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(54) **COMBINED TIP FLAG BLADE CORE**

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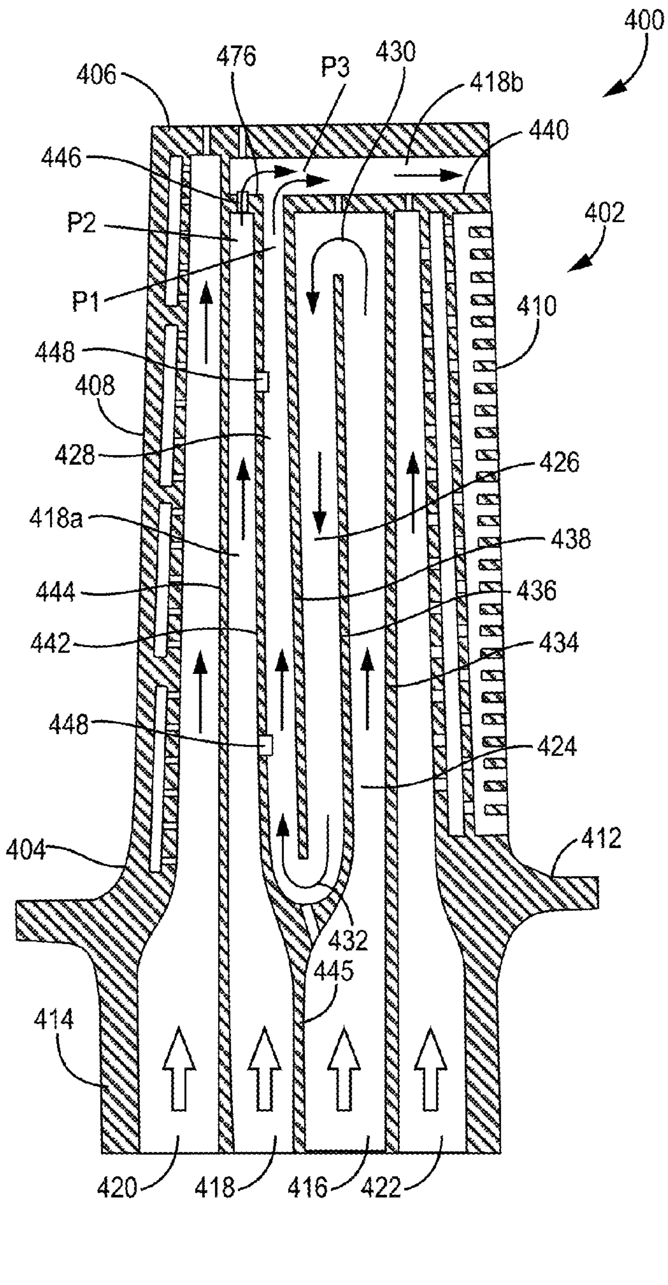
(57) **ABSTRACT**

A cooling circuit of an airfoil for a gas turbine engine includes a serpentine channel having a plurality of fluidly connected radially extending flow passages and a tip flag channel disposed adjacent to the serpentine channel. The tip flag channel includes a first tip flag passage extending radially and a second tip flag passage extending axially from a terminal end of the first tip flag passage, the second tip flag passage disposed radially outward of the serpentine channel. The second tip flag passage is in direct fluid communication with each of the first tip flag passage and a final passage of the serpentine channel.



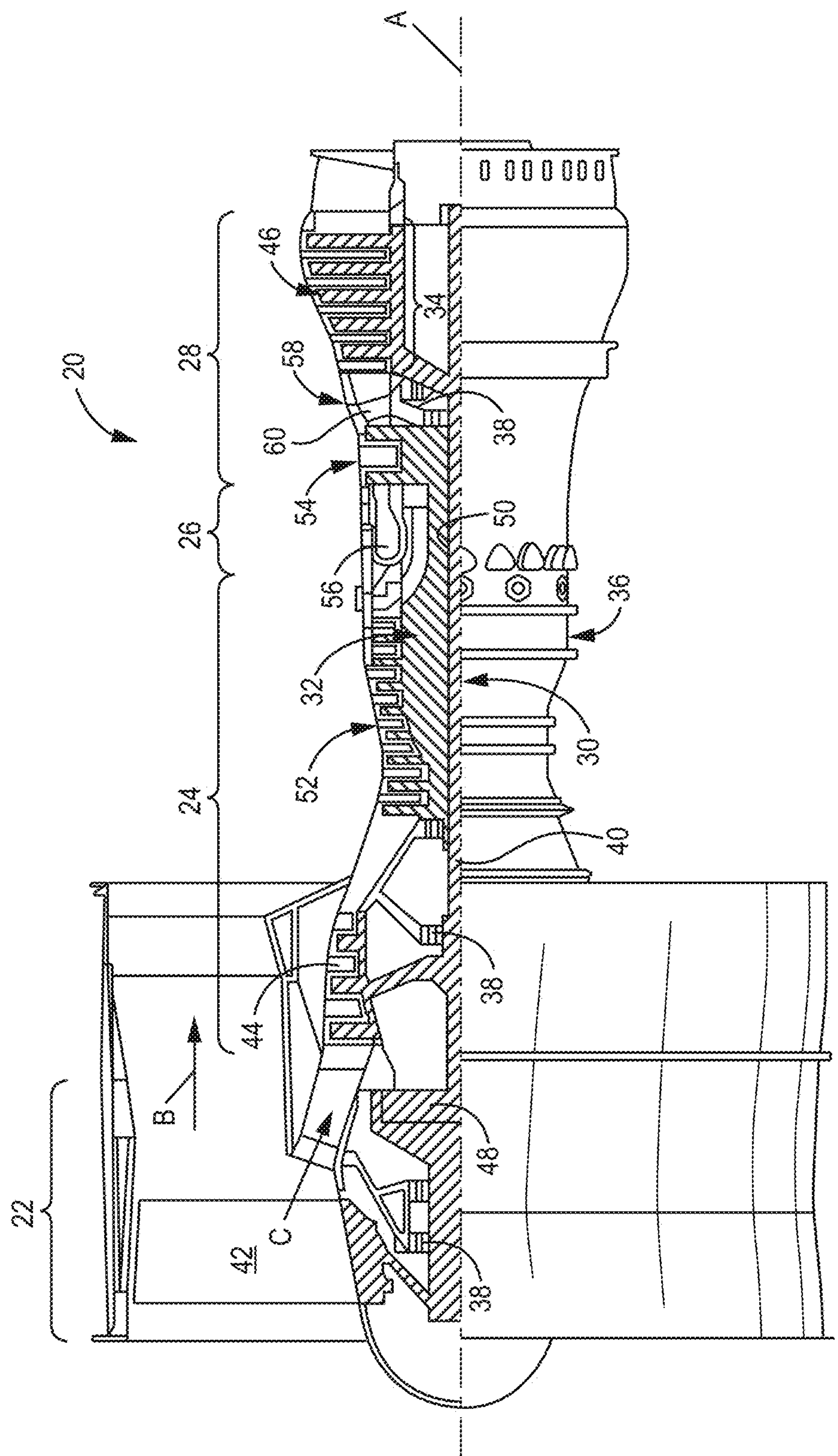
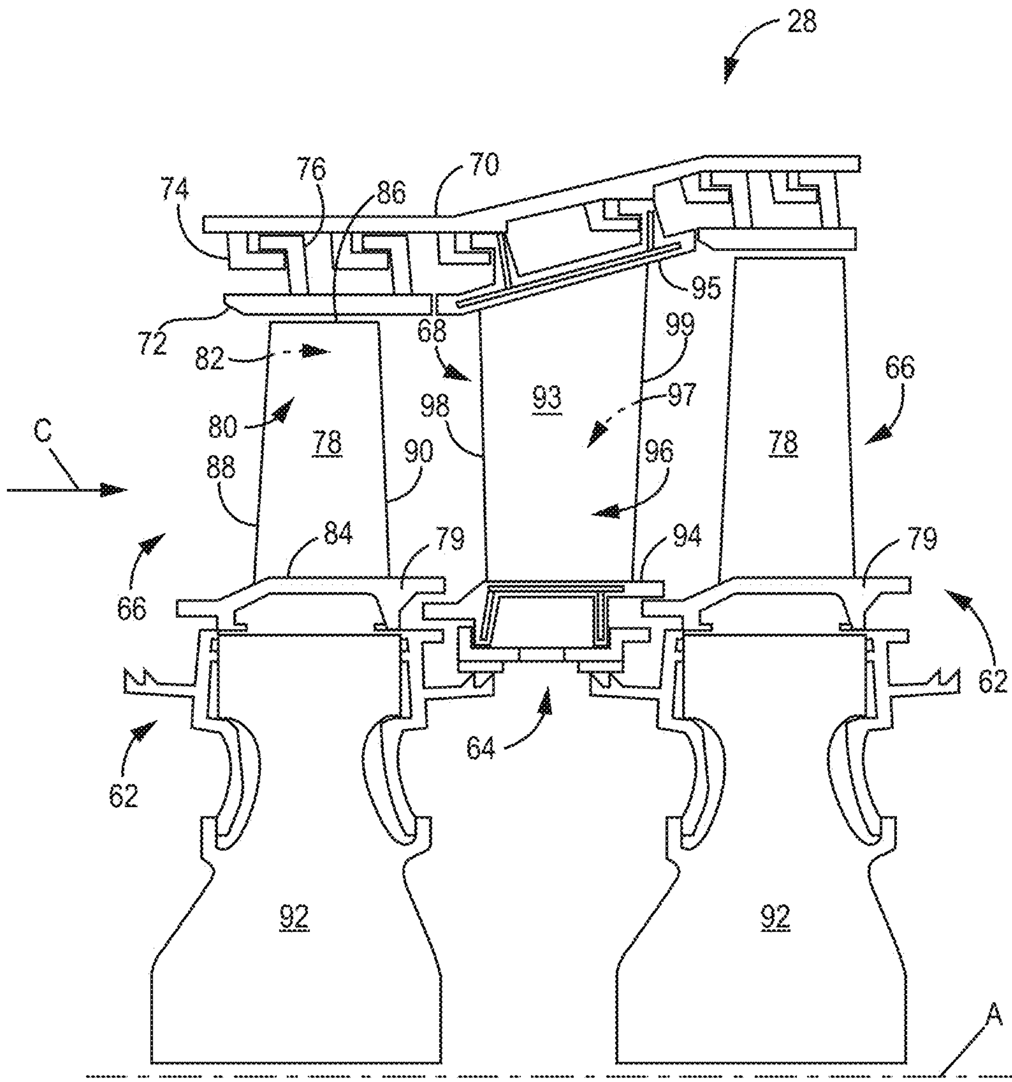


