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(54) VAPOR CYCLE SYSTEM WITH DE-SUPERHEATER

(75) Inventors: **Adam M. Finney**, Rockford, IL (US); **Young K. Park**, Simsbury, CT (US)

(73) Assignee: **HAMILTON SUNDSTRAND CORPORATION**, Windsor Locks, CT (US)

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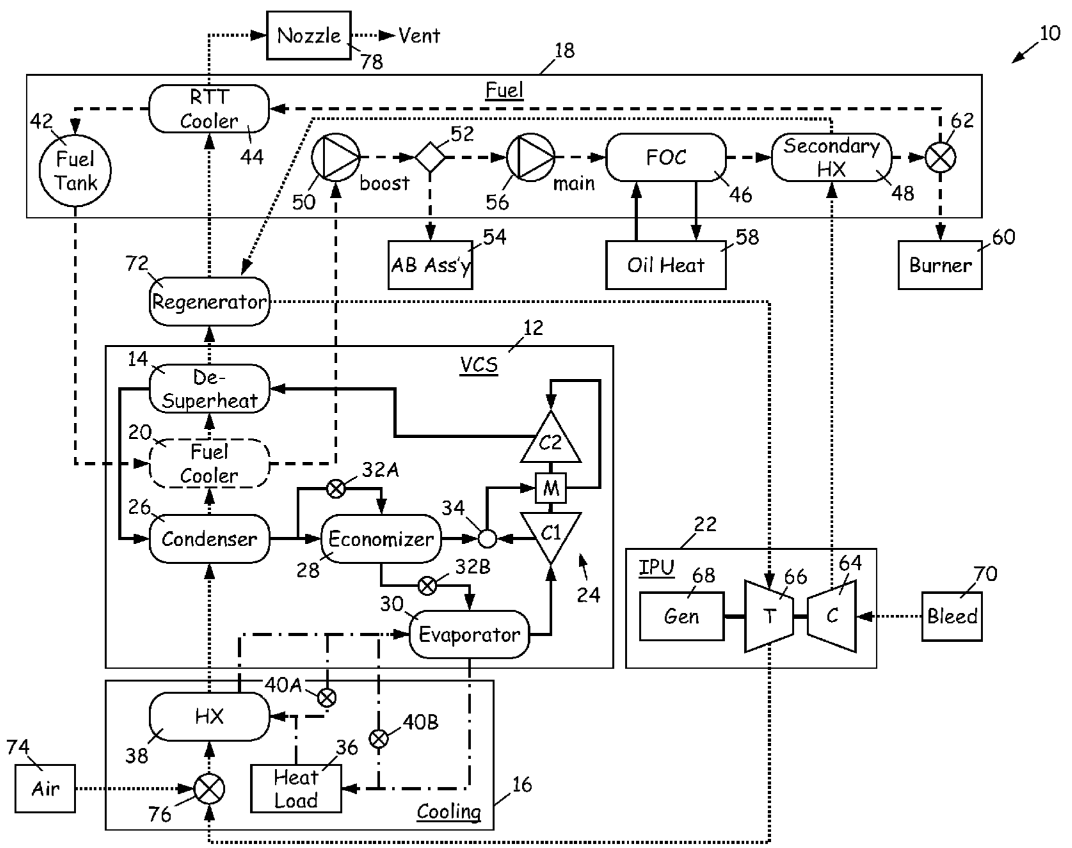
(57) **ABSTRACT**

A vapor cycle system comprises a compressor for compressing a coolant to form a superheated vapor, a de-superheater for cooling the superheated vapor to form a reduced temperature vapor by exchanging heat with a cooling fluid flow, a condenser for condensing the reduced temperature vapor to form a condensed liquid by exchanging heat with the cooling fluid flow, and an evaporator for evaporating the condensed liquid. The de-superheater is located downstream of the condenser in the cooling fluid flow, and a temperature of the cooling fluid flow is higher at the de-superheater than at the condenser.



