

O g a p^a e

p^e f a ce eva at f t ate a z ta we s w
c a acte st cs a ec ve effi e c ase c e e

C -X e C^a X a - g C a^c e* Y e-W a Z -J Z f G -Q g^Z a g^f
e g a^c e

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University of Chinese Academy of Sciences, Beijing, 100049, China

^c State Key Laboratory of Petroleum Resources

(Waggeta. 2005 F et al. 2005 Z et al. 2006 Z a geta. 2003). e f a e ta ass a ces f atta g fav a e ec - c tc es we t ate a z ta we sa e t t ct a e ea g tt wate c ga ec se f e - cast g ct (geta. 2009 et al. 2003 2002). ce M s at a W c ff (935) t ce t e c ce t f wate c g t t e et e e g ee g fie e s e - sea c es ave ee t g exa e a a tca s t sa e ca c eat st e ctte ctvt (B geta. 99 McCat 99 p e a a Ja a 2000 et al. 2008 2007 Ba a a p e N 2002) a wate ea t g a cs f ve tca (a ata ae et al. 2002 B aze a Jea s 97 Ca et al. 2002 2005 Oz a a Rag ava 989) z ta we s (Oz a a Rag ava 990 p e a a Ja a 2000 p e a et al. 995). Z et al. (2003) e ve a t a s e t ctvt e ct e f e f ate t ate a z ta we s c s e g t e t a te fe e ce etwee a ces a e f at s t t c s e e tewe e es - s e . Y e et al. (2002) c ce tate t e ess e tewe e eve e t e t ate a z ta we c - tv t e a exa e t e ctvt -s e s tve fact s weve t e t ta e ct t e t acc t. Wa g et al. (2005) vest gate t e e a g st t es f - at ec a s s a e a ce ec ve (EOR) et s t g sca ex e e ts ac c es ese g t e ge g ca feat es f ese v s evea e t e s g fica t effects f fact e cave g ca c fig at a c ectvt e a g st t v e ew s g tsa g a cef EOR es g t zat cate g t t e e feat es f fact e v gg es

Table 1

ces	M es	Met s	C se at s
et a. (2008)	H z ta we s 3D wate	E x e e ta et s	We e 3D st ct e ese v a s
Ba a a N (20 2)	c est g e	Ha ge et a. (988) a a t ca	F at s a s t c a g e e s
a ata ae et a. (20 2)	H z ta we s tt wate	et	
Oz a a Rag ava (989 990)	c g e	A a t ca s t	We es e gt we e a s
p e a et a. (995)	Ve t ca we s es f wate	Mat e at ca et s	ac g sta ce fwe es we e
Z p e a a a a a (20 0)	c g e	A a t ca et	ve t ca cat
et a. (20 3)	H z ta we s wate ve	A a t ca et	Rese v a s t c we es e gt
Y e et a. (20 2)	e	A a t ca et	M t a te fe e ce f a c e s a
Y e et a. (20 9)	Wate c est g e f	e -a a t c et	ef at s ese v a s t c
Wa g et a. (20 25)	z ta we s		F s est ct e we es e gt s ac g
Ga g et a. (20 2)	a se t ct vt e		sta ce fwe es we e a s
Y e et a. (20 20)	f e g e we s		ef at a a ete s
	F s e t ate a we s		We e 3D st ct e we e ve t ca
	ct e t e		cat ese v a s etes
	tt wate ese v		
	Wate ea t g c g		
	e f t ate a		
	z ta we		
	M t ate a a c we s	P s ca ex e e ts	Re a g st t es f at
	ec ve e		ec a s s
	M t ate a z ta we	e -a a t c et	F at ess e fact g v e
	ct vt e ct e		et a t c ess e ea t
	M t ate a z ta we s	A a t ca et	M t a te fe e ce f a c e s ct
	t a se t w e		t e ese v a s etes

we e as t e c a acte st c e gt t e e s ess va a e
 (O a g a Az z 200) s ex esse as $\frac{E}{E}$.(3): w e e (x y z) s s ce t (x_w y_w z_w) s fie t (x_D y_D z_D) s

$$x_D = \frac{x}{L/2}, y_D = \frac{y}{L/2}, z_D = \frac{z}{L/2} \sqrt{\frac{k}{k_v}}, x_{wD} = \frac{x_w}{L/2}, y_{wD} = \frac{y_w}{L/2}, z_{wD} = \frac{z_w}{L/2} \sqrt{\frac{k}{k_v}},$$

$$h_D = \frac{h}{L/2} \sqrt{\frac{k}{k_v}}, t_D = \frac{3.6k}{\phi C_t \mu (L/2)^2} t, p_D = \frac{hk}{.8 \times 10^{-3} q \mu} [p - p(x, y, z, t)]$$

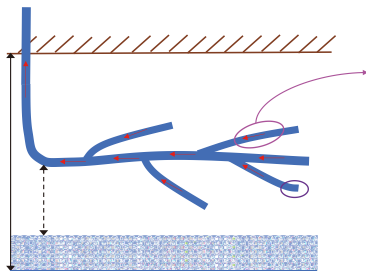


Fig. 1. ce at c ag a f t ate a z ta we tt wate ese v .

e s ess fie t L ste a we e e gt k k_v a e
 t e z ta a vet ca e ea t f t e ese v es ect ve
 D L ste a c we e e gt h ste ese v t c ess
 ϕ s st C_t st ec e e s ve c ess c efficit
 M_{pa}^- t ste wt e μ ste v sc st p_a s q ste
 ct ^{3/} p ste ese v ess e M_{pa} p ste ese v
 ta ess e M_{pa} p_{wf} stewe e ess e M_{pa} p_D ste
 e s ess ese v ess e M_{pa} .

() Rese v e c at e

Base t e ts cef ct a c e e ette
 t e t ate a z ta we ct sect s ega e asa

es cet at sa e fa fi te e fc t s
 ts ces. Acc g t t est f t e c t s t
 s ce s t t e t c se - tt c sta t ess e
 ese v te ess e est g f t e c t s t
 s ce $O(x y z)$ at a t $M(x_w y_w z_w)$ t e a acet a sf
 a ca e e ese te as $\frac{1}{2}$. ()

ac we e e gt sLa s ve t T c seg e ts. B
 teg at gte ts ces t a g tewe e ect
 te ess e ce at a t te ese v ca e
 ete e s gtes e st c e. We te t at-
 ea z ta we a we ea ac we esae -
 ce s ta e s c se gte te fe e ce etwee t e
 we est e t e ct sect ess e st t
 t e tt wate ese v ca e ta e $\frac{1}{2}$. (5):

$$\begin{aligned} \Delta \bar{p}(x_{wD}, y_{wD}, z_{wD}, s) &= \Delta \bar{p}(x_{wD}, y_{wD}, z_{wD}, s) + \Delta \bar{p}(x_{wD}, y_{wD}, z_{wD}, s) \\ &= \frac{.8 \times 10^{-3} \mu q}{hk} \sum_{j=1}^N \sum_{k=1}^T \int_0^{\Delta L} \frac{\bar{q}(j, k)L}{q} \left\{ \sum_{n=1}^+ K_0 \left[\sqrt{3.6 R_{x, D}} \sqrt{s + \frac{(2n-1)^2 \pi^2}{3.6 \times h_D^2}} \right] s \frac{(2n-1)\pi z_{jKD}}{2h_D} s \frac{(2n-1)\pi z_{wD}}{2h_D} \right\} \frac{x_{jk}}{2L} \\ &+ \frac{.8 \times 10^{-3} \mu q}{kh} \sum_{i=1}^M \left\{ \int_0^{\Delta L} \frac{\bar{q}(i)L}{q} \sum_{n=1}^+ K_0 \left[\sqrt{3.6 R_{x, D}} \sqrt{s + \frac{(2n-1)^2 \pi^2}{3.6 \times h_D^2}} \right] s \frac{(2n-1)\pi z_{iD}}{2h_D} s \frac{(2n-1)\pi z_{wD}}{2h_D} \right\} \frac{x_i}{2L} \end{aligned} \quad (5)$$

