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(54) ACTIVELY-COOLED HEAT SHIELD SYSTEM AND VEHICLE INCLUDING THE SAME

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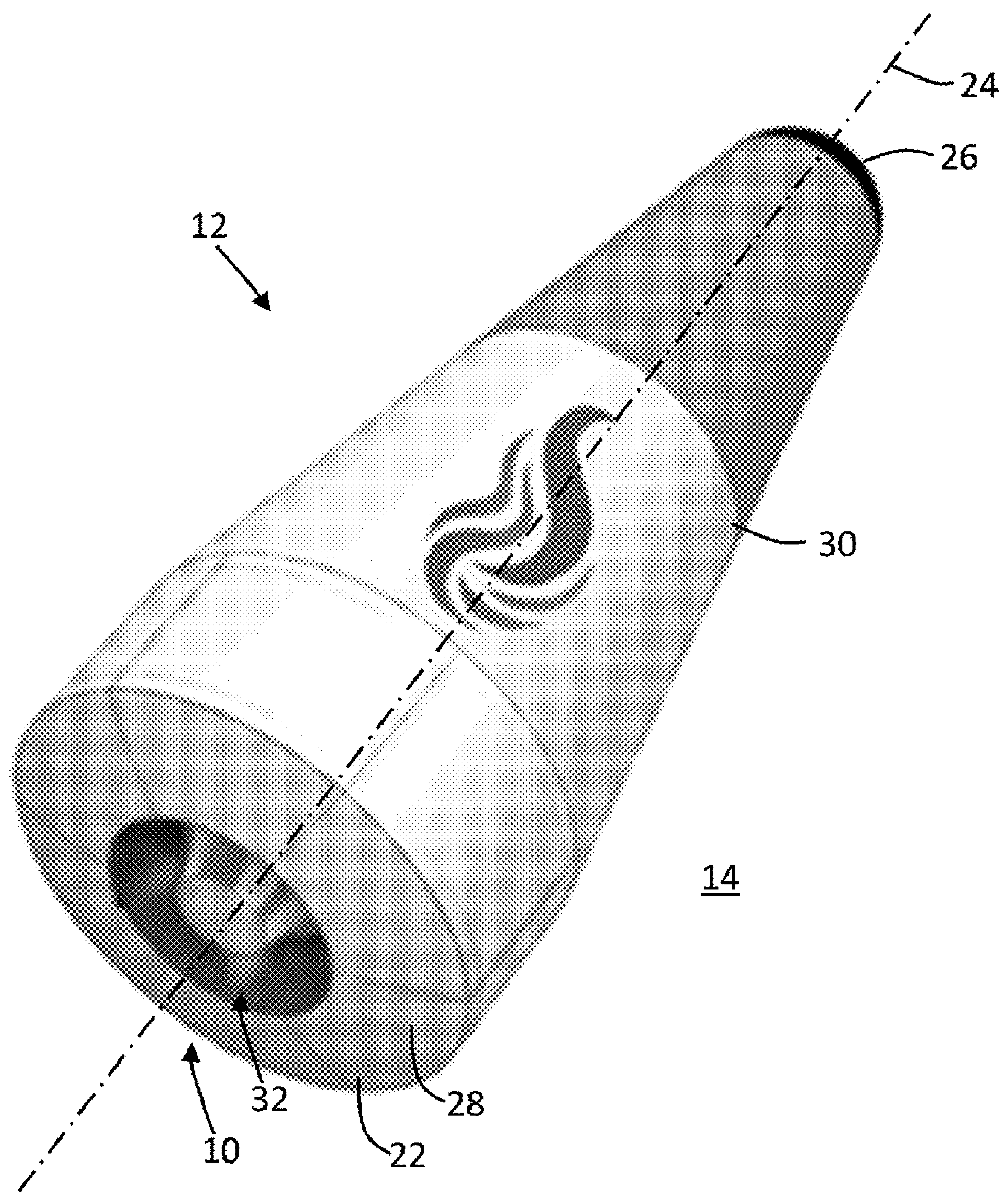
(57) **ABSTRACT**

An actively-cooled heat shield system includes a heat shield, a tank, a pump, a heat exchanger, and a turbine. The heat shield defines a windward side of a vehicle. The tank stores a coolant. The pump receives the coolant from the tank and outputs a pressurized coolant. The heat exchanger is integrally connected with the heat shield. The heat exchanger receives the pressurized coolant from the pump, transfers heat from the heat shield to the pressurized coolant to generate a heated fluid, and outputs the heated fluid. The turbine includes an inlet, a shaft, and an outlet. The inlet receives the heated fluid output from the heat exchanger. The shaft is coupled to the pump and includes turbine blades. The shaft rotates and powers the pump when the heated fluid received from the heat exchanger acts on the turbine blades. The outlet outputs the heated fluid.



