



AEROSPACE INFORMATION REPORT

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Superseding AIR1204

(R) Control of Water Carryover from the Environmental Control System
and Condensation on the Structure

RATIONALE

This document is intended to address the issue of excess moisture on aircraft. AIR1204 was originally released in 1979. This Rev A version brings the document up to date with regard to Environmental Control System design and design best practices that have evolved since this document's original release.

AIR1204A has been reaffirmed to comply with the SAE Five-Year Review policy.

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1. SCOPE

This Aerospace Information Report (AIR) outlines the design considerations and criteria for the control of water carryover from the environmental control system (ECS) with respect to causes and indicated corrective or preventative action. In addition, condensation on structure will be reviewed with possible preventative action described.

1.1 Purpose

This publication will discuss water carryover from the environmental control system and condensation on structures, with the following purpose:

- a. To define sources of water that may cause condensation in the aircraft.
- b. To outline means for minimizing or controlling the condensate.

1.2 Field of Application

The material presented herein is primarily applicable to multi-engine transport airplanes, but in some cases may apply to other types of aircraft, military or civil.

2. REFERENCES

All pertinent and/or reference documents are listed herein.

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale PA 15096-001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

AIR1609	Aircraft Humidification
ARP147	Environmental Control Systems Terminology
ARP987	The Control of Excess Humidity in Avionics Cooling

Proceeds of Moisture Ingress in Aircraft Insulation Symposium, Abbotsford BC Canada, August 5 1993, sponsored by SAE Aerospace Continuing Professional Development Group

3. BACKGROUND

Uncontrolled moisture inside the fuselage of aircraft is a potential source of increased maintenance and expense to operators and can lead to complaints and ill will from passengers. Uncontrolled moisture can manifest itself in the following ways:

- a. Condensation dripping on passengers.
- b. Moist air condensing on exposed structure and on mechanical or electrical equipment. It can also become trapped and be subjected to freezing due to subsequent temperature reduction.
- c. Structural corrosion, electrical shorts, insulating material weight increase and loss of insulating properties result from this water accumulation.

4. CAUSES OF WATER CONDENSATE

The sources of excess moisture within an aircraft can include the Environmental Control System (ECS), condensation on cold surfaces, occupants and humidification systems.

4.1 Environmental Control System

The ECS can cause uncontrolled water condensation in the following ways:

4.1.1 Entrained Moisture from the ECS Refrigeration Unit

Inefficient water separation in the ECS results in carryover of water condensate and humid air into the cabin. This problem is commonly associated with air cycle refrigeration systems.

Low design efficiency, inadequate drainage systems or failure modes of water collectors or separators will produce an unnecessarily large carryover of entrained water in the form of fog or water droplets and occasionally ice particles. Some of this water settles out in low points throughout the ducting system, including overhead areas. From there, it may accumulate until its volume, airplane attitude, etc. may cause sudden spilling of large amounts of water into the cabin, or it may subsequently re-evaporate when the supply air is less than saturated.

Visible fog streamers can occur at cold air outlets during high humidity conditions. Formation of these streamers which is usually a result of entrained moisture in the conditioned cabin supply air in conjunction with supply air temperature is cooler than the dew point at the surrounding cabin pressure.

4.1.2 Moist Air Bypassing Water Removal Devices

The air entering the cabin is not dehumidified unless it passes through the refrigeration unit and the water separator or collector. For temperature control, some refrigeration cycles bypass a portion of the hot supply air around the refrigeration unit and mix it with the refrigerated air downstream. This bypassed air, therefore, adds to the moisture left in refrigerated air that is due to the normal water separator design inefficiencies. It should be pointed out that the proportion of bypassed air to the total air is small, particularly on hot humid days at low altitudes, where maximum refrigeration is required. However, on a humid day with cooler or moderate temperature, the moisture from the bypass air will cause higher compartment humidity. As the altitude is increased and the supply air becomes colder, more air bypasses the refrigeration package. Note that the supply air becomes dryer as altitude increases. Refrigeration cycles that bypass air around the water removal devices include the conventional chilled-recirculation systems used on A320 and 767-200/300. Refrigeration cycles that do not bypass the water removal devices include the simple/bootstrap system on 747-400 and the condensing cycle system used on 777 and 767-400.

