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Modelling and simulation on shut-in wellbore and programming realization of natural gas well*

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Abstract. This paper studied the factors of temperature and pressure in the phase of shut-in wellbore. Based on the theory of wellbore hydraulics, heat transfer, thermodynamics and the vertical pipe flow, a series of mathematical models for calculating temperature and pressure distributions are established. C# language was used as the tool to calculate the mathematical models. Associated with SQL server 2000 database development software, the curves of temperature and pressure distribution were accomplished. The test of the model is done by simulation and the results show that the method of the model is valid for simulating temperature and pressure distributions in shut-in wellbore, and can be served as computer-based tool for users to make predictions for the future production.

Keywords: gas-well, shut-in wellbore, pressure distribution, programming realization, C#

1 Introduction

In the process of shut-in wellbore, changes of pressure and temperature in the gas well will result in deformation to the gas pipe. Researches on how to design model, and realize the algorithm by language programming, then design a series of interface in order to clearly show the visual wellbore pressure and temperature distribution, will have the significance of a practical application. Correct predictions about gas wells' wellbore temperature and pressure distribution give advantageous to dynamic analysis about gas well production system and optimize design of the production facilities.

Several scholars at home or abroad[5, 6, 12] have calculated the underground temperature distribution, they've refer to that the movement of underground temperature was more complicated, there were many factors about downhole temperature distribution, and small temperature difference between wellbore and formation. In the study of Production wells' temperature distribution, the temperature in the wellbore will restore to the original temperature of the state after well shut-in, because there is few case about temperature distribution after well shut-in. Temperature forecast model of the gas well has been conducted[10]. As early as in 1959, articles about forecast on the temperature distribution in the jet well were reported[9], and temperature gradient maps, which can predict gas lift valve temperature on injection gas point were provided. Then, an approximate method of the single-phase incompressible liquid temperature distribution and single-phase ideal gas temperature distribution when flow in the wellbore were developed[12]. Researchers made improvements on the basis of previous work, considered the possibility of transition in steam injection wells[14]. They fitted the coefficient in formula by using the site of the data, and simplified the formula[15]. Some proposed a semi-analytical solution of the gas-lift wells' temperature distribution[6]. The common algorithm of the bottom-hole

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flowing pressure in gas well is that from the energy equation, ignoring the loss of gas kinetic energy, the integral expression of gas flow equation was derived, and then on this base, methods of average temperature and average compression coefficient, Cullender and Smith Methods[3], Aziz iterative methods[1] (trial and error) solution were used. Some researchers developed a method of factor designing and analyzing in statistical test, returning an algebraic formula which was fitted to the bottom-hole pressure of given field best[18]. The formula could predicted the bottom-hole flowing pressure in gas wells.

Microsoft Visual Studio 2005 is a great compositive development environment, including VB, C#, Visual C++ and other applications. Developers can choose language for their development. Visual C# is a modern object-oriented language, which has mature thinking from the design and development, and the realization and expansion of other languages in the best features and functionality. Visual C# 2005 combined the flexibility and function of C++ with the simplicity of Visual Basic. As a programming tool, C# applied to many areas[2, 11, 16]. The tasks of accessing data are completed by ADO. NET(Active Data Objects. NET), which is a new database access technology design by Microsoft company, helping build a link between the data sources and data sets. ADO. NET provides the open unanimous visit the Microsoft SQL server and other open data sources by the adoption of XML and OLE DB. We will use the SQL server 2000 database, connect ADO. NET data components to the database, and then use data binding technology of Windows forms and the use of crystal reports. Based on the above process, the completion of the entire software can be achieved.

The innovation lies in the accordance of a series of issues about model and interface designing, we will take the actual situation of natural gas wells into account. And from the series of previous research findings, we will propose methods of model designing and software simulation. Intuitive curves of temperature and pressure distribution were made by using crystal report of Visual C#. The actual temperature and pressure in production can be forecasted. The article mainly introduces the integral designing of the temperature and pressure distribution of the shut-in wellbore, and the process of programming through Visual C# 2005 & SQL server 2000 database. And the basic data of the Dayi Well No. 1, 5160 meters of depth in Sichuan, are used for case history calculation.