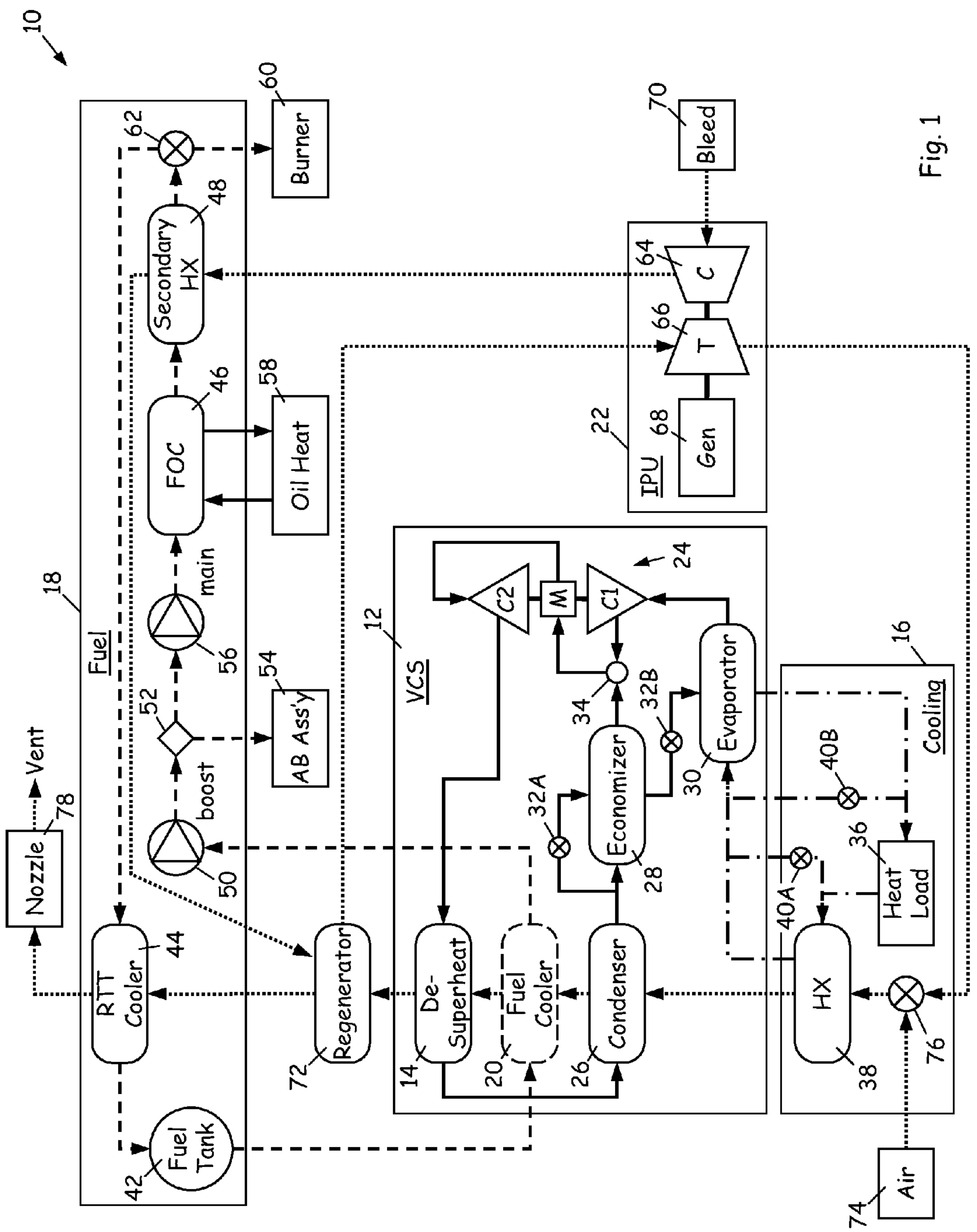

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Fig. 1

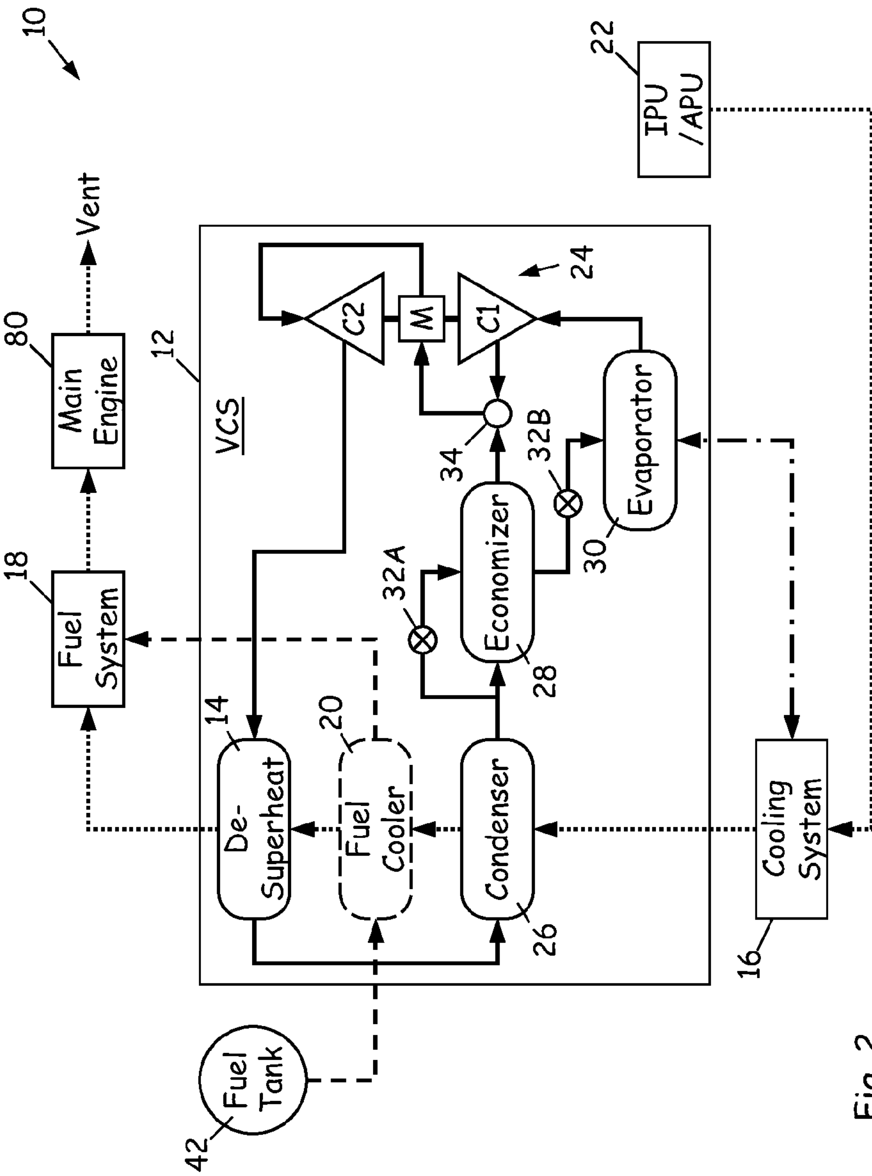
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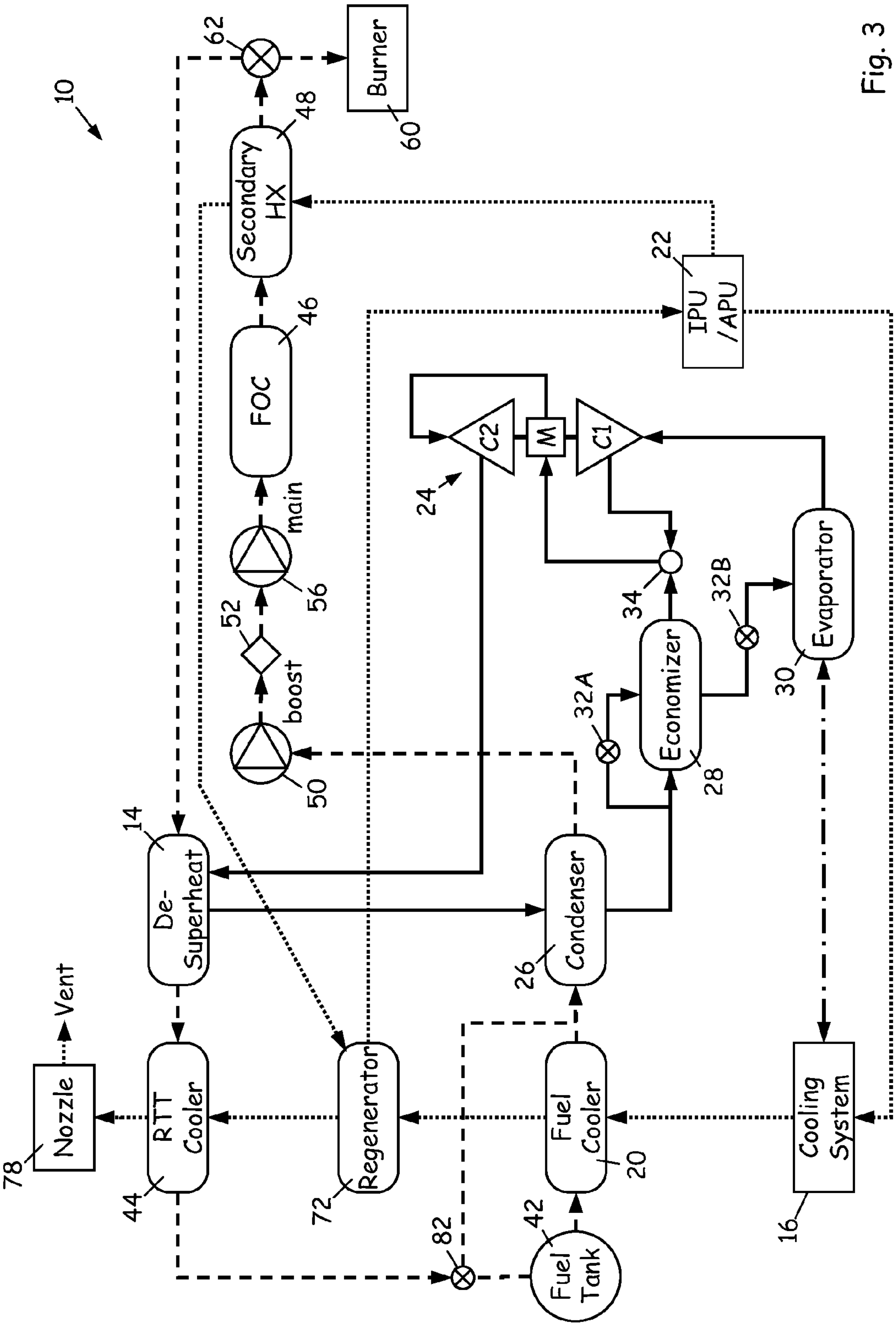
Fig. 2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Fuel Cooler
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Cooling System
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Fuel Tank

