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(54) Title: REGULATED JOULE THOMPSON COOLING SYSTEM WHICH COMPRISES AN ACTIVE CLOSED CONTROL LOOP FOR INCREASING RELIABILITY AND PREVENTING INSTANTANEOUS OVERHEATING

(57) Abstract: The invention relates to a cryogenic Joule Thompson system for cooling an IR sensor, which comprises: (a) a supply source for refrigerant gas; (b) an orifice through which said refrigerant gas flows to cool said IR sensor; (c) valve at said orifice location for closing or opening said orifice, the rate of opening of the orifice by said valve determines the rate of discharge of the refrigerant gas through said opening; (d) a bellows containing gas, said bellows is thermally coupled to said sensor, thereby to cause expansion or contraction of the bellows depending on the sensor temperature; and (e) a displacement rod, one end of which is rigidly connected to the bellows and the other end of which is connected to said valve, thereby to cause the rate of closure of the orifice by said valve to depend on the level of expansion of said bellows; wherein the system further comprises: (f) a resistor which is thermally coupled to said bellows; (g) a temperature measuring element for measuring the temperature of said IR sensor, and providing the temperature measurements to a processor; (h) a processor for receiving said temperature measurements, for detecting a state of sensor temperature increase after a period of said orifice closure or low refrigerant discharge rate below a predefined value, and for activating a current flow through said resistor any time when said state is determined, thereby to cause a boosted expansion of the bellows and acceleration of the opening of the orifice by said valve.



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**REGULATED JOULE THOMPSON COOLING SYSTEM WHICH
COMPRISES AN ACTIVE CLOSED CONTROL LOOP FOR
INCREASING RELIABILITY AND PREVENTING
INSTANTANEOUS OVERHEATING**

Field of the Invention

The field of the invention relates in general to cooling systems of the Joule Thompson type that are used for cooling electro-optical components, particularly infra-red sensors that are used in vision systems.

Background of the Invention

Many infra-red vision apparatuses are provided with a self regulated Joule Thompson type cooling system (hereinafter "cryogenic cooler") which is used for cooling the infra-red sensor, and maintaining its temperature in a cryogenic level. The cryogenic cooler typically uses Argon, Nitrogen, or a combination thereof, gas as the refrigerant, and it comprises a regulation system which provides a gas flow in a level which is sufficient for maintaining the required cryogenic temperature, while still maintaining this flow at the minimum necessary. It should be noted herein that although the term "gas" is used with respect to the refrigerant, this should not limit the invention, as in some cases the refrigerant is provided in another form of fluid, such as liquid, etc.

Typically, regulation systems of the prior art comprise a bellows which contains gas, wherein the bellows is thermally coupled to the infra-red sensor. The bellows controls the opening size of the orifice from which the refrigerant gas discharges to cool the sensor. It should be noted that the refrigerant gas is independent from the gas within the bellows, and said two gases are not necessarily of a same type. In view of the thermal

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coupling between the bellows and the infra-red sensor, the rate of expansion of the bellows depends on the temperature of the sensor, and the refrigerant gas discharge rate also depends on the rate of expansion of the bellow which in turn depends on the temperature of the infra-red sensor. More specifically, in order to increase the level of cooling, the opening area of orifice is increased (and so is the refrigerant discharge rate), and in order to reduce the level of cooling, the opening area of the orifice is decreased (and so is the coolant discharge rate). In other terms, the regulation sub-system increases or decreases the effective orifice area (and the discharge rate) by expanding or shrinking the bellows as a function of the sensor temperature.

During regular conditions, said regulation system of the prior art generally appropriately follows the heating or cooling of the sensor, and therefore it appropriately regulates the sensor temperature. However, in view of its structure, particularly due to the extremely small orifice area, the regulation sub-system is prone to failures, for example, due to contamination. For example, when micro-level contamination particles (such as water or oily material particles) accumulate and freeze at the orifice, they cause a full or partial closure of the opening of the orifice, causing the refrigerant discharge to decrease, which results in over heating of the sensor. More specifically, in such cases of contamination, it has been observed cases in which the system lags in responding fast enough to an increase in the sensor temperature, which results in over heating of the sensor. More specifically, it has been found that there are cases in which the sensor temperature increases above a critical temperature even before the bellows expansion begins, and before the orifice sufficiently opens. It has been found by the inventors that such a situation in which the sensor temperature increases, while the bellows has not yet opened the orifice

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enough to compensate for said temperature increase, generally occurs at times in which the sensor temperature begins to increase, after being for some time at a low temperature in which the refrigerant orifice was essentially closed or very little opened, or particularly at times after a period of no refrigerant discharge or very low discharge rate, typically a discharge rate of 20% or less than the maximal discharge rate. Such a malfunctioning situation may span duration of between several seconds and up to several tens of seconds, until the bellows expands enough, causing flushing of the contamination, which results in sufficient refrigerant flow rate.

It is therefore an object of the present invention to provide a more robust regulation system for such a Joule Thompson type cooling system.

It is still another object of the present invention to eliminate the delay in the expansion of the bellows, and therefore to eliminate failures in the system which regulates the sensor temperature.