This paper is organized as follows. In Section 2, several mathematical models for calculating temperature and pressure distributions in shut-in wellbore was established. In Section 3, the process of programming through Visual C# 2005 & SQL server 2000 database was introduced. Some concluding remarks are finally given in Section4.

2 Mathematical modelling

When the wellhead was shut-in, stratum fluid will continue to flow to the wellbore because stratum pressure is bigger than that at the bottom of the wellbore. At that time, the wellbore is a confined space, with the stratum fluid flow to the wellbore gradually, the pressure in wellbore increased gradually. Stratum fluid will stop to flow to the wellbore until the fluid pressure at the bottom of wellbore will fit in with the current stratum pressure. Because our current study is the exploitation of natural gas, the only fluid in the wellbore is natural gas. The calculation of static gas pressure in the wellbore is the only consideration. When shut-in after a period of time, the temperature distribution in the wellbore should be consistent with the stratum temperature distribution. Fig. 1 shows the simplified model of shut-in wellbore structure. The numerical model,which accords with the actual situation of the gas wells, allows for the oblique angle, structure of well and tubing string, the radial heat transfer of the wellbore, different heat transfer medium in annular and the change, with the depth, of the physical properties of the stratum. The model includes pressure calculation model and temperature calculation model. In the pressure model calculation, the effect of kinetic energy change is considered, using the method of Cullender&Smith[3] to solve it. We also consider the effect of friction in the borehole temperature distribution model. In calculating pressure and temperature, we divided the wellbore to many sections. In every section of the objects, pressure and temperature are just the unknown factors. Using iteration step to solve it.

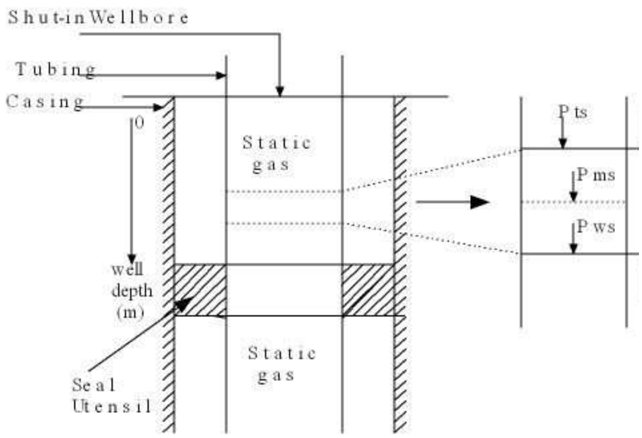


Fig. 1. The simplified model of shut-in wellbore structure

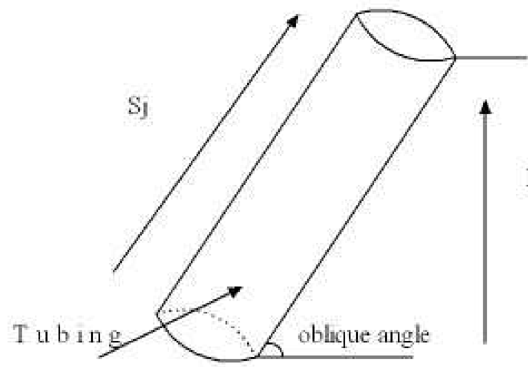


Fig. 2. The simplified model of Tubing

2.1 Pressure calculation model

The pressure calculation model has two parts, first we need to calculate the compression factor of natural gas, then calculate the static gas pressure.

2.1.1 Compression factor model

In order to determine the compression modulus of natural gas, we can take sample of the gas, use the testing method to determine. But nowadays, calculated directly by computer is the most common method. Several common formulas about Z modulus were introduced as follows.

