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(54) Title: INSTRUMENTED STEAM GENERATOR ANTI-VIBRATION BAR

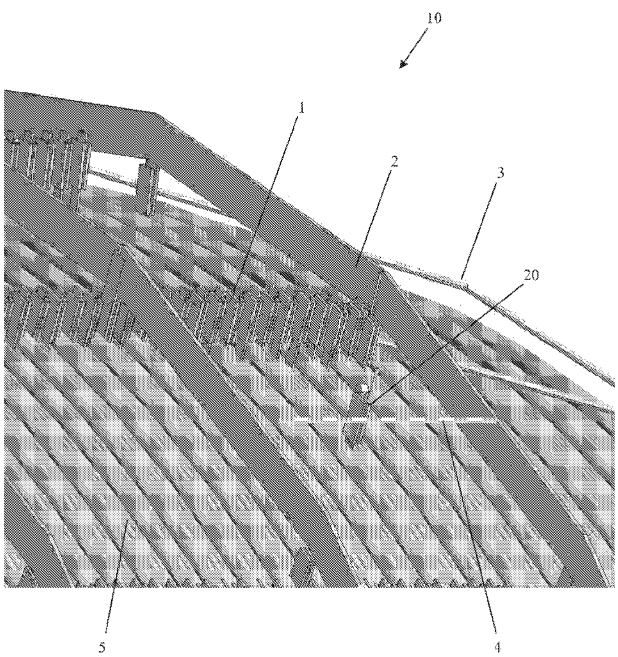

FIG. 6

(57) Abstract: A steam generator anti-vibration bar (A.VB) that extends across multiple rows of tubes and contains a string of sensors is disclosed and claimed. The instrumented anti-vibration bar includes a housing and cover that cooperate to enclose the sensors. The sensors capture data resulting from the fluid flow passing through the steam generator during plant operation. Exemplary sensors that may include: strain gauges to measure loads imposed on the AVBs by the tubes; temperature sensors to sample thermal-hydraulic conditions within the tube bundle; pressure and flow detectors to sample hydraulic conditions within the tube bundle; inductive coils to measure in-plane and out-of-plane motion; and accelerometers to measure AVB motions imposed by surrounding tubes. The captured data is transmitted out of the steam generator in known fashion.

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INSTRUMENTED STEAM GENERATOR ANTI-VIBRATION BAR

CROSS-REFERENCE TO RELATED APPLICATIONS

This patent application claims the benefit of U.S. Provisional Patent Application No. 61/858,844 filed on July 26, 2013 and U.S. Patent Application No. 14/339,647 filed on July 24, 2014, which are incorporated herein by reference in their entireties.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates to a mechanism for supporting the tubes of a steam generator to prevent vibration, and, more particularly, the present invention relates to steam generator anti-vibration bars housing instrumentation to provide on-line condition monitoring of a series of individual steam generator tubes, and conditions between those tubes, without negatively impacting primary or secondary side steam generator conditions.

2. Description of the Related Art

While the present invention may be used in a variety of industries, the environment of a pressurized water reactor (PWR) nuclear power plant will be discussed herein for illustrative purposes. There are two major systems utilized in a PWR to convert the heat generated in the fuel into electrical power. In the primary system, primary coolant is circulated past the fuel rods where it absorbs the emitted heat. The heated fluid, which is in liquid form due to the elevated pressure of the primary loop, flows to the steam generators where heat is transferred to the secondary system. After leaving the steam generators, the primary coolant is pumped back to the core to complete the primary loop. In the secondary loop, heat is transferred to the secondary coolant, or feedwater, from the primary side in the steam generators, producing steam. The steam is used to rotate a turbine, generating electricity. The feedwater leaves the turbine, passes through a condenser to remove residual heat, and the liquid feedwater is pumped back to the steam generators.

Inside of the steam generator, the hot reactor coolant flows inside of the many tubes and the feedwater flows around the outside of the tubes. There are two forms of steam generators: once-through steam generators, in which the tubes are straight, and U-bend steam generators, which are more common and in which the tubes contain a U-shaped bend.

The typical heat exchanger, steam generators in the nuclear industry in particular, are susceptible to vibration-induced wear between the tubing and internal portions of the heat exchanger tube supports. Vibration is due to flow-induced forces acting on the tubing during normal operation, particularly in the U-bend region of the tubes where flow is more predominantly cross-flow rather than axial. Typical steam generators include supports, called anti-vibration bars (AVBs), that are disposed between adjacent rows of the U-shaped tubes to prevent vibration or other movement of the tubes. A traditional AVB system is illustrated in Figure 1. Traditional AVBs include a plurality of U- or V-shaped bars 1 that extend between the steam generator tube columns. The ends of the AVBs are coupled to a retaining bar that extends substantially perpendicularly to the AVBs, and the retaining bars are coupled to bridges 2 that are arranged substantially perpendicularly to the retaining bars and that span across the top of the steam generator tube bundle. The AVB structure is not attached to the shroud or any other steam generator component. The retaining bars are looped under peripheral tubes help prevent the AVB structure from lifting off of the tube bundle. Only friction forces between steam generator tubes and AVBs prevent the support structure from settling on the top of the bundle.