Other objects and advantages of the present invention will become apparent as the description proceeds.

Summary of the Invention

The invention relates to a cryogenic Joule Thompson system for cooling an IR sensor, which comprises: (a) a supply source for refrigerant gas; (b) an orifice through which said refrigerant gas flows to cool said IR sensor; (c) valve at said orifice location for closing or opening said orifice, the rate of opening of the orifice by said valve determines the rate of discharge of the refrigerant gas through said opening; (d) a bellows containing gas, said bellows is thermally coupled to said sensor, thereby to cause expansion or

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contraction of the bellows depending on the sensor temperature; and (e) a displacement rod, one end of which is rigidly connected to the bellows and the other end of which is connected to said valve, thereby to cause the rate of closure of the orifice by said valve to depend on the level of expansion of said bellows; wherein the system further comprises: (f) a resistor which is thermally coupled to said bellows; (g) a temperature measuring element for measuring the temperature of said IR sensor, and providing the temperature measurements to a processor; (h) a processor for receiving said temperature measurements, for detecting a state of sensor temperature increase after a period of said orifice closure or low refrigerant discharge rate below a predefined value, and for activating a current flow through said resistor any time when said state is determined, thereby to cause a boosted expansion of the bellows and acceleration of the opening of the orifice by said valve.

Preferably, said temperature measurement is performed continuously. Alternatively, said temperature measurement is performed periodically.

Preferably, said resistor is attached to said displacement rod of the bellows.

Preferably, said activation of the current flow is performed for a limited duration of time.

Preferably, said duration of time is between 2 to 15 seconds.

In an embodiment of the invention, said resistor is replaced by an element which mechanically increases the opening of said orifice, upon detection by said processor said state of sensor temperature increase after a period of

said orifice closure or low refrigerant discharge rate below a predefined value, thereby to cause a boosted opening of the orifice by said valve.

Brief Description of the Drawings

In the drawings:

- Fig. 1 schematically illustrates a general structure of a typical open loop cryogenic Joule Thompson type system ("cryogenic cooler") 1 for cooling and maintaining an infra-red sensor at a cryogenic temperature;
- Fig. 2 illustrates an embodiment of an active, closed loop regulation system according to an embodiment of the present invention;
- Fig. 3a is a cross sectional view of a typical cryogenic cooler;
- Fig. 3b is an enlarged view of the front section of the cryogenic cooler 200 of Fig. 3a;
- Fig. 3c is an isometric view of the the cryogenic cooler, while the resistor is connected to it, according to the embodiment of Fig. 2; and
- Fig. 4 is a flow diagram illustrating one exemplary procedure for determining the right time to activate the heating of resistor, according to an embodiment of the invention.

Detailed Description of Preferred Embodiments

Fig. 1 schematically illustrates a general structure of a typical open loop cryogenic Joule Thompson type system ("cryogenic cooler") 1 for cooling and maintaining an infra-red sensor at a cryogenic temperature. It should be noted herein that the term "sensor" refers herein to a device which includes one or more detectors for sensing a level of infra-red radiation from a scene. The sensor generally includes plurality of detectors that are arranged in an array structure, and this structure is generally referred to in the art as "focal plane array".

A pressurized refrigerant gas, such as Argon or Nitrogen, for cooling the sensor 15 to a cryogenic temperature is provided from orifice 11 of tube 16. The rate of cooling depends on the rate of the gas flow through the orifice, while the opening area of the orifice is controlled by means of a needle shaped valve 17, which is forced against the orifice. Typically, when opened, the orifice has an opening area in a range of $1 \cdot e^{-8} \text{ m}^2$. Bellows 10, which is thermally coupled to the sensor 15, contains a separate gas (such as Argon or Nitrogen, but another type of gas can be used). The rear facet 22 of bellows 10 is rigidly maintained in place, while the front facet 19 of the bellows is free to move depending on the expansion or contraction of the bellows. Valve 17 is connected to the front facet 22 of bellows 10 by means of displacement rod 18. Therefore, in view of said thermal coupling between the sensor and the bellows, an increase in the sensor temperature causes expansion of the bellows, which in turn causes displacement of valve 17 to the left (i.e., in a direction away from orifice 11), thereby increasing the opening area of orifice 11, and releasing more refrigerant gas. On the other hand, a decrease in the sensor temperature causes contraction of the bellows, which in turn causes displacement of valve 17 to the right (i.e., in a direction towards orifice 11), thereby decreasing the opening area of orifice 11, and releasing less refrigerant gas. This is a self regulating system which applies a passive loop cooling sub-system, that comprises no means for ensuring that the level of opening of orifice 11 follows fast enough at all times the change of temperature of the sensor 15. Therefore, although in most times this type of prior art system appropriately functions, there are times of failures as explained above in the section.

