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Development of a Software for Some Applications of Superposition Principle in Well Testing

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Abstract

This paper presents an interactive computer program that uses Visual Basic 11.0 programming language to develop user friendly and efficient software for application of superposition principle in well testing and analysis.A flow chart was created to outline the basic steps employed in the development of the software. Several user-friendly forms were designed for input and output of parameters and efficient codes were created for fast calculation of the desired output. Result showed that this software can satisfactorily compute for pressure drop, total pressure drop and sandface pressure for all cases of applications of superposition principle considered (multiple wells, variable flow rates, boundary effects and pressure change). Validation of the software showed that results had acceptable level of accuracy, this work provides a basis for development of a suite of well testing software that are problem specific, cheap, user friendly and fast.

1. Introduction

Well testing has proved to be one of the most reliable tools to evaluate flow characteristics and features of a well-reservoir flow system[1,2,3]. The superposition principle which has been used to solve a variety of problems over the years in the sciences, states that any sum of solutions to a linear differential equation is also a solution to that equation .[4] In reservoir engineering superposition principle states that the total pressure drop at any point in a reservoir is equal to the sum of the pressure drops at that point caused by flow in each of the wells in the reservoir [5,6]. Its application has resulted in eradicating the limitations of solutions to the diffusivity equations where there are constraints of only one well, infinite reservoir and a constant flow rate. Hence, the pressure at any point (ΔP), total pressure drop $(\Delta P)_{total}$ and sandface pressure (P_{wf}) can be evaluated for situations where there are multiple wells in the reservoir, variable rates, presence of a fault or boundary[7]. The process of manually computing the solution for these cases is time-consuming, tedious and may yield confusing or erroneous results, hence a fast and efficient method is key.

Software programs have become increasingly important in the oil and gas sector over the last few decades since they are employed in parameter estimation, modelling and simulation processes[8,9]. These software developed with programming languages like Java, C^{++}, Python and Visual Basic, often times are costly and may not be easily accessible. This study attempts to provide a cost effective and efficient computerized process that can generate accurate pressure response of the wells to facilitate quick and easy analysis and prediction.

1.1 Mathematical Expressions

a) ***Multiple Well Effect***: [7] The equation for accounting for effect of multiple wells(three wells) is given by:

$$\left(p_i - p_{wf}\right) = \left(\Delta p\right)_{well1} = \frac{162.6 Q_{o1} B_o \mu_0}{kh}\left[\log\left(\frac{kt}{\phi\mu c_t r_w^{\,2}}\right) - 3.23 + 0.87S\right] \quad (1)$$

$$\left(\Delta p\right)_{drop\ due\ to\ well\ 2} = p_i - p\left(r_1, t\right) = -\left[\frac{70.6 Q_{o2}\mu_o B_o}{kh}\right]\times E_i\left[\frac{-948\phi\mu_o c_t r_1^2}{kt}\right] \quad (2)$$

$$\left(\Delta p\right)_{dropduetowell3} = p_i - p\left(r_2, t\right) = -\left[\frac{70.6 Q_{o3}\mu_o B_o}{kh}\right]\times E_i\left[\frac{-948\phi\mu_o c_t r_2^2}{kt}\right] \quad (3)$$

$$\left(p_i - p_{wf}\right)_{totaldropatwell1} = \frac{162.6 Q_{o1} B_o \mu_0}{kh}\left[\log\left(\frac{kt}{\phi\mu c_t r_w^{\,2}}\right) - 3.23 + 0.87S\right] \quad (4)$$

$$-\left(\frac{70.6 Q_{o2} B_o \mu_o}{kh}\right) E_i\left[\frac{-948\phi\mu c_t r_1^2}{kt}\right] - \left(\frac{70.6 Q_{o3} B_o \mu_o}{kh}\right) E_i\left[\frac{-948\phi\mu c_t r_2^2}{kt}\right] \quad (5)$$

b) ***Variable Flow Rate Effect***: Superposition can be applied for conditions with several rate changes because every flow rate change in a well will result in a pressure response that is independent of the pressure reactions induced by previous rate changes. Equations used to model a well with several rate changes (unsteady state flow condition) are as follows: [7]

$$\left(\Delta p\right)_{total} = \left(\Delta p\right)_{due\ to\,(Q_1-0)} + \left(\Delta p\right)_{due\ to\,(Q_2-Q_1)} + \left(\Delta p\right)_{due\ to\,(Q_3-Q_2)} + \left(\Delta p\right)_{due\ to\,(Q_4-Q_3)} \quad (6)$$