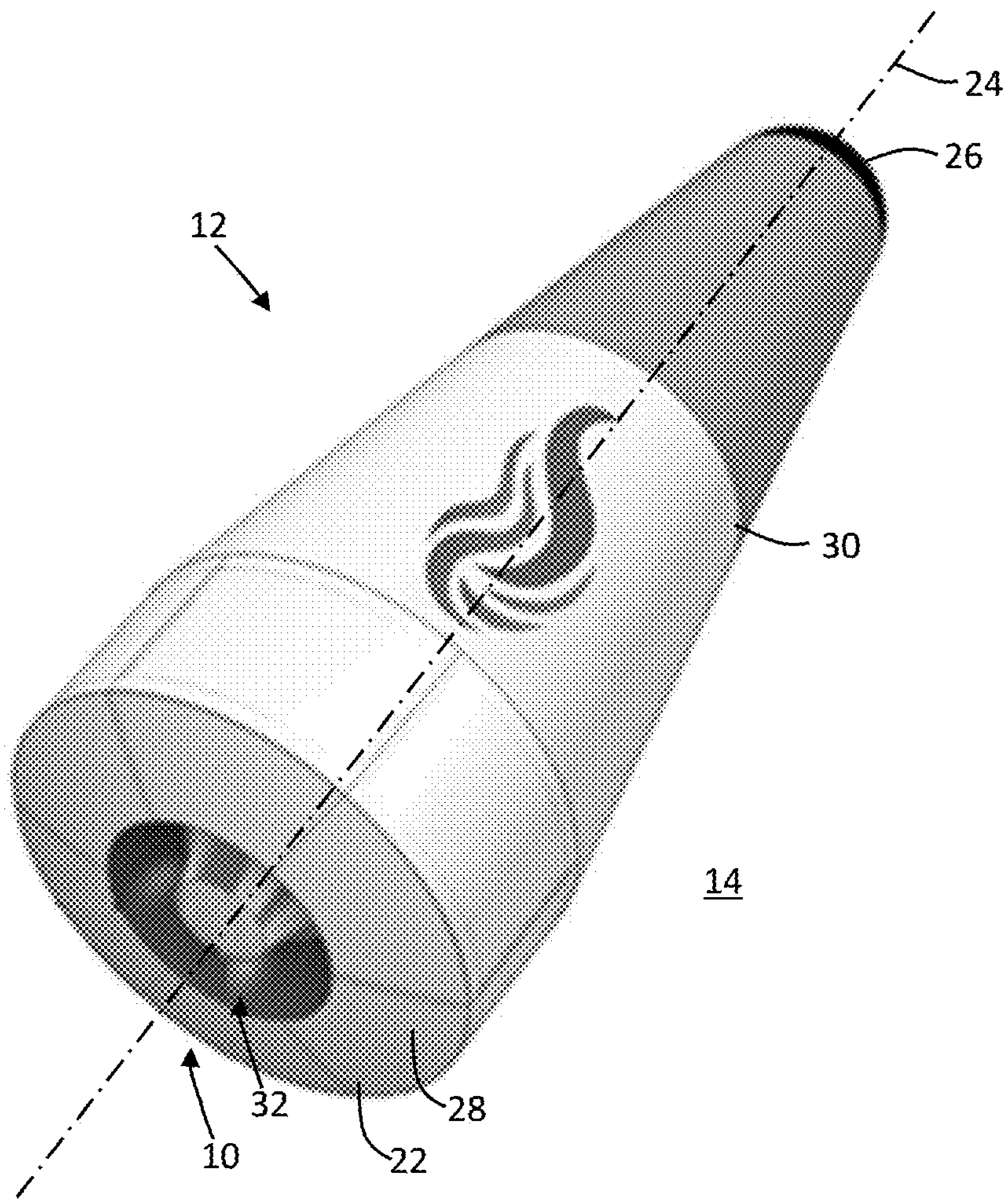


FIG. 1

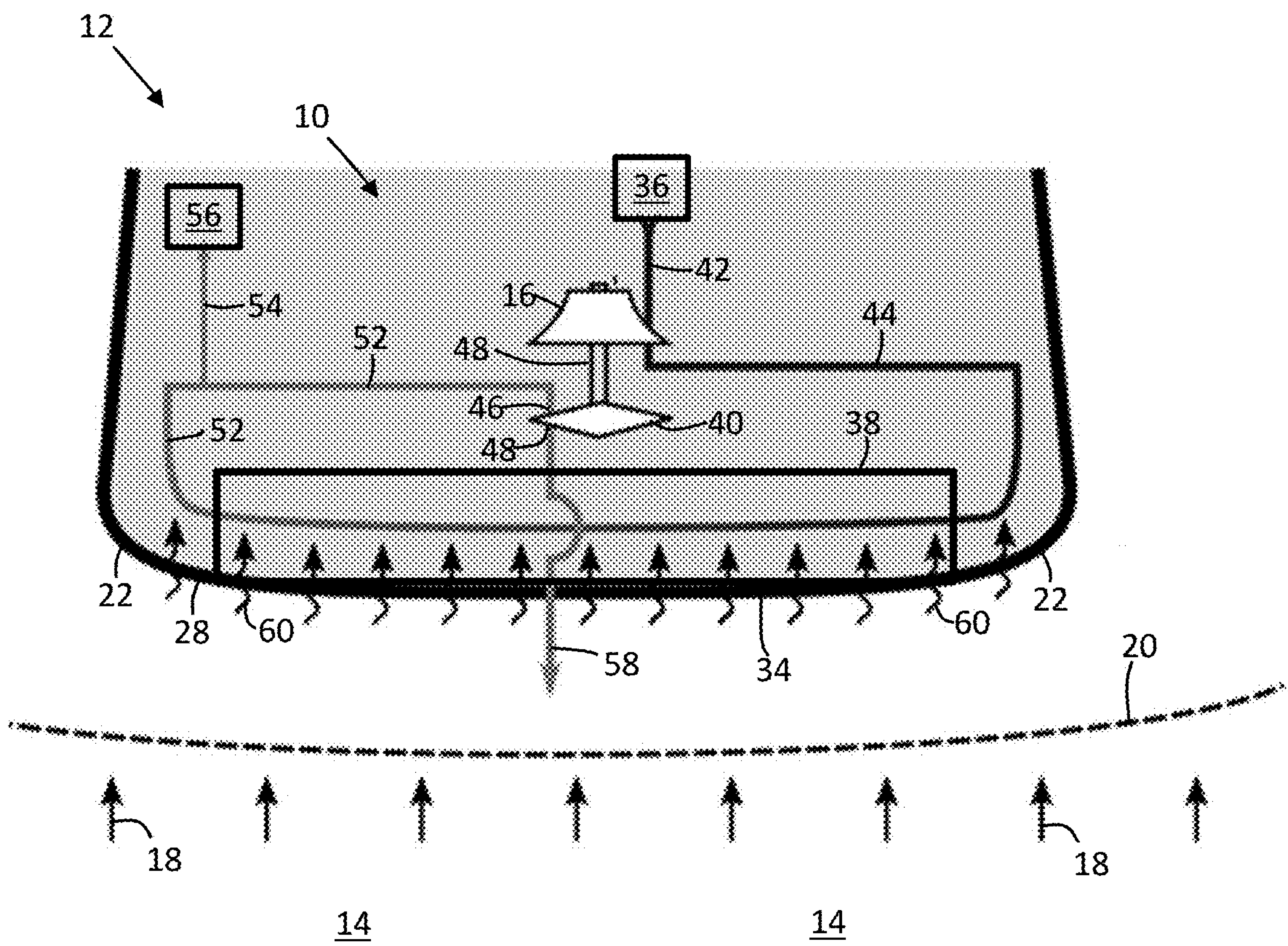

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FIG. 2

ACTIVELY-COOLED HEAT SHIELD SYSTEM AND VEHICLE INCLUDING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application claims priority to U.S. Provisional Patent Application No. 62/942,886, filed on Dec. 3, 2019, the contents of which are incorporated by reference herein in their entirety.

TECHNICAL FIELD

[0002] The present disclosure generally relates to cooling systems for vehicles that are subjected to high levels of heating. The present disclosure more particularly relates to actively-cooled heat shield systems for use in rockets and other vehicles that travel at or above hypersonic speeds, such as space re-entry vehicles, aircraft, and missiles.

