

Claims

1. Apparatus for use in sensing temperature along a wellbore, comprising:
tubing comprising a plurality of temperature sensor modules provided at
locations along the inside of the tubing, having electrical properties that vary with
5 temperature; and
an electrical network comprising a plurality of wires and said plurality of
temperature sensor modules, wherein the plurality of wires and plurality of
temperature sensor modules are configured as a matrix by which the plurality of
wires comprises a first group of wires and a second, different group of wires and
10 each wire of the first group is electrically connected to each wire of the second group
once, each electrical connection being by a respective temperature sensor module of
the plurality of temperature sensor modules, such that each temperature sensor
module can be individually electrically connected by a pair of wires comprising a first
wire from the first group and a second wire from the second group.
- 15 2. Apparatus as claimed in claim 1, wherein at least one, or each temperature sensor
module comprises a single electronic component.
3. Apparatus as claimed in claim 2, wherein the maximum physical extent of the single
electronic component in any axis is less than 7mm, preferably less than 5mm, more
preferably less than 4mm, even more preferably less than 3mm.
- 20 4. Apparatus as claimed in any preceding claim, wherein the temperature sensor
modules comprise temperature sensors provided at least in part by at least one
semiconductor element having electrical properties that vary with temperature.
5. Apparatus as claimed in claim 4, wherein the apparatus is configured to use only the
temperature sensitivity of the or each temperature sensitive semiconductor element
25 of each temperature sensor module to infer a temperature of the temperature sensor
module.
6. Apparatus as claimed in claim 4 or 5, wherein the at least one semiconductor
element is a diode.
7. Apparatus as claimed in claim 6, wherein the diode is selected from at least one of:
30 constant current diodes; constant voltage diodes.
8. Apparatus as claimed in any preceding claim, wherein at least one, or each
temperature sensor module comprises a single passive electronic component.
9. Apparatus as claimed in any of claims 1 to 5, wherein the temperature sensor
modules comprise temperature sensors that are configured as silicon bandgap
35 temperature sensors each having two p-n junctions that, in use, are operated at
different current densities to infer a temperature by determining a voltage difference

between the two p-n junctions at the different current densities, which is proportional to absolute temperature.

10. Apparatus as claimed in any of claims 1 to 3, wherein the temperature sensor modules each further comprise a resistance thermometer, optionally a platinum resistance thermometer, wherein the apparatus is configured such that the temperature sensitivity of each resistance thermometer is used to infer a thermal characteristic of the environment to which the tubing is exposed at the location of that temperature sensor.
11. Apparatus as claimed in any of claims 1 to 3, wherein the temperature sensors each further comprise a crystal oscillator, each crystal oscillator having an electrical oscillation frequency that varies with temperature.
12. Apparatus as claimed in claim 11, wherein the crystal oscillators are quartz crystals.
13. Apparatus as claimed in any preceding claim, wherein the temperature sensor modules each comprise a diode arranged to block current from flowing back through the temperature sensor modules in the matrix.
14. Apparatus as claimed in claim 13, wherein the blocking diode is a low reverse current leakage diode, optionally having a reverse current leakage of less than 50 nA at the operational voltage of the apparatus and at a temperature of 25 degrees Celsius.
15. Apparatus as claimed in any of claims 5 to 7, wherein the temperature sensor modules each comprise a diode arranged to block current from flowing back through the temperature sensor modules in the matrix, and wherein the blocking diode is a low reverse current leakage diode, optionally having a reverse current leakage of less than 50 nA at the operational voltage of the apparatus and at a temperature of 25 degrees Celsius, and wherein the low reverse current leakage diode provides the temperature sensitivity of each temperature sensor module.
16. Apparatus as claimed in any preceding claim, wherein the tubing comprises a matrix of at least 10 wires, preferably at least 15 wires, more preferably at least 18 wires, and in particular 19 wires.
17. Apparatus as claimed in any preceding claim, wherein the tubing comprises 6 temperature sensor modules along its length, preferably at least 16 modules, more preferably at least 19 modules, still more preferably at least 30 modules, still more preferably at least 60 modules, and still more preferably at least 80 modules.
18. Apparatus as claimed in any preceding claim, further comprising a control module electrically connected to multiple temperature sensor modules, via the electrical network, and configured to, in use, periodically switch through combinations of pairs of wires to electrically connect and infer a temperature at each of the temperature sensors.

