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(54) **SYSTEMS AND METHODS FOR SIMULATING CEMENT PLACEMENT**

(57)   A method may include receiving data related to a wellbore fluid, a wellbore, and a geological formation. The method may then determine properties associated with the wellbore fluid over a period of time based on the data; determine temperature values associated with the wellbore fluid based on the data and the properties associated with the wellbore fluid; determine an expected shape of the annulus space based on the data, the properties associated with the wellbore fluid, and the temperature values; and determine bottom-hole fluid properties associated with the wellbore fluid based on the properties of the wellbore fluid and the temperature values. The method may then generate a wellbore fluid placement map based on the bottom-hole fluid properties, the shape of the annulus space, and the temperature values, such that the wellbore fluid placement map includes expected concentration levels of the wellbore fluid.
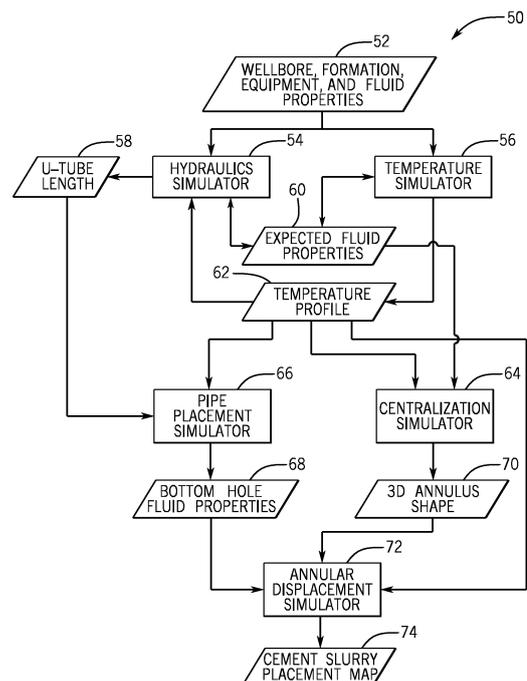
FIG. 2

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Description

BACKGROUND

[0001] This disclosure relates to the placement of cement within an annular space of a wellbore and, more particularly, to simulating the placement of the cement within the annular space of the wellbore.

[0002] This section is intended to introduce the reader to various aspects of art that may be related to various aspects of the present techniques, which are described and/or claimed below. This discussion is believed to be helpful in providing the reader with background information to facilitate a better understanding of the various aspects of the present disclosure. Accordingly, it should be understood that these statements are to be read in this light.

[0003] A wellbore drilled into a geological formation may be targeted to produce hydrocarbons from certain zones of the geological formation. To prevent zones from interacting with one another via the wellbore and to prevent fluids from undesired zones from entering the wellbore, the wellbore may be completed by placing a cylindrical casing into the wellbore and cementing the annulus between the casing and the wall of the wellbore. During cementing, cement may be injected into the annulus formed between the cylindrical casing and the geological formation. When the cement properly sets, fluids from one zone of the geological formation may not be able to pass through the wellbore to interact with one another. This desirable condition is referred to as "zonal isolation." Yet well completions may not go as planned. For example, the cement may not set as planned and/or the quality of the cement may be different than expected. In other cases, the cement may unexpectedly fail to set above a certain depth due to natural fissures in the formation.

[0004] A variety of individual simulators or modeling tools may be used to simulate various individual properties regarding the placement of cement within an annular space of a wellbore. Although each individual simulator may provide some insight on determining how the cement should be pumped into the annular space, each individual simulator may not account for the results of other simulations to accurately determine how the cement is expected to behave (e.g., dry) when placed within the annular space, an amount of pressure that is to be maintained within the well bore to avoid fracturing an adjacent formation, a predicted temperature of the cement that may influence settling of the cement, how various fluids may mix with each other when the cement is being pumped into the annular space, and the like. To effectively design a plan to place cement within the annular space of the wellbore, it may be useful to evaluate the results of each modeling tool with respect to each other, but it may also be impractical (e.g., computationally cost-prohibitive) to incorporate the results of each modeling tool with regard to cement placement to design a workflow for placing the cement within the wellbore.

SUMMARY

[0005] A summary of certain embodiments disclosed herein is set forth below. It should be understood that these aspects are presented merely to provide the reader with a brief summary of these certain embodiments and that these aspects are not intended to limit the scope of this disclosure. Indeed, this disclosure may encompass a variety of aspects that may not be set forth below.

[0006] In one embodiment, a method may include receiving, via one or more processors, data related to a wellbore fluid, a wellbore, and a geological formation. The method may then include determining one or more properties associated with the wellbore fluid over a simulated period of time when the wellbore fluid is to be pumped into an annulus space of the wellbore based at least in part on the data. The method may then determine one or more temperature values associated with the wellbore fluid over the simulated period of time based at least in part on the data and the one or more properties associated with the wellbore fluid; determine an expected three-dimensional shape of the annulus space based at least in part on the data, the one or more properties associated with the wellbore fluid, and the one or more temperature values; and determine one or more bottom-hole fluid properties associated with the wellbore fluid over the simulated period of time based at least in part on the properties of the wellbore fluid and at least a portion of the one or more temperature values. The method may then generate a wellbore fluid placement map associated with the annulus space based on the one or more bottom-hole fluid properties, the three-dimensional shape of the annulus space, and the one or more temperature values, wherein the wellbore fluid placement map comprises one or more expected concentration levels of the wellbore fluid within the annulus space after the simulated period of time expires.

[0007] In another embodiment, one or more tangible, non-transitory computer-readable media comprising instructions configured to cause at least one processor to receive data related to a wellbore fluid, a wellbore, and a geological formation. The at least one processor may then simulate a cement installation workflow for an annulus space of the wellbore based at least partly on the received data using a plurality of simulators to obtain a wellbore fluid placement map of cement placement that is expected to occur when the cement installation workflow is carried out. At least two of the plurality of simulators use a respective output from the at least two of the plurality of simulators to perform a respective operation of the at least two of the plurality of simulators.

[0008] In yet another embodiment, a computer-implemented method for simulating a fluid placement operation to obtain a fluid placement map may include performing a hydraulics simulation of a wellbore for a fluid placement operation to obtain simulated displacements of one or more fluids within an annulus space of the wellbore during the fluid placement operation based on a

hydraulics model of the one or more fluids. The computer-implemented method may then perform a temperature simulation of the wellbore for the fluid placement operation to obtain a simulated temperature profile within the wellbore, such that the temperature simulation is based at least in part on the simulated displacements of the fluids, and the hydraulics simulation is based at least in part on the simulated temperature profile within the wellbore. The computer-implemented method may then perform a centralization simulation of the wellbore to obtain an expected three-dimensional annulus shape of the annulus space based on the simulated temperature profile and the one or more simulated displacements. The computer-implemented method may also perform a pipe placement simulation of the wellbore to obtain one or more bottom-hole properties associated with the fluids based on the simulated temperature profile and the one or more simulated displacements. The computer-implemented method may also perform an annular displacement simulation of the wellbore to obtain a fluid placement map indicating one or more concentration levels of the fluids within the annulus space after the fluid placment operation has been performed based on the expected three-dimensional annulus shape and the one or more bottom-hole properties.