As mentioned above in the "Background of the Invention", there are times, after closure or substantial closure of orifice 11 in which the sensor

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temperature starts to increase, but the orifice 11 still remains closed (by valve 17) for a too long period, causing overheating of sensor 15, and resulting in failure of the sensor operation. This type of failure generally prolongs several tens of seconds, until the Joule Thompson cooling subsystem returns to normal operation in which the overheating of the sensor causes bellows 10 to sufficiently expand, thereby to renew the gas flow through orifice 11. As mentioned, it has been found that this failure occurs particularly at times of no refrigerant discharge or very low refrigerant discharge through said orifice. At these times, the existence of contamination particles in or around the orifice may cause such a failure. The failure may last for several seconds, until the opening of area the orifice 11 is large enough such that the contamination is flushed by the refrigerant gas.

As mentioned, it is an object of the present invention to eliminate said phenomenon and failure. Fig. 2 illustrates an embodiment of an active, closed loop regulation system according to an embodiment of the present invention, which eliminates said phenomenon and failure.

Fig. 2 shows one embodiment of the invention, which comprises an active loop for boosting the opening of the refrigerant orifice at the appropriate time. The improved system of Fig. 2 comprises an additional resistor 160 which is thermally coupled or attached to bellows 110, or a portion thereof. The system further comprises a temperature measuring element 150, which periodically measures the temperature of sensor 115, and provides the measurement indications to processing unit 170. Processing unit 170 determines, based on said sensor temperature indications, when to activate the heating of resistor 160. More specifically, processing unit 170 detects the situation when the temperature of sensor 115 starts to increase

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following a closure state of orifice 111, or a state of low refrigerant discharge rate through the orifice. More specifically, the processing unit 170 determines the specific typical situation in which said failure occurs at the prior art passive loop system, and when said situation is detected, the processing unit provides a signal to the heat activation unit 180, which in turn activates heating of resistor 160 by supplying to it current, for a predetermined period. Therefore, resistor 160, when heated for a short period, boosts the opening of the orifice, by causing an additional expansion of bellows 110, which is sufficient to immediately open orifice 111 by valve 117. Therefore, the said failure is eliminated.

As mentioned, in an embodiment of the invention the resistor 110 is thermally coupled to the displacement rod 118 (preferably there is a physical contact between the two elements), which is in contact with bellows 110.

It should be noted herein that the term "thermal coupling", as used herein, does not necessarily requires physical contact between two elements. For example, typically there is no physical contact between the bellows and the IR sensor. The thermal coupling between these two units is provided by means of the refrigerant which is provided in the space between these two elements. On the other hand, and as mentioned above, the thermal coupling between the resistor 160 and the displacement rod 118 involves physical contact.

Generally, the cryogenic temperature to which the sensor is cooled is about 90°K when Argon is used as the coolant or about 80°K when Nitrogen is used. As mentioned, the failure typically occurs when the sensor temperature starts to increase while the orifice opening is closed, or allows

a very low discharge. The resistor 160 is heated for a period of several seconds, for example between 2 to 15 seconds. It has been found that if current is supplied to the resistor at the appropriate time, the resistor 160 has to increase the bellows (or rod 118) temperature by about 3°-4°K during, for example, 10 seconds in order to eliminate the failure.

Fig. 3a is a cross sectional view of a typical cryogenic cooler 200. Fig. 3b is an enlarged view of the front section of the cryogenic cooler 200 of Fig. 3a, and Fig. 3c is an isometric view of the same cryogenic cooler 200, while the resistor is connected to it, according to the embodiment of Fig. 2. Tube 216, which is arranged in spiral form, provides the refrigerant gas to orifice 211. The bellows is indicated by numeral 210, and the gas within the bellows is indicated by numeral 273. The opening through which the refrigerant gas is supplied into tube 216 is indicated by numeral 274 (Fig. 3c). The refrigerant gas from tube 216 is provided into the orifice element 275, and the valve which controls the opening of the orifice is indicated by numeral 211. The displacement rod is indicated by numeral 217. The resistor which is attached to displacement rod 217 is indicated by numeral 260. Said resistor is attached to the displacement rod, for example, by means of welding, or by means of some thermally conductive glue. The current into resistor 260 is provided through wires 276, shown also at the bottom of Fig. 3c.

It should be noted that the use of a resistor is only one example. Any other type of heating element for causing expansion of the bellows or the displacement rod can be used. In still another example, any type of element for causing a fast opening of the refrigerant orifice at the right time, for example, by mechanically expanding the bellows or the displacement rod, can also be used.

Fig. 4 is a flow diagram illustrating one exemplary procedure 400 for determining the right time to activate the heating of resistor 160, according to an embodiment of the invention. In optional step 410 the procedure checks whether the cooling system is in a state in which there is a chance for the failure to appear, or more particularly, whether at this specific time continuing with the procedure is at all relevant. As mentioned, the failure appears after times of closure of the orifice, or after times of being at a very low discharge rate. Therefore, step 410 may check, for example, whether the temperature of sensor 115 is below some predefined value Y (i.e., that necessarily causes said states of closure or very low flow rate). Otherwise, if the sensor temperature is above said predefined temperature, there is no sense to continue with the procedure, and the procedure repeats step 410 after some period of time. If the sensor temperature is found to be cold enough (i.e., below temperature Y), the procedure continues to step 420, in which the sensor temperature is sampled, and stored in step 430 in a memory as temperature T_s . From this point, the sensor 115 temperature is sampled every predefined period t , for example, every 1 second. In step 440 a new temperature T is sampled from sensor 115. In step 450 said new temperature T is compared to with the previously stored temperature T_s . If the difference between the newly sampled temperature T and the stored temperature T_s is above a predefined value $X^\circ\text{K}$ (for example, 4°K), the procedure concludes that this is the time to activate the heating of resistor 160 (as the temperature sensor increases at a relatively high rate after a state of orifice closure or a very low discharge rate), and the heating of resistor 160 is activated for some predefined period, for example 2-13 seconds in step 480. If, however, it is found in step 450 that the difference between the newly sampled temperature T and the stored temperature T_s is smaller than $X^\circ\text{K}$, the procedure continues to step 460 in which T is