BACKGROUND

[0003] Aircraft-like reusability for rockets has long been the "holy grail" of rocketry due to the potential for huge cost benefits. The ability to recover and reuse an upper stage rocket of a multi-stage rocket system (e.g., the second stage rocket of a two-stage rocket system) remains a significant technical gap that has not yet been solved by the industry. Reusing the upper stage of a multi-stage rocket is challenging due to the harsh re-entry environment and the performance penalties associated with increased structural mass required for robust reuse. Upper stage rockets are typically constructed with the minimum structure and complexity since any mass addition to the second stage is a 1:1 reduction in payload capacity. Reusing an upper stage rocket therefore requires significant additional functionality but with minimal mass addition.

[0004] Rockets and other vehicles that travel at or above hypersonic speeds (e.g., space re-entry vehicles, aircraft, missiles, etc.) require a means to protect themselves from the heating that occurs at such high speeds. Conventional solutions for mitigating such heating include use of one or more of the following: (i) ablative materials, which undergo pyrolysis and generate gases that move downstream in a boundary layer to form a protective film layer; (ii) high-temperature materials (e.g., ceramics, carbon-carbon, etc.); (iii) composite materials, which insulate a base material and radiate heat away therefrom; and (iv) transpiration cooling, which involves use of a thin protective film that is provided by a gas passing through a semi-porous wall.

[0005] Existing heat management solutions have cost, operations, and/or mass impacts that may not trade favorably in certain applications, such as reusable vehicles. For example, ablative materials and fragile ceramics are incompatible with a highly reusable system. Transpiration cooling of a heat shield is costly and difficult to control. What is needed is a cooling system that is highly robust, highly controllable, and well suited for long term reusability.

[0006] Aspects of the present invention are directed to these and other problems.

SUMMARY

[0007] According to an aspect of the present invention, an actively-cooled heat shield system includes a heat shield, a tank, a pump, a heat exchanger, and a turbine. The heat shield defines a windward side of a vehicle. The tank is onboard the vehicle and is configured to store a coolant. The pump is onboard the vehicle and is configured to receive the coolant from the tank and output a pressurized coolant. The heat exchanger is onboard the vehicle and is integrally connected with the heat shield. The heat exchanger is configured to receive the pressurized coolant from the pump, transfer heat from the heat shield to the pressurized coolant to generate a heated fluid, and output the heated fluid. The turbine is onboard the vehicle and includes an inlet, a shaft, and an outlet. The inlet is configured to receive the heated fluid output from the heat exchanger. The shaft is coupled to the pump and includes turbine blades mounted thereon. The shaft is configured to rotate and thereby power the pump when the heated fluid received from the heat exchanger acts on the turbine blades. The outlet is configured to output the heated fluid.

[0008] According to another aspect of the present invention, a vehicle includes an actively-cooled heat shield system. The heat shield system includes a heat shield, a tank, a pump, a heat exchanger, and a turbine. The heat shield defines a windward side of a vehicle. The tank is onboard the vehicle and is configured to store a coolant. The pump is onboard the vehicle and is configured to receive the coolant from the tank and output a pressurized coolant. The heat exchanger is onboard the vehicle and is integrally connected with the heat shield. The heat exchanger is configured to receive the pressurized coolant from the pump, transfer heat from the heat shield to the pressurized coolant to generate a heated fluid, and output the heated fluid. The turbine is onboard the vehicle and includes an inlet, a shaft, and an outlet. The inlet is configured to receive the heated fluid output from the heat exchanger. The shaft is coupled to the pump and includes turbine blades mounted thereon. The shaft is configured to rotate and thereby power the pump when the heated fluid received from the heat exchanger acts on the turbine blades. The outlet is configured to output the heated fluid.

[0009] According to another aspect of the present invention, a re-usable upper stage rocket of a multi-stage rocket system includes an actively-cooled heat shield system that converts heat from a high Mach number flow environment into energy to drive a liquid coolant pump.

[0010] According to another aspect of the present invention, a method for actively cooling a windward side of an upper stage rocket of a multi-stage rocket system during atmospheric re-entry includes the steps of: initiating driving of a pump onboard the upper stage rocket to initiate output of a pressurized coolant from the pump; flowing the pressurized coolant output by the pump through a heat exchanger integrally connected with a heat shield that defines at least a portion of the windward side of the upper stage rocket; transferring heat from the heat shield to the pressurized coolant to generate a heated fluid; inputting the heated fluid to a turbine onboard the upper stage rocket, the turbine including a shaft coupled to the pump and turbine blades mounted to the shaft; and exposing the turbine blades to the heated fluid to drive the shaft and thereby continue driving the pump.

