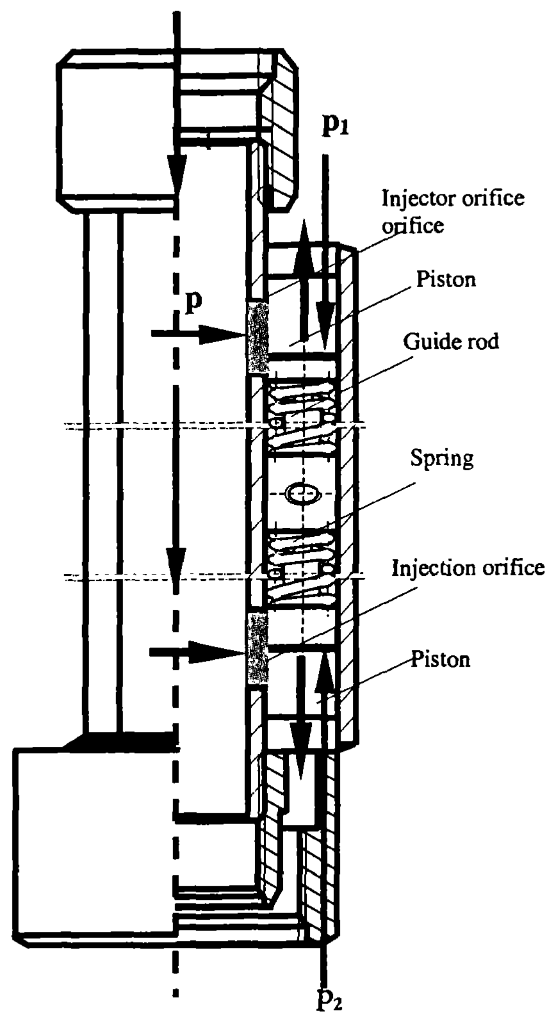

Fig.1 Self-Adaptive Layered Steam Injector

Its operation principle is to eliminate the effect of oil layer steam absorption pressure against the steam injection amount by automatically adjusting the orifice's cross-sectional area, so steam can be assigned to each layer according to the designed proportion.

The Calculation Eqution of Injector Orifice's Area

Assuming the gas-liquid two-phase flow in the injector orifice is separated flow and the gas phase is incompressible, and the flow rate coefficient C_d of gas phase and liquid phase are equal. There is not additional evaporation during the flow process and the cross-sectional air void of gas phase doesn't change. When the two phases pass the injector orifice simultaneously, the pressure difference of gas phase and liquid phase is identical, and equals to the pressure difference Δp of both the two phases.

Based on the energy conservation eqution and continuity eqution, the calculation eqution of injector orifice's area is obtained [2]:

$$A = \frac{G_{tp}\overline{\rho}}{\sqrt{2\psi^2 C_d^2 \rho_l \rho_g (p - p_1) + G_{tp}^2 S^2 \overline{\rho}^2}} \quad (3)$$

Where $\overline{\rho} = \varepsilon(1-x)\sqrt{\rho_g} + x\sqrt{\rho_l}$;

And A denotes the cross-sectional area of hole, m^2; G_{tp} denotes the two phase mass flow rate of the fluid passing through orifice, kg/s; ε denotes the introduced correction factor by considering the deviation between assumption and practice, and its value is determined by experiment; x denotes dryness fraction; ρ_g denotes the density of gas phase, kg/m^3; ρ_l denotes the density of liquid phase, kg/m^3; p denotes pressure in pipe, Pa; p_1 denotes the pressure after the hole, Pa; Ψ denotes the orifice expansion coefficient; C_d denotes the orifice flow rate coefficient; S denotes the pipe cross-sectional area, m^2.

The Relationship between Pressure Change and Orifice Area

Supposing injecting steam into two layers and the allocation proportion are k_1、k_2, then

$$\Delta p = \frac{G_{tp}^2 \overline{\rho}}{2\psi^2 C_d^2 \rho_l \rho_g}\left[\frac{k_2^2}{A_2^2}\left(1-\frac{A_2^2}{S^2}\right) - \frac{k_1^2}{A_1^2}\left(1-\frac{A_1^2}{S^2}\right)\right] \quad (4)$$

Where Δp denotes the alteration quantity of pressure, Pa; k_1、k_2 denotes steam allocation proportion, the determination method can be seen in reference [5]; A_1 denotes the cross-sectional area of the upper orifice, m^2; A_2 denotes the cross-sectional area of the subjacent orifice, m^2; S denotes the pipe cross-sectional area, m^2.