SUMMARY OF THE INVENTION

The present invention is drawn to a steam generator anti-vibration bar that extends across multiple rows of tubes and contains a string of sensors. The instrumented anti-vibration bar (IAVB) includes a housing and cover that cooperate to enclose the sensors. The IAVB sensors can capture data on steam generator tube condition (such as vibration, etc.) as well as data on secondary side environment conditions (such as local temperature, pressure, flow rates, etc.) during plant operation. Exemplary sensors may include: strain gauges to measure loads imposed on the AVBs by the tubes; temperature sensors to sample thermal-hydraulic conditions within the tube bundle; pressure and flow detectors to sample hydraulic conditions within the tube bundle; inductive coils to measure in-plane and out-of-plane motion; and accelerometers to measure AVB motions imposed by surrounding tubes. The captured data is transmitted out of the secondary side of the steam generator in known fashion for processing and display on an online monitoring system, and/or to be recorded for future analysis.

This invention is inspired by a desire for the ability to detect fluid-elastic instability induced in-plane tube motion and the thermal hydraulic conditions that contribute to it. However, this invention is applicable to any steam generator with anti-vibration bars configured in a floating structure, or a structure otherwise secured to the steam generator internals. While most applicable to recirculating steam generators, the instant invention could also be used with once through steam generators.

DESCRIPTION OF THE DRAWINGS

The present invention is described with reference to the accompanying drawings, which illustrate exemplary embodiments and in which like reference characters reference like elements. It is intended that the embodiments and figures disclosed herein are to be considered illustrative rather than restrictive.

Figure 1 shows a cross-sectional view of a traditional anti-vibration bar system.

Figure 2 shows an anti-vibration apparatus of the present invention shows an apparatus of the present invention.

Figure 3 shows an instrumented anti-vibration bar of the apparatus of Figure 2.

Figures 4 and 5 show sensor strings of the instrumented anti-vibration bar of the apparatus of Figure 3.

Figure 6 shows the anti-vibration apparatus of Figure 2 in place above a heat transfer device.

Figure 7 shows a detailed view of a proximal end of the instrumented anti-vibration bar of Figure 3.

DETAILED DESCRIPTION OF THE INVENTION

The present invention relates to a mechanism for supporting the tubes of a steam generator to prevent vibration, and, more particularly, the present invention relates to steam generator anti-vibration bars housing instrumentation to provide on-line condition monitoring of a series of individual steam generator tubes, and conditions between those tubes, without negatively impacting primary or secondary side steam generator conditions.

Figure 2 shows an apparatus 10 of the present invention. The apparatus 10 stabilizes tubes within a tube bundle of a heat transfer device such as a pressurized water reactor steam generator. A plurality of AVBs 1 extend from outside the tube U-bend portion of the tube bundle into tube lanes between adjacent tubes so as to resist flow-induced vibration of the tubes. Ends of the AVBs are connected by retaining bars 3 that extend substantially perpendicularly to the AVBs. The retaining bars 3 are coupled to bridges 2 that are arranged substantially perpendicularly to the retaining bars and that span across the top of the steam generator tube bundle.

The apparatus further includes an instrumented AVB (IAVB) 20. The IAVB 20 is an elongate arm that extends from the bridge 2 into a tube lane. Preferably, the IAVB has the same exterior form as the other AVBs in a given AVB structure, which detects the conditions of the steam generator that would exist if a non-instrumented AVB were used instead. In a preferred embodiment, the IAVB 20 includes a housing 22 that defines an attachment surface 23. A cover 25 connects to the housing 22 to define an enclosed area that includes the attachment surface 23. The housing 22 and cover 25 can be coupled in known manner, such as by welding or through the use of adhesives. The IAVB 20 includes one or more sensors 30 for measuring operational condition data of the heat transfer device. Preferably, the sensors 30 are coupled to the attachment surface 23. Packing (not shown) may be included within the IAVB to protect the sensors 30 and the electrical connections thereof. In use, the IAVB 20 locates the sensors 30 in targeted areas of the steam generator tube bundle to measure operational condition data of the steam generator. Such operational condition data may include, for example, in-plane and out-of-plane tube motion, AVB accelerations induced by the steam generator tubes, thermal hydraulic conditions, secondary side thermal hydraulic conditions in a region of the tube bundle, load imposed on the AVBs by the steam generator tubes, and other similar data.

Exemplary sensors 30 may include inductive sensors, thermocouples, accelerometers, pressure transducers, and strain gauges. Inductive sensors inside the IAVB 20 detect relative motion of tubes adjacent to the IAVB 20. An oscillating signal generated outside of the steam generator would be used to create an electromagnetic field in the proximity of the coil mounted inside the IAVB 20. Motion of the metallic steam generator tubes in the proximity of the electromagnetic field changes the oscillation amplitude, providing a signal proportionate to the frequency and amplitude of tube motion. Analysis of that signal, performed with equipment outside of the steam generator, provides information on the frequency and amplitude of tube motion at the location of the IAVB 20 inductive sensor.