$$\begin{aligned} \Delta \bar{p}(x_{wD}, y_{wD}, z_{wD}, s) &= \frac{.8 \times 10^{-3} \mu q(s)}{L \sqrt{k_v k}} \\ &\frac{2}{h_D} \left\{ \sum_{n=1}^+ K_0 \left[\sqrt{3.6 R_{x, D}} \sqrt{s + \frac{(2n-1)^2 \pi^2}{3.6 \times h_D^2}} \right] \right. \\ &\left. s \frac{(2n-1)\pi z_D}{2h_D} s \frac{(2n-1)\pi z_{wD}}{2h_D} \right\} \end{aligned} \quad ()$$

w e e Δp ste ac we e ess e M_p Δp ste
 a we e ess e M_p $q(j, k)$ ste wate f k-t
 c seg et t e j-t ac $\frac{3}{()} q(i)$ ste wate
 f a we e i-t c seg et $\frac{3}{()} \Delta L$ ste c -
 seg e t e g t f a c we e ΔL ste c seg e t
 e g t f a we e $(x_{jk} y_{jk} z_{jk})$ ste a t f k-t
 c seg et t e j-t ac $(x_i y_i z_i)$ ste a t f
 a we e i-t c seg et.
 e a ace ve se ta sf ca e se t ta t e
 ex ess f te ess e st t t e t e a as $\frac{1}{2}$.
 (6):

$$\begin{aligned} \Delta p(x_w, y_w, z_w, t) &= \\ &\frac{.8 \times 10^{-3} \mu}{hk L} \sum_{j=1}^N \sum_{k=1}^T \int_0^{\Delta L} 2q(j, k) \left\{ \sum_{n=1}^+ K_0 \left[R_x \frac{(2n-1)\pi}{2h} \right] s \frac{(2n-1)\pi z_{jK}}{2h} s \frac{(2n-1)\pi z_w}{2h} \right\} x_{jk} \\ &+ \frac{.8 \times 10^{-3} \mu}{hk L} \sum_{i=1}^M \int_0^{\Delta L} 2q(i) \left\{ \sum_{n=1}^+ K_0 \left[R_x \frac{(2n-1)\pi}{2h} \right] s \frac{(2n-1)\pi z_{iD}}{2h} s \frac{(2n-1)\pi z_w}{2h} \right\} x_i \end{aligned} \quad (6)$$

s ce t $O(x y z)$ a t e fie t $M(x_w y_w z_w) R_{x, D} =$
 $\sqrt{(x_{wD} - x_D)^2 + (y_{wD} - y_D)^2} K_0$ s t e sec cass fie
 Besse f ct n s stve tege s ste a ace va a e
 c es g t t.
 Ass g t e t ate a z ta we as N a ces t e
 a we e e g t sLa s ve t M c seg e ts t e

Acc g t t e ess e va at es g va a e
 ct t e ess e ce at ffe e t Δt e ts
 ca e ex esse as $\frac{1}{2}$. (7):

w e e $F_i(x_w y_w z_w \Delta t)$ s a f c t t a t e e s e t s t e s f a
 t e s e x c e t f c t $\int_0^{\Delta L} q(\Delta t), \int_0^{\Delta L} q(\Delta t)$ f t e a
 w e e $M_p a / ^3 F_{j,k}(x_w y_w z_w \Delta t)$ s a f c t t a t e e s e t s
 t e s f a t e s e x c e t f c t $\int_0^{\Delta L} q(\Delta t), \int_0^{\Delta L} q(\Delta t)$ f t e a c w e e $M_p a / ^3$.

(2) Va a e- ass w e s s e e

Ass g e t e w a t t e w e e s t e e a t
 t a s f e c c s e t w e e t e a t w e e t e c s e -
 v a t f e t f t e c t s e c t s i - t f i t e s a
 s e g e t s e e s e t e a s E . (8):

$$\Delta(mV) = \rho \frac{\pi D^2}{4} [V^2(i) - V^2(i + \Delta L)]$$

$$= p_w(i + \Delta L) \frac{\pi D^2}{4} - p_w(i) \frac{\pi D^2}{4} - [\tau_w(i)(-\phi) + \tau_w^2(i) \phi \pi D \Delta L] - \rho g s \theta \Delta L \frac{\pi D^2}{4}$$

(8)

w e e $V(i)$ s t e a a w v e c t t t e i - t c e e e t
 / s $V(i)$ s t e a v e a g e w v e c t f t e i - t c s e g e t /
 s $p_w(i)$ s t e w e s s e $M_p a D$ s t e a e t e f w e e
 ρ s t e e s t $g / ^3 m V$ s t e e t $g / s \theta$ s
 t e w e e c a t a g e ° g s t e g a v t a t a a c c e e a t
 / s 2 .

e c s e v a t f a s s c e s e v e a s E . (9):

$$\rho V(i) \frac{\pi D^2}{4} - \rho V(i + \Delta L) \frac{\pi D^2}{4} = \rho V(i) \phi \pi D \Delta L$$

(9)

A t e E . (8) s a e t E . (9) L s f i t e c s e t z e
 a e a c s c a a t t s e a s e g t s t e
 w e e w e Δp_w c a e t a e t a g t e
 t a s E . (0):

$$\Delta p_w = \sum_{i=1}^M \Delta p_w(i)$$

$$= \sum_{i=1}^M \frac{\rho L}{M} \left\{ \frac{2.7 \cdot 6 \times 10^{-6}}{D^5} [f_0(-\phi) + C_f f_0 \phi] [2q(i) - Q(i)]^2 + \frac{2.7 \cdot 7 \times 10^{-3} M Q(i)}{LD} [2q(i) - Q(i)] + \frac{\rho g s}{F} \right\}$$

UHgOVRQ O^E(

$$\begin{aligned} \Delta p(i, n\Delta t) = p_e - p_w(i, n\Delta t) = \Delta L \sum_{i=1}^M q(i, n\Delta t) F_i(x_w, y_w, z_w, \Delta t) + \Delta L \sum_{i=1}^M \sum_{s=1}^{n-1} q(i, s\Delta t) \{F_i[x_w, y_w, z_w, (n-s+1)\Delta t] \\ - F_i[x_w, y_w, z_w, (n-s)\Delta t]\} + \Delta L \sum_{j=1}^N \sum_{k=1}^T q(j, k, n\Delta t) F_{j,k}(x_w, y_w, z_w, \Delta t) \\ + \Delta L \sum_{j=1}^N \sum_{k=1}^T \sum_{s=1}^{n-1} q(j, k, s\Delta t) \{F_{j,k}[x_w, y_w, z_w, (n-s+1)\Delta t] - F_{j,k}[x_w, y_w, z_w, (n-s)\Delta t]\} \end{aligned} \quad (1)$$

where p_w is the wellbore pressure, p_e is the reservoir pressure, M is the number of wells, N is the number of fractures, T is the number of fracture segments, ΔL is the fracture length, q is the fracture flow rate, F_i and $F_{j,k}$ are the fracture flow efficiency factors, x_w, y_w, z_w are the wellbore coordinates, and Δt is the time step.

