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- (54) **Title:** DETECTION OF PERMEABILITY ANISOTROPY IN THE HORIZONTAL PLANE WITH A FORMATION TESTING TOOL

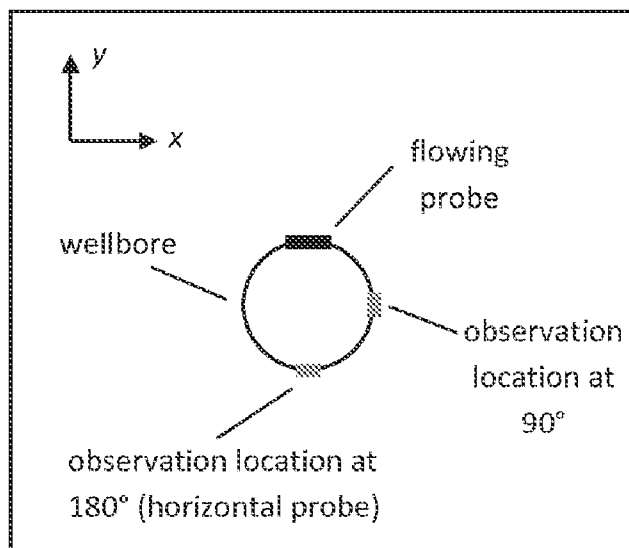


FIG. 1

(57) **Abstract:** A method including positioning a formation testing tool within a wellbore formed within a subsurface reservoir, wherein the tool has a focused opening to enable fluid communication with the reservoir, and the tool has a horizontally-displaced observation probe configured to obtain pressure data; determining one of horizontal permeability and horizontal mobility of the reservoir based on measuring a flow response of the subsurface reservoir one of at and adjacent to the observation probe; and determining orthogonal components of one of the horizontal permeability and horizontal mobility based on the measured flow response.



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DETECTION OF PERMEABILITY ANISOTROPY IN THE HORIZONTAL PLANE WITH A FORMATION TESTING TOOL

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority as a Patent Cooperation Treaty patent application of United States Non-Provisional Patent Application Serial Number 13/923,220 filed June 20, 2013 with the same title.

FIELD OF THE INVENTION

[0002] Aspects described relate to testing of geological formations. More specifically, aspects disclosed relate to testing for anisotropy in the horizontal plane with a formation testing tool.

BACKGROUND INFORMATION

[0003] Formation testing tools with discrete openings, such as a multi-probe module, can withdraw formation fluid in a focused direction. With the multi-probe module, formation pressure can be monitored at the flowing probe and two or more observation probes, one positioned on the opposite side of the borehole on the same horizontal plane as the sink probe and others displaced vertically on the same azimuthal plane as the sink probe.

[0004] Permeability determination with the multi-probe module has received considerable attention. In particular, the detection and quantification of permeability anisotropy in the horizontal-vertical plane, k_h/k_v has been studied. The detection and quantification of permeability anisotropy within the horizontal plane has received no attention. Knowledge of such anisotropy can be critical for optimum design of reservoir drainage patterns, secondary and tertiary recovery projects, and stimulation treatments, to name but a few examples. Anisotropy within the horizontal plane usually creates three-dimensional anisotropy, with vertical permeability differing from both components (k_x and k_y) of horizontal permeability.

SUMMARY

[0005] A method comprising positioning a formation testing tool within a wellbore formed within a subsurface reservoir is described, wherein the tool has a focused opening to enable fluid communication with the reservoir, and the tool has a horizontally-displaced observation probe configured to obtain pressure data; determining one of horizontal permeability and horizontal mobility of the reservoir based on measuring a flow response of the subsurface reservoir one of at and adjacent to the observation probe; and determining orthogonal components of one of the horizontal permeability and horizontal mobility based on the measured flow response.

BRIEF DESCRIPTION OF THE DRAWINGS

[0006] FIG. 1 shows the x and y coordinate plane of a wellbore with associated flowing probe and two observation locations.

[0007] FIG. 2 is a plot of pressure change and derivative at the flowing probe, numerical and analytical models.

[0008] FIG. 3 is a plot of pressure change at the flowing probe, numerical and analytical models.

[0009] FIG. 4 is a plot of pressure change and derivative at the 180 deg horizontal probe, numerical and analytical models.

[0010] FIG. 5 is a plot of pressure change at the 180 deg horizontal probe, numerical and analytical models.

[0011] FIG. 6 is a plot of pressure change and derivative at the vertical probe, numerical and analytical models.

[0012] FIG. 7 is a plot of pressure change at the vertical probe, numerical and analytical models.

[0013] FIG. 8 is a plot of pressure change and derivative at the flowing probe, numerical model, 3D anisotropy.

[0014] FIG. 9 is a plot of pressure change at the flowing probe, numerical model and 3D anisotropy.

[0015] FIG. 10 is a plot of pressure change and derivative at the 180 deg horizontal probe, numerical model, and 3D anisotropy.

[0016] FIG. 11 is a plot of pressure change at the 180 deg horizontal probe numerical model, 3D anisotropy.

[0017] FIG. 12 is a plot of pressure change and derivative at 90 deg horizontal probe, numerical model, 3D anisotropy.

[0018] FIG. 13 is a plot of pressure change at 90 deg horizontal probe, numerical model, 3D anisotropy.

[0019] FIG. 14 is a plot of pressure change and derivative at the vertical probe, numerical model, 3D anisotropy.

[0020] FIG. 15 is a plot of pressure change at the vertical probe, numerical model, 3D anisotropy.

[0021] FIG. 16 is a plot of pressure change and derivative at the flowing probe, sensitivity to 3D anisotropy.

[0022] FIG. 17 is a plot of pressure change at the flowing probe, sensitivity to 3D anisotropy.

[0023] FIG. 18 is a plot of pressure change and derivative at the 180 deg horizontal probe, sensitivity to 3D anisotropy.

[0024] FIG. 19 is a plot of pressure change at 180 deg horizontal probe sensitivity to 3D anisotropy.

[0025] FIG. 20 is a plot of pressure change and derivative at the 90 deg horizontal probe, sensitivity to 3D anisotropy.

[0026] FIG. 21 is plot of pressure change at the 90 deg horizontal probe, sensitivity to 3D anisotropy.

[0027] FIG. 22 is a plot of pressure change and derivative at vertical probe, sensitivity to 3D anisotropy.

[0028] FIG. 23 is a plot of pressure change at the vertical probe, sensitivity to 3D anisotropy.

[0029] FIG. 24 is a plot of pressure change and derivative at the flowing probe – effect of flowing probe alignment, isotropic horizontal permeability.

[0030] FIG. 25 is a plot of pressure change at the flowing probe – effect of flowing probe alignment, isotropic horizontal permeability ($k_x = k_y = 200$ md).

[0031] FIG. 26 is a plot of pressure change and derivative at the flowing probe, effect of flowing probe aligned at 45 degrees.

[0032] FIG. 27 is a plot of pressure change at the flowing probe, effect of flowing probe aligned at 45 degrees.

[0033] FIG. 28 is a plot of pressure change and derivative at the 180 deg horizontal probe (; effective of flowing probe aligned at 45 degrees.

[0034] FIG. 29 is a plot of pressure change at the 180 deg horizontal probe; effect of flowing probe aligned at 45 degrees.

[0035] FIG. 30 is a plot of pressure change and derivative at the 90 deg horizontal probe ; effect of flowing probe aligned at 45 degrees.

[0036] FIG. 31 is a plot of pressure change at the 90 deg horizontal probe; effect of flowing probe aligned at 45 degrees.

[0037] FIG. 32 is a plot of pressure change and derivative at the vertical probe; effect of flowing probe aligned at 45 degrees.

[0038] FIG. 33 is a plot of pressure change at the vertical probe; effect of flowing probe aligned at 45 degrees.

DETAILED DESCRIPTION

[0039] “Anisotropy” refers to a variation of a property with the direction in which the value is measured. Rock permeability is a measure of conductivity to fluid flow through pore space. Reservoir rocks often exhibit permeability anisotropy whereby conductivity to fluid depends on the direction of flow of the fluid. This is most often true when comparing permeability measured parallel or substantially parallel to the formation bed boundaries which may be referred to as horizontal permeability, k_h , and permeability measured perpendicular or substantially perpendicular to the formation bed boundaries which may be referred to as vertical permeability, k_v . Such permeability anisotropy is

referred to as two-dimensional (hereinafter “2D”) anisotropy. In some cases, there may be anisotropy within the plane parallel or substantially parallel to the formation bed boundaries, such that instead of a single value of horizontal, k_h , there may be separate components measured in orthogonal or substantially orthogonal directions, such as, for example, x- and y-directions, referred to as k_x and k_y , respectively. Rock that exhibits variation in permeability when measured vertically or substantially vertically, as well as both horizontal or substantially horizontal directions is said to have three dimensional (hereinafter “3D”) anisotropy. Rock that exhibits no directional variation in permeability is referred to as “isotropic”.

[0040] A numerical simulation method and model have been created to study the formation pressure response for flow from a discrete-opening (probe) source. Features of the model include:

- 3D flow using a rectangular reservoir grid
- Singular phase, slightly compressible fluid with constant fluid properties
- Rectangular shaped reservoir with no flow outer boundaries
- Logarithmic time stepping

[0041] The reservoir grid used for analysis may be chosen to allow the grid to approximate the circular shape of the wellbore and the small size of the probes. In a non-limiting example, the smallest grid cells were 0.1 inch cubes. The wellbore was placed at the center of the formation in both the (x-y) and vertical (z) directions. Therefore, because of symmetry, only one quarter of the system needs to be simulated. Additionally, to the standard multi-probe observation positions of horizontal (180 degrees) and vertical, another observation location in the horizontal plane at 90 degrees was monitored. FIG. 1 shows these positions. It will be understood that the below described methods and apparatus are applicable to both measure while drilling and logging while drilling methods and apparatus.

[0042] FIG. 2 shows the pressure change and derivative results for a flowing probe. The agreement between the numerical method and the analytical model is acceptable.

Analysis of the numerical model results for spherical flow ($\Delta t=1$ to 100 sec.) and radial flow ($\Delta t>1000$ sec.) yields permeability values with about 2% error. There is a slight shift in the Δp values. FIG. 3 presents the Δp values on a semilog scale, and the shift of 20 psi is apparent. This shift is less than 3 % of the analytical Δp and the shift is caused by the different geometries of the probe for the two models.

[0043] FIG. 4 (log-log) and FIG. 5 (semilog) display the comparison between the numerical and analytical models for the pressure response at the horizontal observation probe at 180 degrees. The agreement is good after 0.1 seconds. FIG. 6 (log-log) and FIG. 7 (semilog) show the comparison between the two models for the pressure response at the vertical observation probe. The agreement is good after one second. Note that the analytical model does not have the solution for an observation probe at 90 degrees.

[0044] In summary, FIGS. 2 through 7 show that the numerical model adequately reproduces the analytical results at the sink and observation probes for the case of 2D (k_h/k_v) permeability anisotropy. The validation test case is typical of field cases where interference testing with formation test tools is performed. These results give a sufficient level of confidence that the numerical model will provide accurate results for a system with 3D permeability anisotropy, for which there is no analytical model for the formation test scale wellbore-pressure response.

[0045] Permeability anisotropy within the horizontal plane implies k_x does not equal k_y . Furthermore, if vertical permeability (k_z) differs from both k_x and k_y , then there is 3D anisotropy. To study the effect of anisotropy within the horizontal plane, a validation test case ($k_x = k_y = 200$ millidarcy) was run for two additional cases: $k_x = 800$ with $k_y = 50$ md, and $k_x = 50$ with $k_y = 800$ md. Thus, for all three cases the effective horizontal permeability, given by the square root of the product of k_x and k_y was 200 md. All three cases had vertical permeability $k_z = 20$ md.

[0046] As in the validation case, a constant rate of 6 barrels per day was used but now for 10^7 seconds (116 days), which is sufficiently long for the outer boundary effects to fully develop. In practice, a formation test would never be run for such a duration, but it is nevertheless a check on the model performance to see that the correct outer boundary effects develop.

[0047] FIG. 8 shows the pressure change, Δp , and derivative results for the flowing probe. There is an offset in Δp values between the three cases, with the largest Δp values for the case of $k_y = 50$ md. That is, when the permeability perpendicular to the probe face is smallest, the pressure change is the largest. FIG. 9 presents the Δp values on a semilog scale and the offset between the curves is apparent. FIG. 8 also shows the derivative curves for all three cases overlay (until late times when the boundary effects are reached; note that the two anisotropic cases overlay, and exhibit a linear boundary flow prior to pseudosteady-state boundary flow).