Fig. 3

# VAPOR CYCLE SYSTEM WITH DE-SUPERHEATER

## BACKGROUND

**[0001]** This invention relates generally to thermal management, and particularly to vapor cycle systems. In particular, the invention concerns thermal management for an aircraft-based vapor cycle system.

**[0002]** Modern commercial aircraft typically include a number of different heating and cooling systems for the cabin and cargo bay areas, galley facilities, power electronics, and avionics and radar systems. Each of these components has different thermal requirements and power constraints, making overall efficiency an important design criterion.

**[0003]** Most aircraft cooling systems utilize at least one vapor cycle system or VCS unit. The vapor cycle system includes a compressor for compressing the coolant, and a condenser for condensing the compressed fluid, with heat dispersed to different cooling fluid streams. The coolant then flows through an expansion valve to an evaporator, where the fluid expands and cools.

**[0004]** In some configurations, cold VCS fluid is cycled through an AC pack for cooling cabin air. Alternatively, a number of independent cooling loops can be used to cycle specialized coolants to heat loads distributed throughout the aircraft, cooling the coolant by exchanging heat with the vapor cycle system at the evaporator.

**[0005]** In either configuration, weight and efficiency are always at a premium. This makes thermal management an important design consideration, with particular respect to increasing efficiency, reducing the overall weight and size envelope, and maintaining system reliability and service life.

## SUMMARY

**[0006]** A vapor cycle system comprises a compressor, a de-superheater, a condenser, and an evaporator. The compressor compresses a coolant to form a superheated vapor, and the de-superheater cools the superheated vapor by heat exchange with a cooling fluid flow, forming a reduced temperature vapor. The condenser condenses the reduced temperature vapor by exchanging additional heat with a cooling fluid flow, forming a condensed liquid.

**[0007]** The condensed liquid is expanded then evaporated in the evaporator, absorbing thermal energy and starting the cycle again. The de-superheater is located downstream of the condenser in the cooling fluid flow, so that the cooling fluid temperature is higher at the de-superheater than at the condenser.

## BRIEF DESCRIPTION OF THE DRAWINGS

**[0008]** FIG. **1** is a schematic illustration of a thermal management system for an aircraft, with a vapor cycle system having a de-superheater.

**[0009]** FIG. **2** is a schematic illustration of the vapor cycle system and de-superheater, in an air-cooled embodiment.

**[0010]** FIG. **3** is a schematic illustration of the vapor cycle system and de-superheater, in a fuel-cooled embodiment.

## DETAILED DESCRIPTION

**[0011]** FIG. **1** is a schematic illustration of thermal management system **10** for an aircraft. System **10** includes vapor cycle system (VCS) **12** with de-superheater **14**, cooling system **16**, fuel circulation system **18** with fuel cooler **20** (dashed lines), and integrated power unit (IPU) **22**. Integrated power unit **22** generates electrical power and regenerates cooling air flow (dotted lines) for thermal management system **10**. De-superheater **14** reduces losses in vapor cycle system **12** (solid lines), raising the coefficient of performance (COP) for thermal transfer to cooling system **16** (dot-dashed lines), and increasing the overall efficiency of thermal management system **10**.

**[0012]** Vapor cycle system **12** includes de-superheater **14**, compressor **24**, condenser **26**, economizer **28** and evaporator **30**. In one embodiment, vapor cycle system **12** operates on a two-phase coolant or refrigerant fluid such as 1,1,1,2-tetrafluoroethane or R-134a (hydrofluorocarbon HFC-134a). Vapor cycle system **12** is also operable on older refrigerants such as R-12 (chlorofluorocarbon CFC-12) or R-22 (hydrochlorofluorocarbon HCFC-22), but in modern applications "green" fluids are typically used, including R-134a and other HFC, haloalkane and halocarbon-based refrigerant fluids with relatively short environmental lifetimes and reduced potential for ozone depletion.

**[0013]** The VCS loop is driven by compressor **24**, which compresses the refrigerant to a superheated phase. The superheated phase is a gaseous or vapor state, at a temperature and pressure above the saturation and condensation points. De-superheater **14** cools the superheated vapor by exchanging heat with the cooling fluid stream, "de-superheating" the fluid to improve efficiency or decrease weight for the vapor/liquid phase transition in condenser **26**.