Thermocouple temperature sensors inside the IAVB 20 provide data on local steam generator secondary side temperature in the form of voltage fluctuations proportionate to temperature changes at the location of the sensor. Equipment outside of the steam generator detects these fluctuations and converts them to information for the steam generator operator. An array of IAVBs 20 with thermocouples is used to map local temperatures across a tube bundle providing the steam generator operator with the ability to detect hotspots, before conditions in those areas cause tube damage.

Accelerometers mounted inside the IAVB 20 provide a means of detecting relative motion in a local area of the steam generator tube bundle by sensing the amount of dynamic acceleration at each accelerometer location. An array of IAVBs 20 with accelerometers can be used to determine whether or not detected motion is occurring in a specific area of the tube bundle or across the entire tube bundle assembly.

Pressure transducers are installed to the IAVB 20 in a manner that exposes the elastic membrane component of the sensor directly to the steam generator secondary side environment. The electrical device component of the sensor, which can be resistive, inductive, or capacitive, generates electrical signals proportionate to changes in membrane geometry. These signals are measured and analyzed outside of the steam generator to determine local environment pressures within the steam generator secondary side.

Strain gauges mounted inside the IAVB 20 provide a means of detecting loads imposed on the IAVB 20 by adjacent steam generator tubes. The strain gauge is assembled to the IAVB 20 when the IAVB 20 has a neutral, non-deflected geometry. The installed strain gauge has a given electrical resistance. When that IAVB 20 is installed to the steam generator tube bundle, loads from tubes adjacent to the IAVB 20 will cause deflections its housing 22 and cover 25. Deflections in the IAVB 20 housing 22, or cover 25, to which the strain gauge is mounted cause proportionate changes in the electrical resistance of the strain gauge. These changes in electrical resistance are measured and processed with equipment outside of the steam generator.

The magnitudes of steam generator tube loads on the IAVBs 20 can be determined by comparing strain gauge electrical resistance values measured during steam generator operation to those measured when the IAVB 20 was in its neutral state.

Tube vibration can be detected by measuring the frequency of deflections detected by the strain gauge(s).

Motion of the tube bundle assembly can be detected by measuring and comparing strain gauge magnitudes and signal frequencies across an array of AVBs.

This device works in both triangular and square pitch steam generator tube configurations. This device can provide empirical data on tube bundle loads when the steam generator is cold (during fabrication or when shut down) and hot (during operation). This type of information could be used in conjunction with eddy current, or other existing NDE, gap measurements to provide new insight into how NDE data collected during a plant outage relates to conditions inside the generator during operation (when NDE equipment cannot be used).

In a preferred embodiment, the sensors 30 are provided as a string of sensors across multiple tube rows (as opposed to single tube measurements). Preferably, the IAVB 20 also functions as an AVB. Multiple IAVBs 20 can be installed to develop an array of sensors. An exemplary sensor string 35 is illustrated in Figures 4 and 5. The sensors 30 are positioned along the span of the IAVB 20 to collect data from a variety of locations and depths within the tube bundle. Preferably, the IAVB has a form and fit equal to other AVBs in a given AVB structure, allowing it to extend into the critical area of the tube bundle to provide an abundance of operational condition data, without modifying the environment in a manner different than non-instrumented AVBs.

Figure 6 shows the anti-vibration apparatus of Figure 2 in place above a steam generator tube bundle 5. In use, the IAVB extends from above or outside the U-bend portion of the tube bundle 5 into a tube lane between two adjacent tubes. The IAVB may be incorporated into a given AVB structure and take the place of a non-instrumented AVB. Alternatively, an IAVB retaining bar 4 may be provided between adjacent bridges 2 to support the IAVB. As shown in Figure 2, the distal end of the IAVB 20 may be located adjacent or coupled to an AVB. By extending within the tube bundle 5, the IAVB 20 is subjected to the same fluid flow and other operational conditions as the AVBS. Thus, the IAVB 20 provides real-time measurements of the operating conditions within the steam generator, including the loads and reactions of the AVBs.

As shown in Figure 7, the IAVB 20 further includes a transmission line 27 for transmitting data collected by the sensors 30. This may be accomplished in a variety of known manners. For example, the sensor data transmission line 27 can pass out of the steam generator through a secondary side penetration and be connected to additional equipment, such as tools for analyzing the captured data or transmitting the captured data outside of the containment building for evaluation.

It should be noted that the form of the IAVB 20 illustrated in the drawing figures is exemplary in nature. Various changes, such as to the length, can be made without departing from the spirit and scope of the present invention.