$$\left(\Delta p\right)_{Q_1-0} = \left[\frac{162.6\left(Q_1 - 0\right)B\mu}{kh}\right]\times\left[\log\left(\frac{kt_4}{\phi\mu c_t r_w^{\,2}}\right) - 3.23 + 0.87S\right] \quad (7)$$

$$\left(\Delta p\right)_{Q_2-Q_1} = \left[\frac{162.6\left(Q_2 - Q_1\right)B\mu}{kh}\right]\times\left[\log\left(\frac{k\left(t_4 - t_1\right)}{\phi\mu c_t r_w^{\,2}}\right) - 3.23 + 0.87S\right] \quad (8)$$

$$\left(\Delta p\right)_{Q_3-Q_2} = \left[\frac{162.6\left(Q_3 - Q_2\right)B\mu}{kh}\right]\times\left[\log\left(\frac{k\left(t_4 - t_2\right)}{\phi\mu c_t r_w^{\,2}}\right) - 3.23 + 0.87S\right] \quad (9)$$

$$\left(\Delta p\right)_{Q_4-Q_3} = \left[\frac{162.6\left(Q_4 - Q_3\right)B\mu}{kh}\right]\times\left[\log\left(\frac{k\left(t_4 - t_3\right)}{\phi\mu c_t r_w^{\,2}}\right) - 3.23 + 0.87S\right] \quad (10)$$

Where t_1 t_2 t_3 t_4 = time corresponding to rate changes (hours)

c) Reservoir Boundary Effect: The pressure of a well in a constrained (bounded) reservoir can also be predicted using the superposition theorem method sometimes known as the method of images. This is achieved by placing an image well at a double distance from the actual well and its effect(pressure drop) determined. For the case of a well located in between two faults the following equations applies [7].

$$(p - p_{wf}) = (\Delta p)_{actual} = \frac{162.6 Q_0 B_0 \mu_0}{kh}\times\left[\log\left[\frac{kt}{\phi\mu c_t r_w^{\,2}}\right] - 3.23 + 0.87S\right] \quad (11)$$

$$(\Delta p)_{image\ well\,1} = (p_1 - p)(2L_1, t) = \left[\frac{-70.6 Q_o \mu_o B_o}{kh}\right] E_i\left[\frac{-948\phi\mu c_t (2L_1)^2}{kt}\right] \quad (12)$$

$$(\Delta p)_{image\ well\,2} = (p_1 - p)(2L_2, t) = \left[\frac{-70.6 Q_o \mu_o B_o}{kh}\right] E_i\left[\frac{-948\phi\mu c_t (2L_2)^2}{kt}\right] \quad (13)$$

$$\left(\Delta p\right)_{total} = \left(\Delta p\right)_{Actual} + \left(\Delta p\right)_{Due\ to\ image\ well1} + \left(\Delta p\right)_{Due\ to\ image\ well\ 2} + \cdots\cdots \quad (14)$$

Where L_1, L_2 = distance from boundary to $well_1$ and $well_2$ (ft)

c) ***Pressure Change Effect***: In order to determine the total water influx into a reservoir at any given time, it is necessary to determine the water influx as a result of each successive pressure drop that has been imposed on the reservoir and aquifer (Van Everdingen and Hurst water influx model) which is essentially an application of the principle of superposition [7].

$$\frac{\partial p_D}{\partial r_D} + \frac{1}{r_D}\frac{\partial P_D}{\partial r_D} = \frac{\partial P_D}{\partial t_D} \qquad (15)$$

Dimensionless radius $r_D = \frac{r_a}{r_e}$ (16)

Dimensionless Pressure $P_D = \frac{(p_i - p)}{p_i - p_{wf}}$ (17)

Total Compressibility $c = c_w + c_f$ (18)

Dimensionless time: $t_D = 0.0002637\frac{kt}{\phi \mu c_t r^2}$ (19)

The total cumulative water influx can be calculated using

$$W_e = (W_e)_{\Delta p1} + (W_e)_{\Delta p2} + (W_e)_{\Delta p3} + ...(We_{\Delta pn}) \qquad (20)$$