**[0014]** In particular, de-superheater **14** improves the performance of condenser **26** by delivering fluid in a cooler vapor state, as compared to the superheated vapor output of compressor **24**. Cooler vapor condenses more quickly, because less heat must be removed to reach the condensation temperature, increasing the efficiency of vapor cycle system **12**.

**[0015]** De-superheater **14** also utilizes a higher-temperature (hotter) flow, downstream of condenser **26** and fuel cooler **20**, while condenser **26** use a cooler fluid flow, upstream of fuel cooler **20** and de-superheater **14**. Because the de-superheat temperature is higher than the condensation temperature, temperature differential $\Delta T$ is less at both de-superheater **14** and condenser **26**. This reduces the change in entropy and improves the coefficient of performance, as described below.

**[0016]** Refrigerant exits condenser **26** in a two-phase (liquid/vapor) state, at approximately the condensation temperature. Upstream expansion valve **32**A provides a minor expansion into economizer **28**, further reducing the temperature before entering evaporator **30** through downstream (major) expansion valve **32**B.

**[0017]** The refrigerant fluid enters evaporator **30** as a sub-cooled liquid or compressed fluid, or in a two-phase liquid/vapor state. The refrigerant evaporates and expands in evaporator **30** to produce a gas or vapor phase, absorbing heat from cooling system **16** as described below.

**[0018]** Fluid from evaporator **30** enters compressor **24** in a substantially gaseous or vapor state. In two-stage compressor embodiments, as shown in FIG. **1**, economizer **28** also delivers cooled fluid to mixer **34**, which reduces the temperature of fluid exiting first compressor stage C**1**. This improves heat transfer for cooling motor M, and eases second-stage compression by reducing the energy required to compress the refrigerant to a superheated vapor state in second compressor stage C**2**. Along with de-superheater **14**, these additional VCS components further increase the coefficient of performance by reducing temperature differentials, and lowering the total entropy of vapor cycle system **12**.

**[0019]** Cooling system **16** absorbs heat from load **36**, and disperses the heat through thermal transfer to evaporator **30** of vapor cycle system **12**. In some cooling systems **16**, heat is also dispersed to the cooling air flow via heat exchanger (HX) **38**.

**[0020]** Heat load **36** includes one or more aircraft systems that require heating or cooling, for example a cabin, cockpit, cargo bay or galley chiller, or electronics components for radar, weapons control, avionics and cabin-based electronics or display systems. In power electronics cooling system (PECS) embodiments, heat load **36** may include power electronics for flight control actuators and other flight-critical systems.

**[0021]** Cooling system (or cooling loop) **16** operates on a refrigerant fluid with high heat transfer capability over a wide temperature range, for example polyalphaolefin (PAO) or hydrogenated PAO. Alternatively, cooling system **16** operates on a silicate ester or oil-based coolant fluid such as Coolanol®, as available from Exxon Mobile of Fairfax, Va., or another fluid such as water, glycol, etc.

**[0022]** The relative flows of cooling system refrigerant through heat exchanger **38** and evaporator **30** are controlled via bypass valves **40**A and **40**B, based on cooling demands, ambient temperature, flight conditions and the available cooling air flow. For example, bypass valves **40**A and **40**B can be adjusted to regulate higher levels of air cooling in heat exchanger **38** during cruise flight conditions, and higher levels of evaporator cooling in evaporator **30** during takeoff and landing, or during ground operations.

**[0023]** Fuel circulation system **18** comprises fuel-air cooler **20**, fuel tank **42**, return-to tank (RTT) cooler **44**, fuel-oil cooler (FOC) **46**, and secondary (fuel-air) heat exchanger **48**. Fuel system **18** typically operates on a kerosene-type jet fuel such as Jet A or Jet A-1, or a naphtha-type fuel such as Jet B for low-temperature performance. In military applications, fuel system **18** operates on a modified kerosene-based fuel such as JP-5 or JP-8, or a modified naphtha or “wide-cut” fuel such as JP-4.

**[0024]** Heat transfer in fuel circulation system **18** is determined according to the temperature requirements of the various fuel subsystems, and based on the different performance demands and fuel system capabilities of military-type aircraft, as compared to commercial designs. In the particular embodiment of FIG. **1**, for example, flow from fuel tank **42** circulates through fuel cooler **20** to reduce downstream operating temperatures, with fuel cooler **20** located between condenser **26** and de-superheater **14** in the cooling fluid flow. The fuel-air exchange temperature at fuel cooler **20** is thus higher than the condensation temperature at condenser **26**, and lower than the de-superheat temperature at de-superheater **14**.

**[0025]** On afterburning turbofan engines, boost pump **50** supplies fuel to inlet valve **52** for afterburner (AB assembly) **54**, in order to provide thrust augmentation during short periods of peak operational demand. Boost pump **50** also provides a downstream pressure drop through fuel cooler **20**, and generates an overpressure to limit cavity formation at the inlet to main fuel pump **56**.

