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Grondahl

[11] **3,849,025**

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[54] **SERPENTINE COOLING CHANNEL CONSTRUCTION FOR OPEN-CIRCUIT LIQUID COOLED TURBINE BUCKETS**

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[52] **U.S. Cl.** 416/97, 416/96

[51] **Int. Cl.** **F01d 5/18**

[58] **Field of Search** 416/92, 95, 96, 97

[56] **References Cited**

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3,220,697	11/1965	Smuland et al.	416/96
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3,658,439	4/1972	Kydd	416/97
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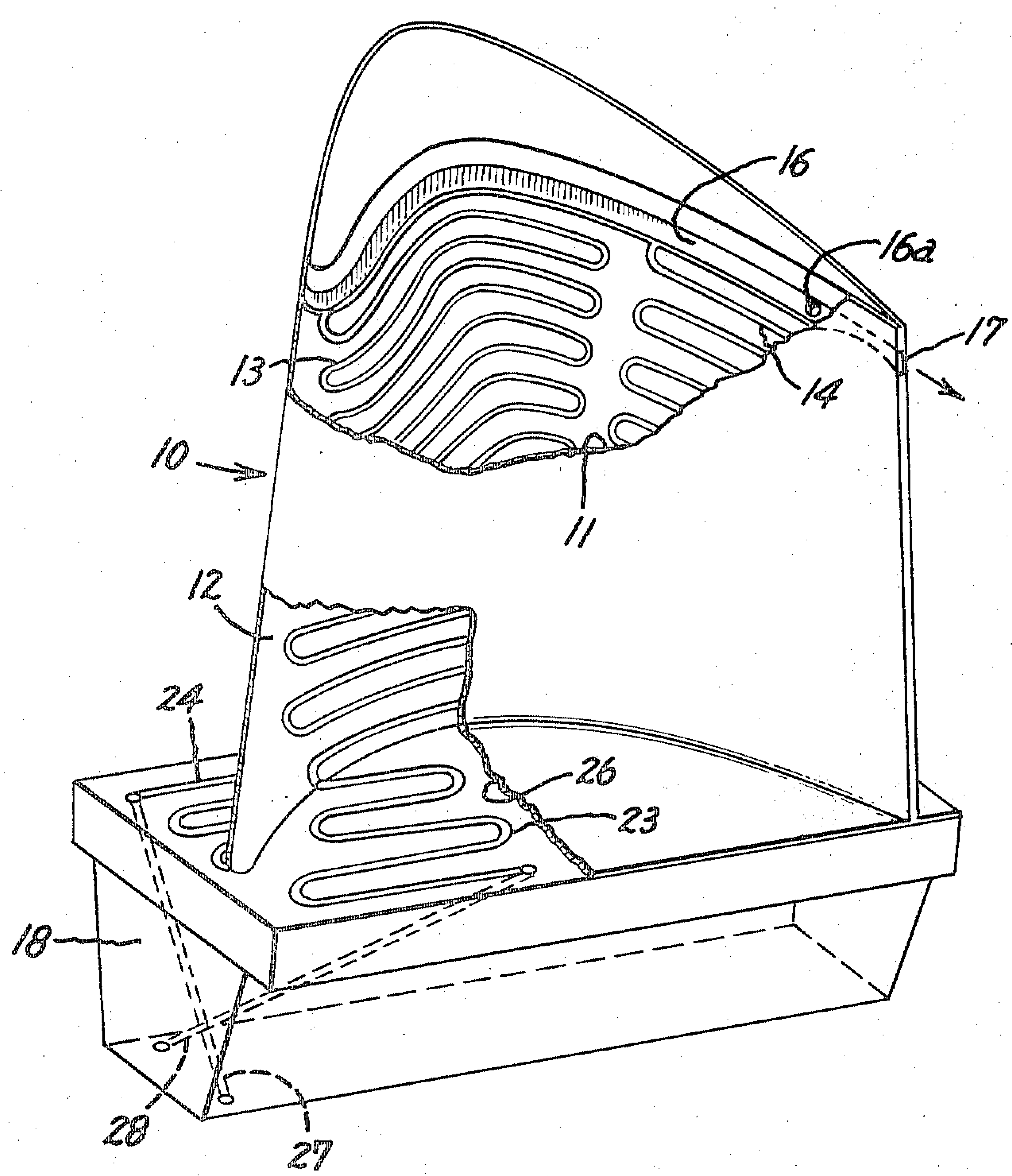
[57] **ABSTRACT**

Individually fed serpentine or spiraled cooling channels are provided for open-circuit liquid cooled turbine buckets. Each convoluted coolant channel is fed liquid coolant directly from a gutter on the rotor rim via a coolant supply conduit. Openings to the coolant supply conduits are preferably spaced at even intervals along the circumference of the gutter.

