

GAS TURBINE ENGINE TREATMENT SYSTEM

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] The present application claims priority to U.S. Provisional Application Serial No. 63/733,534, titled “Gas Turbine Engine Treatment System,” filed on December 13, 2024, which is incorporated herein by reference in its entirety for all purposes.

FIELD

[0002] The present subject matter relates generally to a treatment system for a gas turbine engine, and a method for operating the same.

BACKGROUND

[0003] Typical aircraft propulsion systems include one or more gas turbine engines. For certain propulsion systems, the gas turbine engines generally include a fan and a core arranged in flow communication with one another. Additionally, the core of the gas turbine engine generally includes, in serial flow order, a compressor section, a combustor section, a turbine section, and an exhaust section. In operation, air is provided from the fan to an inlet of the compressor section where one or more axial compressors progressively compress the air until it reaches the combustor section. Fuel is mixed with the compressed air and burned within the combustor section to provide combustion gases. The combustion gases are routed from the combustor section to the turbine section. The flow of combustion gasses through the turbine section drives the turbine section and is then routed through the exhaust section, e.g., to atmosphere.

[0004] During operation, a substantial amount of air is ingested by such gas turbine engines. However, such air may contain foreign particles. A majority of the foreign particles will follow a gas path through the engine and exit with the exhaust gases. However, at least certain of these particles may stick to certain components within the gas turbine engine’s gas path, potentially changing aerodynamic properties of the engine and reducing engine performance. In addition, some ingested particles or compounds may result in corrosion on engine components.

[0005] In order to remove such foreign particles from within the gas path of the gas turbine engine, a cleaning operation can be performed that directs water or other fluids towards an inlet of the gas turbine engine, while the core engine is cranked using, e.g., using a starter motor. However, such cleaning operations are often not tailored to the type of cleaning actually needed in a particular portion of the engine. For example, depending on the prior operating conditions of the gas turbine engine, a quick and simple water wash may be needed. In other situations, a long wash cycle with a cleaning foam having particular foam characteristics may be needed to properly clean the engine and return it to peak efficiency. Moreover, conventional cleaning methods lack the ability to inhibit corrosion of components within the engine.

[0006] Accordingly, a treatment system for providing improved and customized cleaning and/or treatment of a gas turbine engine would be useful.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] A full and enabling disclosure of the present invention, including the best mode thereof, directed to one of ordinary skill in the art, is set forth in the specification, which makes reference to the appended figures, in which:

[0008] FIG. 1 is a perspective view of a modular foam cart that may contain certain components of an example treatment system according to an example embodiment of the present subject matter.

[0009] FIG. 2 is a schematic view of the example treatment system of FIG. 1 according to an example embodiment of the present subject matter.

[0010] FIG. 3 is a schematic view of a distribution manifold of the example treatment system of FIG. 1 according to an example embodiment of the present subject matter.

[0011] FIG. 4 is a schematic view of a wash module of the example treatment system of FIG. 1, operable with a gas turbine engine according to an example embodiment of the present subject matter.

[0012] FIG. 5 provides a method of cleaning a gas turbine engine according to an example embodiment of the present subject matter.

[0013] Repeat use of reference characters in the present specification and drawings is intended to represent the same or analogous features or elements of the present invention.

DETAILED DESCRIPTION

[0014] Reference will now be made in detail to present embodiments of the invention, one or more examples of which are illustrated in the accompanying drawings. The detailed description uses numerical and letter designations to refer to features in the drawings. Like or similar designations in the drawings and description have been used to refer to like or similar parts of the invention. As used herein, the terms “first”, “second”, and “third” may be used interchangeably to distinguish one component from another and are not intended to signify location or importance of the individual components. The terms “forward” and “aft” refer to relative positions within a gas turbine engine, with forward referring to a position closer to an engine inlet and aft referring to a position closer to an engine nozzle or exhaust. The terms “upstream” and “downstream” refer to the relative direction with respect to fluid flow in a fluid pathway. For example, “upstream” refers to the direction from which the fluid flows, and “downstream” refers to the direction to which the fluid flows.

[0015] As explained herein, aspects of the present subject matter are generally directed to additives and/or treatment rinses that may be applied within a gas turbine engine to improve corrosion resistance, dust shedding attributes, additional cleaning benefits, residue removal, etc. For example, these additives may include Gadolinium doped ceria particles suspended in an aqueous solution and may be added directly to detergent or may be used as a “post-foam wash” rinse or treatment (e.g., the corrosion-resistance additive may be applied after a foam wash procedure). Application of these additives may improve engine durability during or after a cleaning procedure, e.g., by introducing catalytic or reactive oxides or chemistries directly into a foam wash detergent to aid in the prevention of corrosion and/or oxidation. For example, according to an example embodiment, the corrosion-resistance additives may include an inorganic additive, an environmentally reactive oxide, etc.

[0016] The inclusion of the additives described herein facilitates the unique delivery of treatments aimed to continuously refresh corrosion protection via foam washing at target intervals throughout an engine cycle life. These additives and treatments may provide better particle carrying capacity and uniform distribution suspension and dispersion throughout engine and on target hardware. These corrosion treatments may be introduced immediately following a clean cycle that removes corrodents and may provide the best opportunity for adhesion and corrosion prevention within the engine.