[0009]   Various refinements of the features noted above may be undertaken in relation to various aspects of the present disclosure. Further features may also be incorporated in these various aspects as well. These refinements and additional features may be determined individually or in any combination. For instance, various features discussed below in relation to the illustrated embodiments may be incorporated into any of the above-described aspects of the present disclosure alone or in any combination. The brief summary presented above is intended to familiarize the reader with certain aspects and contexts of embodiments of the present disclosure without limitation to the claimed subject matter.

BRIEF DESCRIPTION OF THE DRAWINGS

[0010]   Various aspects of this disclosure may be better understood upon reading the following detailed description and upon reference to the drawings in which:

    FIG. 1 is a schematic diagram of a system for installing cement within a well, in accordance with an embodiment;

    FIG. 2 is a block diagram of a workflow for using various simulators to determine an expected cement placement map of a prospective cement placement design plan, in accordance with an embodiment; and

    FIG. 3 is an example wellbore fluid placement map determined according to the workflow of FIG. 2, in accordance with an embodiment.

DETAILED DESCRIPTION

[0011]   One or more specific embodiments of the present disclosure will be described below. These described embodiments are examples of the presently disclosed techniques. Additionally, in an effort to provide a concise description of these embodiments, some features of an actual implementation may not be described in the specification. It should be appreciated that in the development of any such actual implementation, as in any engineering or design project, numerous implementation-specific decisions may be made to achieve the developers' specific goals, such as compliance with system-related and business-related constraints, which may vary from one implementation to another. Moreover, it should be appreciated that such a development effort might be complex and time consuming, but would still be a routine undertaking of design, fabrication, and manufacture for those of ordinary skill having the benefit of this disclosure.

[0012]   When introducing elements of various embodiments of the present disclosure, the articles "a," "an," and "the" are intended to mean that there are one or more of the elements. The terms "comprising," "including," and "having" are intended to be inclusive and mean that there may be additional elements other than the listed elements. Additionally, it should be understood that references to "one embodiment" or "an embodiment" of the present disclosure are not intended to be interpreted as excluding the existence of additional embodiments that also incorporate the recited features.

[0013]   When a well is drilled, metal casing may be installed inside the well and cement placed into the annulus between the casing and the wellbore. When the cement sets, fluids from one zone of the geological formation may not be able to pass through the annulus of the wellbore to interact with another zone. This desirable condition is referred to as "zonal isolation." Proper cement installation may also ensure that the well produces from targeted zones of interest.

[0014]   Embodiments of this disclosure relate to various systems, methods, and devices for efficiently generating a workflow or design for forming an annular ring within a wellbore using wellbore fluids, such as cement, cement slurry, drilling fluids or muds, completion fluids or muds, workover fluids or muds, and the like. As an example, the systems, methods, and devices of this disclosure describe various ways of generating an expected cement slurry placement map within a wellbore based on various properties of the fluids pumped into the wellbore to properly place the cement within the annular space, the temperature of the cement slurry as it is pumped into the annular space, a position of a case string while the cement is pumped into the annular space, a position of a pipe within the wellbore, and the like. The expected cement slurry placement map may thus be determined based on a number of simulators; however, the order and manner in which each simulator is performed may prove

to efficiently determine the expected cement slurry placement map for a particular cement job design.

[0015] By way of introduction, FIG. 1 schematically illustrates a system 10 for placing cement within an annular space of a well. In particular, FIG. 1 illustrates surface equipment 12 above a geological formation 14. In the example of FIG. 1, a drilling operation has previously been carried out to drill a wellbore 16. Within the wellbore 16, a casing string 18 may be positioned. Between the casing string 18 and the formation 14, an annulus space 20 may be present, such that cement may be injected into the annulus space 20 to create a cement sheath between the casing string 18 and the geological formation 14.

[0016] The cement sheath may provide a hydraulic seal that establishes zonal isolation that may prevent fluid communication between producing zones within the wellbore 16 and may block the escape of fluids to the surface. The cement sheath may also anchor and support the casing string 18 and protect other casing (e.g., steel casing) against corrosion due to contact with formation fluids.

[0017] The bottom end of the casing string 18 may include a shoe 22. The shoe 22 may be a guide shoe or a float shoe. In either case, the shoe 22 may be a device that guides the casing string 18 toward the center of the wellbore 16 to minimize contact with rough edges or washouts during installation. In addition, centralizers 24 may be placed within the annulus space 20 to prevent the casing string 18 from sticking while it is lowered into the wellbore 16. The centralizers 24 also help keep the casing string 18 in the center of the wellbore 16 to help ensure placement of a uniform cement sheath in the annulus space 20.

[0018] Generally, when the casing string 18 is initially placed within the wellbore 16, the interior of the casing string 18 may fill with drilling fluid that may be present after the wellbore 16 has been drilled. As such, a cementing operation includes removing the drilling fluid from the interior of the casing string 18, placing a cement slurry in an annulus, and filling the interior of the casing string 18 with a displacement fluid, such as a drilling fluid, brine, or water.

[0019] In addition to the material disposed within the wellbore 16, the system 10 may include surface equipment 26 that may carry out a cement installation operation, various well logging operations to detect conditions of the wellbore 16, and the like. As used herein, the cement operation may generally refer to the process of pumping cement into the wellbore 16 to form an annular ring of cement between the casing string 18 and the geological formation 14. In one embodiment, the surface equipment 26 may include equipment that store cement slurries, drilling fluids, displacement fluids, spacer fluids, chemical wash fluids, and the like. The surface equipment 26 may include piping and other materials used to transport the various fluids described above into the wellbore 16. The surface equipment 26 may also include pumps and other equipment (e.g., batch mixers, centrifugal pumps, liquid additive metering systems, tanks, etc.) that may fill in the interior of the casing string 18 with the fluids discussed above.

[0020] Generally, when performing a cement operation (e.g., filling in the annulus space 20), chemical washes and spacer fluids may initially be pumped into the interior of the casing string 18, thereby displacing the drilling fluid that may be present inside the casing string 18 from previous drilling operations. In one embodiment, a bottom plug (not shown) may then be placed inside the casing string 18 followed by a volume of cement slurry that is sufficient to fill the annulus space 20. As the wellbore fluid is pumped into the interior of the casing string 18, the cement slurry may force the drilling fluid out of the casing interior via the shoe 22 and up the annulus space 20 until the bottom plug lands at the bottom of the casing string 18.