(1) The calculation of low-pressure(p<35MPa) Z modulus

Standing and Katz published gas deviation coefficient maps in 1941[17], which was used in engineering mathematics.

$$Z = 1 + (0.31506 - \frac{1.0467}{T_{pr}} - \frac{0.5783}{T_{pr}^3})\rho_{pr} + (0.053 - \frac{0.6123}{T_{pr}})\rho_{pr}^2 + 0.6815\frac{\rho_{pr}^2}{T_{pr}^3} \tag{1}$$

where $\rho_{pr} = 0.27\frac{P_{pr}}{ZT_{pr}}$, $T_{pr} = \frac{T}{T_{pc}}$, $P_{pr} = \frac{P}{P_{pc}}$, T_{pc} is critical temperature, P_{pc} is critical pressure, pressure p and temperature T of natural gas are all known. When we want to use the equations upon to calculate Z modulus, iteration step is often selected to solve it on computer calculation. We take the following four steps:

Step 1. According to the given pressure p and temperature T, critical pressure and critical temperature, calculate the contrastive pressure P_{pr} and contrastive temperature T_{pr}.

Step 2. Give the first value to Z, we set $Z^{(0)} = 1$, calculate ρ_{pr}.

Step 3. Substitute ρ_{pr} into equation (1), calculate $Z^{(1)}$.

Step 4. Determine the value of Z by comparing the value of $Z^{(1)} - Z^{(0)}$, if the value meets the setting precision, $Z^{(1)}$ is the value of Z, otherwise let $Z^{(1)}$ go back to Step 2, calculate in a circle until meets the precision.

(2) The calculation of high-pressure (p≥35MPa) Z modulus

Hall and Yarborough made the following empirical formula of how to calculate deviation coefficient[4]. Empirical formula was the relational formula which was established on the basis of the isotherm in Standing-Katz chart.

$$Z = (90.7t - 242t^2 + 42.4t^3)y^{(1.18+2.82t)} - (14.76t - 9.76t^2 + 4.58t^3)y + \frac{1 + y + y^2 - y^3}{(1-y)^3} \tag{2}$$

$$Z = 0.06125P_{pr}te^{-1.2(1-t)^2} \tag{3}$$

The two equation are combined to one as follows:

$$\begin{aligned} F(y) &= -0.06125P_{pr}te^{-1.2(1-t})^2 + (90.7t - 242.2t^2 + 42.4t^3)y^{(2.18+2.82t)} \\ &\quad + \frac{y + y^2 + y^3 - y^4}{(1-y)^3} - (14.76t - 9.76t^2 + 4.58t^3)y^2 \\ &= 0 \end{aligned} \tag{4}$$

where $t = \frac{1}{T_{pr}}$, t is pseudo-reduced temperature, y is contrastive density for special definition. Because P_{pr} and T_{pr} are known , variable y can be gained from this equation. But it is non-linear equation, so determine y by Newton iteration step.

$$\begin{aligned} F'(y[k]) = &\frac{1 + 4y[k] + 4y[k]^2 - 4y[k]^3 + y[k]^4}{(1-y[k])^4} - (29.52t - 19.52t^2 + 9.16t^3)y[k] \\ &+(2.18 + 2.82t)(90.7t - 242.2t^2 + 42.4t[k]^3)y^{(1.18+2.82t)} \end{aligned} \tag{5}$$

$$y[k+1] = y[k] - \frac{F(y[k])}{F'(y[k]} \tag{6}$$

To determine Z explicitly, we take the following six steps:
Step 1. Give the first value to y, set $y^{(0)} = 0.001$ or set $Z = 1$, then $y^{(0)} = 0.06125P_{pr}te^{-1.2(1-t)^2}$.
Step 2. Calculate F(y) by equation (4).
Step 3. Calculate F'(y) by equation (5).
Step 4. Calculate new value of y by equation (6).
Step 5. Calculate in a circle until $F(y^k) \approx 0$, or $|y^{k+1} - y^k| < 0.00001$.
Step 6. Substitute y into equation (2) or equation (3), then Z will be calculated.

2.1.2 Static gas pressure model

By using the method of Cullender&Smith, static gas pressure can be calculated[19]. According to the energy equation of gas flow steadily, the integral equation of static gas can be educed:

$$\int_{P_{ws}}^{P_{ts}} \frac{ZT}{P} dp = \int_0^H 0.03415\gamma_g d_H$$

Set $I = \frac{ZT}{P}$, then it can be predigested as follows:

$$\int_{P_{ws}}^{P_{ts}} Idp \approx \frac{1}{2}[(P_1 - P_0)(I_1 + I_0) + (P_2 - P_1)(I_2 + I_1) + \cdots + (P_n - P_{n-1})(I_n + I_{n-1})]$$

where $I_n = (\frac{ZT}{P})_n$, $n = 0, 1, 2, \cdots, n$

The problem-solving ideas of this method which can be shown in Fig. 1 are as follows:

