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VAPOR CYCLE VERSUS AIR CYCLE ENVIRONMENTAL CONTROL SYSTEM SELECTION CRITERIA ON MODERN HELICOPTERS

by

Achille MANNINI

MICROTECNICA S.p.A. - TORINO (ITALY)

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ABSTRACT

Minimum Weight, together with High Reliability and Good Performance, is very often one of the most stringent criteria in the selection of an Environmental Control System for an aircraft (air plane or helicopter).
From this point of view, the systems based on air cycle solution are usually lighter than those based on vapor cycle; moreover, the air cycle system is the typical and well known solution of virtually any airborne application. Therefore, also for installation on the helicopters, the same air cycle systems developed for air planes are usually considered.
However, if in the selection process the target is not the minimum system weight itself, but, as more appropriate, the minimum payload penalty deriving from the operation of the ECS and its impact on the engine performance, fuel consumption and aircraft configuration for a datum mission profile, the selection of the best ECS is not so immediate because a lighter system could be more penalising than a heavier one on the aspect of the total payload.
General rules and considerations for the comparison of typical air cycle and vapor cycle systems are given in this paper together with an example of evaluation of the payload penalty for a helicopter having known carachteristics.

1. Introduction

The Environmental Control of cabins and cockpits is a normal practice on several modern aircraft. All new air planes are equipped with such systems and also on the modern helicopters an air conditioning is very often requested.

As far as the helicopter application is concerned, the same solutions developed for the air planes have been usually considered, which, in the most cases, are based on air cycle. Some time, also vapor cycle ECS have been adopted, as derived from other applications (not necessarily airborne). Therefore these systems are never optimised considering the helicopter peculiarities.

The recent renewed interest in the vapor cycle ECS in airborne applications gives the designer the opportunity to consider also the modern vapor cycle solution in the selection of the most suitable ECS for a new helicopter, selecting the right solution for the need of minimum weight, size and, first of all, minimum pay load penalty, which is one of the most demanding requirement of a helicopter.

2. ECS for helicopters and for air planes

Several reasons explain why the ECS is always useful and often needed on board of a modern helicopter.

The most obvious is the crew and passenger comfort. In fact the aircraft shall be able to operate from extreme cold environment to the extreme hot one.

Of course, if the operation of the helicopter is restricted to the medium/cold temperatures, just the heating system can be sufficient. This could be done either simply bleeding an amount of hot compressed air from the aircraft engine (if the bleed is available) or using a burner or an electric heater.

If the mission includes operations in hot ambient temperatures, a cooling system is needed. Such equipment is necessary for the comfort and is essential for the safety too because it helps the crew in keeping their reflexes ready in any emergency case and guarantees the reliability of the avionic equipment which is becoming responsible of several safety functions on a modern helicopter.

In the selection of the most suitable ECS for a helicopter, several differences between the air planes and the helicopters must be taken into account. These often lead to the fact that a very good system developed for an air plane is not necessarily the best choice for a helicopter.

In order to demonstrate and understand this fact, the main differences between an air plane and a helicopter will be discussed herein.

<u>Cabin</u> <u>Pressurisation</u>: Modern air planes (both military and commercial) are always pressurised. This is done by bleeding air from a suitable engine compressor stage and introducing it into the cabin, controlled by a dedicated valve system. Of course, before to introduce it into the cabin ducts, the air temperature shall be greatly reduced and controlled.
This is the linkage between the Pressurisation System and the Air Conditioning system for an air plane.

The helicopters, on the other hand, are usually not pressurised, or, if any, the pressurisation consists in the order of few Pa which are requested in order to avoid the contamination of the cabin from sand, dust or other pollutants. In this case, the compressed air bleed is not needed and a powerfull fan is sufficient, provided that the helicopter cabin has a suitable sealing characteristic.

Fresh air ventilation: The modern regulations applicable to the airborne air conditioning systems require that a not negligible amount of fresh air, taken from the outside ambient, is introduced into the cabin and mixed with the conditioned recirculating air. On the commercial transport aircraft, the amount of the fresh air, bled from the engine, is 1/2 to 2/3 of the total cabin flow. In these cases, this is the driving parameter (much bigger than the flow requested for the pressurisation) in the selection and sizing of the ECS.

