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A New Steam Properties Calculation Models for Horizontal Well

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Abstract

During steam flows in horizontal wellbore, the mass flow rate decreases with steam draining into the formation, which causes acceleration pressure drop. Acceleration pressure drop can change steam physical parameters, wellbore pressure distribution and temperature distribution. Based on the rules of mass conservation and energy conservation, model for steam quality variation along the horizontal section was built. Pressure and temperature distribution of injected steam along horizontal section were deduced on the principle of momentum conservation. Models were solved by pressure increment iteration method. The calculation results are compared with the reservoir numerical simulator, which showed that the models in the paper were succinct and accurate.

Key words: Variable mass flow; Horizontal wellbore; Steam quality distribution; Pressure distribution; Temperature distribution

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INTRODUCTION

When steam is injected into horizontal well, part of steam drains into the formation through perforations along the radial direction, which is variable mass flow[1-3], and different with flowing in a horizontal circular pipe. So the pressure distribution models of typical circular pipe are not suitable for steam stimulation[4-5]. In the context of variable mass flow, mass exchange and energy exchange occur between steam and formation. Steam flow rate decreases along flow direction, and steam parameters such as steam density and enthalpy change too. Varied steam parameters can influence the pressure and temperature distribution in the horizontal section dramatically. But few current models consider above factors which can lead to greater calculation error[6-7].

After studying the steam properties considering variable mass flow in horizontal well, new models were presented to calculate the distribution of steam quality, steam pressure and steam temperature.

1. THE MODELS AND SOLUTION

Horizontal well model in infinite formation is shown in Figure 1. Variable mass flow in horizontal well bore is shown in Figure 2. Derivation of the models is shown in Appendices A and B. Assumption conditions, resultant equations and solution are summarized in this section. Notations are explained in the Nomenclature section.

1.1 Assumption Conditions

Assumption conditions of models are given as follows:

(a) The reservoir is homogeneous and extends in horizontal direction infinitely. As shown in Figure 1.

(b) Mass flow rate, pressure and quality of steam are constant at the heel of horizontal well. Steam flows in steady-state.

(c) Heat loss caused by tubing coupling is ignored. Heat transfer from casing to cement is one dimensional steady-state. Heat transfer in the horizontal direction is not considered.

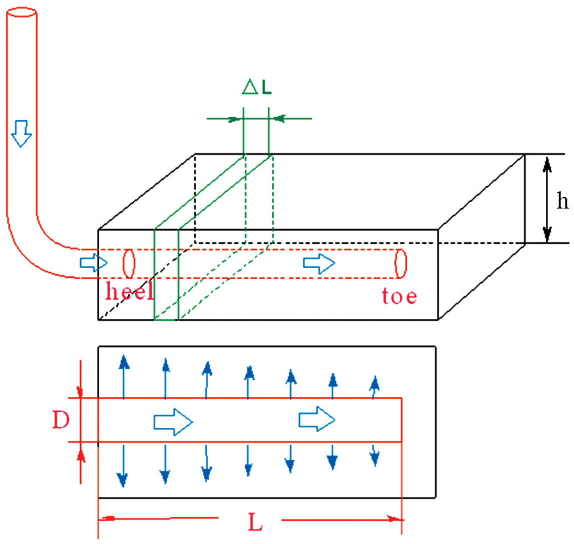

Figure 1
Schematic Diagram of Horizontal Well and Variable Mass Flow in Infinite Formation

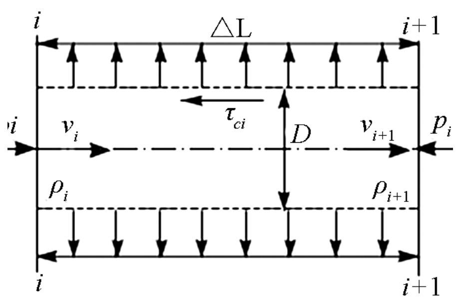

Figure 2
Micro-Unit of the Horizontal Wellbore

1.2 Steam Properties Calculation Models

Micro-unit of horizontal section was selected as the research object (Figure 3). By establishing mass conservation equation and the energy conservation equation for micro-unit, model for steam quality variation along the horizontal section is obtained by solving Equation (1):