[0017] Referring now to the drawings, wherein identical numerals indicate the same elements throughout the figures, FIG. 1 provides a modular foam cart 10 according to an exemplary embodiment of the present subject matter. As described in detail below, modular foam cart 10 may be configured for housing some or all components of a treatment system 20 (which will be described in more detail below in reference to FIG. 2). Treatment system 20 is generally configured for washing, rinsing, or otherwise cleaning a gas turbine engine, such as a turbofan gas turbine engine (e.g., turbofan 100; see FIG. 4). Additionally, or alternatively, however, the treatment system 20 may be utilized with any other suitable gas turbine engine, such as a turboprop engine, a turboshaft engine, turbojet engine, etc. Moreover, it should be appreciated that aspects of treatment system 20 described herein could be performed without modular foam cart 10, e.g., using a stationary treatment system.

[0018] According to the exemplary illustrated embodiment, treatment system 20 is configured as a modular system that is housed at least in part on or within modular foam cart 10. As illustrated, modular foam cart includes a support frame 12 mounted on a plurality of wheels 14 to improve the mobility of the cart and facilitate quick and easy cleaning of turbofan 100. In addition, modular foam cart 10 may include a pivoting tug bar 16 such that modular foam cart 10 may be towed by a vehicle to a desired location proximate to turbofan 100. In addition, modular foam cart 10 can contain various storage compartments 18 for storing all equipment necessary for cleaning turbofan 100 and other features for facilitating the quick and easy cleaning of turbofan 100.

[0019] Referring now to FIG. 2, treatment system 20 in accordance with an exemplary embodiment of the present disclosure will be described. More specifically,

FIG. 2 provides a schematic view of treatment system 20 and its various cleaning modules in accordance with an exemplary embodiment of the present disclosure. For example, treatment system 20 generally includes one or more detergent supply tanks 22, a wash module 24, a foam generating assembly 26, and a collection module 28. In general, as will be described in detail below, detergent supply tanks 22 store and/or heat wash fluid, wash module 24 receives and pressurizes the wash fluid (e.g., using any suitable combination of pumps, valves, flow regulation devices, and/or plumbing), foam generating assembly 26 processes the wash liquid to form cleaning foam, and collection module 28 collects and/or recycles waste wash fluid.

[0020] In general, foam generating assembly 26 is configured for receiving a flow of wash fluid (e.g., from detergent supply tank 22). In addition, foam generating assembly 26 is configured for receiving a stream of air and for generating a flow of foamed wash fluid. In this regard, a pump of wash module 24 may urge the flow of wash fluid along with a stream of air (e.g., from an external pump or air compressor). Foam generating assembly 26 is generally configured for mixing the flow of wash fluid and the stream of air to aerate the wash fluid and generate the flow of foamed wash fluid.

[0021] In this regard, for example, the flow of foamed wash fluid includes wash fluid with a desired foam density, or the ratio of air to fluid. The foam characteristics may be manipulated by adjusting a temperature or a flow rate of either the flow of wash fluid or the stream of air into the foam generating assembly 26. Alternatively, mechanical means may be used to agitate the flow of wash fluid and generate more bubbles and thus lower foam density. For example, according to an exemplary embodiment, a foaming or aeration system may include three porous aeration devices through which the flow of wash fluid is passed. The porous aeration devices are fluidly coupled in series such that the flow of wash fluid passes successively through each aeration device and the bubble size is progressively refined and/or decreased. It should be appreciated that other aeration devices and configurations are possible and within the scope of the present subject matter.

[0022] Each of the various modules are, for the embodiment depicted, operably connected to a control system 30. The control system 30 may include one or more computing device(s) 32. The computing device(s) 32 may include one or more

processor(s) 32A and one or more memory device(s) 32B. The one or more processor(s) 32A may include any suitable processing device, such as a microprocessor, microcontroller, integrated circuit, logic device, or other suitable processing device. The one or more memory device(s) 32B may include one or more computer-readable media, including, but not limited to, non-transitory computer-readable media, RAM, ROM, hard drives, flash drives, or other memory devices.

[0023] The one or more memory device(s) 32B may store information accessible by the one or more processor(s) 32A, including computer-readable instructions 32C that can be executed by the one or more processor(s) 32A. The instructions 32C can be any set of instructions that when executed by the one or more processor(s) 32A, cause the one or more processor(s) 32A to perform operations. The instructions 32C may be software written in any suitable programming language or can be implemented in hardware. In some embodiments, the instructions 32C may be executed by the one or more processor(s) 32A to cause the one or more processor(s) 32A to perform operations, such as the washing operations of a gas turbine engine, as described herein, and/or any other operations or functions of the one or more computing device(s) 32. Additionally, and/or alternatively, the instructions 32C may be executed in logically and/or virtually separate threads on processor 32A. The memory device(s) 32B can further store data 32D that can be accessed by the processors 32A.

[0024] The computing device(s) 32 can also include a communications interface 32E used to communicate, for example, with the other components of treatment system 20. The communications interface 32E may include any suitable components for interfacing with one more communications network(s), including for example, transmitters, receivers, ports, controllers, antennas, or other suitable components. Control system 30 may also be communication (e.g., via communications interface 32E) with the various modules 22, 24, 26, 28, described below, and may selectively operate the treatment system 20 in response to user input and feedback from these modules 22, 24, 26, 28. More specifically, for the embodiment depicted, the control system 30 is configured to communicate through a wireless communication network 34 through communications interface 32E, such that the control system 30 may send or receive information and/or commands to or from the various modules 22, 24, 26,

28 of the exemplary treatment system 20 wirelessly. It should be appreciated, however, that in other embodiments, the control system 30 may additionally, or alternatively, use a wired communication bus to communicate with various modules 22, 24, 26, 28.