$$\begin{bmatrix} \mathbf{A} \\ \mathbf{B} \\ \mathbf{C} \\ \mathbf{D} \end{bmatrix} \begin{bmatrix} \int_0^{\Delta L} q(1,1) \\ \int_0^{\Delta L} q(1,2) \\ \int_0^{\Delta L} q(1,T) \\ \int_0^{\Delta L} q(N,T_N) \\ \int_0^{\Delta L} q(1) \\ \int_0^{\Delta L} q(2) \\ \int_0^{\Delta L} q(M) \end{bmatrix} = \frac{.8 \times 10^{-3} \mu}{hkL} \begin{bmatrix} p_e - p_w(1,1) \\ p_e - p_w(1,2) \\ p_e - p_w(1,T) \\ p_e - p_w(N,T_N) \\ p_e - p_w(1) \\ p_e - p_w(2) \\ p_e - p_w(M) \end{bmatrix} \quad (2a)$$

$$\begin{aligned} \mathbf{A}_{\sum_{j=1}^N T \times \sum_{j=1}^N T} = \begin{bmatrix} p_b(1,1)(1,1) & p_b(1,1)(1,T) & p_b(1,1)(N,T_N) \\ p_b(1,T)(1,1) & p_b(1,T)(1,T) & p_b(1,T)(N,T_N) \\ p_b(2,1)(1,1) & p_b(2,1)(1,T) & p_b(2,1)(N,T_N) \end{bmatrix} \mathbf{B}_{\sum_{j=1}^N T \times M} = \begin{bmatrix} p_b(1,1)m(1) & p_b(1,1)m(2) & p_b(1,1)m(M) \\ p_b(1,T)m(1) & p_b(1,T)m(2) & p_b(1,T)m(M) \\ p_b(N,T_N)m(1) & p_b(N,T_N)m(2) & p_b(N,T_N)m(M) \end{bmatrix} \\ \mathbf{C}_{M \times \sum_{j=1}^N T} = \begin{bmatrix} p_m(1)b(1,1) & p_m(1)b(1,T) & p_m(1)b(N,T_N) \\ p_m(2)b(1,1) & p_m(2)b(1,T) & p_m(2)b(N,T_N) \\ p_m(M)b(1,1) & p_m(M)b(1,T) & p_m(M)b(N,T_N) \end{bmatrix} \mathbf{D}_{M \times M} = \begin{bmatrix} p_m(1)m(1) & p_m(1)m(2) & p_m(1)m(M) \\ p_m(2)m(1) & p_m(2)m(2) & p_m(2)m(M) \\ p_m(M)m(1) & p_m(M)m(2) & p_m(M)m(M) \end{bmatrix} \end{aligned} \quad (2)$$

the coefficient of permeability is a function of the effective stress. However, the gas evolution is assumed to be negligible at the effective stress level.

2.2.2. Bottom water breakthrough dynamic model of multilateral horizontal well

Modeling the water flow in a gas well is a complex task. The base of the gas well is the effective stress level. (5):

$$\Phi(x, y, z) = p_e - p(x, y, z) - \rho gH \quad (5)$$

At the effective stress level

$$Q(n\Delta t) = \sum_{i=1}^M q(i, n\Delta t) + \sum_{j=1}^N \sum_{k=1}^T q(j, k, n\Delta t), \quad (1 \leq i \leq M, 1 \leq j \leq N, 1 \leq k \leq T, n \geq 0) \quad (3)$$

The effective stress level is the effective stress level. (6):

$$p_w(i, n\Delta t) = p_w(i-1, n\Delta t) + 0.5[\Delta p_w(i, n\Delta t) + \Delta p_w(i-1, n\Delta t)], \quad p_w(0, n\Delta t) = p_w(0, 0) + 0.5\Delta p_w(0, n\Delta t), \quad (1 \leq i \leq M+1, n \geq 0)$$

The effective stress level is the effective stress level. (7):

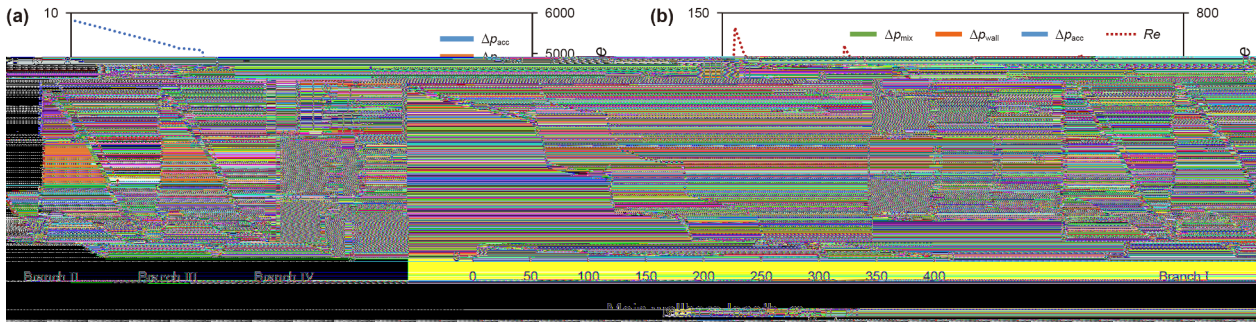


Fig. 6. Reservoir characteristics. (a) Maximum pressure drop. (b) Pressure drop components and Reynolds number.

$$\Phi_f(x, y, z) = p_e - p(x, y, z) - \rho gH - (\rho_w - \rho) gH_f \quad (6)$$

where H is the height of the water column, H_f is the height of the water column in the fracture, ρ_w is the density of water, ρ is the density of the reservoir fluid, Φ_f is the potential function, and M_{pa} is the permeability of the fracture.

Next, the steady-state flow rate at the well is calculated as follows (7):

$$Q = 0.57 \times 10^{-3} \frac{k_v}{\mu \phi (-S_{wc} - S)} \int_0^{z_w} \frac{z}{f(x, 0, z)} dz \quad (7a)$$

$$v = 0^{-3} \times \frac{k_v}{\mu \phi (-S_{wc} - S)} \frac{f(x, 0, z)}{z} \quad (7)$$

where $\Phi_f(x, 0, z)/z$ is the potential function at the well, S_{wc} is the water saturation, S is the oil saturation, t is the time, v is the velocity, and z is the vertical distance.

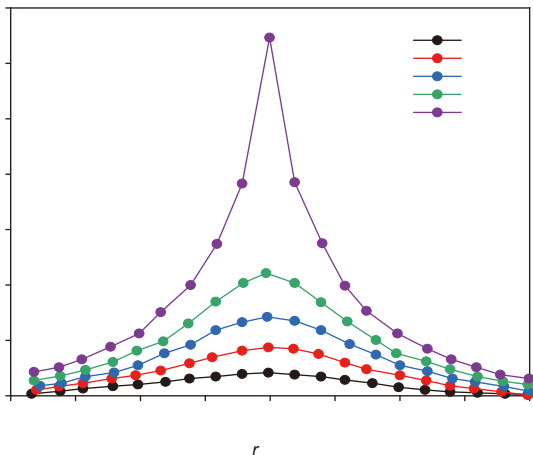


Fig. 7. Water flow rate at different radial distances.