[0021] The bottom plug may include a membrane that ruptures when the bottom plug reaches the bottom of the casing string 18. As such, the bottom plug may now have a pathway form the cement slurry to enter the annulus space 20 via the membrane of the bottom plug after the bottom plug reaches the bottom of the casing string 18. A top plug (not shown) may then be placed on top of the cement slurry followed by displacement fluid. The displacement fluid may then be pumped into the interior of the casing string 18 forcing the cement slurry into the annulus space 20 until the top plug reaches the bottom plug, thereby isolating the interior of the casing string 18 from the slurry within the annulus space 20.

[0022] After the cement slurry is placed within the annulus space 20, the slurry may take time to cure. The cured cement may then be evaluated using certain logging tools to ensure that the cement placed within the annulus space 20 is robust and capable of maintaining a threshold stress between the casing string 18 and the geological formation 14. That is, after the cement has set, the cement should withstand stress and be a hydraulics barrier to prevent any formation fluid (e.g., gas) flow through the cement.

[0023] In some embodiments, the cement operation may be controlled by a data processing system 28 that includes a processor 30, memory 32, storage 34, and/or a display 36. The processor 30 may include any suitable processor capable of executing computer-readable instructions (e.g., non-transitory). Moreover, it should be understood that the processor 30, in some embodiments, may include multiple processors operating in conjunction with each other. The data processing system 28 may control the cement operation described above including the operation of the pumps, the placement of the plugs, the switching between various fluids, and the like. In addition, the data processing system 28 may evaluate the integrity of the cement annular ring after the cement operation is completed. Additionally, the data processing system 28 or any other suitable computing device may perform a design workflow or simulation of the cement operation prior to placing the cement within the wellbore

16. That is, the data processing system 28 may use one or more models or simulations to determine various parameters (e.g., amount of cement, displacement fluid, pressure to pump cement, size of plugs) to use when performing the 32 and/or storage 34. As such, the memory 32 and/or the storage 34 of the data processing system 28 may be any suitable article of manufacture that can store the instructions. The memory 32 and/or the storage 34 may be ROM memory, random-access memory (RAM), flash memory, an optical storage medium, or a hard disk drive, to name a few examples. The display 36 may be any suitable electronic display that can display a cement slurry placement map, expected parameters for performing the cement operation, or the like.

[0024]   Placing cement in the annulus space 20 located between casing string 18 and formation 14 is a challenging operation. That is, before the cement may be pumped into the annulus space 20, the drilling mud originally in place in the annulus space 20 at the end of the drilling phase is fully displaced from the annulus space 20 before the cement slurry may replace it. There are many challenges associated with properly placing the cement slurry within the annulus space 20. For instance, the annulus space 20 may not be concentric, despite the use of the centralizers 24. The casing string 18 will naturally lean towards the bottom of the hole of the wellbore 16. In addition, since the drilling mud and cement slurry are both viscoplastic and exhibit a yield stress, these two fluids may remain unyielded in the narrow part of an eccentric portion of the annulus space 20, thus preventing the correct placement of the cement slurry. Moreover, drilling mud and slurry may have a different density leading to flow segregation whereby the lighter fluid flows at the top of the annulus, bypassing the heavier fluid lying at the bottom. With this in mind, designing a cement operation may include assessing whether the drilling mud will be sufficiently removed from the annulus space 20 and the slurry will be correctly put in place within the annulus space 20.

[0025]   By employing the data processing system 28 or any other suitable processor-based computing device to simulate the placement of cement within the annulus space 20, operators performing the cement operation may adjust various parameters regarding the operations to correctly place the cement slurry within the annulus space 20 to ensure that the cement casing is capable to withstand the forces that may be exerted on the cement for the life of the well. In one embodiment, the data processing system 28 may receive various types of information regarding the wellbore 16 (e.g., type of rock formation within the formation 14, depth of wellbore 16, properties of drilling mud, wellbore fluid, and other fluids, temperature within the wellbore 16, pressures within the wellbore 16) and generate a simulation or model that accounts for the effects of each of these types of information while the cement operation is being performed. However, when performing this single simulation, it may prove to be impractical to generate a resulting simulation

of the cement operation due to the amount of computing resources (e.g., power, memory) used to perform such simulations with respect to a large and complex wellbore 16. As such, in the presently disclosed embodiments, the data processing system 28 or any other suitable computing device (e.g., desktop computer, cloud-based computing system, laptop, mobile computing device) may generate simulations for various attributes of the cement operation independently or according to a particular workflow, such that the simulations are generated in a practical manner within an acceptable amount of time to implement the determined design.

[0026]   In one embodiment, the data processing system 28 may use a cloud-based computing system 38 to assist performing the computations associated with generating the model or simulation of the cement operation. The cloud-based computing system 38 may include a number of computers that may be connected through a real-time communication network, such as the Internet. In certain embodiments, large-scale analysis operations may be distributed over the computers that make up the cloud-based computing system 38. Generally, the computers or computing devices provided by the cloud-based computing system 38 may be dedicated to performing various types of complex and time-consuming analysis that may include analyzing a large amount of data and generating simulations and/or models described herein.

[0027]   In any case, by generating a model or simulation of the cement operation that represents a plan of how the wellbore fluid should be pumped into the annulus space 20 over time according to the workflow described herein, the data processing system efficiently uses various computing resources provided by the data processing system 28 or the like. That is, the presently disclosed workflow for generating a model of the cement operation and an expected wellbore fluid placement map provides an improvement in which the data processing system 28 or any other suitable computing device may perform the simulation or modeling operations of the cement operation. As such, the presently disclosed systems and techniques are directed to a specific implementation of a solution to a problem in the software arts related to efficiently generating a model or simulation of a cement operation that accounts for the complexities of a wellbore.

[0028]   With the foregoing in mind, FIG. 2 illustrates a block diagram of a workflow 50 for using various types of simulators to determine an expected wellbore fluid placement map in accordance with embodiments described herein. Although the workflow 50 will be discussed below as being performed by the data processing system 28, it should be noted that any suitable computing device may perform the workflow 50.

[0029]   Referring now to FIG. 2, the data processing system 28 may initially receive information related to the location in which a cement annular ring may be built. As such, the data processing system 28 may receive wellbore, formation, equipment, and fluid properties 52, which may include various types of data regarding the

wellbore 16, the formation 14, the equipment to be used for the cement operation, the various fluids that may be used for the cement operation and the like. The data regarding the wellbore 16 may include details regarding the wellbore 16 including, for example, the depth of the wellbore 16, the temperature at various locations within the wellbore 16, the pressure values at various locations within the wellbore 16, and the like. In addition, the data may include information from previous well logs regarding the wellbore 16 with regard to formation properties, well trajectory, density of the provided fluids, the viscosity of the provided fluids, and the like. In addition, the data may include viscosity and/or rheology properties related to the fluids as measured by various surface equipment.