[0025] The technology discussed herein makes reference to computer-based systems and actions taken by and information sent to and from computer-based systems. It should be appreciated that the inherent flexibility of computer-based systems allows for a great variety of possible configurations, combinations, and divisions of tasks and functionality between and among components. For instance, processes discussed herein can be implemented using a single computing device or multiple computing devices working in combination. Databases, memory, instructions, and applications can be implemented on a single system or distributed across multiple systems. Distributed components can operate sequentially or in parallel. For example, although the exemplary control system 30 is depicted as including a separate computing device 32, in certain embodiments, the computing device 32 may be included within, e.g., one or more of the modules 22, 24, 26, 28, an onboard computing device of an aircraft, a controller of a gas turbine engine, etc.

[0026] It should be appreciated that modular foam cart 10 and treatment system 20 as described herein may allow for a more versatile treatment system for a gas turbine engine, such as turbofan 100. For example, utilizing tank modules that are interchangeable with a wash module and/or a foam wash module may allow for extended washing operations, without having to refill a wash tank and wait for the wash liquid in such wash tank to heat up to a desired temperature. Instead, once all of a wash liquid within a given tank module has been utilized by the treatment system, a second tank module may be fluidly connected to the wash module to allow for the washing operations to continue with minimal interruption. Similarly, utilizing a wash module that is interchangeable with, e.g. a foam wash module may allow for multiple wash operations to be completed on a given gas turbine engine without requiring two completely separate treatment systems. In addition, according to exemplary embodiments of the present subject matter, a power module could be configured for providing compressed air and/or electrical power, e.g., when treatment system 20 is used in a location where such facilities are inconvenient or unavailable.

[0027] Additionally, as stated, the exemplary treatment system may be controlled through a control system in communications with a wireless network. Accordingly, the control system may be operably connected to the various modules through a wireless communication network, and further, may receive control signals/commands through a wireless communication network. Such a configuration may allow for an operator located remotely from the treatment system, such as an operator within a cockpit of an aircraft, to wirelessly control certain aspects of the treatment system.

[0028] It should be appreciated, that as used herein the term “fluid,” “wash fluid,” “wash liquid,” and the like may refer to any suitable fluid for performing washing operations and/or rinsing the gas turbine engine. Such wash fluid is typically made up of water that may include other additives such as detergent or other treatments. For example, the wash fluid may refer to water, or a combination of water and detergent, soap, and/or other additives. Moreover, treatment system 20 is not limited to utilizing water or any particular detergent as a wash fluid. Instead, treatment system 20 may utilize any suitable wash liquid for performing desired washing operations of the gas turbine engine.

[0029] Referring now particularly to FIG. 3, wash module 24 will be described according to an exemplary embodiment of the present subject matter. More specifically, FIG. 3 provides a schematic view of the wash module 24 in accordance with an exemplary aspect of the present disclosure. The exemplary wash module 24 of FIG. 3 may, in certain exemplary embodiments, be utilized with the exemplary treatment system 20 described above with reference to FIG. 1. However, it should be appreciated that in other embodiments the wash module 24 described with reference to FIG. 3 may instead be utilized with any other suitable treatment system 20, such as a single, integrated treatment system.

[0030] As illustrated, the wash module 24 generally includes a pump 54, and distribution manifold 56, and a plurality of wash lines 58. More specifically, the pump 54 is configured to receive a flow of wash liquid and pressurize the flow of wash liquid. The pump 54 is configured to be releasably fluidly connected to an outlet of a wash detergent supply tank 22. For example, for the embodiment depicted, the wash module 24 includes a fluid connection line 60, with the fluid connection line 60

configured to be releasably fluidly connected to an outlet of wash detergent supply tank 22, e.g., through a quick release connection.

[0031] Although not depicted, the pump 54 may include a variable frequency drive motor, such that it may operate at various power levels. However, in other embodiments, any other suitable pump may be utilized, including any other suitable type of motor (such as a constant frequency motor). Additionally, the pump 54 is electrically connected to a power source, which may be a battery, or any other suitable power source. The power source may provide the pump 54 with a necessary amount of electrical power to pressurize the wash liquid received to a desired pressure.

[0032] An outlet of the pump 54 is fluidly connected to a duct 66 extending to the distribution manifold 56, such that the distribution manifold 56 is fluidly connected to the pump 54 for receiving a flow of pressurized wash liquid from the pump 54. For the embodiment depicted in FIG. 3, upstream of the distribution manifold 56, the wash module 24 includes a sensor 68 for, e.g., sensing a temperature and or pressure, and a valve 70. The valve 70, for the embodiment depicted, is positioned in the duct 66 and movable between an open position allowing full flow of wash liquid through the duct 66 and a closed position, preventing any flow of wash liquid through the duct 66. In certain exemplary embodiments, the valve 70 may be a variable throughput valve movable between various positions between the open position and the closed position to allow a desired amount of wash liquid through the duct 66.

[0033] Referring still to FIG. 3, for the embodiment depicted, the distribution manifold 56 is configured to receive a flow of wash liquid from the duct 66 (i.e., a flow of pressurized wash liquid from the pump 54), and distribute such flow of wash liquid to the plurality of wash lines 58. The distribution manifold 56 may be operably connected to a controller 72 of the wash module 24 (e.g., such as computing device 32). Notably, the controller 72 may further be operably connected to various other components of the wash module 24. Specifically, for the embodiment depicted, the controller 72 is operably connected to the power source, the pump 54, the sensor 68, and the valve 70, in addition to the distribution manifold 56. The controller 72 may be configured similar to the computing device 32 of the control system 30 and may be in communication with the control system 30 of the treatment system 20 through, e.g., a wireless communication network 34. For example, as will be described in greater

detail below, the controller 72 may be configured to control a flow of pressurized wash liquid to the plurality of wash lines 58 through the distribution manifold 56.