The present invention positions sensors in steam generator tube bundle locations that provide information on the condition of specific tubes in the steam generator while those tubes are still in service. Similarly, when installed as an array of IAVBs, the present invention provides a means for determining secondary side thermal hydraulic conditions in a very specific region inside a steam generator. This gives the steam generator operator information on local conditions inside a tube bundle that cause tube vibration. At present these types of conditions are only detected after they have existed long enough to cause damage to the tubes. The present invention provides early detection of such adverse conditions, allowing action to be taken prior to damage occurring.

Since the IAVB also functions as a normal AVB it can exist within the steam generator tube bundle whether or not the sensors in the IAVB are functioning. This feature allows state of the art sensor technology to be used, which may include integrated circuits with a limited lifetime in secondary side temperatures. Such devices can provide information such as the effectiveness of a repair immediately after it is installed and conditions inside the steam generator as it is first brought online.

While the preferred embodiments of the present invention have been described above, it should be understood that they have been presented by way of example only, and not of limitation. It will be apparent to persons skilled in the relevant art that various changes in form and detail can be made therein without departing from the spirit and scope of the invention. For example, while a steam generator has been discussed above, the instant invention can be applied to other heat transfer devices. Thus the present invention should not be limited by the above-described exemplary embodiments, but should be defined only in accordance with the following claims and their equivalents. Furthermore, while certain advantages of the invention have been described herein, it is to be understood that not necessarily all such advantages may be achieved in accordance with any particular embodiment of the invention. Thus, for example, those skilled in the art will recognize that the invention may be embodied or carried out in a manner that achieves or optimizes one advantage or group of advantages as taught herein without necessarily achieving other advantages as may be taught or suggested herein.

What is claimed is:

1. An apparatus for stabilizing tubes within a heat transfer device from vibration generated by fluid flow around the tubes, the tubes including straight portions joined together by U-bend portions and being arranged in rows with tube lanes therebetween, the apparatus comprising:

an elongate arm extending from above the tube U-bend portions into a tube lane between two adjacent tubes so as to resist flow-induced vibration of the two adjacent tubes, said elongate arm including a sensor for measuring operational condition data of the heat transfer device.

2. The apparatus of claim 1, wherein said sensor is configured to measure and provide operational condition data regarding the tubes.

3. The apparatus of claim 1, wherein said sensor is configured to measure and provide operational condition data regarding the fluid flow.

4. The apparatus of claim 1, wherein:

the heat transfer device contains a plurality of anti-vibration bars extending from above the tube U-bend portions into a the tube lanes; and

said sensor is a strain gauge to measure loads imposed on the anti-vibration bars by the tubes.

5. The apparatus of claim 1, wherein said sensor is a temperature sensor to sample thermal-hydraulic conditions within the tube bundle.

6. The apparatus of claim 1, wherein said sensor is a pressure detector to sample hydraulic conditions within the tube bundle.

7. The apparatus of claim 1, wherein said sensor is a flow detector to sample hydraulic conditions within the tube bundle.

8. The apparatus of claim 1, wherein said sensor is an inductive coil to measure in-plane and out-of-plane motion of one or more tubes within the tube bundle.

9. The apparatus of claim 1, wherein said sensor is an accelerometers to measure anti-vibration bar motion imposed by adjacent ones of the tubes.

10. The apparatus of claim 1, further comprising a plurality of sensors for measuring operational condition data of the heat transfer device.

11. The apparatus of claim 1, further comprising a transmitter for transmitting said measured operational condition data.

12. The apparatus of claim 1, wherein said elongate arm comprises:

a housing defining an attachment surface; and

a cover configured to couple to said housing in such a manner as to define an enclosed area, said attachment surface being within said enclosed area.

13. The apparatus of claim 12, wherein said sensor is coupled to said mounting surface.

14. The apparatus of claim 12, further comprising a plurality of sensors coupled to said mounting surface.

15. The apparatus of claim 14, wherein said sensors include one or more of a strain gauge, a temperature sensor, a pressure detector, a flow detector, an inductive coil, and an accelerometer.

16. An apparatus for stabilizing tubes within a tube bundle of a heat transfer device, the tubes including straight portions joined together by U-bend portions and being arranged in rows with tube lanes therebetween, the device comprising:

a plurality of anti-vibration bars extending from outside the tube U-bend portions into tube lanes between adjacent tubes so as to resist flow-induced vibration of the tubes;

a plurality of retaining bars connecting respective ends of said anti-vibrations bars;

a bridge connecting said plurality of retaining bars; and

an elongate arm extending from said bridge into a tube lane between two adjacent tubes, said elongate arm including one or more sensors for measuring operational condition data of the heat transfer device.

17. The apparatus of claim 16, wherein said one or more sensors includes one or more of a strain gauge, a temperature sensor, a pressure detector, a flow detector, an inductive coil, and an accelerometer.

18. The apparatus of claim 16, wherein said elongate arm comprises:

a housing defining an attachment surface to which said one or more sensors are coupled; and

a cover configured to couple to said housing in such a manner as to define an enclosed area, said attachment surface being within said enclosed area.