4.1.3 Low-pressure Water Separation Anomalies

Water separator anti-icing systems may malfunction or be set to maintain temperatures too close to the freezing point. In the latter case, normal control tolerances can cause continuous or intermittent freezing. Freezing of the water separator forces the moisture laden supply air through the relief valve bypass system introducing moisture in the form of water droplets and/or fog into the cabin and into direct air cooled electronic equipment. Undersized water drains plugged with lint, dirt, etc. can severely degrade low pressure water separator effectiveness.

4.1.4 Liquid Water Accumulation

Liquid water can accumulate in low points of air conditioning distribution ducting systems, pack discharge or other ducts that encounter free moisture - especially after system shutdown on the ground. To preclude this accumulation, drains should be placed at low points of ducting systems in which entrained moisture is present.

Drains should be oversized to avoid blockage. Drain hole sizes of about 3.1 mm (0.125 in.) diameter have been found to be acceptable for large commercial installations, but drain sizes should be established and verified for each application without the requirement for periodic servicing of the drain. Drains should carry water to a location where the water can go overboard. Drained water should be prevented from coming into contact with equipment that can be harmed by water.

4.2 Condensation on Cold Surfaces

Condensation forms on parts of the cold air outlets where cabin air comes in contact with cold, high conductivity (usually metal) parts. Condensation forms when relatively warm, moist ambient air comes in contact with chilled cold air ducts which are not insulated or insufficiently insulated.

4.2.1 Structural Condensation

Most condensation on the airplane structure occurs during flight when the temperature of both the outside air and the structure are very cold. Structure temperatures are usually below the dew point of the cabin air, causing condensation to form during most flights. In addition, because structure temperatures are normally below the freezing point of water, most condensation forms as frost.

Condensation results when moist air moves to the cold structure. The cabin air passes through small gaps in the insulation coverage and cools rapidly. Buoyancy forces induce a continuous flow of air and continuous movement of moisture to the cold structure.

The rate of condensation depends on the rate of buoyancy-driven air movement to the structure as well as the cabin humidity level. In-flight cabin humidity levels are low from a standpoint of human comfort (approximately 10 to 20 percent relative humidity, depending on flight conditions and occupant loading). However, the dew point of cabin air is much higher than aircraft skin temperature and most of the moisture it contains will condense as air moves over the cold structure.

Structure directly connected to the (cold) outer skin is the prime area of condensation. Leaking cold air ducting joints can also reduce the temperature of adjacent surfaces and result in condensation.

Structural or insulation blanket condensation occurs where virtually trapped volumes obtain moisture at sea level and are subject to subsequent cold soaking at altitude.

4.3 Humidifiers

Humidifiers can be a source of condensate, particularly if they are improperly operated. Operation of humidifiers at high altitude can result in frost build-up on cold structure. As the airplane descends increased temperatures and aircraft attitude changes can result in water dripping in occupied compartments.

4.4 Occupants

Human occupant metabolic activity is a source of moisture in aircraft cabins. Certain cargo such as agricultural products or animals can also contribute to moisture problems.

5. EFFECTS OF WATER CONDENSATE

Water condensation within the aircraft affects many areas such as ECS, window fogging, structure, along with other items described in following paragraphs.

5.1 Environmental Control System

The effects of excess water from the ECS are summarized in this sub-section:

5.1.1 Rain-in-the-plane

Water droplets discharged into the cabin from the ECS can spatter passengers and interior trim, which may stain clothing and cabin finish. Re-evaporation of this water into the cabin air adds to the humidity of the cabin. Condensate forming on parts of the cold air outlets or structure may also drip on passengers and interior trim with the same effects. This dripping in the cabin is often referred to as "rain-in-the-plane".