FIG. 1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70
74
76
86
95
72
68
99
82
66
93
97
98
80
78
78
90
96
C
88
94
84
79
79
66
62
64
62
92
92
A

FIG. 2

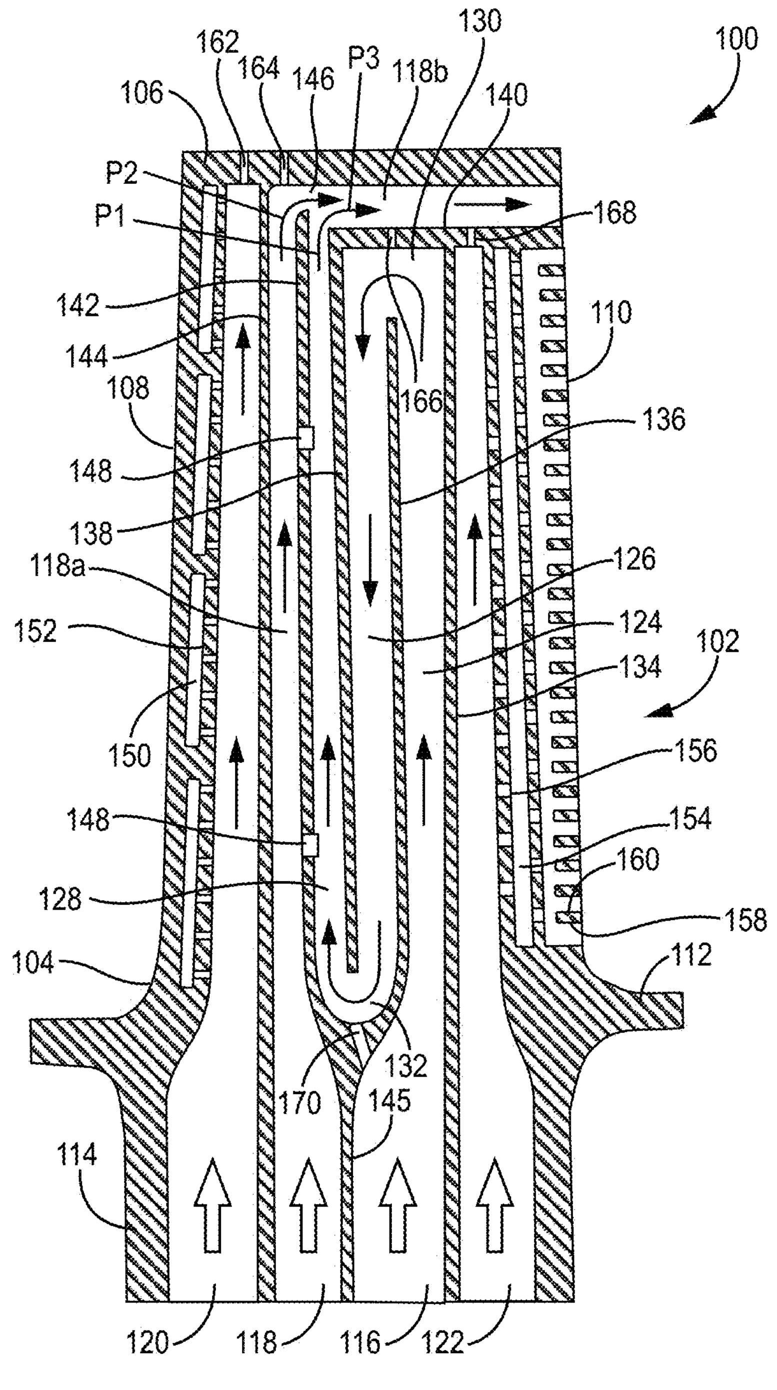
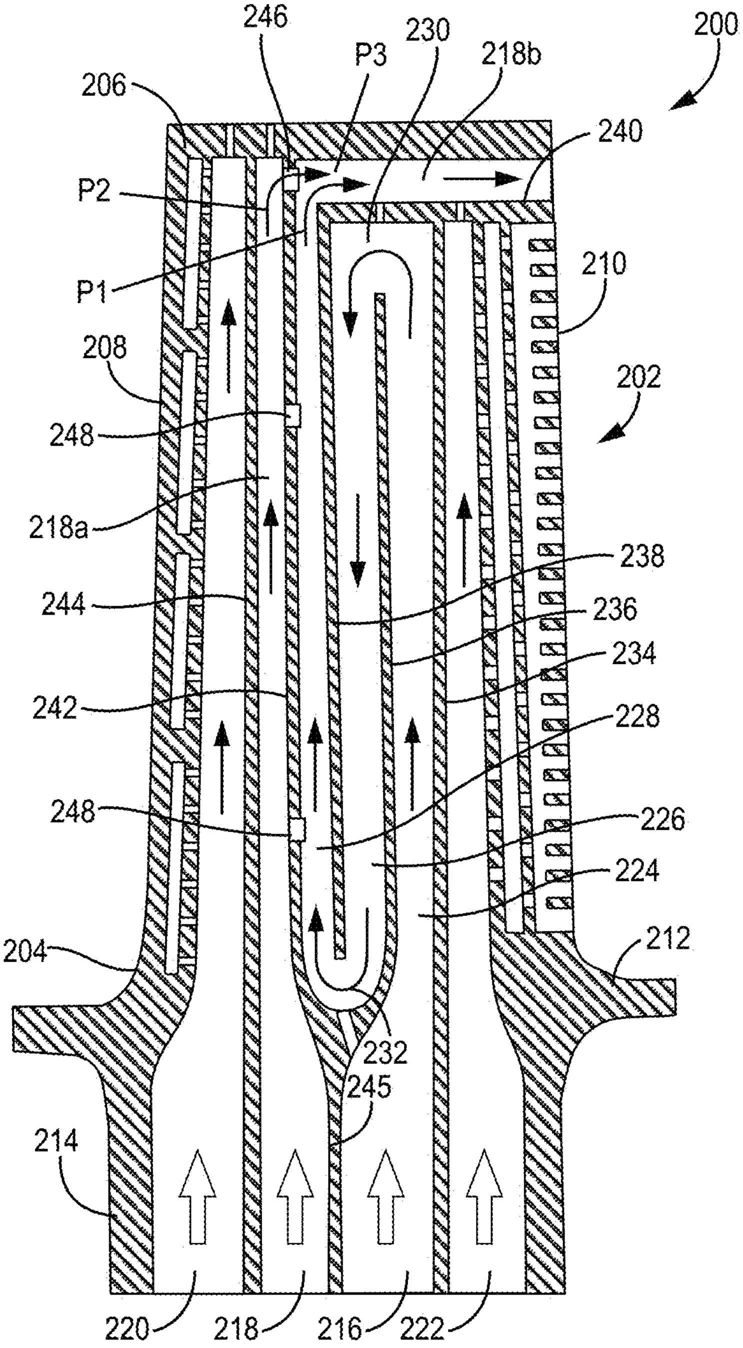

100
106
162
164
146
P3
118b
130
140
P2
P1
168
142
144
110
108
166
136
148
138
126
118a
124
152
102
134
150
156
148
154
160
128
158
104
112
132
170
145
114
120
118
116
122