Where;

$$(W_e)_{\Delta p1} = B\Delta p_1 (W_{eD})_{t_3} \qquad (21)$$

$$(W_e)_{\Delta p2} = B\Delta p_2 (W_{eD})_{t_3 - t_1} \qquad (22)$$

$$(W_e)_{\Delta p3} = B\Delta p_3 (W_{eD})_{t_3 - t_2} \qquad (23)$$

The van Everdingen and Hurst water influx relationship can be expressed in a more generalized form as

$$W_e = B\Sigma \Delta p W_{eD} \qquad (24)$$

$B = 1.119\phi c_t r_e^2 h$ (25)

If the water encroaches in a radial form then the encroachment angle is computed using

$$f = \frac{\theta}{360} \qquad (26)$$

And the constant becomes

$$B = 1.119\phi c_t r_e^2 hf \qquad (27)$$

2.0 Materials and Methods

2.1 Materials: This research was done using Visual Studio 2019, Mathtype 5.1, Lenovo laptop (Intel(R) Core (TM) i5-8265U CPU @ 1.60GHz, 1.80 GHz 8.00 GB RAM), MS Word

***2.2 Methodology*:** Relevant mathematical equations were presented for the four areas of applications of Superposition Principle in well testing treated in this study. A simplified flowchart showing the steps of the program was developed as shown in Figure 1. Graphical User Interfaces (GUI forms) were designed for ease, simplicity and accuracy of execution of the application software. Codes for the program's implementation were created with the mathematical equations for all cases of applications using Visual Basic programming language [10]. It is an object-oriented programming language that supports rapid application development (RAD) and provides easy means of developing efficient programs[11,12,13]. The software's validation was done to ascertain the efficiency and accuracy of the software using numerous examples.

2.3 Programs Design and Development

The visual basic integrated development environment(IDE) has programming tools and windows for efficient programs development. The typical steps involved in developing this program includes

1. Create the project (a windows application and name it)
2. Design the graphical user interface forms by adding controls and defining their properties in the property window
3. Create the codes (in the codes window)
4. *Debug and run(test)*

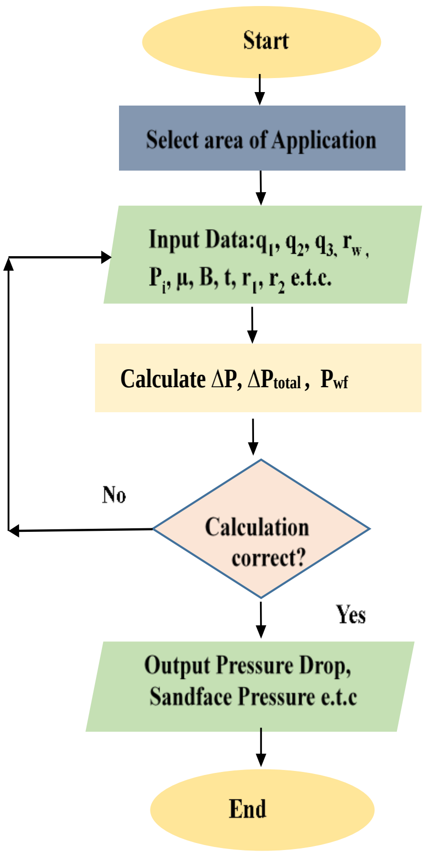

Figure 1: Simplified flow chart for the program

The software OVERLAY has five forms, each uniquely designed for simplicity and ease to achieve a specific objective. The graphical user interface of all but the start page forms has some similar design characteristics, each has controls like labels, textboxes (for input and output) and command buttons. Also there are container tools to group and separate input and output parameters. Clear and back buttons (that refreshes all input / output data and enables the user to navigate to the start page respectively) are also a common design feature .The first form introduces the program as shown in Figure 2, it provides a pathway to navigate to other forms when a user selects an option. Form 2 uses equations 1 to 5 to create the codes to compute for pressure drop and sandface pressures (multiple producing wells) in the reservoir, in this case three wells were considered. Form 3 was designed for input of data, calculations and output of results, for computation of variable rate effects, codes were written using equations 6 to 10. The case considered was for four rate changes (Q_1, Q_2 , Q_3 , Q_4) in a well with corresponding time (t_1, t_2, t_3, t_4).