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compared with T_s . If T is found to be below the stored temperature T_s , the procedure continues by replacing the "old" stored temperature T_s by T in step 470. The procedure then returns to step 440, in which a new temperature T is sampled. It should be noted that the object of steps 460 and 470 is to determine whether the presently sampled temperature T is lower in comparison with the stored temperature T_s , and if so, to store the newly (presently) sampled temperature in the memory. Therefore, the procedure teaches how to determine a fast sensor temperature increase after a state of orifice closure or of very low discharge rate, and in that case, the heating of resistor 160 is activated in step 480. It should be further be noted that in some cases the sampled temperature T may be an average temperature of plurality of samples during a period t . In this manner, a "noise" in the temperature measurement is reduced.

The procedure of Fig. 4 is only one example. In still another example, a simpler procedure which does not activate the heating of the resistor as long as the sensor temperature is below $A^\circ\text{K}$, and activates the boosting resistor for a predetermined time when the sensor temperature increases to above $A^\circ\text{K}$. Alternatively, instead of heating the boosting resistor for a predetermined time, the resistor may be heated for a period until the sensor temperature decrease to below some temperature of $B^\circ\text{K}$.

The inventors have found it is preferable to heat the resistor 160 for a predefined period, instead of a period which is temperature dependent. The reasons are: (a) in tests which have performed it has been found that even 2 seconds of the resistor heating are sufficient to eliminate the failure. Therefore, use of a predefined heating period which is several times longer, for example, 10 seconds is preferable, as it ensures elimination of all the failures; (b) early termination of the resistor heating may not be sufficient

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to ensure opening of the orifice, and the sensor may continue to heat; (c) the heating of the resistor is performed not only to ensure opening of the valve, but also to ensure cleaning of the orifice from dirt that may accumulate at the orifice. Therefore, heating for a too short period may be found sufficient to ensure opening of the orifice, but not to ensure full cleaning; (d) making the heating period be dependent on the temperature of the sensor may suffer from some measurement inaccuracies; and (e) the inventors have found no negative consequences due to the heating of the resistor for a period much longer than required (for example, 10 seconds).

It has been found that the invention as described above eliminates the above described failure of the cooling system which, as mentioned, occurs at the times when the temperature of the IR sensor begins to increase, after some time of being at a state of the orifice closure or of a very low refrigerant discharge. The invention forms an active, closed loop cooling system, which accelerates the opening of the refrigerant valve at the time in which said failure typically occurs.

While some embodiments of the invention have been described by way of illustration, it will be apparent that the invention can be carried out with many modifications, variations and adaptations, and with the use of numerous equivalents or alternative solutions that are within the scope of persons skilled in the art, without departing from the spirit of the invention or exceeding the scope of the claims.

Claims

1. A cryogenic Joule Thompson system for cooling an IR sensor, which comprises:

- a. a supply source for refrigerant gas;
- b. an orifice through which said refrigerant gas flows to cool said IR sensor;
- c. valve at said orifice location for closing or opening said orifice, the rate of opening of the orifice by said valve determines the rate of discharge of the refrigerant gas through said opening;
- d. a bellows containing gas, said bellows is thermally coupled to said sensor, thereby to cause expansion or contraction of the bellows depending on the sensor temperature; and
- e. a displacement rod, one end of which is rigidly connected to the bellows and the other end of which is connected to said valve, thereby to cause the rate of closure of the orifice by said valve to depend on the level of expansion of said bellows;

wherein the system further comprises:

- f. a resistor which is thermally coupled to said bellows;
- g. a temperature measuring element for measuring the temperature of said IR sensor, and providing the temperature measurements to a processor;
- h. a processor for receiving said temperature measurements, for detecting a state of sensor temperature increase after a period of said orifice closure or low refrigerant discharge rate below a predefined value, and for activating a current flow through said resistor any time when said state is determined, thereby to cause a boosted expansion of the bellows and acceleration of the opening of the orifice by said valve.

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2. System according to claim 1, wherein said temperature measurement is performed continuously.
3. System according to claim 1, wherein said temperature measurement is performed periodically.
4. System according to claim 1, wherein said resistor is attached to said displacement rod of the bellows.
5. System according to claim 1, wherein the activation of the current flow is performed for a limited duration of time.
6. System according to claim 1, wherein said duration of time is between 2-15 seconds.
7. System according to claim 1, wherein said resistor is replaced by an element which mechanically increases the opening of said orifice, upon detection by said processor said state of sensor temperature increase after a period of said orifice closure or low refrigerant discharge rate below a predefined value, thereby to cause a boosted opening of the orifice by said valve.