$$\begin{cases} x = \exp\left(-\dfrac{N_2}{N_1} l\right) \cdot \left[-\dfrac{N_3}{N_2} \exp\left(\dfrac{N_2}{N_1} l\right) + x_0 + \dfrac{N_3}{N_2}\right] \\ N_1 = i_s\left(h_s - h_w\right) \\ N_2 = i_s\left(\dfrac{\mathrm{d}h_s}{\mathrm{d}p} - \dfrac{\mathrm{d}h_w}{\mathrm{d}p}\right)\dfrac{\mathrm{d}p}{\mathrm{d}l} \\ N_3 = \dfrac{\mathrm{d}Q}{\mathrm{d}l} + \left(\dfrac{v_m^2 - v_r^2}{2}\right)\dfrac{\mathrm{d}i_s}{\mathrm{d}l} + \dfrac{\mathrm{d}W}{\mathrm{d}l} + \dfrac{\mathrm{d}h_w}{\mathrm{d}p}\dfrac{\mathrm{d}p}{\mathrm{d}l} i_s \\ \qquad + v_m i_s\left[\dfrac{i_s}{A_h \rho_m}\left(\dfrac{1}{T}\dfrac{\mathrm{d}T}{\mathrm{d}p} - \dfrac{1}{p}\right)\dfrac{\mathrm{d}p}{\mathrm{d}l} + \dfrac{1}{A_h \rho_m}\dfrac{\mathrm{d}i_s}{\mathrm{d}l}\right] \\ x\big|_{l=0} = x_0 \\ p\big|_{l=0} = p_0 \end{cases} \quad (1)$$

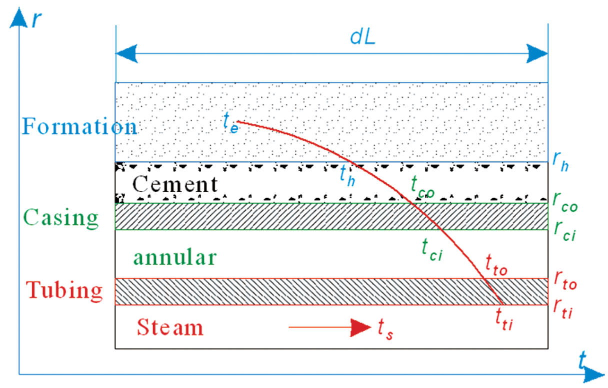

Figure 3
Schematic Diagram of Temperature Distribution During Steam Injection

Model for steam pressure distribution along horizontal wellbore is obtained according to momentum conservation and is given by:

$$\frac{\mathrm{d}p}{\mathrm{d}l} = -\frac{1}{A_h}\frac{2v_m\dfrac{\mathrm{d}i_s}{\mathrm{d}l} + \dfrac{\tau_c}{\mathrm{d}l}}{\left[1 + \left(\dfrac{1}{T}\dfrac{\mathrm{d}T}{\mathrm{d}p} - \dfrac{1}{p}\right)\dfrac{v_m i_s}{A_h}\right]} \quad . \quad (2)$$

There is a specific relationship between steam temperature and pressure (Zhou, T.Y. et al., 2009) and shown as follows:

$$T=210.2376 \cdot p^{0.21}-30. \quad (3)$$

After obtaining the pressure value of micro-unit, temperature of micro-unit can be obtained by Equation (3).

1.3 Solution Procedures

The models in paper can be solved by the pressure increment iteration method. The steps are listed in detail as follows:

(a) Known parameters at the heel of horizontal well include: steam quality x_0, steam pressure p_0, steam temperature t_0, and steam mass flow rate i_{s0}. Horizontal section is divided into N parts equably, with length of each one being $\Delta l=L/N$.

(2b) The pressure drop range Δp and steam quality range Δx are estimated and used as initial value of iterative method.

(c) Average pressure $\overline{p}$ and average temperature $\overline{T}$ in dl length are calculated, and steam properties are identified according to Beggs-Brill method under current average pressure $\overline{p}$ and temperature $\overline{T}$.

(d) Work done by friction can be identified by Equation (A.14). Pressure drop $\Delta p'$ in Δl length are calculated by Equation (2). Heat loss dQ can be calculated by Equation (A.12). Steam quality variation $\Delta x'$ can be obtained by Equation (1).