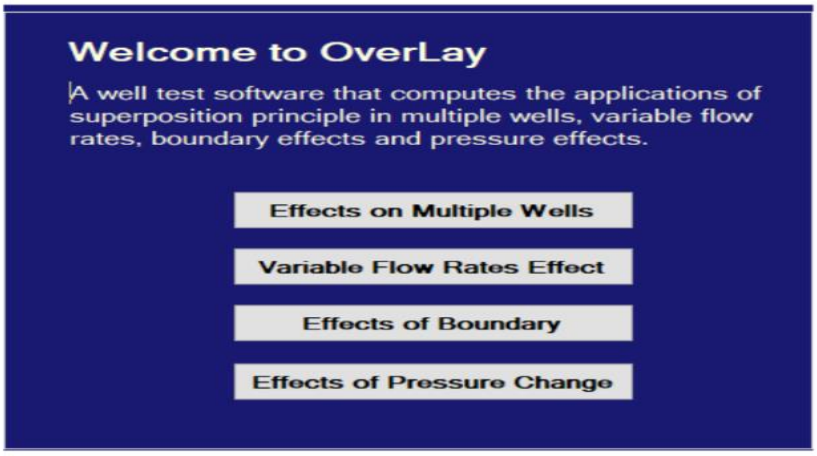

Figure 2: Screenshot of Start page

Form 4 was designed to compute the pressure drop and the sand face pressure where a well is located close to a boundary or boundaries. Equations 11 to 14 were employed in developing the codes for the program.Form 5 design in a unique way as it requires a data table for input and also an output table for the results. Employing equations 15 to 27 codes were written for pressure change effects (water influx). All data involved in the computations were declared using visual basic syntax in the codes window and converted using type conversion function. Employing various subroutine and subprograms, the software calculates the pressure drops (ΔP), the total pressure drop (ΔP_{total}) and the bottom hole flowing pressure (P_{wf}) for all cases but that of pressure change effect, where it further computes the water influx and cumulative water influx.

3.0 Results and Discussion

In order to test the program, example problems were used to demonstrate its efficiency for all four cases considered in this work (data in Table1).

Table 1: Data for example problems for all the cases.

Properties	Multiple wells	Variable rate	Boundary effects	Pressure change Effects
Initial reservoir pressure, Pi (psi)	4500	5000	5200	-
Pay Thickness, h (ft)	25	25	20	25
FVF, Bo (bbl/STB)	1.25	1.12	1.12	-
Porosity, ϕ (%)	15	15	15	20
Viscosity, μ (cp)	2	3	3	0.8
Compressibility, C_t (Psi^{-1})	$20x10^{-6}$	$20x10^{-6}$	$25x10^{-6}$	$30x10^{-6}$

Wellbore radius, r_w (ft)	0.25	0.2	0.25	-
Permeability, k (md)	45	45	55	10
t_1, t_2, t_3, t_4 (hrs)	-	3, 6, 12, 18	-	-
t_1, t_2, t_3, t_4 , t_5 (days)				0, 185.2, 365, 547, 730
Q_1, Q_2, Q_3, Q_4 (STB/day)	150, 200, 240	100, 70, 150, 85	150	-
t (hours)	15	-	15	-
Skin, S	-0.5	0	1	-
Distance to well r_1, r_2, (ft)	450, 600	-	-	200ft
Length L_1 , L_2 (ft)	-	-	100, 200	-
Compressibility of water c_w (Psi^{-1})				$70x10^{-6}$
Pressure(psi,(@ t_1 ,t_2 , t_3 t_4, t_5)	-	-	-	2500, 2490, 2472, 2444, 2408