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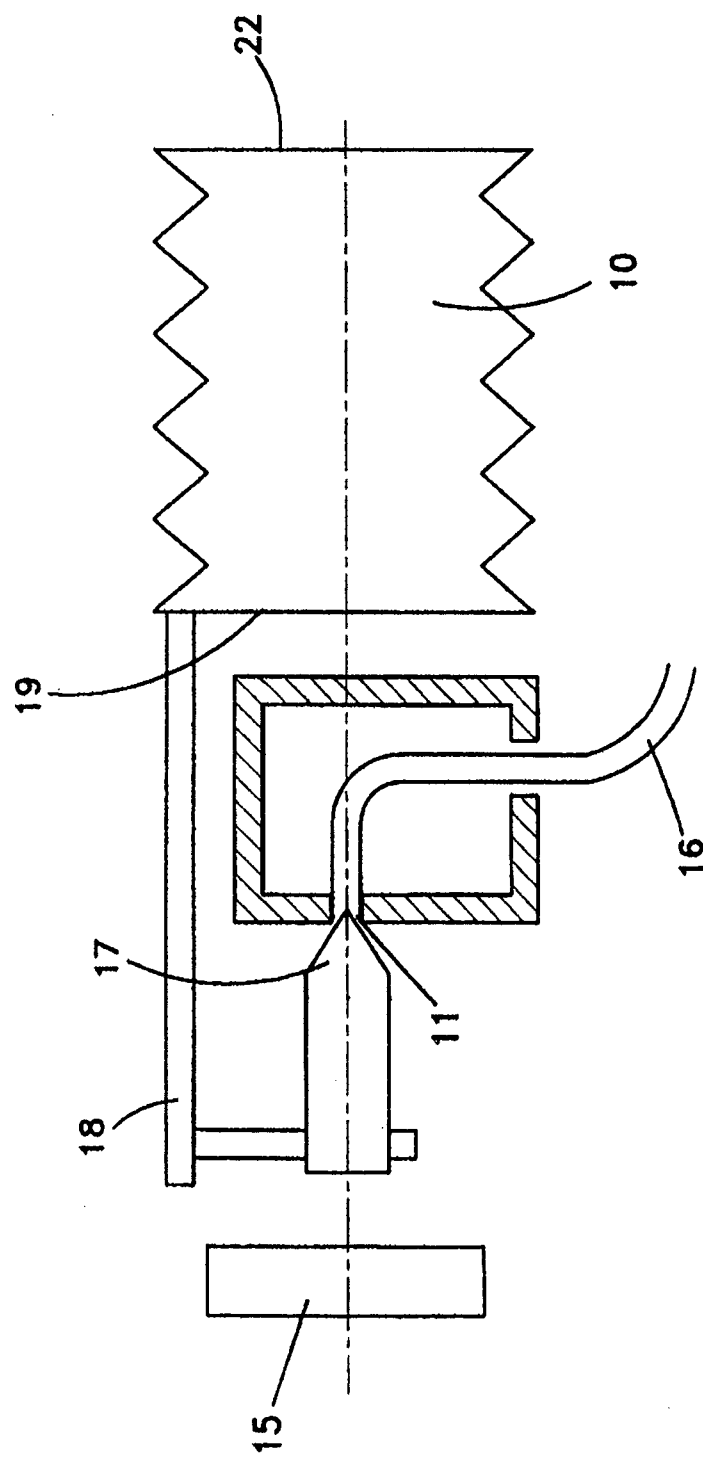