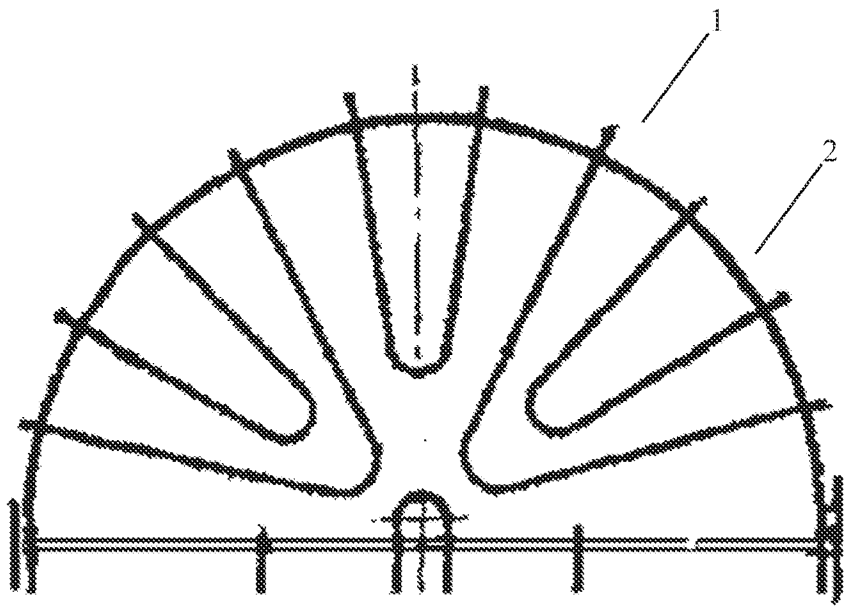

FIG. 1
Prior Art

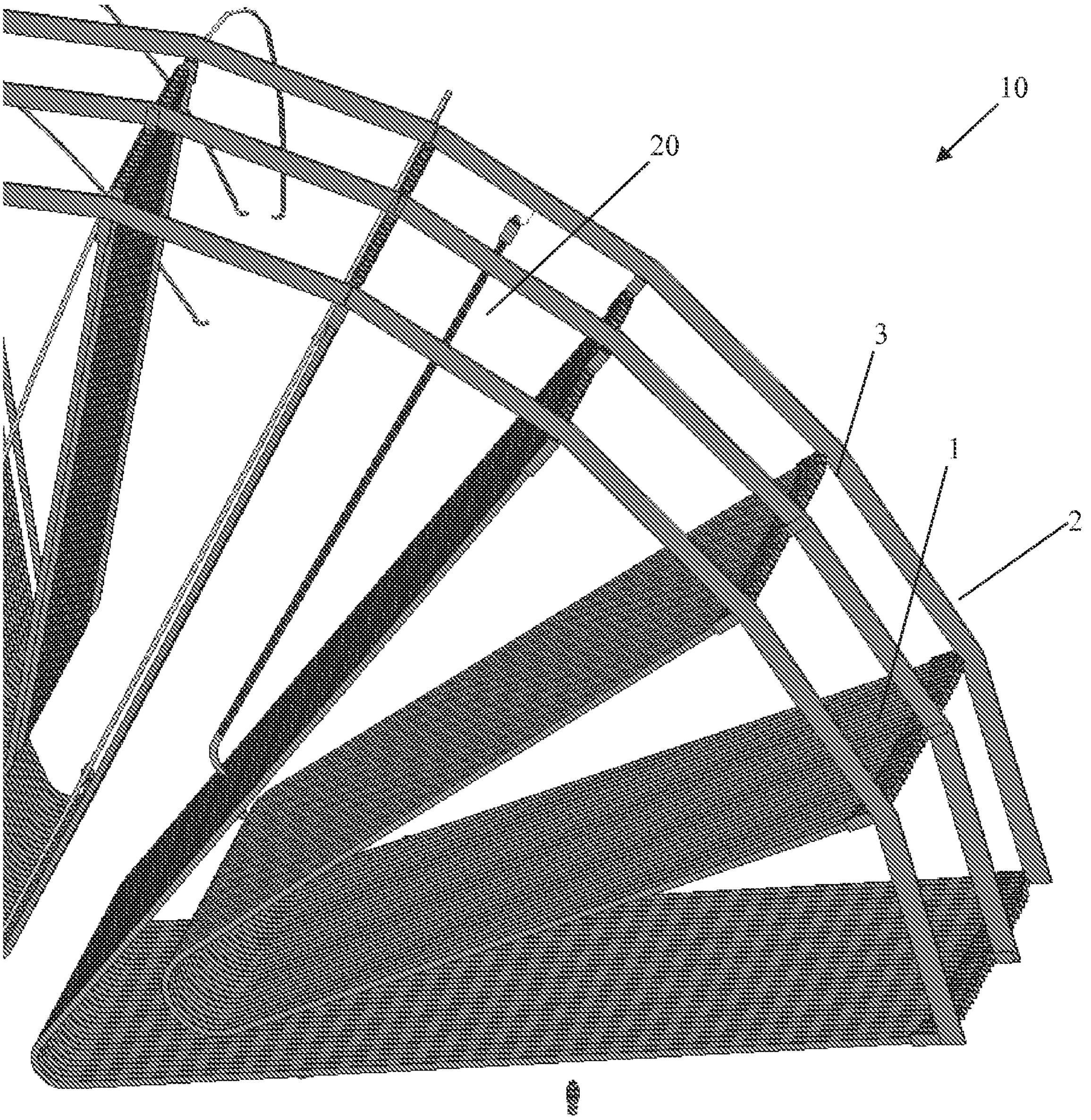