5.1.2 Damage to ECS Equipment

Besides general corrosion concerns, slugs of liquid water ingested by rotating equipment, such as ACM turbines, can cause component failure. In some cases, air bearings within the ECS pack may be affected by condensate, resulting in excessively high starting torque, which may prevent the air cycle machine from functioning.

ECS components should be designed to be robust and tolerant of liquid water ingestion, while at the same time the system should be designed to safely manage and control any liquid water generated within the system.

5.1.3 Collateral Damage to Equipment

Free moisture in the electrical equipment cooling air supplied by the ECS can cause electrical shorts and equipment failures.

5.2 Window Visibility

Condensation may result in fogging of windows that may impair visibility.

5.3 Structural Condensation

The effects of moisture caused by structural condensation are as follows:

5.3.1 Wet Insulation Blankets

Condensation on structural members runs down onto the insulation blankets and soaks into the insulation at improperly made joints and/or tears in the cover. Absorption of the condensate into the insulation results in appreciable increase in aircraft weight, and in a significant loss of insulation characteristics.

5.3.2 Water/Ice Accumulation in Bilge

Condensation on structure protruding through the blankets or on exposed skin will also find its way down to pockets in structure causing structural corrosion. During high-altitude flight, the accumulated water can freeze. When the aircraft is subjected to repetitive use, the ice may not completely melt while the airplane is on the ground. Water accumulation from subsequent flights can cause the ice build-up to increase in size and could result in a significant increase in aircraft weight.

5.3.3 Overboard Icing

Condensate drained overboard can freeze and subsequently break off as ice particles that may damage engine, instrumentation probes or flight control surfaces.

5.3.4 Rain-in-the-plane

Water drippage during descent can occur due to the melting of frost on the interior of the aircraft skin. While most of this resulting water will drain down to the bilge, some can get inboard of the blankets and drip into the cabin, having the same effects on the passenger cabin as mentioned in paragraph 5.1.1 but from a different source.

6. CONTROL OF EXCESS MOISTURE

Excess moisture within the aircraft can be mitigated by proper ECS and humidifier design and operation, and by proper design of aircraft structure and moisture control features.

6.1 Environmental Control System Water Carryover

To prevent environmental control system water carryover, one must provide a water removal system which has high efficiency, high reliability and is readily maintainable. This section provides suggestions to limit moisture problems caused by the ECS.

6.1.1 General ECS Suggestions

The following items apply to both air and vapor cycle systems:

6.1.1.1 Auxiliary Drain

Provide traps and drains not only at the low points but also throughout the ducting system between the separator and the cabin. Downstream drains should be designed for very high liquid water contents such as those resulting from a blocked water separator coalescer (open relief valve).

6.1.1.2 Cold Air Discharges

Use nonmetallic materials for cold air duct outlets where possible and insulate any metal cold air ducts to preclude ambient air contact with the bare metal. It is desirable to place air discharge points where water carryover will not drip on passengers or avionics in the event of a malfunction of the water removal system.

6.1.1.3 Pneumatic Sense Lines

Water accumulation in ECS sense lines can cause equipment to operate improperly. In particular, the pneumatic signal to a sensor or pneumatic actuator may be lost if water trapped in a sense line freezes. This could lead to system failure. To prevent problems, sense lines should be routed and oriented so low points or water "traps" are avoided. If necessary, drains may be used in the sense lines. These can include pressure-operated plugs that would close and not allow leakage during system operation, but would open and allow drainage with the system in a quiescent state.

6.1.2 Air Cycle Systems

For air cycle ECS, there are two basic types of water removal systems. The first type is a low pressure water separator, which removes free moisture downstream of the cooling turbine. An example of a low pressure water separator system is shown schematically in Figure 1. The second type is a high pressure water collector, which removes free moisture upstream of the cooling turbine. An example schematic of a high pressure water collector system is provided on Figure 2.