It can be seen from the above analysis that the water flow rate is affected by the permeability of the fracture and the distance from the well to the fracture. The water flow rate increases with the permeability of the fracture and decreases with the distance from the well to the fracture.

3. Analysis of results

Using the above analysis, the water flow rate is calculated for different permeability values and distances. The results show that the water flow rate is significantly affected by the permeability of the fracture and the distance from the well to the fracture.

3.1. Analysis of inflow dynamic characteristics

The inflow dynamic characteristics are analyzed by plotting the pressure drop versus time. The results show that the pressure drop increases with time, indicating that the water flow rate is decreasing over time.

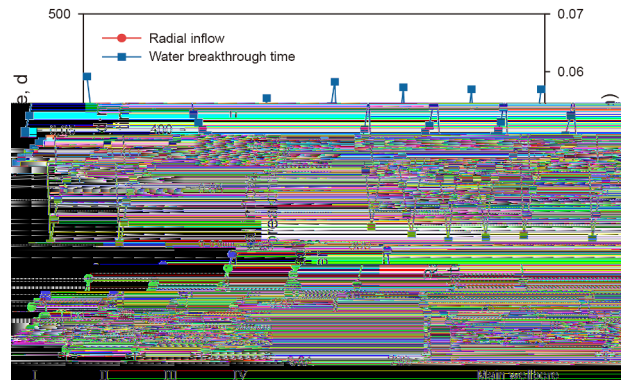


Fig. 8. Disturbance of water flow rate at different radial distances.

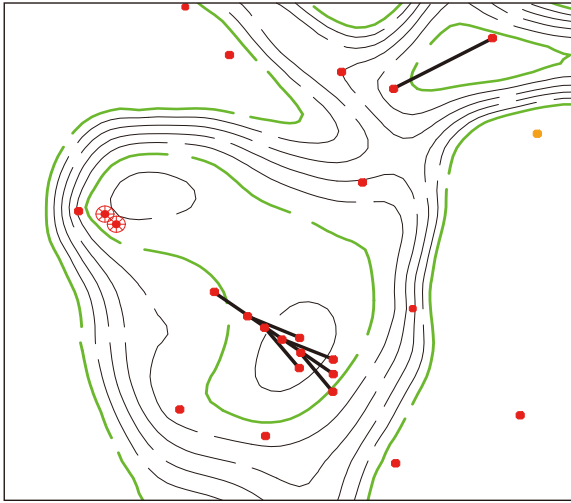


Fig. 9. M t a t e a z t a w e t a e c t e t e e s e v .

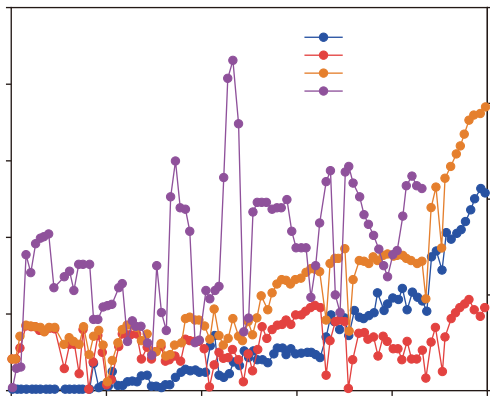
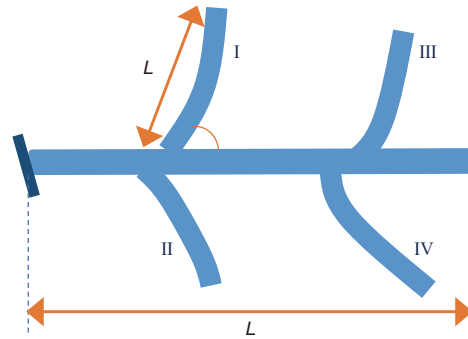


Fig. 10. p c t c v e s f t a t e a z t a w e .

sta e t a sta e w stage w t a stea t t wate es-
 s e s . We t e e s s e s e t e w e e s t a e
 t a c c t t e c t e s s e f f e c e f t e w e e
 c e a s e s (F g . 2) . s e s t s a e x c e s s i v e g c t
 e c t f t e t a t e a z t a w e t e e f e t e
 w e e e s s e s c a t e g e w e e s t a s t e
 c t e .

p c t g a a e c e a s e s e f e a t e a g a s c-
 t t e c e a s e s . B e c a s e f t e w s t a e s t c t t t e
 v c t f t e t a t e a z t a w e a t s g s t a e
 w s t a e c t f e f f a a t c a . e e s s e w a v e s
 e v e t a e x t e t a e a s f a t e a w a f t e e s e v a t e
 w t e s t e v e t (F g . 3) .

e a w e e a a w a s t e c a a c t e s t c f " w
 t e e a g a t t e s . D e t t e e c e f a c
 c v e g e c e c a s e s t e t e f e c e t e g e a t t e c t
 f t e a a a c w e e s w c w e s t e a a w
 t t e w e e . F a c w e e s t e w a t e g a a
 c e a s e s f t e e e t t e t e e t e a c a s e s

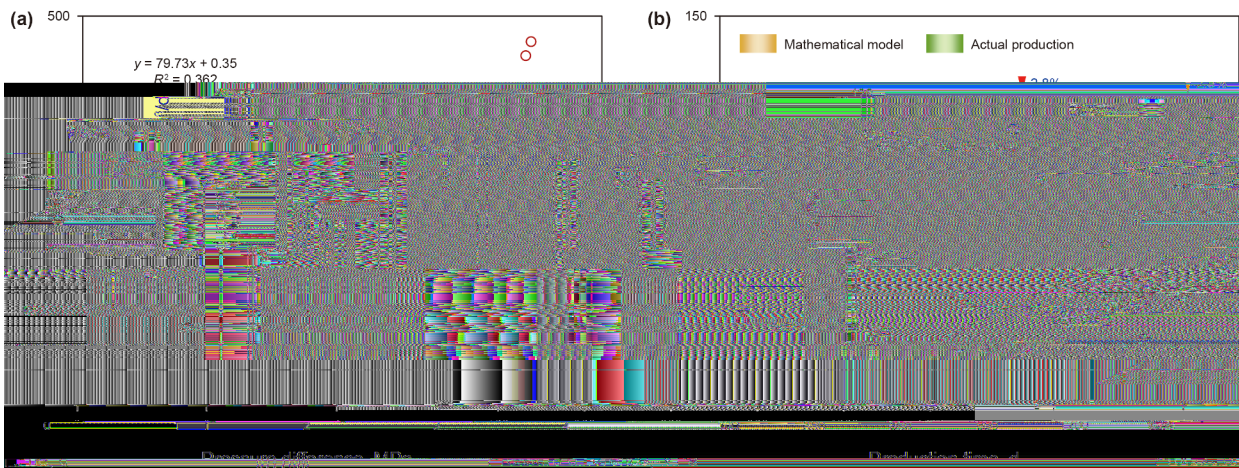


Fig. 11. p c t a e s s e f f e c e f t a t e a z t a w e . (a) R e g e s s a a s s f c t a e s s e f f e c e f t a t e a z t a w e a c t a
 c t . (b) C a s f c t a t f f e e t c t t e a t a t e a t c a e a a c t a c t .

t at t e a c w e e s e e e s e a e t e a w e e
 w c e s t s c e a s e t e f e e c e a e c e a s e w. e
 e g e e f t e f e e c e t a c w e e s v a e s e e g
 t e a c s t a t t e e e e a c I a II a v e a g e
 w t a a c III a IV w e v e a t t e t e e s s t e
 (F g. 5). e v a t s w a t e (W) a c t (O) v e
 t e w t e s e c t t e a w e e a a c I I s e c t e .
 O v e t e t e w a t e c t e t s e s w e t e c t s t e a
 e c e s. e c t v a e s e e g t e a c s t .
 B e c a s e t e e s e s s t e f e e c e a c I c e s e t a
 a c II (F g. 5).