[0048] This overlay of derivatives implies that spherical-flow analysis for each case yields the same value for spherical permeability and radial flow analysis for each case yields the same value for horizontal permeability. Thus, the offset in Δp has the appearance of a skin effect. In practice, the flowing location is nearly always influenced by a skin effect, such as drilling damage. Therefore, even though the probe response is clearly influenced by anisotropy in the horizontal plane, from an interpretation perspective, it would be impossible to distinguish between horizontal anisotropy and skin effect at the flowing probe. However, the $k_x = k_y$ case yields a negative skin component, so the total skin could be negative. Negative skin is fairly unusual, and thus it could be an indicator of anisotropy in the horizontal plane.

[0049] FIG. 10 is a log-log graph and FIG. 11 is a semilog plot displaying the pressure responses at a 180 degree horizontal observation probe. After 0.1 seconds, all three derivative curves overlay until late time. Also, the two anisotropic cases $k_x > k_y$ and $k_x < k_y$, are nearly identical and they are offset from the isotropic case by about 3 psi, which is significant. Unlike the flowing probe, the observation probe is largely

unaffected by skin effect. Therefore, from an interpretation perspective, FIGS. 10 and 11 indicate that data from the 180 degree horizontal observation probe could be used to determine k_h as well as unique values for the two components, k_x and k_y . It is not possible to determine which value is in the x- direction and which value is in the y direction.

[0050] FIGS. 12 (log-log) and 13 (semilog) show the pressure responses at the observation location in the horizontal plane at 90 degrees. These results have the same characteristics as the 180 degree horizontal observation probe. The data illustrated allows detection of horizontal anisotropy and quantification of the component values, but it would not be possible to determine which component value is k_x and which is k_y .

[0051] FIGS. 14 (log-log) and 15 (semilog) display the pressure responses at the vertical observation probe. These results indicate that a vertically-displaced observation probe is largely unaffected by anisotropy in the horizontal plane (until outer boundaries affect the data). It would be possible to determine k_h but not the component values.

[0052] To further confirm the trends observed with the $k_x = 800$, 50 with $k_y = 50$, 800 md (16:1 and 1:16) cases, two additional sets of permeability pairs were modeled:

$k_x=400$, 100 with $k_y = 100$, 400 md (4:1 and 1:4 cases)

$k_x=2000$, 20 with $k_y = 20$, 2000 md (100:1 and 1:100 cases).

Thus all cases have an effective horizontal permeability of $k_h = \text{square root } (k_x \cdot k_y) = 200$ md.

[0053] FIGS. 16 (log-log) and 17 (semilog) present the pressure responses at the flowing probe. All derivative curves overlay during spherical and radial flow, so the effect of horizontal anisotropy is the appearance of a skin effect. The results for the 180 degree horizontal observation probe (FIGS. 18 and 19), and the 90 degree horizontal

observation probe (FIGS. 20 and 21) show that the pressure response always decreases as anisotropy increases, but that the direction of anisotropy is not significant. That is, detection and quantification of horizontal anisotropy from a horizontal observation probe is possible, but it is not possible to determine which component value is k_x and which is k_y . The results for the vertical observation probe (FIGS. 22 and 23) show that this location is practically insensitive to horizontal anisotropy.

[0054] The previous examples all assumed that the flowing and observation probes were aligned with the principal directions of horizontal permeability. In the set of examples that follow, the effect of alignment is investigated. As provided, the flowing probe was oriented at an angle of 45 degrees with respect to the horizontal permeability directions. Observation probes are still referenced with respect to the flowing probe.

[0055] The validation test case used earlier is isotropic in the horizontal plane ($k_x = k_y = 200$ md), so the results should be independent of probe alignment. FIG. 24 illustrates the numerical model results (pressure change and derivative) for the flowing probe aligned at 0 degrees and 45 degrees, the curves overlay well. FIG. 25 presents the Δp values on a semilog scale and a slight shift of 3 psi. is apparent. The shift represents a relative difference of less than 0.5% and is caused by grid orientation effects. Thus, even using small grid blocks to represent the probe, it is impossible to exactly model a 45 degree rectangular source (probe) with an x-y grid. In summary, FIGS. 24 and 25 show that the numerical model produces accurate results when the flowing probe is not aligned with the principal directions of permeability. Although not shown, the results for the three observation locations also show virtually no change depending on flowing-probe alignment for the $k_x = k_y$ case.

[0056] To examine sensitivity to flowing probe alignment, the same three cases as displayed earlier in FIGS. 8 to 15 were run – the validation test case (k_x and $k_y = 200$ md), $k_x = 800$ and $k_y = 50$ md, and $k_x = 50$ with $k_y = 800$ md. All three cases again had vertical permeability $k_z = 20$ md.

[0057] FIGS. 26 (log-log) and 27 (semilog) show the results for the flowing probe. There is an offset in Δp values between the isotropic case and the anisotropic cases. However, the results from the two anisotropic cases are identical. That is, with the flowing probe oriented at 45 degrees, the pressure change at the flowing probe is dependent on the magnitude of horizontal anisotropy but independent of the direction of anisotropy. This behavior is in sharp contrast to that of FIGS. 8 and 9 with the probe oriented at 0 degrees, which show a strong dependence on the direction of anisotropy.

[0058] FIGS. 28 (log-log) and 29 (semilog) display the pressure responses at the 180 degree horizontal observation probe. In all respects, these results mimic those of the flowing probe – the pressure change is dependent on the magnitude of horizontal anisotropy but independent of the direction of anisotropy. As noted earlier, the observation probe is largely unaffected by skin effect. Therefore, from an interpretation perspective, FIGS. 28 and 29 indicate that data from the 180 degree horizontal observation probe could be used to determine k_h as well as unique values for the two components, k_x and k_y , regardless of the orientation of the flowing probe. However, it would not be possible to determine which value is in the x-direction and which value is in the y-direction.

[0059] FIGS. 30 (log-log) and 31 (semilog) show the pressure responses at the observation location in the horizontal plane at 90 degrees. These figures show that the flowing probe orientation now has a strong influence on the results. The pressure change is sensitive to both the magnitude and direction of anisotropy; it would be possible to determine component values, k_x and k_y , and it would be possible to determine which value is in the x-direction and which value is in the y-direction. This behavior is again in sharp contrast to that of the 0 degree oriented flowing probe of FIGS. 12 and 13.

[0060] FIGS. 32 (log-log) and 33 (semilog) display the pressure responses at the vertical observation probe. Comparing these results with those of FIGS. 14 and 15 for

the 0 degree oriented flowing probe shows that a vertically displaced observation probe is unaffected by the flowing probe orientation.

[0061] A numerical simulation model has been developed to study the formation pressure response for flow from a discrete opening (probe) source in a reservoir with 3D permeability anisotropy. The model was validated by comparing its results with those from an analytical model for 2D anisotropy. Results of the 3D numerical cases show that:

- The alignment of the flowing probe with respect to the principal directions of horizontal permeability has a strong influence on the responses of the flowing probe and 90 degree horizontal observation probe. Conversely, a 180 degree horizontal observation probe is not sensitive to the flowing probe alignment.
- The response at the flowing probe may contain information about the direction of anisotropy; however the anisotropy-influenced response at the flowing location mimics a skin effect, so in practice, it would not be possible to estimate unique values for skin and horizontal anisotropy from the location.
- A 90 degree horizontal observation probe is sensitive to both the magnitude and direction of anisotropy. This probe location is largely unaffected by skin effect; therefore it could be possible to determine component values k_x and k_y as well to determine which value is in the x-direction and which value is in the y direction.
- A 180 degree horizontal observation probe is sensitive to the magnitude of horizontal anisotropy, but not the direction. This is true regardless of the orientation of the flowing probe.
- A vertical probe is not sensitive to anisotropy in the horizontal plane.

[0062] A method for determining permeability anisotropy in a horizontal plane of a subsurface reservoir is described, comprising: positioning a formation testing tool within a wellbore formed within the subsurface reservoir, wherein the tool has an opening to enable fluid communication with the reservoir, and the tool has a horizontally displaced observation probe configured to obtain data; measuring a flow response of the subsurface reservoir; determining at least one of horizontal permeability and horizontal mobility of the reservoir based on the measuring of the flow response of the subsurface reservoir; and determining orthogonal components of at least one of the horizontal permeability and horizontal mobility based on the measured flow response.

[0063] In another embodiment, the method may be accomplished wherein the opening is a focused opening.

[0064] In another embodiment, the method may be accomplished wherein the observation probe is configured as a horizontally displaced observation probe.

[0065] In another embodiment, the method may be accomplished wherein the observation probe is configured to obtain pressure data.

[0066] In another embodiment, the method may be accomplished wherein the determining the one of horizontal permeability and horizontal mobility of the reservoir based on the measuring of the flow response of the subsurface reservoir is at the observation probe.

[0067] In another embodiment, the method may be accomplished wherein the determining the one of horizontal permeability and horizontal mobility of the reservoir based on the measuring of the flow response of the subsurface reservoir is adjacent to the observation probe.

[0068] In another embodiment, the method may further comprise comparing the determined orthogonal components of the at least one of the horizontal permeability and horizontal mobility.

[0069] In another embodiment, the method may be accomplished wherein the measuring the flow response of the subsurface reservoir is performed by the probe.

[0070] In another embodiment, an article of manufacture is provided having a processor readable code embodied on the processor, said processor readable code for programming at least one processor to perform a method for determining permeability anisotropy in a horizontal plane of a subsurface reservoir, comprising: positioning a formation testing tool within a wellbore formed within the subsurface reservoir, wherein the tool has an opening to enable fluid communication with the reservoir, and the tool has an observation probe configured to obtain data; measuring a flow response of the subsurface reservoir; determining at least one of horizontal permeability and horizontal mobility of the reservoir based on the measuring of the flow response of the subsurface reservoir; and determining orthogonal components of at least one of the horizontal permeability and horizontal mobility based on the measured flow response.

[0071] While the aspects have been described with respect to a limited number of embodiments, those skilled in the art, having benefit of this disclosure, will appreciate that other embodiments can be devised which do not depart from the scope of the invention as disclosed herein. Accordingly, the scope of the invention should be limited only by the attached claims.

What is claimed is:

1. A method for determining permeability anisotropy in a horizontal plane of a subsurface reservoir, comprising:
 - positioning a formation testing tool within a wellbore formed within the subsurface reservoir, wherein the tool has an opening to enable fluid communication with the reservoir, and the tool has a horizontal observation probe configured to obtain data;
 - measuring a flow response of the subsurface reservoir;
 - determining at least one of horizontal permeability and horizontal mobility of the reservoir based on the measuring of the flow response of the subsurface reservoir; and
 - determining orthogonal components of at least one of the horizontal permeability and horizontal mobility based on the measured flow response.
2. The method according to claim 1, wherein the opening is a focused opening.
3. The method according to claim 1, wherein the horizontal observation probe is configured as a horizontally displaced observation probe.
4. The method according to claim 1, wherein the horizontal observation probe is configured to obtain pressure data.
5. The method according to claim 1, wherein the determining the one of horizontal permeability and horizontal mobility of the reservoir based on the measuring of the flow response of the subsurface reservoir is at the observation probe.
6. The method according to claim 1, wherein the determining the one of horizontal permeability and horizontal mobility of the reservoir based on the measuring of the flow response of the subsurface reservoir is adjacent to the observation probe.

7. The method according to claim 1, further comprising:
 - comparing the determined orthogonal components of the at least one of the horizontal permeability and horizontal mobility.
8. The method according to claim 1, wherein the measuring the flow response of the subsurface reservoir is performed by the probe.
9. An article of manufacture having a processor readable code embodied on the processor, said processor readable code for programming at least one processor to perform a method for determining permeability anisotropy in a horizontal plane of a subsurface reservoir, comprising:
 - positioning a formation testing tool within a wellbore formed within the subsurface reservoir, wherein the tool has an opening to enable fluid communication with the reservoir, and the tool has a horizontal observation probe configured to obtain data;
 - measuring a flow response of the subsurface reservoir;
 - determining at least one of horizontal permeability and horizontal mobility of the reservoir based on the measuring of the flow response of the subsurface reservoir; and
 - determining orthogonal components of at least one of the horizontal permeability and horizontal mobility based on the measured flow response.
10. The article of manufacture according to claim 9, wherein the opening is a focused opening.
11. The article of manufacture according to claim 9, wherein the observation probe is configured as a horizontally displaced observation probe.