11 Claims, 7 Drawing Figures



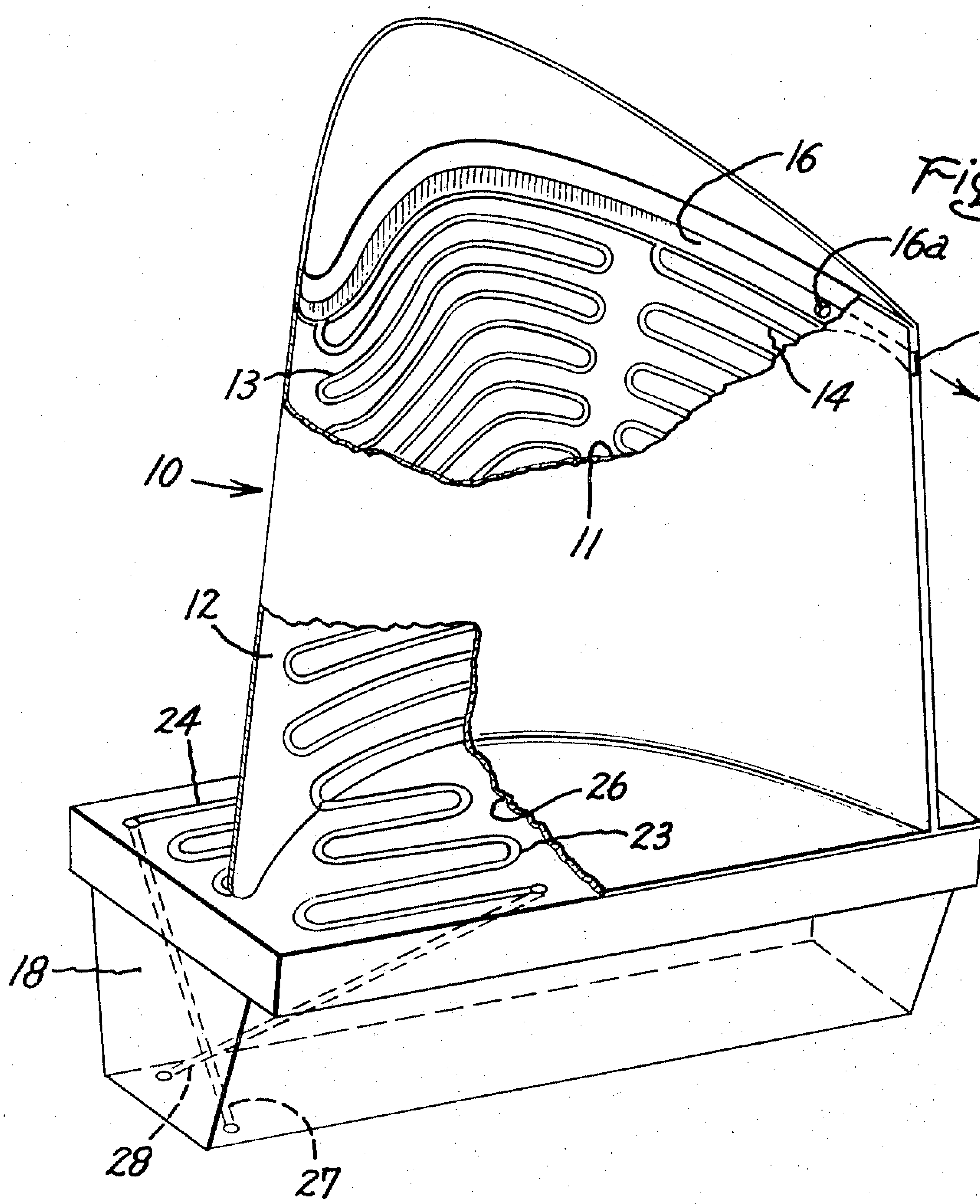

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Fig.1.

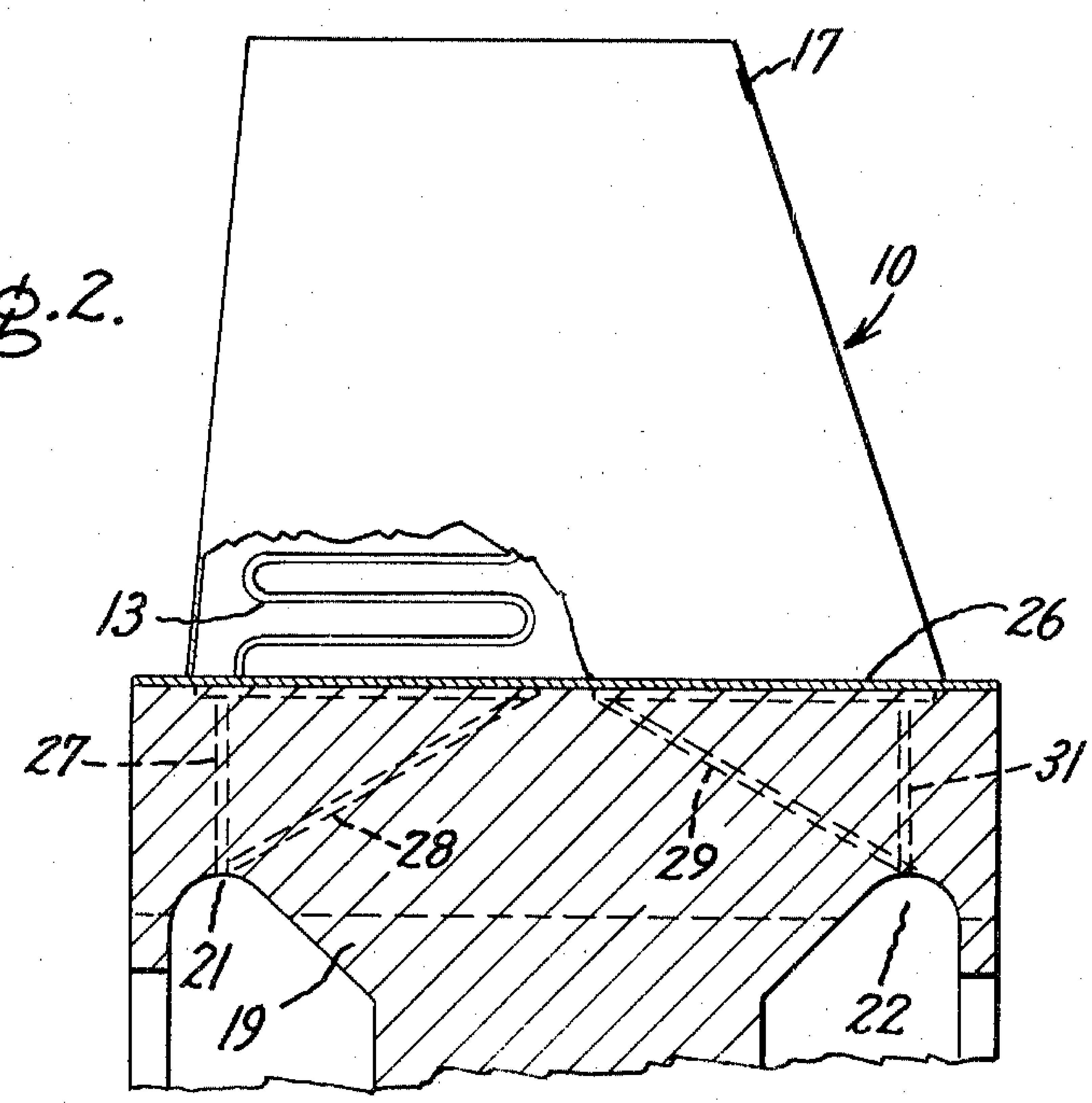
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Fig.2.