The same rules apply to both air planes and helicopters; however the main difference is that in a pressurised air plane the "fresh" air shall be bled from the engine at some hundreds °C, while in a helicopter it can be taken directly from outside at few tens °C of difference respect to the cabin temperature. This, of course, has a big impact on the selection and sizing of the ECS that shall process the ventilation air before to introduce it into the cabin ducts.

Power Consumption and Aircraft Performance. ECS have energetic costs with important impact on the aircraft performance. This derives from the amount of the energy which is bled from the engine or in terms of air bleed or as power extracted from a gearbox; in both cases this is a not negligible amount of power payed in terms of fuel and diverted from the propulsion to the Air Conditioning System.

It is known that the performances of the turboshaft engines installed on the helicopters are greatly sensitive to the air bleeds, much more than the turbojet engines installed on the air planes. For this reason very often the engine bleed is not available on the helicopters or, if any, it is a small amount sufficient just for heating purposes. Instead of the bleed, on the helicopters a mechanical pad on the gearbox is available for driving an ECS dedicated compressor.

Using this power available on the gearbox, any kind of compressor, in principle, could be driven (air or refrigerant fluid), therefore either air cycle or vapor cycle solutions could be suitable. For the right system selection it is mandatory to evaluate the fuel consumption deriving from the ECS operation and its impact on the aircraft performance (pay load, operative range, etc.).

Instead of a mechanical driven compressor, of course also electrically driven compressors (hermetic or open) can be considered; however, also in this case the energy balance and the related fuel consumption shall be taken into account.

System weight and payload. Any airborne application is sensitive to the weight due to the very close correlation between the equipment weight and the payload. This is always true, even if with different emphasis, depending case by case on the balance of costs of a heavy versus a light equipment. However, for a helicopter this is particularly true and very often critical.

It must be pointed out that, speaking about the weight of an equipment and its impact on the aircraft payload, the evaluation should be based not only on the weight, but also in the same time should include important considerations on the power spent for the operation of the system itself.

Therefore, it could happen (and it shall be checked case by case) that a heavier equipment, but requiring lower power consumption, is more convenient in terms of aircraft payload, than a lighter one which requires higher power consumption.

Installation, environmental factors, ECS reliability. The very different basic mechanical arrangements of the helicopters and the air planes can lead to different problems and requirements for the ECS. The vibratory environment of a helicopter is typically more severe than an aircraft. An other important aspect of the installation consists in the possibility to have a package or separately installed components.

The consideration of the installation characteristics and the evaluation of their impact on the sealing capability of the ECS, is very important in the selection of the system type, bearing in mind that the reliability of a vapor cycle system is much more leakage sensitive than an air cycle.

3. Environmental Control System schematics

Many schematics are available which meet the different requirements of several airborne applications. Each solution can be modified and optimised; however, keeping in mind the purpose of this paper which is a general information and first orientation of the engineer in the preliminary feasibility study for a helicopter ECS, a Vapor Cycle solution will be compared with the Air Cycle which could a turbofan, a bootstrap or a 3-wheel.

Moreover, all the air cycle systems can be directly fed by engine bleed driven by a gearbox or hydraulically or electrically driven.

As far as the vapor cycle systems are concerned, they can be of different types (open or closed loops). Several kinds of refrigerant compressors are available: centrifugal, screw, rotative, scroll; reciprocating; also these compressors, like the air compressors, can be driven mechanically, electrically or hydraulically.

In fig. 3-1 the solutions discussed herein are shown in graphic form.

In Table 3-I the various solutions are compared each other under several aspects and criteria: power consumption (COP), installation, weight, reliability, pull down performance.

4. Selection of the ECS for a datum helicopter application.

Let's consider now, as application case, an ECS for a two seat helicopter having the carachteristics reported in the following Table 4-I.
No engine bleed is available in quantity sufficient to feed an air cycle system. To this purpose, certain amount of mechanical power, to drive a dedicated compressor, is available from the transmission gearbox.