Fig. 1

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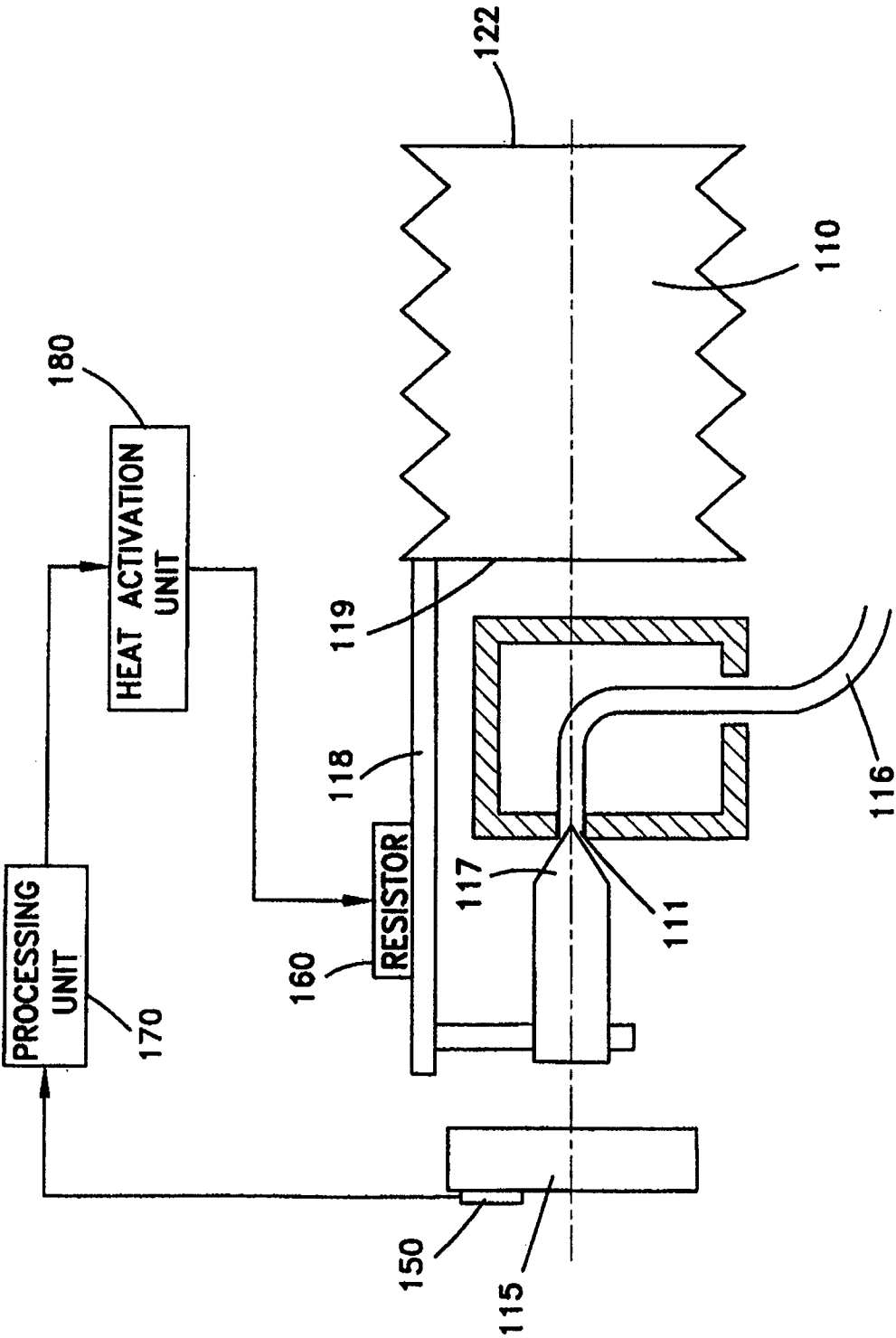


Fig. 2

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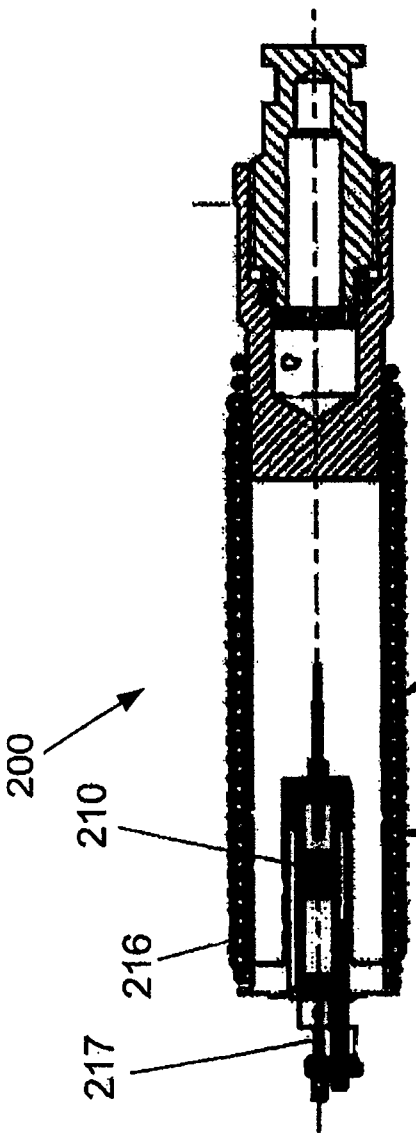