Figure 3: Results for Case1, presence of multiple wells

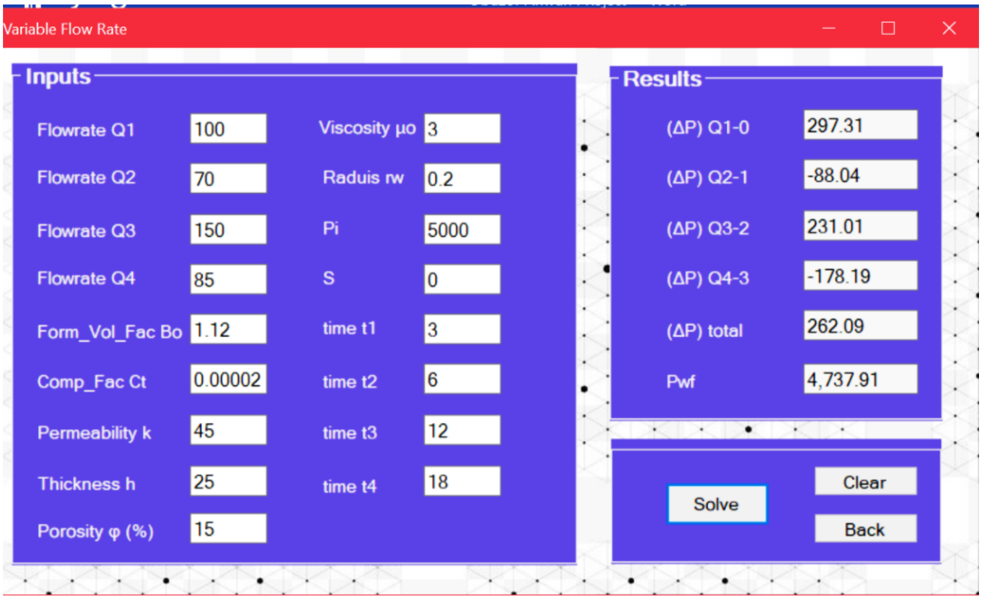

Figure 4: Output results for case 2, variable flow rate

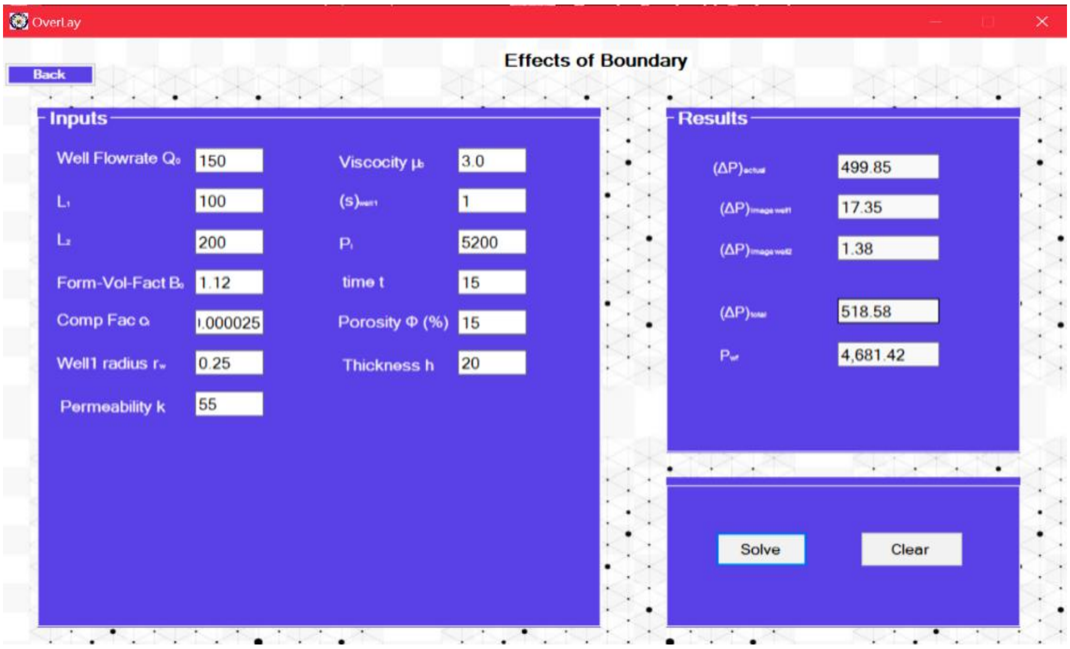

Figure 5: Screenshot of results for case 3, boundary effects