[0030] The data regarding the formation 14 may include the locations of various rock types or geological layers within the formation 14. The data regarding the formation 14 may also include information related to the location of various hydrocarbon deposits, the existing fractures within the formation 14, and the like.

[0031] The data regarding the equipment may include information related to the types of equipment (e.g., capacity tank, pumps, storage equipment for both solids and liquids, blending equipment, mixers, metering equipment) that may be available to perform the cement operation. The fluid information may include details related to the types of fluids (e.g., drilling fluid, chemical washout, wellbore fluid, displacement fluid) including, for example, the amount of fluid available, the temperature of the fluid, the viscosity of the fluid, the density of the fluid, and other relevant parameters that describe the properties of the various fluids used in the cement operation. In addition, the fluid information may include a description of the fluids, which may include a density model, a viscosity model, and a multi-phase model. The fluid information may be detailed with models because the respective modeled properties are not constant and usually change with time, pressure, temperature, fluid velocity, fluid contamination, and the like. The multi-phase model may indicate an expected percentage of solid, water, and hydrocarbons that may make up a formation fluid. The solids percentage may provide information regarding the particles size distribution within the fluid. Generally, it may be useful to measure each of the above-listed properties at regular intervals at known conditions (e.g., pressure, temperature) and then use the properties as inputs to another model that may predict certain values related to the formation fluids under the conditions experienced in the well.

[0032] Additional data regarding the wellbore 16 may include a flow rate at which certain fluids are injected in the wellbore 16, a pressure at various surface pumps, a pressure at a wellhead (e.g., cement head), and the like. For the various models described above, it may be useful to determine a starting point for the simulation based on, for example, a temperature profile in the wellbore 16 at t = 0, fluid(s) in the well, properties of the fluids, and the like.

[0033] In one embodiment, at least a portion of the information 52 may be provided as inputs into the hydraulics simulator 54 and the temperature simulator 56. The hydraulics simulator 54 may include a one-dimensional simulator (e.g., hydraulics model) that assumes piston-like displacement of all of the fluids within the wellbore 16. Since the hydraulics simulator 54 is a one-dimensional simulator, it may assume a homogeneous azimuthal distribution. As such, the hydraulics simulator 54 may not indicate the azimuthal position of the cement slurry within the annulus space 20. However, the hydraulics simulator 54 may provide details regarding a location of each fluid within the wellbore 16 and the annulus space 20 during the cement operation assuming that different fluids are not mixed with each other. As such, in one embodiment, the output of the hydraulics simulator 54 may include fluid position with respect to time during the cement operation (e.g., down the flow patch and up the annulus space 20). The hydraulics simulator 54 may also provide information related to the pressure of the fluid throughout the flow path with respect to time. As such, the hydraulics simulator 54 may determine whether the pressure in the annulus space 20 will remain above a pore pressure of the formation 14 and below a fracture pressure of the formation 14 during the cement operation. The pressure information related to the fluids pumped into the annulus space 20, as well as the fluid position with respect to time, may then be output by the hydraulics simulator as expected fluid properties 60 of the fluids.

[0034] The hydraulics simulator 54 may also determine a dynamic length of an air gap, called u-tube (e.g., u-tube length 58), at the top of the casing string 18 that may occur due to hydrostatic imbalance between the casing string 18 and the annulus space 20. This imbalance may result from the density contrasts between the fluids present within the wellbore 16 during the cement operation. For example, the cement slurry may be denser than the drilling mud being displaced by the cement slurry.

[0035] In certain embodiments, a temperature simulator 56 may be coupled with the hydraulics simulator 54, such that the temperature simulator 56 may provide an expected temperature of each fluid type within the flow path of the wellbore 16 over a period of time associated with the cement operation. The temperature simulator 56 may be coupled with the hydraulics simulator 54 in that at various time steps, the position of a particular fluid type (e.g., wellbore fluid, cement slurry) and the velocity of the fluid type may be provided to the temperature simulator 56 from the hydraulics simulator 54 (e.g., via the expected fluid properties 60). For instance, since fluid properties, such as density and rheology are a function of temperature, the temperature simulator 56 may use this information, as provided via the expected fluid properties 60, to determine the expected temperature of each fluid type throughout the course of the cement operation. The output of the temperature simulator 56 may thus include a temperature profile 62 that details the expected temperature values of various fluid types employed dur-

ing the cement operation with respect to time and the position of the respective fluid type within the flow path.

[0036] In addition to providing the expected fluid properties 60 to the temperature simulator 56, the hydraulics simulator 54 may also receive the temperature profile 62 output by the temperature simulator 56 and update its respective simulation to more accurately determine the expected fluid properties 60 and the u-tube length 58 during the course of the cement operation. As such, the hydraulics simulator 54 and the temperature simulator 56 may assist each other in determining how the cement slurry is behaving during the cement operation. In some embodiments, the hydraulics simulator 54 and the temperature simulator 56 may exchange relevant information upon completion of a respective iteration of the respective simulation. For instance, after the hydraulics simulator 54 completes one iteration and determines the expected fluid properties 60, the temperature simulator 56 may receive this information to determine the corresponding temperature profile 62 in one iteration. The resulting temperature profile 62 may then be passed to the hydraulics simulator 54, which may perform an updated iteration of its respective simulation using the updated temperature profile 62. Each iteration may be related to a time step and the iterative process may then continue for the expected duration of the cement operation. Indeed, to determine the expected fluid properties, the temperature simulator 56 may use the pressure data determined by the hydraulics simulator 54 and the hydraulics simulator 54 may use the temperature data determined by the temperature simulator 56. As such, the coupling between both simulators enables each respective simulator to output improved results. Moreover, based on the results of each simulator, the presently disclosed techniques may include iteratively determining the expected fluid properties 60 until the expected fluid properties 60 converge towards a stable solution.

[0037] It should be noted that various simulators described herein, such as the hydraulics simulator 54 and the temperature simulator 56, may be coupled together in a variety of techniques. For instance, various simulators may be coupled to each other using linear coupling coefficients, such as the method described in U.S. Patent Application Publication No. 2013132050, a functional mock-up interface (FMI), and the like. In general, a functional mock-up interface (FMI) is a standardized protocol to communicate between solvers (e.g., simulators) to carry out a coupled simulation between two or more simulators. The coupled simulations can be carried out in a co-simulation mode with data being exchanged between functional mock-up units (FMU). With this in mind, two approaches may be used to couple, for example, a fluid simulator and a structure simulator. The first approach may be characterized as a strong coupling that uses an implicit time integration method, such that the fluid simulator and the structure simulator share results with each other to formulate respective outputs. The second approach may be characterized as a weak coupling where

the time integration method is classified as explicit, and the fluid simulator and structure simulator share results obtained from a previous time step. As a result, no iteration is used for the data exchange.