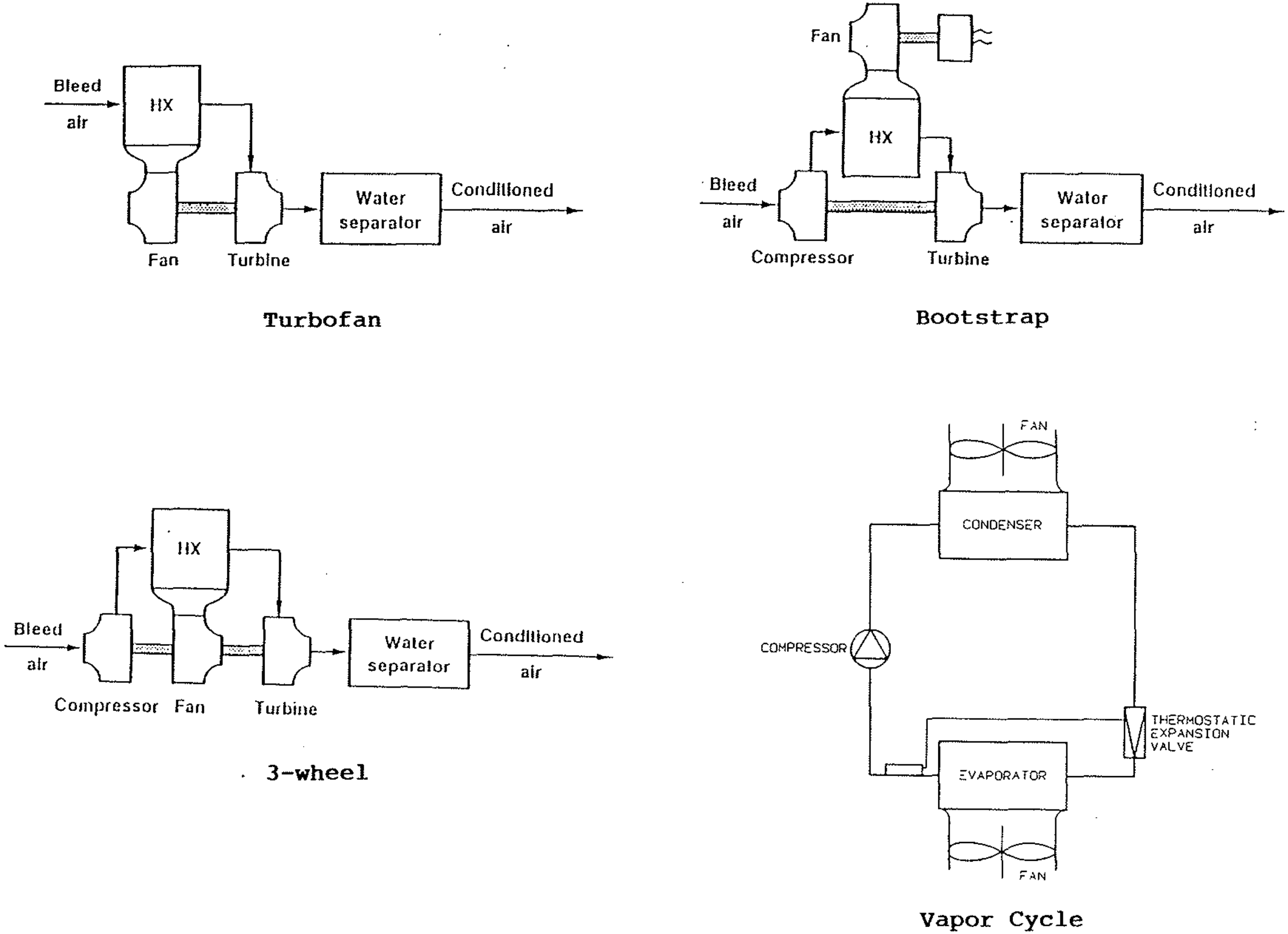


Fig. 3-1 Basic ECS Schematics

	Turbofan	Bootstrap	3-wheel	Vapor cycle
Coefficient of Performance	poor	better	better	excellent
Installation	excellent	better	good	good
Weight	excellent	good	better	poor
Tolerance to Leakages	good	good	good	poor
Pull down Performance	good	good	good	excellent

Table 3-I

ECS Comparison

Ambient temperature ...	50	°C
Ambient humidity	40.3	g/kg
Number of crew members...	2	
Ventilation air flow ..	34	m3/h
Cabin temperature	27	°C
Cabin humidity	7.5	g/kg
Total Heat Load	9700	W

Table 4-I
Sample case carachteristics

Of course, for this modern application, the equipment that we are looking for shall have a "state of the art" technology ad shall give the requested performance with the minimum penalty in terms of payload.
The basic question concerns the best system philosophy: air cycle or vapor cycle? In our case, the main selection criterium consists in the evaluation of both equipment weight and related absorbed power.