Divide the well depth H into two parts, that are wellhead to the midpoint(H/ 2) and the midpoint to bottom; put the first two of the above equation out

$$\int_{P_{ws}}^{P_{ts}} Idp \approx \frac{1}{2}[(P_{ms} - P_{ts})(I_{ms} + I_{ts}) + (P_{ws} - P_{ms})(I_{ws} + I_{ms})]$$

In order to calculate P_{ws}, first we have to calculate pressure P_{ms} on the midpoint by the known parameters of wellhead, then calculate pressure P_{ws} on the bottom by the known parameters of midpoint, that means the well will be divided into two wells of upper and lower, and will be calculated separately. For upside of the gas pipe:

$$0.03415\gamma_g H = (P_{ms} - P_{ts})(I_{ms} + I_{ts}) + (P_{ws} - P_{ms})(I_{ws} + I_{ms})$$

For underside of the gas pipe:

$$0.03415\gamma_g H = (P_{ws} - P_{ms})(I_{ws} + I_{ms})$$

Then calculated P_{ms} and P_{ws} separately. For upside

$$P_{ms} = P_{ts} + 2 * 0.03415 \frac{\gamma_g H}{I_{ms} + I_{ts}} \tag{7}$$

whereI_{ms} and P_{ms} are unknown, they need to be calculated in iterative steps. For underside

$$P_{ws} = P_{ms} + 2 * 0.03415 \frac{\gamma_g H}{I_{ms} + I_{ws}} \tag{8}$$

whereI_{ms} and P_{ws} are unknown, they need to be calculated in iterative steps.

Then use iteration step in each section to calculate the pressure distribution.We set 2 meter as one section to calculate the pressure distribution of the static gas, take the following steps:

For upside of the gas pipe:

Step 1. Calculate $0.03415\gamma_g H$. (γ_g–gas relative density, H–the length of the upside of the gas pipe)

Step 2. Calculate I_{ts} of the wellhead. ($I = \frac{ZT}{P}$, Z–the compression factor; T–the absolute temperature, K; P–the pressure of the gas, MPa)

Step 3. To be the first approximative calculation, we suppose $I_{ms} = I_{ts}$.

Step 4. Calculate P_{ms} by the equation(7).

Step 5. Calculate I_{ms} in the middle by P_{ms} gained in Step 4.

Step 6. Calculate P_{ms} in a circle by the equation(7) until P_{ms} meets the precision.

For underside of the gas pipe:

Step 1. Suppose $I_{ms} = I_{ws}$.

Step 2. Calculate P_{ws} by the equation(8).

Step 3. Calculate I_{ws} by P_{ws} gained in Step 2.

Step 4. Calculate P_{ws} in a circle by the equation(8) until P_{ws} meets the precision.

($I_{ms} = \frac{Z_{ms}T_{ms}}{P_{ms}}$; $I_{ts} = \frac{Z_{ts}T_{ts}}{P_{ts}}$; $I_{ws} = \frac{Z_{ws}T_{ws}}{P_{ws}}$.)

Where:

P_{ms}– the unknown pressure on the midpoint, MPa; T_{ms}–the temperature on the midpoint, K; I_{ms}– I, under the condition of P_{ms}, T_{ms}, K/ MPa;

P_{ts}– the pressure on the wellhead, MPa; T_{ts}– the temperature on the wellhead, K; I_{ts}– I, under the condition of P_{ts}, T_{ts}, K/ MPa;

P_{ws}– the pressure on the bottom of well, MPa; T_{ws}– the temperature on the bottom of well, K; I_{ws}– I, under the condition of P_{ws}, T_{ws}, K/ MPa;

2.2 Temperature calculation model

After the wellbore was shut-in, gas in the wellbore will have heat exchange with the surrounding stratum because there are different temperatures between them. At that time, the temperature of wellbore gas is a function of depth and time. With the shut-in time be extended, the two of them will reach thermodynamic equilibrium state, and the temperature of wellbore gas will not change along with the time, it's only a function of depth. Iteration step was used to solve it. Fig. 2 shows the simplified model of Tubing.

$$T_j = \alpha h_j + T_0 \tag{9}$$

$$h_j = s_j \cos \varphi_j \tag{10}$$

Where:

α– Temperature gradient, h– Vertical depth of the wellbore, T_o– Surface temperature;

s_j– The j^{th} depth of the wellbore, φ_j– The j^{th} oblique angle of the wellbore.