The Determination of Correction Factor

It's discovered by many researchers through experiments that the main factor effecting the correction factor ε is the gas/liquid phase density ratio ρ_g/ρ_l, it is also one of the main characteristic parameters in two-phase flow and denotes the magnitude of the saturated steam pressure.

It can be obtained by experimental curve regression [6]:

When $0.00772 \leqslant \rho_g/\rho_l < 0.1425$,

$$\varepsilon = 36.48\left(\frac{\rho_g}{\rho_l}\right)^2 - 9.329\left(\frac{\rho_g}{\rho_l}\right) + 1.49 \quad (5)$$

When $0.1425 \leqslant \rho_g/\rho_l \leqslant 1$,

$$\varepsilon = 1.1299 + 0.1210\ln\left(\frac{\rho_g}{\rho_l}\right) \quad (6)$$

If the mass flow rate G and the steam assignment proportion k_1、k_2 between layers are known, combining the designed injector orifice area, the mass flow rate G_{tp} passing through each injector orifice can be obtained. Based on the distribution characteristics of pressure and dryness fraction in well bore, the steam assignment pressure, dryness fraction and other corresponding physical parameters at corresponding depth can be attained too. Substituting the parameters into the expression (4), the alteration quantity of piston pressure corresponding to the designed steam assignment proportion and the variation of the injector orifice area can be gained, so it can provide the necessary theory basis for the designing of automatic adjustment spring.

THE APPLICATION EXAMPLE

Based on above theory, we developed "Layered steam assignment process system", and achieved well effect in the field experiments and applications over ten times. The following example is a layered steam injection well – well B 45-18-205, and its basic data are shown in table 1. The pressure in well bore is 4.22MPa and the dryness fraction is 0.59 at 1200m depth by ring space test, the computed results are shown as figure 2 and 3. The computed pressure of this well is 4.32MPa and dryness faction is 0.534. Compared with the practical test values, the pressure error is $\frac{4.31-4.22}{4.22}\times 100\% = 2.13\%$; the dryness fraction error is $\frac{0.534-0.57}{0.57}\times 100\% = -7.01\%$, so we can see they are coincident.

Table 1 Basic Data of Well B45-18-205

Tube structure		Heat transfer characteristics	
The inner diameter of injector pipe(mm)	62	Ground surface temperature(℃)	10.4
The outer diameter of injector pipe(mm)	73	Earth temperature gradient (℃/100m)	2.9
The inner diameter of outer oil pipe(mm)	100.5	Layer thermal diffusion coefficient (m^2/d)	0.09
The outer diameter of outer oil pipe(mm)	114.3	Layer thermal conductivity(W/(m·℃))	1.73
The inner diameter of casing pipe(mm)	161.7	Cement ring thermal conductivity(W/(m·℃))	0.933
The outer diameter of casing pipe(mm)	177.8	Heat-protection material type	Other materials
The diameter of well(mm)	240	Heat-protection material thermal conductivity(W/(m·℃))	2.25
Layered data		Injection calculation work conditions	
Middle depth (m)	Steam injection proportion (%)	Injection rate (t/h)	15
1000	40	Well head pressure (MPa)	8
1200	60	Well head dryness fraction	0.60