FIG. 2

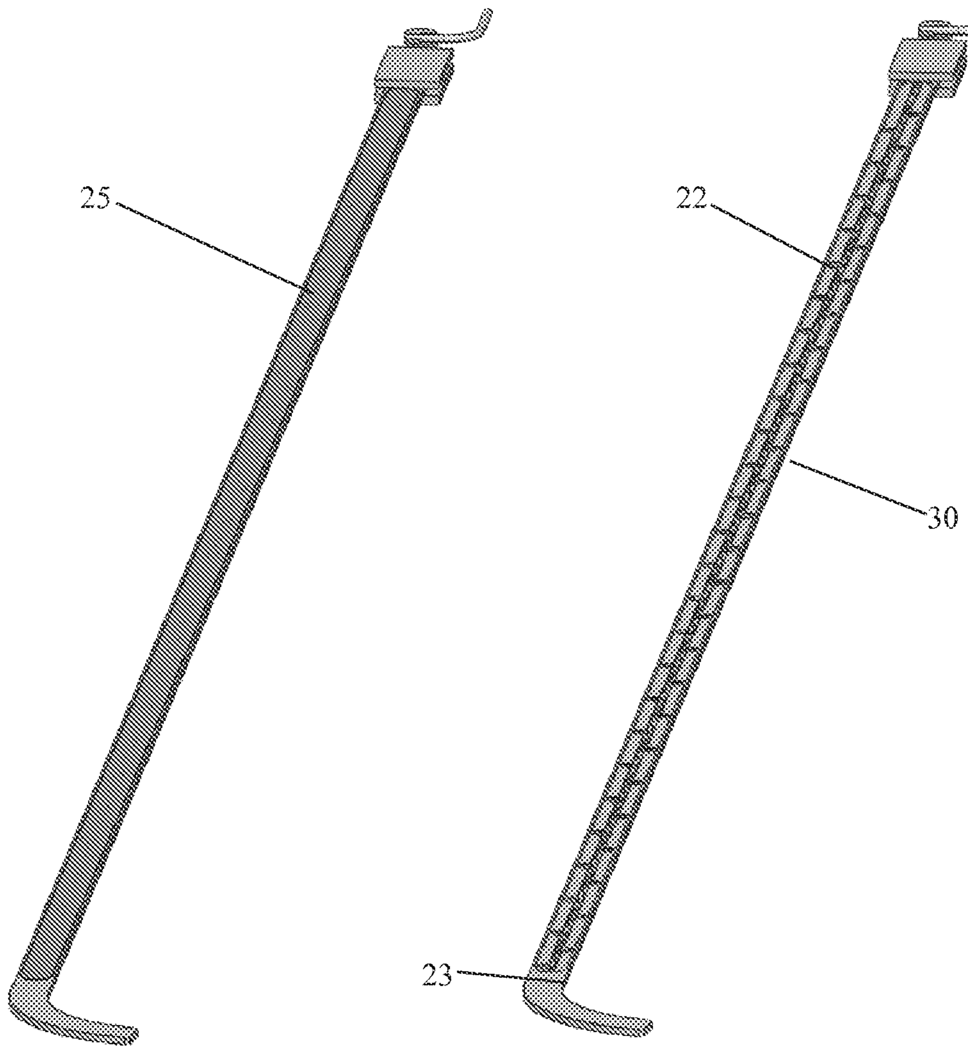

FIG. 3