2.3 Deformation length model

The deformation length model includes temperature deformation length calculation model and pressure deformation length calculation model.

2.3.1 Temperature deformation length model

We can get the formula of temperature deformation length by investigating and verifying the information[19]. The following equations are the temperature deformation length model.

$$U_T(s) = U_T(s_0) + \int_{s_0}^{s} \alpha[T(s) - T_0(s)]ds \tag{11}$$

In order to calculate the equation expediently, we change the equation(11) into the iteration step:

$$U_{T,j+1} = U_{T,j} + \alpha(T_j - T_0)\Delta s_j \tag{12}$$

2.3.2 Pressure deformation length model

We can get the formula of pressure deformation length by investigating and verifying the information[19]. The following equations are the pressure deformation length model.

$$U_P(s) = U_P(s_0) + \frac{2\mu}{E(A_o - A_i)}\left[A_o \int_{s_0}^{s} P_o(s)ds - A_i \int_{s_0}^{s} P_i(s)ds\right] \tag{13}$$

In order to calculate the equation expediently, we change the equation(13) into the iteration step:

$$U_{P,j+1} = U_{P,j} + \frac{2\mu_j}{E_j(A_{o,j} - A_{i,j})}(A_{o,j}P_{o,j} - A_{i,j}P_{i,j})\Delta s_j \tag{14}$$

Where:

μ– The Poisson's ratio, E– Modulus of elasticity; $A_{o,j}$– Outer-cylindrical area, $A_{i,j}$– Inner- cylindrical area; $P_{o,j}$– The pressure of outer liquid, $P_{i,j}$– The pressure of inner liquid.

3 Software implementation and case analysis

After comprehensive analyzed the mathematical model, the arithmetic can be calculated by C# language software programming. The calculation results can be shown clearly through the design of software interface, and the curves of the calculation results by C# programming language was realized. Users can observe the wellbore state directly in order to guide their practical work. The main objective of this section is to introduces the integral designing of the models and the process of programming through Visual C# 2005 & SQL server 2000 database.

3.1 Interface design

The procedures were established based on forms under Visual C# 2005, and the corresponding controls were added in forms. Interface design includes basic information interface, data calculation interface, and the interface of derived report forms. The basic information interface is a form about the basic information of the wellbore to be tested. In this paper, the Da Well No.1, 5160 meters of depth in Sichuan are used for case history calculation. Fig. 3 shows the basic information interface. The data calculation interface is a form about the display of the calculated data. Users can see the data result through this interface. The interface of derived report forms is a form about the display of the reports. Users can see data report and curve report, and save it if they want through this interface.

According to the model given above, a calculation program was developed. We use the test data of the Da Well No.1 in Sichuan as the actual data analysis. Tab. 1 is the datasheet of the thimble. Tab. 2 is the datasheet of the gas pipe. Tab. 3 is the datasheet of the wellbore collection point data. Fig. 4 shows the basic data of shut-in wellbore.

Table 1. Tubing data

diameter(m)	cement radius(m)	use length(m)
88. 9	6. 45	4220
73. 02	5. 51	940

Table 2. Casing data

outside diameter(m)	inside diameter(m)	use length(m)
177. 8	144. 9	326. 96
177. 8	151. 6	201. 85
177. 8	153. 9	303. 73
177. 8	153. 9	1761. 61
177. 8	153. 9	44. 69
177. 8	149. 3	1732. 66
177. 8	149. 3	210. 04
177. 8	151. 6	578. 46