FIG. 3


246
P3
230
218b
200
206
240
P2
P1
210
208
202
248
218a
238
244
236
234
242
228
248
226
224
204
212
232
245
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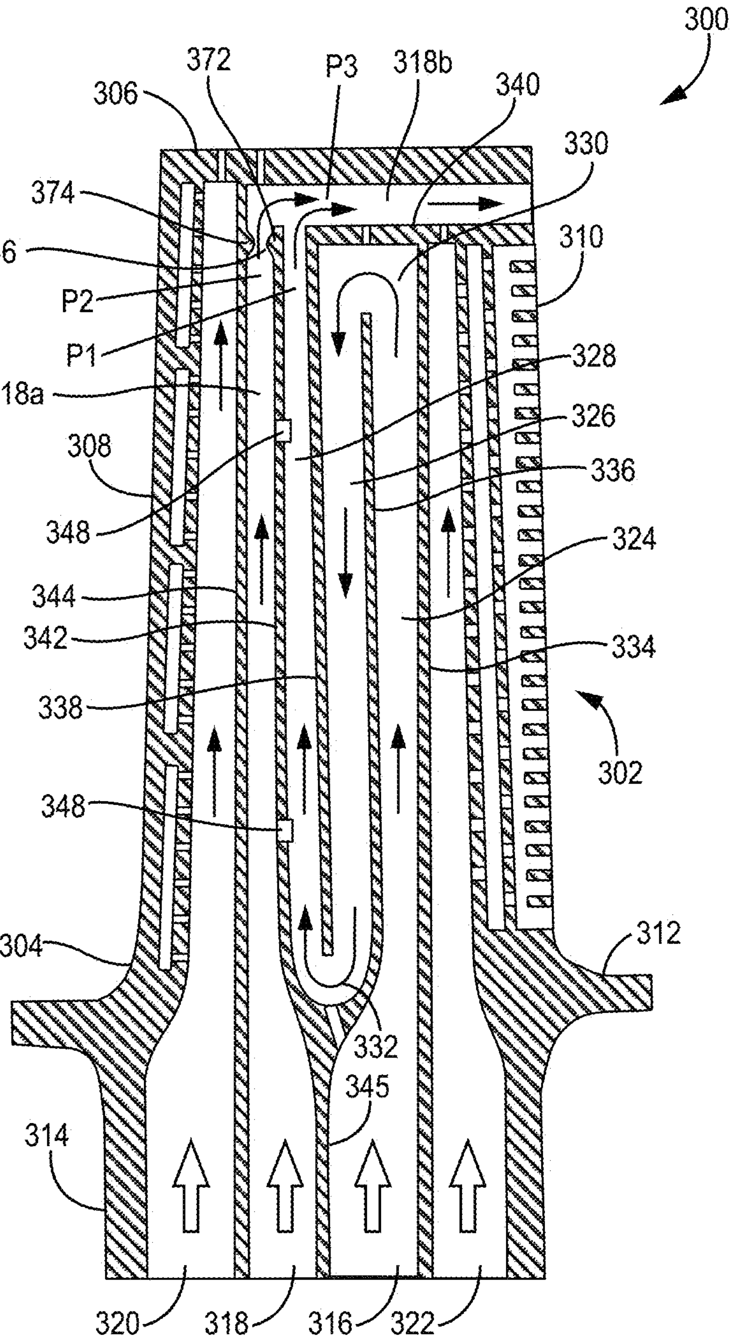
220
218
216
222

FIG. 4


300
306
372
P3
318b
340
330
374
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310
P2
P1
328
318a
326
308
336
348
324
344
342
334
338
302
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304
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332
345
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316
322

FIG. 5

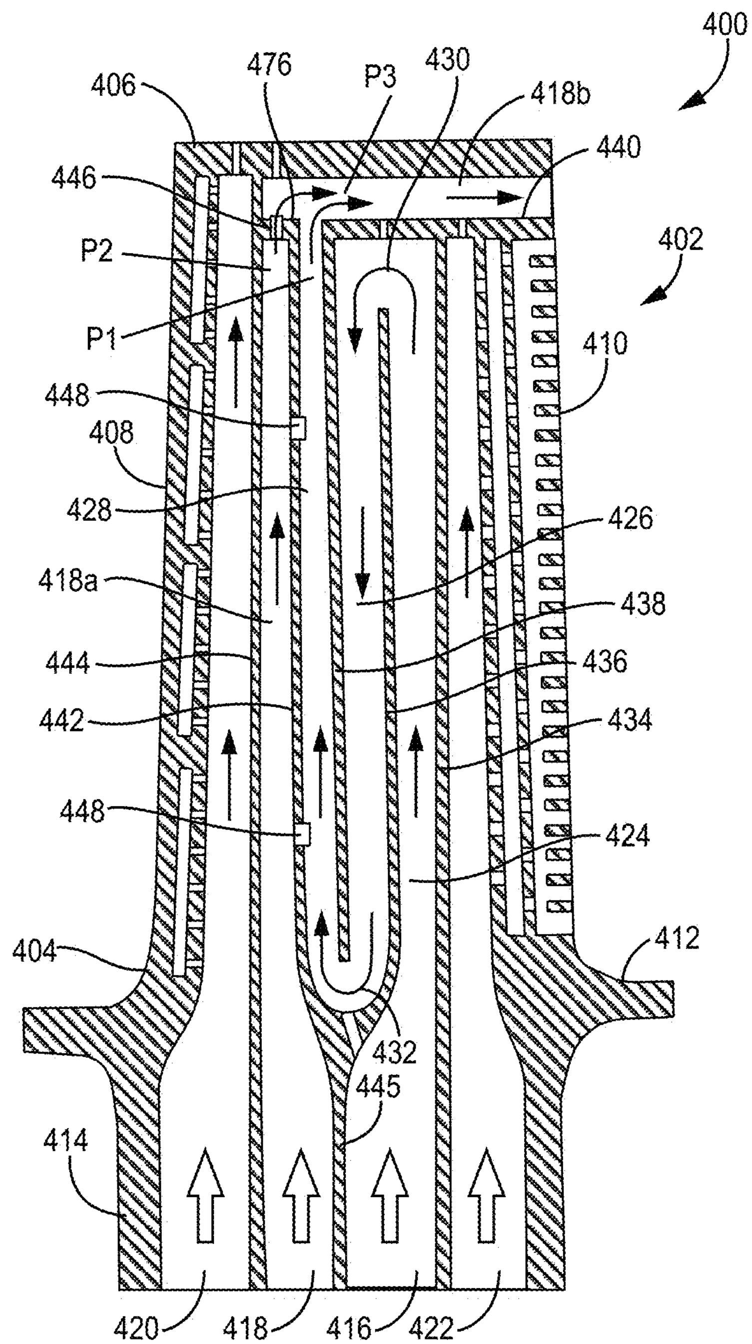
400
406
476
P3
430
418b
440
446
402
P2
P1
410
448
408
428
426
418a
438
444
436
442
434
448
424
404
412
432
445
414
420
418
416
422

FIG. 6

COMBINED TIP FLAG BLADE CORE

STATEMENT OF GOVERNMENT INTEREST

[0001] This invention was made with government support under Contract No. N00019-21-G-0005 awarded by United States Air Force. The government has certain rights in the invention.

BACKGROUND

[0002] The present invention relates generally to cooling components of gas turbine engines and, more particularly, to airfoil cooling circuits.

[0003] A gas turbine engine may include a turbine section with multiple rows or stages of stator vanes and rotor blades that interact or react with a high temperature gas flow to create mechanical power. The efficiency of the engine can be increased by passing a higher temperature gas flow through the turbine. However, the turbine inlet temperature is limited to the vane and blade (airfoils) material properties and the cooling capabilities of the airfoils. Hollow airfoils of a turbine section include internal cooling circuits or cores configured to achieve a higher cooling effectiveness and to reduce airfoil metal temperatures. A blade core design that reduces cooling air heat pick-up and increases the internal heat transfer coefficient without compromising back flow margin is desirable. This is of particular interest in the tip region of a blade where gas path temperatures are generally the hottest. Blade tips encompass a relatively large mass of hot metal, often experience thermal mechanical fatigue cracks due to mismatch between outboard airfoil wall thickness and a tip cap thickness, and are difficult to cool due to poor film cooling attachment in the tip region. Another area of interest is the last passage of a serpentine cooling channel, which typically ends in a dead-end and has low flow and internal heat transfer as a result. Serpentine tip turns and the last passages of dead-ended serpentine cooling channels do not provide good heat transfer due to flow separation and low flow rate and/or flow separation, respectively. An axially extending tip flag cavity disposed at a tip of the blade helps reduce heat pickup throughout the serpentine channel by reducing the length the cooling fluid travels. A dedicated tip flag has the added benefit of providing cool air to the tip of the blade but does not solve the shortfalls of a dead-ended serpentine cavity.

[0004] New cooling circuit designs are needed to enable higher internal heat transfer in the last passage of a serpentine cooling channel while providing relatively cool tip temperatures.

SUMMARY

[0005] An airfoil for a gas turbine engine, configured to extend in a radial direction relative to an engine axis from an inner diameter to an outer diameter, includes a body and a cooling circuit disposed in the body. The body has a base disposed at the inner diameter, a tip disposed at the outer diameter, a leading edge, a trailing edge, a pressure side wall extending between the leading edge and the trailing edge and between the base and the tip, and a suction side wall extending between the leading edge and the trailing edge and between the base and the tip. The cooling circuit includes a serpentine channel having a plurality of radially extending passages connected in flow series from a first passage to a final passage and a tip flag channel disposed adjacent to the serpentine channel. The tip flag channel includes a first tip flag passage disposed adjacent to the final passage of the serpentine channel and extending radially, and a second tip flag passage disposed between the serpentine channel and the tip and extending axially from the first tip flag passage and disposed direct fluid communication with each of the first tip flag passage and the final passage of the serpentine channel.