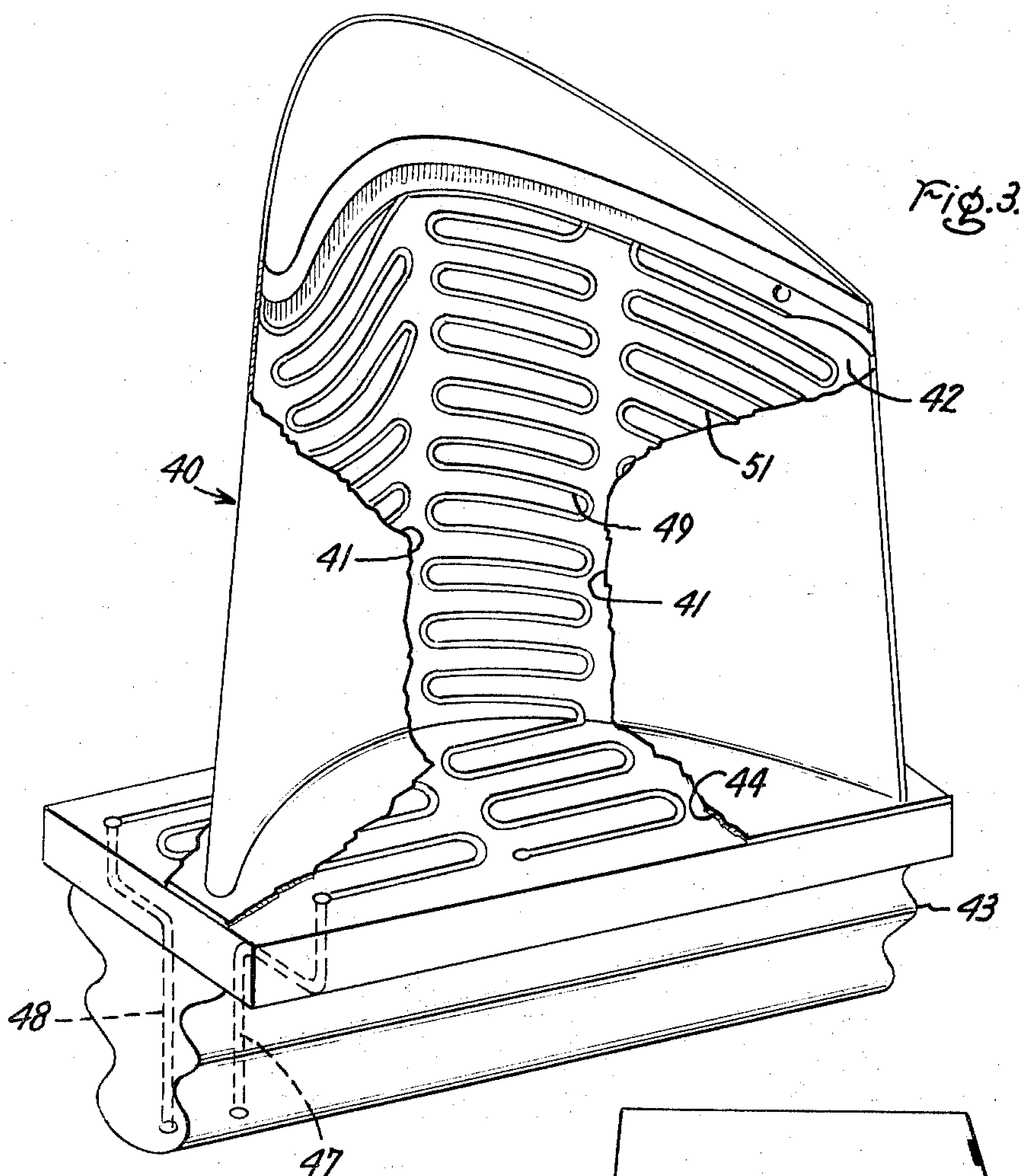


Fig. 3.