(e) Compare $\Delta p'$ with Δp and $\Delta x'$ with Δx, if $|\Delta x'-\Delta x| \le \delta$ and $|\Delta p'-\Delta p| \le \delta$, go to next step, else let $\Delta p=\Delta p'$, $\Delta x=\Delta x'$ and return to step (3).

(f) The length and pressure corresponding to current micro-unit are calculated.

$$l_j = \sum_{k=1}^{j} \Delta l_k \,, \quad p_j = p_0 + \sum_{k=1}^{j} \Delta p_k \qquad (j = 1,2,3,\cdots\cdots, N).$$

(g) Calculate steam temperature at current micro-unit by Equation (3) and mass flows rate at the beginning of next micro-unit.

(h) Step (2) to step (7) is repeated and steam quality, temperature, pressure distribution and mass flow rate are calculated until accumulative length of every part is bigger than total length of horizontal section. If mass flow rate of injecting into the formation is bigger than mass flow rate in wellbore during calculation, the mass flow rate of injecting into the formation at remaining micro-unit is set as zero;

(i) Compare τ with steam injecting duration τ_{max}. If $\tau<\tau_{max}$, let $\tau=\tau+\Delta\tau$ and return to step (1), else stop calculation.

2. EXAMPLES AND RESULTS ANALYSIS

An example horizontal well was drilled in Shengli oilfield in China. The well data are shown in Table 1. Distribution of steam pressure, steam temperature and steam quality were calculated by models of this paper. Because measured data were not obtainable, the calculation results were compared with the results of reservoir numerical simulator. The simulation results are shown in Figure 4, and compare with calculation results in Figures 5, 6 and 7.

Table 1
Basic Data of Example Wells for Calculation

Parameters	Values	Parameters	Values
Reservoir depth (m)	750	Casing external diameter (mm)	177.8
Reservoir thickness (m)	12	Casing thickness (mm)	9.19
Reservoir temperature (℃)	48.5	Tubing inside diameter (mm)/	76
Reservoir pressure (MPa)	7.5	Tubing external diameter (mm)	89
Oil density (kg/m^3)	997.5	Steam injection duration (d)	11
Oil viscosity (mPa•s)	46536-60936	Steam injection rate (t/h)	9
Horizontal permeability (μm^2)	0.6	Steam pressure at heel (MPa)	14.1
Vertical permeability (μm^2)	0.2-0.3	Steam quality at heel	0.56
Horizontal length (m)	200	Steam temperature at heel (℃)	337.27
Wellbore diameter (mm)	254		