The comparison should be done among all the solutions listed in Fig. 3-1 but, for ease of exemplification, we can limit the exercise to a vapor cycle and an air cycle 3-wheel type.

4.1 Air Cycle System

In fact the first selection of the 3-wheel among the air cycle solution can be done by means of the following qualitative considerations.

The Turbofan type should be discarded because it requires a higher energy consumption than the other air cycles. This inherent drawback is magnified in our case by the non availability of the engine bleed. For this reason, the air compressor, which is in any case needed also for the 3-wheel, should have higher pressure ratio and shaft power, which increases the payload penalty.

Compressor air flow	0.30	kg/s
Compressor pressure ratio	3.74	
Compressor mechanical power	66	kW
Cabin air flow	0.31	kg/s
Cabin temperature	27	°C
Thermal capacity	9700	W
COPO.	15	
System weight	52	kg

Table 4.1-I

Air cycle 3-wheel ECS Performance

Comparing the Bootstrap with the 3-wheel solution, we can say that the last one has a lighter or equivalent weight to the Bootstrap; in terms of total absorbed power (including air compressor and fans) they are almost equivalent, but in terms of reliability the 3-wheel is preferred due to the absence of the fan of the heat exchanger which is included in the Air Cycle Machine.

For the above reasons, the 3-wheel schematic has been preferred among the air cycle solutions.

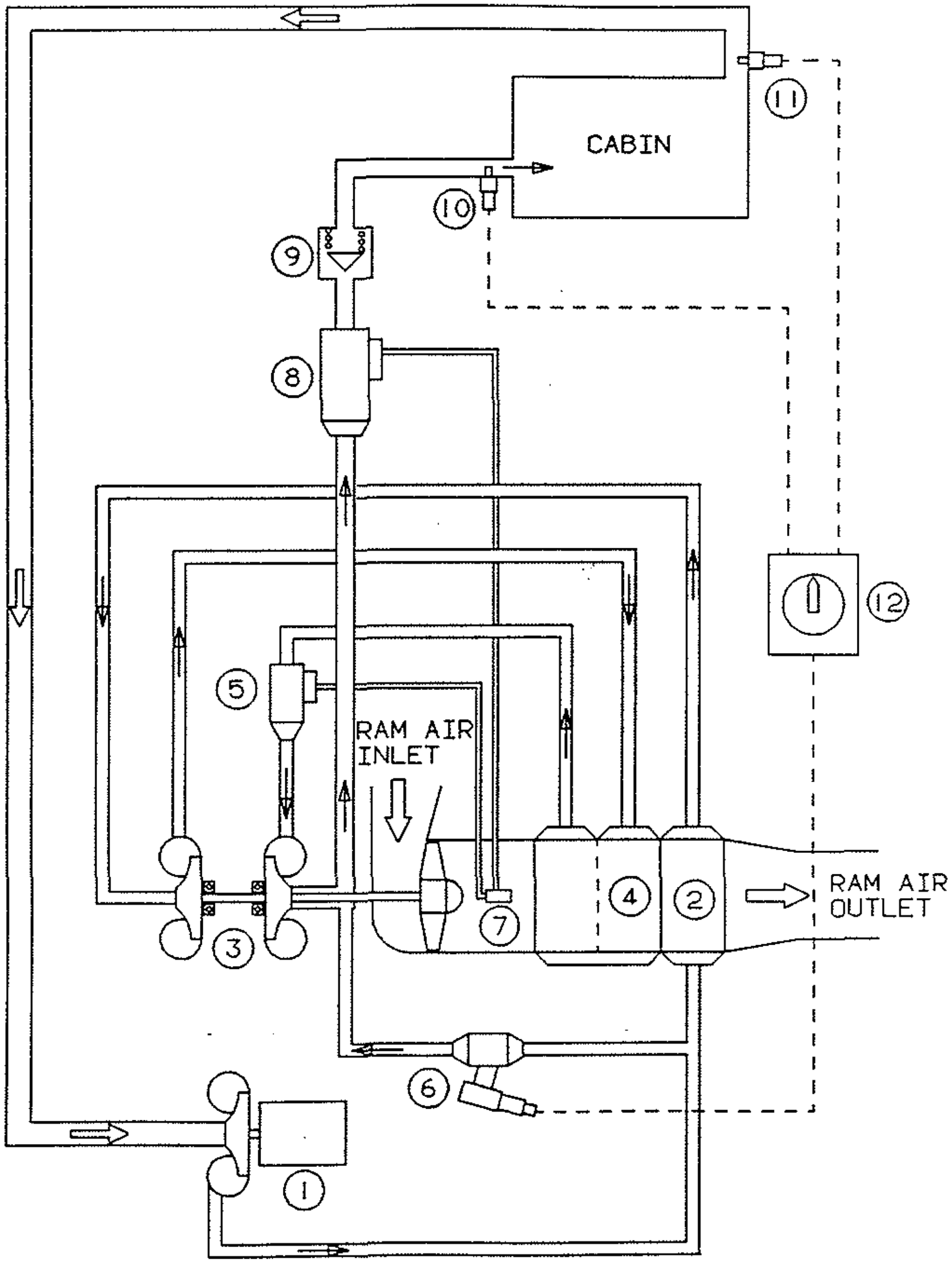
The schematic of the 3-wheel system suitable for our application is shown in Fig. 4.1-1; the leading system performance parameters are reported in Table 4.1-I.
It is important to note that, even if the weight is quite interesting the power requested by the compressor is quite high.