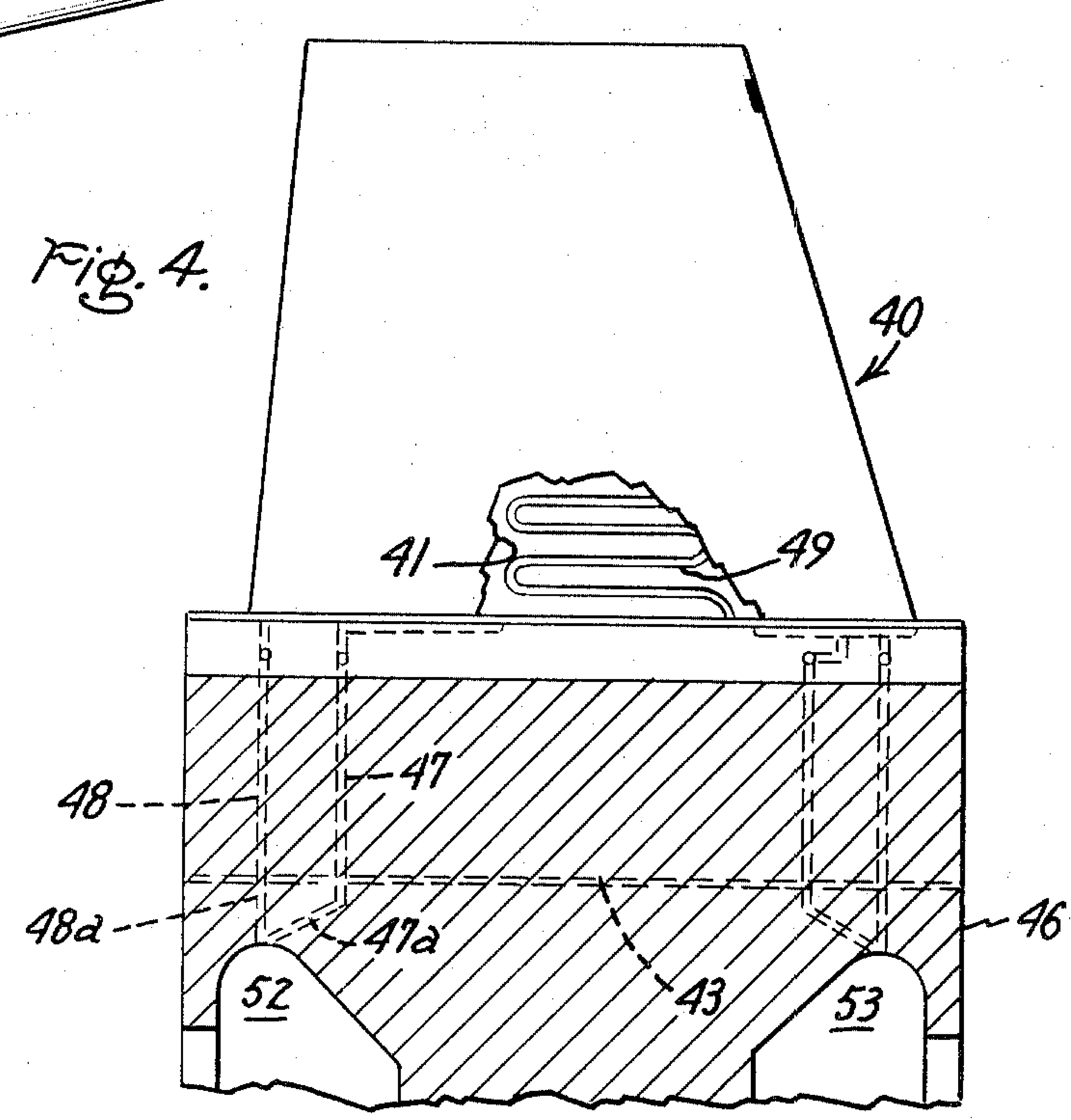


Fig. 4.

Fig. 5.

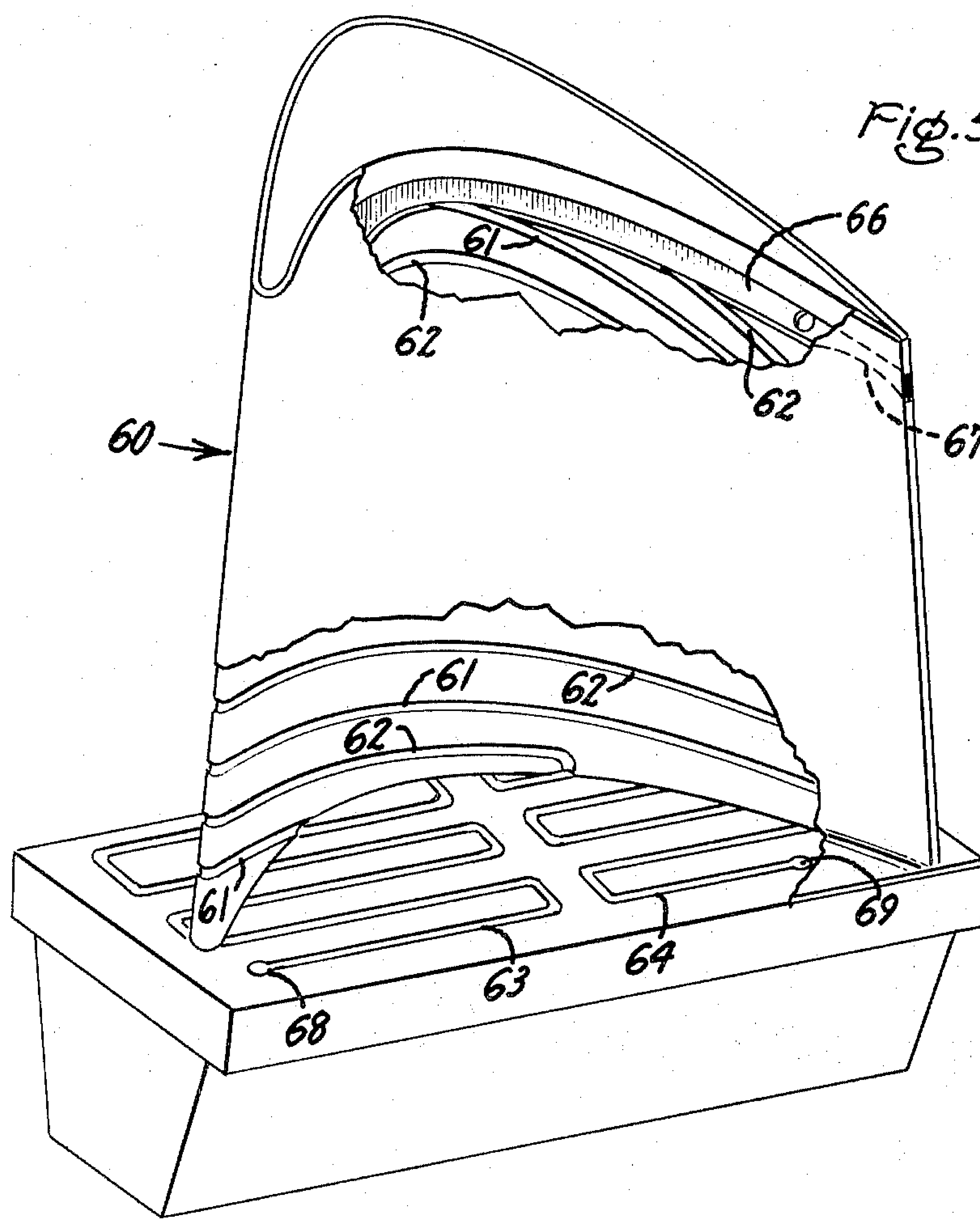


Fig. 7.