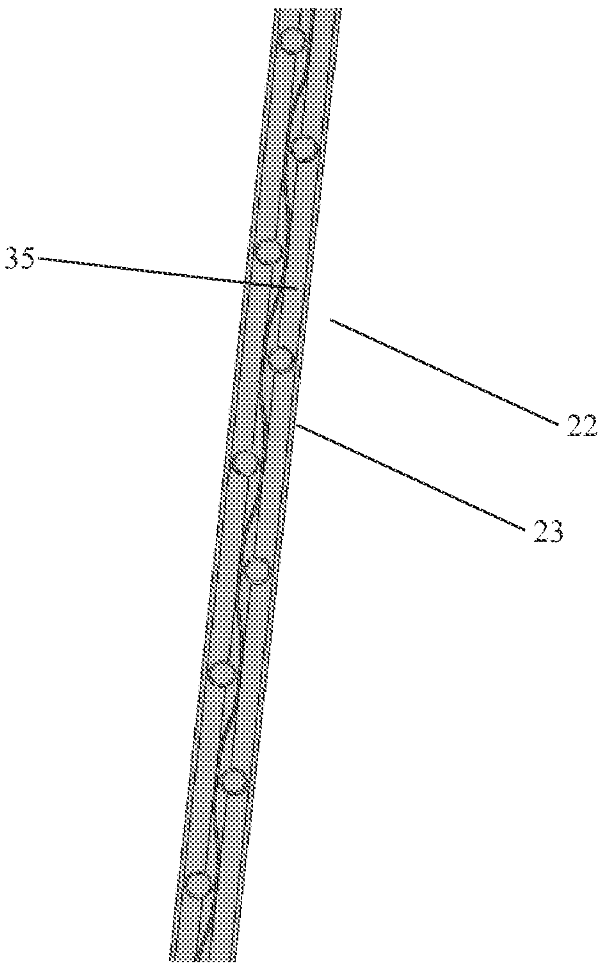

FIG. 4

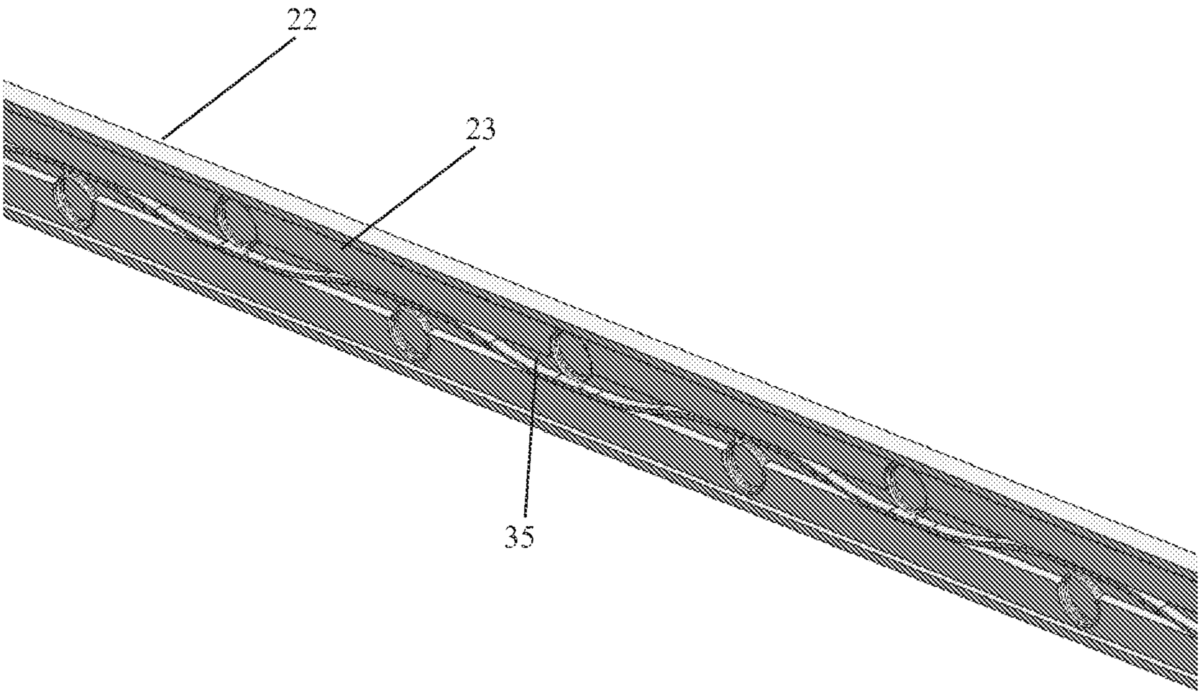

FIG. 5