For this reason, the Coefficient of Performance, which is the ratio between the system cooling capacity and the compressor shaft power, is only 0.15.
If the engine bleed was available, the relevant situation would be better than the solution just now discussed as far as weight and reliability are concerned (because the shaft driven compressor is no longer needed). However, it would be even worst from the energetic point of view because the bleed from the engine is causeof unbalance between the compressor and the turbine; this penalises the propulsion more than the mechanical power extraction from the gearbox.

4.2 Vapor Cycle System

Let us evaluate now the vapor cycle solution. As refrigerant fluid we will adopt HFC-134a which has replaced CFC-12 in its air conditioning applications. Other fluids are presently under development which in the future should replace the HFC-134a itself because like this one they have Non Ozone Depletion Potential and moreover have lower Warming Potential. However, at present HFC-134a is the most common and known replacement of CFC-12.

Several kinds of refrigerant compressors for airborne applications are presently available on the market. They are the following: screw, rotative, piston, scroll, centrifugal. Each type has a recommended range of operation,



1. Compressor
2. Primary Heat Exchanger
3. Air Cycle Machine
4. Secondary Heat Exchanger
5. High Pressure Water Separator
6. Motorized Valve
7. Water Spray Nozzle
8. Low Pressure Water Separator
9. Non Return Valve
10. Temperature Sensor
11. Temperature Sensor
12. Temperature Controller/Selector

Fig. 4.1-1 3-wheel SystemSchematic

defined as speed, cooling capacity, evaporation and condensation temperatures. For the purpose of our exercise, we will select the compressor assuming that, in order to save weight, the mechanical power available on the gearbox pad will be used. This solution, which of course is mandatory if other power sources like electrical or hydraulic are not available in sufficient amount, has also some drawbacks respect to the others. An electrically driven hermetic solution, for example, is more reliable from a system point of view because it has not the problem of the fluid leakages from the shaft seal. An other advantage of the electrically driven hermetic solution is the flexibility of installation which allows to find the most appropriate position of the compressor. Eventually, the electric or hydraulic driven compressor allows the on/off control of the system without any clutch on the compressor shaft which is often source of reliability problems.

The schematic of a vapor cycle ECS designed for our sample application is shown in Fig. 4.2-1; the main performance parameters are reported in Table 4.2-I.