[0038] After the hydraulics simulator 54 and the temperature simulator 56 determines the expected fluid properties 60 and the temperature profile 62 over the course of the cement operation, the data processing system 28 may input these datasets into a centralization simulator 64. The centralization simulator 64 may provide a position of the casing string 18 within the wellbore 16 at a given time during the cement operation based on the expected number and positions of the centralizers 24 within the annulus space 20. After determining an expected number of centralizers and the expected locations of each centralizer, the centralization simulator 64 may use the centralizer information (e.g., number and position) and data related to fluids positions, the pressure profile in the flow path, the drag force profile in the flow path due to the flow, and the temperature in the casing string, acquired via the expected fluid properties 60 and the temperature profile 62, to determine an expected three-dimensional annulus shape 70 for the annulus space 20. In one embodiment, the centralization simulator 64 may be executed iteratively to determine a number and position for each centralizer that may be placed within the annulus space to achieve a specified (e.g., input) annulus shape of the annulus space 20 or an annulus shape that is within a threshold of the specified annulus shape.

[0039] While the centralization simulator 64 is generating the 3D annulus shape 70, a pipe displacement simulator 66 may be executed to determine bottom-hole fluid properties 68. That is, the pipe displacement simulator 66 may determine the properties of the fluid types as they pass through the shoe 22. Unlike the hydraulics simulator 54, the pipe displacement simulator 66 may not assume that the fluids in the wellbore 16 behave according to a piston-like displacement. As such, the pipe displacement simulator 66 may provide concentration profiles (e.g., the bottom-hole fluid properties 68) of the fluids within the casing at the shoe 22 as a function of depth and time. To determine the bottom-hole fluid properties 68, the pipe displacement simulator 66 may receive the u-tube length 58 and the temperature profile 62 information described above as inputs to determine fluids concentrations and flow rate with respect to time at the shoe 22 for the course of the cement operation. In this way, the pipe displacement simulator 66 may focus on the behavior of the fluids at the shoe 22 with respect to the u-tube length 58, as provided by the hydraulics simulator 54.

[0040] After the bottom-hole fluid properties 68 and the 3D annulus shape 70 is determine by the pipe displacement simulator 66 and the centralization simulator 64, respectively, the data processing system 28 may provide these inputs, along with the temperature profile 62, to an annular displacement simulator 72. The annular displacement simulator 72 may determine a cement slurry

placement map 74 based on the full three-dimensional shape of the annulus (e.g., 3D annulus shape 70). That is, the annular displacement simulator 72 may account for the uneven flow of the slurry in the eccentric portion of the annulus space 120 that may be created due to the movement or lack of movement of the casing string 18 during the cement operation and the like.

[0041] In one embodiment, the annular displacement simulator 72 may simulate or model how fluids may flow faster in the larger part of the annulus space 20 and sometimes remain unyielded in a narrow part of the annulus space 20. In addition, by-passing of drilling mud may also be caused by fluid property contrasts such as rheology and density contrasts. The annular displacement simulator 72 may also accounts for such effects in addition to handling the actual annulus geometry. Generally, the annular displacement simulator 72 receives the 3D annulus shape 70, the bottom-hole fluid properties 68 (e.g., fluids concentrations and flow rate), and the temperature profile 62 (e.g., temperature within the annulus space 20) to determine how various fluid types may mix or move unevenly within the annulus space 20 during the cement operation. The fluid mixing may then be propagated to the end of the simulation of the cement operation to determine a cement slurry placement or concentration map 74. The cement slurry placement map 74 may detail the slurry volume fraction as a function of depth and azimuth. As such, the cement slurry placement map 74 may provide information regarding how well the cement will cure and will remain in place after being placed within the annulus space 20. Moreover, the cement slurry placement map 74 may account for the various fluids (e.g., drilling fluid, spacer fluid, mud) that may not have been removed from the annulus space 20 and may have instead mixed with the cement slurry and remained in the annulus space 20 after the cement has cured. As a result, the cement placement map 74 may enable the data processing system 28 to determine whether the cement operation would adequately maintain a threshold stress or hydraulic barrier between the casing string 18 and the formation 14, prevent formation fluids from moving within the annulus space 20, and the like.

[0042] FIG. 3 illustrates an example cement slurry placement map 80 that details the concentration of levels of the slurry within the annulus space 20. The vertical axis of the example cement slurry placement map 80 corresponds to a measured depth along the well bore 16 and the horizontal axis corresponds to the azimuthal distance around the annulus. As shown in the example cement slurry placement map 80, the annulus space 20 is primarily filled with slurry with near 100% concentration, as indicated in region 82. However, various portions 84 within the cement slurry placement map 80 may indicate that the concentration of the slurry may be less than 100%.

[0043] Based on how the concentration of the cement slurry may be placed within the annulus space 20 according to the cement slurry placement map 74, the data

processing system 28 may evaluate whether cement annular ring will sufficiently maintain a threshold stress level or hydraulic barrier between the formation 14 and the casing string 18. For instance, the data processing system 28 may use the cement slurry placement map 74 as an input into a structural finite element simulator to determine whether the annular cement ring will sustain the various stresses that may be placed on the annular cement ring during operation of the well (e.g., hydrocarbon production for the life of the well and after the well has been decommissioned). In some embodiments, additional inputs, such as locations in which the formation 14 will be fractured, locations in which the annular cement ring may be perforated, and other structural parameters related to the annular cement ring that may change during the life of the well, may also be provided to the structural finite element simulator to determine whether the annular cement ring will sustain the various stresses that may be placed on the annular cement ring during operation of the well (e.g., hydrocarbon production for the life of the well).

[0044] If the data processing system 28 determines that the cement annular ring will not maintain the threshold pressures or sustain the expected stresses, the data processing system 28 may adjust various parameters of one or more of the simulators of the workflow 50 to improve the concentration levels of the cement slurry within the cement annular ring. For instance, the data processing system 28 may adjust the fluid properties of the fluids used during the cement operation, adjust the pump rates used during the cement operation, control the friction pressure drop, control the mixing of the fluids during the cement operation, and the like. In addition, the data processing system 28 may adjust the number and/or placement of the centralizers used in the centralization simulator 64 to improve the concentration levels of the cement slurry within the annular ring.