19. Apparatus as claimed in claim 18, wherein the control module comprises one or more relays arranged to, in use, switch through the combinations of pairs of wires, wherein the relays are optionally electromechanical relays or a semiconductor switches.
20. Apparatus claimed in claim 18 or 19, wherein the control module is configured to infer
5 a thermal characteristic of each temperature sensor module based on the known sensitivity of the current in or voltage across the temperature sensor to variations in temperature and by measuring variations in the current in and/or voltage across the temperature sensor over time.
21. Apparatus as claimed in any of claims 18 to 20, wherein the temperature sensors are
10 configured to, in use, encode and transmit a digital signal to the control module indicative of the temperature-sensitive electrical property of the temperature sensor, and wherein the control module is configured to, in use, determine a sensed temperature at each temperature sensor using said received digital signals.
22. Apparatus as claimed in claim 21, wherein a plurality of, and optionally all,
15 temperature sensor modules are configured to transmit digital signals to the control module using the same wire.
23. Apparatus as claimed in any of claims 18 to 22, further comprising calibration means configured to compensate for the resistance of wires in the electrical network that connect the temperature sensor modules to the control module, and preferably also
20 for the temperature dependence of the resistivity of those wires, wherein optionally the calibration means is provided as part of the control module.
24. Apparatus as claimed in any of claims 18 to 23, wherein the control module further comprises a common reference signal generator used to calibrate the measurement of the voltage or current of each of the temperature sensor modules to changes in
25 temperature.
25. Apparatus as claimed in claim 24, wherein the common reference signal generator is a reference voltage source.
26. Apparatus as claimed in claim 24 when dependent on claim 14 or 15, wherein the common reference signal generator is a reference oscillating electrical signal
30 generated at the control module by a reference crystal oscillator common to a plurality of, optionally all, the temperature sensors.
27. Apparatus as claimed in claim 26 wherein the apparatus is configured to, in use, determine a temperature variation at each crystal oscillator temperature sensor by comparing a signal derived from the crystal oscillator temperature sensor with a
35 signal derived from the reference crystal oscillator.
28. Apparatus as claimed in any preceding claim, wherein the tubing is filled with and encapsulates a non-conducting liquid, optionally an oil, and optionally wherein the

tubing comprises a pressure balancing means, optionally including a bellows or flexible bladder, configured to act to equalise internal pressure in the tubing with the ambient environment.

29. Apparatus as claimed in any preceding claim, wherein the tubing is metallic,
5 preferably, one of a stainless steel, a duplex or super-duplex stainless steel, a nickel alloy, titanium or a titanium alloy.
30. Apparatus as claimed in any preceding claim, wherein the tubing outer diameter is in the range of 3 mm to 14 mm, optionally in the range of 6 mm to 10 mm, at the
10 location in the tubing of at least one of the temperature sensor modules, preferably at least 50%, more preferably at least 90%, and particularly 100% of the temperature sensor modules.
31. Apparatus as claimed in any preceding claim, wherein the outer diameter of the tubing is not increased at locations in the tubing of at least one of the temperature
15 sensor modules, preferably at least 50%, more preferably at least 90%, and particularly 100% of the temperature sensor modules.
32. Apparatus as claimed in any preceding claim, wherein the outer diameter of the tubing is not increased at the location of tubing of at least one of the temperature
sensor modules, preferably at least 50%, more preferably at least 90%, and particularly 100% of the temperature sensor modules.
- 20 33. Apparatus as claimed in any preceding claim, wherein the external profile of the tubing is not changed at the location in the tubing of at least one of the temperature sensor modules, preferably at least 50%, more preferably at least 90%, and particularly 100% of the temperature sensor modules.
- 25 34. Apparatus as claimed in any preceding claim, wherein multiple control modules are provided, wherein individual control modules control sets of temperature sensor modules, and the control modules are linked to one or more master control modules, wherein optionally the apparatus further comprises communication means within the
tubing to enable data communication along the tubing to enable communication
30 between control modules, or to enable communication with other devices within the well.
- 35 35. Apparatus as claimed in any preceding claim, wherein temperature sensor modules are spaced in the tubing at a spacing distance in the range 0.05 to 100 metres, more preferably 0.25 to 10 metres, and/or wherein the length of tubing containing the temperature sensor modules is between 0.25 to 10000 metres, more preferably 1 to
1000 metres, more preferably 10 to 200 metres.

36. Apparatus as claimed in any preceding claim, wherein the tubing containing the temperature sensor modules is arranged as a ring or helix to extend around a tubular element of a well apparatus.
- 5 37. Apparatus as claimed in any preceding claim, further comprising a power source configured to provide operational power to the apparatus for sensing temperature in the wellbore in use, wherein the power source is arranged to be provided as an in-well power source in use, wherein optionally the power source may be replaceable in the well, and wherein optionally the battery or power generator may be replaced using wireline, or coiled tubing.
- 10 38. Apparatus as claimed in claim 37, wherein the power source comprises one or more primary cells, secondary cells and/or downhole power generators.
39. Apparatus as claimed in any of claims 1 to 36, wherein the apparatus is configured to be powered in use from a position higher in the well, optionally from surface, and optionally via inductive or capacitive coupling.
- 15 40. Apparatus as claimed in any preceding claim, further comprising data storage means.
41. Apparatus as claimed in any preceding claim, further comprising a wireless data communication module coupled to the apparatus for use in sensing temperature in a wellbore and arranged to, in use:
- 20 wirelessly transmit along the well signals indicative of a temperature sensed in the wellbore by the apparatus, optionally using relays or repeaters; and optionally
- wirelessly receive control signals for controlling the operation of the apparatus, optionally for control of data acquisition, data transmission, and/or
- 25 to control heating or cooling of the sensors .
42. Apparatus as claimed in claim 41, wherein the wireless data communication module is configured to transmit said signals acoustically or electromagnetically.
43. A well comprising a well apparatus having apparatus for use in sensing temperature in a wellbore as claimed in any of claims 1 to 42 arranged to sense a temperature in
- 30 a wellbore of the well.
44. A well as claimed in claim 43, wherein the well apparatus comprises a tubular element and an annular sealing device provided at least 100m below a surface of the well, and between the wellbore or a casing of the wellbore and a tubular.
45. A well as claimed in claim 44, wherein the apparatus for use in sensing temperature
- 35 in a wellbore is provided entirely below the annular sealing device.