Before comparing the results of the ECS air cycle with those of ECS vapor cycle, it must be noted that the cooling load for which the vapor cycle shall be designed is higher than the air cycle one by about 2 kW. This is due to the presence of the evaporator fan which activates the cabin circulation in the vapor cycle ECS, while in the previous air cycle solution the cabin circulation is provided by the compressor itself.

4.3 Discussion of the results

In comparing the Vapor Cycle versus Air Cycle ECS, the discussion, for our immediate purposes, will be restricted to their weight and to the related absorbed power. It is evident that, while the Air Cycle equipment is lighter than the Vapor Cycle, its power consumption is much higher. This is shown by the value of the Coefficient of Performance (COP) of both systems which is 0.59 for the Vapor Cycle and 0.15 for the Air Cycle.

The comparison has been done considering, for the vapor cycle ECS, the "Total COP" which is the ratio between the system cooling capacity and the total power consumption, corresponding to the sum of the compressor power and fan power. If the comparison had to be restricted just to the compressor power consumption in the two systems, the advantage of the vapor cycle would be even more evident, being the vapor cycle COP 1.5 against 0.15 for air cycle.

If some other criteria (for example installation problems) are not prevailing, for the selection of the most suitable system, the weight and the power consumption parameters shall be considered together in the payload penalty evaluation, as it will be shown in the next paragraph.
However, also some other considerations can play an important role in the system selection.

<u>Installation</u> Usually, the Air Cycle System is more easily installable then a Vapor Cycle. In the basic schematic, the number of components is lower than the Vapor