[0034] Moreover, as is depicted, the plurality of wash lines 58 are fluidly connected to the distribution manifold 56 for receiving at least a portion of the pressurized wash liquid therefrom. Although for the embodiment depicted, the distribution manifold 56 is fluidly connected to eight (8) wash lines 58, in other embodiments, the wash module 24 of the treatment system 20 may instead include any other suitable number of wash lines 58 fluidly connected to the distribution manifold 56. As will be appreciated from the description below, the distribution manifold 56 may be configured, in certain embodiments, to distribute the flow of pressurized wash liquid in a fixed manner. For example, the distribution manifold 56 may be configured to split the flow of pressurized wash liquid substantially evenly between each of the plurality of wash lines 58 fluidly connected thereto.

Alternatively, the distribution manifold 56 may be configured to split the flow of pressurized wash liquid in an uneven manner between the plurality of wash lines 58 fluidly connected thereto (i.e., distributing more wash liquid to certain wash lines 58 than others). In still other exemplary embodiments, the distribution manifold 56 may be configured to vary a distribution of the flow of the pressurized wash liquid between the various wash lines 58 according to, e.g., individual spray schedules for the various wash lines 58.

[0035] For example, referring now to FIGS. 3 and 4, the exemplary distribution manifold 56 is fluidly connected to the pump 54 of the wash module 24 via a duct 66. Additionally, as is discussed in greater detail below, the wash module 24 further includes a plurality of spray nozzles 74, with each spray nozzle 74 attached to a respective wash line 58. Each of the plurality of spray nozzles 74 includes an attachment portion 76 for attachment to a respective borescope hole in a gas turbine engine, providing a substantially air-tight and water-tight connection to a borescope hole (see, e.g., borescope hole 146 in FIG. 4).

[0036] Furthermore, the exemplary distribution manifold 56 is configured to vary a distribution of the flow of pressurized wash liquid between the various wash lines 58. Specifically, the distribution manifold 56 includes a plurality of valves 78, with each of the plurality of valves 78 fluidly connecting a respective wash line 58 to the

pump 54. Each of the valves 78 may be a variable throughput valve movable between a fully open position allowing complete flow of pressurized wash liquid therethrough, a fully closed position allowing no flow of pressurized liquid therethrough, as well as a variety of positions therebetween. For example, one or more of the variable throughput valves 78 may be configured as solenoid valves, or solenoid activated valves, or alternatively as ratio regulation valves.

[0037] Moreover, for the embodiment depicted each of the plurality of valves 78 is individually operably connected to the controller 72, such that the plurality of valves 78 are operable independently of one another. Accordingly, the controller 72 may control the plurality of valves 78 such that each operates according to its own unique flow schedule (e.g., flow rate, pressure, duration, etc.).

[0038] In addition to the plurality of valves 78, the distribution manifold 56 further includes a plurality of flow meters 80, wherein each flow meter 80 is in fluid communication with a wash line 58 of the plurality of wash lines 58 to measure a flowrate of the pressurized wash liquid flowing therethrough. More specifically, for the embodiment depicted, the distribution manifold 56 includes a flow meter 80 downstream from each of the valves 78, for measuring a flowrate of wash liquid flowing to (and through) each wash line 58. However, in other embodiments, one or more of the flow meters 80 may instead be positioned upstream of a respective valve 78, or at any other suitable location.

[0039] As with the plurality of valves 78, each of the flow meters 80 is operably connected to the controller 72, such that the controller 72 may receive information indicative of a flowrate of wash liquid through each wash line 58 from the respective flow meters 80. The controller 72 may utilize such information in controlling one or more of the plurality of valves 78. For example, the controller 72 may operate on a feedback loop to ensure wash liquid is flowing to and through a particular wash line 58 at a desired flow rate.

[0040] Referring now to FIG. 4, the exemplary wash module 24 is illustrated as being used in washing operations of a gas turbine engine, also depicted schematically. The exemplary gas turbine engine depicted is configured as a high bypass turbofan engine, referred to herein as gas turbine engine 100 or turbofan 100. As is depicted, the exemplary turbofan 100 defines an axial direction A (extending parallel to a

longitudinal centerline 101 provided for reference), a radial direction R, and a circumferential direction C (extending about the axial direction A). Additionally, the turbofan 100 includes a fan section 102 and a turbine engine 104 disposed downstream from the fan section 102. The exemplary turbine engine 104 depicted generally includes a substantially tubular outer casing 106 that defines an annular booster inlet 108. The outer casing 106 encases, in serial flow relationship, a compressor section including a second, booster or low pressure (LP) compressor 110 and a first, high pressure (HP) compressor 112; a combustor section 114; a turbine section including a first, high pressure (HP) turbine 116 and a second, low pressure (LP) turbine 118; and a jet exhaust nozzle section 120. The compressor section, combustor section 114, and turbine section together define a core air flowpath 121 extending from the annular booster inlet 108 through the LP compressor 110, HP compressor 112, combustor section 114, HP turbine 116 section 116, LP turbine section 118 and jet nozzle exhaust section 120. A first, high pressure (HP) shaft or spool 122 drivingly connects the HP turbine 116 to the HP compressor 112. A second, low pressure (LP) shaft or spool 124 drivingly connects the LP turbine 118 to the LP compressor 110.