[0045] In addition to performing the workflow 50 using the data processing system 28 or another suitable computing device, the workflow 50 may be performed in parallel with respect different input parameters (e.g., wellbore, formation, equipment, and fluid properties 52). In one embodiment, upon determining that the cement slurry may not maintain the threshold pressures or sustain the expected stresses, the data processing system 28 may identify a range of parameters that may be adjusted to improve the structural integrity of the resulting annular cement ring. To efficiently determine which of the parameters within the identified range may be best suited to provide an improved annular cement ring, the data processing system 28 may specify the range of parameters to the cloud-based computing system 38. The cloud-based computing system 38 may perform the workflow 50 for each parameter (or a portion of the parameters) of the identified range. By using the computing efficiency and power of the cloud-based computing system 38, multiple cement slurry placement maps 74 may be generated in parallel and provided to the data process-

ing system 28. The data processing system 28 may then compare the generated cement slurry placement maps 74 with each other to identify which of the generated cement slurry placement maps 74 may be best suited for maintaining the threshold pressures or sustaining the expected stresses during the life of the well.

[0046] Although the foregoing description of the systems and techniques for simulating cement placement has been detailed with respect to cement slurries, it should be noted that the systems and techniques described herein may also be employed to determine the placement of other fluids that may be pumped into the wellbore 16. For instance, the presently disclosed methods may be used to determine the placement of drilling mud, spacers, wash, and the like.

[0047] Although only a few example embodiments have been described in detail above, those skilled in the art will readily appreciate that many modifications, equivalents, and alternatives are possible in the example embodiments without materially departing from the systems and methods herein. Accordingly, all such modifications are intended to be included within the scope of this disclosure as defined in the following claims. In the claims, means-plus-function clauses are intended to cover the structures described herein as performing the recited function and not only structural equivalents, but also equivalent structures. Thus, although a nail and a screw may not be structural equivalents in that a nail employs a cylindrical surface to secure wooden parts together, whereas a screw employs a helical surface, in the environment of fastening wooden parts, a nail and a screw may be equivalent structures. It is the express intention of the applicant not to invoke 35 U.S.C. §112, paragraph 6, for any limitations of any of the claims herein, except for those in which the claim expressly uses the words 'means for' together with an associated function.

Claims

1. A method, comprising:

    receiving, via one or more processors, data related to a wellbore fluid, a wellbore, and a geological formation;
    determining, via the one or more processors, one or more properties associated with the wellbore fluid over a simulated period of time when the wellbore fluid is to be pumped into an annulus space of the wellbore based at least in part on the data;
    determining, via the one or more processors, one or more temperature values associated with the wellbore fluid over the simulated period of time based at least in part on the data and the one or more properties associated with the wellbore fluid;
    determining, via the one or more processors, an

    expected three-dimensional shape of the annulus space based at least in part on the data, the one or more properties associated with the wellbore fluid, and the one or more temperature values;
    determining, via the one or more processors, one or more bottom-hole fluid properties associated with the wellbore fluid over the simulated period of time based at least in part on the one or more properties associated with the wellbore fluid and at least a portion of the one or more temperature values; and
    generating, via the one or more processors, a wellbore fluid placement map associated with the annulus space based on the one or more bottom-hole fluid properties, the three-dimensional shape of the annulus space, and the one or more temperature values, wherein the wellbore fluid placement map comprises one or more expected concentration levels of the wellbore fluid within the annulus space after the simulated period of time expires.

2. The method of claim 1, wherein the one or more properties comprise pressure information associated with the wellbore fluid over the simulated period of time.

3. The method of claim 1, wherein the one or more properties comprise a location of the wellbore fluid over the simulated period of time.

4. The method of claim 1, wherein the one or more properties associated with the wellbore fluid comprises a length of a u-tube, wherein the u-tube comprises an air gap at a top of the wellbore.

5. The method of claim 1, comprising determining, via the one or more processors, at least one of the one or more properties associated with the wellbore fluid based on at least one of the temperature values.

6. The method of claim 1, wherein the expected three-dimensional shape of the annulus space is determined based at least in part on a pressure profile of the wellbore fluid over the simulated period of time and a drag force profile associated with the wellbore fluid.

7. The method of claim 1, wherein the one or more bottom-hole properties are associated with a portion of the simulated period of time when the wellbore fluid passes through a shoe of the wellbore.

8. The method of claim 1, wherein the wellbore fluid placement map comprises a volume fraction of the wellbore fluid within the annulus space as a function of depth and azimuth.

9. The method of claim 1, comprising:

determining, via the one or more processors, whether the wellbore fluid would maintain a threshold stress between a casing string and the geological formation based on the wellbore fluid placement map;
adjusting, via the one or more processors, the data related to the wellbore fluid, the wellbore, the geological formation when the wellbore fluid is determine to not maintain the threshold stress; and
determining, via the one or more processors, a length of a u-tube associated with the wellbore and the one or more properties associated with the wellbore fluid over the simulated period of time when the wellbore fluid is pumped into the annulus space of the wellbore based at least in part on the adjusted data.

10. One or more tangible, non-transitory computer-readable media comprising instructions configured to cause one or more processors to:

receive data related to a wellbore fluid, a wellbore, and a geological formation; and
simulate a cement installation workflow for an annulus space of the wellbore based at least partly on the received data using a plurality of simulators to obtain a wellbore fluid placement map of cement placement that is expected to occur when the cement installation workflow is carried out, wherein at least two of the plurality of simulators use a respective output from the at least two of the plurality of simulators to perform a respective operation of the at least two of the plurality of simulators.

11. The computer-readable media of claim 10, wherein the plurality of simulators comprise a hydraulics simulator, a temperature simulator, a pipe placement simulator, a centralization simulator, and an annular displacement simulator.

12. The computer-readable media of claim 10, wherein the instructions configured to cause the one or more processors to simulate the cement installation workflow comprise instructions to:

determine a length of a u-tube associated with the wellbore and one or more properties associated with the wellbore fluid over a simulated period of time when the wellbore fluid is pumped into an annulus space of the wellbore based at least in part on the data;
determine one or more temperature values associated with the wellbore fluid over the simulated period of time based at least in part on the

data and the one or more properties associated with the wellbore fluid;
determine an expected three-dimensional shape of the annulus space based at least in part on the data, the one or more properties associated with the wellbore fluid, and the one or more temperature values;
determine one or more bottom-hole fluid properties associated with the wellbore fluid over the simulated period of time based at least in part on the length of the u-tube and at least a portion of the one or more temperature values; and
generate the wellbore fluid placement map associated with the annulus space based on the one or more bottom-hole fluid properties, the three-dimensional shape of the annulus space, and the one or more temperature values, wherein the wellbore fluid placement map comprises one or more expected concentration levels of the wellbore fluid within the annulus space after the simulated period of time expires.

13. The computer-readable media of claim 11, wherein the expected three-dimensional shape of the annulus space is determined based at least in part on a number of centralizers associated with the wellbore.