6.1.2.1 Low Pressure Water Separators

Low pressure water separation systems have been in existence since the first air cycle environmental control systems. Today, high pressure water collector systems tend to be preferred for new designs. However, low pressure water separator systems are still in widespread use.

If moisture is present in the high pressure supply air (for example, ground operation), air leaving the cooling turbine will contain free moisture. The free moisture leaving the turbine will always be in the form of very small droplets and will appear fog-like. A low pressure water separation system uses a water separator that coalesces the very small droplets into larger ones that can be centrifugally collected and removed from the air stream. Turning vanes within the water separator are typically used to impart a swirl to the air. The low pressure water separator uses a coalescing element that is made from fabric or fine mesh. A sump is generally provided to collect the droplets of water, and the water is drained from the sump. The water can simply be dumped overboard, but is generally sprayed on the heat exchanger core face to enhance cycle efficiency. To do this, an aspirator or other means of pumping the water is required, because the water is not under pressure.

“Ice screens” are sometimes employed to collect ice and snow and help prevent it from going into the cockpit or avionics. As the ice accumulates, the flow resistance increases, which backpressures the turbine and causes the turbine outlet temperature to increase. In early air cycle systems, ice screens were used in place of temperature controls so the system would intentionally backpressure deice itself. Water carryover problems are expected with systems of this type.

To prevent freezing of the coalescer element, the low pressure water separator system turbine exit is typically limited to a minimum temperature of 1.7 °C (35 °F).

Advantages of the low pressure water separator system are as follows:

- a. Simplicity – the low pressure water separator system has fewer components than a high pressure water collector system. The only control required is a temperature control to prevent the turbine outlet air from freezing.
- b. Light weight – for equal flow rates, the low pressure water separator system is lighter than the high pressure system. For applications where the air change rate rather than the heat load sets system capacity, the low pressure system may be the appropriate choice. In this case, one couldn't make use of one of the chief advantages of the high pressure water collector system – the ability to achieve higher specific cooling capacity via sub-freezing conditioned air discharge temperatures.