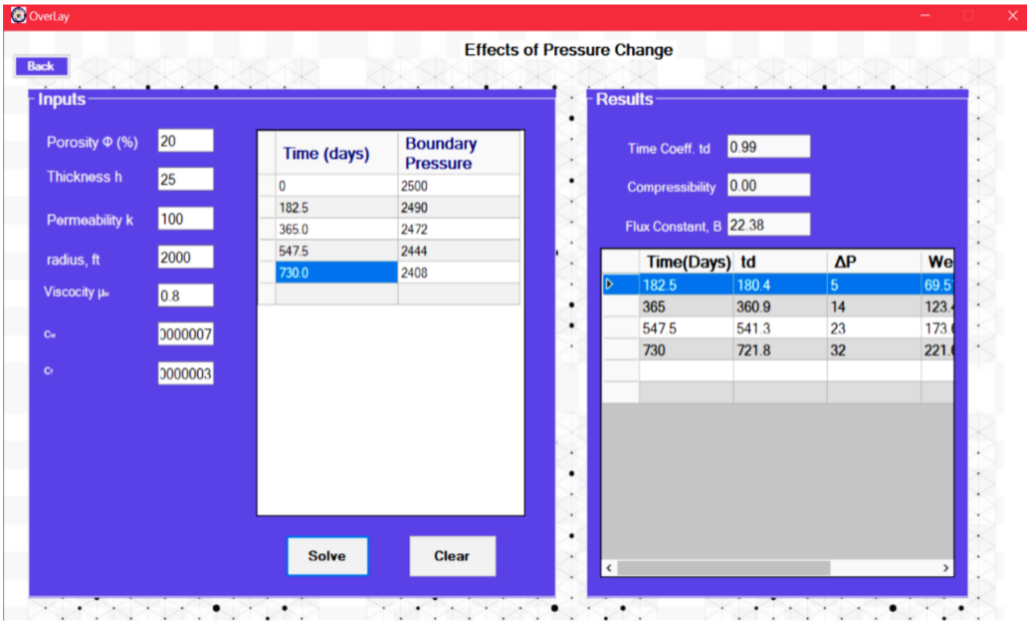

Figure 6a: Screenshot of output results for Pressure change effect

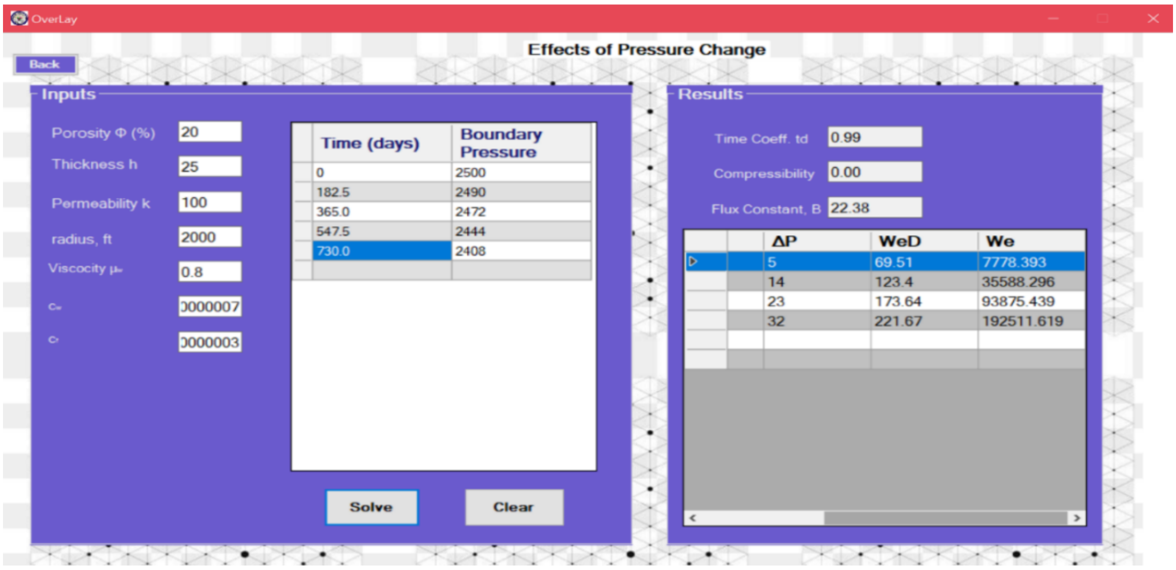

Figure 6b: Screenshot of output results for Pressure change effect continued.