[0006] A cooling circuit of an airfoil for a gas turbine engine includes a serpentine channel having a plurality of fluidly connected radially extending flow passages and a tip flag channel disposed adjacent to the serpentine channel. The tip flag channel includes a first tip flag passage extending radially and a second tip flag passage extending axially from a terminal end of the first tip flag passage, the second tip flag passage disposed radially outward of the serpentine channel. The second tip flag passage is in direct fluid communication with each of the first tip flag passage and a final passage of the serpentine channel.

[0007] The present summary is provided only by way of example, and not limitation. Other aspects of the present disclosure will be appreciated in view of the entirety of the present disclosure, including the entire text, claims, and accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] FIG. **1** is a quarter-sectional view of a gas turbine engine.

[0009] FIG. **2** is a schematized cross-sectional view of a turbine section of the gas turbine engine of FIG. **1**.

[0010] FIG. **3** is a cross-sectional view of one embodiment of an airfoil of the turbine section of FIG. **2** having an axial metering hole connecting a radially extending passage to an axially extending passage of a tip flag cooling channel.

[0011] FIG. **4** is a cross-sectional view of another embodiment of an airfoil of the turbine section of FIG. **2** having an axial wall-to-wall metering slot connecting a radially extending passage to an axially extending passage of a tip flag cooling channel.

[0012] FIG. **5** is a cross-sectional view of yet another embodiment of an airfoil of the turbine section of FIG. **2** having a radial metering hole connecting a radially extending passage to an axially extending passage of a tip flag cooling channel.

[0013] FIG. **6** is a cross-sectional view of yet another embodiment of an airfoil of the turbine section of FIG. **2** having radial wall-to-wall metering slot connecting a radially extending passage to an axially extending passage of a tip flag cooling channel.

[0014] While the above-identified figures set forth one or more embodiments of the present disclosure, other embodiments are also contemplated, as noted in the discussion. In all cases, this disclosure presents the invention by way of representation and not limitation. It should be understood that numerous other modifications and embodiments can be devised by those skilled in the art, which fall within the scope and spirit of the principles of the invention. The figures may not be drawn to scale, and applications and embodiments of the present invention may include features and components not specifically shown in the drawings.

DETAILED DESCRIPTION

[0015] FIG. **1** is a quarter-sectional view of gas turbine engine **20** that includes fan section **22**, compressor section **24**, combustor section **26** and turbine section **28**. Fan section **22** drives air along bypass flow path B while compressor section **24** draws air in along core flow path C where air is compressed and communicated to combustor section **26**. In combustor section **26**, air is mixed with fuel and ignited to generate a high pressure exhaust gas stream that expands through turbine section **28** where energy is extracted and utilized to drive fan section **22** and compressor section **24**.

[0016] Although the disclosed non-limiting embodiment depicts a turbofan gas turbine engine, it should be understood that the concepts described herein are not limited to use with turbofans as the teachings may be applied to other types of turbine engines; for example a low-bypass turbine engine, or a turbine engine including a three-spool architecture in which three spools concentrically rotate about a common axis and where a low spool enables a low pressure turbine to drive a fan via a gearbox, an intermediate spool that enables an intermediate pressure turbine to drive a first compressor of the compressor section, and a high spool that enables a high pressure turbine to drive a high pressure compressor of the compressor section.

[0017] As used herein, "aft" refers to the direction associated with the exhaust (e.g., the back end) of a gas turbine engine. As used herein, "forward" refers to the direction associated with the intake (e.g., the front end) of a gas turbine engine. As used herein, "aft" and "forward" refer to axial positions relative to an engine central longitudinal axis. As used herein, "radially outward" and "radial inward" refer to radial positions relative to the engine central longitudinal axis.

[0018] Example engine **20** generally includes low speed spool **30** and high speed spool **32** mounted for rotation about an engine central longitudinal axis A relative to an engine static structure **36** via several bearing systems **38**. It should be understood that various bearing systems **38** at various locations may alternatively or additionally be provided.

[0019] Low speed spool **30** generally includes inner shaft **40** that connects fan **42** and low pressure (or first) compressor section **44** to low pressure (or first) turbine section **46**. Inner shaft **40** drives fan **42** through a speed change device, such as geared architecture **48**, to drive fan **42** at a lower speed than low speed spool **30**. High-speed spool **32** includes outer shaft **50** that interconnects high pressure (or second) compressor section **52** and high pressure (or second) turbine section **54**. Inner shaft **40** and outer shaft **50** are concentric and rotate via bearing systems **38** about engine central longitudinal axis A.

[0020] Combustor **56** is arranged between high pressure compressor **52** and high pressure turbine **54**. In one example, high pressure turbine **54** includes at least two stages to provide a double stage high pressure turbine **54**. In another example, high pressure turbine **54** includes only a single stage. As used herein, a "high pressure" compressor or turbine experiences a higher pressure than a corresponding "low pressure" compressor or turbine.

[0021] The example low pressure turbine **46** has a pressure ratio that is greater than about 5. The pressure ratio of the example low pressure turbine **46** is measured prior to an inlet of low pressure turbine **46** as related to the pressure measured at the outlet of low pressure turbine **46** prior to an exhaust nozzle.

[0022] Mid-turbine frame **58** of engine static structure **36** is arranged generally between high pressure turbine **54** and low pressure turbine **46**. Mid-turbine frame **58** further supports bearing systems **38** in turbine section **28** as well as setting airflow entering low pressure turbine **46**.

[0023] The core airflow C is compressed by low pressure compressor **44** then by high pressure compressor **52** mixed with fuel and ignited in combustor **56** to produce high speed exhaust gases that are then expanded through high pressure turbine **54** and low pressure turbine **46**. Mid-turbine frame **58** includes airfoils/vanes **60**, which are in the core airflow path and function as an inlet guide vane for low pressure turbine **46**. Utilizing vanes **60** of mid-turbine frame **58** as inlet guide vanes for low pressure turbine **46** decreases the length of low pressure turbine **46** without increasing the axial length of mid-turbine frame **58**. Reducing or eliminating the number of vanes in low pressure turbine **46** shortens the axial length of turbine section **28**. Thus, the compactness of gas turbine engine **20** is increased and a higher power density may be achieved.

[0024] Each of the compressor section **24** and the turbine section **28** can include alternating rows of rotor assemblies and vane assemblies (shown schematically) that carry airfoils that extend into the core flow path C. To improve efficiency, static outer shroud seals (shown in FIG. **2**), such as a blade outer air seal (BOAS), can be located radially outward from rotor airfoils to reduce tip clearance and losses due to tip leakage.

[0025] FIG. **2** is a schematic view of a portion of turbine section **28** that may employ various embodiments disclosed herein. Turbine section **28** includes alternating rows of rotor assemblies **62** and vane assemblies **64**. Rotor assemblies **62** include a plurality of rotor blades **66** that extend into core flow path C. Vane assembly **64** includes a plurality of stationary vanes **68** that extend into core flow path C. Turbine section **28** is housed within a case **70**, which can include multiple parts (e.g., turbine case, diffuser case, etc.). In various locations, components, such as seals, may be positioned between blades **66**, vanes **68**, and case **70**. For example, BOAS **72** are located radially outward from blade **66**. BOAS **72** can include BOAS supports that are configured to fixedly connect or attach BOAS **72** to case **70**. For example, case **70** can include a plurality of hooks **74** that engage with BOAS hooks **76** to secure the BOAS **72** between case **70** and a tip of blade **66**.

[0026] Blades **66** include airfoil **78** and platform **79**. Airfoil body includes pressure side wall **80**, suction side wall **82**, base region **84**, tip **86**, leading edge **88**, and trailing edge **90**. Pressure side wall **80** is disposed opposite suction side wall **82**. Pressure side wall **80** and suction side wall **82** each extend radially from base region **84** toward tip **86**. As used herein, the term "radial" refers to an orientation perpendicular to engine axis A. Pressure side wall **80** and suction side **82** each extend generally axially and/or tangentially (e.g., with respect to engine axis A) between leading edge **88** and trailing edge **90**. Each of base region **84** and tip **86** extend from leading edge **88** to trailing edge **90** at an innermost radial extent and an outermost radial extent of airfoil **78**. Platform **79** joins airfoil **78** at base region **84**. Platform **79** forms an inner boundary of core airflow C. Blades **66** are joined to rotor disks **92**. Each bade **66** can include a root portion (not shown) received in rotor disk **92**.

[0027] Vanes **68** include airfoil body **93**, inner diameter platform **94**, and outer diameter platform **95**. Airfoil body **93**

includes pressure side wall **96**, suction side wall **97**, leading edge **98**, and trailing edge **99**. Airfoil **93** extends radially from inner diameter platform **94** to outer diameter platform **95**. Inner and outer diameter platforms **94**, **95** form inner and outer boundaries for core airflow C.

[0028] Blades **66** and vanes **68** are hollow bodies with internal cavities. Internal cavities can include one or more cooling circuits defined by a plurality of channels and flow passages configured to direct a cooling fluid. The channels can be separated by walls disposed in the internal cavity. Walls can extend, for example, radially or in a spanwise direction between base region **84** and tip **86** of blades **66**, joining pressure side wall **80** and suction side wall **82** to form radially extending channels. Walls can extend a full or partial radial span of airfoils **78** and **93**. Walls can additionally or alternatively extend axially or in a chordwise direction between leading edge **88** and trailing edge **90** of blade **66**, joining pressure side wall **80** and suction side wall **82** to form axially extending channels. Channels can be fluidly connected via turns or crossover holes through walls to form a cooling fluid flow path through blade **66** or vane **68**. Cooling fluid can be provided to the internal cavity of blades **66** via one or more openings in a base of blade **66** (e.g., through a root of the blade). A cooling fluid supply channel can extend through disk **92** and a root of blade **66** to deliver cooling fluid to the internal cooling circuit. Cooling fluid can be provided to the internal cavity of vanes **68** via one or more openings in outer diameter platform **98**.