14. The computer-readable media of claim 13, wherein the instructions are configured to cause the one or more processors to:

determine whether the expected three-dimensional shape of the annulus space is within a threshold of a specified three-dimensional shape of the annulus space;
adjust the number of centralizers when the expected three-dimensional shape of the annulus space is not within the threshold of a specified three-dimensional shape of the annulus space; and
determine the expected three-dimensional shape of the annulus space based at least in part on the adjusted number of centralizers.

15. The computer-readable media of claim 13, wherein the expected three-dimensional shape of the annulus space is determined based at least in part on a location of each of the number of centralizers associated with the wellbore.

16. The computer-readable media of claim 12, wherein the one or more properties associated with the wellbore fluid are determined assuming that the wellbore fluid behaves according to a piston-like displacement.

17. A computer-implemented method for simulating a fluid placement operation to obtain a fluid placement

map, comprising:

> performing a hydraulics simulation of a wellbore for the fluid placement operation to obtain simulated displacements of one or more fluids within an annulus space of the wellbore during the fluid placement operation based on a hydraulics model of the one or more fluids;
> performing a temperature simulation of the wellbore for the fluid placement operation to obtain a simulated temperature profile within the wellbore, wherein the temperature simulation is based at least in part on the simulated displacements of the fluids, and wherein the hydraulics simulation is based at least in part on the simulated temperature profile within the wellbore;
> performing a centralization simulation of the wellbore to obtain an expected three-dimensional annulus shape of the annulus space based on the simulated temperature profile and the one or more simulated displacements;
> performing a pipe placement simulation of the wellbore to obtain one or more bottom-hole properties associated with the fluids based on the simulated temperature profile and the one or more simulated displacements; and
> performing an annular displacement simulation of the wellbore to obtain a fluid placement map indicating one or more concentration levels of the fluids within the annulus space after the fluid placement operation has been performed based on the expected three-dimensional annulus shape and the one or more bottom-hole properties.

18. The method of claim 17, comprising:

> determining whether the fluids will maintain a threshold stress for a life of a well based on the fluid placement map; and
> adjusting one or more properties of the fluids when the fluids will not maintain the threshold stress; and
> performing the hydraulics simulation again based on the one or more properties.

19. The method of claim 17, wherein the hydraulics simulation is configured to obtain pressure information regarding the fluids.