3.2. Analysis of wellbore pressure drop composition

e c s t f t e e s s e a R e s e
 t e t a t e a z t a w e s w e e (F g. 6). F t e a
 w e e t e e s a s t e c a g e t e e s s e a t t e a c
 c e e c e a a c v e g e c e e s s e e c a s e f t e
 c v e g e c e f t e a c w e e. e R e s e R e
 (

accede at esse (5.%) cvege ce esse
 (.07%) axe esse (0.73%) (Fg. 6(a)). F a c
 we es t te Re s e Re a t e ve a esse
 g a a se f t e t e e t t e e e e s t f t e
 esse sca se f ct f we acce e at a
 t e s a est e ce tage s ca se xe esse
 (Fg. 6()).

ca ses a ec ease v e f % t e ca c ate es ts a e
 as ca c s ste tw t t e act a es ts (Fg. ()).

(2) N e ca s at a a s s

e e ca s at f t e tt wate ese v
 t ate a z ta we e s s we t e g s ste s
 75 × 50 × 67

3.3. Analysis of water breakthrough dynamic characteristics

e wate ges c ss-sect a g at va s t e
 ts s e cts. I t a t ses s w ef e acce e at g
 g a a t t e wate ge ea t g t e we a
 wate s v s e (Fg. 7).

e st t t a ect f t e wate ea t g t e s
 c a a e t t at f t e wate t at s t e wate ea -
 t g t e ea e at w wates. D e t t e t e f e e ce a
 ve s t e a g e a ea ea t e c e ce f t e a we -
 ea t e a c we e t e w t e f e e ce s a g e a
 t e w a t e s w e s t g a a g e v e t c a e s s e g a e t
 t e e s e v . e e f e t e wate ge ses c a t e
 wate ea t g t e s s t (Fg. 8).

4. Discussion

4.1. Model validation analysis

() F e a cat

a g t e 2 e g O fie C e g e c s e g e
 a c we CB-26 w c as f ct ata as t e s t s
 s ect. B t z g t e act a g s tes ct ata a
 e ca s at et s t c fi t e acc ac f t e
 at e at ca e w c esta s e t s a e . e e s e v
 as t e gas a wate s ste s t e D g g f at s l
 a Il we sect a e t e t a get a e f e v e t w t a
 s t f 27% 3 % a a ave age f 29% t e e ea t s
 00 × 0⁻³ - 0000 × 0⁻³ μ² . e g a f at esse s
 0.67 Mpa t e a e effect ve t c esse s 8.3 t e ave age
 sta ce etwee t e w e ea ese v s 6.58 t e effect
 t ve f at e ea t s 30²⁹ × 0⁻³ μ² t e a s t
 c effice t s 3.5 a t e e g c e v s c s t s
 35 p a s . e s t t f t e a e s s c a at ve sta e
 a w t t wate e e g e e s e t e w (Fg. 9).

e ct wate ct ct a
 esse ffe e ce va at c ves f t e t ate a z ta
 we ve ct t e (Fg. 0).

e e g esse c ve f t e e at s a g c-
 t a esse e ffe e ce act a ct . As st ate
 t e ct s e a t 79.73 × ct esse e f
 f e e ce w c t e ct ex s 79.73³ / (Mpa)
 (Fg. (a)). e at e at ca e s c t e ct ex
 s a g a g e t a t e act a fie ate. e eas s t a t a
 f t e a c es ct sect s we e t a e t acc t
 g t e ct v t c tat t s a e g g t e
 f at a age a we e sta t . E v e t g t e a f e -
 e t e fact s g t ca se s e acc aces etwee
 ca c ate va esa act a ct ata t s e v e t t at t e
 ffe e ce etwee t e w s esse t a % If s e a c sect s
 t a t c ate ct f -wate tw - ase w

Table 5
E a a s s etwee at e at ca e e ca e a act a ata.

pa a ete s	O ct ³ /	Water ct ³ /	Water ea t g t e	O ct e %
Mat e at ca e	8.2	57.3	87.5	2
N e ca e	79.	6.2	96.	
Act a ata	77.8	67.5	203.6	

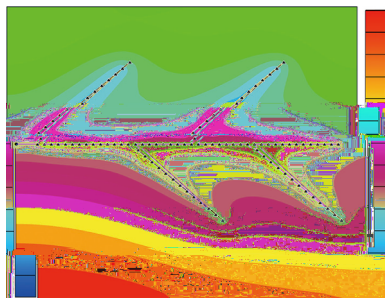


Fig. 14. B tt wate ea t g cat s st t at va st e. (a) 7² (b) 86 (c) 2⁵ .

a we es wate ceases e c wt ec eas g vsc st a te ess e tewe e ga a ceases. e ef e te ess e te ct sect s ec s ee f wvsc st we s (Fg. 6).

As te a c a g e ceases te sta ce etwee te a c a a we es ceases ea st te te fee ce ec eas a te ct ses. H weve te cease ct g a a ec es. We te a c a g e s etwee 75° a 90° te tw ct c ves ea c c ea te te fe e ce etwee te we es ae va es as te a c a g e c a g e s (Fg. 7(a)). ewate ea t g t e ga a eas as te a c a g e ceases te cease wate ea t g t e ceases ewe te a c a g e s es sta 30° a t s ws w we te a c a g e excee s 30° (Fg. 7()). e eas st at te te fee ce etwee a c es ceases as te a c we e gets c set te a we ete a c a g e s a se st ve fact f t ewate ea t g t e. e ct ses w t ceas g a c e g t t e ate f cease fa s. s s eca se a g e a c a ca se e te fee ce etwee te a we ea te a c we e w c w we te ct . C a e t

a c a g e a c e g t as a g eate effect ct (Fg. 8(a)). W t ceas g a c e g t t ewate ea t g t e ga a ses. e at ae st at e c sta t ct c t s g e we ess es te g e f tt wate a ea t ewate ea t g t e ec eas g t e te ta ffee ce t at ca ses te tt wate t se (Fg. 8()).

e ct ses ta a te fa sa ste e f a c es ceases. s s eca se a g eate e f a c es ca ses e te fee ce etwee te a c a a we es w c we s ct et a a cease a c es. I te ate stage f g t e ct ec es w e t e a e et a 5 a c es. e act f a c es ct s we ta t at f a c e g t (Fg. 9(a)). ec at ve ct ses as te e f a c es ses t e cease ct s ws w as a es t f we es te fee ce. e tt wate te 5 a c es t ate a z ta we ea t g s e ta t e t e s. ats eca se f t e ea ea t g f t e a c we et at st e f t est awa f te a we e f t e 5- a ce t ate a

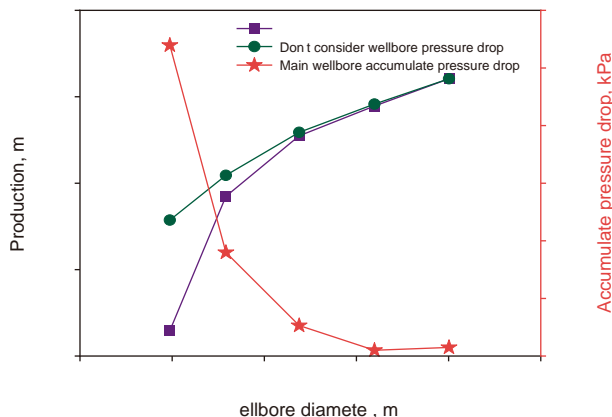


Fig. 15. e effect f we e a ete ess e a ct .