Fig. 3a

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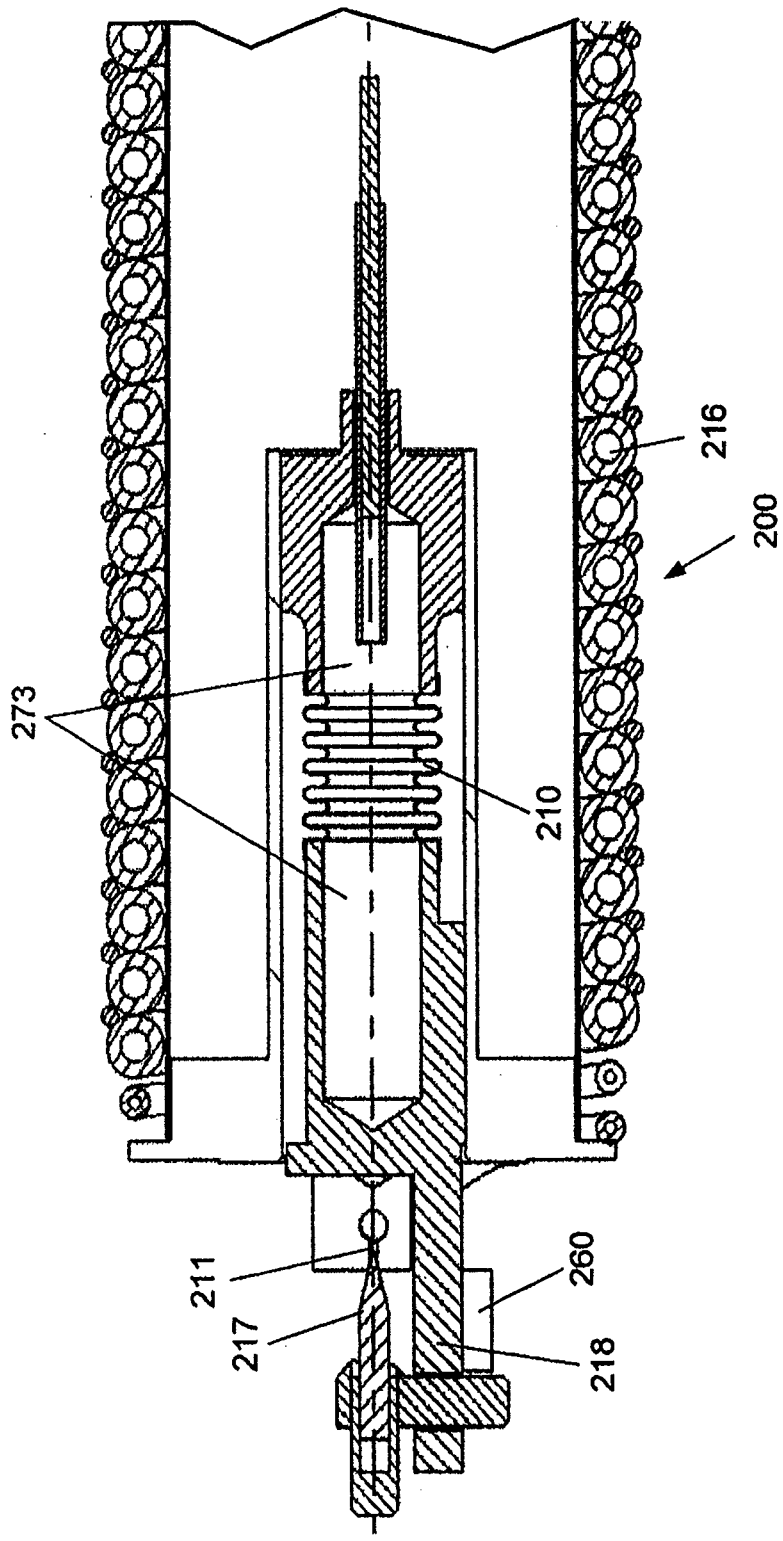


Fig. 3b

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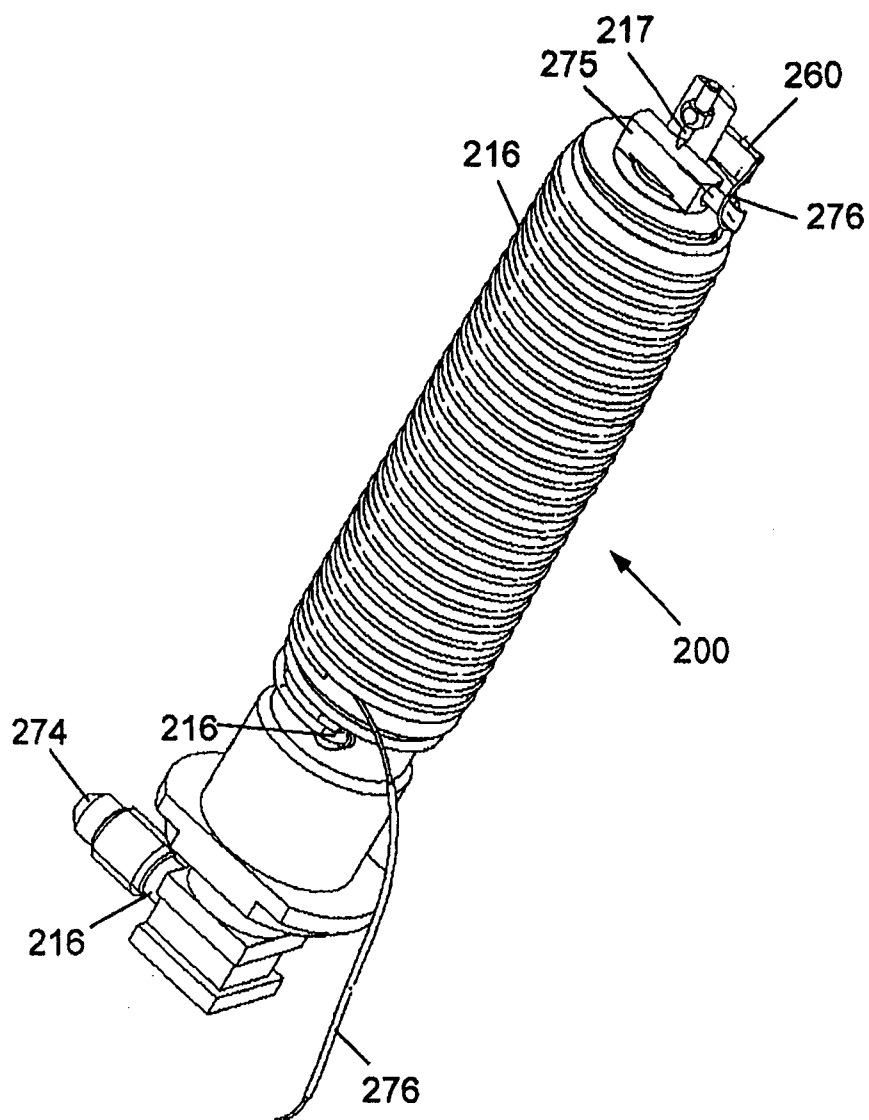