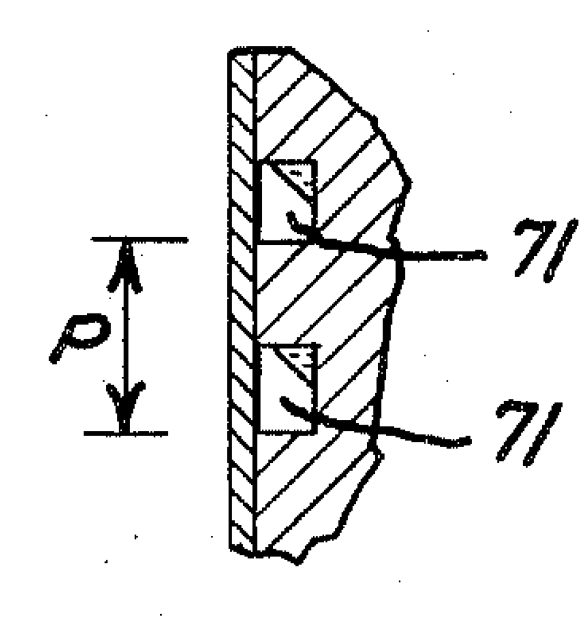
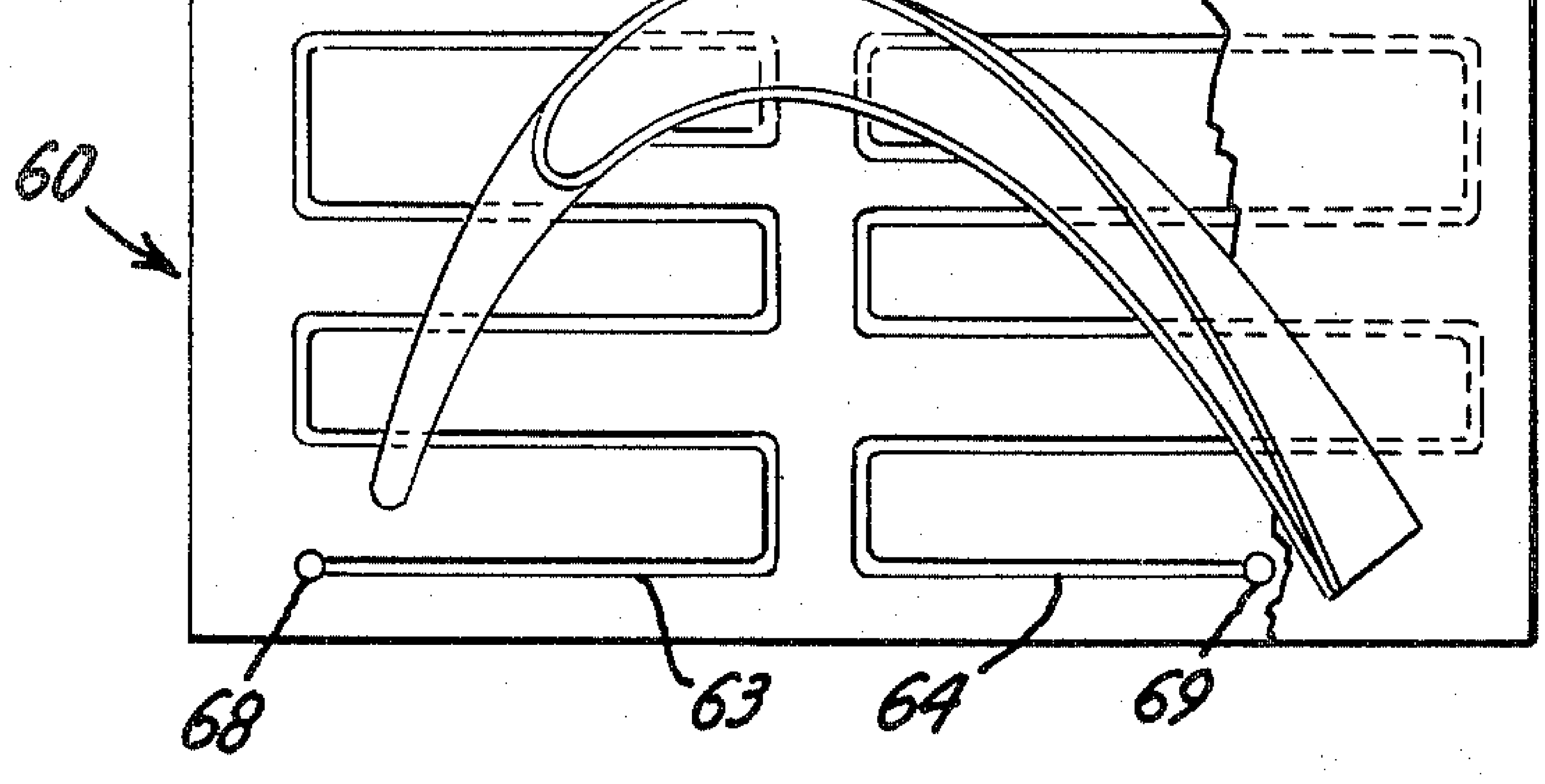


Fig. 6.



SERPENTINE COOLING CHANNEL CONSTRUCTION FOR OPEN-CIRCUIT LIQUID COOLED TURBINE BUCKETS

BACKGROUND OF THE INVENTION

Structural arrangements for the open-circuit liquid cooling of gas turbine buckets are shown in U.S. Pat. Nos. 3,446,481 — Kydd and 3,446,482 — Kydd. The bucket cooling is accomplished by means of a large number of cooling channels extending radially from the root toward the tip. Arrangements for metering liquid coolant to each of such cooling channels are shown in U.S. Pat. No. 3,658,439 — Kydd and in U.S. application Ser. No. 285,633 — Moore (now U.S. Pat. No. 3,804,551 assigned to the assignee of the instant invention). Both Kydd U.S. Pat. No. 3,658,439 and the Moore application employ axially-extending weir construction for the metering. These patents and patent application are incorporated by reference.

Open-circuit liquid cooling capability is particularly important, because it make feasible increasing the turbine inlet temperature to an operating range of from 2,500°F to at least 3,500°F thereby obtaining an increase in power output ranging from about 100 to 200 percent and an increase in thermal efficiency ranging to as high as 50 percent. Such open-circuit liquid-cooled turbine structures are referred to as "ultra high temperature" gas turbines.

Liquid coolant metering is complicated by the extremely high bucket tip speeds employed resulting in centrifugal fields of the order of 250,000 G. Under such severe operating conditions even slight errors in manufacture of the weir structure can orient the weir slightly askew of the axis of rotation and produce non-uniform coolant distribution to the cooling channels. Also, any distortion of the turbine disk or disk rim induced at speed can produce a similar effect.

SUMMARY OF THE INVENTION

The instant invention minimizes the number of cooling channels used in open-circuit liquid cooling of turbine buckets by arranging each cooling channel in a convoluted configuration in which most of the length of the cooling channel extends generally chordwise of the airfoil under the surface thereof with successive convolutions progressing from the root toward the tip thereof. Each such convoluted coolant channel is in direct flow communication with a circumferentially disposed gutter in the rotor rim via a coolant supply conduit, whereby liquid coolant is supplied directly to each such winding cooling channel. Preferably, a coolant conduit of serpentine or sinuous configuration extending over at least a portion of the bucket platform is employed interposed in series between the coolant supply conduit and a serpentine coolant channel in the airfoil. A uniform supply of liquid coolant to the inlet to each coolant supply conduit is insured by spacing the openings (gutter-end) of these coolant supply conduits at equal intervals around the circumference of the gutter.