[0041] For the embodiment depicted, the fan section 102 includes a fan 126 having a plurality of fan blades 128 coupled to a disk 130 in a spaced apart manner. As depicted, the fan blades 128 extend outwardly from disk 130 generally along the radial direction R. In certain exemplary aspects, the fan 126 may be a variable pitch fan, such that each of the plurality of fan blades 128 are rotatable relative to the disk about a pitch axis, by virtue of the plurality of fan blades being operatively coupled to an actuation member.

[0042] Referring still to the exemplary embodiment of FIG. 4, the disk 130 is covered by rotatable front hub 136 aerodynamically contoured to promote an airflow through the plurality of fan blades 128. Additionally, the exemplary fan section 102 includes an annular fan casing or outer nacelle 138 that circumferentially surrounds the fan 126 and/or at least a portion of the turbine engine 104. The nacelle 138 is supported relative to the turbine engine 104 by a plurality of circumferentially-spaced outlet guide vanes 140. A downstream section 142 of the nacelle 138 extends over an

outer portion of the turbine engine 104 so as to define a bypass airflow passage 144 therebetween.

[0043] Referring still to FIG. 4, the fan blades 128, disk 130, and front hub 136 are together rotatable about the longitudinal axis 101 directly by the LP spool 124. Accordingly, for the embodiment depicted, the turbofan engine 100 may be referred to as a “direct drive” turbofan engine. However, in other embodiments, the turbofan engine 100 may additionally include a reduction gearbox for driving the fan 126 at a reduced rotational speed relative to the LP spool 124.

[0044] Throughout the turbofan engine 100, the turbine engine 104 defines a plurality of borescope holes 146. Specifically, for the embodiment depicted, the turbine engine 104 includes one or more borescope holes 146 defined in the compressor section, in the combustor section 114, and in the turbine section. More specifically, still, for the embodiment depicted, the turbine engine 104 includes one or more borescope holes 146 defined in the LP compressor 110, the HP compressor 112, a combustion chamber of the combustor section 114, the HP turbine 116, and the LP turbine 118. The borescope holes 146 may allow for inspection of the turbine engine 104 between operations, and more specifically, may open into the core air flowpath 121 of the turbofan engine 100 to allow for inspection of, e.g., one or more blades, nozzles, or combustion liners of the turbofan engine 100 between operations. By contrast, during normal operations, the borescope holes 146 within the combustor section 114 and turbine section may be plugged with a borescope plug (not shown), such that the borescope holes 146 do not affect operation of the turbofan engine 100.

[0045] Moreover, as previously stated, the exemplary turbofan engine 100 is depicted schematically as being cleaned by the wash module 24 of the treatment system 20. More specifically, the wash module 24 of the treatment system 20 further includes a plurality of spray nozzles 74, each of the plurality of spray nozzles 74 attached to a respective wash line 58 and configured for extending at least partially into or through one of the borescope holes 146 of the turbofan engine 100 for providing at least a portion of the flow of the pressurized wash liquid to the turbofan engine 100. More specifically, the plurality of spray nozzles 74 may provide at least a portion of the flow of pressurized wash liquid directly to the core air flowpath 121 of the turbine engine 104, at a location downstream from the booster inlet 108. It should

be appreciated, that in certain embodiments, the plurality of spray nozzles 74 may extend at least partially into or through borescope holes 146 of the turbofan engine 100 at locations spaced along, e.g., the circumferential direction C of the turbofan engine 100. Such a configuration may allow for a more even cleaning of the turbofan engine 100, or rather of the turbine engine 104, during such wash operations.

[0046] Referring still to FIG. 4, for the embodiment depicted, the plurality spray nozzles 74 includes a compressor spray nozzle 74A for extending at least partially into or through one of the borescope holes 146 defined in the compressor section of the turbofan engine 100, as well as a turbine spray nozzle 74B for extending at least partially into or through one of the borescope holes 146 defined in the turbine section of the turbofan engine 100. Further, for the embodiment depicted, the plurality spray nozzles 74 includes a combustor section spray nozzle 74C for extending at least partially into or through one of the borescope holes 146 defined in a combustion chamber of the combustor section 114 of the gas turbine engine.

[0047] More specifically, for the embodiment depicted, the compressor spray nozzle 74A includes a plurality of compressor spray nozzles 74A (a first plurality of spray nozzles 74 positioned within borescope holes 146 in a first region of the turbofan engine 100), with at least one spray nozzle 74A extending into or through a borescope hole 146 defined in the LP compressor 110 and at least one spray nozzle 74A extending into or through a borescope hole 146 defined in the HP compressor 112. Further, for the embodiment depicted, the turbine spray nozzle 74B includes a plurality of turbine spray nozzles 74B (a second plurality of spray nozzles 74 positioned within borescope holes 146 in a second region of the turbofan engine 100), with at least one spray nozzle 74B extending into or through a borescope hole 146 defined in the HP turbine 116 and at least one spray nozzle 74B extending into or through a borescope hole 146 defined in the LP turbine 118.

[0048] Additionally, the exemplary wash module 24 further includes an inlet nozzle assembly 82 fluidly connected to one or more of the plurality of wash lines 58 for providing at least a portion of the flow of pressurized wash liquid to the turbofan engine 100, or rather to the turbine engine 104, through the booster inlet 108 of the turbine engine 104. As is depicted, the inlet nozzle assembly 82 includes one or more inlet nozzles 84 positioned proximate the booster inlet 108 to the turbine engine 104

to spray wash liquid directly into and through the booster inlet 108 of the turbine engine 104. In other exemplary embodiments, however, the inlet nozzle assembly 82 may instead be located at least partially forward of the fan 126.