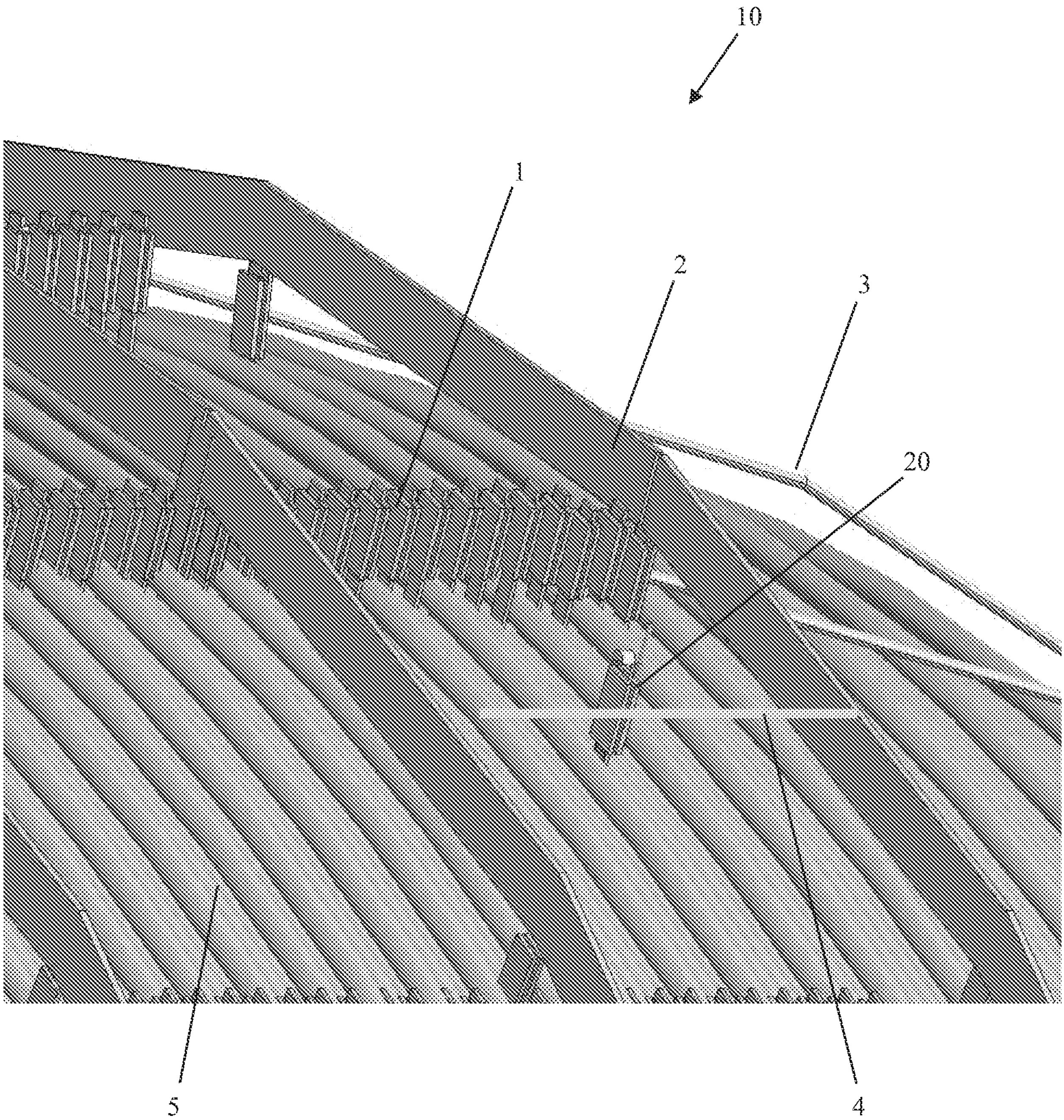

FIG. 6

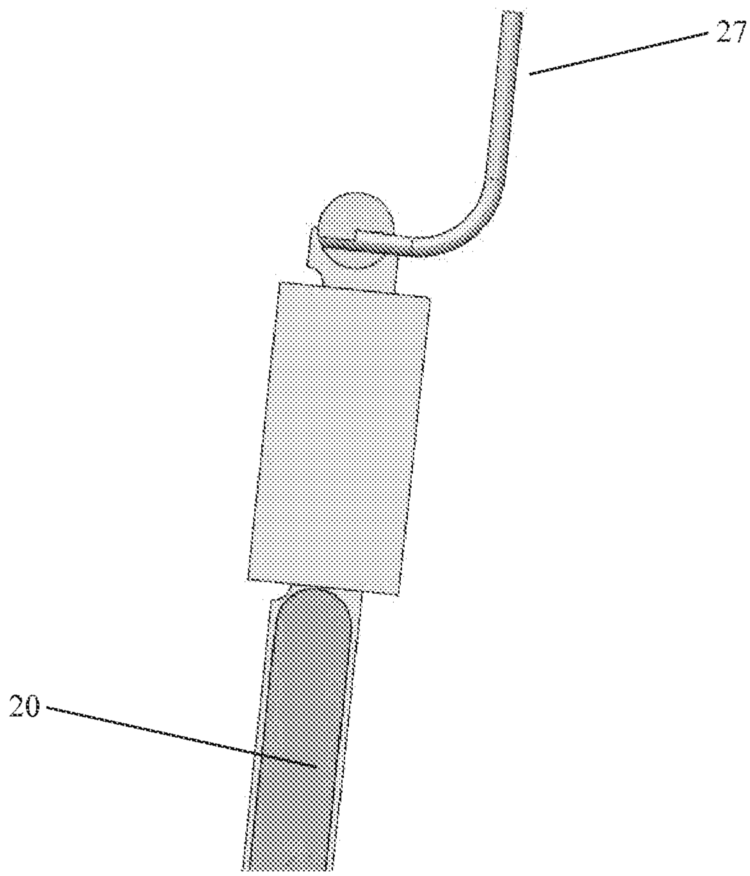

FIG. 7