BRIEF DESCRIPTION OF THE DRAWING

The exact nature of this invention as well as objects and advantages thereof will be readily apparent from consideration of the following specification relating to the annexed drawings in which:

FIG. 1 is a three-dimensional view, partly cut away, showing a typical overall arrangement for at least one of the coolant paths for a turbine bucket constructed according to this invention;

FIG. 2 is a view in section through the rotor disk showing the pressure side of the bucket of FIG. 1 in elevation and coolant supply conduits for two coolant paths on each side of the bucket;

FIG. 3 is a view similar to FIG. 1 specifically applied to dovetailed bucket attachment;

FIG. 4 is a view in section through the rotor disk with the pressure side of the bucket of FIG. 3 in elevation showing the coolant supply conduits for two coolant paths on each side of the bucket;

FIG. 5 is a three-dimensional view, partly cut away, showing a spiraled configuration of a cooling channel for a turbine bucket according to this invention;

FIG. 6 is a plan view, partially cut away, of the bucket shown in FIG. 5 setting forth each platform cooling channel connected in series between a spiral bucket cooling channel and the coolant supply conduit therefor and

FIG. 7 is a section taken through any of the bucket cooling channels showing that in spite of the tortuous nature of the coolant path under the bucket skin, it still remains an open, high velocity flow system throughout.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Metal skin **11** providing the airfoil configuration for the bucket **10** is shown cut away from the pressure side of bucket **10.** Skin **11** is bonded to strut, or core, **12** having a plurality of serpentine grooves, such as grooves **13** and **14,** formed in the surfaces thereof, these grooves winding generally chordwise thereacross with the overall bucket cooling pattern extending from the root toward the tip of strut **12.** As may be seen, the chordwise-extending portions of grooves **13, 14** constitute by far the greatest amount of the total length of these grooves. The cooling channels, or passages, for the surfaces of the completed bucket **10** are thus defined by the skin **11** and grooves, such as the grooves **13, 14.** A similar arrangement of one or more groove patterns (not shown) extending in a serpentine pattern is disposed on the suction face of strut **12.** At the radially outer ends thereof the serpentine cooling channels (preferably rectangular in cross section as shown in FIG. 7) are in flow communication with, and terminate at, manifold **16** (and a similar length of manifold, not shown, on the suction side) recessed into core **12.** Near the trailing edge of bucket **10,** a cross-over conduit (not shown) connects the manifold on the suction side with manifold **16** via opening ***16a***.

U.S. Pat. No. 3,533,712 — Kercher discloses the use of internally-located radially-extending serpentine passages for the flow of cooling fluid (air) through a turbine bucket. The patentee recognizes that the heat flux chordwise of the bucket will vary greatly while the heat flux is essentially constant along a radial line. He puts this information to use by connecting together in a serpentine configuration several radially-extending passages each with a constant cross-sectional area that differs from the cross-sectional area of the other passages. Such an arrangement is not adaptable to liquid cooling. If such radially-directed serpentine passages were to be used for liquid cooling all legs of the serpentine series would have to remain full of the liquid (except for slugs of vapor that may develop and be pushed along in the liquid) moving at relatively low velocity except for the last leg of the serpentine passage in which the coolant stream would move radially outward. The restriction of having most of the length of the serpentine passage operate full of low velocity liquid flow would result in,

a. an unstable cooling system,
b. isolation of liquid coolant from portions (wherever large slugs of vapor prevail) of the cooling channel producing localized overheating and
c. deposition of any impurities in the coolant.

Even the use of very pure coolant is only a partial solution to these problems. Thus, the arrangement disclosed in Kercher is unsuitable to liquid cooling although it provides an effective approach to air cooling.

The use of serpentine passages communicating directly (i.e, without interposed metering means) with liquid coolant supplied to the turbine disk is, therefore, an unworkable solution to the problem at hand (namely, the elimination of the metering weir) in the absence of the realization that long tortuous coolant paths can be operated as "open" coolant paths, if centrifugal force is properly applied to the coolant flow. Just such a condition is found to exist, if the convolutions of the tortuous coolant path are made to extend predominantly in the generally chordwise direction. This phenomenon is described in greater detail in connection with the discussion of FIG. **7,** hereinbelow.

Preferably, the open-circuit coolant discharge from manifold **16** (and, thereby, from the manifold on the suction side) is accomplished via the convergent-divergent nozzle **17** as described in U.S. Patent application Ser. No. 285,631 — Day, filed Sept. 1, 1972 and assigned to the assignee of the instant invention.

The root portion **18** fits into a mating slot in rim **19** of the turbine disk, being brazed thereto. After buckets **10** have been brazed into the rim **19,** the gutters **21, 22** are machined into the rim.

Steel alloys may be used for the skin and core, preferably those containing at least 12 percent by weight of chromium or corrosion resistant and heat treatable to achieve high strength. Conventional brazing alloys having melting points ranging from 700° to 1,200°C. may be used.

As has been shown for serpentine groove **13,** at the root end thereof each serpentine cooling channel pattern formed in the surface of core **12** is connected to (and is in flow communication with) a serpentine groove (e.g., grooves **23, 24**) formed in the platform surface of root portion **18.** Serpentine platform cooling channels are defined by such grooves together with platform skin **26** and each such channel serves to cool a portion of the platform surface.

The cooling of the platform may be accomplished by the use of a single pool (or a series of interconnected pools) so long as any given pool cavity is properly baffled and in flow communication with one of gutters **21, 22** and with one of the convoluted cooling channels below the surface of the airfoil portion of bucket **10.** Care must be taken to design for stress transfer between airfoil and root, of course.