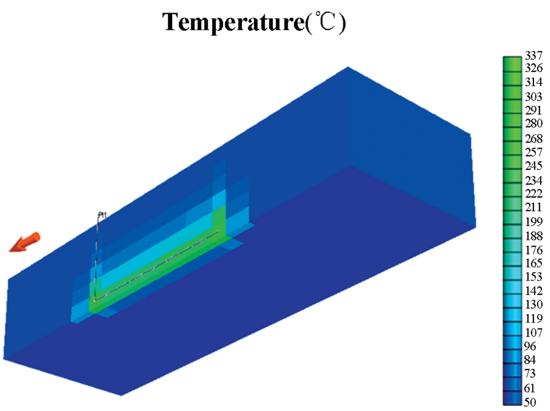

Figure 4
3D Result With CMG Simulator

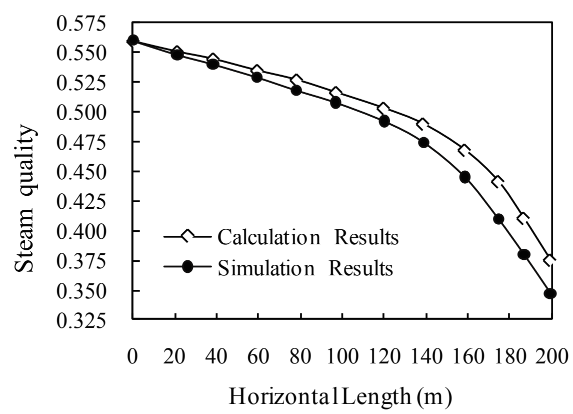

Figure 5
Steam Quality Distribution Along Horizontal Wellbore

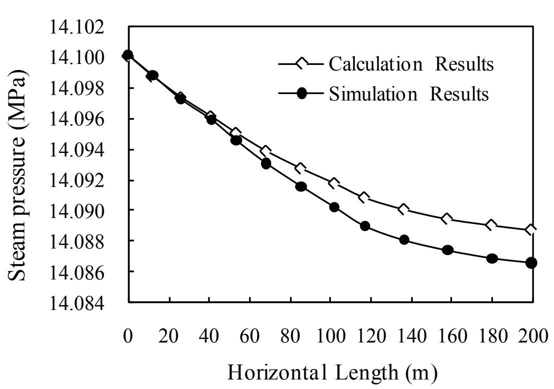

Figure 6
Steam Pressure Distribution Along Horizontal Wellbore

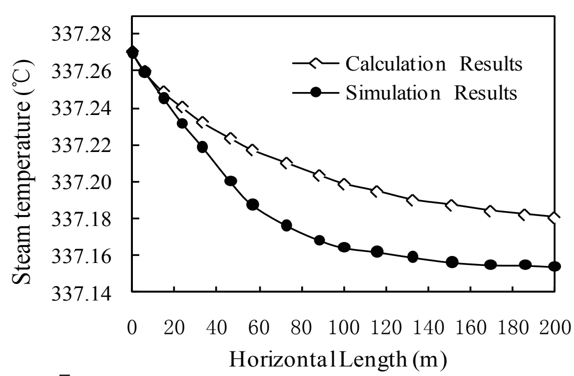

Figure 7
Steam Temperature Distribution Along Horizontal Wellbore

The results of comparison show that max calculation error of steam quality, pressure distribution, temperature distribution are 5.17%, 0.015% and 0.012% respectively. So it can be got that calculation results have higher accuracy.

Figure 5 shows steam quality decreased with the length to the heel of horizontal, i.e. from heel to toe of the horizontal section, and decreased magnitude increased with it. Variable mass flow can explain the phenomenon. Variable mass flow caused decrescent mass flow rate along horizontal wellbore. Decrescent mass flow rate brings forth increscent heat loss and increscent steam quality variation scope. Figure 6 shows that pressure distribution is non-linear, and has small change along the horizontal wellbore, which was mainly caused by steam mass flow rate. Because heel of horizontal section has higher mass flow rate, friction pressure drop at the heel is higher than toe. While the pressure drop caused by friction is low, so pressure change along horizontal wellbore is small. Because there is a specific relationship between steam pressure and temperature, steam temperature distribution in horizontal well has the same trend with steam pressure.

CONCLUSION

(a) The models for distribution of steam quality, steam pressure and steam temperature in horizontal wellbore were built in this paper. Variable mass flow and change of steam properties were all considered in models. Comparison shows the models are succinct and accurate.

(b) The calculation shows that distribution of steam quality, pressure and temperature are non-linear. The nearer to toe of horizontal wellbore, the higher percentage of steam quality decreases, while the decrease percentage of steam pressure and temperature are contrary.

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Nomenclature

x = Steam quality, fraction

l = Distance of calculation position from heel of horizontal well, m

x_0 = Steam quality at heel of horizontal well, fraction

i_s = Steam mass flow rate in horizontal section, kg/s

h_s = Enthalpy of gas in steam, kJ/kg

h_w = Enthalpy of water in steam, kJ/kg

p = Steam pressure, Pa

Q = Heat transfer between micro-unit and formation, W

v_m = Flow rate of steam which flows along horizontal wellbore, m/s

v_r = Flow rate of steam which injects into the formation, m/s

A_h = Cross section area of micro-unit, m^2

W = Work done by friction, W/s

ρ_m = Steam density, kg/m^3

p_0 = Steam pressure at heel of horizontal well, Pa

τ_c = Friction between steam and casing, N

T = Steam temperature, ℃

l_j = Distance of segment j from heel of horizontal well, m

p_j = Steam pressure at segment j, Pa

APPENDIX A: DERIVATION OF MODEL FOR STEAM QUALITY CALCULATION

Horizontal length of wellbore is L, and wellbore diameter is D. Micro-unit of horizontal section was selected as the research object. The micro-unit of horizontal wellbore is shown in Figure 2.