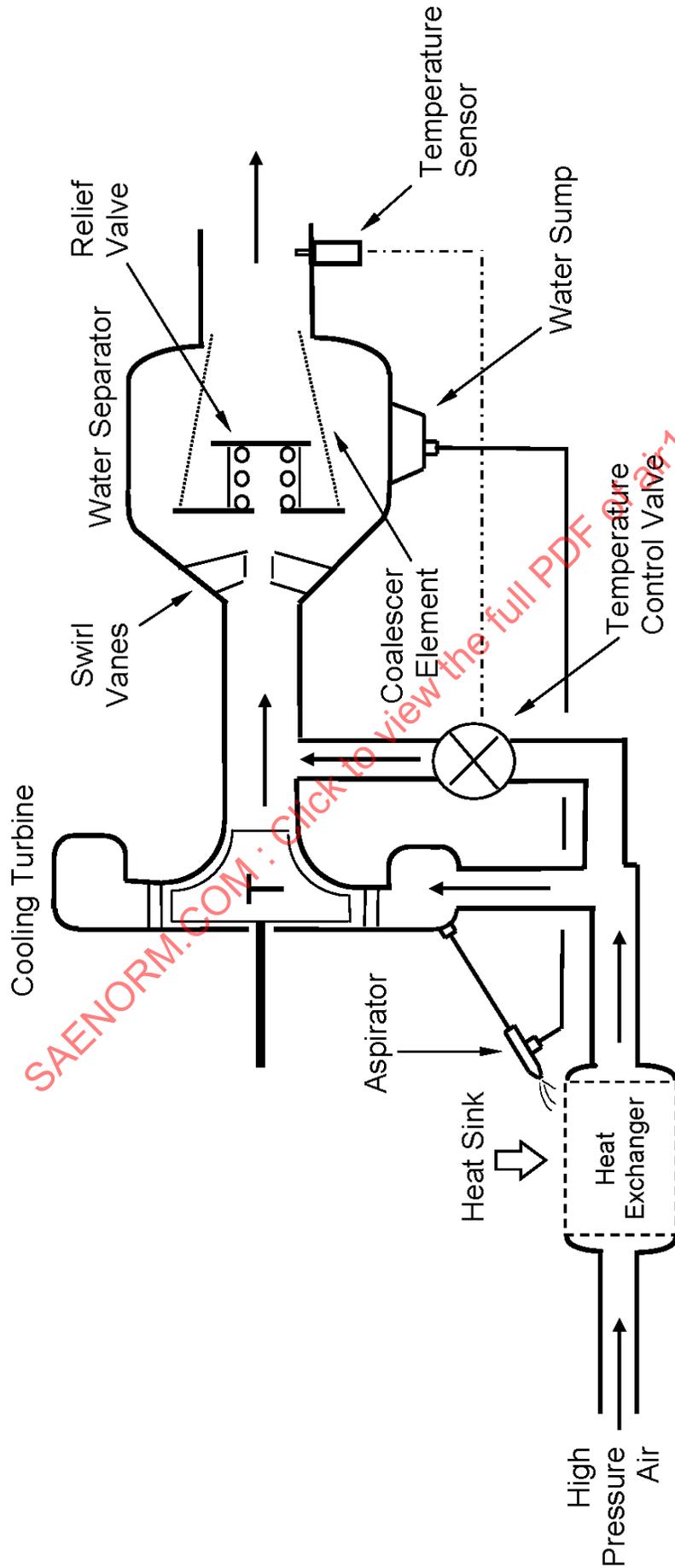


FIGURE 1 – LOW PRESSURE WATER SEPARATOR ECS

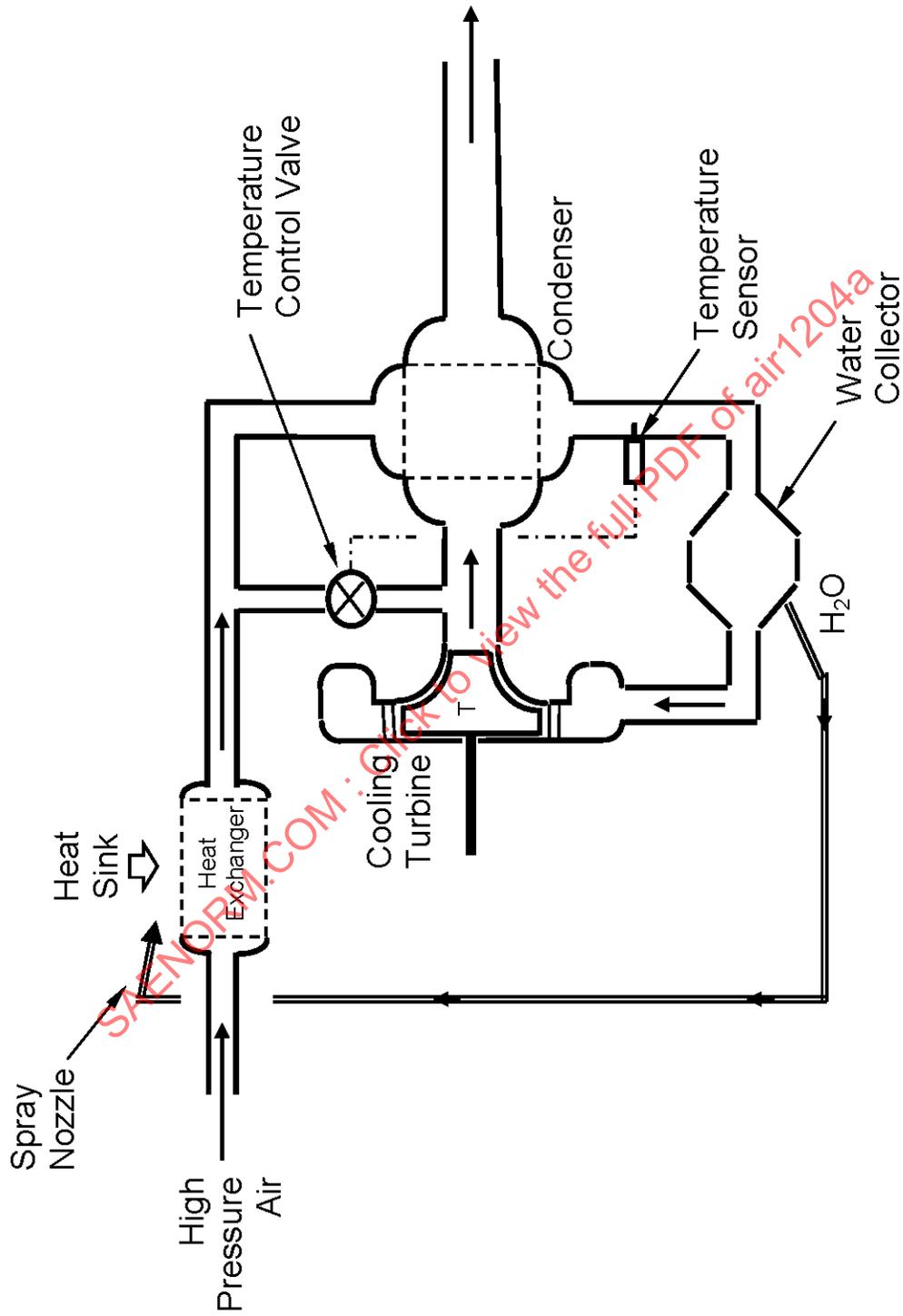


FIGURE 2 – HIGH PRESSURE WATER COLLECTION SYSTEM

To avoid water carryover problems within low-pressure water separator systems, the following suggestions are provided:

- a. The water separator anti-icing system should ensure reliable performance in all operating modes of the ECS without interaction with the relief valve.
- b. Coalescers should have a low tendency to collect dirt or to mat. Coalescer materials should be selected which will not shed particles that could cause blockage of the drain. Synthetic fibers in a low pressure drop weave have been found to appropriately meet these requirements while maintaining high coalescer efficiencies.
- c. Settings of pressure differential anti-ice controls and relief valves must take into account an increase in coalescer pressure drop as a function of time due to dirt and other contamination.
- d. Drains should have excess capacity to allow for partial blockage and to ensure rapid and complete drainage of the separator sump, thereby precluding water "spatter" from the sump into the downstream duct system.
- e. Drain lines should not have low points where the water can be trapped and frozen, and the drain should discharge into an area where the temperature is above freezing. If drain lines cannot be located in heated areas, heating the lines should be considered.
- f. Ensure that the drain discharges to an area that is at a lower pressure than the drain inlet pressure for both static and flight operation.
- g. Sensing elements for anti-icing systems should be sealed so that large quantities of water impinging on the sensors will not adversely affect their operation.
- h. The cabin air distribution system ducting should be water-tight and completely insulated, including the duct connectors.
- i. In the event of a malfunction of the anti-icing system, the bypass relief valve should be designed to be fully operable during icing conditions.
- j. Provide means for rapid and easy inspection and maintenance of the separator. Coalescers become clogged with dirt forcing the air to bypass, thereby reducing the effectiveness of the unit.
- k. Integral bypass valves (within the water separator) should be designed to preclude sticking open.
- l. Means for ready and simple checking of separator effectiveness, such as separator pressure drop and temperature ranges, should be provided to ensure early detection of problem areas.

Water separators should be designed for rapid and easy changing of components such as coalescer bags.