[0029] FIGS. **3-6** are cross-sectional views of alternative embodiments of a cooling circuit for an airfoil of a gas turbine engine. The cooling circuits of FIGS. **3-6** are configured to enable higher internal heat transfer in a final passage of a serpentine channel and relatively cool tip temperatures. This is achieved by providing a dedicated tip flag channel fluidly connected to the final passage of the serpentine channel and a metering orifice that connects a radially extending passage of the tip flag channel disposed adjacent to and forward of the serpentine channel to an axially extending passage of the tip flag channel. The axially extending passage of the tip flag channel provides a low-pressure sink and a location for cooling holes downstream of the last passage of the serpentine channel. The reduced pressure and cooling holes can pull additional fluid flow through and increase heat transfer in the serpentine channel, which, in turn, helps reduce a creep critical section average temperature. The metering orifice provides a pressure drop to encourage fluid flow from the radially extending passage of the tip flag channel axially aft through the axially extending passage of the tip flag channel as opposed to radially inward through a portion of the final passage of the serpentine channel.

[0030] FIGS. **3-6** illustrate cooling circuits for a rotor blade (e.g., blade **66**) of a gas turbine engine. It will be understood by one of ordinary skill in the art that the disclosed cooling circuits may be similarly implemented in a stator vane.

[0031] FIG. **3** shows blade **100**. Blade **100** includes airfoil body **102**. Airfoil body **102** extends from base region **104** to tip **106** and from leading edge **108** to trailing edge **110**. Airfoil body **102** includes a pressure side wall and an oppositely disposed suction side wall (not shown) as described with respect to FIG. **2**. Airfoil body **102** joins platform **112** at base region **104**. Platform **112** forms an inner boundary of core airflow C (shown in FIG. **2**). Blade **100** can be joined to a rotor disk (i.e., disk **92**, FIG. **2**) by root portion **114**, which can be received in a corresponding slot (not shown) in the rotor disk.

[0032] Blade **100** has an internal cooling circuit including serpentine channel **116** and an adjacent and fluidly connected tip flag channel **118**. Blade **100** can additionally include leading edge channel **120** and trailing edge channel **122**. Each of serpentine channel **116**, tip flag channel **118** (including radially extending passage **118*a*** and axially extending passage **118*b***), leading edge channel **120**, and trailing edge channel **122** can have an inlet disposed in root portion **114** configured to receive a cooling airflow.

[0033] Serpentine channel **116** is a forward flow channel and includes a plurality of radially extending passages **124**, **126**, **128** connected in flow series by end turns **130**, **132**. Passages **124**, **126**, **128** and end turns **130**, **132** are defined between walls **134**, **136**, **138**, **140** and **142**, which connect suction and pressure side walls. A first passage **124** extends radially outward from an inlet at a base of root portion **114** to wall **140**. Wall **140** extends axially. Wall **140** defines a radially inner boundary of a portion of axially extending passage **118*b*** of tip flag channel **118** as described further herein and a radially outer boundary of first passage **124**, second passage **126**, and end turn **130**. First passage **124** is an up pass through which cooling fluid is directed from the inlet at root portion **114** radially outward. First passage **124** is defined between radially extending walls **134** and **136**. Radially extending wall **134** extends from root portion **114** to wall **140**, joining wall **140**. Wall **134** defines an aftmost boundary of serpentine channel **116**. Wall **134** can be solid to confine the cooling flow to serpentine channel **116**.

[0034] A second passage **126** of serpentine channel **116** is disposed adjacent to and forward of first passage **124**. Second passage **126** is fluidly connected to first passage **124** by end turn **130** and defined between radially extending walls **136** and **138**. End turn **130** is defined between radially extending walls **134** and **138** and axially extending wall **140**, which are configured to turn a cooling flow 180 degrees between first passage **124** and second passage **126**. Each of walls **134** and **138** joins wall **140** to define end turn **130** therebetween. Second passage **126** is a down pass through which cooling fluid is directed radially inward from wall **140** toward root portion **114**. Second passage **126** can extend into base region **104** of airfoil body **102** as shown in FIG. **3**. Wall **136** can be curved to define a portion of end turn **132** in base region **104**. Wall **136** extends radially outward from base region **104** toward wall **140**. Wall **136** is radially separated from wall **140** to provide end turn **130**.

[0035] A final passage **128** of serpentine channel **116** is disposed adjacent to and forward of second passage **126**. Final passage **128** is fluidly connected to second passage **126** by end turn **132** and defined between radially extending walls **138** and **142**. Walls **136** and **142** can join at a radially inner end to form end turn **132**, which is configured to turn a cooling flow 180 degrees between second passage **126** and final passage **128** of serpentine channel **116**. Walls **136** and **142** can join to form a curved profile at end turn **132** to promote the redirection of cooling flow. Walls **136** and **142** can join wall **145** radially inward of end turn **132**. Wall **145** extends to root portion **114** and separates serpentine channel **116** from tip flag channel **118**. Final passage **128** is an up pass through which cooling fluid is directed radially outward from end turn **132** toward tip **106**. Final passage **128** opens to axially extending passage **118*b*** of tip flag channel **118** at a radially outermost extent to direct cooling flow from serpentine channel **116** into tip flag channel **118**. An outlet of final passage **128** is defined between walls **142** and **138**, the pressure side wall, and the suction side wall.

[0036] As illustrated in FIG. **3**, serpentine channel **116** can be disposed in a mid-chord region of airfoil body **102** to provide cooling thereto. Serpentine channel **116** extends radially outward from base region **104** to axially extending passage **118***b* of tip flag channel **118** to cool a span of airfoil body **102** extending between base region **104** and axially extending passage **118***b* of tip flag channel **118**. Cooling flow (illustrated by arrows) exiting final passage **128** can have a pressure P**1**. Cooling flow through serpentine channel **116** increases in temperature and drops in pressure between the inlet in root portion **114** and outlet in final passage **128**. Serpentine channel **116** is radially separated from tip **106** by axial tip flag channel **118***b*, which locates low heat transfer end turn **130** away from tip **106**, which improves tip cooling. Serpentine channel **116** does not extend a full span of airfoil body **102** and is thereby shorter in length than some prior art designs. Reducing the length of serpentine channel **116** reduces cooling air heat pick-up, which can improve the life of the blade at creep critical sections (usually between 30% and 60% of the span).

[0037] Tip flag channel **118** is disposed immediately adjacent to serpentine channel **116**. Tip flag channel **118** can provide dedicated cooling flow to tip **106** by conveying cooling flow directly from an inlet in root portion **114** to tip **106**. Tip flag channel **118** includes radially extending passage **118***a* and axially extending passage **118***b*. Radially extending passage **118***a* is disposed immediately adjacent to final passage **128** of serpentine channel **116** and is defined by walls **142** and **144**, the pressure side wall, and the suction side wall. Radially extending passage **118***a* extends from an inlet in root portion **114** toward tip **106**. Radially extending passage **118***a* can extend fully to tip **106**. Wall **144** extends from root portion **114** to tip **106** to define a forward boundary of tip flag channel **118**. Wall **144** can be solid to separate tip flag channel **118** from a leading edge channel (e.g., leading edge channel **120**).

[0038] Axially extending passage **118***b* is immediately adjacent to and radially outward of serpentine channel **116**. Axially extending passage **118***b* extends aftward from radially extending passage **118***a* to trailing edge **110** and is defined by tip **106**, wall **140**, the pressure side wall, and the suction side wall. Axially extending passage **118***b* is open to trailing edge **110**. The outlet of final passage **128** of serpentine channel **116** opens to axially extending passage **118***b*. Axially extending passage **118***b* provides cooling to tip **106**.

[0039] Tip flag channel **118** includes metering orifice **146** configured to control cooling flow exiting radially extending passage **118***a* and entering axially extending passage **118***b*. Specifically, metering orifice **146** is configured to reduce the pressure of cooling flow entering axially extending passage **118***b* from radially extending passage **118***a* to promote cooling flow through axially extending passage **118***b* and prevent cooling flow from entering and flowing radially inboard through a portion of final passage **128** of serpentine channel **116**. Cooling fluid exiting radially extending passage **118***a* can have a pressure P**2**. Metering orifice **146** can be configured to reduce pressure P**2** to P**3** at an outlet of metering orifice **146** and intersection with the outlet of final passage **128** of serpentine channel **116**. P**3** can be equal to or less than P**1** to drive cooling flow axially through tip flag channel **118** and to prevent cooling fluid from being ingested by serpentine cooling channel **116**.