**[0026]** Main fuel pump **56** drives flow through fuel-oil-cooler **46** and secondary heat exchanger **48**. Fuel-oil-cooler **46** accepts heat from oil heat load **58**, including rotor bearings and other elements of a combustion turbine or turbofan engine (e.g., the main engines for a jet aircraft). Alternatively, oil heat load **58** represents a gearbox or other differential rotation system for a turboprop, turboshaft or geared turbofan engine. Secondary heat-exchanger **48** comprises a fuel-air heat exchanger to cool the compressed air flow from integrated power unit **22**, and to pre-heat the fuel before combustion in burner **60**.

**[0027]** Valve **62** regulates the recirculation of fuel flow back through RTT cooler **44** to fuel tank **42**. As opposed to secondary heat-exchanger **48**, which raises the fuel temperature by exchanging heat with compressed air flow from integrated power unit **22**, RTT cooler **44** exchanges heat with the expanded cooling air flow to reduces fuel temperatures for storage in fuel tank **42**.

**[0028]** Integrated power unit **22** includes an air-cycle machine with compressor **64** and turbine **66**, or an auxiliary power unit (APU) comprising compressor **64** and turbine **66** in flow series with a combustor or burner. In some embodiments, generator **68** is rotationally coupled to turbine **64** and compressor **66**, for example using a coaxial shaft and clutch mechanism to swap generator **68** in and out during ground operations, or based on flight conditions and real-time electrical demand.

**[0029]** Source **70** of bleed air comprises a compressed air supply such as a first-stage compressor bleed or fan air bleed from the main engine, or a third-stream air source such as an independently modulated bleed flow from a downstream compressor section. Alternatively, bleed air is provided by a ram air intake. In further embodiments, source **70** comprises a static inlet for use during ground operations, or a compressed air supply generated by an APU.

**[0030]** Incoming air is compressed and heated by compressor **64**, then cooled by heat transfer to fuel circulation system **18** in secondary (fuel-air) heat exchanger **48**. In some embodiments, a primary heat exchanger may also be included, typically upstream of compressor **64**.

**[0031]** The compressed air exchanges heat with the downstream cooling air flow in regenerator (air-air heat exchanger) **72**, then expands in turbine **66** to produce a low temperature, relatively low-pressure cooling air flow for thermal management system **10**. In air-cycle machine embodiments, there is an overall pressure drop from source **70** to the outlet of expansion turbine **66** or energy input from a motor/generator, providing the energy required to turn compressor **64** and generator **68**.

**[0032]** Depending on embodiment, cooling air from integrated power unit **22** may be mixed with additional cooling fluid from air source **74**. Air source **74** includes an additional fan or compressor bleed air supply, a ram air intake or a third-stream compressed air source providing a supply of relatively cool compressed air. Valve **76** regulates or switches the source between integrated power unit **22** and air source **74**, depending on flight conditions, ambient pressure and temperature, and cooling demands.

**[0033]** Downstream of mixer valve **76**, the cooling air flow exchanges heat with vapor cycle system **12**, cooling system **16** and fuel circulation system **18**. Generally, temperatures increase in the downstream direction, as heat is transferred to the cooling air from different components of thermal management system **10**. The order of the flow series thus depends on the individual cooling needs of each component, as well as the temperature differential and corresponding entropy and efficiency considerations.

**[0034]** There is an advantage in using the hottest available sink of thermal energy, as compared to the source temperature; that is, with small temperature differential ΔT, because this allows more heat to be rejected from the system. To promote rapid heat transfer, however, larger differentials are desired, because the heat transfer (Q) is proportional to temperature differential ΔT. That is,

$$Q=hA\Delta T, \quad [1]$$

where h is the heat transfer coefficient and A is the heat transfer surface area.

**[0035]** Thermal management also depends on other critical design factors including condensation points and other phase transition temperatures, thermal loading, and environmental (ambient) temperatures and pressures, as compared to the desired cabin and cargo bay conditions across a full range of different flight conditions, and the operating temperature ranges for heat loads including galley chillers, avionics, radar systems and power electronics. Thermal management thus requires constant tradeoffs among different air, fuel, oil, cooling system and VCS components, presenting an almost unlimited number of possible system configurations and corresponding design choices, and making the net results of any particular change or modification difficult to predict.

**[0036]** In the embodiment of FIG. **1**, cooling flow passes first through heat exchanger **38** of cooling system **16**. This provides the coldest available cooling fluid at relatively high ΔT, to provide rapid chilling of low-temperature galley and cabin air systems, and for flight control and other mission-critical systems including radar, avionics and power electronics.