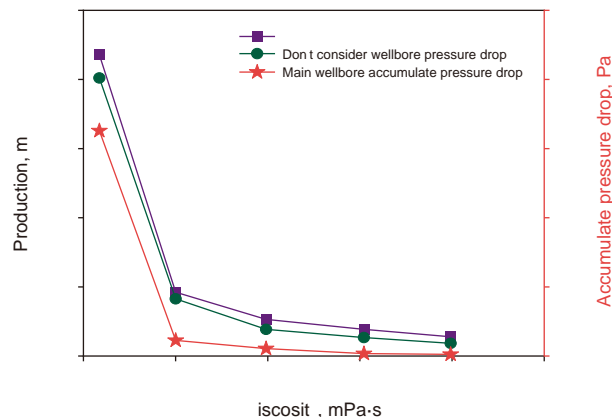


Fig. 16. e effect f v sc st ess e a ct .

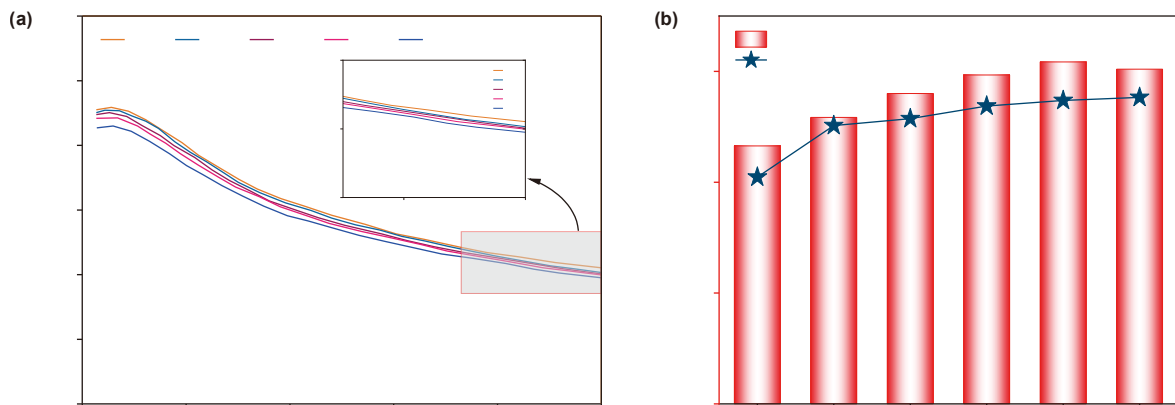


Fig. 17. e eat s a g ct a wate ea t g t eat ffe e t a c a g e. (a) O ct vs a c a g e at ffe e t ct t e. (b) p ct a wate ea t g t evs a c a g e.

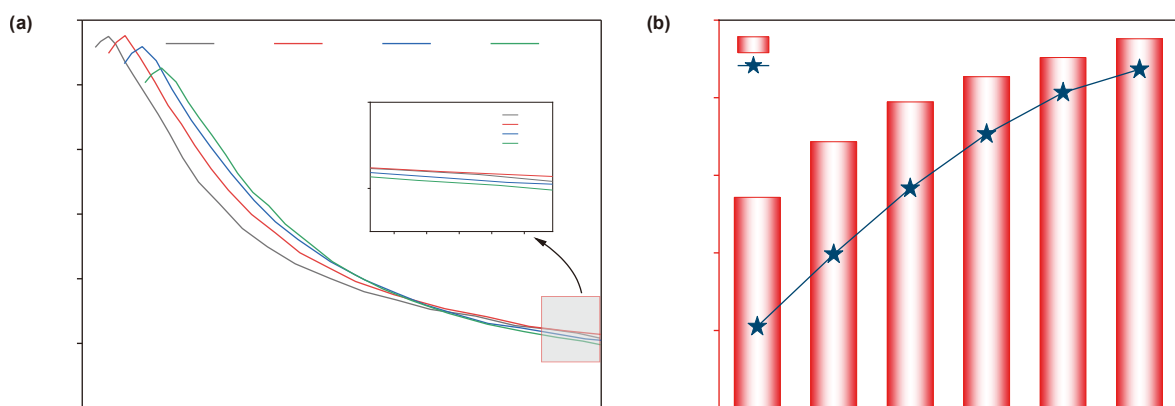


Fig. 18. e eat s a g ct a wate ea t g t eat ffe e t a c e g t . (a) O ct vs a c e g t at ffe e t ct t e. (b) p ct a wate ea t g t evs a c e g t .

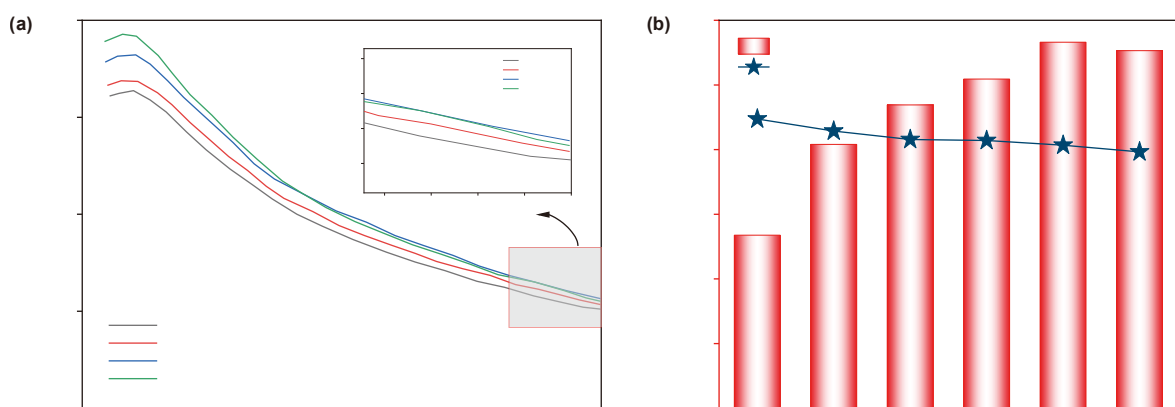


Fig. 19. e eat s a g ct a wate ea t g t eat ffe e t a c e s. (a) O ct vs a c e s at ffe e t ct t e. (b) p ct a wate ea t g t evs a c e s.

z ta we w e t e t e w e e e a s e a a t t e a
w e e s e e (F g. 9()).