[0040] Metering orifice **146** is an opening between tip **106** and wall **142** and defined by tip **106**, wall **142**, the pressure side wall, and the suction side wall. In this embodiment, metering orifice **146** is a slot that fully extends between the pressure side wall and the suction side wall. Metering orifice **146** can be formed by providing radial separation between tip **106** and wall **142**. A height of wall **142** can be selected to provide metering orifice **146** with a cross-sectional area needed to provide a desired pressure drop or pressure P**3**. The distance between wall **142** and tip **106** can vary based on engine and application. A terminal end of wall **142** can be disposed radially outward of wall **140**. A radially outermost edge of wall **142** can be curved to promote turning of cooling fluid between radially extending passage **118***a* and axially extending passage **118***b* as illustrated in FIG. **3**. In some embodiments, wall **142** can curve with an axially extending component at radially outermost end to direct cooling flow axially and radially outward of the outlet of final passage **128** of serpentine channel **116** and further help prevent cooling flow from entering final passage **128**.

[0041] During operation, cooling flow is provided to each of serpentine channel **116** and tip flag channel **118** via inlets in root portion **114**. Cooling flow in serpentine channel **116** is conveyed forward through airfoil body **102** via first passage **124** (up pass), second passage **126** (down pass), and final passage **128** (up pass) as indicated by cooling flow arrows. Cooling flow is conveyed radially outward through first passage **124**, radially inward through second passage **126**, and radially outward through final passage **128**. Cooling flow is exhausted from airfoil body **102** via axial tip flag channel **118***b*. Cooling flow exiting final passage **128** of serpentine channel **118** is conveyed aftward though axially extending passage **118***b* to trailing edge **110** where cooling flow exits airfoil body **102**.

[0042] Cooling flow in tip flag channel **118** is conveyed radially outward from root portion **114** through radially extending passage **118***a* to tip **106**. Cooling flow is conveyed from radially extending passage **118***a* to axially extending passage **118***b* via metering orifice **146**. Metering orifice **146** is sized to reduce a pressure P**2** of cooling flow exiting radially extending passage **118***a* to a pressure P**3** in axially extending passage **118***b* to promote axial cooling flow through axially extending passage **118***b*. Each of radially extending passage **118***a* and axially extending passage **118***b* are defined in part by tip **106** and thereby provide cooling to tip **106**. Radially extending passage **118***a* can also provide cooling of wall **142** and cooling flow through final passage **128** of serpentine channel **116**.

[0043] In some embodiments, wall **142** separating serpentine channel **116** and tip flag channel **118** can include one or more orifices or crossover holes **148** configured to provide fluid communication between radially extending passage **118***a* and final passage **128** of serpentine channel **116**. Crossover holes **148** can provide additional cooling flow to final passage **128** of serpentine channel **116** and/or can be provided to increase a pressure P**1** of final passage **128** at an outlet of final passage **128** or balance the pressure P**1** and P**2** exiting final passage **128** and radially extending passage **118***a* of tip flag channel **118**. Inclusion of one or more crossover holes **148** can influence the design or cross-sectional area of metering orifice **146** needed to provide pressure P**3**. Crossover holes **148** can be defined within wall

142 and can be centrally located between the pressure side wall and the suction side wall or can be biased toward one of the pressure side wall or suction side wall to provide desired cooling. Crossover holes **148** can be disposed at any location along a length of final passage **128** suitable for providing improved cooling, increased pressure in final passage **128**, and/or structural stability. In some embodiments, it may be necessary to provide one or more crossover holes **148** as core ties to connect a tip flag channel core and a serpentine channel core in a casting process in the manufacture of blade **100**. Use of core ties reduces undesirable movement and part breakage during the manufacturing process.

[0044] Leading edge channel **120** can be disposed adjacent to and forward of tip flag channel **118**. Leading edge channel **120** can extend radially outward from an inlet in root portion **114** to tip **106**. Leading edge channel **120** can be fluidly coupled to a plurality of leading edge boxcar cavities **150** via crossover holes **152**. Boxcar cavities **150** can be disposed along leading edge **108** between base region **104** and tip **106** of airfoil body **102**. Leading edge channel **120** can provide direct cooling of tip **106** at a radially outermost end of leading edge channel **120** and can provide indirect cooling of tip **106** via a boxcar cavity **150** disposed adjacent to tip **106**. Leading edge channel **120** can have other configurations and is not limited to the configuration shown. In some embodiments, tip flag channel **118** may provide cooling to leading edge **108**. Cooling flow through leading edge channel **120** can be discharged through tip **106** and cooling holes through airfoil body **102** (e.g., cooling holes connecting boxcar cavities **150** to an exterior surface of airfoil body **102**).

[0045] Trailing edge channel **122** can be disposed adjacent to and aft of serpentine channel **116** and, specifically, immediately adjacent to and aft of first passage **124**. Trailing edge channel **122** can extend from an inlet in root portion **114** to wall **140**, forming a radially inner boundary of tip flag channel **118**. Trailing edge channel **122** is configured to provide cooling to trailing edge **110**. Trailing edge channel **122** is fluidly coupled to trailing edge **110**. Trailing edge channel **122** may be fluidly coupled to one or more trailing edge cavities or passages **154** via crossover holes **156**. Cooling fluid can be exhausted from trailing edge channel **122** via trailing edge slots **158** defined between axially extending trailing edge ribs **160**. Trailing edge channel **122** and trailing edge cooling features are not limited to the structures shown.

[0046] One or more core ties **162**, **164**, **166**, and **168** may be provided to help position cooling channel cores (e.g., leading edge channel **120**, tip flag channel **118**, serpentine channel **116**, and trailing edge channel **122**) during the casting process. Resulting orifices formed by core ties **162**, **164**, **166**, and **168** can purge dirt during operation of the gas turbine engine. Core tie **170** connecting first passage **124** with last passage **128** via end turn **132** can provide core stiffness during the casting process and can provide a bypassed cooling flow from first passage **124** directly to final passage **128** to further cool final passage **128**.

[0047] FIG. **4** is a cross-sectional view of blade **200**. Blade **200** is substantially similar to blade **100** with a variation in the configuration of a metering orifice connecting the radially extending passage of the tip flag channel to the axially extending passage of the tip flag channel. Airfoil body **202**, base region **204**, tip **206**, leading edge **208**, trailing edge **210**, platform **212**, root portion **214**, serpentine channel **216**, tip flag channel **218** (including radially extending passage **218*a*** and axially extending passage **218*b***), leading edge channel **220**, trailing edge channel **222**, first passage **224**, second passage **226**, final passage **228**, end turns **230** and **232**, walls **234**, **236**, **238**, **240**, **242**, **244**, and **245** metering orifice **246**, and crossover holes **248** are shown. With the exception of metering orifice **246** and wall **242**, all elements are consistent with corresponding elements of blade **100** and described with respect thereto. Reference numbers have been increased by 100 for ease of comparison. Features not labelled are consistent with the corresponding features shown in FIG. **3** and discussed with respect thereto.

[0048] As illustrated in FIG. **4**, wall **242**, which defines an aft boundary of radially extending passage **218*a*** of tip flag channel **218**, extends fully to tip **206**. Metering orifice **246** is a hole through wall **242** disposed between the pressure side wall and the suction side wall. In contrast to metering orifice **146**, metering orifice **246** does not fully extend from the pressure side wall to the suction side wall. Metering orifice **246** can be disposed radially inward of tip **206** and radially outward of wall **240** to direct cooling flow into axially extending portion **118*b*** of tip flag channel **118**. Metering orifice **246** can be centered radially between tip **206** and wall **240** and/or can be centered between the pressure side wall and the suction side wall. In some embodiments, metering orifice **246** may be biased toward tip **206** or wall **240** and/or toward the pressure side wall or the suction side wall. Metering orifice **246** can have a circular cross-sectional shape or any shape suitable for conducting cooling flow. Metering orifice **246** has a cross-sectional area selected to provide a reduction in pressure from P**2** to P**3** to promote axially directed cooling flow through axially extending passage **218*b*** of tip flag channel **218** and to discourage cooling flow exiting metering orifice **246** from entering final passage **228** of serpentine channel **216** and being conveyed inboard through a portion of final passage **228**. Metering orifice **246** can be shaped and oriented in various configurations to provide desired flow and temperature benefits.

[0049] FIG. **5** is a cross-sectional view of blade **300**. Blade **300** is substantially similar to blade **100** with a variation in the configuration of a metering orifice connecting the radially extending passage of the tip flag channel to the axially extending passage of the tip flag channel. Airfoil body **302**, base region **304**, tip **306**, leading edge **308**, trailing edge **310**, platform **312**, root portion **314**, serpentine channel **316**, tip flag channel **318** (including radially extending passage **318*a*** and axially extending passage **318*b***), leading edge channel **320**, trailing edge channel **322**, first passage **324**, second passage **326**, final passage **328**, end turns **330** and **332**, walls **334**, **336**, **338**, **340**, **342**, **344**, and **345** metering orifice **346**, and crossover holes **348** are shown. All elements, with the exception of metering orifice **346** and walls **342** and **344**, are consistent with corresponding elements of blade **100** and described with respect thereto. Reference numbers have been increased by 200 for ease of comparison. Features not labelled are consistent with the corresponding features shown in FIG. **3** and discussed with respect thereto.

[0050] As illustrated in FIG. **5**, wall **342**, which defines an aft boundary of radially extending passage **318*a*** of tip flag channel **318**, has a radially outermost terminal end disposed radially inward of tip **306** such that a gap is formed between tip **306** and wall **342**. Metering orifice **346** is an opening at a radially outer end of radially extending passage **318***a* of tip flag channel **318** defined between walls **342** and **344**, the pressure side wall, and the suction side wall. Metering orifice **346** fluidly connects radially extending passage **318***a* with axially extending passage **318***b* of tip flag channel **318**. In contrast to metering orifices **146** and **246**, which direct cooling flow axially from radially extending passages **118***a* and **218***a*, metering orifice **346** is oriented to direct cooling flow radially outward toward tip **306**. This configuration of metering orifice **346** can have the added benefit of providing impingement cooling to a back side of tip **206**.