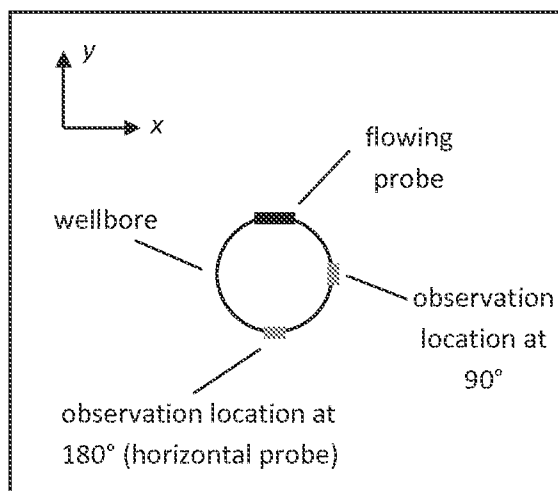


FIG. 1

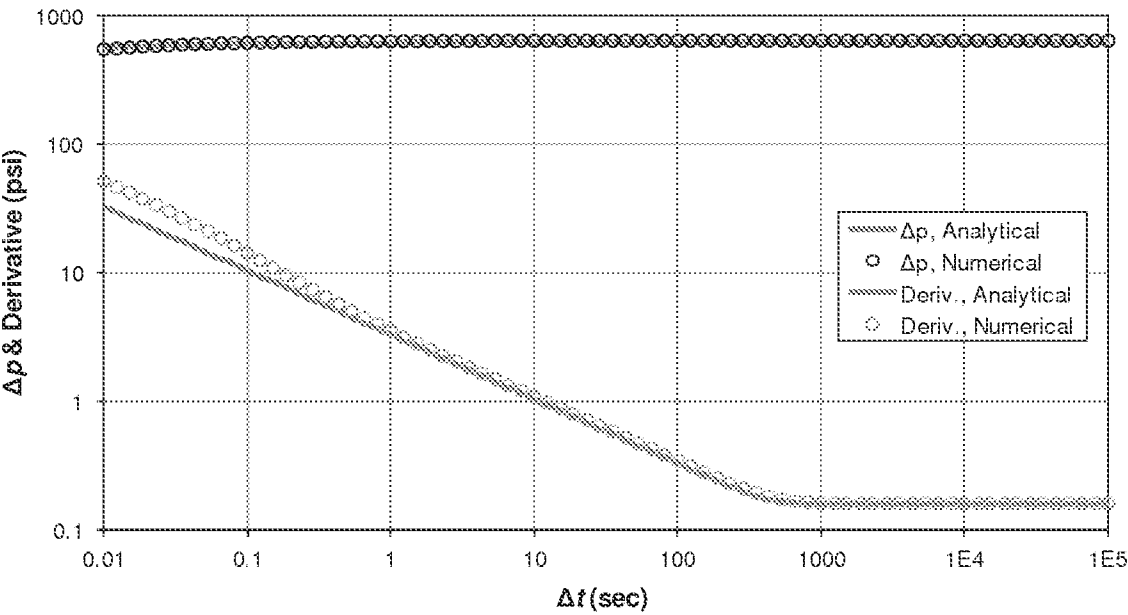


FIG. 2

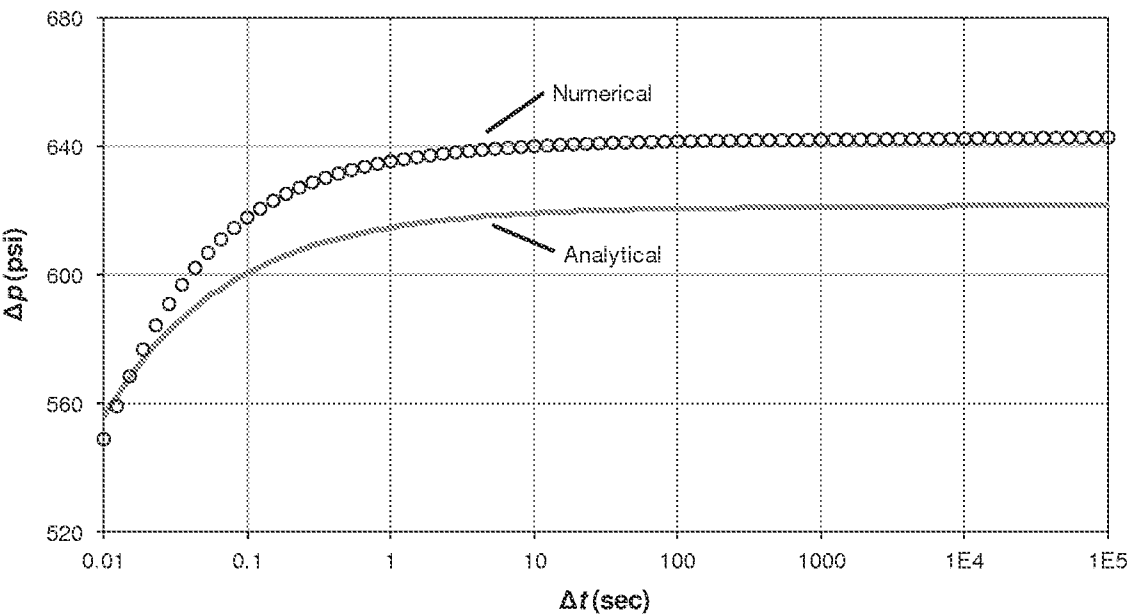


FIG. 3

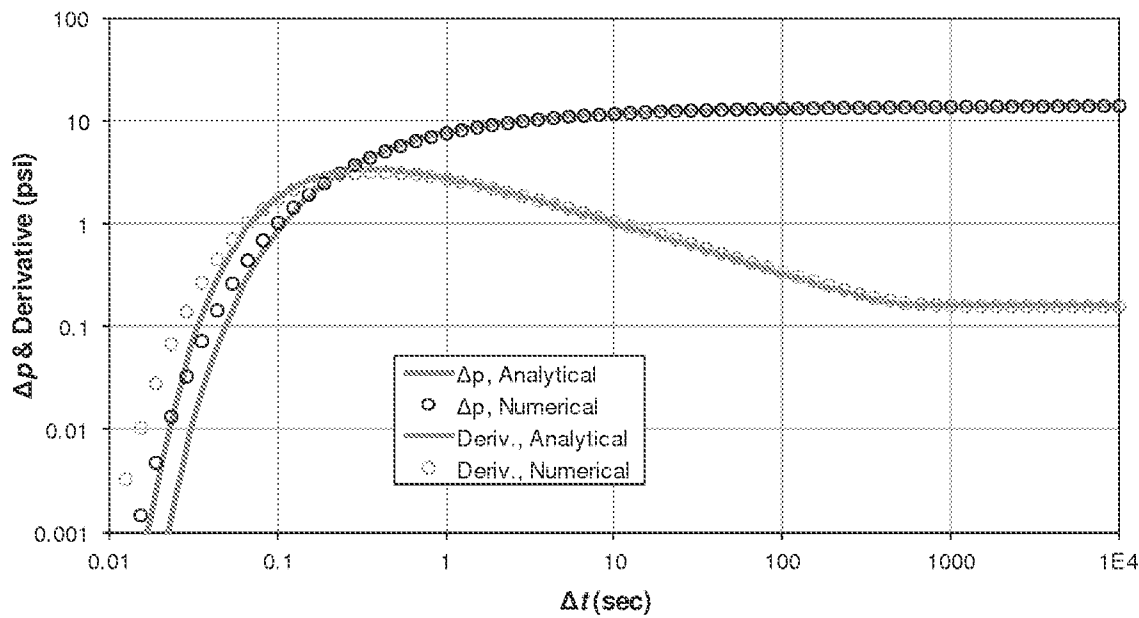


FIG. 4

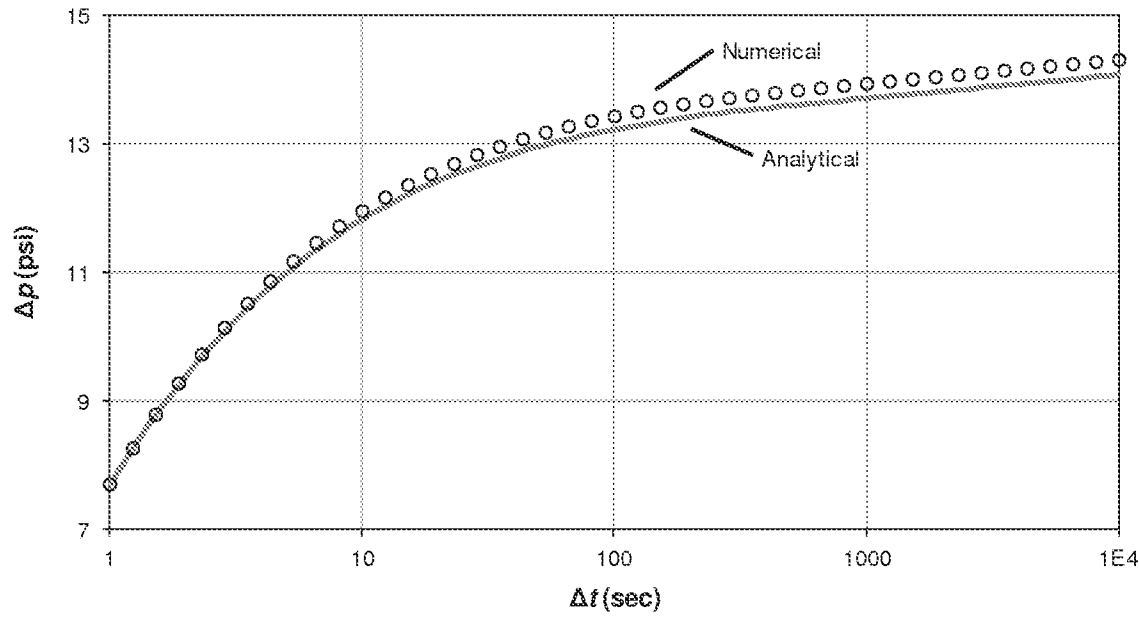


FIG. 5

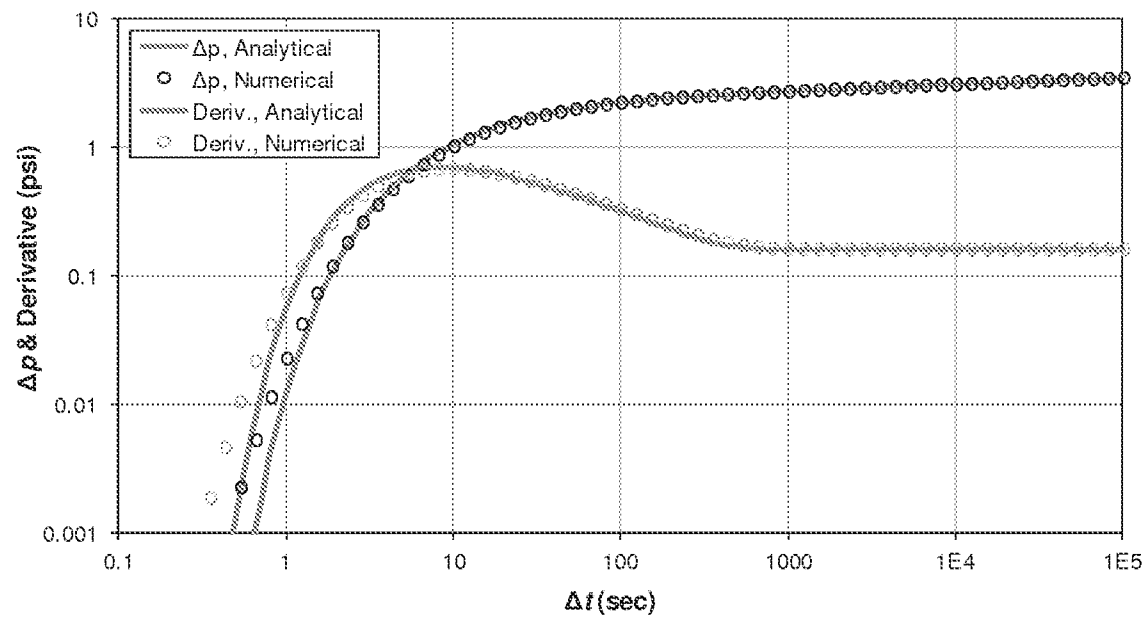


FIG. 6

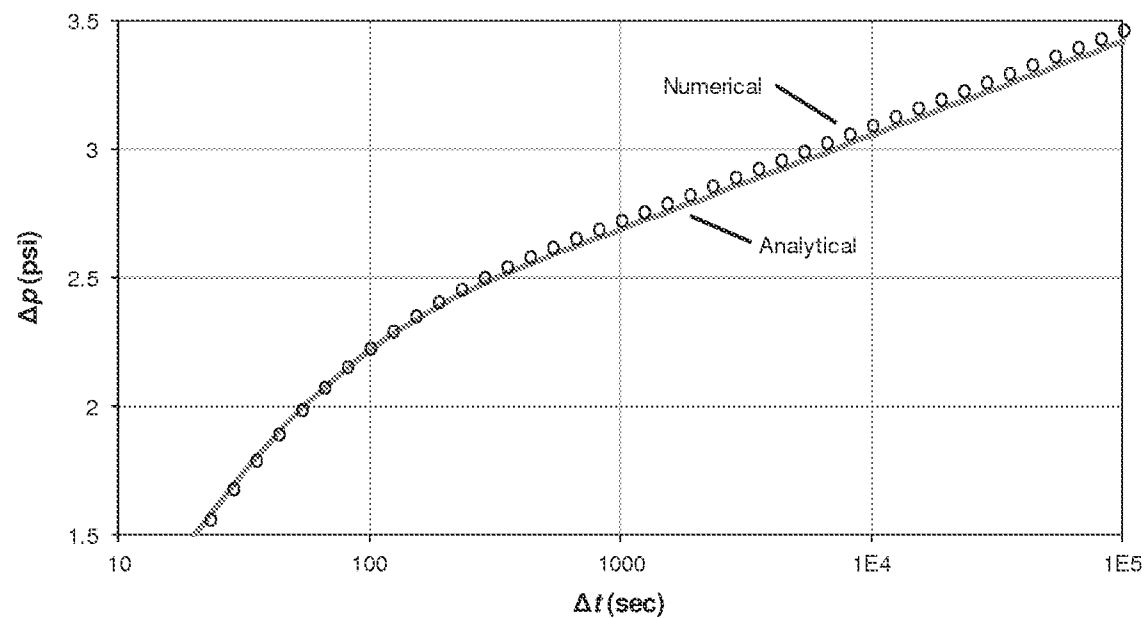


FIG. 7

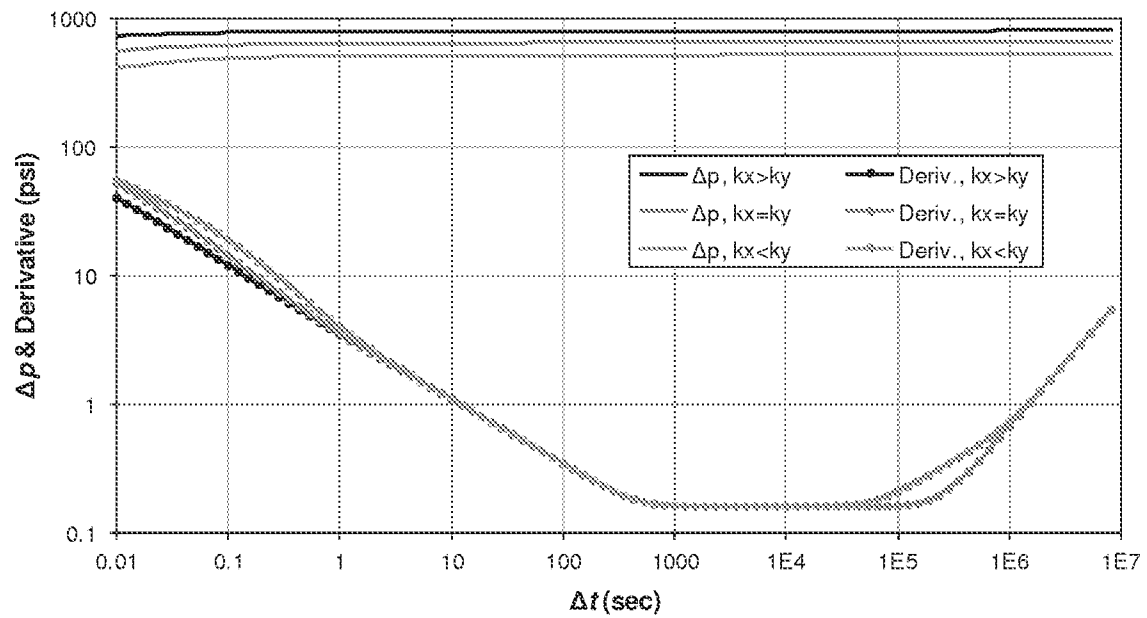


FIG. 8

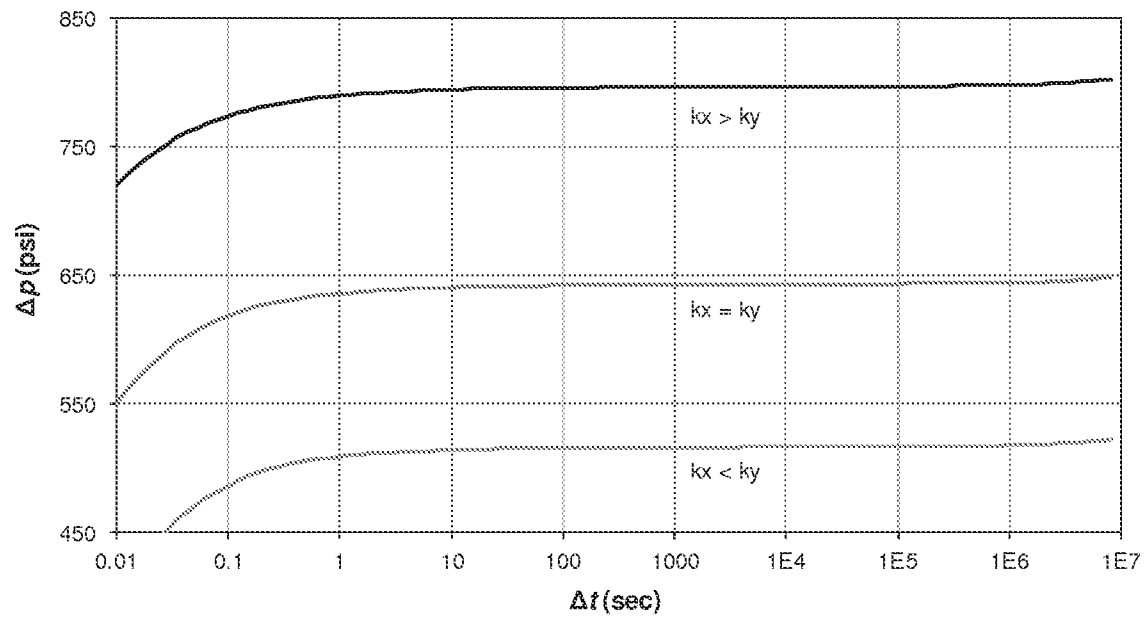


FIG. 9

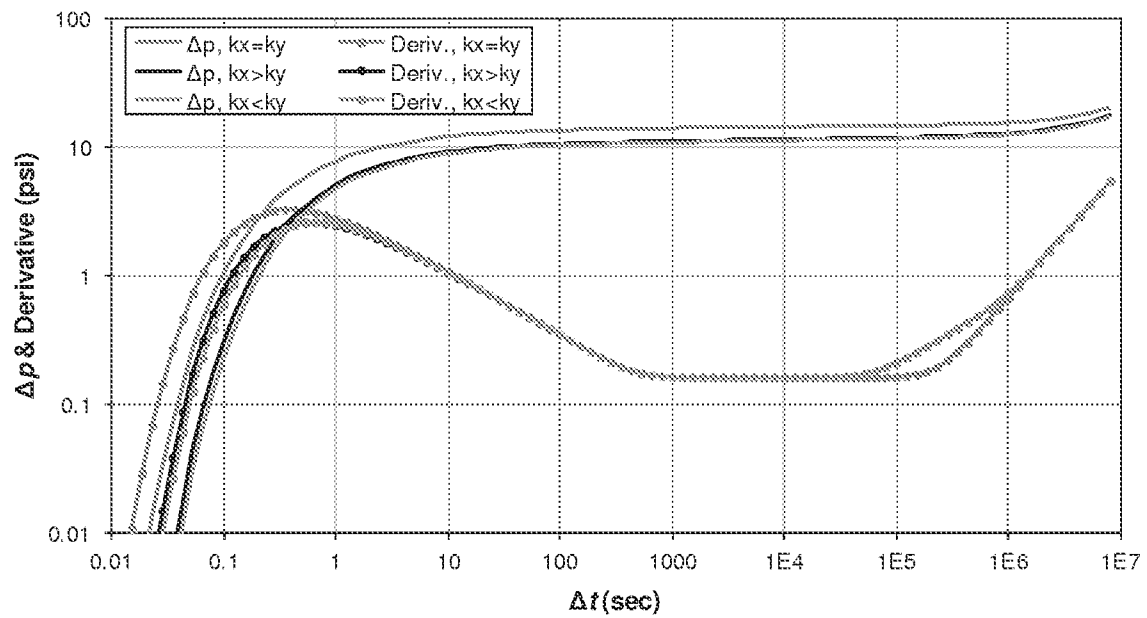


FIG. 10

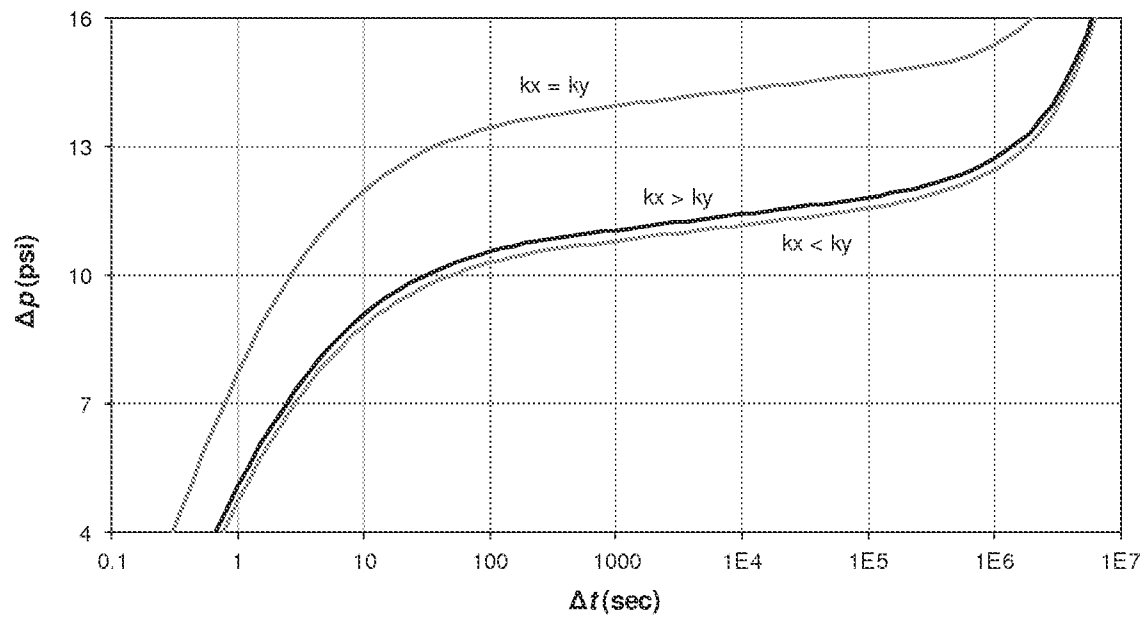


FIG. 11

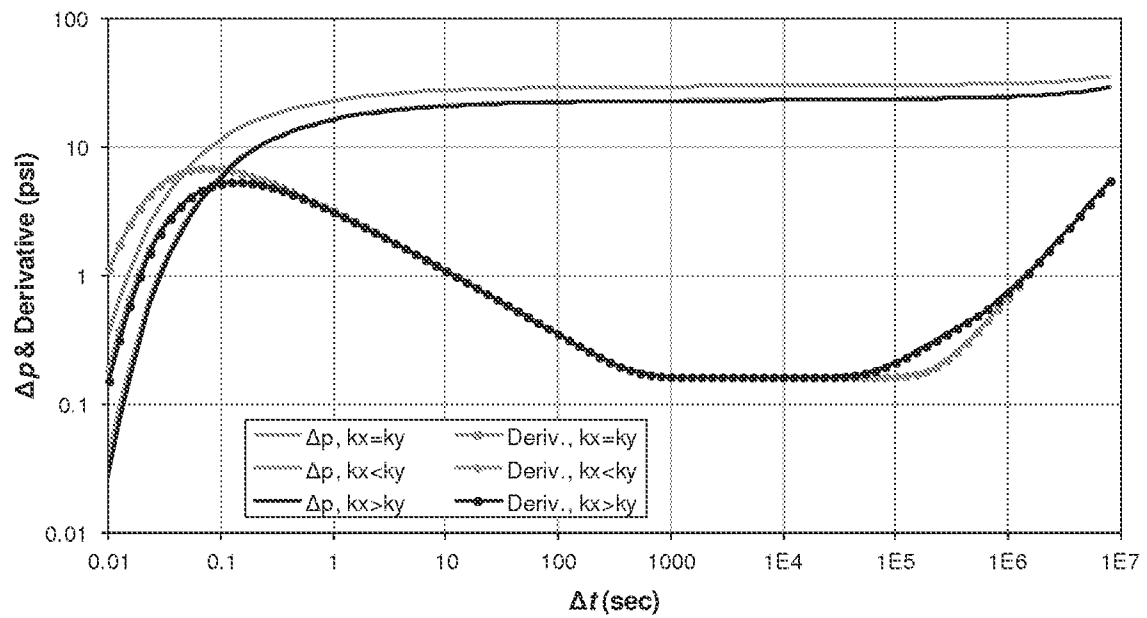