The terminal end of each platform serpentine segment (such as serpentine grooves **23, 24**) is in flow communication with one or the other of gutters **21, 22** via coolant supply conduits, such as conduits **27, 28, 29** and **31.** To promote clarity no attempt has been made to show the connection between conduits **29, 31** (shown in FIG. **2**) and serpentine cooling channels in the platform fed thereby, the principles being fully illustrated with conduits **27** and **28.** The design of the rim, bucket root and gutters may be varied, of course, and as a consequence part of the length of conduits **27, 28, 29, 31** may extend through the rim structure to reach the gutters. Such construction, for example, is shown in FIG. **4.**

Thus, as is described in the aforementioned Kydd patents, cooling liquid (usually water) is sprayed at low pressure in a generally radially outward direction from nozzles (not shown), but preferably located on each side of disk **32.** The coolant impinges on disk **19** and moves into gutters **21, 22** defined in part by downwardly extending lip portions formed in rotor rim **19.** The cooling liquid is retained in the gutters until this liquid has been accelerated to the prevailing disk rim velocity.

After the cooling liquid in gutters **21, 22** has been so accelerated, this liquid drains in one or more continuous path from gutters **21, 22** in the generally radially outward direction via:

a. the coolant conduits (e.g., conduits **27, 28, 29, 31**),
b. the serpentine platform cooling channel patterns (e.g., the cooling channels defined by grooves **23** and **24** and skin **26**),
c. the serpentine cooling channel patterns under the airfoil surfaces of bucket **10** (e.g., the cooling channels defined by grooves **13, 14** and skin **11**),
d. chordwise-extending manifolds (e.g., manifold **16**) and
e. nozzle **17** from which the heated coolant (liquid and gas, or vapor, mixture) is discharged.

A uniform supply of coolant to each coolant supply conduit is insured by spacing the openings from the gutters to the coolant supply conduits at equal intervals along the circumference of the gutters.

The turbine buckets described herein are made by investment casting as generally described in U.S. Pat. No. 3,678,987 — Kydd. Preferably the bucket cores are made solid. Any passageways passing through the bucket root or formed in the platform surface of the root and extending under the base of the core airfoil portion are provided for by the inclusion of appropriately shaped leachable ceramic (e.g., quartz tubing) bodies in the wax replicas from which the ceramic shell molds are made. After the castings (bucket cores and roots) have been made with the cooling groove patterns cast in the surface thereof, the ceramic shells are removed. Thereafter, the leachable ceramic members are removed in a molten salt bath.

FIGS. **3** and **4** illustrate the application of the improvement of this invention to a dovetail bucket **40** made up of metal skin **41,** strut **42,** dovetail root portion **43,** and platform skin **44.** At least part of three convoluted cooling passage patterns are shown and most of one cooling path from gutter to exit nozzle is shown. Such buckets are held in place in rim **46** by retaining rings (not shown) or retaining pins (not shown).

In FIG. **3,** as in FIG. **1,** the only coolant supply conduits (conduits **47, 48**) shown are those for which connections to serpentine platform groove patterns are shown. Other such coolant supply channels must, of course, be provided for the conduct of liquid coolant to serpentine pattern 49, 51 and other patterns (not shown) on the suction face of core 42. As is shown in FIG. 4 in order for the coolant supply conduits to reach gutters 52, 53, they must communicate with connecting passages in rim 46. Thus, conduit 47 cooperates with passage 47*a* and conduit 48 cooperates with passage 48*a* to act as coolant supply ducts. A pair of similar supply ducts is shown connected to gutter 53, but in the interest of clarity the connections from these supply ducts to platform cooling patterns are not shown. Gutter openings to passages connecting the gutters to the channels in the bucket roots for the total number of buckets are evenly spaced in any given gutter to insure equal feed of coolant thereto.

Still another configuration for a convoluted cooling pattern according to this invention is shown in FIGS. 5 and 6. The cooling pattern for the airfoil of bucket 60 in this instance is a pair of spiraling conduits 61, 62 connected at the platform level to separate serpentine platform cooling patterns 63, 64, respectively, and discharging their coolant flows into manifold 66 for exit through nozzle 67. Platform cooling patterns 63, 64 would be connected to separate gutters (not shown) via supply conduits 68, 69, respectively, for the construction shown. Although a double helical pattern is shown, either single or multiple helical patterns can be employed.

The number of convoluted cooling channel patterns employed under the airfoil surfaces of the buckets and the span of metal permitted between the successive chordwise-extending portions of these channels on a given bucket face can be designed to match the amount of local heat transfer required. Thus, a single convoluted pattern may be utilized to cool the entire suction face and a similar such cooling channel pattern may be employed to cool the entire pressure face or any number of zoned cooling patterns may be devised wherein two, three or even more separate serpentine patterns may be disposed under either or both of the airfoil surfaces of the bucket.

FIG. 7 is a section taken through a portion of a cooling channel pattern and the adjacent skin and bucket core regions. The generally radial distance indicated by the letter P between corresponding points on chordwise-extending segments of the same convoluted cooling channel as well as the dimensions of the cooling channels are a function of:

1. the local heat flux at the exterior of turbine bucket 10 (which in turn is a function of the local working fluid temperature, pressure and flow field);
2. the thickness of the skin;
3. the thermal conductivities of the skin and core materials;
4. allowable skin surface temperature (which in turn is dependent upon the fatigue life of the skin material under the thermal strain imposed by the operating conditions) and
5. the coolant heat transfer coefficient as determined by the coolant flow conditions and the thermodynamic state (temperature, pressure and enthalpy) of the coolant.

A very important feature of this invention is the utilization of convoluted patterns for the cooling channels, in which channels in spite of the tortuous nature thereof coolant liquid always has a free surface (i.e., the channels do not, and need not, run full). The coolant path is open such that liquid and vapor are each free to move without disturbing each other. The extremely large centrifugal force exerted on the system readily urges the liquid coolant through the most tortuous, small cross section channel pattern required. In the case illustrated in FIG. 7 at the suction face of the bucket, the liquid coolant is disposed over surfaces of channels 71 that are the most radially-outward and are toward the pressure side of the bucket. Thus, the liquid coolant has a free surface and, as vapor is generated, the continuity of the liquid flow is not interrupted. Although the velocity of the thin layer of coolant is reduced from the velocities that would prevail for liquid passing through radial cooling channels as in the Moore application, the velocity would still be of the order of about 25 times the velocity of the same liquid coolant, if used in the radially-directed serpentine passages of Kercher.