Equation (A.1) is obtained from mass conservation:

$$i_{si}\Delta\tau - i_{si+1}\Delta\tau - A_h \mathrm{d}l \frac{\partial \rho_m}{\partial \tau}\Delta\tau = i_{\mathrm{is}}\mathrm{d}l \cdot \Delta\tau \tag{A.1}$$

Where, $\Delta\tau$ is flow time, s; $i_{si}\Delta\tau$ is steam mass which flows into the micro-unit during $\Delta\tau$ period, kg; $i_{s(i+1)}\Delta\tau$ is steam mass which flows out of the micro-unit during $\Delta\tau$ period, kg;. $A_h \mathrm{d}l \frac{\partial \rho_m}{\partial \tau}\Delta\tau$ is mass accumulation of steam in micro-unit during $\Delta\tau$ period, kg; i_{is} is steam mass which injects into the formation, kg/(m·s).

If Equation (A.1) is divided by ($dl \cdot \Delta\tau$), a different form of the Equation (A.1) can be get as follows:

$$-\frac{di_{si}}{dl} - A_h \frac{\partial \rho_m}{\partial \tau} = i_{is} \,. \tag{A.2}$$

According to the assumption of steady-state flow in the article above, steam density ρ_m don't change with the flow time, so it can be get that $\partial\rho_m / \partial\tau = 0$. The Equation (A.2) is given as:

$$\frac{di_s}{dl} = -i_{is} \,. \tag{A.3}$$

Because steam flows along horizontal direction, the influence of gravity can be ignored. According to the principle of energy conservation, it can be got that energy loss of steam equals to the sum of heat loss in wellbore, energy increase in formation and energy loss caused by friction. The energy conservation equation of micro-unit is shown as follows:

$$\frac{dQ}{dl} + i_{is}\left(h_m + \frac{v_r^2}{2}\right) + \frac{dW}{dl} = -\frac{d}{dl}\left(i_s h_m + \frac{i_s v_m^2}{2}\right). \tag{A.4}$$

Where, dl is micro-unit length, m; dQ is heat loss in dl length, W; h_m is steam enthalpy, kJ/kg.

Equation (A.4) considers the energy change of the micro-unit of horizontal section, which includes internal energy change, friction loss, heat energy transfer between horizontal wellbore and formation under variable mass flow condition. The model for steam quality change could be derived from Equation (A.4). The follows are detailed derivation procedures.

Steam energy loss at the micro-unit which was showed at the right term of Equation (A.4) can be expressed as follows:

$$\frac{d}{dl}\left(i_s h_m + \frac{i_s v_m^2}{2}\right) = \frac{di_s}{dl}\left(h_m + \frac{v_m^2}{2}\right) + i_s\left(\frac{dh_m}{dl} + v_m \frac{dv_m}{dl}\right). \tag{A.5}$$

And $\rho_m A h v_m = i_s$. (A.6)

By derivation of Equation (A.6):

$$dv_m = \frac{1}{A_h}\left[di_s \cdot \frac{1}{\rho_m} + i_s \cdot d\left(\frac{1}{\rho_m}\right)\right]. \tag{A.7}$$

Steam density ρ_m is the function of pressure and temperature, so:

$$d\left(\frac{1}{\rho_m}\right) = \frac{1}{\rho_m}\left(\frac{1}{T}\frac{dT}{dp} - \frac{1}{p}\right)dp \,. \tag{A.8}$$

Substitute Equation (A.8) into Equation (A.7):

$$dv_m = \frac{i_s}{\rho_m A_h}\left(\frac{1}{T}\frac{dT}{dp} - \frac{1}{p}\right)dp + \frac{di_s}{\rho_m A_h} \,. \tag{A.9}$$

Auxiliary equation is listed as follows:

$$\frac{dh_m}{dl} = \left(\frac{dh_s}{dp} - \frac{dh_w}{dp}\right)\frac{dp}{dl}x + (h_s - h_w)\frac{dx}{dl} + \frac{dh_w}{dp}\frac{dp}{dl} \,. \tag{A.10}$$