FIG. 12

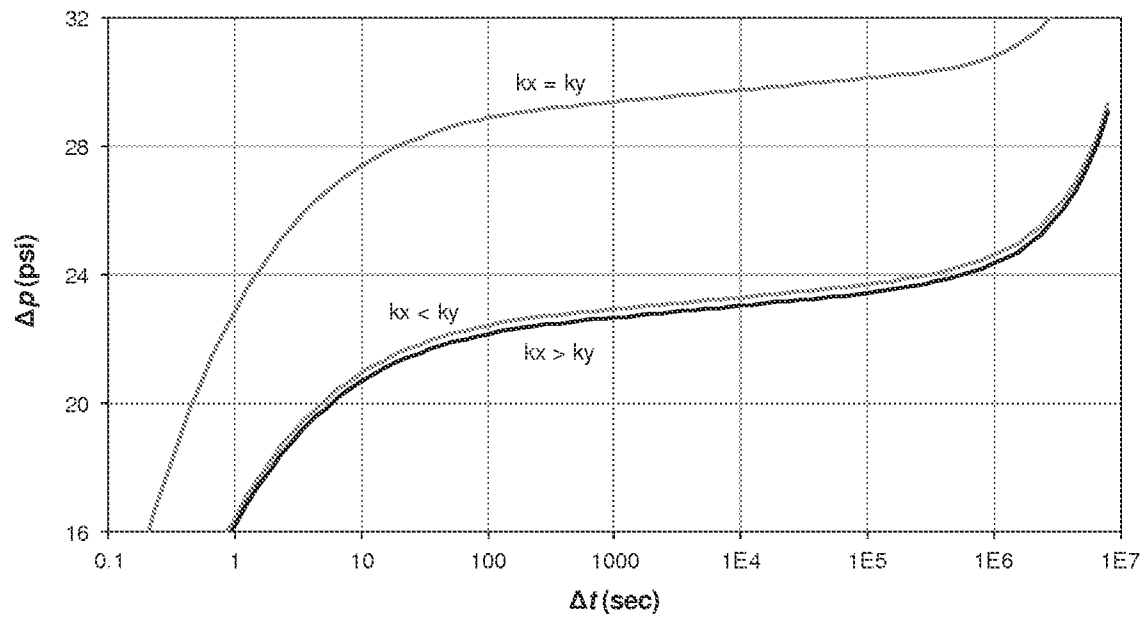


FIG. 13

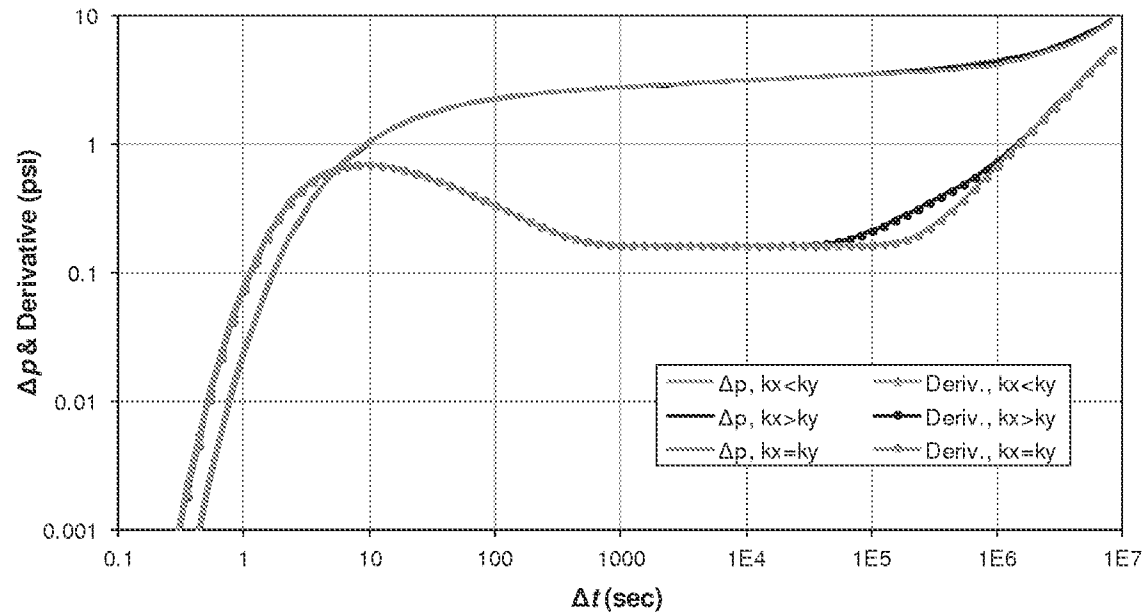


FIG. 14

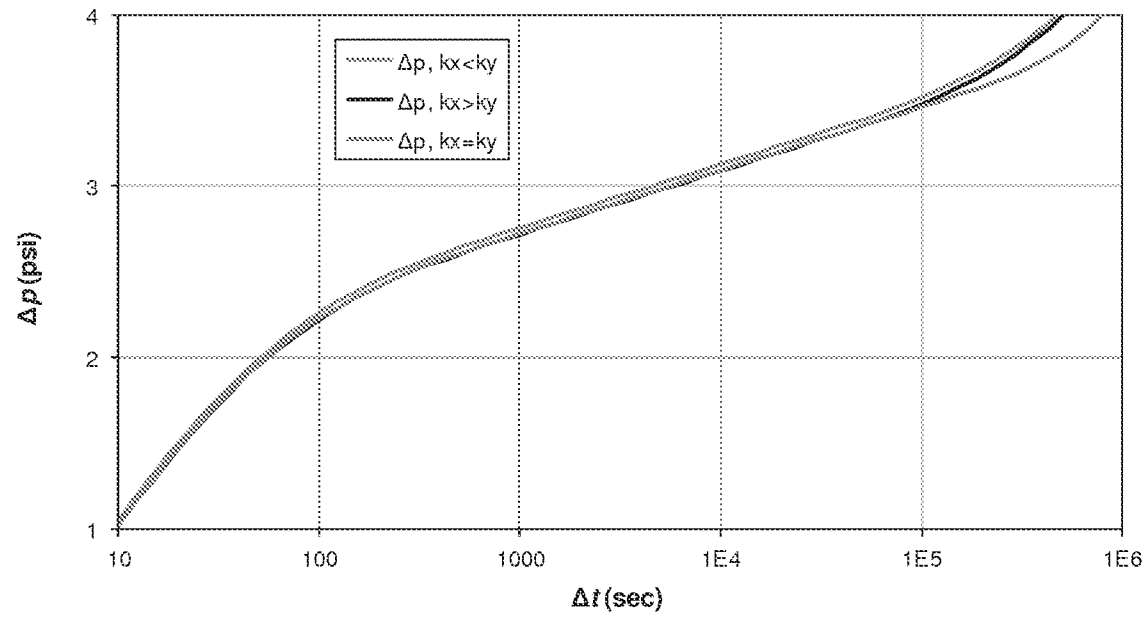


FIG. 15

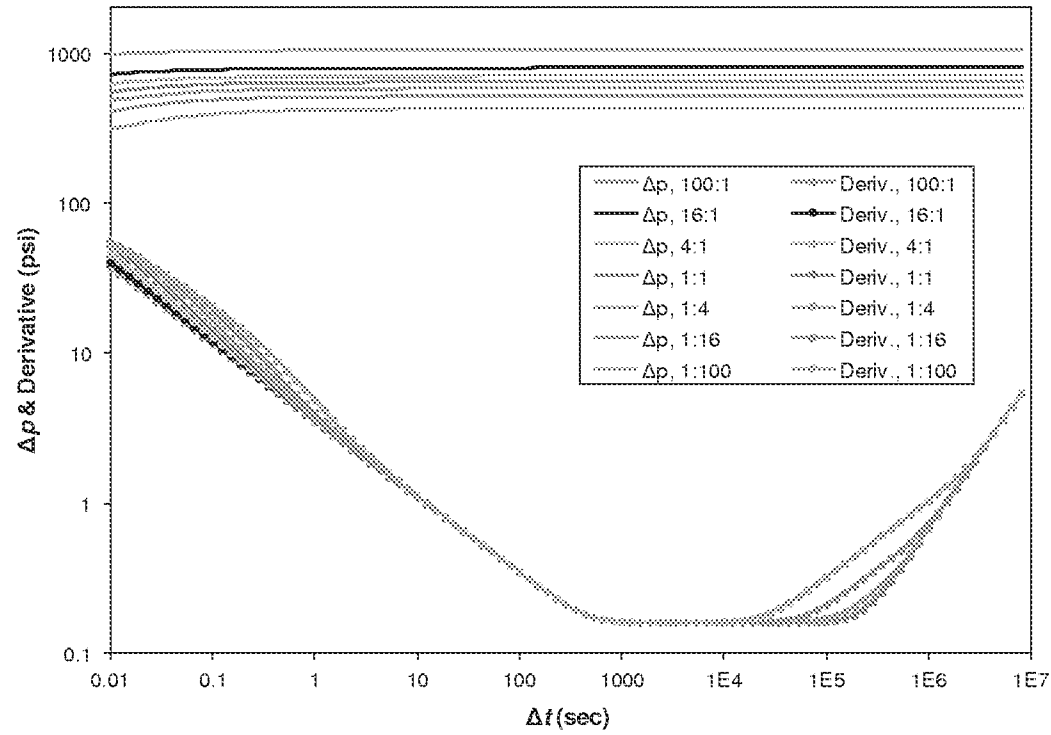


FIG. 16

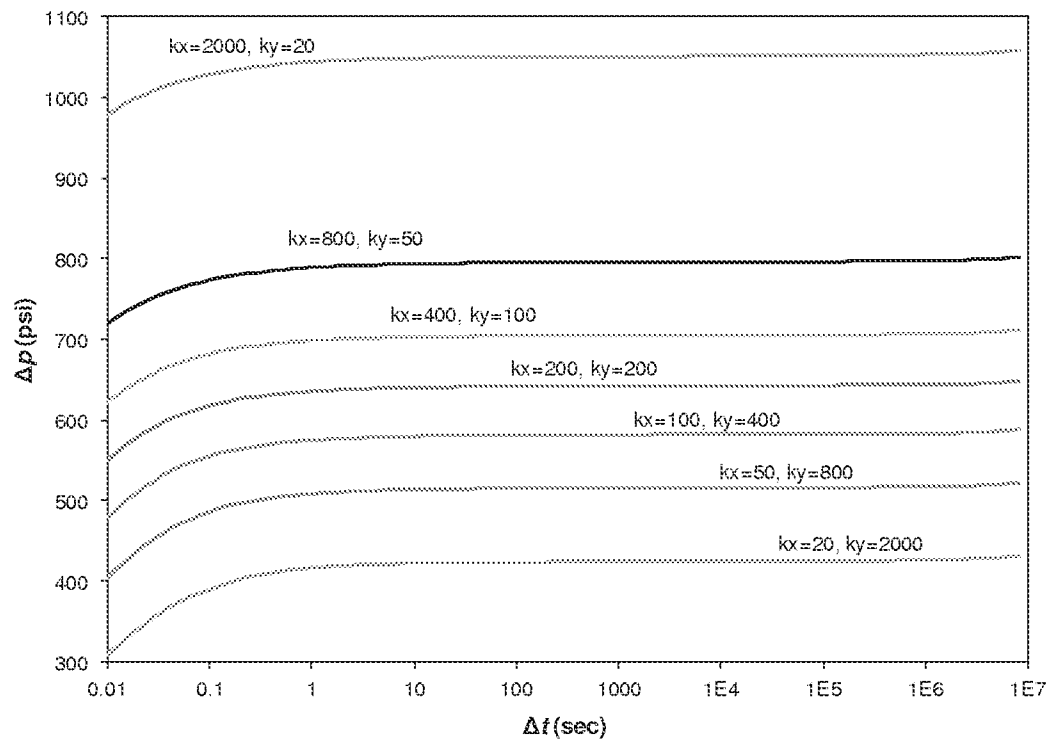


FIG. 17

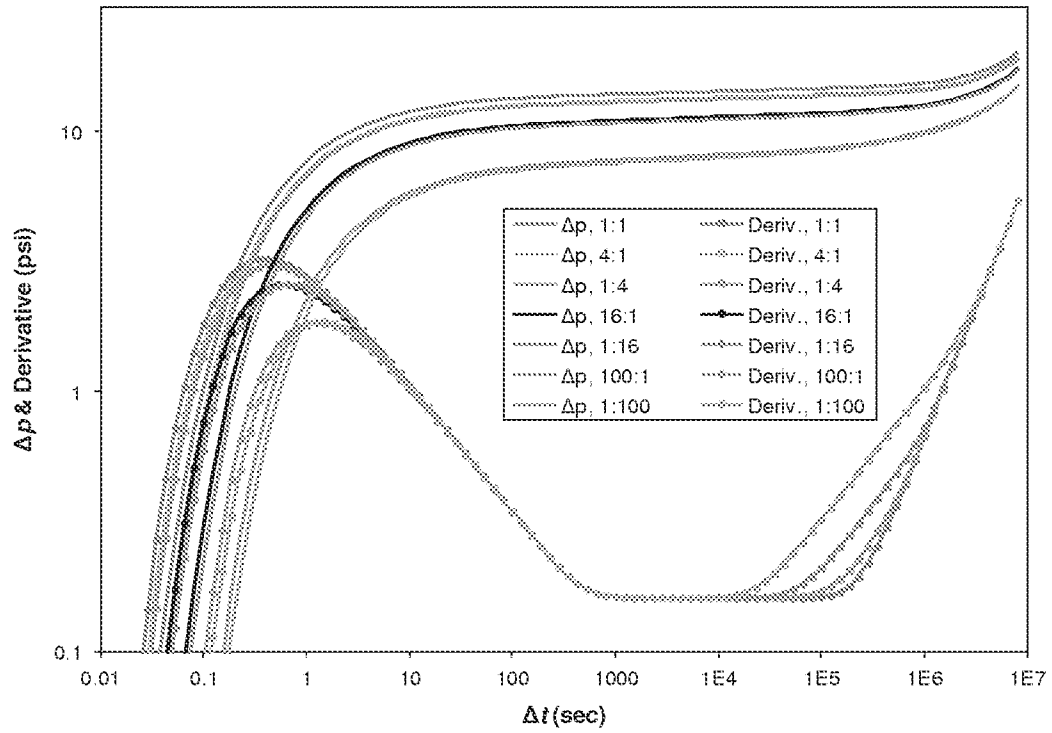


FIG. 18

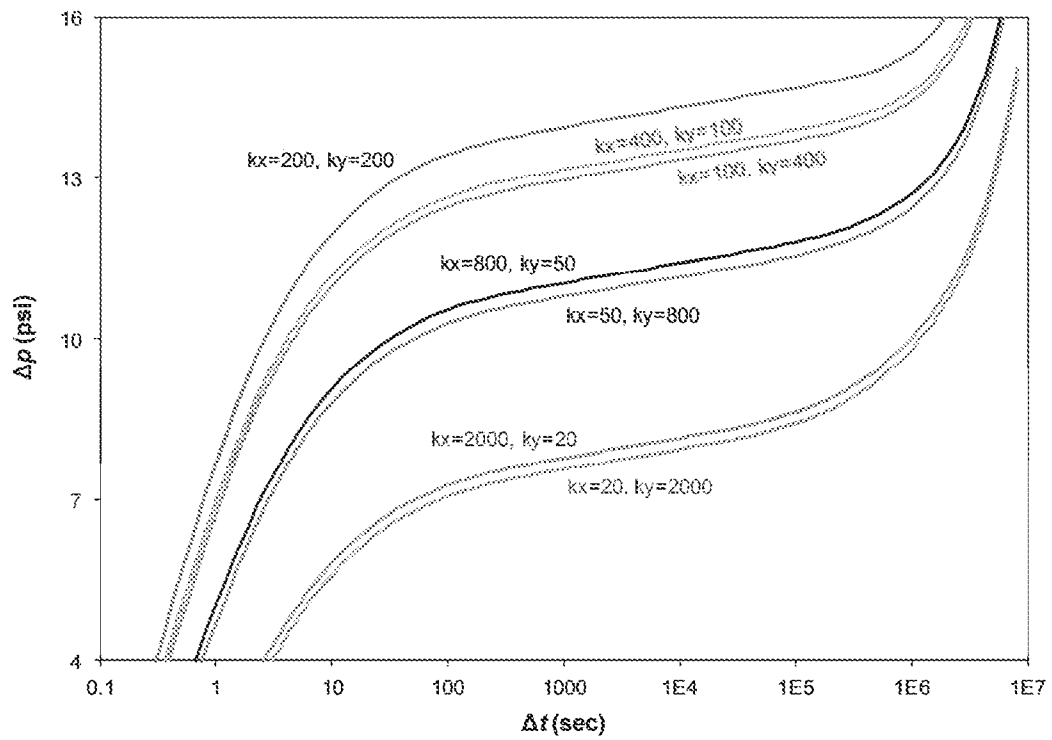


FIG. 19

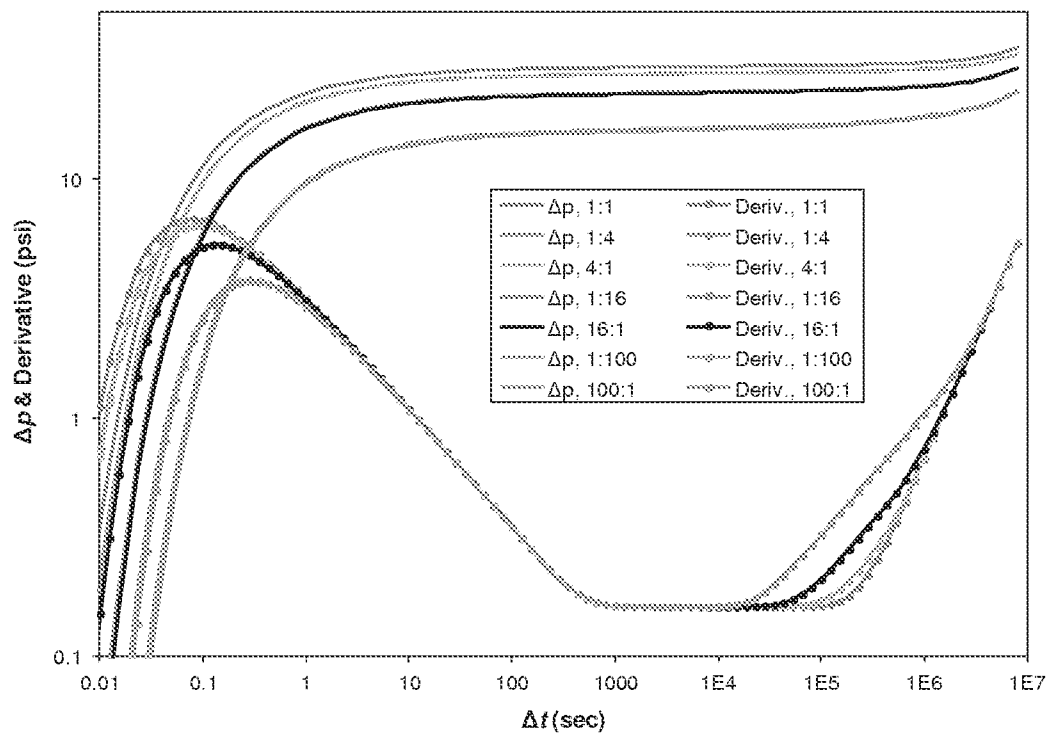


FIG. 20

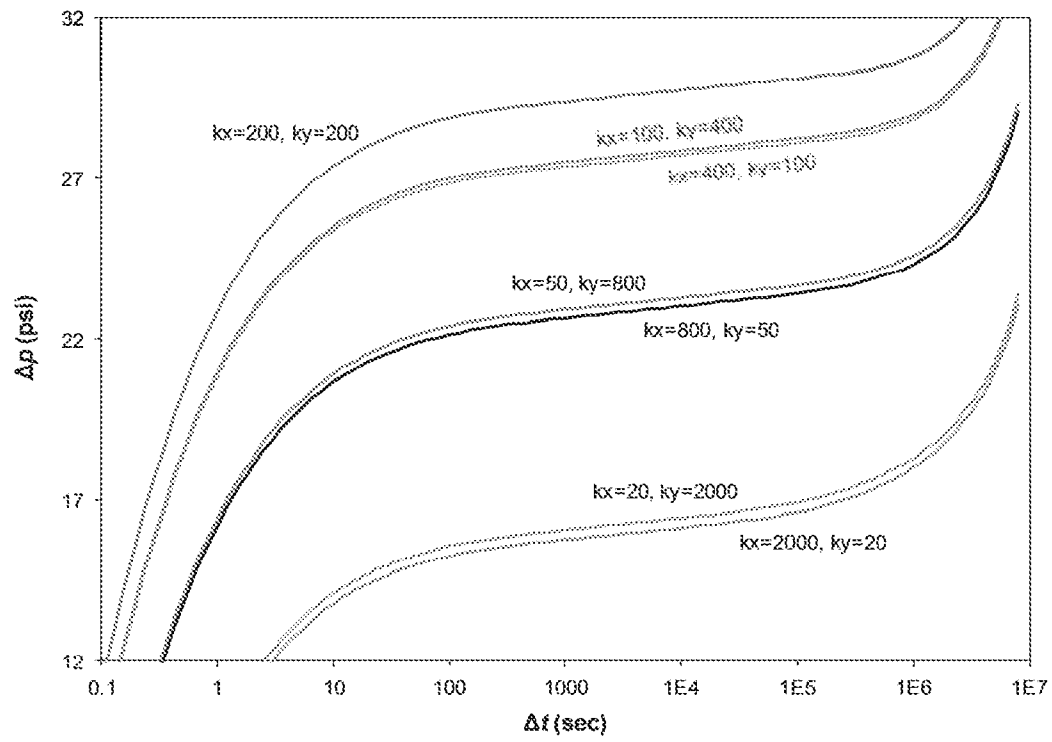


FIG. 21

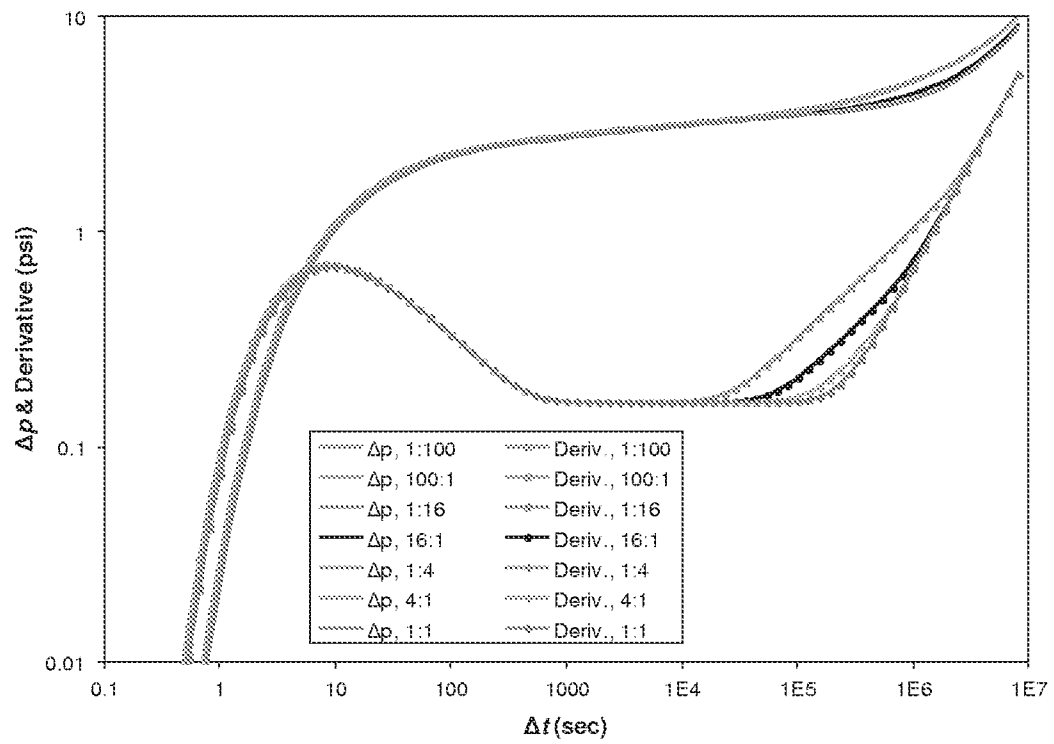


FIG. 22

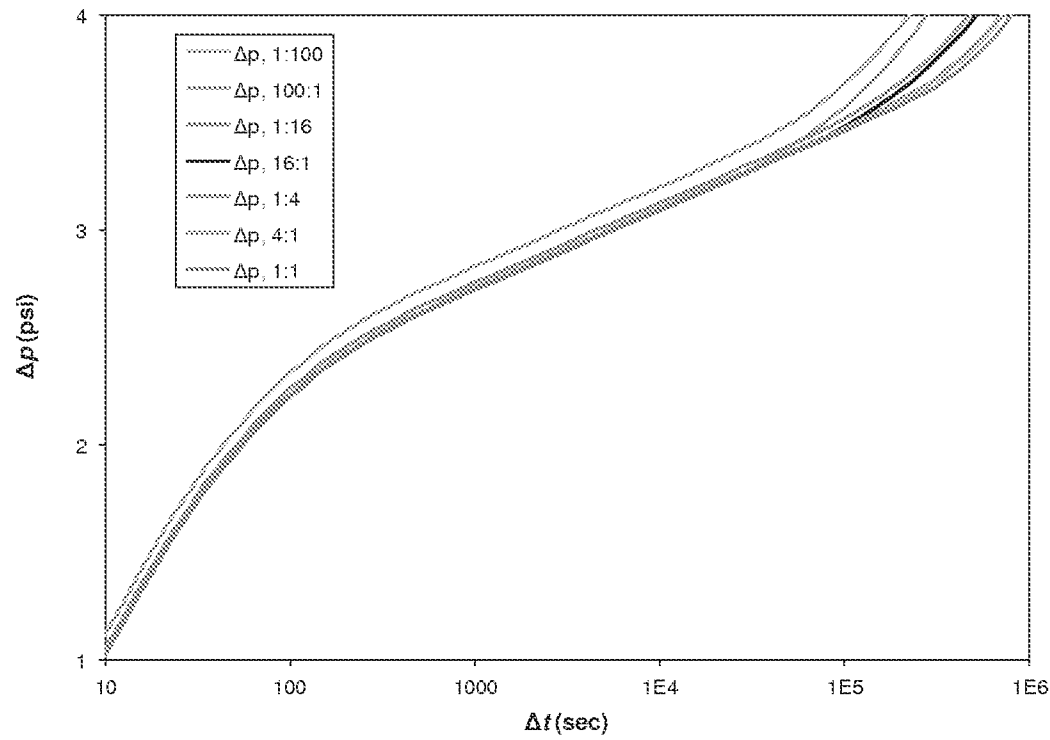


FIG. 23