46. A well as claimed in claim 44, wherein the tubing of the apparatus for use in sensing temperature in a wellbore does not extend across the annular sealing device.
47. A well as claimed in claim 44, wherein the tubing of the apparatus for use in sensing temperature in a wellbore is provided below and extending across the annular sealing device, and wherein a control module of the apparatus for use in sensing temperature is provided in the wellbore above the annular sealing device.
48. A well as claimed in claim 44, wherein the tubing of the apparatus for use in sensing temperature in a wellbore is provided below and extending across the annular sealing device, and wherein a control module of the apparatus for use in sensing temperature is provided in the wellbore below the annular sealing device.
49. A well as claimed in any of claims 44 to 47, wherein a control module of the apparatus for use in sensing temperature in a wellbore is located at the end of the tubing, optionally at the end of the tubing nearest the surface, optionally below the annular sealing device.
50. A well as claimed in any of claims 43 to 49, wherein the apparatus is used to create a thermal profile of a section of the well whilst flowing and/or shut-in.
51. A well as claimed in any of claims 43 to 50, wherein the well apparatus comprises a tubular element and wherein the tubing of the apparatus for use in sensing temperature in a wellbore extends along and/or around the tubular element.
52. A well as claimed in claim 51 wherein the tubular element in the well is one of a drill string, a test string, a completion string, a production string, an injection string, a work-over string, an observation string, a suspension string, an abandonment string, a casing string, a fracturing string, a gravel pack string, a screen or a liner.
53. A well as claimed in 52, wherein the drill string comprises a drill bit or mill.
54. A well as claimed in any of claims 51 to 53, wherein the tubing is clamped to the tubular element in the well.
55. A well as claimed in any of claims 43 to 50, wherein the apparatus is deployed in the well on wireline, or coiled tubing, and optionally set and/or suspended in the well.
56. A well as claimed in any of claims 43 to 54, wherein the tubing is clamped to and extends across perforating guns.
57. A well as claimed in 56, wherein the apparatus is configured to monitor the firing of the perforating gun.
58. A well as claimed in claim 56 or 57, wherein the apparatus, or a plurality of the apparatus, extend across multiple guns, and multiple perforating guns are independently activatable.
59. A well as claimed in any of claims 43 to 49, wherein the apparatus is configured to monitor the temperature at a barrier in the well.

60. A well as claimed in any of claims 43 to 58, wherein the apparatus is configured to monitor the well during a well test or drill stem test.
61. A well as claimed in any of claims 43 to 60, wherein the well is a production and/or injection well.
- 5 62. A well as claimed in any of claims 43 to 61, wherein the well is a subsea well.
63. A well as claimed in any of claims 43 to 62, wherein the apparatus is configured to monitor an exothermic reaction associated with a fluid treatment of the well.
64. A well as claimed in any of claims 43 to 63, where the well is in a suspended or abandoned phase, and the apparatus is configured to monitor the well.
- 10 65. A method of calibrating apparatus as claimed in any of claims 1 to 42, comprising:
determining the resistance characteristics of the individual circuits associated with each temperature sensor of the apparatus, and
compensating for that circuit resistance to isolate the responsiveness of the electrical properties of the temperature sensors to temperature variations.
- 15 66. A method of operation of apparatus as claimed in any of claims 1 to 42 to determine a thermal characteristic of a temperature sensor thereof, comprising:
actively heating and/or cooling at least one of the temperature sensors in the tubing; and
monitoring a change of temperature of the or each sensor during and/or after
20 heating and/or cooling.
67. A method as claimed in claim 66, further comprising, based on the change of temperature, or the rate of change of temperature or the power to create a change temperature of a sensor during and/or after heating and/or cooling, inferring a temperature or a fluid characteristic of the environment to which the tubing is
25 exposed at the location of that temperature sensor.
68. A method as claimed in claim 66 or 67, wherein actively heating at least one of the temperature sensors in the tubing comprises self-heating the sensors by applying a current therethrough.
69. A method as claimed in any of claims 66 to 68, wherein at least one temperature
30 sensor of the apparatus is heated by applying a current through a resistor or resistance associated with the temperature sensor module.