Table 3. Wellbore collection point data

serial number	oblique angle (degrees)	well depth (m)	vertical depth (m)	serial number	oblique angle (degrees)	well depth (m)	vertical depth (m)
1	0	0	0	14	2. 8	998. 05	997. 86
2	0. 69	19. 37	19. 37	15	3. 19	1258. 13	1257. 53
3	0. 7	74. 73	74. 72	16	5. 78	1719. 95	1718. 08
4	0. 83	132. 55	132. 54	17	14. 95	2870. 47	2859. 47
5	0. 71	247. 67	247. 65	18	21. 21	3043. 42	3021. 29
6	1. 01	334. 16	334. 30	19	24. 61	3418. 78	3370. 58
8	0. 65	420. 87	420. 84	20	24. 64	3562. 95	3501. 01
9	0. 7	536. 39	536. 35	21	22. 69	3706. 98	3634. 64
10	0. 75	565. 27	565. 23	22	33. 74	4168. 68	4045. 52
11	0. 76	622. 98	622. 93	23	29. 8	4635. 08	4444. 09
12	0. 74	709. 16	709. 10	24	14. 9	4910	4707. 9
13	1. 35	824. 9	824. 83	25	13	5160	4945. 51

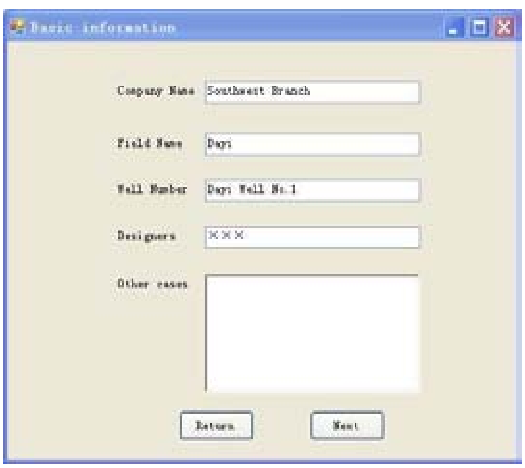


Fig. 3. The basic information interface

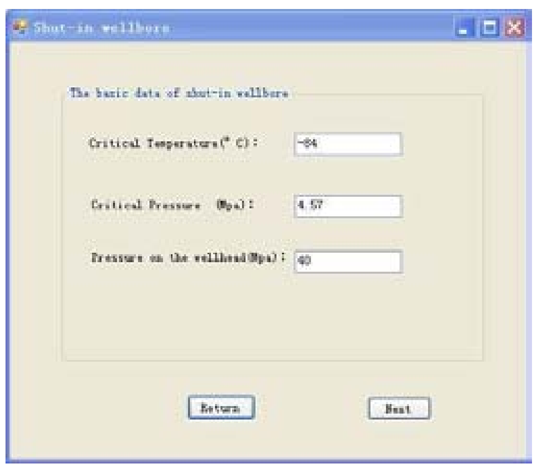


Fig. 4. The basic data of shut-in wellbore

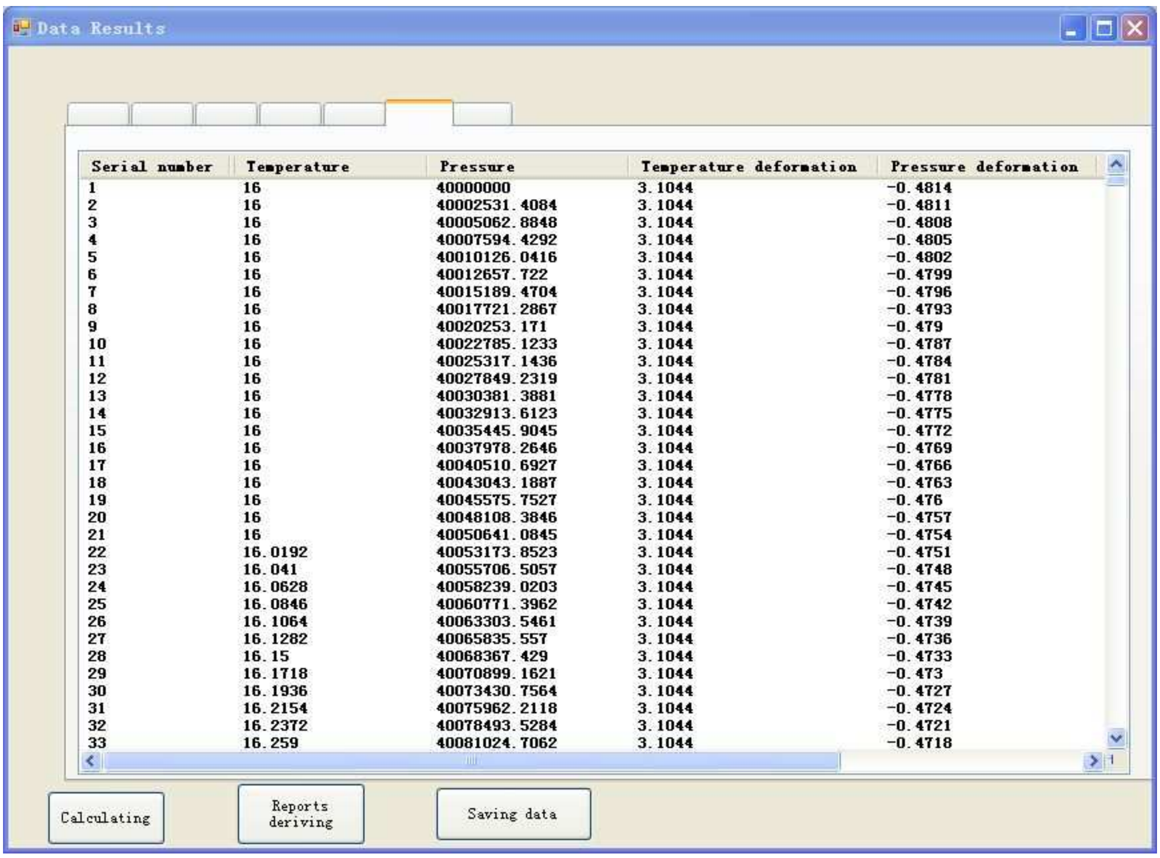
3.2 Database establishment

We use SQL Server 2000 database to establish the database and datatables. Database "jieguo" was established firstly, then datatable "guanjing" and "guanjing1" were established in it. Table "guanjing" was used to save all the data, while table "guanjing" only to save the the relevant data with the curves. There are five columns in each table, they are the serial number, temperature distribution, pressure distribution, temperature deformation length, pressure deformation length.

We joint the outlook interface together with the background database through compilation of the code in programme. The code is: string cons = "Persist Security Info = false; Data Source = .; Initial Catalog = jieguo; User ID = sa; Password = sql", where "jieguo" stands for database name, "sa" means the user name, "sql" means the password.

3.3 Function realization