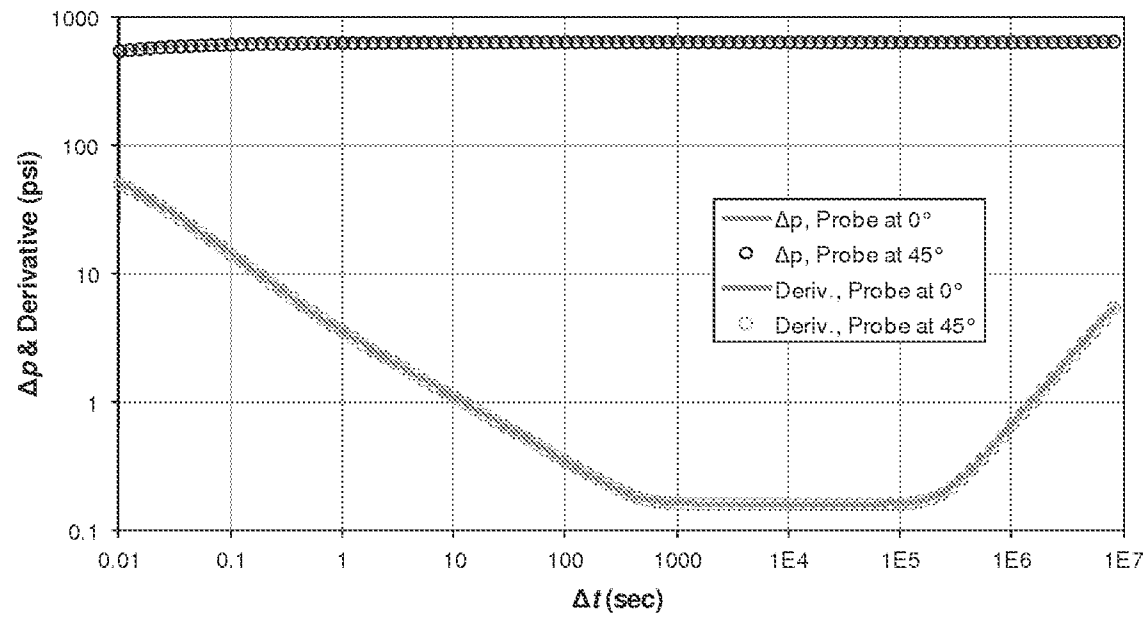


FIG. 24

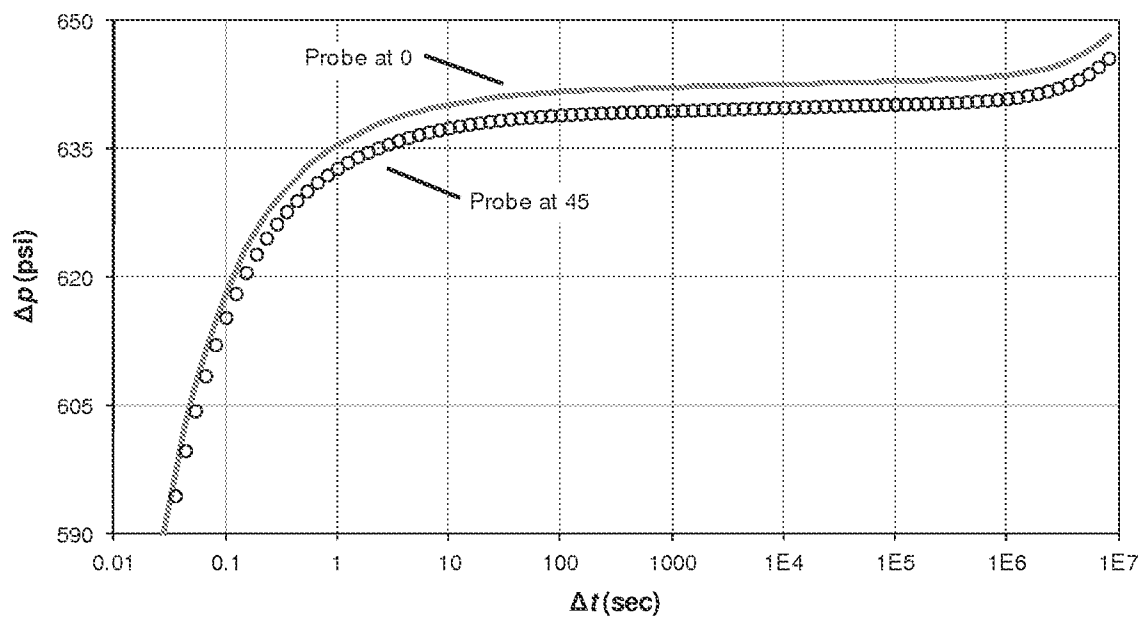


FIG. 25

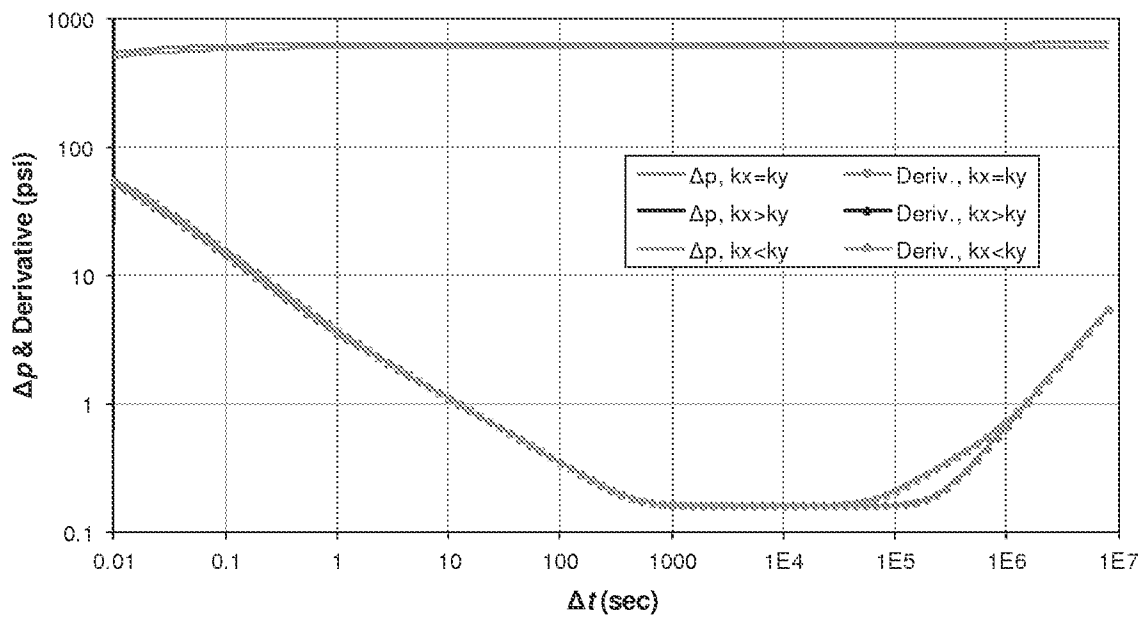


FIG. 26

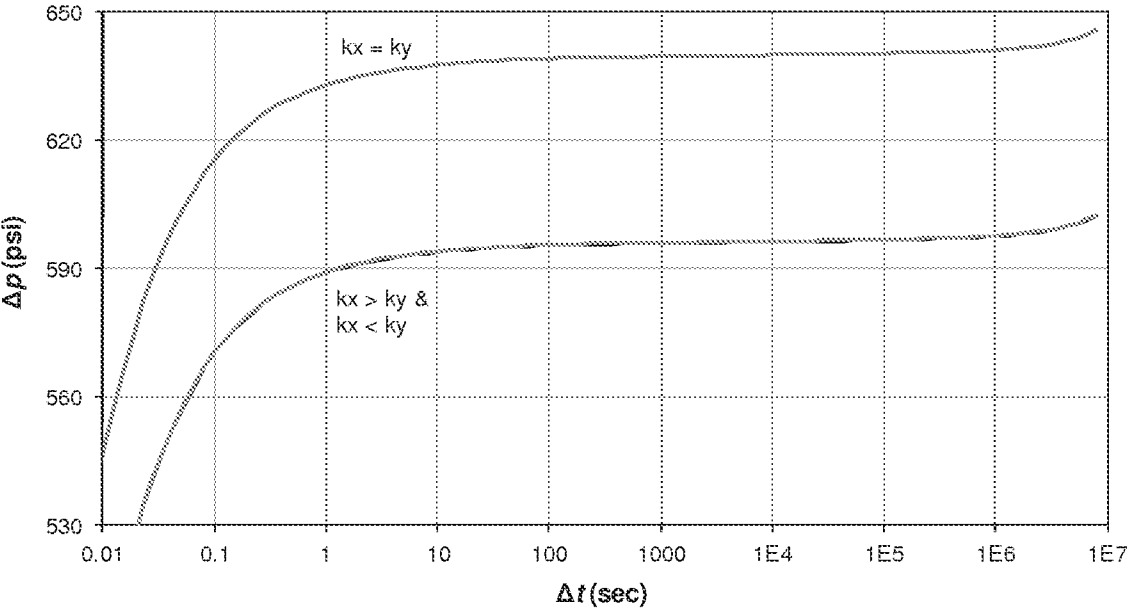


FIG. 27

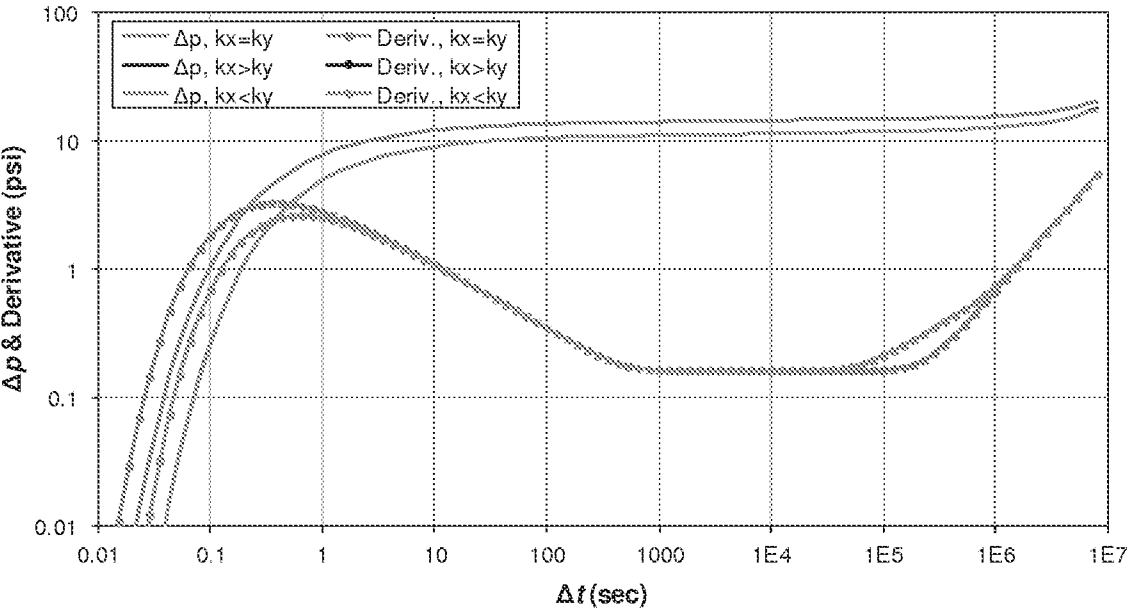


FIG. 28

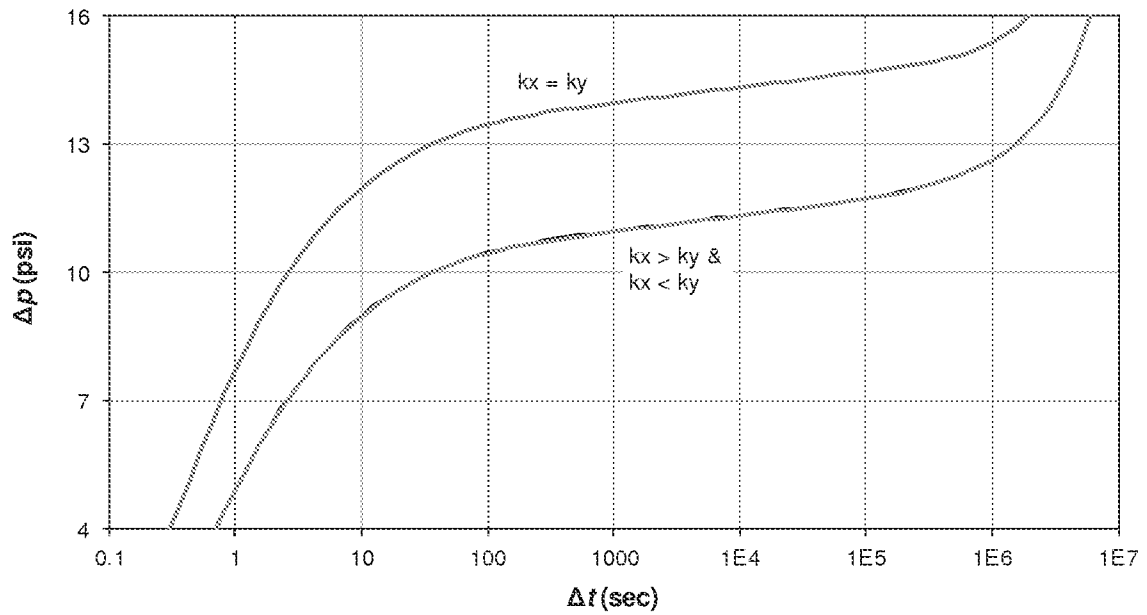


FIG. 29

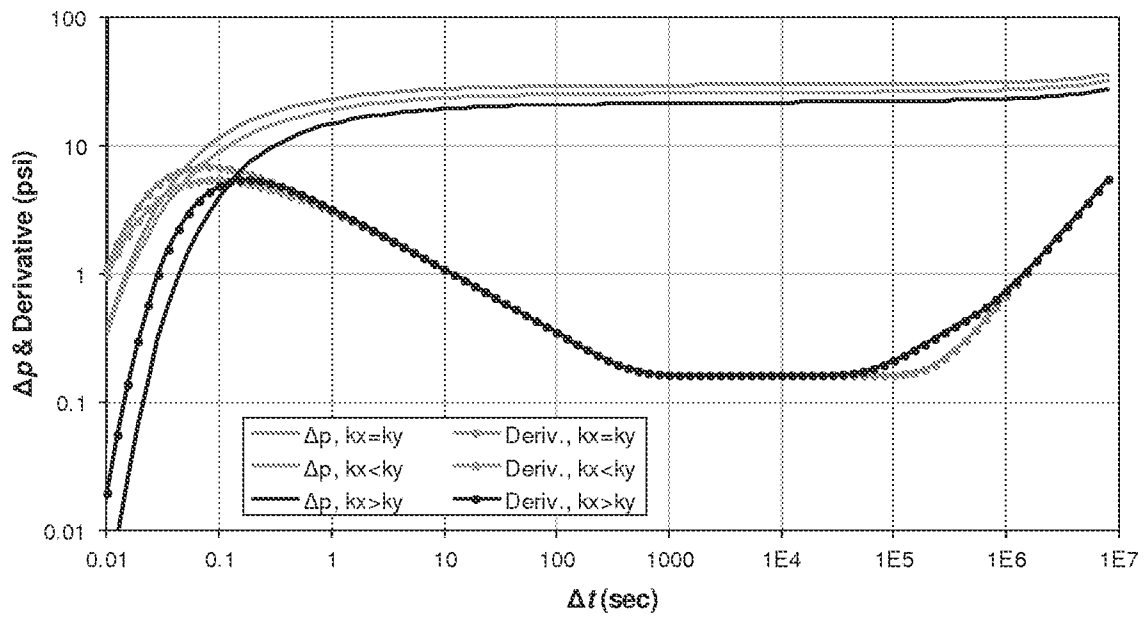


FIG. 30

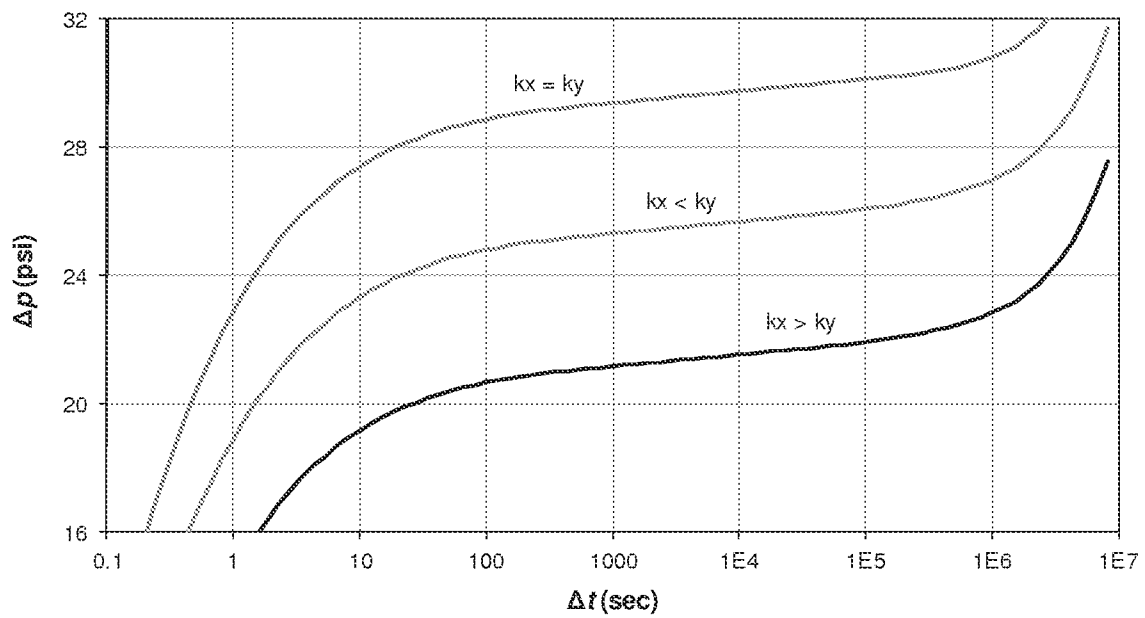


FIG. 31

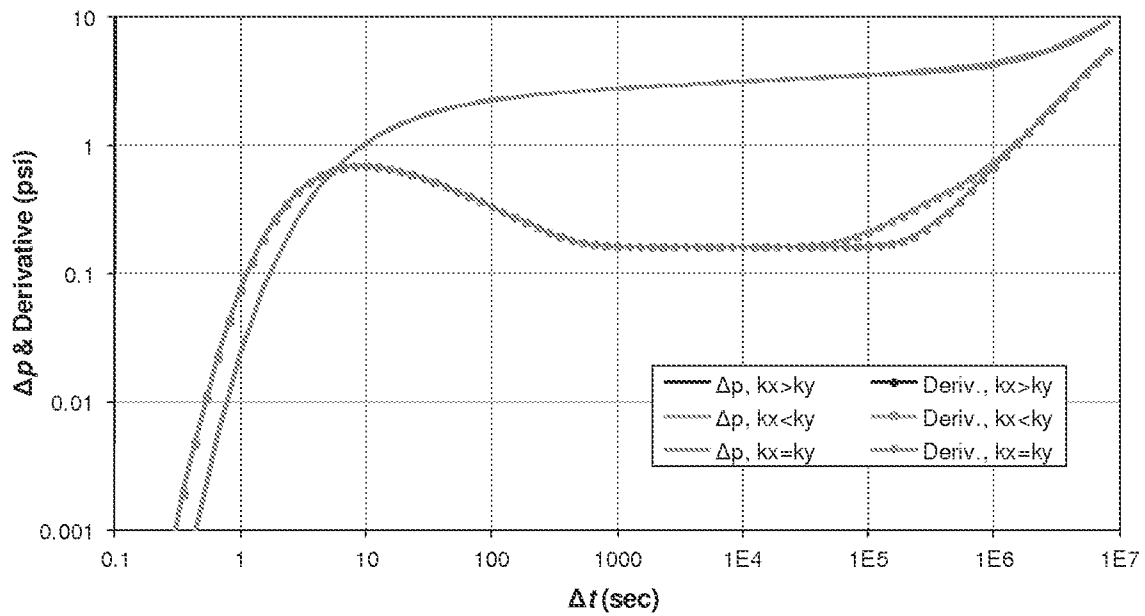


FIG. 32

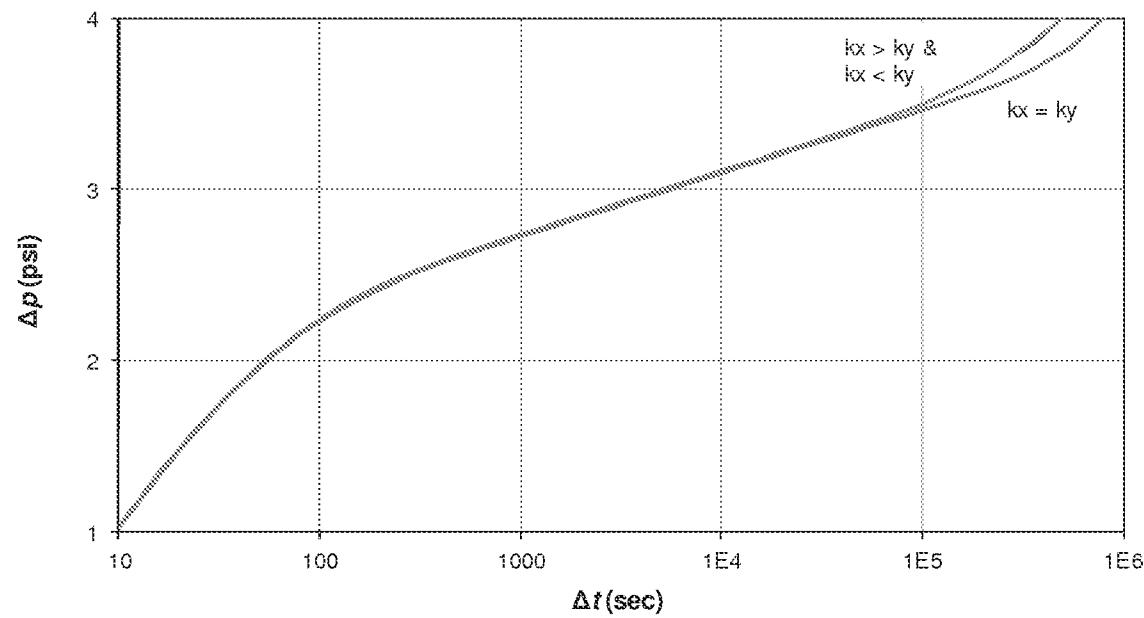


FIG. 33

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US2014/043409**A. CLASSIFICATION OF SUBJECT MATTER****E21B 49/00(2006.01)i, E21B 47/06(2006.01)i**