**[0037]** Within vapor cycle system **12**, cooling air flows through condenser **26** first, in order to effect a vapor/liquid phase transition at a temperature at or below the condensation point. De-superheater **14** is downstream of condenser **26** in the cooling flow series, so that the de-superheat temperature is above the condensation temperature. The superheated vapor phase is hotter than the condensate, so heat can be transferred at higher temperature (lower ΔT), thereby reserving the cooler air for heat sources that required a lower temperature sink.

**[0038]** As shown in FIG. **1**, the cooling air flow also exchanges heat with fuel circulation system **18**, reducing the fuel temperature in fuel cooler **20**. This puts vapor cycle system **12** in thermal contact with fuel circulation system **18**, via the cooling air flow over condenser **26**, fuel cooler **20** and de-superheater **14**. Downstream of vapor cycle system **12**, cooling air also passes through regenerator (air-air heat exchanger) **72** and RTT cooler **44**, as described above.

**[0039]** Depending on embodiment, downstream air may be used to cool thrust nozzle **78**, or other main engine components such as blade or vane airfoils for the compressor and turbine section, or hot components of afterburner assembly **54** and burner **60**. After core engine or nozzle cooling, cooling air is typically vented to the outside atmosphere.

**[0040]** FIG. **2** is a schematic illustration of vapor cycle system **12** for thermal management system **10**, with air-cooled de-superheater **14** and condenser **26**. Cooling system **16** is shown in generic form, exchanging thermal energy with evaporator **30** of vapor cycle system **12**. Integrated power unit **22** utilizes an air cycle machine or an APU to produce a regenerating cooling air flow from one or more sources of compressed air, as described above with respect to FIG. **1**. Fuel system **18** is also shown in generic form, and thrust nozzle **78** is replaced by a generic cooling load **80**.

**[0041]** As shown in FIG. **2**, de-superheater **14** is located between compressor **24** and condenser **26** in the vapor cycle flow series, and between fuel cooler **20** and regenerator **72** in the cooling air flow series. In particular, de-superheater **14** is downstream of condenser **26**, where the air is hotter, so the de-superheat temperature is higher than the condensation temperature. Condenser **26** is located downstream of cooling system **16**, so the cooling air temperature is higher at condenser **26** than cooling system **16**.

**[0042]** Air-cooled de-superheater **14** include a vapor-air heat exchanger to cool the superheated VCS fluid by exchanging heat with the cooling air flow, lowering the superheated VCS fluid temperature before entering condenser **26**. The air temperature is increased downstream of condenser **26**, reducing ΔT (and the change in entropy) at de-superheater **14**. This increases efficiency and raises the system coefficient of performance, as described above.

**[0043]** De-superheater **14** exchanges thermal energy with fuel circulation system **18** via the cooling air flow through fuel cooler (air-fuel heat exchanger) **20**, in flow series between condenser **26** and de-superheater **14**. In particular, fuel cooler **20** raises the cooling air temperature above the condensation point, at which condenser **26** operates. De-superheater **14** exchanges additional thermal energy with the fuel flow via downstream components of fuel circulation system **18**, as shown FIG. **1**, above.

**[0044]** Condenser **26** is also air cooled, and is located between cooling system **16** and fuel cooler **20** in the cooling air flow series. Condenser **26** exchanges additional thermal energy with the cooling air flow through the cycling of VCS refrigerant through economizer **28**, evaporator **30**, compressor **24** and back to de-superheater **14**, where de-superheater **14** is located downstream of fuel cooler **20** in the cooling air flow. Condenser **26** exchanges thermal energy with fuel circulation system **18** via air flow over fuel cooler **20**, and via downstream components as described above for de-superheater **14**.

**[0045]** FIG. **3** is a schematic illustration of vapor cycle system **12** for thermal management system **10**, with fuel-cooled de-superheater **14**. In this embodiment, de-superheater **14** is located between compressor **24** and condenser **26** in the vapor cycle flow series, and between secondary (fuel-air) heat exchanger **48** and RTT cooler **44** in the fuel flow series.

**[0046]** Fuel-cooled de-superheater **14** comprises a fuel-vapor heat exchanger to cool the superheated VCS fluid by direct heat exchange with the fuel flow, lowering the superheated refrigerant temperature before entering condenser **26**. The fuel temperature is increased downstream of secondary heat exchanger **48**, lowering ΔT for de-superheater **14** and reducing the change in entropy to improve the coefficient of performance and overall operating efficiency, as described above.

**[0047]** Condenser **26** is also fuel-cooled, and is located downstream of fuel cooler **20** and upstream of boost pump **50** in the fuel flow series. In this embodiment, condenser **26** condenses the cooled, superheated VCS fluid by direct heat exchange with the fuel flow. Bypass valve **82** regulates the relative fuel flow through fuel tank **42** and fuel cooler **20**, maintaining the fuel temperature below the condensation point to encourage a vapor/liquid phase transition in condenser **26**.