[0051] Metering orifice **346** can be defined between protrusions **372**, **374** extending axially from walls **342** and **344**, respectively. Protrusions **372**, **374** can be ridges extending fully across walls **342**, **344** from the pressure side wall to the suction side wall. Protrusions **372**, **374** can have any cross-sectional shape to promote cooling flow through metering orifice **346**. Metering orifice **346** can be a slot defined between protrusions **372** and **374** and extending fully from the pressure side wall to the suction side wall. Metering orifice **346** has a cross-sectional area selected to provide a reduction in pressure from P**2** to P**3** to promote axially directed cooling flow through axially extending passage **318***b* of tip flag channel **318** and to discourage cooling flow exiting metering orifice **346** from entering final passage **328** of serpentine channel **316** and being conveyed inboard through a portion of final passage **328**. The cross-sectional area of metering orifice **346** can be defined by a minimum distance between protrusions **372** and **374** that extends axially from walls **342** and **344**, respectively.

[0052] Metering orifice **346** is spaced radially inward from tip **306**. Protrusion **372** can be disposed at the terminal end of wall **342** or spaced radially inward of but adjacent to the terminal end of wall **342**. Protrusions **372** and **374** can be axially aligned. As illustrated in FIG. **5**, wall **342** extends a height substantially equal to wall **338** and is axially aligned with wall **340**. In other embodiments, it may be desirable to position the terminal end of wall **342** radially outward of walls **338** and **340** to help promote axial flow of cooling fluid from each of radially extending passage **318***a* and final passage **328** or serpentine channel **316** through axially extending passage **318***b* of tip flag channel **318**. Locating metering orifice **346** closer to tip **306** may also improve impingement cooling of tip **306** adjacent to a corner formed by the intersection of wall **344** and tip **306**. Metering orifice **346** can be shaped and oriented in various configurations to provide the described flow and temperature benefits.

[0053] FIG. **6** is a cross-sectional view of blade **400**. Blade **400** is substantially similar to blade **100** with a variation in the configuration of a metering orifice connecting the radially extending passage of the tip flag channel to the axially extending passage of the tip flag channel. Airfoil body **402**, base region **404**, tip **406**, leading edge **408**, trailing edge **410**, platform **412**, root portion **414**, serpentine channel **416**, tip flag channel **418** (including radially extending passage **418***a* and axially extending passage **418***b*), leading edge channel **420**, trailing edge channel **422**, first passage **424**, second passage **426**, final passage **428**, end turns **430** and **432**, walls **434**, **436**, **438**, **440**, **442**, **444**, and **445** metering orifice **446**, and crossover holes **448** are shown. All elements, with the exception of metering orifice **446** and walls **442** and **444**, are consistent with corresponding elements of blade **100** and described with respect thereto. Reference numbers have been increased by 300 for case of comparison. Features not labelled are consistent with the corresponding features shown in FIG. **3** and discussed with respect thereto.

[0054] As illustrated in FIG. **6**, a terminal end of radially extending passage **418***a* of tip flag channel **218** is defined by wall **476**. Wall **476** extends axially aft from wall **444** to wall **442**. Wall **476** joins walls **442**, **444**, the pressure side wall, and the suction side wall and defines a radial outermost boundary of radially extending passage **418***a* of tip flag channel **418**. Metering orifice **446** is a hole through wall **476**, fluidly connecting radially extending passage **418***a* with axially extending passage **418***b* of tip flag channel **418**. Metering orifice **446** is oriented to direct cooling flow radially outward toward tip **406**. This configuration of metering orifice **446** can have the added benefit of providing impingement cooling to the back side of tip **406**. Metering orifice **446** can have a circular cross-sectional shape or any shape suitable to provide a desired cooling flow through metering orifice **446**. Metering orifice **446** can be centered axially between walls **442** and **444** and/or can be centered between the pressure side wall and the suction side wall. In some embodiments, metering orifice **446** may be biased toward wall **442** or **444** and/or toward the pressure side wall or the suction side wall. Metering orifice **446** has a cross-sectional area selected to provide a reduction in pressure from P**2** to P**3** to promote axially directed cooling flow through axially extending passage **418***b* of tip flag channel **418** and to discourage cooling flow exiting metering orifice **446** from entering final passage **428** of serpentine channel **416** and being conveyed inboard through a portion of final passage **428**.

[0055] Wall **476** is disposed radially inward of tip **406**. As illustrated in FIG. **6**, wall **476** can be axially aligned with wall **440**. In other embodiments, it may be desirable to position wall **476** radially outward of wall **440** to help promote axial flow of cooling fluid from each of radially extending portion **418***a* and final passage **428** of serpentine channel through axially extending passage **418***b* of tip flag channel **418**. Locating metering orifice **446** closer to tip **406** may also improve impingement cooling of tip **406** at a corner formed by the intersection of wall **444** and tip **406**. Metering orifice **446** can be shaped and oriented in various configurations to provide the described flow and temperature benefits.

[0056] Each of the disclosed cooling circuits enables higher internal heat transfer in a final passage of a serpentine channel and relatively cool tip temperatures by providing a dedicated tip flag channel fluidly connected to the final passage of the serpentine channel and a metering orifice that connects a radially extending passage of the tip flag channel disposed adjacent to and forward of the serpentine channel to an axially extending passage of the tip flag channel. The axially extending passage of the tip flag channel provides a low-pressure sink and a location for cooling holes downstream of the last passage of the serpentine channel. The reduced pressure and cooling holes can pull additional fluid flow through and increase heat transfer in the serpentine channel, which, in turn, helps reduce a creep critical section average temperature. The metering orifice provides a pressure drop to encourage fluid flow from the radially extending passage of the tip flag channel axially aft through the axially extending passage of the tip flag channel as opposed to radially inward through the final passage of the serpentine channel. It will be understood by one of ordinary skill in the art that the disclosed airfoils and cooling circuits can include other features not discussed herein, including but not limited to cooling holes through the airfoil body (i.e., pressure or suction side walls) from the tip flag channel (e.g., passages **118**_a_ and **118**_b_) and the final passage of the serpentine channel (e.g., passage **128**) to discharge cooling flow for film cooling of external airfoil surfaces.

[0057] The embodiments disclosed herein are intended to provide an explanation of the present invention and not a limitation of the invention. The present invention is not limited to the embodiments disclosed. It will be understood by one skilled in the art that various modifications and variations can be made to the invention without departing from the scope and spirit of the invention.

[0058] Any relative terms or terms of degree used herein, such as “substantially”, “essentially”, “generally”, “approximately” and the like, should be interpreted in accordance with and subject to any applicable definitions or limits expressly stated herein. In all instances, any relative terms or terms of degree used herein should be interpreted to broadly encompass any relevant disclosed embodiments as well as such ranges or variations as would be understood by a person of ordinary skill in the art in view of the entirety of the present disclosure, such as to encompass ordinary manufacturing tolerance variations, incidental alignment variations, transient alignment or shape variations induced by thermal, rotational or vibrational operational conditions, and the like. Moreover, any relative terms or terms of degree used herein should be interpreted to encompass a range that expressly includes the designated quality, characteristic, parameter or value, without variation, as if no qualifying relative term or term of degree were utilized in the given disclosure or recitation.

Discussion of Possible Embodiments

[0059] The following are non-exclusive descriptions of possible embodiments of the present invention.

[0060] An airfoil for a gas turbine engine, configured to extend in a radial direction relative to an engine axis from an inner diameter to an outer diameter, includes a body and a cooling circuit disposed in the body. The body has a base disposed at the inner diameter, a tip disposed at the outer diameter, a leading edge, a trailing edge, a pressure side wall extending between the leading edge and the trailing edge and between the base and the tip, and a suction side wall extending between the leading edge and the trailing edge and between the base and the tip. The cooling circuit includes a serpentine channel having a plurality of radially extending passages connected in flow series from a first passage to a final passage and a tip flag channel disposed adjacent to the serpentine channel. The tip flag channel includes a first tip flag passage disposed adjacent to the final passage of the serpentine channel and extending radially, and a second tip flag passage disposed between the serpentine channel and the tip and extending axially from the first tip flag passage and disposed direct fluid communication with each of the first tip flag passage and the final passage of the serpentine channel.

[0061] The airfoil of the preceding paragraph can optionally include, additionally and/or alternatively, any one or more of the following features, configurations, and/or additional components:

[0062] An embodiment of the airfoil of the preceding paragraphs can further include a metering orifice fluidly connecting the first tip flag passage and the second tip flag passage.

[0063] In an embodiment of the airfoil of any of the preceding paragraphs, the metering orifice can have a cross-sectional area selected to reduce a pressure of a fluid flow exiting the first tip flag passage to a value equal to or less than a pressure of a fluid exiting the final passage of the serpentine channel.

[0064] In an embodiment of the airfoil of any of the preceding paragraphs, the metering orifice can be between the tip and a first wall separating the first tip flag passage and the final passage of the serpentine channel along a length of each of the first tip flag passage and the final passage.