[0011] In addition to, or as an alternative to, one or more of the features described above, further aspects of the present invention can include one or more of the following features, individually or in combination:

[0012] at least the heat exchanger, the turbine, and the pump are configured such that, once operation of the pump is started, an amount of energy supplied to the turbine from the heat exchanger is alone sufficient to continue operation of the pump;

[0013] the heat shield system is configured such that, once operation is started, an amount of energy transferred to the coolant by the heat exchanger is at least sufficient to sustain operation;

[0014] the heat shield, the tank, the pump, the heat exchanger, and the turbine are configured such that an amount of energy transferred to the coolant by the heat exchanger is at least sufficient to sustain operation of the heat shield system;

[0015] the heat shield, the tank, the pump, the heat exchanger, and the turbine are configured such that an amount of energy transferred to the coolant by the heat exchanger is at least sufficient to supply the turbine with an amount of power required to drive the pump;

[0016] the coolant is at least one of an active coolant, a liquid coolant, and a cryogenic coolant;

[0017] the heated fluid is at least one of a gas and a supercritical fluid;

[0018] the heat shield system further includes a primary heated fluid conduit configured to transfer the heated fluid from the heat exchanger to the inlet of the turbine, and a bypass conduit configured to bypass, from at least a portion of the primary heated fluid conduit, an excess of energy in the heated fluid for power use by an auxiliary system;

[0019] a pressure of the coolant in the tank alone provides energy sufficient to start spinning the turbine and the pump, creating an increasing pressure and increasing power available to the turbine;

[0020] the heat exchanger and the heat shield are configured such that flow of the coolant through the heat exchanger maintains acceptable temperatures on the heat shield while the vehicle re-enters a planetary atmosphere;

[0021] the heat shield is configured to be exposed to a high Mach number flow environment during normal operation;

[0022] the vehicle is an upper stage rocket of a multi-stage rocket system;

[0023] the upper stage rocket includes a propulsion engine disposed at an aft end thereof, and the aft end defines the windward side of the upper stage rocket during operation of the heat shield system;

[0024] the heat shield system and the propulsion engine share a multi-purpose component, and the multi-purpose component is at least one of the heat shield, the tank, the pump, the heat exchanger, and the turbine;

[0025] the pump of the heat shield system is a fuel pump of the propulsion engine;

[0026] the vehicle further includes an exhaust conduit through which at least a portion of the heated fluid output from the turbine exits the upper stage rocket; and

[0027] the transferring and inputting steps of the method supply an amount of energy to the turbine that is alone sufficient to continue driving the pump.

[0028] These and other aspects of the present invention will become apparent in light of the drawings and detailed description provided below.

BRIEF DESCRIPTION OF THE DRAWINGS

[0029] FIG. **1** is a perspective view of a vehicle including the present heat shield system.

[0030] FIG. **2** is a schematic sectional view of an aft end portion of the vehicle of FIG. **1** showing components of the heat shield system.

DETAILED DESCRIPTION

[0031] Referring to FIGS. **1** and **2**, the present disclosure describes an actively-cooled heat shield system **10** and a vehicle **12** including the same. The heat shield system **10** converts heat from a high Mach number flow environment **14** into energy to drive a liquid coolant pump **16** (see FIG. **2**).

[0032] Referring to FIG. **1**, the vehicle **12** is a rocket (e.g., a multi-stage rocket, a single-stage-to-orbit (SSTO) rocket, an upper stage rocket, a booster rocket, etc.), a missile, a spacecraft, an aircraft, or another vehicle designed for travel (e.g., flight) up to at least supersonic speeds (e.g., supersonic speeds, hypersonic speeds, re-entry speeds, etc.) in atmospheric, sub-orbital, orbital, extraterrestrial, and/or outer space environments.

[0033] In the illustrated embodiment, the vehicle **12** is a second stage rocket of a two-stage rocket system (not shown). The vehicle **12** (hereinafter the "second stage rocket **12**") extends along a centerline **24** between a forward end **26** and an opposing aft end **28** thereof. The second stage rocket **12** includes a payload **30** toward the forward end **26**, and an engine **32** toward the aft end **28**. The aft end **28** defines the windward side **22** of the second stage rocket **12**. In the illustrated embodiment, the engine **32** is an augmented aerospike nozzle engine as disclosed in U.S. Provisional Patent Application No. 62/941,383, filed Nov. 27, 2019 by the same inventors, and in the International Patent application claiming priority to U.S. Provisional Patent Application No. 62/941,383, the contents of which are incorporated herein by reference in their entirety. In other embodiments, the engine **32** is a bell nozzle engine or another type of rocket engine, or the vehicle may not include an engine at all.