**[0048]** While this invention has been described with reference to exemplary embodiments, 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 spirit and scope of the invention. In addition, 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, the invention is not limited to the particular embodiments disclosed herein, but includes all embodiments falling within the scope of the appended claims.

**1**. A vapor cycle system comprising:
- a compressor for compressing a refrigerant to form a superheated vapor;
- a de-superheater for cooling the superheated vapor to form a reduced temperature vapor by exchanging heat with a cooling fluid flow;
- a condenser for condensing the reduced temperature vapor to form a condensed liquid by exchanging heat with the cooling fluid flow; and
- an evaporator for evaporating the condensed liquid;
- wherein the de-superheater is located downstream of the condenser in the cooling fluid flow, such that a temperature of the cooling fluid flow is higher at the de-superheater than at the condenser.

**2**. The system of claim **1**, wherein the cooling fluid flow comprises an air flow.

**3**. The system of claim **2**, further comprising an air cycle system for generating the air flow from at least one source selected from the group consisting of a ram air supply, a bleed air supply, or a third-stream air supply from an aircraft engine.

**4**. The system of claim **2**, wherein the de-superheater comprises an air-vapor heat exchanger to cool the superheated vapor by heat exchange with the air flow.

**5**. The system of claim **2**, further comprising a heat load located between the condenser and the de-superheater in the cooling air flow; wherein the heat load comprises a heat exchanger to cool a fluid by heat exchange with the air flow.

**6**. The system of claim **1**, wherein the cooling fluid flow comprises a fuel flow.

**7**. The system of claim **6**, wherein the de-superheater comprises a fuel-vapor heat exchanger to cool the superheated vapor by direct heat exchange with the fuel flow.

**8**. The system of claim **1**, further comprising a cooling loop for exchanging heat between a heat load and the evaporator.

**9**. The system of claim **8**, wherein the cooling loop comprises a heat exchanger located upstream of the condenser in the cooling fluid flow, such that the temperature of the cooling fluid flow is lower at the heat exchanger than at the condenser.

**10**. The system of claim **9**, wherein the heat load comprises at least one selected from the group consisting of a passenger cabin, a cargo bay, a galley, an avionics system, a radar system and power electronics for actuating a flight control surface.

**11**. A thermal management system for an aircraft, the system comprising:
- a cooling loop, wherein the cooling loop circulates coolant inside the aircraft; and
- a vapor cycle unit, wherein the vapor cycle unit operates on a fluid to cool the coolant, the vapor cycle unit comprising:
  - a compressor, configured to compress the fluid to a superheated vapor phase;
  - a de-superheater, configured to cool the fluid from the superheated vapor phase to a cooled vapor phase by exchanging heat with a cooling flow;
  - a condenser, configured to condense the fluid from the cooled vapor phase to a condensed liquid phase by exchanging heat with the cooling flow;
  - an expansion device, configured to expand the fluid from the condensed liquid phase to an expanded phase; and
  - an evaporator, configured to cool the coolant by evaporation of the fluid from the expanded phase to the vapor phase;
- wherein the de-superheater is located downstream of the condenser in the cooling flow, such that the cooling flow is hotter at the de-superheater than at the condenser.

**12**. The system of claim **11**, wherein the cooling flow comprises a fuel flow for the aircraft, and wherein the de-superheater comprises a vapor-fuel heat exchanger for cooling the superheated vapor phase by direct heat exchange with the fuel flow.

**13**. The system of claim **11**, wherein the cooling flow comprises a cooling air flow.

**14**. The system of claim **13**, further comprising a fuel cooler located downstream of the condenser and upstream of the de-superheater in the cooling air flow, such that the cooling flow is hotter at the de-superheater than at the fuel cooler.

**15**. The system of claim **13**, wherein the cooling loop comprises a heat exchanger located upstream of the condenser in the cooling air flow, such that the cooling air flow is colder at the heat exchanger than at the condenser.

**16**. A method for cooling an aircraft system, the method comprising:
- circulating a coolant through the aircraft system;
- cooling the coolant by exchanging heat with an evaporating fluid;
- compressing the evaporating fluid to form a superheated vapor;
- de-superheating the superheated vapor by exchanging heat with a cooling flow at a de-superheat temperature; and
- condensing the superheated vapor by exchanging heat with the cooling flow at a condensation temperature, wherein the condensation temperature is lower than the de-superheat temperature.

**17**. The method of claim **16**, further comprising generating the cooling flow as a fuel flow for the aircraft by pumping fuel from a fuel tank.

**18**. The method of claim **16**, further comprising generating the cooling flow as a stream of cooling air by expansion of a compressed air source.

**19**. The method of claim **16**, further comprising cooling the coolant by exchanging heat with the cooling flow at a temperature lower than the condensation temperature.

**20**. The method of claim **16**, further comprising cooling a fuel flow for the aircraft by exchanging heat with the cooling flow at a temperature higher than the condensation temperature and lower than the de-superheat temperature.

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