[0065] In an embodiment of the airfoil of any of the preceding paragraphs, the metering orifice can extend from the pressure side wall to the suction side wall.

[0066] In an embodiment of the airfoil of any of the preceding paragraphs, the metering orifice can be a hole through a first wall separating the first tip flag passage and the final passage of the serpentine channel along a length of each of the first tip flag passage and the final passage, the first wall extending to the tip.

[0067] In an embodiment of the airfoil of any of the preceding paragraphs, the metering orifice can be disposed between radially extending walls defining the first tip flag passage and is configured to direct a cooling flow radially toward the tip.

[0068] In an embodiment of the airfoil of any of the preceding paragraphs, the metering orifice can extend from the pressure side wall to the suction side wall.

[0069] In an embodiment of the airfoil of any of the preceding paragraphs, the metering orifice can be a hole through an axially extending wall defining a radially outermost boundary of the first tip flag passage.

[0070] An embodiment of the airfoil of any of the preceding paragraphs can further include a first wall separating the first tip flag passage and the final passage of the serpentine channel along the length of each of the first tip flag passage and the final passage, and an orifice through the first wall providing fluid communication between the first tip wall passage and the final passage.

[0071] In an embodiment of the airfoil of any of the preceding paragraphs, the second tip flag passage can extend to the trailing edge.

[0072] An embodiment of the airfoil of any of the preceding paragraphs can further include a leading edge channel disposed forward of the first tip flag passage and fluidly separated from each of the first tip flag passage and the second tip flag passage.

[0073] An embodiment of the airfoil of any of the preceding paragraphs can further include a trailing edge channel disposed aft of the serpentine channel and fluidly separated from each of the serpentine channel and the tip flag channel.

[0074] A cooling circuit of an airfoil for a gas turbine engine includes a serpentine channel having a plurality of fluidly connected radially extending flow passages and a tip flag channel disposed adjacent to the serpentine channel. The tip flag channel includes a first tip flag passage extending radially and a second tip flag passage extending axially from a terminal end of the first tip flag passage, the second tip flag passage disposed radially outward of the serpentine channel. The second tip flag passage is in direct fluid communication with each of the first tip flag passage and a final passage of the serpentine channel.

[0075] The cooling circuit of the preceding paragraph can optionally include, additionally and/or alternatively, any one or more of the following features, configurations, and/or additional components:

[0076] An embodiment of the cooling circuit of the preceding paragraphs can further include a metering orifice fluidly connecting the first tip flag passage and the second tip flag passage, wherein the metering orifice has a cross-sectional area selected to reduce a pressure of a fluid flow exiting the first tip flag passage to a value equal to or less than a pressure of a fluid exiting the final passage of the serpentine channel.

[0077] In an embodiment of the cooling circuit of any of the preceding paragraphs, the metering orifice can be between a tip of the airfoil and a first wall separating the first tip flag passage and the final passage of the serpentine channel along a length of each of the first tip flag passage and the final passage.

[0078] In an embodiment of the cooling circuit of any of the preceding paragraphs, the metering orifice can be disposed through a first wall separating the first tip flag passage and the final passage of the serpentine channel along a length of each of the first tip flag passage and the final passage, the first wall extending to a tip of the airfoil.

[0079] In an embodiment of the cooling circuit of any of the preceding paragraphs, the metering orifice can be disposed between radially extending walls defining the first tip flag passage and is configured to direct a cooling flow radially toward the tip.

[0080] In an embodiment of the cooling circuit of any of the preceding paragraphs, the metering orifice can be a hole through an axially extending wall defining a radially outermost boundary of the first tip flag passage.

[0081] An embodiment of the cooling circuit of any of the preceding paragraphs can further include a first wall separating the first tip flag passage and the final passage of the serpentine channel along the length of each of the first tip flag passage and the final passage, and an orifice through the first wall providing fluid communication between the first tip flag passage and the final passage.

[0082] While the invention has been described with reference to an exemplary embodiment(s), it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment(s) disclosed, but that the invention will include all embodiments falling within the scope of the appended claims.

1. An airfoil for a gas turbine engine, the airfoil configured to extend in a radial direction relative to an engine axis from an inner diameter to an outer diameter and comprising:

a body having a base disposed at the inner diameter, a tip disposed at the outer diameter, a leading edge, a trailing edge, a pressure side wall extending between the leading edge and the trailing edge and between the base and the tip, and a suction side wall extending between the leading edge and the trailing edge and between the base and the tip; and

a cooling circuit disposed in the body, the cooling circuit comprising:

a serpentine channel having a plurality of radially extending passages connected in flow series from a first passage to a final passage, wherein the first passage is fluidly connected to a first inlet;

a tip flag channel disposed adjacent to the serpentine channel, the tip flag channel comprising:

a first tip flag passage extending radially and disposed immediately adjacent to the final passage of the serpentine channel, wherein a first wall separates a full radial extent of the final passage from the first tip flag passage, and wherein the first tip flag passage is fluidly connected to a second inlet, the second inlet separated from the first inlet by a second wall;

a second tip flag passage disposed between the serpentine channel and the tip, the second tip flag passage extending axially from the first tip flag passage and in direct fluid communication with each of the first tip flag passage and the final passage of the serpentine channel; and

a metering orifice fluidly connecting the first tip flag passage and the second tip flag passage, the metering orifice having a cross-sectional area less than a cross-sectional area of each of the first tip flag passage and the second tip flag passage and wherein the cross-sectional area is selected to reduce a pressure of a fluid flow exiting the first tip flag passage to a value equal to or less than a pressure of a fluid exiting the final passage of the serpentine channel such that a cooling fluid is prevented from being ingested by the serpentine channel at an outlet of the final passage.

2-3. (canceled)

4. The airfoil of claim **1**, wherein the metering orifice is between the tip and the first wall.

5. The airfoil of claim **1**, wherein the metering orifice extends from the pressure side wall to the suction side wall.

6. The airfoil of claim **1**, wherein the first wall extends to the tip and wherein the metering orifice is a hole through the first wall.

7. The airfoil of claim **1**, wherein the metering orifice is disposed between the first wall and a third wall, to direct a cooling flow radially toward the tip, wherein the first wall and the third wall define the first tip flag passage.

8. The airfoil of claim **7**, wherein the metering orifice extends from the pressure side wall to the suction side wall.

9. The airfoil of claim **7**, wherein the metering orifice is a hole through an axially extending wall defining a radially outermost boundary of the first tip flag passage.

10. The airfoil of claim **3**, wherein the metering orifice is a first orifice and wherein the airfoil further comprises:

a second orifice through the first wall providing fluid communication between the first tip flag passage and the final passage.

11. The airfoil of claim **1**, wherein the second tip flag passage extends to the trailing edge.

12. The airfoil of claim **1** and further comprising a leading edge channel disposed forward of the first tip flag passage and fluidly separated from each of the first tip flag passage and the second tip flag passage.

13. The airfoil of claim **12** and further comprising a trailing edge channel disposed aft of the serpentine channel and fluidly separated from each of the serpentine channel and the tip flag channel.

14. A cooling circuit of an airfoil for a gas turbine engine, the cooling circuit comprising:

a serpentine channel having a plurality of fluidly connected radially extending flow passages including a first passage fluidly connected to a first inlet and a final passage;

a tip flag channel disposed adjacent to the serpentine channel and comprising:

a first tip flag passage extending radially and disposed immediately adjacent to the final passage of the serpentine channel, wherein a first wall separates a full radial extent of the final passage from the first tip flag passage, and wherein the first tip flag passage is fluidly connected to a second inlet, the second inlet separated from the first inlet by a second wall;

a second tip flag passage extending axially from a terminal end of the first tip flag passage, the second tip flag passage disposed radially outward of the serpentine channel, wherein the second tip flag passage is in direct fluid communication with each of the first tip flag passage and the final passage of the serpentine channel; and

a metering orifice fluidly connecting the first tip flag passage and the second tip flag passage, the metering orifice having a cross-sectional area less than a cross-sectional area of each of the first tip flag passage and the second tip flag passage.

15. The cooling circuit of claim **14**, wherein the the cross-sectional area of the metering orifice is selected to reduce a pressure of a fluid flow exiting the first tip flag passage to a value equal to or less than a pressure of a fluid exiting the final passage of the serpentine channel such that a cooling fluid is prevented from being ingested by the final passage of the serpentine channel.

16. The cooling circuit of claim **15**, wherein the metering orifice is between a tip of the airfoil and the first wall.

17. The cooling circuit of claim **15**, wherein the first wall extends to a tip of the airfoil and wherein the metering orifice is disposed through the first wall.

18. The cooling circuit of claim **15**, wherein the metering orifice is disposed between the first wall and a third wall, to direct a cooling flow radially toward a tip of the airfoil, wherein the first wall and the third wall define the first tip flag passage.

19. The cooling circuit of claim **18**, wherein the metering orifice is a hole through an axially extending wall defining a radially outermost boundary of the first tip flag passage.

20. The cooling circuit of claim **15** wherein the metering orifice is a first orifice and wherein the cooling circuit further comprises:

a second orifice through the first wall providing fluid communication between the first tip flag passage and the final passage.

21. The airfoil of claim **1**, wherein the first wall separating the first tip flag passage from the final passage of the serpentine channel comprises a crossover hole configured to provide additional cooling fluid to the final passage of the serpentine channel.

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