[0049] Referring still to FIG. 4, as noted above, the exemplary turbofan engine 100 includes the outer nacelle 138 which defines the bypass passage 144 with the turbine engine 104. For the embodiment depicted, the plurality of wash lines 58 extend from an aft end of the turbine engine 104 to each of the respective plurality of borescope holes 146. With such a configuration, the treatment system 20 may operate without having to remove one or more portions of the fan section 102. More specifically, a treatment system having such a configuration may allow for conducting washing operations (i.e., providing pressurized wash liquid through the plurality of wash lines and wash nozzles), while allowing for the turbofan engine to be cranked or rotated using, e.g., a starter motor or turning tool, to increase in effectiveness of the washing operations. In addition, a controller, such as a system controller or computing device 32, can automatically control the speed of the engine core rotation to improve cleaning performance or to prevent unwanted wash fluid intrusion into internal engine air circuits or other passageways. Moreover, such a controller can be configured for monitoring motor torque, e.g., to protect gearbox components.

[0050] Utilizing a treatment system in accordance with one or more of the exemplary embodiments described herein may allow for more efficient cleaning of the gas turbine engine. More specifically, by providing a wash liquid directly to a core air flowpath of the turbine engine of the gas turbine engine may allow the treatment system to provide such portions with heated and pressurized wash liquid. By contrast to prior configurations, in which wash liquid is provided solely at an inlet to the turbine engine (in which case such wash liquid may be neither pressurized nor heated by the time it reaches e.g., a turbine section), providing wash liquid directly to e.g., a turbine section of the turbine engine may allow the treatment system to provide heated and pressurized wash liquid to such section. Additionally, embodiments including the individual valves fluidly connecting wash lines to a pump in a distribution manifold may allow for relatively precise cleaning of the gas turbine engine and/or targeted cleaning of a gas turbine engine. Moreover, the duration of the cleaning cycle may be adjusted, the density of the cleansing foam may be altered, and

other adjustments to the cleaning cycle may be adjusted to improve cleaning efficiency.

[0051] As explained herein, aspects of the present subject matter are generally directed to additives and/or treatment rinses that may be applied within a gas turbine engine to improve corrosion resistance, dust shedding attributes, additional cleaning benefits, residue removal, etc. For example, these additives may be added directly to detergent or may be used as a “post-foam wash” rinse or treatment (e.g., the corrosion-resistance additive may be applied after a foam wash procedure). Application of these additives may improve engine durability during or after a cleaning procedure, e.g., by introducing catalytic or reactive oxides or chemistries directly into a foam wash detergent to aid in the prevention of corrosion and/or oxidation. For example, according to an example embodiment, the corrosion-resistance additives may include an inorganic additive, an environmentally reactive oxide, etc.

[0052] In addition, the additives may be designed to target Type I and/or Type II corrosion. In this regard, Type I corrosion may occur at temperatures above the melting point of alkali metal salts such as sodium and potassium sulphate (e.g., above 800°F). By contrast, Type II corrosion may occur at temperatures between about 600°F and 800°F, where base metals react with alkali metals to form low-melting-point salts. It should be appreciated that the corrosion-resistance additive described herein may be tailored to preventing Type I corrosion, Type II corrosion, or both.

[0053] In addition, application of these additives may introduce catalytic or reactive oxides or chemistries following an engine foam wash clean as a treatment, e.g., via light foaming and/or rinsing throughout the engine in a carrier solution. In addition, additives and/or chemistries may be added that will improve particle stability, suspension, and delivery to target engine hardware during foam wash. Although examples of such additives are described herein, it should be appreciated that the present subject matter is not limited to the precise additives described. Indeed, variations and modifications may be made to the described additives while remaining within the scope of the present subject matter.

[0054] According to an example embodiment, the additives or treatments, which may be referred to herein as corrosion-resistance additives or treatments, may include

Gadolinium doped ceria particles. For example, the gadolinium doped ceria particles may be a hot corrosion inhibitor, e.g., not a conventional aqueous corrosion inhibitor. For example, these Gadolinium doped ceria particles may be introduced into foam wash detergent prior to foaming. It should be appreciated that the Gadolinium doped ceria particles may vary in particle size and the concentration within a load of detergent as needed depending on the application, e.g., such that the particles are sized such that they remain suspended in the foam or liquid. These particle sizes may thus depend on the type, quality, composition, or characteristics of the detergent or foam. For example, the Gadolinium doped ceria particles may have an average particle size of between about 0.1 micrometer and 40 micrometers, between about 0.5 micrometers and 20 micrometers, or about 10 micrometers.

[0055] In addition, the amount, volume, or weight of corrosion-resistance additives that are included in an aqueous solution may vary depending on the application. For example, the corrosion-resistance additive may be between 0.1% and 20%, between about 1% and 10%, or about 5% of the weight of the detergent or aqueous solution plus the corrosion-resistance additive. Other variations in the cleaning or wash solution may be made while remaining within the scope of the present subject matter.

[0056] It should be appreciated that other corrosion-resistance additives may be used in the same or similar matter as Gadolinium doped ceria (GDC) as described herein. For example, Ceria stabilized zirconia (CZO15), nickel cobalt iron oxide (NiFeAlO), nickel iron oxide (NiFeO), or nickel Oxide (NiO). In addition, any suitable combination of these corrosion-resistance additives may be used, e.g., such as GDC+Pd, GDC+Pt, NiFeO+20%NiO, etc. Other corrosion-resistance additives are possible and within the scope of the present subject matter.