A determination of maximum cooling channel pitch as a function of heat flux has been set forth in Table I below assuming a given set of conditions to allow for the utilization of various materials for the construction of the bucket cores and skins. These assumptions are:

1. The skin and core thermal conductivities are considered equal to about 45 BTU ft/hr ft^2 °F; lower values of thermal conductivity will decrease the maximum allowable pitch.
2. The maximum allowable bucket skin surface temperature is to be 1,400°F; a lower temperature limit will decrease the maximum allowable pitch.
3. The temperature of the liquid coolant is to be 100°F; an increase in this limit will decrease the maximum allowable pitch.
4. The skin thickness is to be 0.010 inch; increasing the thickness of the skin will decrease the maximum allowable pitch.
5. Cooling channel dimensions are to be 0.030 inch × 0.030 inch; an increase in the channel cross-sectional area will decrease the pitch in those locations on the bucket at which the cooling problem is the most severe (coolant film not in contact with the skin).
6. The liquid coolant is in contact with the skin inside the cooling channel. Of course, in most locations on the bucket less favorable conditions prevail and the coolant flows along one side of the cooling channel (FIG. 7) possibly, even the bottom. Maximum allowable cooling channel pitch will be smaller, because of such areas.

TABLE I

Heat Flux (BTU/ft²/hr)	Maximum Pitch (inches)
1×10^6	0.6 in.
1.5×10^6	0.4 in.
2×10^6	0.33 in.

By feeding the coolant directly from the gutter to the various coolant supply conduits, the limitations placed upon coolant metering by the use of axially directed weirs have been removed and, in addition, a greatly simplified turbine rotor design has been produced. More positive control of the coolant flow along each coolant circuit results and, as well, the effect of internal coolant erosion on the controlled distribution of coolant through the system is diminished due to the reduction in coolant flow velocities in the cooling channels. This invention is equally applicable to the fabrication of both large and small turbine buckets.

The cross-sectional area of the convoluted cooling channels can be varied as a function of the heat flux, which is widely variant chordwise of the bucket. However, it is preferred that the dimensions of any given cooling channel (e.g., pattern 13) be kept substantially constant.

This invention has been illustrated in connection with a liquid cooled gas turbine, but application can be made thereof to any liquid cooled rotor system, e.g., a compressor, which would in essence comprise the general structure shown herein operated in reverse to work on a gas instead of having gaseous working fluid exert force on a rotor disk via the buckets. The term "vane," where employed in the claims, is intended to encompass airfoilshaped elements used both in high temperature turbomachines and in compressor rotors in which cooling is required. The term "pitch" (as in distance P of FIG. 7) as employed in the claims refers to the distance between corresponding points on successive chordwise-extending segments of the same convoluted cooling channel. Preferably this is substantially a uniform dimension.

What I claim as new and desire to secure by Letters Patent of the United States is:

1. In a vane structure adapted for mounting in a rotating element of a machine wherein the airfoil surfaces of the vane are subjected to contact with hot gas, the vane comprising an airfoil-shaped core and a conforming skin affixed thereto, said core and said skin defining at least one open-ended subsurface passage therebetween for the transit of coolant therethrough, said at least one passage being adapted to receive coolant flow at the radially inner end thereof from a source of coolant and to discharge the coolant flow from the radially outer end thereof into a chordwise-extending manifold, said manifold in turn being adapted to discharge coolant flow from said vane, the improvement in which a plurality of subsurface passages are employed, each passage being arranged in a serpentine pattern confined to one face of the vane and having a substantially constant depth along the length thereof, most of each successive convolution of said serpentine pattern extending in the generally chordwise direction.

2. The improvement of claim 1 wherein one face of the vane is provided with a plurality of separate subsurface serpentine cooling patterns.

3. The improvement of claim 1 wherein the maximum pitch for the serpentine pattern is about 0.6 inch.

4. In a gas turbine wherein a turbine disk is mounted on a shaft rotatably supported in a casing, said turbine disk extending substantially perpendicular to the axis of said shaft and having turbine buckets affixed to the outer rim thereof, each bucket comprising an airfoil-shaped core and a conforming skin affixed thereto, said buckets receiving a driving force from a hot motive fluid moving in a direction generally parallel to said axis of said shaft and the driving force being transmitted to said shaft via said turbine disk, means located radially inward of said buckets for introducing liquid coolant within said turbine in a radially outward direction to enter an open-ended coolant distribution circuit comprising in the airfoil of each of said buckets at least one subsurface cooling channel defined by said core and said skin, said at least one cooling channel being adapted to receive liquid coolant at the radially inner end thereof, and a manifolding and discharge portion located in the radially outer end region of the airfoil of the given bucket, said manifolding and discharge portion being in flow communication with the radially outer end of said at least one cooling channel, the improvement in the above combination comprising:

a. at least one annular gutter region forming part of the rim of said turbine disk to receive liquid coolant,

b. said at least one subsurface cooling channel being of a substantially constant depth along the length thereof and being arranged in a serpentine pattern confined to one face of the vane with most of each of the successive convolutions thereof extending in the generally chordwise direction, the radially inner end of said cooling channel being in flow communication with said gutter region.

5. The improvement of claim 4 wherein the inner end of each cooling channel is connected to the gutter region by a separate closed conduit having as part of the length thereof a subsurface cooling passage of convoluted configuration located in platform structure at the base of the airfoil.

6. The improvement of claim 5 wherein the airfoil of the given bucket is provided with a plurality of subsurface cooling channels of serpentine pattern, each of said channels being connected to a separate closed conduit in flow communication with a gutter region, said closed conduit having as part of the length thereof a subsurface cooling passage of serpentine configuration located in the platform structure.

7. The improvement of claim 4 wherein the one face of the airfoil is provided with a plurality of separate subsurface serpentine cooling patterns.

8. The improvement of claim 4 wherein each subsurface cooling channel is connected to a separate closed conduit in flow communication with an annular gutter region, the opening from each closed conduit into the same gutter region being equally spaced from openings of closed conduits adjacent thereto on each side thereof.

9. The improvement of claim 8 wherein each airfoil is provided with a plurality of subsurface cooling channels.

10. The improvement of claim 8 wherein each closed conduit has as part of the length thereof a subsurface cooling passage of convoluted configuration located in platform structure at the base of the airfoil.

11. The improvement of claim 4 wherein the maximum pitch for the convoluted configuration is about 0.6 inch.

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