Fig. 3c

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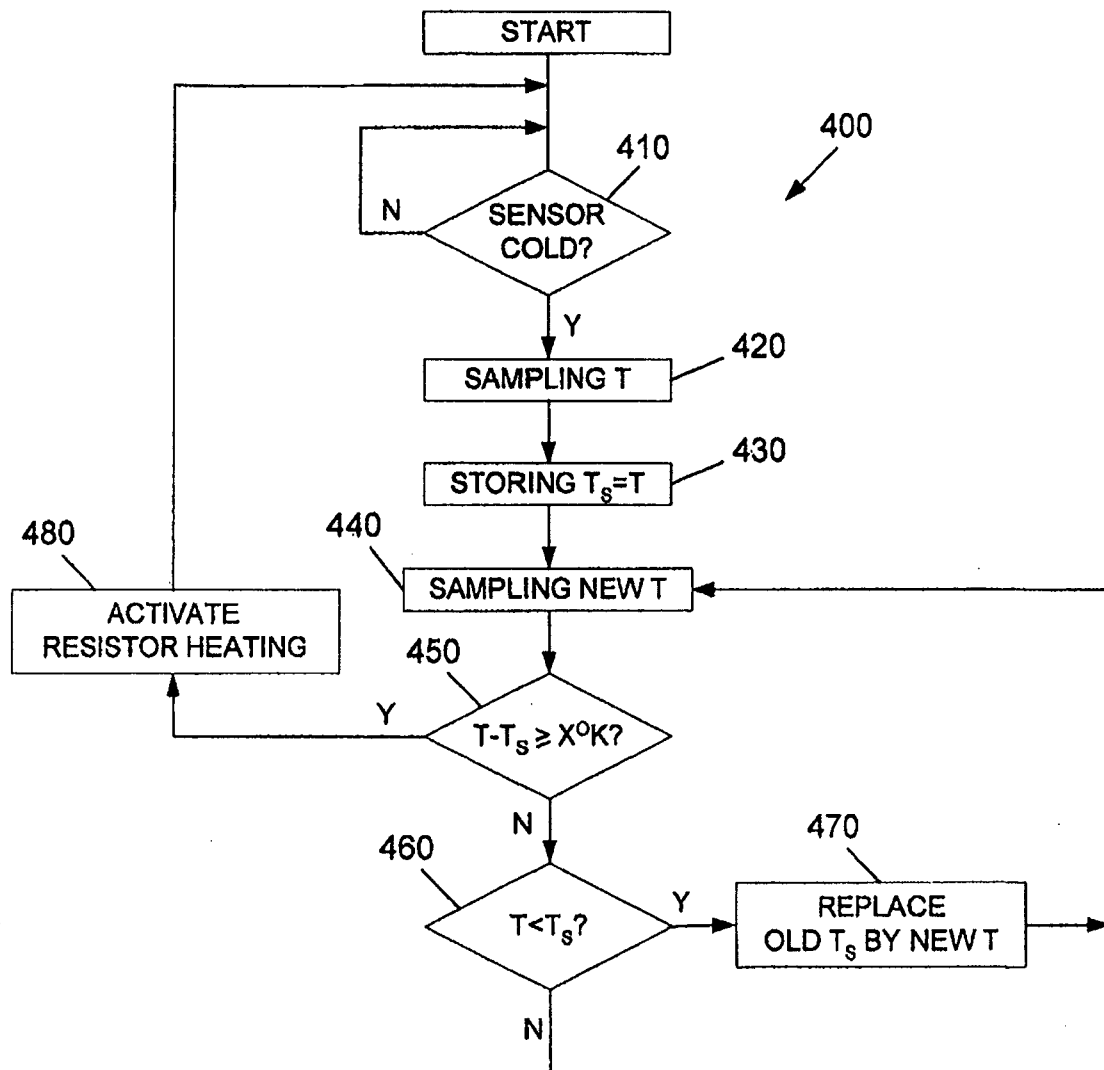


Fig. 4