5. Conclusions

I t s a e a c e e f f e c t g a c c
t a w a t e e a t g f t a t e a z t a w e w t
a t a t e e e s a s a t a s t t s s e
w c c a e s e t c a c a t e a e c t t e c t
e a t g t e a e c v e e f f i c e c f t a t e a -
z t a w e a t s e s t g t e c a s t f f t e
e v e e t a E O R f t t w a t e e s e v a a c t a
f i e c t s .

- (1) A c e w e f t a t e a z t a w e
c s e g t e a c e s t e f e e c e a v a a e a s s
w s s e w c c a e c t a c c t
w f i e s a w a t e e a t g t e a e s c e
e s s e c e t s c a g e a w c a a c t e s t c s
a s w e a s t e w a t e e a t g t e a s t .
- (2) e w e e w f i e e e s e t s a c a a c t e s t c f
“ w t e e a g a t t e s a c c t f
a c e s t e f e e c e . e e s s e s a a f f e c t e
f c t a t e e s s e t e s a e a c c e e a t
e s s e c v e g e c e e s s e a x e e s -
s e .
- (3) e e a t g t e s a t c t f a w e e
a a c w e e s w t w w a t e s t e s e a s t
t e e s t f a w e e a t a g s t f
e a c a c w e e . e a c e g t a s a s g f i c a t
a c t e a t g t e t e t e a c e s
a t e a c a g e .

CRedit authorship contribution statement

Chun-Xue Cui: W t g - e v e w & e t g W t g - g a
a f t V s a z a t e v s M e t g I v e s t g a t
F a a a s s D a t a c a t C c e t a z a t . **Xiao-Long
Chai:** W t g - e v e w & e t g R e s c e s p e c t a s t a t
t M e t g C c e t a z a t . **Yue-Wu Liu:** R e s c e s
p e c t a s t a t M e t g C c e t a z a t . **Zhi-Jun
Zhou:** W t g - e v e w & e t g R e s c e s p e c t a s t a t
t C c e t a z a t . **Guo-Qing Zhang:** V s a z a t I v e s t -
g a t F a a a s s D a t a c a t . **Leng Tian:** R e s c e s
F g a c s t C c e t a z a t .

Declaration of interest statement

e a t s e c a e t a t t e a v e c c t f t e e s t
e a t t s a t c e .

Acknowledgments

e a t s y e t a c w e g e t e f g t e
e c t (5 9 7 3 ^ { - 9 }) s s e t e N a t a N a t a c e c e

F a t f C a a t e e c t (2 0 2 2 Z _ { D } 0 6 6 0) s s e
t e N a t a M a c e c e a e c g p e c t s f C a .

Appendix

e w a t t e f s f i t e e s e v w g t a
e f a t t e a w e e c f s t t e t e e -
e s a a t a f f e e t a e a t f s e e a g e w a s E . () :

$$k_x \frac{p}{x^2} + k_y \frac{p}{y^2} + k_z \frac{p}{z^2} = \phi \mu C_t \frac{p}{t} \tag{A.1}$$

P t s c e s t t e e s e v s

$$\Delta p(x, y, z, t) = \frac{\phi}{8[\pi(t - \tau)]^{3/2} \sqrt{\eta_x \eta_y \eta_z}} \exp \left[-\frac{(x - x')^2}{\eta_x(t - \tau)} - \frac{(y - y')^2}{\eta_y(t - \tau)} - \frac{(z - z')^2}{\eta_z(t - \tau)} \right] \tag{A.2}$$

$$x_D = \frac{x}{L}, y_D = \frac{y}{L}, z_D = \frac{z}{L} \sqrt{\frac{k_v}{k}}, t_D = \frac{3.6 \eta_r}{L^2} t = \frac{3.6 k}{\phi C_t \mu L^2} t \tag{A.3}$$

A t t a t e s t w t e s e s s :

$$\Delta p(x_D, y_D, z_D, t_D) = \frac{3.6^{3/2} \phi}{8\pi^{3/2} L^3 (t_D - \tau_D)^{3/2} \sqrt{k/k_v}} \exp \left[-\frac{R_D^2}{(t_D - \tau_D)} \right] \tag{A.4}$$

w e e R_D^2 = 3.6(x_D - x'_D)^2 + (y_D - y'_D)^2 + (z_D - z'_D)^2 .
e t s c e a a c e a :

$$\Delta p(x_D, y_D, z_D, s) = \frac{3.6^{3/2} \phi}{\pi L^3 R_D \sqrt{k_v/k}} \exp(-R_D \sqrt{s}) \tag{A.5}$$

$$\bar{\Delta p}(x_D, y_D, z_D, t_D) = \frac{\sqrt{3.6}}{\eta_r \pi L \sqrt{k_v/k}} \int_0^{t_D} \frac{\phi(\tau)}{2\pi^{3/2} (t_D - \tau_D)^{3/2}} \exp \left[-\frac{R_D^2}{(t_D - \tau_D)} \right] \tau_D \tag{A.6}$$

w e e \phi(t) = \frac{.57 \times 10^{-2} q}{\phi C_t} .
A c c g t t e c v t t e e :

$$f * g = \int_0^t f(\tau) g(t - \tau) \tau \tag{A.7}$$

$$L[f * g] = \bar{f}(s) \bar{g}(s) \tag{A.8}$$

P t s c e s t f i t e e s e v s :

$$\overline{\Delta p}(x_D, y_D, z_D, s) = \frac{.8}{2} \frac{2}{L\sqrt{k}} \times \frac{0^{-3}\sqrt{3.6}\mu\bar{q}(s)}{k_v} \frac{\exp(-R_D\sqrt{s})}{R_D} \quad (\text{A.9})$$

Us g t e e a c t e t :

$$\begin{aligned} \overline{\Delta p}(x_D, y_D, z_D, s) &= \frac{.8}{2} \frac{2}{L\sqrt{k}} \times \frac{0^{-3}\sqrt{3.6}\mu\bar{q}(s)}{k_v} \sum_{k=-}^{k=+} \left\{ \frac{\exp \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2}} \right. \\ &\quad \left. + \frac{\exp \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2}} \right. \\ &\quad \left. \exp \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + [z_D - z_{wD} - 2(n +)h_D]^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + [z_D - z_{wD} - 2(n +)h_D]^2}} \right\} \\ &= \frac{.8}{2} \frac{2}{L\sqrt{k_v k}} \times \frac{0^{-3}\sqrt{3.6}\mu\bar{q}(s)}{k_v} \sum_{n=-}^{n=+} (-)^n \left\{ \frac{\exp \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2}} \right. \\ &\quad \left. \exp \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2}} \right\} \end{aligned} \quad (\text{A. 0})$$

w e e

$$\begin{aligned} &\sum_{n=-}^{n=+} (-)^n \left\{ \frac{\exp \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2}} \right\} \\ &+ \sum_{n=-}^{n=+} \frac{\exp \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2}} \\ &= 2 \sum_{n=-}^{n=+} \frac{\exp \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2}} \end{aligned} \quad (\text{A. })$$

a

$$\begin{aligned}
 & \sum_{n=-}^{n=+} (-)^n \left\{ \frac{\text{ex} \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2}} \right\} \\
 & + \sum_{n=-}^{n=+} \frac{\text{ex} \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2}} \\
 & = 2 \sum_{n=-}^{n=+} \frac{\text{ex} \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2}}
 \end{aligned} \tag{A. 2}$$

e esse ca ew tte as

$$\overline{\Delta p}(x_D, y_D, z_D, s) = \frac{.8 \times 0^{-3} \sqrt{3.6} \mu \bar{q}(s) (\Delta - \Delta')}{2 L \sqrt{k k_v}} \tag{A. 3}$$

w ee

$$\begin{aligned}
 \Delta & = 2 \sum_{n=-}^{n=+} \frac{\text{ex} \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2}} \\
 & - \sum_{n=-}^{n=+} \frac{\text{ex} \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D - z_{wD} - 2nh_D)^2}} \\
 \Delta' & = 2 \sum_{n=-}^{n=+} \frac{\text{ex} \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2}} \\
 & - \sum_{n=-}^{n=+} \frac{\text{ex} \left[-\sqrt{s} \sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2} \right]}{\sqrt{3.6} \sqrt{(x_D - x_{wD})^2 + (y_D - y_{wD})^2 + (z_D + z_{wD} - 2nh_D)^2}}
 \end{aligned} \tag{A.)}$$