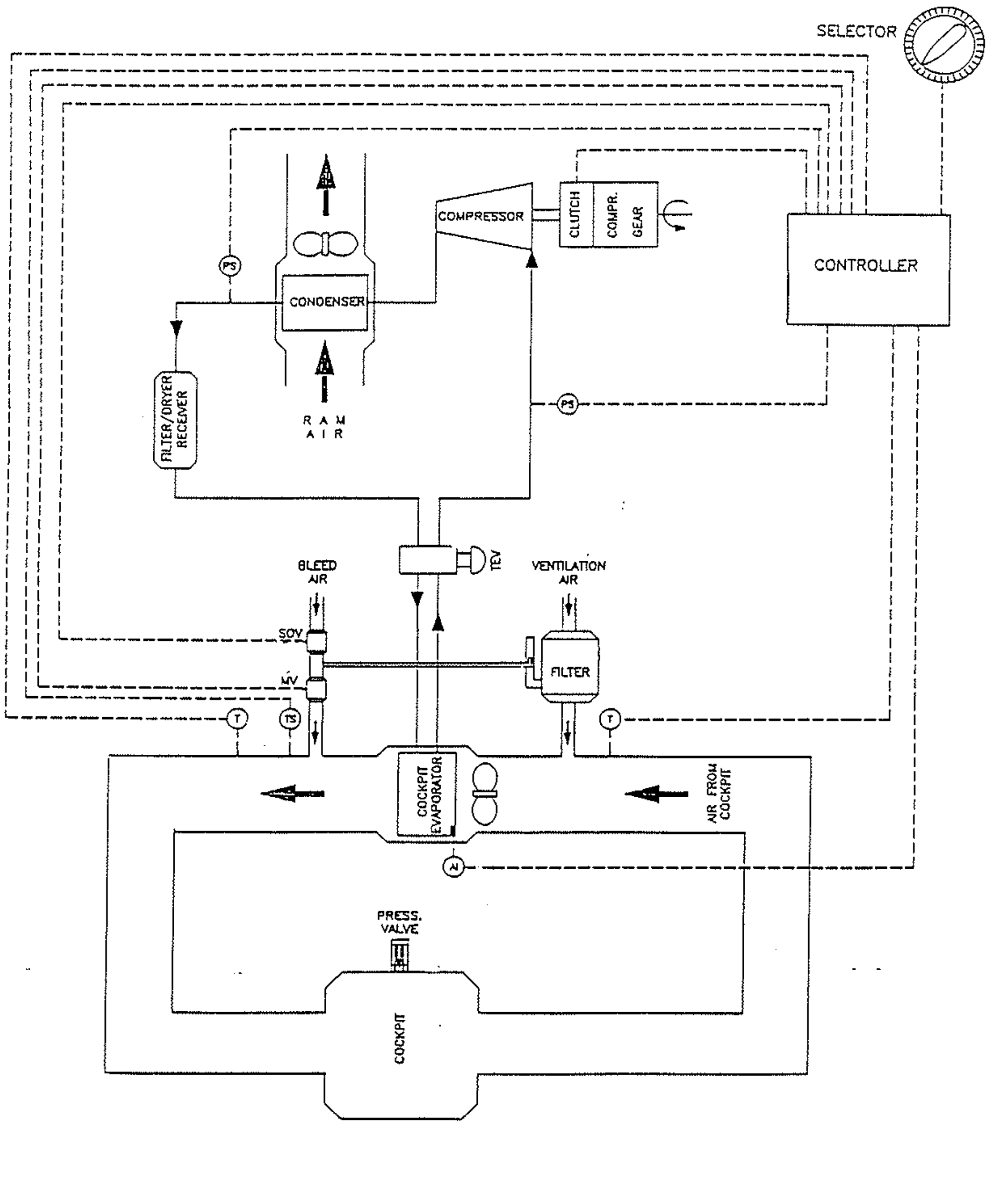


Fig. 4.2-1

Vapor Cycle System Schematic

Cabin air flow (total)	0.31	kg/s
Cabin temperature	27	C
Thermal capacity	11700	W
Compressor mechanical power	8.4	kW
COP (thermodynamic)	1.5	
COP (total)	0.59	
System weight	62	kg

Table 4.2-I
Vapor Cycle ECS leading parameters

Cycle. The Air Cycle System does not need any room available in the conditioned area, for the installation of the evaporator, expansion valve and fan; moreover, evaporators and condensers have a frontal area larger than the usual design of compact heat exchangers for air cycle system applications. This of course has an important effect on the installation

Some time the fan for the cabin air recirculation is not needed for the air cycle system, when the air recirculation is operated by the compressor itself. This is a not negligible advantage on the vapor cycle, as far the installation is concerned.

Reliability As we have already noted, most of the ECS applications on aircraft are based on Air Cycle type. Except a few well known cases, the equipment used in the airborne applications (general aviation air planes and helicopters) come from the automotive air conditioning market. The quite different environment of the helicopters (mainly the vibrations) has caused in the past some reliability problems to the vapor cycle equipment which have ingenerated a diffused feeling that the vapor cycle system is inherently less reliable than the air cycle. This is no longer true, at least for a couple of reasons:

- The Companies interested in this kind of products have developed and are developing the key components (compressors, heat exchangers, electric motors) using advanced airborne technologies.

- Also the Companies involved in automotive market are recently using high technology techniques, very often in advance on the aeronautical companies. The quality control and reliability concepts have become a must for this market, allowing an interesting growth of the technological content of the related products. Moreover, also the automotive Companies are interested in the development and production of more and more light and compact equipment, which therefore meet some of the basic requirements of the airborne applications.

Fluid leakages The Air Cycle Systems are more tolerant to the refrigerant leakages than the Vapor Cycles which loose very quickly their performance, while for Air Cycles just a deterioration happens. However, also this problem can be controlled by means of careful seal design and installation selection; a package solution, which allows shorter refrigerant pipes with lower number of joints, is helpful on this aspect.

5. Pay Load Penalty

After the separate calculation of the performance of a Vapor Cycle system and of an Air Cycle 3-wheel system, these two solutions have now to be evaluated, for the sample case selected, from the point of view of the payload penalty deriving from the use of the ECS.

In order to perform this exercise, a helicopter having the carachteristics shown in the table 5-I has been considered.