This calculational module can be realized in the design of three major functional statements, that are data calculation, data saving and reports deriving. Click on the "Calculating" button in the data calculation interface, it will show results. Fig. 5 shows it. Click on the "Saving data" button, results of the data will be stored in the corresponding datatables in database. Click on the "Reports deriving" button, it will pop up a new form, in which the temperature and pressure distribution curves can be derived and displayed, and the data saved in the database also can be derived and displayed expediently.



Serial number	Temperature	Pressure	Temperature deformation	Pressure deformation
1	16	40000000	3.1044	−0.4814
2	16	40002531.4084	3.1044	−0.4811
3	16	40005062.8848	3.1044	−0.4808
4	16	40007594.4292	3.1044	−0.4805
5	16	40010126.0416	3.1044	−0.4802
6	16	40012657.722	3.1044	−0.4799
7	16	40015189.4704	3.1044	−0.4796
8	16	40017721.2867	3.1044	−0.4793
9	16	40020253.171	3.1044	−0.479
10	16	40022785.1233	3.1044	−0.4787
11	16	40025317.1436	3.1044	−0.4784
12	16	40027849.2319	3.1044	−0.4781
13	16	40030381.3881	3.1044	−0.4778
14	16	40032913.6123	3.1044	−0.4775
15	16	40035445.9045	3.1044	−0.4772
16	16	40037978.2646	3.1044	−0.4769
17	16	40040510.6927	3.1044	−0.4766
18	16	40043043.1887	3.1044	−0.4763
19	16	40045575.7527	3.1044	−0.476
20	16	40048108.3846	3.1044	−0.4757
21	16	40050641.0845	3.1044	−0.4754
22	16.0192	40053173.8523	3.1044	−0.4751
23	16.041	40055706.5057	3.1044	−0.4748
24	16.0628	40058239.0203	3.1044	−0.4745
25	16.0846	40060771.3962	3.1044	−0.4742
26	16.1064	40063303.5461	3.1044	−0.4739
27	16.1282	40065835.557	3.1044	−0.4736
28	16.15	40068367.429	3.1044	−0.4733
29	16.1718	40070899.1621	3.1044	−0.473
30	16.1936	40073430.7564	3.1044	−0.4727
31	16.2154	40075962.2118	3.1044	−0.4724
32	16.2372	40078493.5284	3.1044	−0.4721
33	16.259	40081024.7062	3.1044	−0.4718