Substituted Equation (A.3), Equation (A.5), Equation (A.9), and Equation (A.10) into Equation (A.4), following equation is obtained:

$$\begin{aligned} &\frac{dQ}{dl} + \frac{dW}{dl} + \frac{di_s}{dl}\left(\frac{v_m^2 - v_r^2}{2}\right) \\ &= -i_s\left\{\left[\frac{dx}{dl}(h_s - h_w) + \left(\frac{dh_s}{dp} - \frac{dh_w}{dp}\right)\frac{dp}{dl}x + \frac{dh_w}{dp}\frac{dp}{dl}\right]\right. \\ &\left.+ v_m\left[\frac{i_s}{A_h\rho_m}\left(\frac{1}{T}\frac{dT}{dp} - \frac{1}{p}\right)\frac{dp}{dl} + \frac{di_s}{dl}\frac{1}{A_h\rho_m}\right]\right\}. \end{aligned} \tag{A.11}$$

Equation (A.11) is first-order linear differential equation. With the Boundary conditions, model for steam quality distribution along horizontal section can be obtained by solving Equation (A.11).

Heat transfer between micro-unit and formation can be calculated by following formula:

$$\frac{dQ}{dl} = \frac{t_s - t_e}{R} \,. \tag{A.12}$$

Where, t_s is steam temperature in horizontal wellbore, ℃; t_e is formation temperature, ℃; R is total thermal resistance between wellbore and formation, $\left[\mathrm{W}/(\mathrm{m}\cdot{}^\circ\mathrm{C})\right]^{-1}$.

According to the assumption conditions, the reservoir extends in horizontal direction infinitely and has enormous heat capacity. The formation near cement is heated slowly by steam, while the formation far from the cement keeps initial reservoir temperature. It is unsteady heat transfer. The heat transfer process is simplified to a simple form: Heat transfer from wellbore to cement is steady-state, while from cement to formation is unsteady-state. Heat transfer from wellbore to formation is shown in Figure 3. Thermal resistance of tubing and casing are low and can be ignored, so thermal resistance between wellbore and formation can be simplified to following equation:

$$R = \frac{1}{2\pi}\left[\frac{1}{h\cdot r_{to}} + \frac{\ln\left(\frac{2\sqrt{\alpha\tau}}{r_h}\right) - 0.29}{\lambda_e} + \frac{\ln(r_h / r_{co})}{\lambda_{ce}}\right] . \tag{A.13}$$

Where, h is convective heat transfer coefficient of annulus, W/m^2·℃; r_{to} is tubing outer radius, m; α is thermal diffusivity of formation, m^2/s; τ is steam injection duration, h; r_h is horizontal wellbore radius, m; r_{co} is casing outer radius, m; λ_e is thermal conductivity coefficient of formation, W/m^2·℃; λ_{ce} is thermal conductivity coefficient of cement, W/m^2·℃.

Work done by friction can be calculated by following formula:

$$\frac{\mathrm{d}W}{\mathrm{d}l} = f_c \cdot \rho_m \cdot \frac{\pi D}{64}\left(v_{mj} + v_{m(j+1)}\right)^3 . \tag{A.14}$$

Where, f_c is friction coefficient between steam and casing under the consideration of variable mass flow, dimensionless; D is casing inner diameter, m; v_{mj} is average steam flow rate in segment j, m/s; $v_m(j+1)$ is average steam flow rate in segment ($j+1$), m/s.

APPENDIX B: DERIVATION OF MODEL FOR STEAM PRESSURE DISTRIBUTION

When steam flows in horizontal wellbore, steam is affected by surface force, which includes pressure difference between two points of micro-unit and shear resistance caused by friction. Flow rate at two points of micro-unit are different because of the presence of radial flow, which causes the change in momentum. The following equation is established according to momentum conservation:

$$\left(p_j - p_{j+1}\right)A_h - \tau_c = d\left(v_m i_s\right) . \tag{B.1}$$

Pressure drop of micro-unit can be obtained by dividing either side of the Equation (B.1) by A_h:

$$\mathrm{d}p = -\left[\frac{\mathrm{d}\left(v_m i_s\right)}{A_h} + \frac{\tau_c}{A_h}\right] = -\left(\frac{v_m \mathrm{d}i_s + i_s \mathrm{d}v_m}{A_h} + \frac{\tau_c}{A_h}\right) . \tag{B.2}$$

The model for pressure distribution along horizontal section can be derived by substituting Equation (A.6), Equation (A.7), and Equation (A.8) into Equation (B.2)