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

E21B 49/00; E21B 47/10; E21B 47/00; E21B 43/00; E21B 47/06

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Korean utility models and applications for utility models

Japanese utility models and applications for utility models

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

eKOMPASS(KIPO internal) & Keywords: permeability, anisotropy, horizontal, mobility, orthogonal, reservoir, flow, response, probe

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2010-0126717 A1 (KUCHUK et al.) 27 May 2010 See abstract, paragraphs [0034], [0038], [0046], [0051], [0057], [0059], [0060], [0064], [0094], [0101]-[0106], and figures 1-3A, 7A, 7B, 9.	1-11
Y	US 5156205 A (PRASAD, RAJ K.) 20 October 1992 See abstract, column 4, lines 67-68, and claim 1.	1-11
A	US 2011-0107830 A1 (FIELDS et al.) 12 May 2011 See abstract, paragraphs [0048]-[0053], claims 13-18, and figure 2.	1-11
A	US 2006-0042371 A1 (SHENG et al.) 02 March 2006 See abstract, paragraphs [0038]-[0041], claims 1-10, and figure 1.	1-11
A	US 2003-0094040 A1 (PROETT et al.) 22 May 2003 See abstract, paragraphs [0025]-[0027], claim 1, and figure 1.	1-11



Further documents are listed in the continuation of Box C.



See patent family annex.

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search

23 October 2014 (23.10.2014)

Date of mailing of the international search report

24 October 2014 (24.10.2014)

Name and mailing address of the ISA/KR

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KIM, Jin Ho

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INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/US2014/043409

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