Table 2: Validation

Application in Well Testing	Ahmed Tarek [7]	Mustafa et al. [14]	OVERLAY Software	Error %
Multiple Wells	4225.31	-	4226.43	2.7×10^{-4}
Variable Flow Rates	4716.51	-	4717.80	2.7×10^{-4}
Boundary	4718.20	-	4718.30	2.11×10^{-5}
Pressure change (We at end of 24 months)	-	190410	192511.62	1.1×10^{-2}

For the case of multiple wells, three wells produced at different but constant flow rates from an infinite acting reservoir for 15 hours, having other input data as shown in Table 1, computation of sandface pressure is required. The software quickly calculates the pressure drop (ΔP) at well one due to its own production (reference well) and additional ΔP from the other 2 wells (well two and well three). It then outputs ΔP_1, ΔP_2 and ΔP_3 (302.99psi, 2.31psi and 0.49psi) for each well, ΔP_{total} (305 .79psi) and P_{wf} (4194.21psi) as shown in Figure 3. All wells in reality produce at varying flow rates hence for each rate change the pressure behavior of the well can be predicted. For the case of varying flow rates, a well producing under transient flow condition with four rate changes at different times for 18 hours is considered. Utilizing sets of flow rate -time sequence, well/reservoir and fluid data in Table1, the software computes and outputs results of each ΔP (297.31psi, -88.04psi, 231.01psi and -178.19psi) for rate changes from Q_1 to Q_2, Q_3 and Q_4, ΔP_{total} (262.09psi) and P_{wf} (4737.91psi) as shown in Figur4.The presence of a boundary/fault always affects the pressure behavior of the well as it results in greater pressure drops. The case of a well located in between two sealing faults produced at constant flow rate under unsteady state flow condition was considered. In order to calculate the sandface pressure the contributions of pressure drop due to the actual well, the first fault (image well 1), the second fault (image well 2) are computed. Figure 5 shows output results as $\Delta P_{actual\ well}$(499.85psi), $\Delta P_{imagewell1}$ (17.35psi), $\Delta P_{image\ well2}$ (1.38psi), ΔP_{total} (518.58psi) and P_{wf} (4681.42psi). Effect of Pressure change was investigated using the case of an aquifer reservoir system, the water influx (Van Everdingen and Hurst model) as a function of time and pressure was determined. Input data includes time pressure history, reservoir rock and fluid properties as shown in Table 1. Results are shown in Figure 6a and Figure 6b.

3.1 ***Software Validation:*** Results for cases of multiple wells, variable flow rates and boundary effects were compared with analytical solutions given by Ahmed Tarek [7] and the average error was negligible (0.00027%). Mustafa et al(14) used MATLAB to develop a program to calculate waterinflux using the Van Everdingen and Hurst computational procedure (pressure change effect), results from this work compares well with theirs (small error) as shown in Table 2.

4. Conclusion

In this work a software program was designed and developed using visual basic programming language for applications of the principle of superposition. Relevant equations were presented, a flow chart was created and friendly graphical user interfaces (forms) were designed to provide a visual platform for interaction with the program. Codes were created using various tools available in Visual basic IDE (integrated development environment). The developed software is problem specific, it reduces the complexity involved in the computations of pressure drop and sand face pressure when analyzing and computing for the effects of the presence of multiple wells, variable rates, boundary and pressure changes in the well and reservoir. The efficiency of the software was seen in numerous examples problem that were solved in a fast and easy manner. The accuracy of the program was highlighted by validation results. The program's structure is flexible and can be updated. The results from this study could provide a platform for the development of software suites in reservoir engineering.

Nomenclature

Δp	Pressure drop (psi)
B	Water influx constant (bbl/psi)
B_o	oil formation volume factor (bbl /STB),
c_f	Formation compressibility (psi^{-1})
c_t	Total compressibility coefficient(psi^{-1}),
Ei	Exponential integral function

k	Permeability(md)
h	Thickness (ft)
S	Skin factor,
P_D	Dimensionless pressure
r_D	Dimensionless radius
P_i	Initial reservoir pressure, (psi)
p_{wf}	Wellbore flowing pressure(psi)
Q_o	Oil flow rate (bbl/day)
Q_{o1}, Q_{o2}, Q_{o3}, Q_{o4}	Oil flow rate change in 1, 2, 3, 4 sequence (bbl/day)
r_1, r_2	Distance from wells to the reference point.
r_a	Aquifer radius (ft)
r_e	Reservoir radius (ft)
r_w	Well radius (ft)
t_D	Dimensionless time
t_1, t_2, t_3, t_4	Time for corresponding rate changes (days)
t	Time (hrs)
W_e	Cumulative water influx (bbl)
W_{eD}	Dimensionless water influx

Greek letters

μ	Viscosity, cp
ϕ	Porosity, fraction
θ	Angle, degrees
f	Encroachment angle

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