[0034] Referring to FIG. **2**, during use the second stage rocket **12** moves through an environment **14** (e.g., the atmosphere, space) at freestream Mach numbers **18** that can approach Mach thirty (30) for space re-entry vehicles. A bow shock **20** is formed upstream of the second stage rocket **12**, and temperature on the vehicle side of the bow shock **20** can reach thousands of degrees Kelvin. The windward side **22** of the second stage rocket **12** is exposed to these high temperatures and therefore cooling and/or other thermal protection is necessary for reusability.

[0035] The actively-cooled heat shield system **10** includes a heat shield **34**, a tank **36**, a pump **16**, a heat exchanger **38**, and a turbine **40**.

[0036] The heat shield **34** defines an outer surface of the windward side **22** of the second stage rocket **12**.

[0037] The tank **36** is onboard the second stage rocket **12** and stores a coolant (e.g., an active coolant, a liquid coolant, a cryogenic coolant, etc.).

[0038] The pump **16** is onboard the second stage rocket **12** and receives the coolant from the tank **36**. The pump **16** outputs a pressurized coolant (e.g., a coolant having a pressure of several hundred psi or higher). That is, the pressure of the coolant is greater after it passes through the pump **16** than it is when stored in the tank **36**. The coolant is transferred from the tank **36** to the pump **16** via a coolant conduit **42** (e.g., ducting, tubing, etc.).

[0039] The heat exchanger **38** is onboard the second stage rocket **12** and is integrally connected with the heat shield **34**. The heat exchanger **38** receives the pressurized coolant from the pump **16**, transfers heat from the heat shield **34** to the pressurized coolant to generate a heated fluid (e.g., a gas, a supercritical fluid, etc.), and outputs the heated fluid. The pressurized coolant is transferred from the pump **16** to the heat exchanger **38** via a pressurized coolant conduit **44** (e.g., ducting, tubing, etc.).

[0040] The turbine **40** is onboard the second stage rocket **12** and includes an inlet **46**, a shaft **48**, and an outlet **50**. The inlet **46** receives the heated fluid that is output from the heat exchanger **38** via a primary heated fluid conduit **52** (e.g., ducting, tubing, etc.). In some embodiments, there will be an excess of energy in the heated fluid which will be bypassed around the turbine **40** via a bypass conduit **54** (e.g., ducting, tubing, etc.) and used to pressurize or power an auxiliary system **56** (e.g., a tank, a gas thruster, a transpiration cooling system, an auxiliary power unit (APU), etc.). The shaft **48** of the turbine **40** is coupled (e.g., directly coupled, indirectly coupled via a coupler, etc.) to the pump **16** and includes turbine blades (not shown) mounted thereon. The shaft **48** rotates and thereby powers the pump **16** when the heated fluid received from the heat exchanger **38** acts on the turbine blades (not shown). The outlet **50** of the turbine **40** outputs the heated fluid. In some embodiments, the second stage rocket **12** includes an exhaust conduit **58** through which the heated fluid exits the second stage rocket **12** (e.g., for providing thrust). Additionally or alternatively, the heated fluid output from the outlet **50** of the turbine **40** can be used to pressurize or power an auxiliary system (e.g., a tank, a gas thruster, a transpiration cooling system, an APU, etc.). The heated fluid that is output from the outlet **50** of the turbine **40** will have a pressure and energy that is less than that of the heated fluid diverted through the bypass conduit **54** to the auxiliary system **56**. In some embodiments, the heat shield system **10** further includes bearings, gears, and/or seals (not shown) that facilitate the coupling of the turbine **40** and the pump **16** via the shaft **48**.

[0041] During operation of the heat shield system **10**, the pressurized coolant passes into the heat exchanger **38** (e.g., into channels or other conduits formed in the heat shield **34**) and picks up heat **60** at a rate (i.e., a heat flux) that is typical of hypersonic and re-entry vehicles and may be in the range of 0.01-10 BTU/in^2–s, for example. The heat exchanger **38** serves a dual purpose of cooling the windward side **22** of the second stage rocket **12**, and adding energy to the coolant which is used to drive the turbine **40** and then power the pump **16**. The pressure of the coolant drops while overall enthalpy increases along the heat exchanger **38**, until the coolant exits the heat exchanger **38** as a heated fluid. The primary flow of heated fluid enters the turbine **40**, where energy is extracted. The heated fluid exiting the turbine **40** is expelled out of the second stage rocket **12** into the external environment **14** or used for another purpose (e.g., re-chilled by onboard systems and passed back through the heat exchanger **38** in a closed loop cycle).