[0057] According to an example embodiment, the Gadolinium doped ceria particles may be put into water and/or another type of carrier solution (e.g., ethanol, another detergent type, etc.) at any suitable range of concentrations and particle sizes. For example, the carrier solution may be water, cleaning detergent or engine wash foam, or any other suitable aqueous solution. The carrier solution and additive may then be delivered through engine following a foam wash, e.g., either by using the same tooling or a re-designed nozzle or wand. In this regard, for example, the foam or

carrier solution including the corrosion-resistance additives may be supplied into the gas turbine engine while it is on-wing of an aircraft.

[0058] In addition, it should be appreciated that the corrosion-resistance additive is configured to persist within the engine and on its exposed surfaces after the remainder of the detergent or carrier solution is burned off. In this regard, after the foam wash and corrosion treatment procedure, when the engine is started, the remaining organic compounds within the engine may be burned off and/or ejected from the engine. However, the corrosion-resistance additive may remain even after such burn off, e.g., to protect engine components from corrosion that might otherwise occur during prolonged operation of the engine. For example, the corrosion-resistance additive may persist through normal operation of gas turbine engine, e.g., until a subsequent treatment cycle is performed.

[0059] According to still other example embodiments, an aqueous solution of fully dissolved constituents may be supplied, e.g., including anionic and nonionic surfactants. Both anionic and nonionic surfactants may play multiple roles, e.g., to create a meta-stable foam, to impart detergency capabilities, and to stabilize and promote suspension of inorganic oxide particles (e.g., Gadolinium doped ceria particles, etc.). This carrier solution may deliver the suspended active particles to be deposited throughout an engine's flowpath. The aqueous solution may also be stabilized by utilizing pH control, e.g., by adding an acid or base to the solution to stabilize the solution and promote suspension of the corrosion-resistance additives. In addition, stabilizers like buffers may also be added.

[0060] The inclusion of the additives described herein facilitates the unique delivery of treatments aimed to continuously refresh corrosion protection via foam washing at target intervals throughout an engine cycle life. These additives and treatments may provide better particle carrying capacity and uniform distribution suspension and dispersion throughout engine and on target hardware. These corrosion treatments may be introduced immediately following a clean cycle that removes corrodents and may provide the best opportunity for adhesion and corrosion prevention within the engine.

[0061] Referring now to FIG. 5, a method 200 for washing a turbine engine is provided according to an exemplary embodiment of the present subject matter. In at

least certain exemplary aspects, the method 200 may be utilized with one or more of modular foam cart 10, treatment system 20, and/or wash module 24 described above with reference to FIGS. 1 through 4. Moreover, in certain exemplary aspects, the method 200 may be utilized for washing a turbine engine configured in a manner similar to the exemplary turbofan 100 and turbine engine 104 described above. Accordingly, the turbine engine may include a compressor section, a combustor section, and a turbine section. Further, the turbine engine may define a plurality borescope holes located within one or more of the compressor section, combustor section, and turbine section.

[0062] Method 200 includes, at step 210, providing a detergent supply containing a detergent including a corrosion-resistance additive. As noted above, this corrosion-resistance additive may include Gadolinium doped ceria particles that are suspended in a carrier solution. The particle size of these particles and the weight percentage of them within the carrier solution may vary as needed depending on the application.

[0063] Step 220 may include operating a foam generating assembly operably coupled to the detergent supply to generate a foam using the detergent. In this regard, the carrier solution including the corrosion-resistance additives may be heated, aerated, or otherwise formed into a foam or water wash. Step 230 may include supplying the foam into the gas turbine engine through a foam supply line that fluidly couples the foam generating assembly to a cleaning port of the gas turbine engine, e.g., such as a borescope port.

[0064] FIG. 5 depicts steps performed in a particular order for purposes of illustration and discussion. Those of ordinary skill in the art, using the disclosures provided herein, will understand that the steps of any of the methods discussed herein can be adapted, rearranged, expanded, omitted, or modified in various ways without deviating from the scope of the present disclosure. Moreover, although aspects of method 200 are explained using gas turbine engine 100 and treatment system 20 as an example, it should be appreciated that this method may be applied to the cleaning of any suitable engine using any suitable wash system.

[0065] Further aspects are provided by the subject matter of the following clauses:

[0066] A treatment system for a gas turbine engine, the treatment system comprising: a detergent supply containing a detergent, the detergent comprising a

corrosion-resistance additive; a foam generating assembly operably coupled to the detergent supply, the foam generating assembly being configured to generate a foam using the detergent; and a foam supply line fluidly coupling the foam generating assembly to a cleaning port of the gas turbine engine to supply the foam into the gas turbine engine.

[0067] The treatment system of any preceding clause, wherein the corrosion-resistance additive comprises Gadolinium doped ceria particles.

[0068] The treatment system of any preceding clause, wherein the Gadolinium doped ceria particles have an average particle size of between about 0.1 micrometer and 40 micrometers.

[0069] The treatment system of any preceding clause, wherein the Gadolinium doped ceria particles have an average particle size of between about 0.5 micrometers and 20 micrometers.

[0070] The treatment system of any preceding clause, wherein the corrosion-resistance additive is an inorganic additive.

[0071] The treatment system of any preceding clause, wherein the corrosion-resistance additive is an environmentally reactive oxide.

[0072] The treatment system of any preceding clause, wherein the corrosion-resistance additive persists after the detergent burns off.

[0073] The treatment system of any preceding clause, wherein the detergent including the corrosion-resistance additive is applied after a foam wash procedure.

[0074] The treatment system of any preceding clause, wherein the detergent is configured to treat previously wash surfaces of the gas turbine engine to facilitate between adhesion of the corrosion-resistance additive.

[0075] The treatment system of any preceding clause, wherein the detergent is an engine wash foam.