For the evaluation of the payload penalty, it has been assumed that the total weight of the helicopter at the take off must be kept constant; therefore, the payload reduction is given by the quantity of fuel consumed during the mission just for the ECS operation plus the weight of the system itself and the induced weight

Weight	3800	kg
Main Rotor Diameter....	11,9	m
Cruise Speed..........	270	km/h
Cruise Altitude......	2000	m
Mission duration........	2,5	h
SFC.................	0,35	kg/h/kW
Installed Power.....	1230	kW

Table 5-I
Helicopter's parameters

(i.e. the weight of the ducts, harnesses and other ancillary components not included in the value declared for the ECS weight, but in any case unavoidable for the system installation and operation).

$$Q_{payload} = Q_{fuel} + Q_{ecs} + Q_{ind}$$

The method discussed in ref.1 for the penalty evaluation on the air planes has been modified and adapted to the helicopters, using the criteria of "Operation Analysis" shown in ref. 2.

The weight and power parameters related to the two solutions under *evaluations are reported in the* Table 5-II.

Air cycle

System weight ....52 kg
Compressor Power ......66 kW

Vapor cycle

System weight ....62 kg
Compressor Power .....8,4 kW
Electric Power........5,5 kW
Power conversion efficiency......0,8

Induced weight

For Air and Vapor ECS ..8 kg

Table 5-II
Weight & Power Parameters

It must be noted that for the vapor cycle system an efficiency of 0.8 has been assumed for the electric generator in order to evaluate the power consumption *needed for the generation of the* electric power of the evaporator and condenser fans.

The method of the "Operations Analysis" applied to the helicopter parameters of Tab. 5-I, leads to the graphical correlation reported in Fig. 5-1 where the liaison between the total payload, the system weight and the absorbed power is shown.

In order to analyse more in detail the results of our comparison study, the splitting of the total penalty into the portions deriving

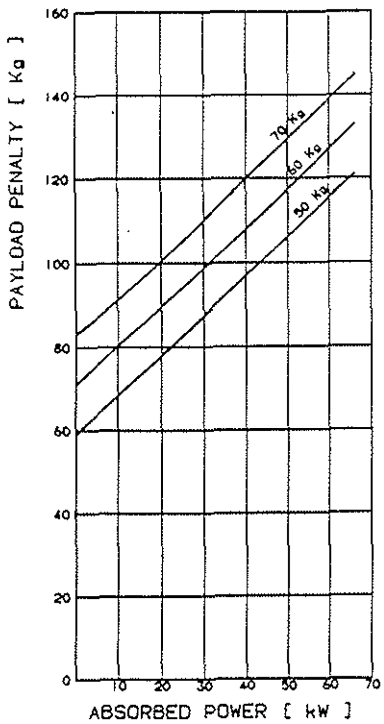


Fig. 5-1
Helicopter Pay Load penalty

Air cycle

Total absorbed Power ..... 66 kW

Total ECS Weight .... 60 kg
Penalty for weight .... 69 kg
Penalty for power .... 61 kg
Total penalty ....190 kg

Vapor cycle

Total absorbed Power ..... 15 kW

Total ECS Weight .... 72 kg
Penalty for weight .... 85 kg
Penalty for power ....15 kg
Total penalty ....172 kg

Table 5-III

Pay Load Penalty Analysis

from the weight of the ECS hardware and that connected to the power consumption is reported in table 5-III. In this table, under the label "Total ECS weight" the weight of the ECS hardware and the induced weight are included; under the definition "Total absorbed power" the compressor power and the mechanical power necessary for the generation of the electricity for fan driving are included. The "Total penalty" deriving from the ECS installation and operation is the sum of the ECS weight and fuel quantities due to the extra weight and power consumption.

From the data reported in the table, it is evident that, for our sample case, approximately 1 kg of payload penalty is corresponding to 1 kW of absorbed power. Vice versa, for 1 kg of system weight the payload penalty is approximately 2.2 kg.

6. Conclusions

The minimum payload penalty ECS has been selected for a helicopter.

It has been demonstrated that the selection can not be done looking just at the lighter system because of the great importance due to the consumed power.

In our sample case, the Vapor Cycle, in spite of being a heavier solution, causes a much lower payload penalty due to its reduced power consumption.

This statement is not always true. The right selection of a minimum payload penalty system greatly depends from the combination of the helicopter carachteristics, ECS performance and mission profile. The optimum selection depends from all these factors, some time conflicting one to each other.

However, the opportunity of a wide spectrum of solutions for the selection of the most suitable system is given to the designer by the recent technological development in air cycle and mainly in vapor cycle systems.

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