Coalescer cleaning is usually required after 300-500 hr of use, but each operator, on the basis of the operator's own experience, should determine a specific interval. Replacement coalescer elements not made to the water separator specification shall not have excessive pressure drop that would overlap anti-ice control or relief valve settings.

6.1.2.2 High Pressure Water Collectors

The high pressure water collector has been adopted for most new aircraft designs. This is because the maintenance required of the low pressure water separator coalescer element is eliminated, and the high-pressure system offers greater cooling capacity per unit of bleed air. A functional schematic of a simplified high-pressure water collector system is shown in Figure 2.

Unlike the low pressure water separator system, high pressure water collection takes place upstream of the cooling turbine. Typically, after leaving the secondary heat exchanger, the air is further cooled in the condenser. The condenser is a heat exchanger that typically uses turbine discharge air to cool turbine inlet air. After the turbine inlet air is cooled, the water condenses in droplets that are mechanically removed via centrifugal means. The collected water exits the collector under pressure and is usually sprayed on the pack heat exchanger using a spray nozzle.

Advantages of the high pressure water collector system are as follows:

- a. Drier air - The system can be sized to provide drier air than is possible with a low pressure water separator system.
- b. More cooling per unit of bleed air - Sub-freezing discharge temperature can be achieved if the system is sized accordingly. This provides more cooling capacity than the low pressure system, without increasing the system mass flow rate.
- c. Reduced maintenance - Maintenance is reduced as coalescer elements do not have to be provisioned since a coalescer is not required.

To avoid water carryover problems with high pressure systems, the following suggestions are provided:

- a. High pressure spray nozzles have smaller water passages than low pressure aspirators and are subject to clogging. Filters can be used in the water line just upstream of the nozzle. If the water circuit becomes clogged or frozen, provisions should be incorporated to prevent water carryover to the air cycle machine that could result in damage. Note that if the water collector allows liquid water to enter the turbine, air cycle machine damage can result.
- b. Duct geometry and air velocities must be taken into account when designing the water collector and associated swirl vanes. Performance of the water collector should be verified using a test setup that duplicates duct routing and installation orientation, and a full range of normal and failure cases should be tested.
- c. Note that the worst case water removal condition may not be at the worst case hot day thermal design point. Performance for off-design cases with cooler humid day conditions should also be evaluated.
- d. Also note that water condensation can occur in the secondary (main) heat exchanger. This may occur during ground operation on cooler humid days, or in flight at intermediate altitudes such as for hold or diverting cruise conditions. Appropriate water collection and extraction devices should be placed at the secondary heat exchanger outlet.
- e. The outer surfaces of certain components on a high pressure water collector pack can be sub-freezing, and can be subject to condensation. Cooling pack installation and aircraft structure in the vicinity of cold areas of the pack should be designed to ensure adequate collection and drainage of this condensed water.
- f. High pressure water collectors are often equipped with a water overflow port to prevent water ingestion into the ACM when the water spray nozzle is clogged. Since this is a latent failure, the system must be designed to operate properly in this condition.

6.1.3 Vapor Cycle Systems

An advantage of vapor cycle systems is that the evaporator can be located in the pressurized area of the aircraft, so recirculated air as well as the bleed (outside) air can be readily chilled. Thus, more complete dehumidification of cabin inlet air can be obtained by refrigeration of all cabin inlet air (fresh and recirc). Examples of this type of system are found on the Cessna Mustang and on the Convair 880 and 990.

Water droplets condensing on the evaporator coil can become entrained in the airflow and carried into the ducts and outlets. Entrained moisture carryover ("spitting") can be eliminated by:

- a. Using a sump and drain on the air side of the evaporator to catch and remove condensation.
- b. Designing and orienting the evaporator coil to collect and drain condensation on the back side of vertical refrigerant tubes.
- c. Reducing the velocity of air through the evaporator so that water droplets settle into the sump.
- d. Adjusting the angle of the evaporator outlet duct, or using baffles to return water droplets exiting the evaporator to the sump.