[0042] In some embodiments, the pressure of the coolant in the tank **36** alone provides enough energy to start spinning the turbine **40** and pump **16**, creating an increasing pressure and increasing power available to the turbine **40**. In other embodiments, the pressure of the coolant in the tank **36** does not provide enough energy to start spinning the turbine **40** and pump **16**. In some such embodiments, the heat shield system **10** further includes an external starter source, such as a motor connected to the turbine shaft **48** or a high pressure gas directed at the turbine **40**.

[0043] In some embodiments, at least one component (e.g., the tank **36**, the pump **16**, the turbine **40**, etc.) is an already-existing component of the engine **32**. For example, in some embodiments the engine **32** includes at least a pump and a turbine which push coolant through a heat exchanger of the engine. In such embodiments, the fuel pump and the turbine of the engine **32** serve dual-purposes by functioning as the pump **16** and the turbine **40** of the heat shield system **10**, respectively, and the heat exchanger of the engine **32** forms at least a portion of the heat exchanger **38** of the heat shield system **10**.

[0044] In some embodiments, the heat shield system **10** further includes at least one component that is additionally or alternatively cooled passively (e.g., using high temperature materials, etc.).

[0045] Once operation of the heat shield system **10** is started, thermal energy added to the coolant is enough to sustain operation. Specifically, the energy added to the coolant is enough to supply the turbine **40** with the required power to drive the pump **16** after taking into consideration all of the losses in the system **10**, including pump **16** and turbine **40** inefficiencies, pressure losses in the heat exchanger **38**, and other losses from friction and other mechanisms.

[0046] The coolant flowing through the heat exchanger **38** integrated into the windward side **22** of the second stage rocket **12** is enough to maintain acceptable temperatures on the heat shield **34** and other walls of the second stage rocket **12** while the second stage rocket **12** passes through the severe heat environment (e.g., while the second stage rocket **12** re-enters the atmosphere). The heat shield system **10** therefore enables the second stage rocket **12** to perform a base-first re-entry trajectory. This provides several key advantages over other proposed nose-first or body-first (a/k/a belly flop) strategies: (i) it eliminates the need for challenging in-atmosphere reorientation maneuver required for nose-first or body-first (a/k/a belly flop) re-entry vehicles with vertical landing profiles; (ii) it keeps the primary load paths in the axial direction during all phases of flight, allowing for a more efficient structural solution; (iii) the common vertical orientation during ascent and re-entry simplifies the cryogenic fluid management challenge by minimizing slosh and associated boil-off; and (iv) it minimizes the heat shield surface area while also maintaining a low ballistic coefficient, minimizing the overall heat load managed by the vehicle during re-entry.

[0047] While several embodiments have been disclosed, it will be apparent to those having ordinary skill in the art that aspects of the present invention include many more embodiments. Accordingly, aspects of the present invention are not to be restricted except in light of the attached claims and their equivalents. It will also be apparent to those of ordinary skill in the art that variations and modifications can be made without departing from the true scope of the present disclosure. For example, in some instances, one or more features disclosed in connection with one embodiment can be used alone or in combination with one or more features of one or more other embodiments.

What is claimed is:

1. An actively-cooled heat shield system, comprising:

a heat shield defining a windward side of a vehicle;

a tank onboard the vehicle, the tank configured to store a coolant;

a pump onboard the vehicle, the pump configured to receive the coolant from the tank and output a pressurized coolant;

a heat exchanger onboard the vehicle, the heat exchanger integrally connected with the heat shield and configured to receive the pressurized coolant from the pump, transfer heat from the heat shield to the pressurized coolant to generate a heated fluid, and output the heated fluid;

a turbine onboard the vehicle, the turbine including:

an inlet configured to receive the heated fluid output from the heat exchanger;

a shaft coupled to the pump and including turbine blades mounted thereon, the shaft configured to rotate and thereby power the pump when the heated fluid received from the heat exchanger acts on the turbine blades; and

an outlet configured to output the heated fluid.

2. The heat shield system of claim **1**, wherein at least the heat exchanger, the turbine, and the pump are configured such that, once operation of the pump is started, an amount of energy supplied to the turbine from the heat exchanger is alone sufficient to continue operation of the pump.