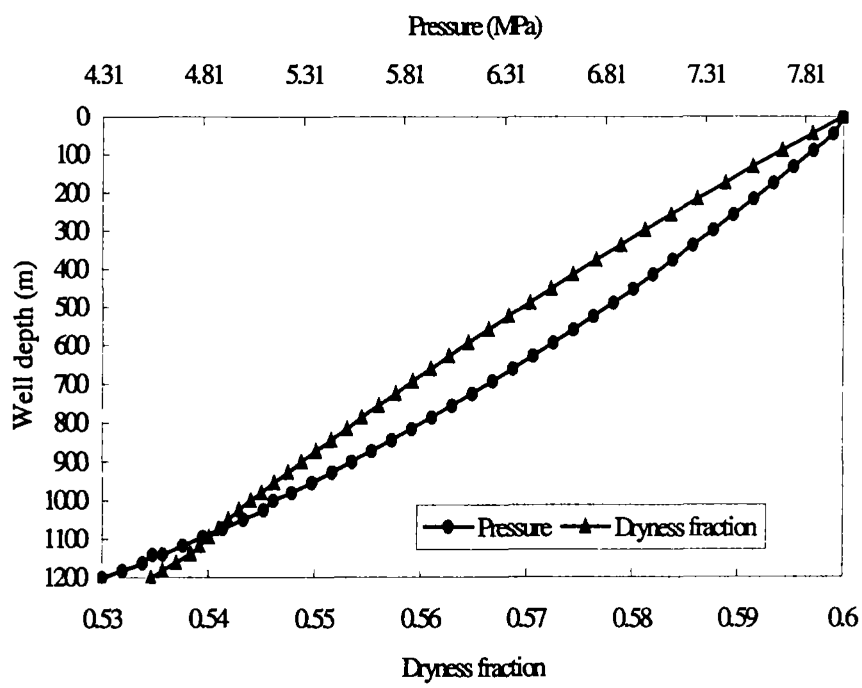

Fig.2 Pressure and Dryness Fraction Regularity

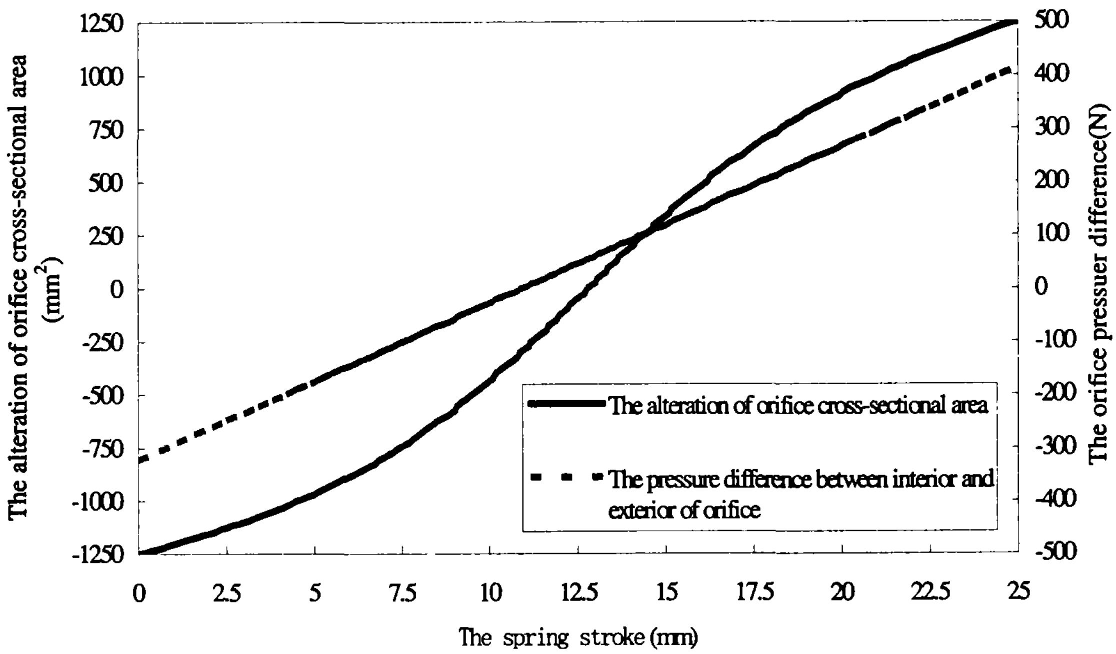

Fig.3 Working Performance of Injector Hole

CONCLUSIONS

1. Based on the multiphase flow mechanics and heat transfer theory, the mathematical model about the well bore work condition analysis of layered steam assignment is established, and it provides the theory basis to design local layered steam injector.

2. Based on the dynamic equilibrium theory, a new self-adaptive layered steam injector is designed, so the objective of fixing steam assignment proportion can be achieved effectively.

3. The operation principle of self-adaptive layered steam injector is represented in this paper and a set of new design and calculation method is provided, and the problem in designing some key parameters is solved.

4. The theoretical calculation results accord with the field practical test data well, and the calculation accuracy can satisfy the engineering requests. The applications of self-adaptive layered steam injector obtained well production effect.

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