Fig. 5. The data calculation interface

The derived curves and data were realized by Crystal Reports under Visual C#. Crystal Reports for Visual Studio. NET is an integral part of Visual Studio. NET. It can display data and show charts to users. Users can export the reports for the format of Microsoft Word and Excel, and other format of files, like PDF(Portable Document Format), HTML(Hyper Text Markup Language) or Crystal Reports for Visual Studio. NET.

The use of Crystal Reports in Windows forms are as follows: New windows item, adding Crystal Report Viewer Control, adding the "Shut-in wellbore" button and "Shut-in chart" button, and adding button response incident. We use Push mode to identify data sources, joint the database through compilation of the code, set up a dataset and save the data to it, then sent it to the reports. Then Crystal Report Viewer will display data and curves clearly. Fig. 7 shows the curve of temperature deformation length. Fig. 6 shows the curve of pressure deformation length.

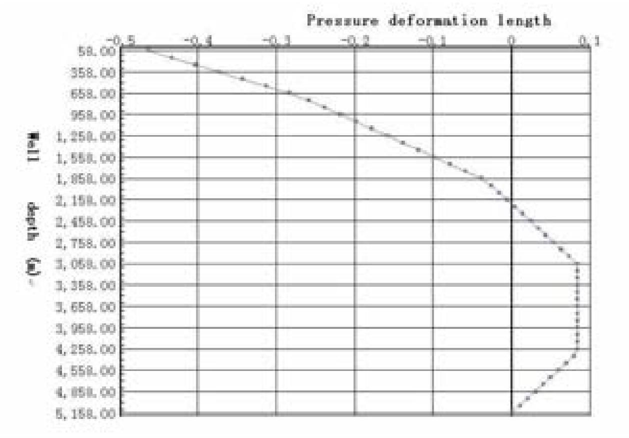


Fig. 6. The curve of pressure deformation length

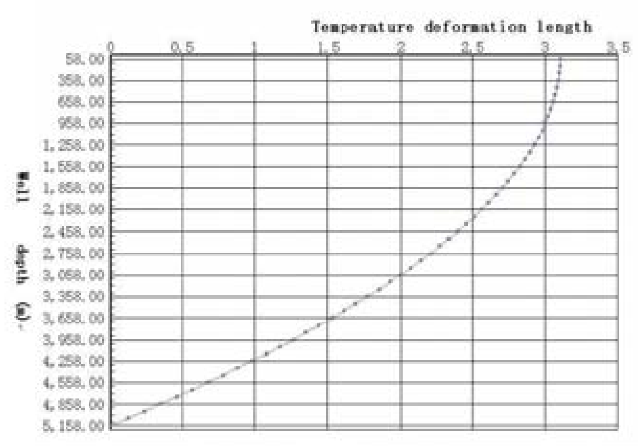


Fig. 7. The curve of temperature deformation length

4 Conclusion

This paper mainly studies the model design and software implementation of the gas well in the state of shut-in phase. The article is divided into two parts, the first part is the design and analysis of mathematical models, the latter part is the algorithm realization of models. The chapters of models mainly introduce the temperature distribution model, pressure distribution model and deformation length model. The detailed analysis of these calculation models are also introduced. The chapters of software realization mainly introduce the interface design of models. The algorithm and curves are realized through Visual C# 2005 and SQL server 2000, so that the calculation results can be showed more directly and clearly. Through the complete integration of models and software, the models showed that they can effectively simulate the temperature and pressure distributions. With the simulation result, users will find issues in the process of production, and correct them promptly to prevent the occurrence of accidents and better guide practice.

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