3. The heat shield system of claim **1**, wherein the heat shield system is configured such that, once operation is started, an amount of energy transferred to the coolant by the heat exchanger is at least sufficient to sustain operation.

4. The heat shield system of claim **1**, wherein the heat shield, the tank, the pump, the heat exchanger, and the turbine are configured such that an amount of energy transferred to the coolant by the heat exchanger is at least sufficient to sustain operation of the heat shield system.

5. The heat shield system of claim **1**, wherein the heat shield, the tank, the pump, the heat exchanger, and the turbine are configured such that an amount of energy transferred to the coolant by the heat exchanger is at least sufficient to supply the turbine with an amount of power required to drive the pump.

6. The heat shield system of claim **1**, wherein the coolant is at least one of an active coolant, a liquid coolant, and a cryogenic coolant.

7. The heat shield system of claim **1**, wherein the heated fluid is at least one of a gas and a supercritical fluid.

8. The heat shield system of claim **1**, further comprising:

a primary heated fluid conduit configured to transfer the heated fluid from the heat exchanger to the inlet of the turbine; and

a bypass conduit configured to bypass, from at least a portion of the primary heated fluid conduit, an excess of energy in the heated fluid for power use by an auxiliary system.

9. The heat shield system of claim **1**, wherein a pressure of the coolant in the tank alone provides energy sufficient to start spinning the turbine and the pump, creating an increasing pressure and increasing power available to the turbine.

10. The heat shield system of claim **1**, wherein the heat exchanger and the heat shield are configured such that flow of the coolant through the heat exchanger maintains acceptable temperatures on the heat shield while the vehicle re-enters a planetary atmosphere.

11. A vehicle, comprising:

an actively-cooled heat shield system including:

a heat shield defining a windward side of a vehicle;

a tank onboard the vehicle, the tank configured to store a coolant;

a pump onboard the vehicle, the pump configured to receive the coolant from the tank and output a pressurized coolant;

a heat exchanger onboard the vehicle, the heat exchanger integrally connected with the heat shield and configured to receive the pressurized coolant from the pump, transfer heat from the heat shield to the pressurized coolant to generate a heated fluid, and output the heated fluid;

a turbine onboard the vehicle, the turbine including:

an inlet configured to receive the heated fluid output from the heat exchanger;

a shaft coupled to the pump and including turbine blades mounted thereon, the shaft configured to rotate and thereby power the pump when the heated fluid received from the heat exchanger acts on the turbine blades; and

an outlet configured to output the heated fluid.

12. The vehicle of claim **11**, wherein at least the heat exchanger, the turbine, and the pump are configured such that, once operation of the pump is started, an amount of energy supplied to the turbine from the heat exchanger is alone sufficient to continue operation of the pump.

13. The vehicle of claim **11**, wherein the heat shield is configured to be exposed to a high Mach number flow environment during normal operation.

14. The vehicle of claim **11**, wherein the vehicle is an upper stage rocket of a multi-stage rocket system.

15. The vehicle of claim **14**, wherein the upper stage rocket includes a propulsion engine disposed at an aft end thereof; and

wherein the aft end defines the windward side of the upper stage rocket during operation of the heat shield system.

16. The vehicle of claim **15**, wherein the heat shield system and the propulsion engine share a multi-purpose component; and

wherein the multi-purpose component is at least one of the heat shield, the tank, the pump, the heat exchanger, and the turbine.

17. The vehicle of claim **16**, wherein the pump of the heat shield system is a fuel pump of the propulsion engine.

18. The vehicle of claim **14**, further comprising an exhaust conduit through which at least a portion of the heated fluid output from the turbine exits the upper stage rocket.

19. A method for actively cooling a windward side of an upper stage rocket of a multi-stage rocket system during atmospheric re-entry, comprising:

initiating driving of a pump onboard the upper stage rocket to initiate output of a pressurized coolant from the pump;

flowing the pressurized coolant output by the pump through a heat exchanger integrally connected with a heat shield that defines at least a portion of the windward side of the upper stage rocket;

transferring heat from the heat shield to the pressurized coolant to generate a heated fluid;

inputting the heated fluid to a turbine onboard the upper stage rocket, the turbine including a shaft coupled to the pump and turbine blades mounted to the shaft; and

exposing the turbine blades to the heated fluid to drive the shaft and thereby continue driving the pump.

20. The method of claim **19**, wherein the transferring and inputting steps supply an amount of energy to the turbine that is alone sufficient to continue driving the pump.

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