[0076] The treatment system of any preceding clause, wherein the detergent is water or an aqueous solution.

[0077] The treatment system of any preceding clause, wherein the corrosion-resistance additive is between 0.1% and 20% of a weight of the detergent plus the corrosion-resistance additive.

[0078] The treatment system of any preceding clause, wherein the corrosion-resistance additive is between 1% and 10% of a weight of the detergent plus the corrosion-resistance additive.

[0079] The treatment system of any preceding clause, wherein the foam generating assembly supplies the foam into the gas turbine engine while the gas turbine engine is on-wing of an aircraft.

[0080] A method of cleaning a gas turbine engine, the method comprising: providing a detergent supply containing a detergent, the detergent comprising a corrosion-resistance additive; operating a foam generating assembly operably coupled to the detergent supply to generate a foam using the detergent; and supplying the foam into the gas turbine engine through a foam supply line that fluidly couples the foam generating assembly to a cleaning port of the gas turbine engine.

[0081] The method of any preceding clause, wherein the corrosion-resistance additive comprises Gadolinium doped ceria particles.

[0082] The method of any preceding clause, wherein the Gadolinium doped ceria particles have an average particle size of between about 0.5 micrometers and 20 micrometers.

[0083] The method of any preceding clause, wherein the corrosion-resistance additive is between 0.1% and 20% of a weight of the detergent plus the corrosion-resistance additive.

[0084] The method of any preceding clause, wherein the corrosion-resistance additive is an inorganic additive or an environmentally reactive oxide.

[0085] The method of any preceding clause, wherein the foam is supplied into the gas turbine engine after a foam wash procedure and the corrosion-resistance additive persists after the detergent burns off.

[0086] The method of any preceding clause, wherein the foam is supplied into the gas turbine engine while the gas turbine engine is on-wing of an aircraft.

[0087] This written description uses examples to disclose the invention, including the best mode, and also to enable any person skilled in the art to practice the invention, including making and using any devices or systems and performing any incorporated methods. The patentable scope of the invention is defined by the claims, and may include other examples that occur to those skilled in the art. Such other

examples are intended to be within the scope of the claims if they include structural elements that do not differ from the literal language of the claims, or if they include equivalent structural elements with insubstantial differences from the literal languages of the claims.

WHAT IS CLAIMED IS:

1. A treatment system for a gas turbine engine, the treatment system comprising:

a detergent supply containing a detergent, the detergent comprising a corrosion-resistance additive;

a foam generating assembly operably coupled to the detergent supply, the foam generating assembly being configured to generate a foam using the detergent; and

a foam supply line to fluidly couple the foam generating assembly to a cleaning port of the gas turbine engine to supply the foam into the gas turbine engine.

2. The treatment system of claim 1, wherein the corrosion-resistance additive comprises Gadolinium doped ceria particles.

3. The treatment system of claim 2, wherein the Gadolinium doped ceria particles have an average particle size of between about 0.1 micrometer and 40 micrometers.

4. The treatment system of claim 2, wherein the Gadolinium doped ceria particles have an average particle size of between about 0.5 micrometers and 20 micrometers.

5. The treatment system of claim 1, wherein the corrosion-resistance additive is an inorganic additive.

6. The treatment system of claim 1, wherein the corrosion-resistance additive is an environmentally reactive oxide.

7. The treatment system of claim 1, wherein the corrosion-resistance additive persists after the detergent burns off.

8. The treatment system of claim 1, wherein the detergent including the corrosion-resistance additive is to be applied after a foam wash procedure.

9. The treatment system of claim 1, wherein the detergent is configured to treat previously washed surfaces of the gas turbine engine to facilitate adhesion of the corrosion-resistance additive.

10. The treatment system of claim 1, wherein the detergent is water or an aqueous solution.

11. The treatment system of claim 1, wherein the corrosion-resistance additive is between 0.1% and 20% of a weight of the detergent plus the corrosion-resistance additive.

12. The treatment system of claim 1, wherein the corrosion-resistance additive is between 1% and 10% of a weight of the detergent plus the corrosion-resistance additive.

13. The treatment system of claim 1, wherein the foam generating assembly is to supply the foam into the gas turbine engine while the gas turbine engine is on-wing of an aircraft.

14. The treatment system of claim 1, wherein the corrosion-resistance additive comprises at least one of ceria stabilized zirconia (CZO15), platinum (Pt), palladium (Pd), nickel cobalt iron oxide (NiFeAlO), nickel iron oxide (NiFeO), or nickel Oxide (NiO).

15. A method of cleaning a gas turbine engine, the method comprising:
providing a detergent supply containing a detergent, the detergent comprising a corrosion-resistance additive;
operating a foam generating assembly operably coupled to the detergent supply to generate a foam using the detergent; and

supplying the foam into the gas turbine engine through a foam supply line that fluidly couples the foam generating assembly to a cleaning port of the gas turbine engine.

16. The method of claim 15, wherein the corrosion-resistance additive comprises Gadolinium doped ceria particles.

17. The method of claim 16, wherein the Gadolinium doped ceria particles have an average particle size of between about 0.5 micrometers and 20 micrometers.

18. The method of claim 15, wherein the corrosion-resistance additive is between 0.1% and 20% of a weight of the detergent plus the corrosion-resistance additive.

19. The method of claim 15, wherein the corrosion-resistance additive is an inorganic additive or an environmentally reactive oxide.

20. The method of claim 15, wherein the foam is supplied into the gas turbine engine after a foam wash procedure and the corrosion-resistance additive persists after the detergent burns off.