20. The method of claim 17, wherein the hydraulics simulation is configured to obtain a dynamic length of an air gap at a top of a casing string.
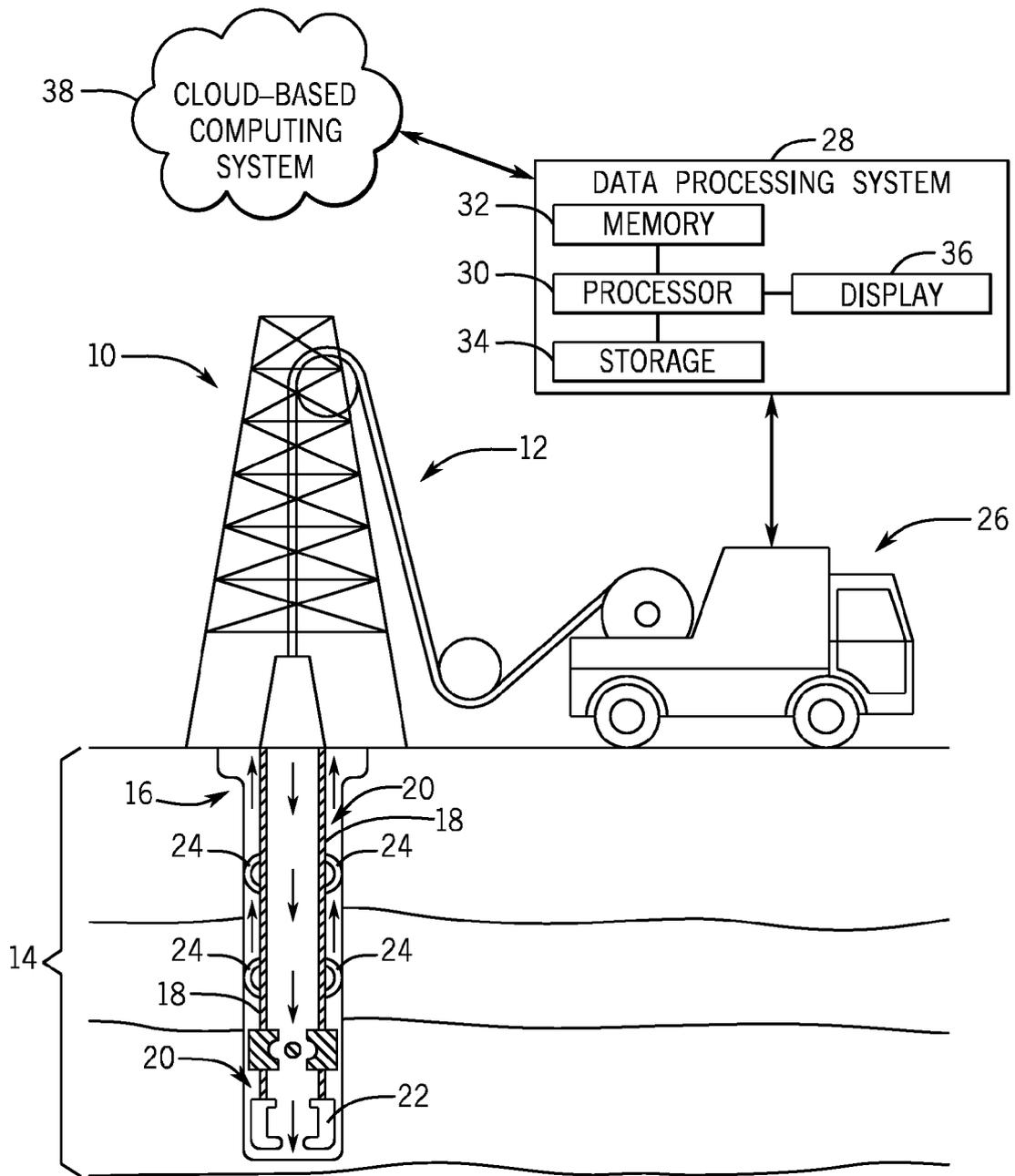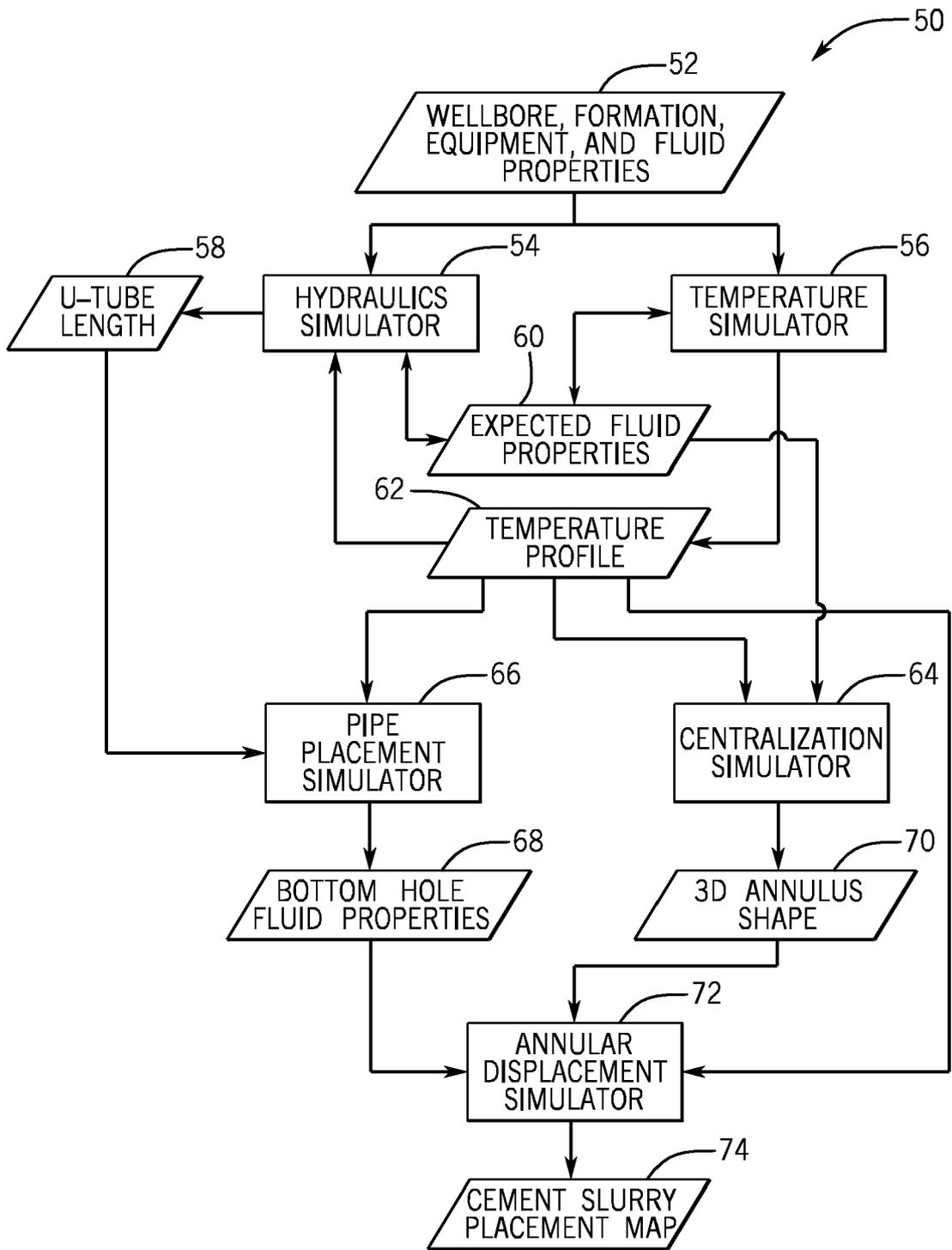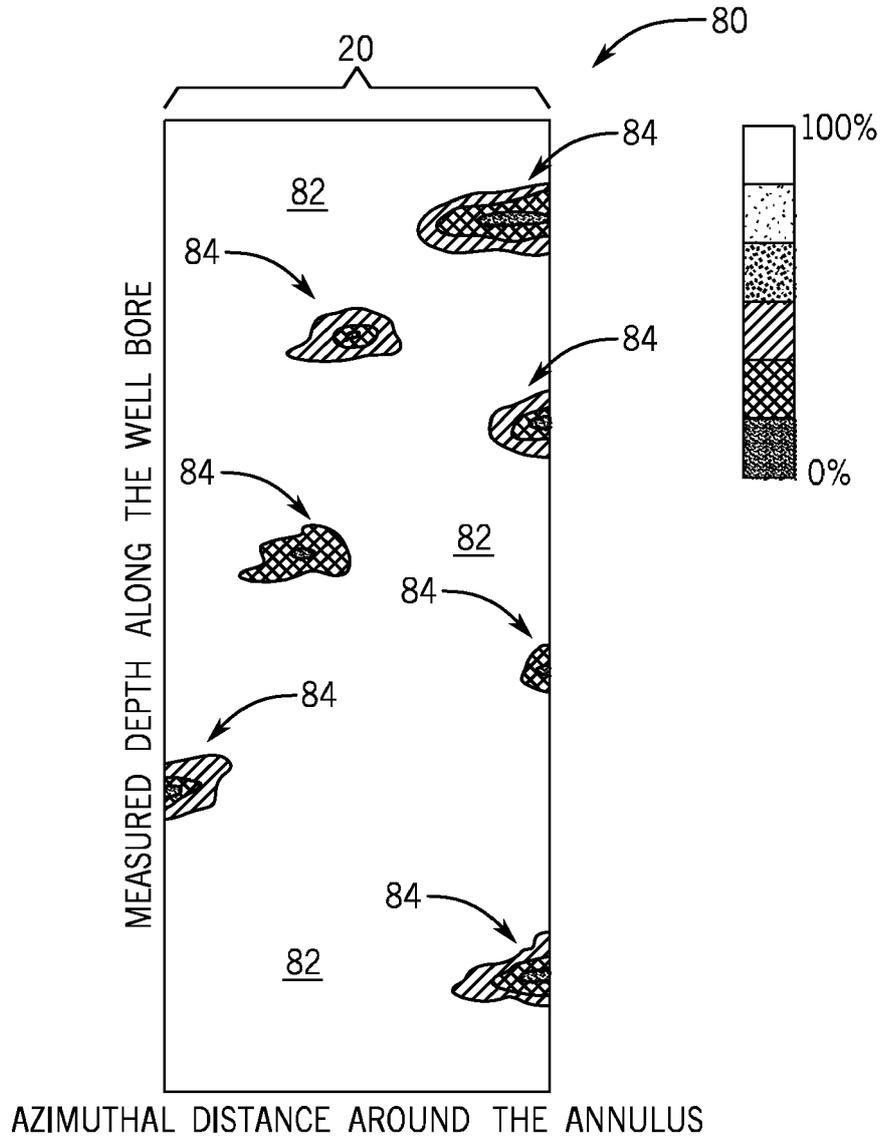
FIG. 1

FIG. 2

FIG. 3

Europäisches
Patentamt

European
Patent Office

Office européen
des brevets

EUROPEAN SEARCH REPORT

Application Number

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1

Place of search	Date of completion of the search	Examiner
The Hague	21 March 2017	Maukonen, Kalle

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