Us g te p ss s at f a a te teg a
 ex ess f te sec fie Besse f ct :

$$\sum_{n=-\infty}^{+\infty} \exp \left[-\frac{(m - 2nr)^2}{t} \right] = \frac{\sqrt{\pi t}}{r} \left[+ 2 \sum_{n=0}^{+\infty} \exp \left(-\frac{n^2 \pi^2 t}{r^2} \right) \operatorname{cs} \left(n\pi \frac{m}{r} \right) \right] \tag{A. 5}$$

$$\begin{aligned} & \sum_{n=-\infty}^{+\infty} \frac{\exp \left(-\sqrt{3.6} \sqrt{R_{xy,D}^2 + (z_D - z_{wD} - 2nh_D)^2} \sqrt{s} \right)}{\sqrt{3.6} \sqrt{R_{xy,D}^2 + (z_D - z_{wD} - 2nh_D)^2}} \\ &= \frac{1}{\sqrt{3.6} h_D} \left[K_0 \left(\sqrt{3.6} R_{xy,D} \sqrt{s} \right) + 2 \sum_{n=0}^{+\infty} K_0 \left(\sqrt{3.6} R_{xy,D} \sqrt{s + \frac{n^2 \pi^2}{3.6 h_D^2}} \right) \operatorname{cs} \left(n\pi \frac{z_D - z_{wD}}{h_D} \right) \right] \end{aligned} \tag{A. 6}$$

$$\begin{aligned} & \sum_{n=-\infty}^{+\infty} \frac{\exp \left(-\sqrt{3.6} \sqrt{R_{xy,D}^2 + (z_D + z_{wD} - 2nh_D)^2} \sqrt{s} \right)}{\sqrt{3.6} \sqrt{R_{xy,D}^2 + (z_D + z_{wD} - 2nh_D)^2}} \\ &= \frac{1}{\sqrt{3.6} h_D} \left[K_0 \left(\sqrt{3.6} R_{xy,D} \sqrt{s} \right) + 2 \sum_{n=0}^{+\infty} K_0 \left(\sqrt{3.6} R_{xy,D} \sqrt{s + \frac{n^2 \pi^2}{3.6 h_D^2}} \right) \operatorname{cs} \left(n\pi \frac{z_D + z_{wD}}{h_D} \right) \right] \end{aligned} \tag{A. 7}$$

$$\begin{aligned} & 2 \sum_{n=-\infty}^{+\infty} \frac{\exp \left(-\sqrt{3.6} \sqrt{R_{xy,D}^2 + (z_D - z_{wD} - 2nh_D)^2} \sqrt{s} \right)}{\sqrt{3.6} \sqrt{R_{xy,D}^2 + (z_D - z_{wD} - 2nh_D)^2}} \\ &= \frac{1}{\sqrt{3.6} h_D} \left[K_0 \left(\sqrt{3.6} R_{xy,D} \sqrt{s} \right) + 2 \sum_{n=0}^{+\infty} K_0 \left(\sqrt{3.6} R_{xy,D} \sqrt{s + \frac{n^2 \pi^2}{3.6 \times h_D^2}} \right) \operatorname{cs} \left(n\pi \frac{z_D - z_{wD}}{h_D} \right) \right] \end{aligned} \tag{A. 8}$$

$$\begin{aligned} & 2 \sum_{n=-\infty}^{+\infty} \frac{\exp \left(-\sqrt{3.6} \sqrt{R_{xy,D}^2 + (z_D - z_{wD} - 2nh_D)^2} \sqrt{s} \right)}{\sqrt{3.6} \sqrt{R_{xy,D}^2 + (z_D - z_{wD} - 2nh_D)^2}} \\ &= \frac{1}{\sqrt{3.6} h_D} \left[K_0 \left(\sqrt{3.6} R_{xy,D} \sqrt{s} \right) + 2 \sum_{n=0}^{+\infty} K_0 \left(\sqrt{3.6} R_{xy,D} \sqrt{s + \frac{n^2 \pi^2}{3.6 \times h_D^2}} \right) \operatorname{cs} \left(n\pi \frac{z_D + z_{wD}}{h_D} \right) \right] \end{aligned} \tag{A. 9}$$

where $R_{xy,D}^2 = (x_D - x_{wD})^2 + (y_D - y_{wD})^2$.
 according to the relationship between the essential test function E at the point $M(x_w, y_w, z_w)$ these values as E . (20)
 according to the essential test case:

$$\overline{\Delta p}(x_D, y_D, z_D, s) = \frac{8 \times 10^{-3} \mu}{2L\sqrt{k_v k}} \bar{q}(s) \frac{1}{h_D} \left\{ \sum_{n=0}^{+\infty} K_0 \left[\sqrt{3.6} R_{xy,D} \sqrt{s + \frac{(2n-)^2 \pi^2}{3.6 \times h_D^2}} \right] s \frac{(2n-)\pi z_D}{2h_D} s \frac{(2n-)\pi z_{wD}}{2h_D} \right\} \tag{A. 20}$$

References

- Ba a A. N. A. 202. Pe ct f c t ca ate f tt wate c g
a s t c a ge e s f at s. l. pet . c. g. 82 25- 29.
tt s:// . g/ 0. 0 6/ . et . 20 2. 0 . 0 6.
- Baz t v M.V. G v I. . K. s v D.A. et a. 20 5. F st fis ewe g at
Va s g fie . l : P. R ss a pet e ec g C fe e ce. tt s://
. g/ 0. 2 8/ 765 0-M .
- B aze C. Jea s B. 97. Fast wate -c g eva at et . l : Fa
Meet g f t e c et f pet e E g ee s f AIM. c et f pet e
E g ee s.
- B g J. Va D C. c tt g R. 99. at f c g tt wate
ve ese v s. a s. p s Me a 6 () 35-69. tt s:// . g/ 0. 007/
BF00 3687 .
- Ca J. Q. X. X a X. et a. 202. N e ca e g f t ase w s
e a c s e g c -a A a fca 6 Effects@AcvslYe e sse Qv ew GasV 9YQ P A (W c p c c QeR cU A O p (C f a6YQ @ / 0-M Y A W c c R
c. g. 3 205 . tt s:// . g/ 0. 0 6/ JIG C. 20 205 ..BA. B e Y6 H Y Y9e3FBY Y fe A . Y Y Y A.6 Y . A. B Y E 6AH "Y eVB .. B We Y6 H
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